An Environmental-Economic Assessment of Residential Curbside Collection Programs in Central Florida

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Abstract

Inefficient collection and scheduling procedures negatively affect residential curbside collection (RCC) efficiency, greenhouse gas (GHG) emissions, and cost. As Florida aims to achieve a 75% recycling goal by 2020, municipalities have switched to single-stream recycling to improve recycling efficiency. Waste diversion and increased collection cost have forced some municipalities to reduce garbage collection frequency. The goal of this study was to explore the trade-offs between environmental and economic factors of RCC systems in Florida by evaluating the RCC system design of 25 different central Florida communities. These communities were grouped into four sets based on their RCC garbage, yard waste, and recyclables collection design, i.e., frequency of collection and use of dual-stream (DS) or single-stream (SS) recyclables collection system. For the 25 communities studied, it was observed that RCC programs that used SS recyclables collection system recycled approximately 15 to 35%, by weight of the waste steam, compared to 5 to 20% for programs that used DS. The GHG emissions associated with collection programs were estimated to be between 36 and 51 kg CO_{2eq} per metric ton of total household waste (garbage and recyclables), depending on the garbage collection frequency, recyclables collection system (DS or SS), and recyclables compaction. When recyclables offsets were considered, the GHG emissions associated with programs using SS were estimated between -760 and -560, compared to between -270 and -210 kg CO_{2eq} per metric ton of total waste for DS programs. These data suggest that RCC system design can significantly impact recyclables generation rate and efficiency, and consequently determine environmental and economic impacts of collection systems. Recycling participation rate was found to have a significant impact on the environmental and financial performance of RCC programs. Collection emissions were insignificant compared to the benefits of recycling. SS collection of recyclables provided cost benefits compared to DS, mainly due to faster collection time.

Keywords: Curbside collection; recycling; emissions; single-stream; dual-stream; Florida.

1. Introduction

Residential waste collection services provide waste removal from both single family and multi-family dwellings. A single family dwelling is an individual structure with its own lot and is usually serviced by residential curbside collection (RCC), whereas multi-family dwellings are connected structures and are usually provided with dumpsters for waste collection. RCC (the main focus of this study) includes over 8,660 programs throughout the U.S. (Smith, 2012) and serves 71% of the U.S. population (U.S. EPA, 2011a). Collection programs are established by waste management divisions (cities, municipalities, or counties) to provide waste collection and management services for residents. RCC programs usually provide garbage, recyclables, yard waste, and in some cases, food waste collection lines. Typically, such service necessitates a minimum of three weekly collections. These collection services are provided consistently throughout the year for public convenience, although waste generation rates and collection needs vary seasonally, e.g., during holidays and low-growth vegetation seasons (Maimoun et al., 2013).

In the past, populations in the northern part of the US were served weekly by one day of waste collection, whereas the southern part of the US was served weekly by two days of waste collection to minimize odors (Kim et al., 2006). However, RCC programs are faced with rising collection costs due to an increase in collection services, e.g. recyclable and yard waste lines, providing impetus to switch to once per week or every other week (bi-weekly) waste collection. On the other hand, the main disadvantage of reducing waste collection frequency to weekly or bi-weekly is the health concern associated with leaving food waste in containers for up to two weeks (McLeod and Cherrett, 2008).

In the U.S., the implementation of curbside collection of recyclables increased recycling, diverting reusable materials from the waste stream (U.S. EPA, 2011a). However, customer's convenience plays an important role in the amount of the recovered material. Everett and Peirce (1993) studied the effect of collection frequency, collection day, and containers on material recovery rate, weight of recyclables recycled annually per person, for voluntary and mandatory curbside recycling programs. The study concluded that providing containers slightly improved curbside recovery recycling rate for voluntary collection program, but not mandatory programs. On the other hand, increasing recyclables collection frequency had a slightly positive effect on the recovery recycling rate, while collection day had only a slight effect on that. Lave et al. (1999) argued that for most municipal solid waste recycling categories the costs of collection and processing exceeded the avoided disposal fee and revenues from the sales of recyclables.

Weitz et al. (2002) compared the life-cycle emission of waste management practices in the United States between 1974 and 1997. The study found that adopting alternative municipal solid waste (MSW) management practices significantly decrease greenhouse gas (GHG) emissions, despite two-fold increase in waste generation rates between 1974 and 1997. The study also estimated that collection and transportation of MSW and recyclables accounted for 1 million metric tons carbon equivalents in 1997, which was approximate 2-fold increase in emissions over 1974, mainly due 2-fold increase in the amount of MSW generated and needed to be collected. When exploring life-cycle emissions of waste management practices, Chen and Lin (2008) concluded that improving the collection efficiency and reducing the energy consumption of waste collection vehicle will help the solid waste management practice reaches its goal in reducing GHG emissions. To achieve this goal, this study was designed to find the optimal RCC program. The effect of the RCC system design on waste generation rates and recycling efficiency, e.g. less landfilling and more recycling thus avoided use of new resources, was explored. This in turn affects waste management cost and environmental impacts of MSW management practice by altering the fate of the waste at the source.

Recyclables curbside collection can be classified according to the number of collection streams. In the U.S., single-stream (SS) and dual-stream (DS) collection are most common. DS collection requires residents to separate cardboards, papers, and magazines from the rest of recyclable materials using 60-liter (16-gallon) bins, while single stream collection allows residents to mix all recyclable material together using 60-liter (16-gallon) to 240-liter (64-gallon) containers. The number of containers provided for residents varies based on the collection system used and the hauling contract. During the last decade, many communities in the US have switched from DS recyclables collection to SS collection for the ease of operations (Fitzgerald et al., 2012). On average, 14 new SS material recovery facilities (MRFs) have been added every year since 1995 (Berenyi, 2008; Fitzgerald et al., 2012). Fitzgerald et al. (2012) examined the quantities of recycled material at three MRFs and concluded that switching from DS collection to SS generated 50% more recyclables. Jamelske and kipperberg (2006) found that consumers are willing to pay for the combined switch to automated solid waste collection and SS recycling in

Madison, Wisconsin. The study presented a positive net benefit from moving to SS recycling with automated collection.

In Europe, Tucker et al. (2001) evaluated the integrated effects of reducing the frequency of curbside collection of newspapers in the UK from once every two weeks to once every four weeks. The study reported a 41% saving in fuel usage, which obviously had environmental benefits as well as cost savings of 60%. However, the net environmental benefits were less than 41% as more residents transported their recycles to collection centers. It was estimated that tonnage recovered suffered a loss of less than 2%, while participation in the curbside collection program dropped by less than 8%. McDonald and Oates (2003) found that the main reasons for non-participation in a curbside recycling scheme of paper within a UK community were lack of insufficient paper and lack of space to store recycling bins. However, the study also reported that more than half of non-participating customers recycle paper using other facilities. The study recommended changing the scheme design (mainly the color of recycling bins), scheme operation and promotion to encourage recycling. In Australia, Gillespie and Bennett (2012) estimated the willingness of households to pay for curbside collection of waste and recyclables. The study observed that respondents had a positive willingness to pay for once every two weeks or once a week collection services, while being less willing to pay for twice a week collection. Understanding the factors affecting recycling behavior is essential to increasing recycling participation (Williams and Cole, 2013). Two trials in England compared the recycling participation associated with changing to SS or DS, while reducing recyclables collection frequency. There was no difference in the recycling participation between SS and DS trials. In comparing DS and SS, Williams and Cole (2013) found that DS collected an average of 5.94 kg/household/week compared to an average of 5.63 kg/ household /week by SS.

The design of RCC programs varies significantly among U.S. areas; major differences are the number of collection lines provided (defined as the number of collection services provided to a resident); the collection frequency of each service line; the type of recycling collection system (DS or SS); the number, type, and volume of garbage and recycling containers; and the fuel used. These variables can significantly affect the recycling efficiency and participation rate of RCC programs. As municipalities try to balance environmental and financial impacts of collection services and customer satisfaction, optimal design of the RCC system will be their first step toward sustainable waste management. Accordingly, this research explores the trade-offs between environmental and economic factors to optimize RCC systems.

In 2012, Florida MSW was generated by single-family dwellings (32% of the total generation), multi-family residences (13%), and commercial entities (55%) (FDEP, 2014a). Approximately, 35% of the total MSW stream was recycled (FDEP , 2014b). Florida state has an ambitious recycling goal of 75% by 2020 (FDEP, 2013), calling for municipalities throughout the state to modify RCC programs as a mean to improve recycling. To increase the recycling efficiency, many municipalities have switched to SS recyclables collection. Moreover, some RCC programs have provided residents with multiple or larger recycling containers to encourage residents to recycle more. At the same time, many collection providers are switching to less frequent garbage collection, due to waste diversion to other service lines (e.g. recyclables and yard waste) and the rising cost of collection. As a result, a variety of program designs were found across the state of Florida, providing a good opportunity to study the effects of the RCC system design on waste generation rates and recycling efficiency. An environmental-economic assessment model was developed and used to estimate the life-cycle GHG emissions and cost of Florida RCC programs using data provided by commercial haulers. The developed model was used to evaluate the sensitivity of the model outcomes to changing input parameters, in particular, the recycling participating rate (PR_R), and to determine the minimum required PR_R to make curbside recyclables collection environmentally and economically beneficial.

2. Methods

Data collection of 112 Florida's RCC programs, serving about four million single-family households, was conducted using municipality websites. Based on the survey, communities were grouped into four sets based on their RCC garbage, yard waste, and recyclables collection design, i.e., frequency of collection and use of dual-stream (DS) or single-stream (SS) recyclables collection system. For this study, communities, haulers, and municipalities in Central Florida area were randomly asked to provide data for this study. The selection of Central Florida area was to ensure the same demographics of population. Only few communities, haulers, cities, or municipalities agreed to provide data. Twenty-five different Floridian communities, serving about half million households, were identified to participate. The rest of this Section will discuss data collection and analysis for the 25 RCC programs, followed by the development of an environmental-economic assessment model.

