ABSTRACT

HODGE, KEITH LENHART. A Systematic Evaluation of Alternatives for Industrial, Commercial, and Institutional Food Waste Management Strategies in the U.S. (Under the direction of Morton A. Barlaz and James W. Levis.)

Food waste represents the single largest component of municipal solid waste (MSW) in the U.S. Over 90% of food waste is currently disposed in landfills, where it degrades rapidly compared to other materials. The rapid degradation of food waste results in much of the generated methane being emitted before a landfill gas system is in place. Regulations limiting landfill disposal of food waste have recently been enacted in several New England states and west coast cities. The purpose of this analysis is to evaluate the environmental implications of existing and proposed food waste management policies using a life-cycle assessment methodology. A set of scenarios was developed to model possible management alternatives applicable to the solid waste generated at facilities producing large amounts of food waste (e.g., restaurants, grocery stores, food processors). The management options considered include anaerobic digestion (AD), aerobic composting, waste-to-energy combustion (WTE), and landfilling. Using a mixed waste functional unit, net global warming potential results ranged from approximately -110 to 60 kg CO_2/Mg of mixed waste for scenarios including AD, -21 to 105 kg CO_2/Mg for those including composting, -90 to -1 kg CO_2/Mg when all waste was managed by WTE, and 66 to 327 kg CO_2/Mg when all waste was landfilled. While the results confirmed that landfilling was consistently the least preferable management alternative for food waste, the ranking and performance of the remaining alternatives varied based on the energy system (e.g., electrical grid mix) and food waste material properties (e.g., moisture content and lower heating value). These results indicate that U.S. EPA "Food Recovery Hierarchy" may not be applicable in all situations across the country, and other jurisdictions seeking to enact new food waste regulations should carefully consider regional factors before duplicating statutes currently in place.

A Systematic Evaluation of Alternatives for Industrial, Commercial, and Institutional Food Waste Management Strategies in the U.S.

by
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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Environmental Engineering

Raleigh, North Carolina

2015

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BIOGRAPHY

Keith is a child of God, who had the joy of growing up with a loving and supportive family in Pennsylvania. He is deeply in love with his beautiful wife Oksana, and can't wait to meet their first child. His undergraduate Bachelor of Science degrees in Agricultural and Biological Engineering and Mechanical Engineering were completed at Penn State University in 2009, after which he worked as an agricultural engineering consultant until 2013. Pursuit of the Master of Science degree of which this work is a component began in 2013 at North Carolina State University. Keith first became a licensed professional engineer in 2014, in the state of North Carolina.

ACKNOWLEDGMENTS

First and foremost, I thank God for creating and saving me, for making His universe an interesting place with lots to study, and for guiding my steps perfectly in spite of my fumbling efforts. A big shout out (because shout outs are way more fun than acknowledgements!) to my loving wife Oksana for her constant encouragement and patience, even when my school and research work attempted to compete with her for my attention. I would also like to thank my parents, who passed on a desire to work hard and always do my best, and who love me no matter what.

Much gratitude is due to Dr. Barlaz for connecting me with the integrated solid waste management group, then patiently working with me to guide the direction and clarify the communication of this research. I sincerely appreciate all of the time and effort that Dr. Levis spent with me both in the depths of process modeling and fine-tuning the analysis as a whole. Thank you to Dr. DeCarolis for helping me find some direction early in my graduate studies, and for reminding me to keep the big picture in view. I would also like to thank Covanta for funding portions of this work.

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1.0 INTRODUCTION

The United States Environmental Protection Agency (U.S. EPA) estimates that more than 250 million tons of municipal solid waste (MSW) were generated in the U.S. in 2012 (U.S. EPA 2014). Other estimates suggest even higher annual MSW generation in the U.S., on the order of 390 million tons in 2011 (Shin 2014). There is some uncertainty regarding the actual amount of MSW generated, but all of it must be properly managed to protect human health and the environment. Particular components of MSW are associated with specific environmental concerns. For instance, biodegradable components of MSW such as paper products, yard waste, and food waste are a concern when considering climate change because they degrade under anaerobic conditions to produce methane, a potent greenhouse gas (GHG). Biodegradable materials are broken down by microorganisms at varying decay rates and with varying methane yields, depending on material properties, microbial populations, and environmental factors. Food waste degrades relatively quickly in comparison with paper, leaves, or woody materials, (De la Cruz & Barlaz 2010). Realizing the potential for methane emissions and other concerns associated with landfilling yard waste, many U.S. states banned yard waste from landfills in the 1990s. Aerobic composting is a common treatment alternative for source-separated yard wastes (U.S. EPA 2014). Yard waste represents “low hanging fruit” among degradable wastes when considering waste management strategies that may involve separate collection, because it is typically generated separately which facilitates source-separation.

