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David J. Tonjes
Department of Technology and Society, david.tonjes@stonybrook.edu

Sreekanth Mallikarjun
SUNY Stony Brook

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COST EFFECTIVENESS OF RECYCLING: A SYSTEMS MODEL

David J. Tonjes [a, b, c]

david.tonjes@stonybrook.edu

[a]Department of Technology and Society

College of Engineering and Applied Sciences

Stony Brook University

Stony Brook, NY 11794-3560 USA

[b] Waste Reduction and Management Institute

School of Marine and Atmospheric Sciences

Stony Brook University

Stony Brook, NY 11794-5000

[c] Center for BioEnergy Research and Development

Advanced Energy Research and Technology Center

Stony Brook University

1000 Innovation Rd.

Stony Brook, NY 11794-6044

Sreekanth Mallikarjun [a]

sreekanth.mallikarjun@stonybrook.edu

[a]Department of Technology and Society

College of Engineering and Applied Sciences

Stony Brook University

Stony Brook, NY 11794-3560 USA

Corresponding Author

David J. Tonjes

Department of Technology and Society

Stony Brook University

Stony Brook, NY 11794-3560 USA

T 631-632-8518

F 631-632-7809

david.tonjes@stonybrook.edu

Abstract

Financial analytical models of waste management systems have often found that recycling costs exceed direct benefits, and in order to economically justify recycling activities, externalities such as household expenses or environmental impacts must be invoked. Certain more empirically based studies have also found that recycling is more expensive than disposal. Other work, both through models and surveys, have found differently. Here we present an empirical systems model, largely drawn from a suburban Long Island municipality. The model accounts for changes in distribution of effort as recycling tonnages displace disposal tonnages, and the seven different cases examined all show that curbside collection programs that manage up to between 31% and 37% of the waste stream should result in overall system savings. These savings accrue partially because of assumed cost differences in tip fees for recyclables and disposed wastes, and also because recycling can result in a more efficient, cost-effective collection program. These results imply that increases in recycling are justifiable due to cost-savings alone, not on more difficult to measure factors that may not impact program budgets.

Highlights

- Curbside collection of recyclables reduces overall system costs over a range of conditions.
- When avoided costs for recyclables are large, even high collection costs are supported.
- When avoided costs for recyclables are not great, there are reduced opportunities for savings.
- For common waste compositions, maximizing curbside recyclables collection always saves money.

Key words: recycling, disposal, system, costs, yard wastes, collection

1. Introduction

Recycling is often justified because it generates public goods, often expressed in terms of environmental benefits, such as natural resource conservation, pollution avoidance, or global climate change prevention (Craighill and Powell, 1996; Ackerman, 1997; Bohm et al., 2010; Kinnaman, 2010; Manfredi et al., 2011). Having recyclable material collected from each household (curbside recycling) increases participation levels and the amounts collected by recovery programs (Folz 1999b; Domina and Koch, 2002; Jenkins et al., 2003; Dahlen et al., 2007; Best, 2009; Larsen et al., 2010). However, because program managers and participants may not directly gain from these environment benefits, they may not be sufficient to maintain such programs. This is especially so in the face of pressures to reduce present-day expenditures or the scope of government (Folz, 1999b; Blaine et al., 2005; Emery et al., 2007; Chowdhury, 2009; Guimaraes et al., 2010) even in the face of regulatory requirements (Read, 1999), or with the realization that governments have interests other than mere costs when providing local services (Bel and Warner, 2008), such as when Lave et al. (1999) identify avoidance of "environmental nuisances" as an important factor for maintaining recycling services in large cities. The Mayor of New York City, for instance, dropped part of its curbside recyclables collection program in 2002 because the program was thought to be not cost-effective (Aadland and Caplan, 2006). Only when a contractor was willing to pay the City for metal and plastics was source-separated collection re-instated (DSM Environmental, 2008). Paying for management of recyclables may therefore be perceived as an expense that can be foregone in tougher economic times.

This is a misunderstanding of basic waste management economics. The default management of wastes – disposal – costs money. Options other than disposal, if their cost is less, allow for savings through the concept of “avoided disposal costs” (as noted in Lavee and Khatib, 2010). If the total costs associated with the alternative management are less than the incremental costs of standard disposal, then the alternative provides avoided costs savings and so is a money-saving option. The alternative does not need to provide positive revenues but its net costs need to be less than the default option. This concept is well understood; still, as was the case with Mayor Bloomberg in New York City, sometimes it may not be practiced.

1.1 Background

Historically, recycling was initiated because recyclables had value (Miller 2000). Environmental considerations and regulatory requirements have led to the service expansion found in industrialized nations (Tanskanen and Kaila, 2001; Bohm et al., 2010;Miranda and Blanco, 2010). Many recent program evaluations include economic externalities in their calculations, pricing in environmental benefits (Lave et al., 1999; Beigl and Salhofer, 2004; Emery et al., 2007; Manfredi et al., 2011; Yoshida et al., 2012) and/or resident preferences (Powell, 1996; Huhtala, 1997; Read, 1999; Aadland and Caplan, 2006), because “the cheapest system may not be the most environmentally benign” (Chang et al., 2011). This is especially true when separate recyclables collection is found (or is assumed) to be more expensive than disposal (Beede and Bloom, 1995; Goddard, 1995; Hall, 1995 [considering recycling paper generally, not just source separation]; Highfill and McAsey, 1997; Masui et al., 2000; Tanskanen and Kaila, 2001; Caplan et al., 2002; Beigl and Salhofer, 2004; Blaine et al., 2005; Calcott and Walls, 2005; Kinnaman, 2005, 2006; Aadland and Caplan, 2006; Bohm et al., 2010; Kuo and Perrings, 2010; Bouvier and Wagner, 2011; Yoshida et al., 2012). Adding externalities often results in determinations that these programs have overall cost-effectiveness (e.g., Diamadopoulos et al., 1995; Craighill and Powell, 1996; Masui et al., 2000; Lavee, 2010), or based on residents’ willingness-to-pay for services, that programs can be cost-effective to society as a whole (Kinnaman, 2005; Aadland and Caplan, 2006). Goddard (1995) demonstrated that if the waste hierarchy (waste reduction, recycling, waste-to-energy incineration, and lastly landfilling) is justified, it implies, if all externalities are accounted for, marginal costs for recycling should need to be less than disposal (at least initially).