2.1 Hauling Data and Recovered Materials

Each commercial hauler for the 25 identified central Florida communities was asked to report the method of collection, collection schedule, number of households served, and the collected tonnage of garbage, recyclables, and yard wastes during years 2009, 2010, 2011 or 2012 (Table S1). The composition of recyclables leaving SS and DS MRFs during 2012 was obtained from local facility operators (Tables S2 and S3). The U.S. EPA Waste Reduction Model (WARM) version 13 (U.S. EPA, 2014) was used then to estimate GHG emission offsets resulting from recycling through RCC programs. The contamination rate (the portion of recyclables that was contaminated during collection and could not be recycled, i.e. the waste residue) was evaluated by analyzing the composition of materials leaving DS and SS MRFs and validated by hand-sorting of individual collection vehicle contents by commercial haulers. The waste residue reported by the SS MRF was 9.07% compared to a 10.40% reported by the DS MRF. Therefore, for the purpose of this study, 10% of all collected DS and SS recyclables was assumed to be later diverted to landfills.

2.2 Analysis of Waste Generation Characteristics

The total household waste generated was defined as the sum of garbage and recyclables, excluding yard waste. The generation rate of total household waste was calculated using Equation 1.

$$GR_T = \frac{(W_G+W_R) \times 1000}{N_T \times 365} \qquad (1)$$

where:

GR_T: Generation rate of total household waste (kg per served household per day)

N_T: Maximum number of households served by collection contract

W_G: Annual weight of garbage collected from N_T customers (Metric Ton (MT) per year)

W_R: Annual weight of recyclables collected from N_T customers (MT per year)

Recycling Percentage (RP) was calculated as the percent of GR_T that was recycled, as shown in Equation 2.

$$RP\ (\%) = \frac{W_R}{W_R+W_G}\ x\ 100\% \qquad (2)$$

2.3 The Environmental-Economic Assessment Model

An environmental-economic assessment model was developed and used to estimate the GHG emissions and cost of Florida RCC programs as a function of recycling participation rate ($PR_{R,}$

percent of households' participating in curbside recycling). A sensitivity analysis of the results was performed to evaluate the effect of input parameters on model outputs.

2.3.1. Waste Generation Rate as a Function of PR_R

The generation rate of recyclables per participating household (GR_R, kg per participating household per day) was calculated using PR_R as shown in Equation 3.

$$GR_R = \frac{W_R \times 1000}{PR_R \times 365 \times N_T} \qquad (3)$$

In order to calculate the average garbage and recyclables generation rate per household served by collection contract (kg per served household per day), it was assumed that the reported collected tonnage was generated by the total number of households served by collection contract. A statistical analysis was used to test the research hypothesis that Florida's households generate similar quantity of total waste regardless of the RCC program characteristics.

Recyclables collection diverts recyclables from the garbage collection line; the higher the system participation rate and recycling percentage, the less garbage is collected. In 2012, the average recycling participating rate reported in Florida curbside collection programs was 67% (FDEP , 2014c). The average recycling participation rate varied significantly across Florida, thus this study was designed to understand the impact of recycling participation rate on the environmental and economic performance of RCC programs. In this study, garbage participation rate (PR_G) was assumed to be 100%, based on the haulers' input. PR_R was reported to be 70% by only four of the 25 central Florida communities; this value, 70%, was used to analyze the environmental and economic impacts for all 25 communities. The garbage generation rate can be calculated as a function of the PR_R, as shown in Equation 4, to determine the impact of this parameter on the environmental and economic performance of RCC programs.

$$GR_G = \frac{W_G \times 1000}{PR_G \times 365 \times N_T} = \frac{GR_T - (PR_R \times GR_R)}{PR_G} \qquad (4)$$

2.3.2. Households Served per Collection Trip as a Function of PR_R

During each collection trip, a waste collection vehicle starts at the garage and then travels to the collection site where it stops at participating households. At the end of the collection trip, the vehicle transports the collected material to the post-collection facility (e.g., a landfill, transfer station, waste-to-energy facility, or MRF). Then, the waste collection vehicle travels empty from the post-collection facility back to the garage. Time and fuel use for curbside waste collection can be considerably different depending on the housing density along the collection route, however it was estimated that the fuel consumption during waste collection accounts for more than 60% of the total daily fuel use (Nguyen and Wilson, 2010). Because the focus of this study was on waste collection activities that consume most of the fuel and are most impacted by PR_R, this analysis only reflects emissions and costs for a single collection trip. It was assumed that the characteristics (distance and time) for travel between the garage and collection site, between the collection site and post-collection facility, and between the post-collection facility and garage, are constant for all the tested RCC systems, as well as break times and unloading time at the post-collection facility.

Default values for model variables are given in Table 1. For a single trip, the number of households that can be served was constrained by the truck legal weight limit - difference between the gross vehicle weight rating and curb weight -(C, MT) for garbage and yard waste, truck volume (V, m^3) or driver daily hours (T, hours) for recyclables. The maximum number of households that can be served for garbage collection during one trip can be calculated based on truck’s legal weight and generation rates of garbage using Equation 5.

$$N_{G^*} = \frac{C \times 1000}{\frac{7days}{week} \times GR_G} \qquad (5)$$

where:

N_{G^*}: Maximum number of households that can be served for garbage collection during a single collection trip.

In case of two days of garbage collection per week, it was assumed that two-thirds of the weekly garbage generation will be collected on the first day, while the rest will be collected on the second day.

Table 1: The values of the environmental-economic assessment model's input variables.

Model Inputs	Symbol	Default Value	Unit	Justification/Reference
Distance between households	D_{HH}	22.3 (±14.6)	m (meters)	Distance between households based on a random 20 Florid household's sample.
Travel speed between households	S_{HH}	10	km/h (kilometers per hour)	Assumed travel speed
Time to collect garbage per household	$T_{1(G)}$	8.74	S (seconds)	Curtis and Dumas (2000)
Time to collect DS recyclables per household	$T_{1(DS)}$	27	S	Curtis and Dumas (2000)
Time to collect SS recyclables per household	$T_{1(SS)}$	9	S	Curtis and Dumas (2000)
Truck legal weight	C	10.4	MT (metric tons)	Commercial haulers' specifications
Truck volume	V	24.5	m^3	Commercial haulers' specifications
Driver daily hours	T_{max}	10.5	h (hours)	Commercial haulers' specifications
Lunch and Break	L&B	60	Min (minutes)	Curtis and Dumas (2000)
Vehicle driving range	R_{max}	240	km (Kilometer s)	Commercial haulers' specifications
Distance from garage to start collection (Garbage and Recyclables)	D_{GA}	19	km	Curtis and Dumas (2000)
Time from garage to start collection (Garbage and Recyclables)	T_{GA}	20	Min	Curtis and Dumas (2000)
Distance from post-collection facility to garage (Garbage and Recyclables)	D_{FG}	19	km	Curtis and Dumas (2000)
Travel time from post-collection facility to garage (Garbage and Recyclables)	T_{FG}	20	Min	Curtis and Dumas (2000)
Distance from collection site to post-collection facility (Garbage)	$D_{F(G})$	35	km	Curtis and Dumas (2000)
Travel time from collection site to post-collection facility (Garbage)	T_F	44	Min	Curtis and Dumas (2000)
Distance from collection site to post-collection facility (Recyclables)	$D_{F(R)}$	35 (DS); 37 (SS)	km	Curtis and Dumas (2000)
Travel time from collection site to post-collection facility (Recyclables)	$T_{F(R)}$	46 (DS); 44 (SS)	Min	Curtis and Dumas (2000)

In case of one day of recyclables collection per week, the maximum number of households that can be served for recyclables during one trip (N_{R^*}) can be calculated based on V, specific weight (SW, kg/m^3), GR_R and PR_R using Equation 6. Based on field data from the haulers, the SW of recyclables was set to 90 and 130 kg/m^3 for collection without and with compaction, respectively. Equation 6 was used to estimate the number of households that can be served for recyclables collection at different PR_R, while using DS or SS collection, with or without compaction.

$$N_{R^*} = \frac{V \times SW}{\frac{7\ days}{week} \times GR_R \times PR_R} \tag{6}$$

2.3.3. Collection Speed as a Function of PR_R

For a single daily trip, it was assumed that a waste collection vehicle will not exceed the default driver daily hours (T_{max} = 10.5 h) or the driving range (R_{max} = 240 km). In the case of low waste generation or participation rate, the waste collection vehicle will have to stop collecting and head back to the post-collection facility due to either driver or driving range constraint and the truck will reach the post-collection facility less than full. An increase in PR_R will result in greater amount of recycled material; however, this will be accompanied by increased collection time for the same total collection distance and subsequently a reduced average speed. The average speed associated with waste collection was calculated by dividing the total distance travelled (distance between consecutive houses multiplied with number of houses served), by total time (estimated as sum of time traveling between consecutive houses and collection time at stops). The average collection speed of recyclables (S_R, km/h) and garbage (S_G, km/h) were calculated using Equations 7 and 8. The time to collect recyclables per participating household (T_1) depends on the type of collection system, i.e., DS ($T_{1(DS)}$) or SS ($T_{1(SS)}$).

$$S_R = \frac{D_{HH} \times (N_{R^*} - 1)}{(N_{R^*} - 1) \times \left[\frac{D_{HH}}{1{,}000 \times S_{HH}}\right] + \frac{PR_R \times (N_{R^*}) \times \left[T_{1(DS)}\ or\ T_{1(SS)}\right]}{3{,}600}} \tag{7}$$

$$S_G = \frac{D_{HH} \times (N_{G^*} - 1)}{(N_{G^*} - 1) \times \left[\frac{D_{HH}}{1{,}000 \times S_{HH}}\right] + \frac{(N_{G^*}) \times \left[T_{1(G)}\right]}{3{,}600}} \tag{8}$$

where:

D_{HH}: Distance between households (m)

S_{HH}: Travel speed between households (km/h)