In 2012, an estimated 15% of total MSW generation was food waste, and only 5% of that food waste was recovered. As a result, food waste represented the largest portion of degradable waste in the discarded waste stream (21%). Food waste management has received increased attention as a policy issue in the U.S. over the last several years. Several New England states and West Coast cities have implemented policies to limit landfill disposal of food waste and promote biological treatment, as shown in Table 1. While city-level regulations often include the residential sector, laws at the state level currently tend to focus on large volume, high food waste industrial, commercial, and institutional (HFW-ICI) generators, for which a large fraction of the discards is food waste. Once separated, the most common alternative for food waste treatment in the U.S. is aerobic composting; there are at least 340 composting facilities in the U.S. that receive source-separated food waste (Platt et al. 2014). While technically viable, odor control in engineered composting systems is expensive and one large regional facility was recently ordered to close due to problematic odors (Biocycle 2014). An emerging alternative in the U.S. is anaerobic digestion (AD) of source-separated food waste. One advantage of AD is the opportunity for beneficial use of the generated methane.

Table 1 – Summary of U.S. states and large cities with regulations limiting landfill disposal of food waste.

State/City	Description of Regulation
Connecticut[a]	Source separation and management of source-separated organics required of select ICI entities located within 20 miles of an organics management facility that generate >104 tons/year organic waste, decreasing to >52 tons/year in 2020.
Massachusetts[b]	"Commercial Organic Material" (food and vegetative material from entities generating >1 ton/week organic waste) is banned from landfills and incineration.
Vermont[c]	Source separation and management of food residuals required of persons located within 20 miles of an organics management facility that generate >104 tons/year organic waste; threshold decreases to include all food waste by 2020.
Portland, OR[d]	Source separation of food waste required for residential customers and "food waste generating businesses."
San Francisco, CA[e]	Source separation required for all "compostable" waste (including food waste). Landfill ban on source separated compostable materials.
Seattle, WA[f]	Source separation required for all commercial and residential food waste, compostable paper, and food-contaminated paper products.
New York, NY[g]	Source-separation and treatment by AD or composting of commercial food waste generators meeting conditions to be determined and updated at least annually by DSNY, based on available capacity and costs of treatment.

a. CGS Sec. 22a-226e, effective January 1, 2014. Listed ICI entities include "commercial food wholesaler or distributor, industrial food manufacturer or processor, supermarket, resort or conference center."
b. 310 CMR 19.017, effective October 1, 2014.
c. Vermont Act 148 (2012), effective July 1, 2014.
d. Portland City Code Sections 17.102.270 and 17.102.295, effective July 21, 2012. Businesses classified as "food waste generating" are determined by the city (no quantitative criteria). Examples listed include restaurants, grocery stores, hotels with catering operations, institutions with cafeterias, food processors, etc.
e. San Francisco City Ordinance 100-09, effective June 16, 2009.
f. Seattle Municipal Code Sections 21.36.082 and 21.36.083, effective January 1, 2015.
g. New York City Administrative Code Section 16–306.1, effective July 1, 2015. DSNY refers to New York City Department of Sanitation. In addition, DSNY must conduct a pilot program (October 1, 2013 to July 1, 2015) for separate organic waste management at select schools and in select residential areas: New York City Administrative Code Section 16–308.

Modern solid waste management (SWM) often involves complex integrated systems that include multiple collection processes for separate waste streams (e.g., recyclables, yard and food waste, mixed waste), each with associated treatment and disposal processes (e.g., material recovery facility (MRF), aerobic composting, landfill, etc.). Understanding the system-wide environmental consequences of SWM decisions is important for guiding policy and achieving environmental goals. Life cycle assessment (LCA) has been applied to SWM systems in general, and food waste management systems in particular. Morris et al. (2013) performed a meta-analysis of numerous source-separated food waste management LCA studies published through 2010, and found AD to be a consensus best alternative for climate change impact when compared with various configurations of waste-to-energy (WTE), landfill, composting, and other management strategies. More recently, Fruergaard & Astrup (2011) concluded that WTE combustion with combined heat and power (CHP) was generally preferable to AD with CHP in a Danish setting for source-separated organics, and Evangelisti et al. (2014) found that AD with CHP outperformed landfilling and WTE of source-separated organics in the UK when considering climate change and acidification impacts. Levis & Barlaz (2011) was one of a limited number of studies to have analyzed food waste management alternatives in a U.S. context. The study concluded that AD was superior to composting and landfilling, but WTE was not considered. Fruergaard & Astrup (2011), Evangelisti et al. (2014), and Levis & Barlaz (2011) used source-separated food waste in their functional unit definition rather than considering a waste composition corresponding to the total waste that HFW-ICI generators actually must manage. Some studies have examined total system emissions with separate organics treatment and parallel disposal of residual (Cherubini et al. 2009; Assamoi & Lawryshyn 2012), and reported that AD for separated organics coupled with a version of WTE for residual management was superior to landfilling. Of the studies reviewed, only Levis & Barlaz (2011) focused specifically on commercial waste.