Certain studies have addressed economic (pricing) issues by solving systems of equations analytically. This allows for more universality to the solutions, and these systems, if the math was correct, are certainly internally consistent. Many find costs of recycling exceed benefits. A series of studies have evaluated the relationship between landfill capacity and recycling programs, for instance, and all assume recycling costs more than landfilling; however, avoided future costs for a new facility may justify channeling tonnages to "more expensive" recycling programs, as net present values grow quickly under compounded interest (Lund, 1990; Jacobs and Everett, 1992; Ready and Ready, 1995; Highfill and McAsey, 1997; Huhtala, 1997). A model of a waste authority found recycling collection costs were twice disposal costs and operating a MRF was more expensive than landfilling (Modak and Everett, 1996). Increased recycling efforts caused a 36% increase in system costs if recycling was increased from 21% to the "maximal amount" (64%) in Finland (Tanskanen et al., 1998), and although disposal costs decrease with increased recycling, it does not compensate for increased recycling costs (Tanskanen and Kaila, 2001). Bohm et al. (2010) developed a generalized cost term for solid waste management, and then fit data from US national survey responses to determine appropriate parameters for the equation variables, using 1996 data. They found that the marginal costs for waste management decrease for both disposal and recycling. This trend continues for disposal, but eventually marginal costs for recycling begin increasing when there is more than 13,200 tons of annual collection. Marginal costs for recycling were always greater than those of disposal. Recycling evaluations excluded revenues from the sale of recovered materials. One example called out in the paper, for instance, found the marginal costs per ton for disposal were \$59.70, and for recycling were \$76.53.

Not all models find recycling costs exceed benefits. Lombrano (2009) found in Italy that recycling reduced system costs, if the system served more than 50,000 people and recovery rates exceeded 30% or so. A model of a waste system for Port Said (Egypt), including recycling and composting along with landfilling, projected net profits (assuming revenues not only for recyclables but also for the produced compost) (Badran and El-Haggar, 2006). Emery et al. (2007) found collection with a split body truck and 100% recovery of potential recyclables would likely lead to a 7% decrease in costs over landfilling, although all other options involving any recycling (different collection vehicles and recovery rates, and also WTE incineration as a disposal technology) led to higher costs. Callan and Thomas (2001) used 1997 Massachusetts data in a simplified model, finding the average cost for disposal was \$90.25 ton^{-1}, and the average cost of recycling was \$49.82 ton^{-1}. The marginal cost for disposal was \$77.82 ton^{-1}, and the marginal cost for recycling \$13.55 ton^{-1}. Larsen et al. (2010) found that curbside collection of recyclables decreased overall system costs in Denmark because the cost of disposal was sufficiently greater than assumed revenues from recycling. They assumed particular programs would result in set recoveries for particular materials (with ensuing overall recovery rates of 20%-31%). Similarly, De Jaeger et al. (2011) analyzed 299 municipalities in Flanders, based on 2003 data, and found that increased recovery and waste reduction rates did not result in reduced economic efficiency, but rather seemed to be associated with more efficiency (as determined by a Data Envelopment Analysis model). This was a generalized result that was not specific to any of the 299 systems. Lavee (2007) created an empirical model of waste management in Israel, based on 2000-2004 data from 79 municipalities, considering starting recycling services and then achieving specific levels of recycling. Recycling was found to be cost-effective for nearly all large municipalities, but not so for over half of small and regional authorities. Using 2005-2009 Japanese data, Kinnaman et al. (2012) compared municipal costs to collect and manage waste, municipal costs to collect and manage recyclables, and certain positive and negative externalities associated with disposal and recycling. If positive externalities associated with recycling are excluded, 10% recycling is optimal. Incorporating the positive externalities means the optimal rate is 18% recycling. Household recycling costs were key; doubling them decreased optimal recycling to 13%, halving these costs increased optimal recycling to 28%, and leaving them out meant recycling is favored under all conditions (optimal rate of 100% recovery). Work by Palatnik et al. (2005) suggests that household costs may be a necessary element in pricing recycling properly, since participation rates in Israel declined as the effort required to recycle increased.

Other studies have therefore addressed cost issues with much more reliance on empirical data and program descriptions, often collected by survey. Here, too, the determinations of whether recycling costs or saves money are split. Kinnaman (2006) summarized six studies, determining that recycling cost \$3 household^{-1} month^{-1} compared to landfilling, and was therefore, on a per ton basis, twice as expensive as landfilling. He found that external utilities sometimes exceeded costs, but sometimes did not, and so did not think recycling could be considered universally beneficial. Similarly, Aadland and Caplan (2006), using a selection of 12 US municipalities, found that recycling program costs ranged from \$1.62-\$5.10 household^{-1} month^{-1}. McDavid (2000) reported that for Canadian residential solid waste programs mean net costs for recycling were \$124.39 tonne^{-1} and disposal mean net costs were \$48.01 tonne^{-1}, based on surveys carried out from 1995-1999. Lave et al. (1999) combined US national costs of recycling (including credits for avoided disposal) from one study with revenues derived from another, and determined that recycling would cost a net \$97 ton^{-1}.