2.3.4. Collection GHG Emissions

Garbage collection GHG emissions (kg CO_{2eq} per MT of garbage) consist of the summation of collection, garage-to-collection site, collection site-to-post-collection facility, and post-collection facility-to-garage emissions, divided by the collected garbage tonnage. The emission factor (kg CO_{2eq} per km travel) associated with each driving mode was estimated using the average speed calculated based on default driving distance and time listed in Table 1. In this study, the fuel mileage of garbage, recyclables, and yard waste collection vehicles was obtained from commercial haulers for different travel speeds. According to the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model by Argonne National Laboratory, the lower heating value of one liter of diesel is 36,000 kilojoules (kJ), and the well-to-wheel GHG emissions (summation of well-to-pump and pump-to-wheel emissions) associated with each kJ is equal to 0.095 grams of carbon dioxide equivalent (CO_{2Eq}) (U.S. DOE, 2012). Therefore, 3,400 grams of CO_{2eq} are emitted per liter of diesel burned. The average garbage collection speed was estimated using Equation 8 and the variable values given in Table 1. The same approach was used to calculate the GHG emissions associated with recyclables collection (kg CO_{2eq} per MT of recyclables). However, for recyclables, the collection emissions were offset by -2.2 $MTCO_{2eq}$ per MT of recyclables collected using DS or SS collection system. Emission offsets were calculated using WARM version 13 and the recyclables composition leaving SS and DS MRFs provided in Tables S2 and S3. This estimate accounted for each material loses during remanufacturing as specified by WARM. For this study, additional emissions credits associated with diverting recyclables from landfills or other traditional MSW management facilities were not added to the benefits of recycling. The GHG emissions of the total collected household waste were the summation of the GHG emissions of garbage collection and the net GHG emissions of recyclables collection as shown in Equation 9.

$$CE_T = (1 - RP) \times CE_G + RP \times (CE_R - O_R) \quad (9)$$

where:

CE_T: Net collection GHG emissions (kg CO_{2eq} per MT of total household waste generated)

CE_G: Garbage collection emissions (kg CO_{2eq} per MT of garbage collected per trip)

CE_R: Recyclables collection emissions (kg CO_{2eq} per MT of recyclables collected per trip)

O_R: Recyclables emissions offset (kg CO_{2eq} per MT of recyclable collected per trip)

2.3.5. Collection Cost

Collection cost is a function of the initial (capital) costs of vehicle acquirement, fuel mileage of waste collection vehicles, driving routes, truck maintenance costs, driver hourly rates, and overhead management costs. In this study, the overhead management and vehicle initial costs were excluded because they are independent of the driving hours and distances related to RCC system design. The collection cost per trip was measured as a function of driving hours and driving distances, fuel cost, and maintenance and labor cost. In Florida, the avoided costs from recyclables diversion were \$60-80 per ton for waste-to-energy, and \$40 per ton for landfilling. The processing cost of recyclables at a MRF can also be significant. Dubanowitz (2000) estimated that the processing cost of recyclable at \$127 per ton of material diverted. The average selling price of recyclables varies significantly, and during the last and the first quarters of 2012 and 2013 it averaged \$100 per one MT of recyclables collected. . For this study, net revenues (generated by selling recyclables and avoided disposal cost, and adding MRF cost) were subtracted from the collection cost. Three net revenues scenarios were considered: \$50, \$100, \$150 per MT of recyclables. The net collection cost of recyclables was calculated for the RCC programs, varying PR_R, fuel cost, and recyclables revenues at constant maintenance cost and labor wages, because maintenance cost and labor wages are more stable than fuel cost and recyclables revenues. Collection vehicle maintenance cost was reported by commercial haulers at $8.5 per hour of truck operation, while hourly labor wage for haulers was assumed to be $20 per hour.

3. *Results*

The online survey found that 58% of Florida RCC programs utilize SS recycling system and 38% utilize DS recycling system, whereas 4% do not provide any curbside recycling program. Weekly collection schedules were found to vary considerably, with 49% of RCC programs providing two days of garbage (G), one day of recyclables (R), and one day of yard waste collection (YS) [represented by (2G, 1R, 1YW)] and 29% providing one day of garbage, one day of recyclables and one day of yard waste collection (1G, 1R, 1YW). The remaining programs used a variety of collection system designs, but for the most part provided one or two days of garbage collection, no or every-other week recyclables collection, and every-other week yard waste collection. The selected 25 central Florida RCC systems reflected the survey findings and were placed into four categories, representing Florida's most common RCC programs, based on their collection schedule and recyclables collection system as follows:

Group A: 2G, 1R, 1YW-DS Collection (16 communities)

Group B: 1G, 1R, 1YW-DS Collection (3 communities)

Group C: 2G, 1R, 1YW-SS Collection (4 communities)

Group D: 1G, 1R, 1YW-SS Collection (2 communities).

Garbage containers ranged in size from 79 to 360 liters (21 to 96 gallons), while recycling containers were either 61-liter (16-gallon) bins or 240 to 340-liter (64 to 90-gallon) toters. In general, toters were only used with the SS recyclables collection system, while bins were used mainly with the DS system, but in few cases, they were used with the SS recyclables collection system.

3.1 Waste Generation Characteristics of RCC programs

The program design, household count, and the reported tonnage of the 25 studied central Florida communities are provided in Table S1. The data collected from one collection zone represented less than one full year period, therefore it was only used to evaluate recycling percentage. The median garbage generation rate of SS programs was slightly less than DS programs (Figure 1a).. Overall, the mean garbage generation rates for SS and DS recycling programs were 2.32 (±0.71) and 2.69 (±0.47) kg per household per day, respectively.

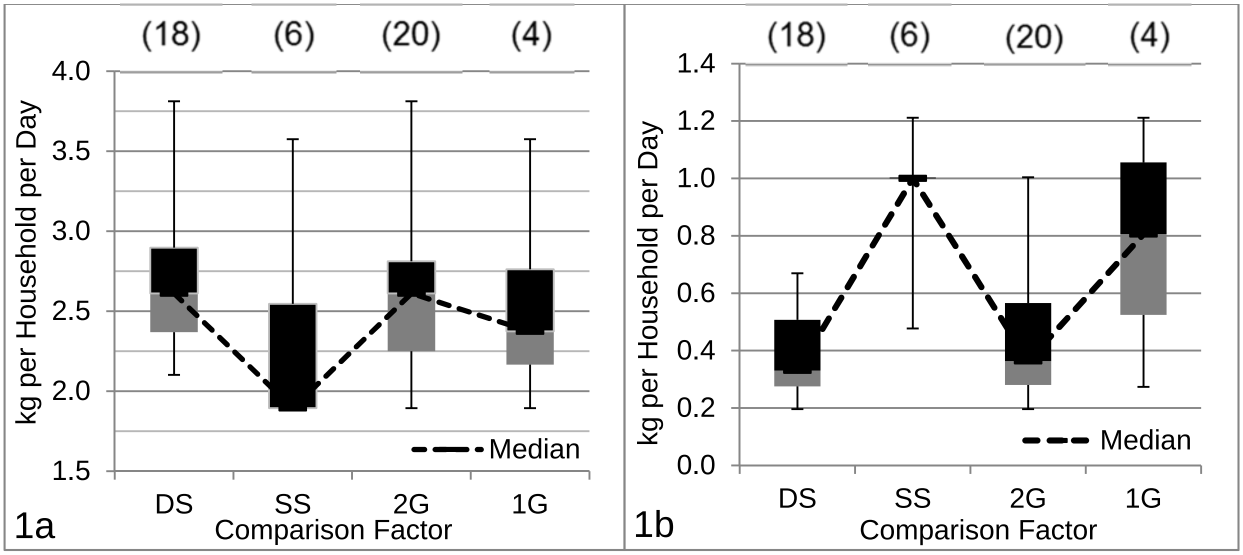

Figure 1: Garbage and recyclables generation rates of dual-stream (DS), single-stream (SS), two-day garbage collection (2G), and 1-day garbage collection (1G) RCC programs. (Box-whisker plots of (a) garbage and (b) recyclables generation rates as calculated for program designs, where median values are indicated by the gray-black color interface, box borders denoted 50% interquartile range and whiskers denote data set range. The sample size of each group is given in parentheses.)

In comparing recyclables generation rates, programs implementing SS collection had a higher recyclables generation rate compared to DS programs (Figure 1b). The mean recyclables generation rates for 2G, 1R, 1YW-DS;1G,1R,1YW-DS; 2G,1R,1YW-SS; and 1G,1R,1YW-SS programs were 0.37 (±0.14); 0.44 (±0.24); 0.87 (±0.26); and 1.11 (±0.15) kg per household per day, respectively. Overall, the mean recyclables generation rates were 0.38 (±0.15) and 0.95 (±0.25) kg per household per day for DS and SS, respectively.

The total household waste generation rates are shown in Figure 2a. For the 25 studied communities, the overall mean total household waste was 3.11 (±0.56) kg per household per day, while the mean recycling percentages, by weight, were 30% (±8%) and 13% (±4%) for SS and DS recycling programs, respectively. These results support the research hypothesis that, on average, central Florida households generate similar quantities of waste (garbage plus recyclables), and the more efficient the recycling system, the less garbage collected.

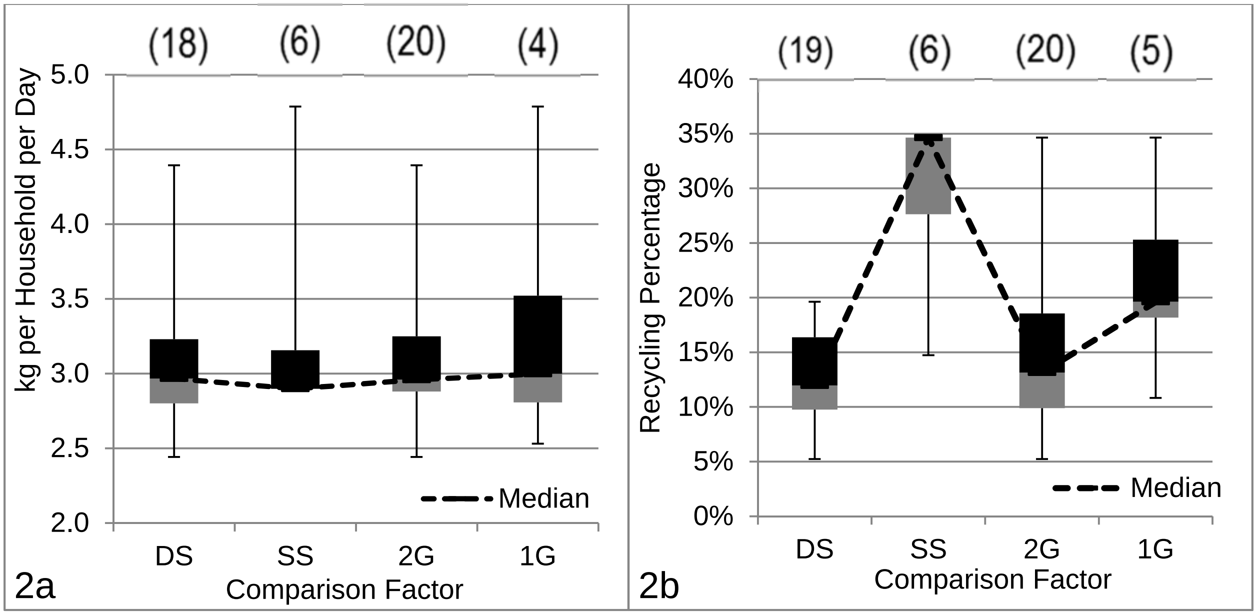

Figure 2: Total household waste and recycling percentage of dual-stream (DS), single-stream (SS), 2-day garbage collection (2G), and 1-day of garbage collection (1G) RCC programs. (Box-whisker plots of (a) household total waste and (b) recycling percentage as calculated for program designs, where median values are indicated by the gray-black color interface, box borders denoted 50% interquartile range and whiskers denote data set range. The sample size of each group is given in parentheses.)