The objective of this study was to compare alternatives for the management of discarded waste from HFW-ICI entities. This study used life-cycle process models with U.S.-relevant data to develop a system-level understanding of the environmental implications of recent food waste policy developments. Treatment and disposal alternatives that were considered include landfilling, mass burn WTE, composting, and AD. The details of the LCA modeling approach employed are described in the next section, followed by a presentation and discussion of the results.

2.0 MODELING APPROACH

2.1 Functional Unit and System Boundaries

An LCA approach was used to quantify emissions and environmental impacts associated with several alternatives for HFW-ICI management. This study was designed to support micro-level decision-making (i.e., How should HFW-ICI be managed?) in which management decisions in the foreground system (i.e., SWM) have limited structural consequences and were assumed to not impact background systems, such as the U.S. electricity and fuel systems.

The functional unit was 1 Mg (1000 kg) of HFW-ICI waste with the composition given in Table 2. (See Appendix A for detailed methodology used to estimate waste composition). For the purposes of this study, HFW-ICI waste includes waste generated by the categories of entities listed in Connecticut’s law (summarized in Table 1), plus restaurants. A mixed waste functional unit was chosen to maintain clarity regarding interactions of food waste management alternatives with the larger SWM system. When comparing waste management scenarios involving separate collection schemes with those involving single mixed collection, management choices for the residual influence the environmental performance of the overall system. It was assumed that HFW-ICI generators already participate in a recycling program independent of the food waste management decision, so recycled materials were excluded from this analysis. The HFW-ICI composition developed for this study was based on as-discarded waste composition data, rather than as-generated information. Selected properties of food waste assumed for this study are provided in Table 3.

System boundaries were chosen to include all activities from waste collection through treatment and final disposal. The physical system boundaries are illustrated in Figures 1-4**Figure 1**. Capital goods (i.e. construction of facilities and manufacturing of equipment) are considered in all systems as recommended by Laurent et al. (2014), as they can have non-negligible contributions to the selected environmental impacts. Defining collection as the beginning of the system is consistent with standard practice for LCAs of SWM systems, referred to as the "zero-burden assumption," in which environmental burdens associated with the production and use of products and materials that ultimately become wastes are not considered in the life-cycle inventory (LCI) for the waste management system (Ekvall et al. 2007). Temporally, the analysis used a 100-year evaluation period, which is long enough to include over 99.9% of landfill gas (LFG) generation from food waste. The duration of the evaluation period is generally less critical for treatment facilities that do not have long-term material storage, including WTE, composting, and AD. Consistent with this time horizon and the zero-burden assumption, any biogenic carbon stored after 100 years is considered stored, and is assigned a global warming impact of -1 kg CO_2e/kg CO_2 stored..

Table 2 – Simplified HFW-ICI as-discarded waste composition.

	Restaurants[a]	Grocery Stores[a]	Large Hotels[a]	Food Proc/Mfg.[b]	Aggregate[c]
Food Waste	59	63	36	75	58
Paper	25	19	32	10	21
Plastics	10	10	10	6	9
Glass	2	1	5	0	2
Metal	2	1	4	2	2
Other	3	7	12	7	8
Contrib. to Total Mixed Waste:[c]	6%	35%	30%	29%	100%

a. Composition obtained from California statewide data (Cascadia Consulting Group 2006).
b. Food processing and food manufacturing plants. Author's estimate, informed by UK study (Jacobs 2011).
c. Aggregate estimated from distribution of Connecticut food waste generation, by generator type. Based on current regulatory threshold mandating separate FW management for generators producing at least 140 tons/year (Connecticut Department of Energy & Environmental Protection 2012).

Table 3 – Selected food waste material properties.

Property	Vegetable Food	Non-Vegetable Food	This Study[a]
Moisture Content (%) [b]	77.0	57.1	73.0
Volatile Solids (% of Total Solids) [b]	96.4	94.2	96.0
Total Carbon Content (kg C/dry Mg) [b]	477	565	495
Total Nitrogen Content (kg N/dry Mg) [b]	19	70	29
Total Phosphorous Content (kg P/dry Mg) [b]	2.3	10	3.8
Lower Heating Value (MJ/dry kg) [b]	10.9	21.5	13.0
Carbon Storage Factor (kg C/dry Mg) [c]	80	80	80
Methane Yield (m^3/dry Mg) [d]	400	400	400
Field Decay Rate (for bulk MSW k=0.04) [e]	0.096	0.096	0.096

a. This study assumed the food component of HFW-ICI waste was a mix of 80% "vegetable" and 20% "non-vegetable" food waste, consistent with the relative composition reported in Petersen & Domela (2003).
b. Values adapted from Riber et al. (2009).
c. Carbon storage factors obtained from Barlaz (1998).
d. Methane yield estimates are based on the default values used in the U.S. EPA's MSW-DST and WARM models, as updated in 2014 (Appendix B).
e. As estimated in De la Cruz & Barlaz (2010) for a landfill with a bulk MSW decay rate of k=0.04.