Folz (1999a, b) surveyed recycling coordinators in US cities in 1990 (gathering 1989 data) and resurveyed the 1990 respondents in 1997 (using 1996 data). By 1996, mean cost for recycling programs (\$66.96 ton^{-1}), defined as program costs (\$103.63 ton^{-1}) minus revenues (\$35.67 ton^{-1}) were less than net disposal costs (\$131.63 ton^{-1}), defined as collection costs (\$81.99 ton^{-1}) plus disposal costs (\$51.83 ton^{-1}). It seems apparent, but is not explicit, that recyclables collection costs were accounted for. The data appear to have been averaged per program, and not weighted for program size. A different approach was taken in an analysis of New York City’s program (DSM Environmental, 2008). Here the New York City Department of Sanitation (NYCDOS) cost allocation model was used (and modified). NYCDOS data for 2005 suggested that refuse collection and management cost \$263 ton^{-1} and recycling cost \$343 ton^{-1}. When costs were reallocated and reconsidered, costs appeared to be \$284 ton^{-1} for recycling, 6% more than disposal costs (\$267 ton^{-1}). This difference was described as "insignificant," given the scope of analyst choices in the allocation of sunk costs and department-wide expenses.

1.2 Study Rationale

Cost effectiveness analysis compares the relative costs and outcomes of two or more courses of action (Levin, 1983). The instrument of cost effectiveness is applied to the planning and evaluation of many types of organized activity, including the economics of service or program usage such as education programs (Levin, 1983), environmental polices (Dissou, 2005; Goulder et al., 1999), and recycling initiatives (Lund, 1990; Deyle and Schade, 1991). In this paper we present a systems model of refuse collection. The model accounts for changes in distribution of effort as recycling tonnages displace disposal tonnages. We consider various costs, labor, trucks, refuse tonnages, etc., to carry out cost effectiveness analysis of seven different scenarios of refuse collection in a Long Island, New York, municipality. The seven cases relatively vary by tipping fees, including or excluding the collection of yard waste, and truck financing (lease or own). We examine the results of all cases to explore the optimum recycling rate in each of scenarios individually (i.e. recycling rate at lowest cost point) and determine which cases are most cost effective and have optimal recycling rates.

The model we present here is empirical, with the terms drawn from practices as we observed them. There may be error from these observations, but the process is transparent, and can be easily validated or rejected by those with practical experience. To make system cost assumptions and calculations transparent and explicit, we have assumed that the Long Island system uses contract services with defined costs to accomplish its tasks (rather than using internal municipal resources and consequent murky accounting). We have grounded the modeling by using data generated in a real-world setting.

2. Materials and Methods

2.1. Model Structure

We created a simplified model of costs associated with a curbside collection program and subsequent management of collected materials (see the Appendix). Our objective function determines the total cost per week (TC):

$$TC = (L + F + TF + TFI) \times (I + P) \tag{Eq. 1}$$

with

L = labor cost (derived in Eq. A10)
F_{tot} = fuel cost (derived in Eq. A11)
TF = tip fees (derived in Eq. A12)
TFI = total financial cost (derived in Eq. A16)
P = profit rate

We applied the model to a set of seven cases, based upon baseline conditions developed from the suburban New York residential waste management program.

2.2 Model Setting

The Town of Brookhaven (Long Island, New York) is a municipality with a population of approximately 500,000, located 125 km east of New York City. The Town organized municipal collections services in 1988 in support of a curbside collection program begun in 1989. All one, two, and three family houses in the Town, outside of nine incorporated villages and exclusive of condominiums and multi-family dwellings, receive Town collection services. About 116,000 households are covered through the program.

Collection services are organized through 35 districts, which are offered for contract services. These districts were organized so as to reflect natural “hamlet” boundaries and to be approximately the same size, although growth throughout the Town since 1988 has distorted the congruencies somewhat. The Town solicits bids from private carting companies to conduct the actual collection work. Currently the Town requires contractors to use CNG-fueled trucks, and has a refueling station at its solid waste complex. The Town specifies collection days, requires each district to be collected separately, has mandatory source separation laws for recyclables and yard waste, and a ban on managing grass clippings and otherwise disposing of yard waste, but otherwise does not manage the means by which collection services are provided. Residents receive twice weekly collection of waste, weekly collection of recyclables (paper materials alternating with glass, metal, and plastic containers), and 19 yard waste collections (twice a month April-December, plus a January Christmas tree collection). Grass clippings are not managed and yard waste management through disposal is forbidden. In 2011, the Town collected 179,321.76 tons of MSW, 23,016.63 tons of recyclables, and 34,914.72 tons of yard waste. This resulted in a curbside source separation rate of 24.4%.

The Town had an agreement to dispose of its waste at the Hempstead Waste-to-Energy plant in exchange for landfilling the ash produced by the plant. The explicitly combined "Ash for Trash" agreement expired in 2011, but the Town has entered into two distinct contracts with the operator of the plant, which accomplishes the same goal. The Town pays approximately \$80 ton^{-1} for disposal at the plant, and \$15 ton^{-1} to a contractor to operate its transfer station and truck wastes to the disposal point. The Town constructed a recycling facility in 1991, and has operated the facility through three successive contractors since then. The Town was responsible for paying the capital costs of construction, and the operator received a per ton fee for processing recyclables and marketing them, one that varies primarily based upon the number of shifts needed at the plant and outside materials solicited by either party. The Town receives 80% of the revenues from recyclables sales, and the operator is responsible for covering any negative markets (e.g., for glass) and disposal of residues. The Town has its own yard waste composting facility, but as development in its immediate vicinity increased, the Town began using the site less (residents complain of odors and noise). The Town, since the inception of its mandatory yard waste separation program in 2001 (with a concurrent ban on collecting grass clippings either for disposal or composting) therefore has used a composting contractor. The 2011 cost for delivery of bagged yard waste to the contractor was \$45 ton^{-1}.