The mean recycling percentages, by weight, for programs 2G,1R,1YW-DS; 1G,1R,1YW-DS; 2G,1R,1YW-SS; and 1G,1R,1YW-SS were 12% (±4%); 16% (±5%), 30% (±10%), and 30% (±10%), respectively. Recycling percentage ranged 5-20% for DS, and 15-35% for SS. The recycling percentage reported by SS (which serve more than 50% of Florida RCC programs) is close to Florida overall recycling average (35%) in 2012. In comparing DS and SS, the number of bins (DS system) provided for residents varies based on the collection system used and the hauling contract. In general, residents are not willing to use more than two bins due to space limitation (Personal Communication with Major hauler Manager, 2012). It was observed that any recyclables placed outside bins was usually discarded as garbage. Moreover, SS recycling collection programs provide residents with bigger recycling containers. As a result, residents are not required to cut cardboard boxes (in most cases), thus provides move convenient recycling.

3.2 Fuel Consumption of Diesel-fueled Waste Collection Vehicles

The fuel consumption and the associated average speed for typical garbage, recyclable and yard waste collection vehicles, which is linked to approximately 600 waste collection routes in Central Florida, was obtained from commercial haulers. In another study, Farzaneh et al. (2009) reported the fuel consumption of waste collection vehicles for 12 different average speeds. The fuel consumption of waste collection obtained from commercial haulers and Farzaneh et al. (2009) was plotted as a function of the average collection speed as shown in Figure 3.

Maimoun et al. (2013) modeled the fuel consumption as a function of the average speed using the U.S. EPA Motor Vehicle Emission Simulator (MOVES) 2010a software (U.S. EPA, 2011b). As shown in Figure 3, MOVES underestimates the fuel consumption for the average collection speed of 7 to 25 km/h; this is a result of the numerous driving cycles that can be characterized by the same average speed, as well as vehicle age, engine size, and weight. Overall, the fuel mileage of waste collection vehicles increased from 0.2 and 1.9 km per liter of diesel consumed as the average collection speed increased from 2 to 25 km per hour.

After 25 km/h, the fuel mileage of waste collection vehicles increased more consistently with MOVES. The fuel mileage increased slightly from 1.9 to 2.0 km per liter of diesel as the average speed increased 25 to 30 km/h. After 30 km/h according to MOVES (not illustrated by the figure due to the limited field data), the fuel mileage continued to increase slightly to reach 2.6 km per liter of diesel at 60 km/h, reflecting highway driving. Next, field measurements (under 25 km/h) and MOVES estimates (above 25 km/h) of fuel consumption were used to estimate the Florida RCC programs' GHG emissions as illustrated in Section 2.3.4.

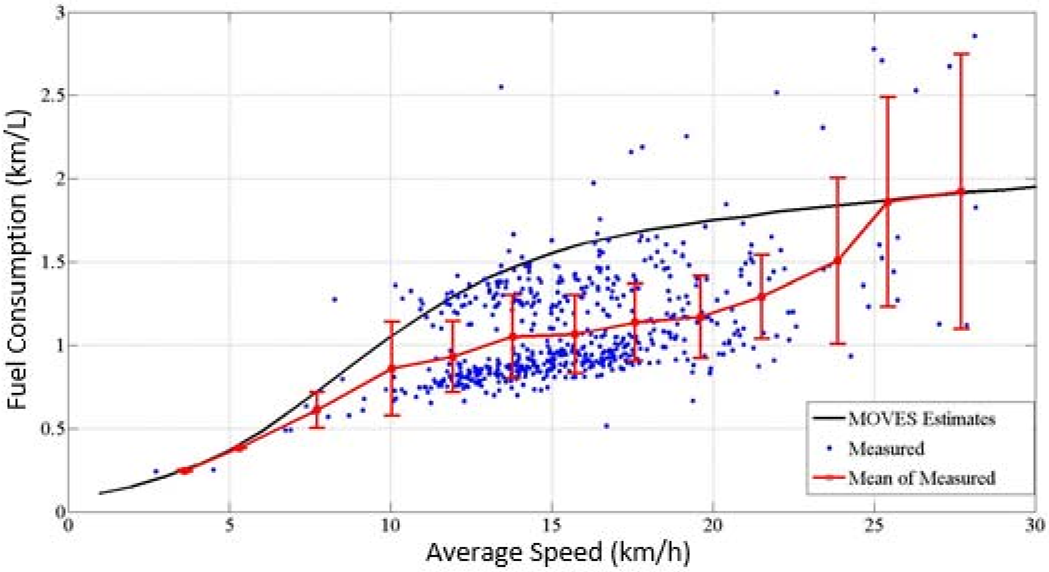

Figure 3: Fuel mileage of diesel-fueled waste collection vehicles as a function of average vehicle speed. (The "mean of measured" represents the mean fuel mileage, for diesel-fueled waste collection, measured by commercial haulers (600 data points) and Farzaneh et al. (2009) (12 data points). Whickers denote one standard deviation. The average fuel mileage reported by Maimoun et al. (2013) using the U.S. EPA MOVES 2010a software is represented by the black curve.)

3.3 Florida RCC Programs' GHG Emissions

3.3.1 Garbage Collection GHG Emissions

As implied by Equation 5, customers' participation in recycling diverts recyclables from the total household waste, generating less garbage. On the other hand, non-participating customers dispose recyclables in the garbage collection line and generate more garbage. Thus, as PR_R increases, the number of households that can be served for garbage collection by one vehicle per trip increases.

Figure 4 illustrates the maximum number of households (N_{G*}) that can be served for garbage collection by one vehicle per trip as a function of PR_R; the daily limit represents the hypothetical maximum number of household that can be served in 10.5 hours, including breaks. The number of households served per trip and the associated PR_R were used to calculate the average garbage collection speed (S_G) using Equation 8.

The fuel mileage was obtained from Figure 3 and was used to estimate the GHG emissions associated with garbage collection (kg CO_{2eq} per MT of garbage) as described in Section 2.3.4. As PR_R increases, the number of households served per trip increases; thus the GHG emissions associated with garbage collection (kg CO_{2eq} per MT garbage) increases, as a truck travels and stops more.

The garbage collection's GHG emissions was found to increase from 20 to 30 kg CO_{2eq} per MT of garbage, for programs with one day of garbage collection as PR_R increased from 0 to 100%. For programs providing two days of garbage collection, the GHG emissions increased from 30 to 45 kg CO_{2eq} per MT of garbage as PR_R increased from 0 to 100%.

In comparison, using the collection model, developed by Curtis and Dumas (2000) and has been incorporated into the US municipal solid waste decision support tool (MSW-DST), the

GHG emissions associated with curbside collection of garbage were estimated to be 28.6 CO_{2eq} per MT of garbage. The range observed in this study was the result of accounting for different collection frequencies, recycling generation rates, and PR_R. In another study in Denmark that supports this study findings, Larsen et al. (2009) observed a considerable variation in fuel consumption, and thus the GHG emissions associated with different collection schemes, ranging from 4.8 and 35 kg CO_{2eq} per MT of waste. The GHG emissions associated with single-family waste collection in urban areas, was estimated to be between 11.4 and 12.4 Kg CO_{2eq} per MT of waste, while the GHG emissions associated with rural waste collection was between 22 and 35 kg CO_{2eq} per MT of waste as trucks travel more to collect waste (Larsen et al., 2009). The variances could be linked to the difference in collection schemes, routes, vehicle, and generation rates between the U.S. and Denmark.

Garbage collection emissions were calculated as kg CO_{2eq} per MT of garbage; however, this analysis cannot be used to compare RCC programs at different PR_R. Emissions should be adjusted to account for the reduction in garbage collection as PR_R increases (Equation 9). As PR_R increases, collected garbage decreases, and garbage collection emissions decline by the change in garbage fraction in the total waste stream. Figure 5 illustrates garbage collection emissions as kg CO_{2eq} per MT of total waste. The emission gap between programs 2G, 1R, 1YW and 1G, 1R, 1YW represents the emissions associated with the second day of garbage collection service, resulting in a 50% increase in GHG emissions at PR_R=0%, compared to a 60% and 80% increase in GHG emissions at PR_R=100% for the DS and SS programs, respectively. Collection of less garbage by SS programs allows garbage trucks to serve more households per trip. However for two day per week garbage collection, the second day of garbage collection provided by SS programs was constrained by daily hours at a PR_R of 40% or higher (Figure 4). Additionally, the

RE of programs using 1G, 1R, 1YW-SS is slightly higher than programs using 2G, 1R, 1YW-SS; therefore, at 100% PR_R, an extra day of garbage collection resulted in an 80% increase in GHG emissions when using SS compared to one day garbage collection (Figure 5). As PR_R increased, the emissions associated with programs serviced with SS decreased more than DS programs, due to the effectiveness of the SS system in diverting more waste to recycling.