Selected life cycle impact assessment (LCIA) categories were considered including global warming potential (GWP), eutrophication potential, acidification potential, cumulative fossil energy demand, and photochemical smog formation potential, all based on their relevance to food waste management. All impacts were calculated using TRACI methodology (Bare 2011) with the exception of GWP, which was estimated using both IPCC 2007 and IPCC 2013 methodologies (100 year GWP for methane of 25 and 34 kg CO_2-eq, respectively), and cumulative fossil energy demand (CED-fossil) (Frischknecht et al. 2007). The LCA modeling approach described herein was implemented using components of the Solid Waste Optimization Life-Cycle Framework (SWOLF) described in Levis et al. (2013), with further information available at go.ncsu.edu/swolf.

2.2 Scenario Descriptions

The four food waste management alternatives identified as the focus of this study included landfill, WTE, composting, and AD. The nature of the functional unit dictated a split between source-separated food waste and residual waste in scenarios involving composting or AD, so a total of 6 scenarios were analyzed as summarized in Table 4. For each scenario, facilities with a range of performance were considered. For each facility, there is the potential for the beneficial use of products (e.g. methane in landfill gas, nutrients in compost). However, these products are not always beneficially used in practice. As such, each facility configuration was modeled under multiple assumptions regarding beneficial use, as summarized in Table 5. Beneficial use assumptions and facility configurations are further defined in Section 2.3. Emissions were estimated for all combinations of applicable facilities for each food waste management scenario.

Table 4 – Waste material routing for each food waste management scenario.

Scenario Name	Description
LF	All waste collected together and disposed in a landfill.
WTE	All waste collected together and combusted in WTE with the bottom and fly ash to an ash landfill.
AD-LF	Food waste collected separately and treated by AD, residuals to landfill.
AD-WTE	Food waste collected separately and treated by AD, residuals to WTE, and WTE bottom and fly ash to ash landfill.
AC-LF	Food waste collected separately and treated by composting, residuals to landfill.
AC-WTE	Food waste collected separately and treated by composting, residuals to WTE, and WTE bottom and fly ash to ash landfill.

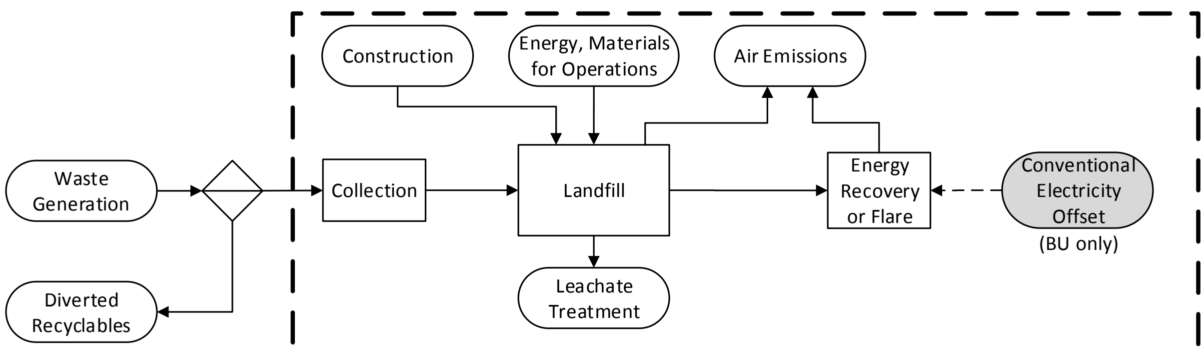


Figure 1 – Illustration of system boundaries for the LF scenario.