The Town charges each household in the waste districts a fixed fee for solid waste services. In 2011, this fee was \$375 yr^{-1}. The fee is intended to cover the cost of the waste districts, plus a portion of administrative costs, some of the facility costs, other services provided to all residents of the Town (drop-off disposal and recycling services, hazardous wastes drop-off and management, collection of bulky and metal wastes, etc.), but accurate accounting is not possible due to the complexity of the intertwined services.

2.3 Base Parameterization of the Model

We simplified elements of the Town setting and conditions for our model. First of all, we considered that all waste districts were exactly the same and that waste generation does not vary over time. Thus, each of the districts generates 130 tons week^{-1} of wastes (excluding grass clippings) and is equidistant from the waste management complex where the transfer station and recycling facility are located, and which also abuts the yard waste contractor's facility (this avoids differential travel times, and is a rough approximation of reality, as the waste management facility is approximately in the center of the Town). We also assumed that the base element of collection was a half-day shift (4 hours). We made this assumption because most trucks in the Town make two disposal stops at the waste facility per day. We translated this to a 4 hour unit where it either takes 4 hours to fill a truck (with the waste being collected) or to complete a transit of the waste district (resulting in an incompletely filled truck). We assumed that the collection contractors could pay partial days' pay to employees, but only in 4 hr increments, and that no overtime was offered. These assumptions were made so as to underscore the shift in collection emphasis and costs as the set-out balances change between disposal, recycling, and composting. We assumed a driver and a helper for each truck, and that each earned the mean New York State wage for the position (see www.bls.gov/oes/current/oes537081.htm). We assumed trucks could be financed at favorable rates (3%) over the life of the contract (currently 5 years with two 1 year extensions possible) and that the trucks had a useful service life for premier collection at 10 years, with some useful life after that (thus, a salvage value of $50,000). We assumed a purchase price of $250,000 (from the US Department of Energy Clean Cities CNG program, information available at http://ecocomplex.rutgers.edu/ray.pdf), and received information that a reasonable estimate for CNG fuel cost is $10 hour^{-1} (Harry Gladfelter, Business Development manager, Clean Energy Fuels Corp., personal communication, February 22, 2013). We drew from an unpublished Town consultant report to determine maintenance and insurance costs for the vehicles. We assumed that all trucks used in the Town were the same size. We used scalehouse data (ignoring very low records, assuming them to be partial loads) from two weeks in October 2012 to determine disposal trucks average 9 tons in weight, recyclables trucks average 8 tons in weight (container trucks hold less and paper trucks hold more, but we assumed a 1:2 container:paper split, based on recycling facility records), and that yard waste trucks could hold 9 tons. We assumed that, on balance, partial loads covered any effort differences between collecting MSW and recyclables-compost (partial loads were allocated full 4-hour shift segments, although presumably all the time was not needed), and our emphasis on system costs means we do not need to allocate costs accurately to each element in the system. We included no margin for profit for the collection contractors. These baseline parameters are listed in Table 1.

*****Table 1 about here*****

2.4 Particular Cases to be Modeled

2.4.1 Case 1

In Case 1, we consider the situation for the Town of Brookhaven when there was no separate collection of yard waste, but there was curbside collection of recyclables. We set the tipping fee for non-recycled MSW (TF_{MSW}) at $80. The true cost for the Town is closer to $95 ton^{-1}; however, that fee is based at least partially on assumed compensation for the ash that is landfilled. The lowest tip fee for a local municipality in the vicinity of Brookhaven is in the range of \$60-\$65 for long-distance transport to off-Long Island landfills (in Pennsylvania or upstate New York) or to Newark, New Jersey, for subsequent rail haul to an Ohio landfill. This, together with a transfer station management fee would lead to an overall disposal tip fee in the vicinity of \$80. We chose this lower value to make the analysis more conservative. For recyclables tip fee (TF_{RM}), we selected \$20 ton^{-1}. The agreement between the Town and the recycling facility operator is not straight-forward, and not especially amenable to simplification to a per ton fee. A good estimate is the Town paid approximately \$1 million in 2011 to manage 45,000 tons that were processed at the facility (some 20,000 tons of which were from sources other than the curbside program). The Town collected on the order of \$2 million from the sale of recyclables in 2011. This would suggest a negative tip fee of \$22 ton^{-1} (getting paid for recyclables) would be in order. Recyclables markets, although more stable than in the 1990s, are still somewhat volatile (hitting lows during 2008, for instance), so assuming continued strong markets may not be warranted. In addition, the Town posts a nominal tip fee of \$20 ton^{-1} for non-District recyclables (although most non-District recyclables processed at the facility were acquired via negotiated contracts, at various rates that were all less than this). We chose to use the 20 ton^{-1} fee as a conservative recyclables processing estimate; this fee suggests that recyclables could go to market at approximately no overall cost. In Case 1, recyclables collection was allowed to vary from 0 tons to 130 tons in 1 ton increments. This is a contrary-to-fact situation for higher tonnages, since NYSDEC (2010) data suggest only 30% or so of suburban New York wastes is recyclable paper and containers; managing tonnages above 40 tons as recyclables suggests that increasing amounts of MSW are being processed as recyclables, which would not be allowed, either operationally by the recyclable facility, or under regulations. However, tracing the change in costs over the entire spectrum of possibilities gave us some insight into the relations among avoided costs, effort, and equipment costs.