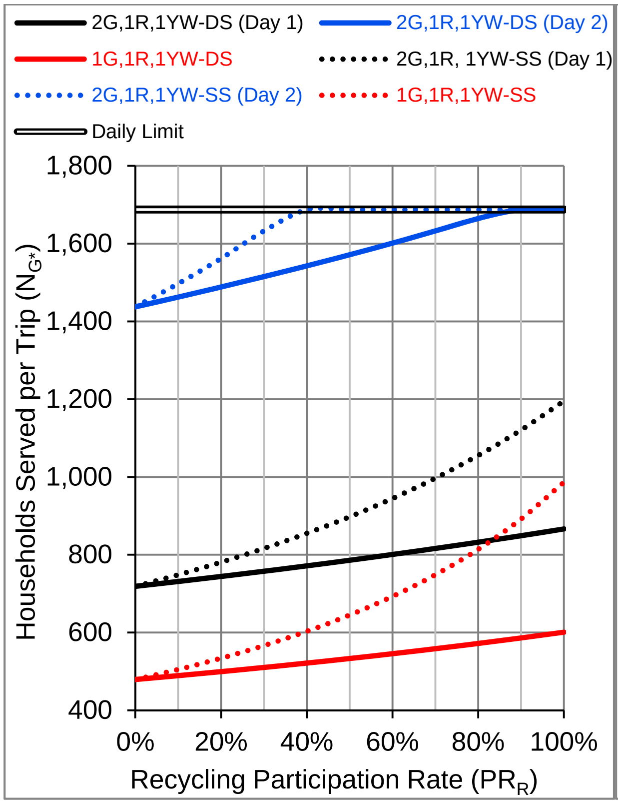

Figure 4: The number of households (N_{G^*}) that can be served for garbage collection per vehicle per trip.

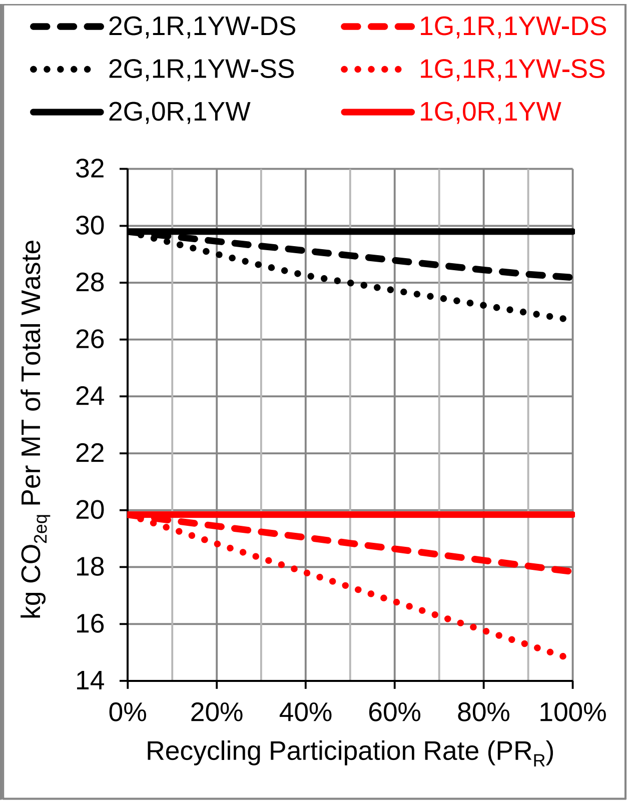

Figure 5: GHG emissions during garbage collection as a function of PR_R (kg CO_{2eq} per MT total waste).

3.3.2 Recyclable Collection GHG Emissions

Figures 6a and 6b illustrate the number of households that can be served for recyclable collection by each vehicle per trip based on Equation 6. As PR_R increases, the number of dwellings served per trip decreases due to more recyclables pickups. Compaction of recyclables enables serving more households per vehicle per trip, although the quality of recyclables may be reduced. The daily limit represents the hypothetical maximum number of households that can be served within 10.5 hours, including time devoted to non-collection activates. SS programs generate more recyclables per dwelling than DS; thus less households can be served per trip compared to DS. The collection of recyclables without compaction limits the number of households that can be served per trip, while a longer collection time ($T_{1(DS)}$) per stop associated with DS collection can also limit the number of dwellings that can be served per trip, i.e. the number of households served per trip using DS recyclables collection system was limited by the drivers daily hours for any PR_R below 30% and 80% for collection without and with compaction, respectively.

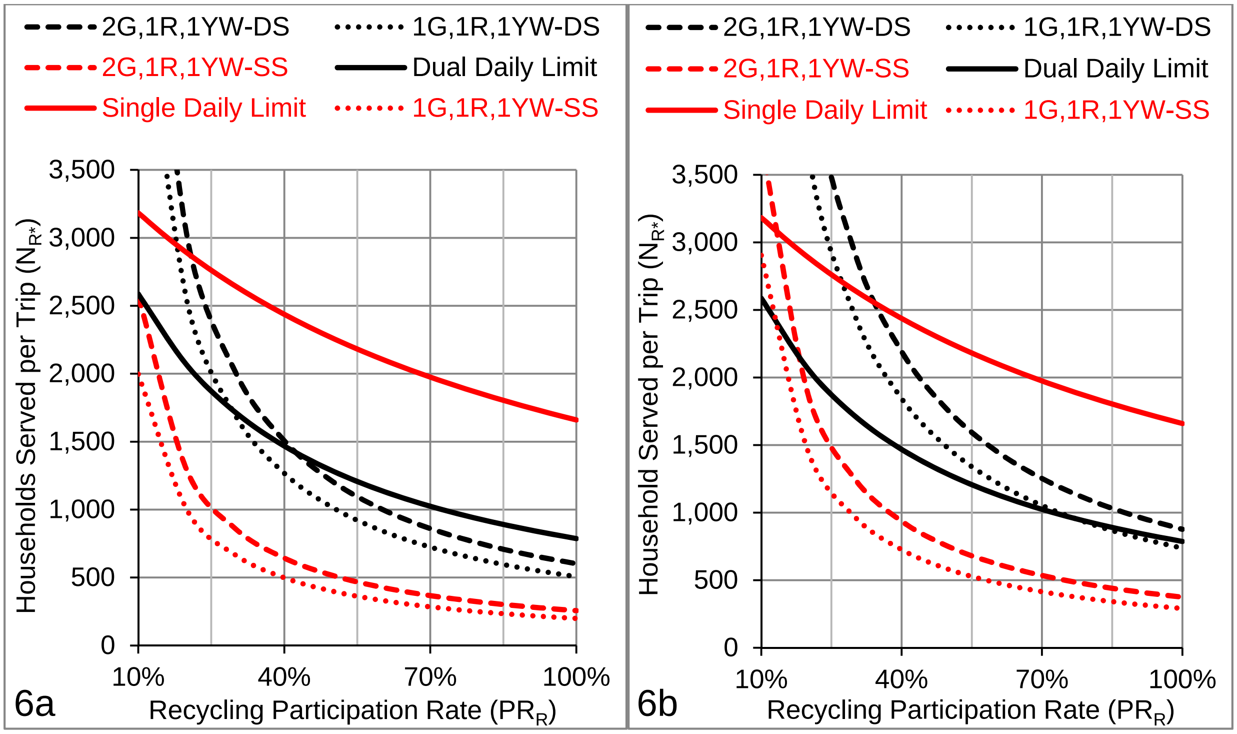

Figure 6: The number of households that can be served for recyclables per vehicle per trip, (a) without compaction, (b) with compaction for each program design**.** The daily limit represents the hypothetical maximum number of households that can be served in one day (10.5 hours including breaks).

The number of household served per trip (N_{R^*}) and the associated PR_R were used to calculate the average collection speed (S_R) using Equation 7. The fuel mileage was obtained from Figure 3 and was used to estimate the GHG emissions associated with recyclables collection (kg CO_{2eq} per MT recyclables) as described in Section 2.3. Although, the average speed of the recyclables collection truck decreases as PR_R increases; it was observed that the GHG emissions associated with recyclables collection (kg CO_{2eq} per MT recyclables) decreases. This was due to shorter distance travelled by collection truck to collect the same amount of recyclables. In this study, SS recyclables collection GHG emissions decreases from 155 to 52 kg CO_{2eq} per MT of recyclables as PR_R increases from 10% to 100%, whereas a decline from 480 to 125 Kg CO_{2eq} per MT recyclables was observed for DS collection as PR_R increases from 10% to 100%. SS collection systems provides faster time to collect recyclables (9 seconds per stop) than DS (27 seconds). Therefore, more households can be served and the fuel consumption drops as the average speed of collection is higher. The average collection speed of SS programs was between 4-9 km/h, compared to 2-7 km/h for DS programs. The GHG emissions associated with SS and DS recyclables collection were 101 and 144 kg CO_{2eq} per MT recyclables, respectively (Curtis and Dumas, 2000). In another study, Fitzgerald et al. (2012) reported the GHG emissions associated with recyclables collection at 55 and 77 kg CO_{2eq} per MT of recyclables using of SS and DS, respectively. The results presented here are consistent with literature ranges; this study also found relatively higher GHG collection emissions associated with SS collection compared to DS. The wide range for collection emissions observed in this study demonstrates the significance of considering PR_R in evaluating the environmental impact of recyclables collection.

Recyclables collection emissions were calculated as kg CO_{2eq} per MT of recyclables; however, this analysis cannot be used to compare RCC programs at different PR_R. Emissions have to be adjusted to account for the increase in recyclables collection as PR_R increases (Equation 9). As a result of increase in PR_R, collected recyclables increases, and recyclables collection emissions increase by the fraction of recyclables in the total waste stream. Figure 7 illustrates recyclables collection as kg CO_{2eq} per MT of total waste. As PR_R increases, GHG emissions per MT total waste associated with recyclables collection increases.

At any PR_R, GHG emissions from SS recyclables collection systems with compaction are less than DS collection systems, even though SS programs are associated with higher recyclables' generation rate and RE. On the other hand, collection without compaction has higher emissions as less recyclables are collected per trip. The collection emissions of recyclables without compaction for 1G, 1R, 1YW-SS exceed emissions of all DS programs' recyclables' emissions for any PR_R higher than 25%. In case of 2G, 1R, 1YW-SS without compaction, recyclables collection emissions exceed emissions of all DS recyclables collection with compaction for any PR_R above 85%.