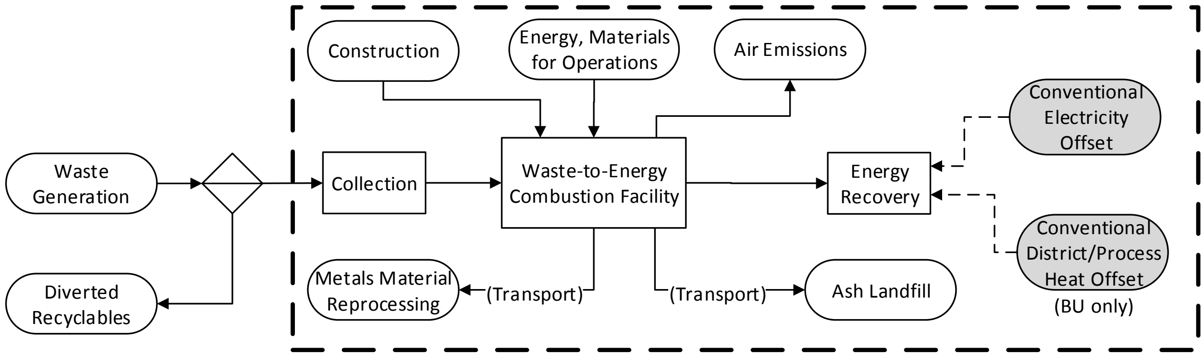


Figure 2 – Illustration of system boundaries for the WTE scenario.

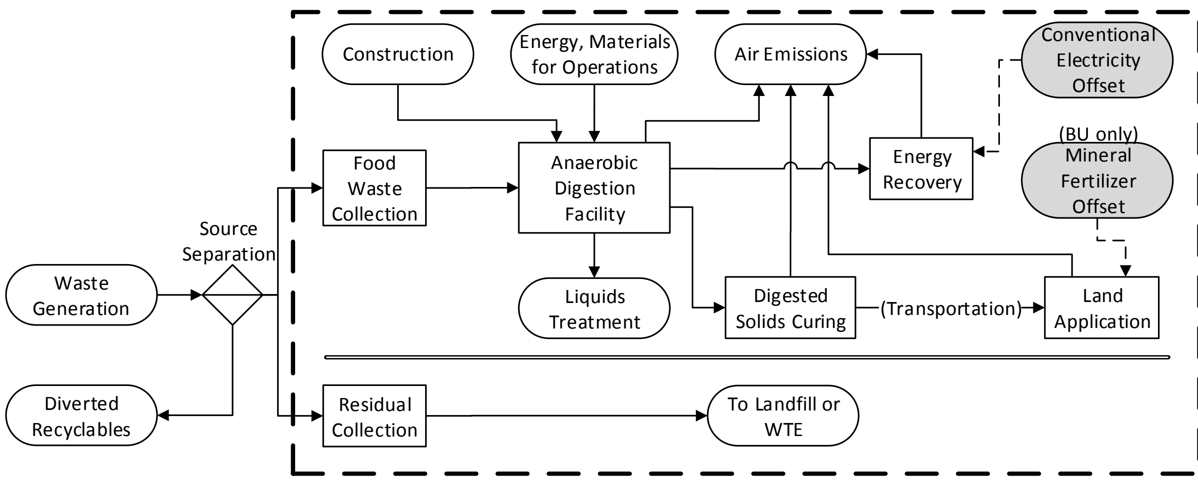


Figure 3– Illustration of system boundaries for the AD-LF or AD-WTE scenarios. Refer to Figures 1 and 2 for boundary details for residual waste stream.

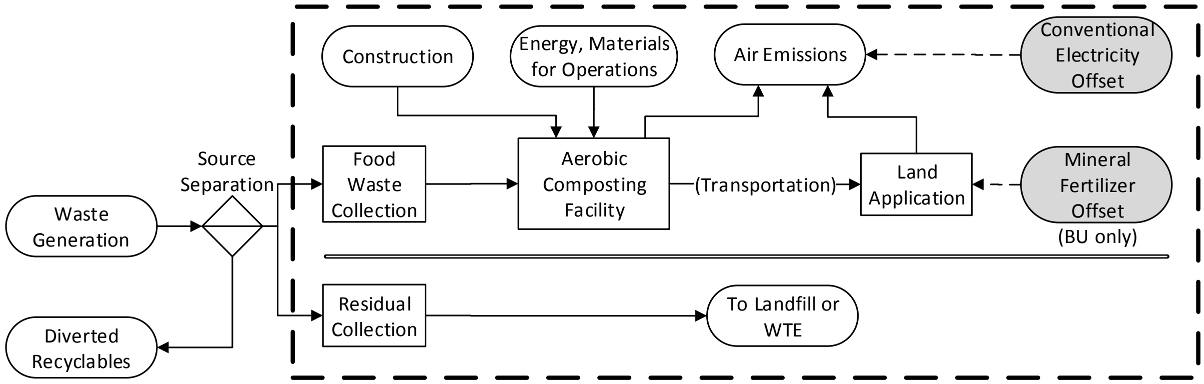


Figure 4 – Illustration of system boundaries for the AC-LF or AC-WTE scenarios. Refer to Figures 1 and 2 for boundary details for residual waste stream.

Table 5 – HFW-ICI waste management facilities, beneficial use options, and facility configurations.