2.4.2 Case 2

In Case 2 we added yard waste services to Case 1. Yard waste collection was assumed to occur each week (instead of 19 weeks of the year) to allow us to use a week as the basic service time. We set the tipping fee at \$45 ton^{-1}. The tons collected were varied from 1 to 20 tons. The residual waste stream was then recycled from 0 tons to the maximum available tonnage for each of the 20 variants.

2.4.3 Case 3 and Case 4

In Cases 3-4, we allowed the trucks to be leased for 7 years, per US Department of Energy Clean Cities CNG program information showing this greatly reduces the costs of operating the trucks (available at http://ecocomplex.rutgers.edu/ray.pdf). We re-ran Case 1 and 2 with the reduced truck costs, but kept all other parameters the same.

2.4.4 Cases 5-7

In Cases 5-6, we reconsidered costs using lower disposal costs, and used the lower cost leasing scenario only. We set the disposal cost at \$40 ton^{-1}, kept recyclables management at \$20 ton^{-1}, and set yard waste composting at \$10 ton^{-1}. Long Island is a high waste management cost area, and tip fees in much of the US are lower. Since recently recycling has been a net source of income for Brookhaven, we believe using \$20 ton^{-1} cost is a conservative estimate for those without processing capabilities or far from markets. We used \$10 ton^{-1} composting costs in order to retain an avoided costs element to the analysis, and to reflect that many insist yard waste composting can be accomplished relatively cheaply (considering net costs, assuming some return on finished products). Recycling and composting facilities are not as common as disposal facilities in the US; therefore, either a site has these facilities, has a transfer station for the facilities not immediately on site, or needs greater transport time to access facilities not at the base facility. It is more likely that extra transport time will be required to reach either (or both) recycling and composting facilities. For Case 7, we used Case 6 conditions and added a 1 hr per trip penalty to address conditions where longer trips may be required to recycling-composting facilities; again, our emphasis on overall systems costs means that accurate allocation of the time to different elements is not necessary. Table 2 summarizes cases 1-7.

*****Table 2 about here*****

3 Results

A range of results followed from the seven cases. The most expensive case was Case 1 (large truck purchase expenses, highest disposal cost). The base cost in Case 1 (all 130 tons disposed, no recycling, no yard waste collection) was \$22,104 week^{-1} (\$40.2M for the all districts yr^{-1}), which compares well to the monies raised by the Town through district fees (\$43.5M) (the model result was 7.5% less), suggesting that our estimated costs model is not entirely inaccurate. The lowest cost result came with the lowest disposal fees and where there were only 15 collection routes week^{-1} (2 for yard waste, 5 for recyclables, 8 for MSW, requiring only 60 hours and 3 trucks). However, in all cases, recycling saved money over at least a portion of the spectrum of diversion tonnage possibilities.

Cases 1 and 2 were defined by balancing between avoided costs and the large capital costs associated with truck purchases. An optimal recovery rate (37% for recycling only, 52% with yard waste collection) resulted in lowest costs (Fig. 1), with the yard waste collection case being offset by 20 tons, and slightly less, than the recycling only case. Charting elasticity for changes in recycling tonnages shows that as truck shifts are added or subtracted small perturbations from the underlying \$60 ton^{-1} difference between disposal and recycling are measured. Larger differences accrue as trucks are subtracted (at 22 tons of recycling, 108 tons of disposal) or added (at 49 tons of recycling and every 16 tons thereafter to 129 tons of recycling) (Fig. 2). The changes in costs associated with adding or subtracting trucks from the district dominate the cost considerations.

*****Figure 1 about here*****

*****Figure 2 about here*****

In Case 3, the lower weekly truck costs associated with leasing allow the avoided costs to control the cost equation (Fig. 3). Recycling more waste reduces costs fairly steeply at first, but after the truck is taken out of service at 22 tons of recycling, there is a general balance between avoided costs, and extra costs associated with adding shifts or trucks. Overall, the avoided costs are slightly more than the extra labor and equipment charges, so it implies that increasing recycling always saves money. Adding yard waste diversion (Case 3) shifts the curve to the right, as for Case 2, and reduces costs a little more.

*****Figure 3 about here*****

Changing the avoided costs calculation (Cases 5-6) changes the controlling factors. The step function created by adding or subtracting trucks is flatter between changes in truck numbers, indicating that labor costs are balancing avoided costs. In Case 5, unlike Case 3, the smaller cost for the trucks is not impacted as much by avoided costs (which is only \$20 ton^{-1}). Again, the function between step changes is primarily flat, and so the optimal recycling rate is 31%, with the costs at 31% recycling not very different from those at 37% recycling. Table 3 shows the maximum and minimum costs for each of the cases.

*****Table 3 about here*****

The primary effect of yard waste collection is to shift the costs curve to the right. The relatively large avoided costs (\$25 ton^{-1} in Cases 2 and 4, \$30 ton^{-1} in Cases 6 and 7) have more impact than additional effort costs (fuel and wages); in some scenarios we have run (not shown here), when avoided costs are much smaller than those associated with recycling, yard waste collection does not have much effect on costs once the number of trucks needed to service the area is reduced (>22 tons week^{-1}, or 17%).