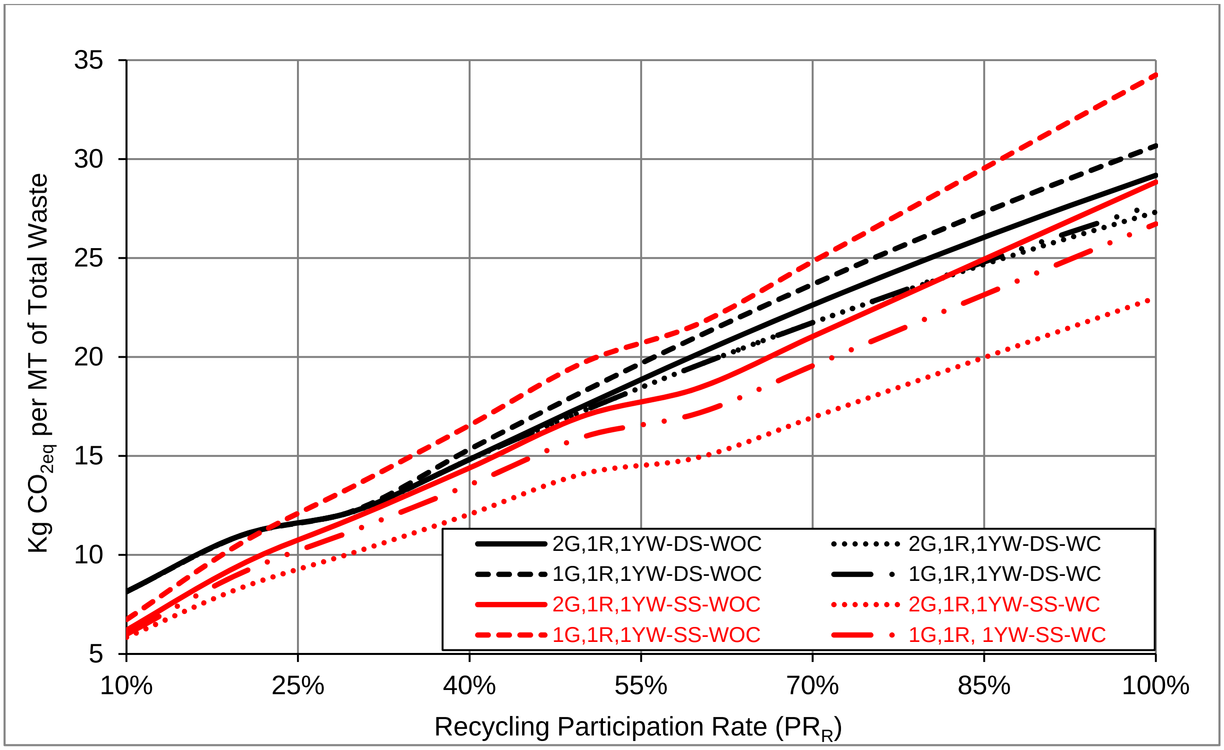

Figure 7: Recyclables collection line's GHG emissions. (For each program, emissions were calculated for recyclables collection using SS or DS collection system with compaction (WC) or without compaction (WOC).)

3.3.3 Total Waste Collection GHG Emissions

The GHG emissions of the garbage collection line were added to the recyclables collection line to estimate the total collection emissions associated with each program (Figure 8a). When PR_R was low, the effect of having a second day of garbage collection was accompanied by a 1.4-fold increase in emissions over programs with one day of garbage collection. An increase in PR_R increased waste diversion, reducing garbage collection emissions while increasing recyclables' collection emissions. The collection of household waste without curbside recycling (2G, 0R, 1YW and 1G, 0R, 1YW), as shown in Figure 8a, had relatively low emissions (30 and 19 kg CO_{2eq} per MT of total waste, respectively); however, the quality and cost of recovering recyclables from the mixed waste stream is a concern.

At PR_R=70%, the GHG emissions associated with the four collection programs are estimated to be between 36 and 51 kg CO_{2eq} per MT of total household waste, depending on the garbage collection frequency, recyclables collection system (DS or SS), and recyclables compaction. RCC programs implementing SS recyclables collection with compaction have lower emissions than DS programs. When recyclables offsets were considered (Figure 8b), the GHG emissions associated with programs using SS were -760 to -570, compared to -270 to -210 kg CO_{2eq} per MT of total waste for DS programs. In any case, collection emissions were negligible when compared to the benefits of recycling offsets. However, the significance given to collection emissions is urban pollution as the bulk of the emissions are considered tail-pipe emissions.

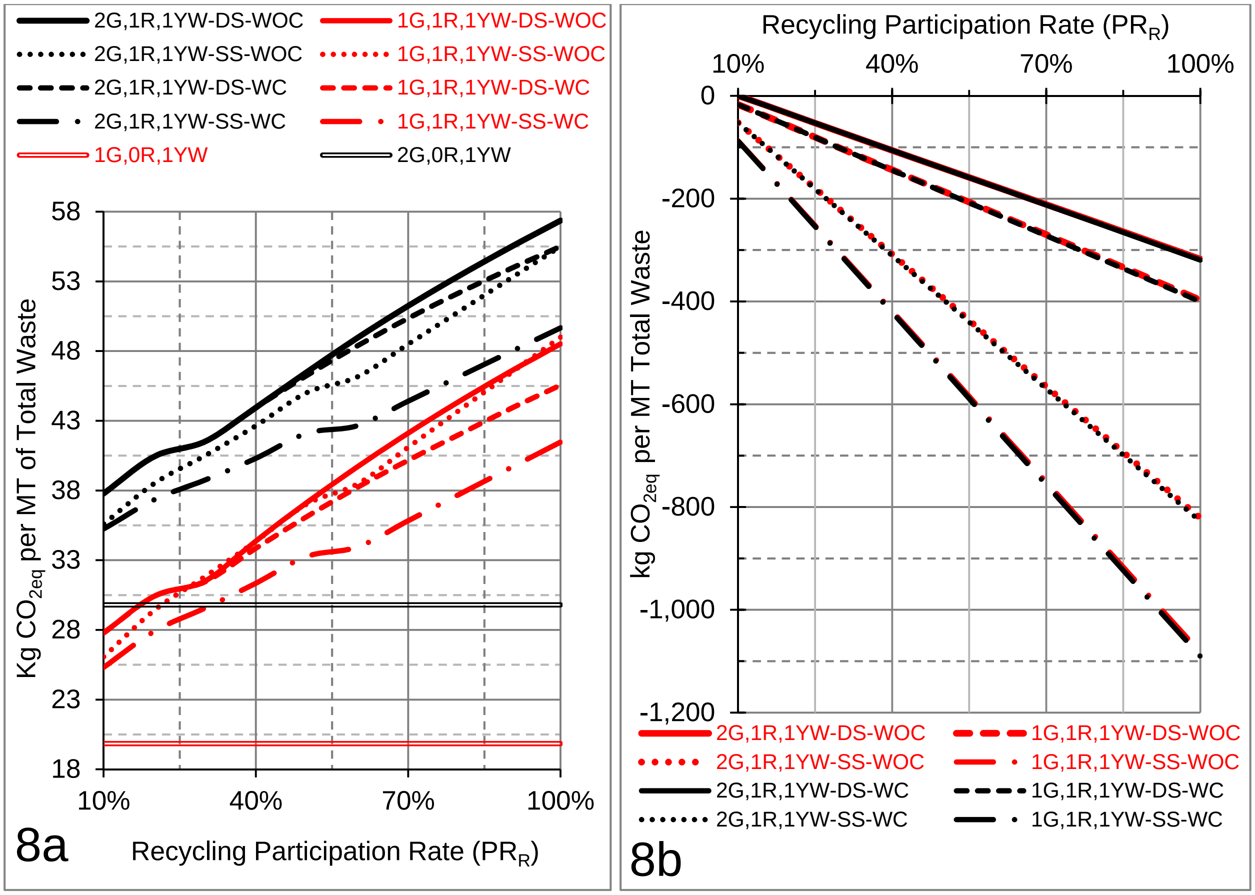

Figure 8: Florida RCC programs' total waste collection's GHG emissions, (a) Total waste collection's GHG emissions, (b) Net GHG emissions. GHG emissions were estimated for different RCC system designs as kg CO_{2eq} per metric ton of total waste (garbage and recyclables) collected. For each program, emissions were evaluated for recyclables collection using SS or DS collection system with compaction (WC) or without compaction (WOC).

3.4 Collection Cost of RCC programs

As PR_R increases, the number of households served for garbage collection per trip increases, as a result the fuel consumption (liters of diesel per MT of garbage) and collection time (hours per MT of garbage) increases. The fuel consumption associated with one day of garbage collection increases from 7.2 to 10 L per MT of garbage as PR_R increases from 0 to 100%. On the other hand, programs providing two days of garbage collection had fuel consumption increases from 10 to 15 L per MT of garbage as PR_R increases from 0 to 100%. Larsen et al. (2009) also observed a considerable variation in the fuel consumed for different collection schemes in

Denmark, ranging from 1.4–10.1 L diesel per ton of waste, where rural areas' waste collection exhibited a fuel consumption of 6-10 L per ton of waste. The estimated fuel consumption was comparable to rural areas fuel consumption; however differences in garbage generation characteristics between the U.S. and Denmark, collection frequency, household setup, non-collection driving activities, and PP_R are responsible for the fuel consumption variability.

Fuel consumption was calculated as L per MT of garbage; however, this analysis cannot be used to compare RCC programs at different PR_R. Fuel consumption should be adjusted to account for the reduction in garbage collection as PR_R increases. As PR_R increases, collected garbage decreases, and the fuel consumed and collection time decease by the garbage fraction in the total waste stream. Garbage collection costs were estimated for RCC programs at two different fuel prices ($1 and $2 per liter of diesel) and are shown in Figure 9. The figure also shows the potential savings in garbage collection as PR_R increases from 0% to 100%. An increase in garbage collection services from one to two days is associated with increased fuel, labor, and maintenance cost resulting in 50% increase in collection costs. Doubling fuel price results in a 35% increase in garbage collection costs. Potential savings in garbage collection are considerably higher for programs implementing SS recycling programs for all PR_R because SS programs are more efficient in diverting recyclables from the waste stream, generating less garbage.