Waste Management Facility	Beneficial Use (BU[a] / No BU)	Configurations		
		Better	**Moderate**	**Worse**
LF	Energy Recovery[b] / Flare[c]	SOTA[d]	U.S. Nat'l Avg.[e]	NSPS Limits[f]
WTE	CHP[g] / No CHP	SOTA[d]	Fleet Avg.[h]	Worse Case[h]
AD	Fertilizer Offset[i] / None[j]	Better Case[k]	Typical[k]	Worse Case[k]
AC	Fertilizer Offset[l] / None[j]	Windrows, Under Roof with Biofilter		Windrows, Open

a. BU = Beneficial Use.
b. Energy Recovery. Collected landfill gas is treated and burned in an internal combustion engine to produce electricity when sufficient gas (350 cfm) is collected.
c. All collected landfill gas is flared without beneficial use.
d. State-of-the-art. Definition for SOTA varies by facility.
e. U.S. national average MSW landfill gas generation and collection characteristics adopted from Levis & Barlaz (2014).
f. New Source Performance Standards set maximum emissions to air and minimum control strategies. Definition for NSPS Limits varies by facility.
g. Combined Heat and Power. Indicates beneficial use of heat outside of on-site process control, either district heat or process heat use by industrial customer, in addition to electricity production. The CHP case here assumes 50% of steam generated in the WTE boiler is exported for heat and 50% is used in a turbine to generate electricity. The no CHP case assumes all steam from the WTE boiler is used for electricity production. Refer to Table A7 for further details.
h. Covanta fleet average and worse case emissions and performance data (M Van Brunt, pers. comm.).
i. Beneficial Use. Curing and subsequent land application of dewatered solids from digestate, with digestate liquids directed to a wastewater treatment plant. Land application of solids offsets inorganic fertilizer use and promotes soil quality.
j. None involves land disposal of cured dewatered digestate or compost product, providing carbon storage but no nutrient offsets or soil quality promotion.
k. Better Case, Typical, Worse Case indicate predicted range of performance for AD facilities using food waste as their primary feedstock. Based on variation of biogas engine efficiency.
l. Beneficial use of compost offsets inorganic fertilizer production.

2.3 Facility and Process Modeling

SWOLF model components are summarized in the following sections and have been described previously. Key model input parameters are presented to characterize facility configurations and further description of modeling parameters is provided in Appendix A.

2.3.1 Collection and Transportation

Based on the scenarios designed for this study, three collection processes representing two collection schemes were required. Mixed waste collection for the full combined functional unit was applied to the landfill and WTE scenarios, while both source-separated food waste and residual mixed waste collection processes were required for scenarios that include composting or AD. Emissions associated with collection were estimated through use of the model described in Jaunich et al. (2015). A subset of model input parameters is shown in Table 6, and further detail and discussion are provided in Section 3.5 of Appendix A.

Table 6 – Selected waste collection model parameters.

Parameter	Food Waste Collection	Residual Collection	Combined Collection
As-discarded waste generation rate (lb/week-location)	9,500	9,900	19,400
Bulk in-truck density (kg/m^3)	800	430	550
Collection frequency (1/week)	2	1	2
Distance between collection route and unloading site (miles)	20	10	10

Transportation-related emissions were estimated for both facility "internal" requirements such as delivery of supplementary materials or hauling of compost to a land application site and inter-facility requirements such as transfer of ash to a landfill. These calculations considered the mode of transportation (e.g. medium-heavy duty truck, heavy-heavy duty truck), and assumed that vehicles were full for one-way travel and empty for a return trip.

2.3.2 Landfill (LF)

The landfill receives mixed or residual waste from HFW-ICI generators, as well as residual material from composting or AD facilities depending on the scenario. The landfill in this study was represented using the model described in Levis & Barlaz (2011a) updated with default values from Levis & Barlaz (2014) to estimate emissions, material use, and energy use associated with construction, operations, closure and post-closure activities, and landfill gas and leachate management, and carbon storage. Landfill configurations were differentiated by landfill gas collection system parameters, and divided into "Flare" and "Energy Recovery" beneficial use options. "Flare" assumed that all collected landfill gas was burned with no beneficial use, while "Energy Recovery" assumed use of an internal combustion engine to produce electricity when greater than 350 cubic feet per minute of gas was available. Table 7 defines the landfill gas collection system parameters used for each landfill configuration.

Table 7 – Selected landfill configuration parameters.