If collection-transportation costs are increased by 25% to address non-local recycling and composting facilities, overall costs increase by 7.5%. This means that disposal only collection can be cheaper than certain scenarios of recycling and composting, as the base cost under Case 5 is \$12,501. It takes longer to achieve systems savings: 22 tons per week recyclables (17% recycling) with no composting, but less recycling as composting increases. For instance with 50% capture of yard waste (10 tons per week), 12 tons per week of recycling (9% recycling) results in systems savings over 100% disposal, and if all yard waste is collected, only 2 tons per week of recyclables collection (1.5% recycling) results in overall decreased systems cost.

4 Discussion

This exercise provides scant support for analytical solutions that show recycling cannot be cost effective (Modak and Everett, 1996; Tanskanen et al., 1998; Tanskanen and Kaila, 2001; Bohm et al., 2010). Similarly, at least some of the results conflict with data collections that found recycling was more expensive than disposal (Lave et al., 1999; McDavid, 2000; Aadland and Caplan, 2006; Kinnaman, 2006). The results here do not accord with models that found consistent advantages for recycling (Badran and El-Haggar, 2006; Callan and Thomas, 2001) nor with the survey by Folz (1999a,b) that implied a consistent advantage for recycling. Rather, these cases suggest that the economic advantage for recycling is contingent, as was found by Emery et al. (2007) for a few select conditions, Lombrano's (2009) model with recovery rates more than 30% or so, and Larsen et al.'s model (2010) with overall recovery rates of 20%-31%. Lavee's study (2007) matched ours best, as his model accounted for changes in collection frequency and avoided costs, which our approach also addressed; however, his model assumed recycling resulted in positive revenues, which ours did not. We note that Judge and Becker (1993) also approached these issues in a similar fashion as we did. They balanced cost of recycling (defined as collection costs, calculated similarly to our effort here minus recyclables sales) versus disposal costs – but did not include any costs for collection of disposed wastes.

We think our result is important because it looks at the systemic interactions of disposal and collection. For instance, most of the studies cited here do not consider differences in the number of trucks as collection emphases shift, but we found this to be a very important factor. Instead, because collection costs have been found to be on the order of 70% of all system costs in both Europe (Tavares et al., 2009) and the US (Ackerman, 1997; Bohm et al., 2010; but modified to "50-57% by Nguyen and Wilson, 2010), it has been assumed that the extra efforts that appear to be required for recycling necessarily cause greater overall costs. That diversion from disposal means less collection effort seems often to have been forgotten. Note that Everett et al. (1998) found overall costs decreased per ton as the rate rose, but Huhtala (1997) assumed the opposite; we found both to be true, over the ranges of rates we observed.

For all of our case studies the first several tons of recyclables collection cause additional system costs. However, again for all cases, generally costs decrease as the next third of the waste stream is source separated, and overall system financial benefits are realized. However, depending on the balance between avoided costs, truck expenses, and increased labor and fuel charges, additional savings associated with recycling are not guaranteed, as marginal costs can sometimes exceed benefits above a 31%-37% recycling rate (overall 46%-52% recovery rates if yard waste collection is conducted). Please note that by optimizing collection routing, Teixeira et al. (2004) were able to model route mileage reductions of 29%, and Arribas et al. (2010) were able to model decreases in overall system costs of up to 50%, which suggests that our assessment may be biased high due to inefficiencies in collection routing.

New York State estimated waste composition for various sectors of New York populations (NYSDEC, 2010). Applying the residential suburban waste composition to the Town of Brookhaven suggests that 22.5% of the waste stream was mandated paper recyclables (newspaper, corrugated cardboard, mail, telephone books, magazines, and printed paper), and 7.5% was mandated container recyclables (aluminum, steel, bi-metal, glass, and PET and HDPE plastic containers). This suggests that the maximum recovery rate for curbside recycling in a suburban residential program targeting this common set of materials is about 30%. Our model suggests that cost savings will accrue under common tip fee-labor cost-fuel cost scenarios if curbside recycling is maximized, therefore. Mandatory separate collection of yard wastes adds to systems savings under the avoided costs scenarios we considered. Increasing labor and fuel costs by 25% to address non-local management sites increased overall costs by 7.5%, and under some combinations of recyclables and compostables collection led to increased systems cost. However, if yard waste were to be banned from disposal (100% yard waste collection), then as little as 1.5% recyclables source separation (to a maximum of 65 tons per week, 59% recycling) causes system savings.

Unit pricing is often identified as the soundest means of incorporating economic decision-making into waste management, and is often described as a good approach to increase diversion and recycling rates, since recycling is explicitly no cost to residents but disposal has defined costs (Palmer and Walls, 1999; Gellynck and Verhelst, 2007; Reichenbach, 2008; Skumatz, 2008; van Beukering et al., 2009; Dahlen and Lagerqvist, 2010). These kinds of programs are difficult to implement in multi-family housing (Porter, 2004), which limits their applicability. Several studies also question whether trying to motivate individuals through economics is universally successful or even effective (Hong and Adams, 1999; Sterner and Bartelings, 1999; Jenkins et al., 2003; Pickin, 2008; Best, 2009; Dahlen and Lagerqvist, 2010; Kinnaman, 2010; DeJaeger et al., 2011). Here we show that fixed cost collection programs also can have favorable economics for recycling, albeit not functionally aimed at the waste producer.