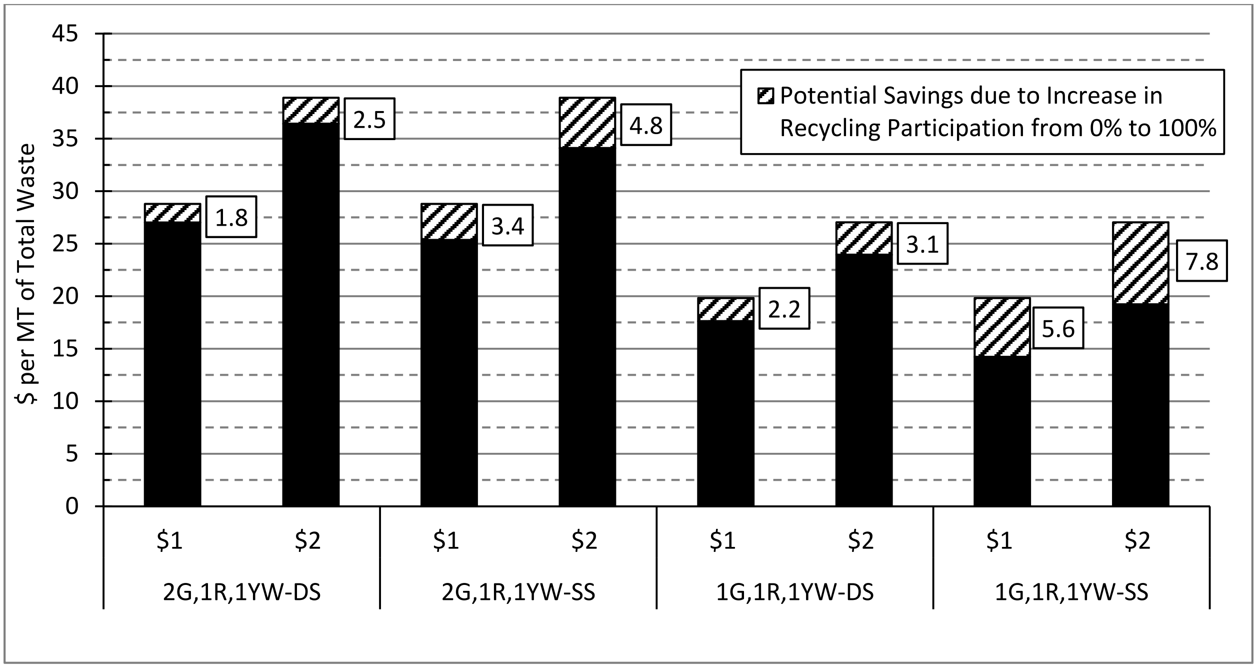

Figure 9: Garbage line collection cost. (The collection cost of garbage was estimated for programs with one or two days of garbage collection at two different fuel prices: $1 per liter and $2 per liter. Potential garbage collection cost savings show the reduction in collection cost as recycling participation rate increases from 0% to 100%).

For recyclables collection, the number of households served per trip decreases as PR_R increases. Although the average recyclables collection speed decreases, the fuel consumed (liters diesel per MT of garbage) and collection time (hours per MT of garbage) decreases as PR_R increases. The fuel consumption associated with SS recyclables collection decreases from 48.2 to 19.8 L per MT of recyclables, while total collection time decreases from 3.8 to 1.3 hours per MT of recyclables as PR_R increases from 10 to 100%. For DS recyclables collection system, the fuel consumption decreases from 155 to 45 liters per MT of recyclables, while the total collection time decreases from 10.8 to 3 hours per MT of recyclables. The fuel consumption associated with DS was also reported to be considerably higher than SS collection (42 liters of diesel per MT of recyclables for DS compared to 29 for SS) (Curtis and Dumas, 2000). Moreover, the fuel consumption reported by Curtis and Dumas (2000) was consistent with this study estimates of fuel consumption at higher PR_R values; however a significant increase in fuel consumption was observed at lower PR_R in this study.

Fuel consumption was calculated as L per MT of recyclables; however, this analysis cannot be used to compare RCC programs at different PR_R. Fuel consumption should be adjusted to account for the increases in recyclables collection as PR_R increases. As PR_R increases, the collected recyclables increases, and the consumed fuel and collection time increases by the fraction of the recyclables in the total waste stream. Figure 10 shows the net revenues of recyclables collection for RCC programs at three scenarios ($50, $100 and $150 per ton of recyclables) and two fuel prices ($1 and $2 per liter). Revenues were estimated as a function of PR_R for programs using DS or SS recyclables collection systems. As shown in Figure 10, the SS recyclables collection systems outperform DS systems for all scenarios. This is due to the high collection time of the DS system which can lead to fuel, labor, and maintenance costs that cannot be compensated by the sale of the collected recyclables. Additionally, SS systems collect more recyclables per stop than DS systems, generating more revenue. An increase in PR_R for DS at moderate recyclables revenues ($100 per ton) will result in further costs associated with collection time that cannot be compensated by selling recyclables. On the other hand, sales of additional recyclables collected by SS systems can compensate for the additional collection time as PR_R increases, except at the lowest recyclables value ($50 per ton) and highest fuel price ($2 per liter).

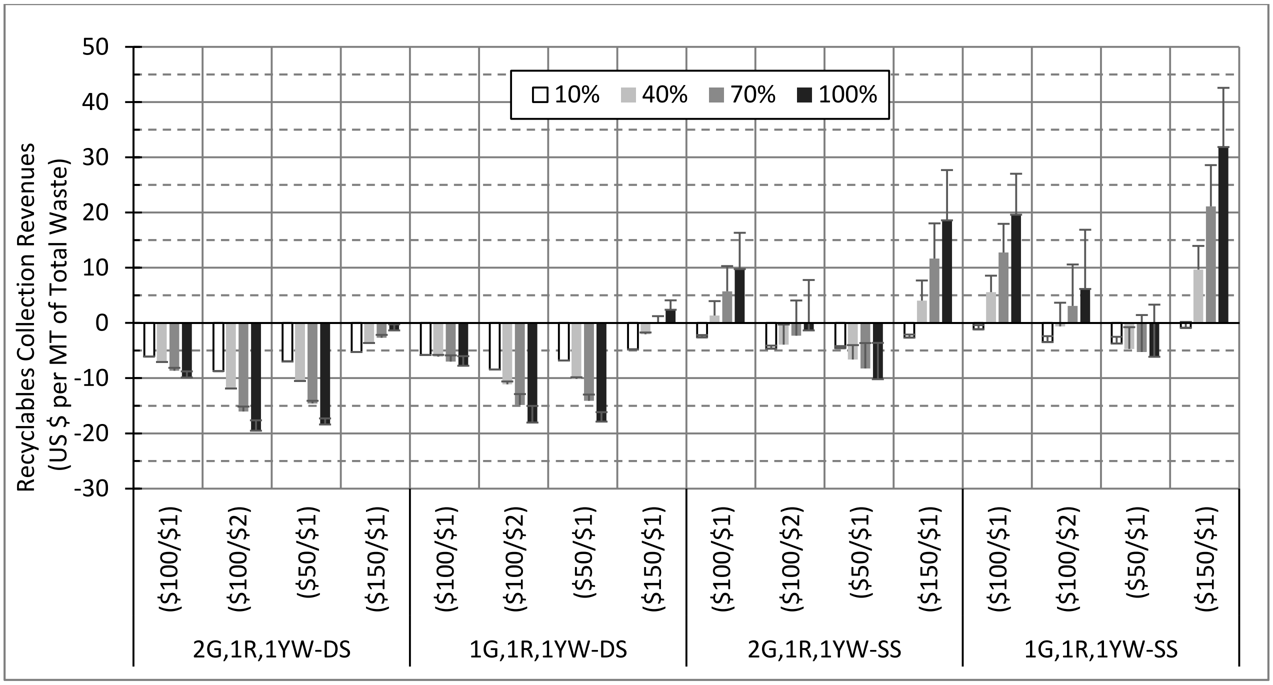

Figure 10: Recyclables line collection revenues. Revenues of recyclables collection were estimated for RCC programs at three recyclables net revenues scenarios ($50, $100 and $150 per MT of recyclables) and two fuel prices ($1 and $2 per liter). Whiskers denote potential increase in revenues as a result of recyclables compaction during collection.)

3.5 Sensitivity Analysis of Model Parameters and Model Limitations

An analysis was conducted to determine the sensitivity of the results to changing model variables, including the distance between households (D_{HH}), travel speed between households (S_{HH}), and collection time per stop (T_1) (Figure 11). The collection time per stop has the greatest effect on collection emissions. For example, a two-fold increase in the collection time increases the collection emissions by 40%. Collection time per stop was based on literature values; however, it can vary based on the number of bins to be collected, collection container, and the collection system technology, e.g., manual, semi, or fully-automated collection.

Travel speed between households was assumed to be independent of the distance between households, which is not necessary true in practice. An increase in the distance between households is usually accompanied by an increase in travel speed. The sensitivity analysis indicated that the effect of collection distance and travel speed on collection emissions are opposite and minimal.

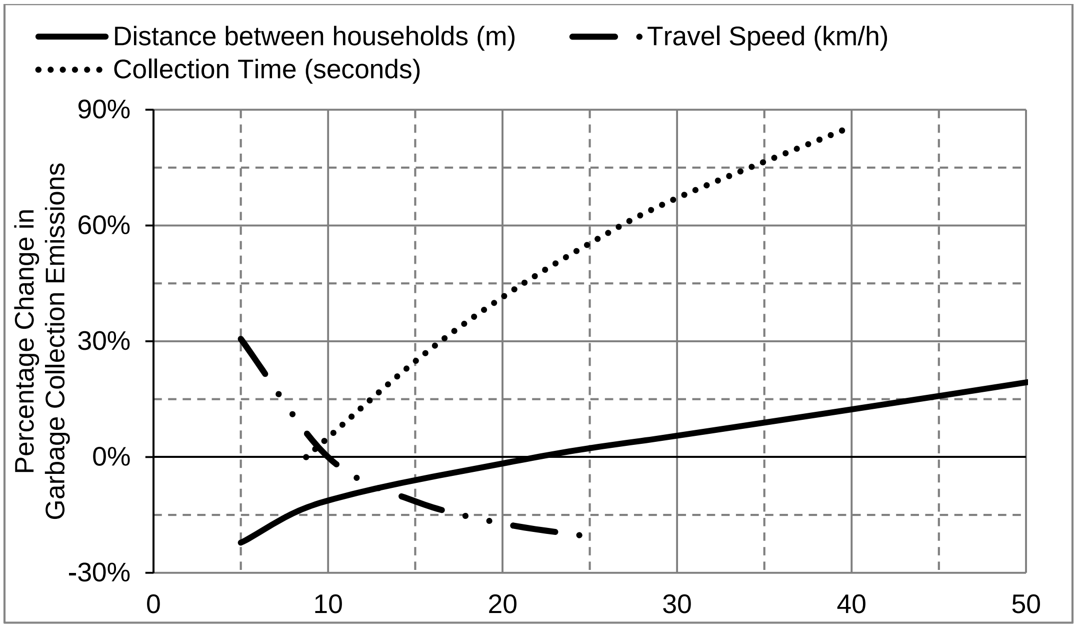

Figure 11: Sensitivity analysis of model variables. (Percentage of change in collection emissions due to changing the distance between household (22 to 40m), collection time per stop (9 to 40 seconds) and travel speed between households (5 to 25 km/h).)