Landfill Gas Collection Parameters	**SOTA**[a]	**U.S. National Avg.**[a]	**NSPS Limits**[a]
Time until initial gas collection (yr)	0.5	2	5
Initial gas collection efficiency (%)	50	50	50
Time to intermediate cover (yr)	3	5	5
Gas collection efficiency under intermediate cover (%)	75	75	75
Time to increased gas collection efficiency (yr)	15	15	15
Increased gas collection efficiency (%)	82.5	82.5	82.5
Time from final waste placement to final cover (yr)	1	1	1
Gas collection efficiency under final cover (%)	90	90	90
Energy Recovery/ Methane Oxidation Parameters			
Electrical energy recovery efficiency[b] (%)	36.5	36.5	36.5
Energy recovery cut-on time[c] (yr)	5	5	5
Energy recovery cut-off time[c] (yr)	52	52	52
Energy recovery downtime (%)	3	3	3
Without gas collection or final cover (%)	10	10	10
With gas collection, before final cover (%)	20	20	20
With final cover (%)	35	35	35

a. Values adopted from Levis & Barlaz (2014) unless otherwise noted.
b. Efficiency chosen based on manufacturer specifications. Refer to Table A5 for details.
c. Energy recovery cut-on and cut-off times indicate the number of years after initial waste placement that the energy recovery system becomes operational and ceases operation, respectively. The chosen values are based on estimates of the time span over which sufficient gas (350 cfm) is collected from the landfill, with a one-year delay of cut-on to account for system installation.

2.3.3 Mass-Burn Combustion with Energy Recovery (WTE)

In the scenarios defined above, the WTE facility receives mixed or residual waste from HFW-ICI generators as well as residual material from composting or AD facilities. Estimates of emissions, mass flows, and resource use for the WTE facility were based on an updated version of the model presented in Harrison et al. (2000). The updates to the model include a consideration of heat lost to moisture and ash in each material, the ability to separate aluminum (in addition to ferrous metal) from bottom ash, and the option to beneficially use steam in addition to that used for electricity generation. The consideration of the heat losses leads the wet (e.g., food waste and grass) and inert materials (e.g., metals and glass) to have greater GHG emissions, while the drier combustible materials (e.g., paper and plastic) have lower emissions and costs due the offsets from the generated electricity. This is particularly important for this study given the emphasis on a relatively high moisture content waste stream. In all modeled configurations, energy released during waste combustion was recovered to produce electricity. For the “CHP” beneficial use option, the WTE plant was assumed to also recover heat released during combustion for use in either a district heating system or an industrial process. Table 8 partially defines the WTE configurations. Direct stack emissions of particular pollutants also varied across configurations, and are described in the SI. Transportation of ash was included in the LCI. Parameters defining the ash landfill were held constant for all WTE configurations, as this process was expected to be a relatively minor contributor to emissions given the absence of biodegradable waste.

Table 8 – Selected WTE configuration parameters.

Parameter	SOTA[a]	Fleet Avg.[a]	Worse[b]
Net Electrical Efficiency (%) (with CHP)[c]	10.3	8.8	7.6
Net Heat Recovery Efficiency (%) (with CHP only)	37.5	33.0	30.6
Net Electrical Efficiency (%) (without CHP)	24.4	20.9	18.2
Ferrous Recovery from Ash (%)	90	90	90
Aluminum Recovery from Ash (%)	65	35	35
Copper Recovery from Ash (%)[d]	0	0	0

a. Values obtained from Covanta.
b. Values adopted from fleet average, except where noted. Note that stack emission rates for particular pollutants vary between fleet average and NSPS. Refer to Table A7.
c. This represents the fraction of the LHV of the waste stream that is converted to electricity. The overall energy recovery efficiency would be the value in this row plus the Net Heat Recovery Efficiency.
d. Though copper recovery is typically practiced, it was not considered in this study due to the low copper content expected in the HFW-ICI composition.

2.3.4 Aerobic Composting

The composting facility in this study was represented using the model described in Levis & Barlaz (2013b). The model estimates process-related direct emissions, emissions associated with land application of finished compost, as well as those associated with energy and material inputs required for the composting process. Soil carbon storage was estimated for the finished compost material. In addition, further soil carbon storage due to increased humus formation was incorporated. Beneficial use of the available nitrogen, phosphorus, and potassium in the compost were counted as credits to offset mineral fertilizer production in the "Fertilizer Offset" beneficial use cases, while the no BU cases did not consider these credits. Other studies have evaluated multiple composting technologies (Levis & Barlaz 2011b), but only windrow configurations were selected for this study because they were estimated to be the most common composting technique currently used in the U.S.. The only difference between the two configurations was addition of an odor control system. Odor was not quantified in this study (for composting or any other facility), but energy associated with operation of the control system was included. Residual from the composting operation was directed either to landfill or WTE, depending on the scenario.