The implications of cost-effective recycling include:

1) program managers can increase outreach-enforcement-reward efforts to increase recycling, knowing that additional collections will improve the system bottom line;
2) commercial source separated recyclables collection, which is stillborn in many areas because of the difficulty of creating efficient collection routes, may be fostered. It is clear that efficiency is not key to realizing savings for the residential sector; rather, savings accrue from avoided costs and offsets of collection efforts, both of which should be realized with even fairly inefficient commercial routing. Greater efficiencies will increase profits, of course.
3) Our analysis did not depend on robust recyclables markets. This suggests that even in poor markets these findings should hold. Therefore, those who wish to reduce the size and scope of municipal government, without losing provided services, could consider turning waste management over to the private sector. Private sector managers should realize that it is profitable to increase recovery rates, and so should take all possible steps

to encourage customers to source separate to the greatest degree possible. Thus, environmentally sound waste management could flow from desires to increase company profits.

Our findings depend on realizing routing efficiencies as waste allocations change among different set-out possibilities. If real-world contingencies, such as union work rules or managerial inability to identify opportunities for more efficient truck allocations, interfere with achieving better arrangements of effort, then smaller savings will be realized. However, savings were generally commonplace, even when additional labor costs were added to simulate poor access to recycling or composting opportunities.

It would seem that all that is necessary for achieving cost savings from curbside collection of recyclables, under an approximation of real world conditions, is to have some avoided costs between disposal and recovery options. This should hold both for residential collection, and, as near as we can tell, commercial collection. Previous considerations that collection costs overwhelm the savings do not appear to hold. This means that if efficient collection practices can be followed, considerable program savings should be achieved under most reasonable recovery conditions.

5 Conclusions

A number of analytical models have found that recycling is not cost effective unless environmental or household cost externalities are considered. We have shown here that over the effective scope of common curbside recycling programs, separate collection programs for yard waste and household recyclables make economic good sense. We used realistic values from a suburban New York waste management program, and also investigated tip fee scenarios that are not as overtly favorable to recycling. This suggests that program managers are justified in pushing for increased recovery for cost effectiveness reasons alone. There is also the suggestion that these results would also apply to commercial collection routes – as they showed efficiency was not a necessary component to garnering cost savings. It also suggests that managers could devolve municipal programs onto the private sector, and that sage private industry managers would then seek to optimize source separation in order to increase profitability.

In most of our scenarios, as the recycling rate rose above a certain level, overall system costs began to increase, as we did not alter the existing schedule of two days of MSW and one day of recyclables collection. An extension of this work to test if different orderings of collection, such as the San Francisco Fantastic Three (one MSW-one recyclable-one compostable collection per week) or Canadian programs where MSW is collected on a less than weekly schedule, also justify themselves economically would appear to be in order.

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Appendix: Model Derivation

The total amount of waste (Q) in a waste district served by a unique set of trucks is composed of three waste categories: disposed municipal solid waste (Q_{MSW}), recycled material (Q_{RM}), and separated yard waste (Q_{YW}). Each collection truck has a payload capacity, meaning the truck can carry an amount of waste less or equal to the payload. By the ceiling of a fraction, we mean the value of the fraction rounded up to the nearest integer. Thus, the number of truck loads for a certain class of waste is the ceiling fraction of the dividend of the waste managed divided by the assigned payload capacity.

So, let TL_{MSW} be the number of disposed solid waste (MSW) collection truck loads:

$$TL_{MSW} = \left\lceil \frac{Q_{MSW}}{P_{MSW}} \right\rceil \tag{Eq. A1}$$

with

Q_{MSW} = disposed MSW in the district (tons)
P_{MSW} = average payload capacity of MSW collection truck (tons)

Let TL_{RM} be the number of recyclable material (RM) collection truck loads:

$$TL_{RM} = \left\lceil \frac{Q_{RM}}{P_{RM}} \right\rceil \tag{Eq. A2}$$

with

Q_{RM} = recycled waste in the district (tons)
P_{RM} = average payload capacity of RM collection truck (tons)

Let TL_{YW} be the number of yard waste (YW) collection truck loads:

$$TL_{YW} = \left\lceil \frac{Q_{YW}}{P_{YW}} \right\rceil$$

(Eq. A3)

with

Q_{YW} = separated yard waste in the district (tons)
P_{YW} = average payload capacity of YW collection truck (tons)

The total number of truck loads required to manage the waste under all classifications in a week is *TL*:

$$TL = \left(TL_{MSW} + TL_{RM} + TL_{YW}\right)$$

(Eq. A4)

A single collection truck can be used for multiple collection trips in any day. The number of trucks needed to manage a waste classification is a function of the number of collection days for that waste class, the number of trips a crew makes in a day, and the respective truck loads of that waste class. The three equations are:

$$TR_{MSW} = \left\lceil \frac{TL_{MSW}}{C_{MSW} \times T} \right\rceil$$

(Eq. A5)

$$TR_{RM} = \left\lceil \frac{TL_{RM}}{C_{RM} \times T} \right\rceil$$

(Eq. A6)

$$TR_{YW} = \left\lceil \frac{TL_{YW}}{C_{YW} \times T} \right\rceil$$

(Eq. A7)

with

TR_{MSW} = number of trucks to manage MSW
TR_{RM} = number of trucks to manage RM
TR_{YW} = number of trucks to manage YW
C_{MSW} = number of collection days week^{-1} for MSW
C_{RM} = number of collection days week^{-1} for RM
C_{YW} = number of collection days week^{-1} for YW
T = number of trips a crew can make in a day

The total number of trucks needed to service an area (TR) is the maximum value of the trucks needed to manage different waste classifications, as it is assumed all classes of waste must be completely collected within the week, and each waste is collected on a unique day or days:

$$TR = Max\{TR_{MSW}, TR_{RM}, TR_{YW}\}$$

(Eq. A8)

Typically, a collection truck is operated by a driver and a helper for specific hours to collect and manage the truck load (effort hours). The total effort in a week (TE) is given by:

$$TE = TL \times T_{eh}$$

(Eq. A9)

with

TL = total number of truck loads (derived in Eq. 5)
T_{eh} = effort required for one truck load (hrs.)