4. Conclusions

The study explored the trade-offs between environmental and economic factors of RCC systems in Florida by evaluating the RCC system design of 25 different Floridian communities. An environmental-economic assessment model was developed and used to estimate the greenhouse gas (GHG) emissions and cost of RCC programs. The study results showed that RCC scheduling can significantly impact garbage and recyclables generation rates, recycling efficiency, and consequently determine environmental and economic impact of collection systems.

Overall, the mean total household waste (recyclables and garbage) was 3.11 (±0.56) kg per household per day, while the mean recycling efficiencies were 0.3 (±0.08) and 0.13 (±0.04) for single-stream (SS) and dual-stream (DS) recycling programs, respectively. At the current recycling participating rate (PR_R =70%), the use of SS recyclable collection system diverted 30% compared to 13% of the waste stream by DS. These results indicated that implementing SS collection system can have a positive impact toward achieving Florida's recycling goal of 75% waste diversion. On the other hand, reducing garbage collection frequency had positive environmental and economic effects. The study findings supported the current trends in switching to SS recycling system combined with larger recycling toters, and reduced garbage collection frequency. In comparison with the other European studies (Williams and Cole, 2013), Florida and other U.S. studies (Fitzgerald et al., 2012) showed a significant increase in recyclables generation rate as a result of switching to SS collection. In this study, the same remanufacturing losses per material were applied for SS and DD as specified by WARM; however, the use of SS might result in more contamination and more losses during remanufacturing. This is beyond non-recyclables "waste residue" in the stream and further research is needed. Moreover, this study did not account for emissions associated with overseas shipping of recyclables.

This study explored RCC programs observed in Central Florida. The study did not explore the possibility of any additional reduction in collection services, e.g. every other week recyclables collection instead of weekly. As municipalities across the U.S. reduces collection frequency of different service lines, future studies are needed to access the environmental, economic and social acceptance of such changes.

PR_R was found to have a significant impact on the environmental and financial performance of RCC programs. An increase in PR_R reduces garbage collection over a single trip, allowing for serving more households. As a result, emissions associated with the collection of each MT of garbage increases. On the other hand, the fraction of garbage in the total waste decreases, and the emissions associated with garbage collection per MT of total waste decline. For recyclables, the number of households served for recyclables per trip decreases as PR_R increases. Although recyclables collection speed decreases as PR_R increases, it was observed that GHG emissions associated with the collection of each MT of recyclables decreases. Overall, the fraction of recyclables in the total waste increases, and the emissions associated with recyclables collection per MT of total waste increase. Overall, recycling benefits increased substantially at higher recycling participation rate, while collection emissions were insignificant compared to the benefits of recycling. An increase in PR_R will have a positive impact on waste diversion, however more research is needed to address the social aspects of recycling behavior in Florida. Moreover, further research is needed to address the relationship between recycling participation and set-out rates in Florida, and their potential impact on recycling.

The fuel mileage of waste collection vehicles increased from 0.2 and 2.6 km per liter of diesel consumed as the average collection speed increased from 2 to 60 km per hour. SS collection offers faster collection time per stop than DS collection, reducing collection emissions and cost. Collection time per stop showed a significant impact on collection emissions and cost; therefore, implementing collection methods that minimize collection time per stop can significantly reduce the collection cost and emissions. Possible examples of other approaches are the automation of the collection system, compliance with bin requirement, and grouping waste containers on shared property lines which cut down the number of stops per route by half.

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Conflict of interest

The authors declares no conflict of interest.

Supplementary

Table S1: Reported tonnage of waste collected by Floridian RCC programs.

No	**Program**	**Household Count (N_T)**	**Recycling System**	**Recycling Container**	**Group**	**Year**	**Garbage Collected W_G (Metric Tonsper year)**	**Recyclables Collected W_R (Metric ton per year**	**Yard Waste Collected (Metric ton per year)**
1	1G,1R,1YW	8,155	DS	Bins†	B	2012	5,101*	1,133*	1,880*
2	2G,1R,1YW	17,000	DS	Bins†	A	2012	20,016	1,407	5,822
3	2G,1R,1YW	22,500	DS	Bins†	A	2012	18,694	4,490	7,259
4	2G,1R,1YW	4,200	DS	Bins†	A	2012	4,534	1,026	1,241
5	2G,1R,1YW	38,293	DS	Bins†	A	2012	29,394	4,746	6,513
6	1G,1R,1YW	69,812	SS	240 Liter (64 gallon) toter	D	2012	91,133	30,870	36,668
7	2G,1R,1YW	3,258	DS	Bins†	A	2012	4,226	233	909
8	2G,1R,1YW	4,700	DS	Bins†	A	2012	5,085	533	1,210
9	2G,1R,1YW	1,040	DS	Bins†	A	2012	1,447	221	64
10	2G,1R,1YW	11,434	DS	Bins†	A	2012	10,963	1,490	2,555
11	2G,1R,1YW	8,900	SS	340 Liter (90 gallon) toter	C	2012	8,980	1,551	2,875
12	2G,1R,1YW	12,900	DS	Bins†	A	2012	12,798	1,143	2,643
13	1G,1R,1YW	33,865	DS	Bins†	B	2012	27,901	3,386	5,770
14	2G,1R,1YW	7,400	DS	Bins†	A	2012	6,789	756	1,592
15	2G,1R,1YW	40,087	DS	Bins†	A	2012	39,115	3,418	9,545
16	2G,1R,1YW	35,924	DS	Bins†	A	2012	34,056	5,117	10,023
17	2G,1R,1YW	40,640	DS	Bins†	A	2012	34,940	4,166	8,595
18	2G,1R,1YW	40,402	DS	Bins†	A	2012	38,882	4,746	7,944
19	2G,1R,1YW	42,478	DS	Bins†	A	2012	33,693	5,742	7,550
20	2G,1R,1YW	10,589	DS	Bins†	A	Oct 09 - Sep10	9,330	2,166	3,347
21	1G,1R,1YW	10,784	DS	Bins†	B	Oct 10 - Sep11	9,806	2,393	3,504
22	1G,1R,1YW	4,500	SS	240-liter (64-gallon) toter	D	2011	3,112	1,650	667
23	2G,1R,1YW	1,400	SS	240-liter (64-gallon) toter	C	2011	968	513	207
24	2G,1R,1YW	2,100	SS	240-liter (64-gallon) toter	C	2011	1452	770	311
25	2G,1R,1YW	1,100	SS	240-liter (64-gallon) toter	C	2011	761	403	163

*Less than one year tonnage, therefore it was used only to evaluate recycling efficiency

†60-liter (16-gallon) bins

A: 2G, 1R, 1YW-DS; B: 1G, 1R, 1YW-DS; C: 2G, 1R, 1YW-SS; D: 1G, 1R, 1YW-SS

Table S2: Composition of the recovered material from Single-stream (SS) collection trucks and MRF output.

Material	Collection Truck Composition* (% of total weight)	MRF Output* (% of total weight)
Amber Glass	6.86	0.02
Clear Glass	8.63	0.03
Green Glass	4.11	0.02
HDPE Colored Containers (Baled)	2.25	0.89
HDPE Natural Containers (Baled)	1.53	0.73
LDPE Film (Baled)	N/A	0.33
Mixed Papers (Baled)	22.40	2.14
Mixed Rigid Plastic (Baled)	N/A	0.39
OCC (Baled)	10.70	0.24
OCC-BL_Baled		14.50
OCC (Baled)		13.50
PET Containers Comingled (Baled)	6.34	2.23
Plastic 1 Thru 7 (Baled)	2.12	0.35
Plastic 3 Thru 7 (Baled)		0.19
Polycarbonate	N/A	0.01
Polycarbonate (Del)	N/A	0.00
Polystyrene	N/A	0.03
Scrap Aluminum (loose)	1.14	0.00
Sorted Office Waste (Baled)	N/A	0.21
Special De Ink New #8 (Baled)	19.50	21.70
Special De Ink New #8 (Baled)		15.80
Steel Cans (Baled)	N/A	1.50
Three Mix Glass	N/A	15.50
Titanium	N/A	0.00
Used Beverage Cans (Baled)	N/A	0.70
Tin Cans	2.50	N/A
Residue	12.10	9.07

N/A: Not applicable

*Based on MRF operators input. Due to rounding, percentages may not appear to add up to 100%.

Table S3: Composition of the recovered material from dual-stream (DS) collection trucks and MRF output.

Material	**Collection Truck Composition* (% of total weight)**	**MRF Output* (% of total weight)**
Aluminum	48.0	0.8
PET/HDPE		0.4
Mixed Plastic		12.3
Mixed Glass		21.3
Ferrous		2.2
Newspaper	52.0	10.2
Cardboard		9.7
Mixed Paper		32
Single Stream	N/A	0.5
Residue	N/A	10.4

N/A: Not Applicable,

*Based on MRF operators input. Due to rounding, percentages may not appear to add up to 100%.

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List of abbreviations

DS	Dual-Stream
FDEP	Florida Department of Environmental Protection
GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GR_T	Generation Rate of Total Waste
MOVES	U.S. EPA Motor Vehicle Emission Simulator
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
MSW-DST	U.S. Municipal Solid Waste Decision Support Tool
MT	Metric Ton
N_T	Maximum Number of Households Served by Collection Contract
PR	Percentage Recycling
PR_G	Garbage Participation Rate
PR_R	Recycling Participation Rate
RCC	Residential Curbside Collection
SS	Single-Stream
U.S. DOE	United States Department of Energy
U.S. EPA	United States Environmental Protection Agency

WARM	Waste Reduction Model (WARM)
WC	With Compaction
WOC	Without Compaction
W_G	Annual Weight of Garbage Collected
W_R	Annual Weight of Recyclables Collected