The total labor cost (L) is a function of the effort and wages:

$$L = \{TE \times (D + H)\}$$

(Eq. A10)

with

TE = total effort in a week (hrs.) (derived in Eq. 10)
D = Driver wage (dollars hr^{-1})
H = Helper wage (dollars hr^{-1})

The total fuel cost for all operated trucks and truck trips in a week (F_{tot}) is a function of total effort hours that the trucks operate in a week and average cost of fuel consumed per hour:

$$F_{tot} = TE \times F_{hr}$$

(Eq. A11)

with

TE = total effort in a week (hrs.) (derived in Eq. 10)
F_{hr} = fuel cost hr^{-1} (dollars hr^{-1})

The tip fee is the tariff paid to manage the collected wastes. Tip fees are charged per ton, and differ across waste classes. The total tip fee (*TF*) is:

$$TF = \{(Q_{MSW} \times TF_{MSW}) + (Q_{RM} \times TF_{RM}) + (Q_{YW} \times TF_{YW})\}$$

(Eq. A12)

with

TF_{MSW} = Tip fee for MSW (in dollars ton^{-1})
TF_{RM} = Tip fee for RM (in dollars ton^{-1})
TF_{YW} = Tip fee for YW (in dollars ton^{-1})

The cost of owning the truck per month (E_{net}) is given by:

$$E_{net} = E_{cap}\left[\frac{E_{IR}(1+E_{IR})^{E_{pp}}}{(1+E_{IR})^{E_{pp}} - 1}\right]$$

(Eq. A13)

with

E_{cap} = cost of the truck
E_{IR} = interest rate (percent mo^{-1})
E_{pp} = finance time (length of the contract) (mos.)

A refuse collection truck is a tangible asset with certain operating life and its value depreciates throughout its service life. The depreciation rate (using straight-line depreciation method) is computed here simply as

$$D_{pp} = \frac{E_{cap} - E_{salv}}{E_{serv}}$$

(Eq. A14)

with

D_{pp} = depreciation per payment period
E_{salv} = salvage value of the truck
E_{serv} = service life of the truck

The trucks are mechanically operated heavy motor vehicles and need regular maintenance and insurance. Weekly financial cost for each truck (*FI*) is given by,

$$FI = (E_{net} + MC + IC)/CF$$

(Eq. A15)

with

E_{net} = Cost of owning the truck per month (derived in Eq. A13)
MC = Average truck maintenance cost per month
IC = Truck insurance cost per month
CF = monthly to weekly conversion factor (4.35 = 365/7/12)

The total financial cost (*TFI*) is dependent on the number of trucks needed:

$$TFI = TR \times FI$$

(Eq. A16)

with

TR = total number of trucks needed to service the area (derived in Eq. 9)
FI = the financial cost for each truck (derived in Eq. 16)

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Tables

Parameter	**Value**
Payload capacity, MSW P_{MSW}	9 tons
Payload capacity, recyclables P_{RM}	8 tons
Payload capacity, yard waste P_{YW}	9 tons
Maximum number of trips day^{-1} (maximum of T)	2
Driver wage D	\$29.36
Helper wage H	\$23.77
Fuel cost hour^{-1} F_{hr}	\$10
Truck capital cost E_{cap}	\$250,000
Interest rate E_{IR}	3%
Truck payment period E_{pp}	7 yrs.
Truck service life E_{serv}	10 yrs.
Truck salvage value E_{salv}	\$50,000
Maintenance cost week^{-1}	\$126
Insurance cost week^{-1}	\$92
Financial cost (Lease payments, maintenance costs, and insurance costs) week^{-1} FI	\$878
Profit	0%

Table 1. Baseline Parameterization

Case	**1**	**2**	**3**	**4**	**5**	**6**	**7***
MSW tip fee (ton^{-1})	\$80	\$80	\$80	\$80	\$40	\$40	\$40
Recyclables cost (ton^{-1})	\$20	\$20	\$20	\$20	\$20	\$20	\$20
Truck financing	Own	Own	Lease	Lease	Lease	Lease	Lease
YW collection	No	Yes	No	Yes	No	Yes	Yes
YW cost (ton^{-1})	-	\$45	-	\$45	-	\$10	\$10

* 25% more time required to collect waste for each truck to account for greater distance to facilities

Table 2. Cases for the model

Case	**No Recovery cost**	**Max. cost**	**Recyclables $_{max}$**	**Min. cost**	**Recyclables $_{min}$**
1	$22,104	$25,018	129	$17,498	48
2	$22,104	$24,983	129 (YW = 1)	$16,798	48 (YW = 20)
3	$17,701	$17,894	1	$13,869	112
4	$17,701	$18,111	1 (YW = 1)	$13,239	112 (YW = 18)
5	$12,501	$15,071	129	$10,823	40
6	$12,501	$15,041	129 (YW = 1)	$10,283	40 (YW = 18)
7	$12,501	$16,177	129 (YW = 1)	$11,230	40 YW = 18

Table 3. Maximum and minimum costs week^{-1}, at associated recyclables tonnages (total of 130 tons)

Figure Captions

Figure 1. Case 1 (solid line) and Case 2 (20 tons week^{-1} yard waste collection) (dashed line) weekly costs

Figure 2. Case 1 elasticity associated with changes in recycling tonnages (RM)

Figure 3. Weekly costs for Case 3