2.3.5 Anaerobic Digestion (AD)

Emissions and energy and material inputs associated with the AD process and downstream material flows were estimated using the AD model presented in Levis & Barlaz (2013a). The modeled AD facility was based on a wet digestion system, as reflected in the assumed moisture content and digestate mass flows. Water addition requirements were modeled, as was treatment of separated digestate liquids at a downstream wastewater treatment plant. Due to the nature of the model with respect to process design, the AD system represented was not explicitly mesophilic or thermophilic, single- or two-stage, continuous mix, or other specific design. Instead, the model used overall system performance parameters to estimate biogas production, energy recovery, and internal energy use, and employed a mass balance on carbon and nitrogen to estimate process emissions and nutrient value. The default data were developed from a continuous single-stage wet mesophilic digester. Land application-related emissions and carbon storage for separated digestate solids were estimated in the same manner as for composting. In the “Fertilizer Offset” case, beneficial use of nutrients in the digested, cured solids were counted as credits to offset mineral fertilizer production; these offsets were not considered in the NBU cases. Three configurations were developed by varying the heat rate of the internal combustion engine used for energy recovery while other parameters were held constant, as shown in Table 9. Residual from AD was directed either to landfill or WTE, depending on the scenario under consideration.

Table 9 – Selected AD configuration parameters.

Parameter	Better Case	Typical	Worse Case
Electricity generation efficiency (%)[a]	40.2	36.5	32.9
Biogas leakage (% of biogas produced)[b]	3	3	3
Percent of captured gas that is flared without electricity generation.	3	3	3
Specific electricity usage (kWh/Mg)[b]	58	58	58

a. Efficiency is expressed as percent of energy in combusted methane, on LHV basis. “Typical” value chosen following procedure described for landfill gas engine. “Better Case” and “Worse Case” are 110% and 90%, respectively, of “Typical.”

b. Adopted from Sanscartier et al. (2012).

2.4 Beneficial Use

Each of the food waste management facilities has one or more opportunities for beneficial use of a product, which can displace consumption of an equivalent product produced by conventional means. Consistent with the decision context of this study, offsets use emissions associated with "system average" rather than marginal units of conventional production. For facilities that generate electricity, the U.S. national average grid mix was assumed, with emissions estimated using a tool developed as part of this study. Heat production in WTE CHP cases was assumed to offset an equivalent quantity of heat generated in a natural gas-fired boiler, using emission factors obtained from the ecoinvent v3.01 database (Weidema et al. 2013). Where specified, available nitrogen, phosphorous, and potassium in compost and cured, digested solids were assumed to avoid conventional N, P, and K fertilizer production, respectively, using emission factors adapted from ecoinvent.

3.0 RESULTS AND DISCUSSION

3.1 Model Results

The net GWP calculated for all configurations in all scenarios is shown in Figure 5. Contribution analysis of select scenarios by process and their key sub-processes is shown in Figures 6-9. Selected LCI results for all scenarios are provided in Appendix A (Tables A16-A21). As expected, all configurations of the LF scenario resulted in higher GWP than the other scenarios, primarily due to emissions of methane prior to installation of a gas collection system (Figure 6.b).

Consistent with previous studies, scenarios involving AD tend to perform better than those involving composting. Comparison of Figures 7.b and 9.b demonstrates that this is largely a result of electricity offsets considered for AD. Figure 7.b also shows that fugitive biogas is the second largest contributor to the gross GWP for AD, which highlights the importance of modeling assumptions regarding biogas leakage. The largest contributor to gross GWP for both composting and AD is direct gaseous emissions associated with biodegradation during composting, solids curing, and after land application. As presented in Appendix A

(Figure A5), N_2O plays a major role in this group of emissions - over 90% for AD and approximately 50% for composting.

While electrical energy generation is common, additional heat recovery at WTE facilities it is still relatively uncommon in the U.S. (Michaels 2010). The best scenarios that do not include WTE CHP are AD-LF (BU), AD-WTE (NBU), and WTE (NBU) scenarios. The WTE (NBU) scenario, which directs all waste to the WTE facility, is comparable in performance to scenarios including AD on a GWP basis when considering the full modeled range. This result suggests that if a state-of-the-art WTE facility (with or without CHP) is operating in a given region, the most beneficial strategy in terms of GWP could be to forgo source separation and direct all HFW-ICI waste to WTE, depending on the alternatives available in that region. This also suggests that if a WTE facility is currently receiving HFW-ICI, there is only marginal GWP benefit associated with diverting food waste to AD, and there is a GWP penalty for diverting food waste to composting. In contrast, there is a large benefit associated with diverting food waste from landfills to either AD or composting. However, when comparing only the moderate cases (representative of typical or average facilities), AD-LF (BU) performed better than WTE (NBU) and AD-WTE (NBU). This remains the case when considering the approximately -14 kg CO_2-eq associated with mineral fertilizer offsets not included in the AD-WTE (NBU) result (but shown in Figure 7.b).

Comparison of Figures 6.b and 7.c shows that the landfill, modeled identically, is a net carbon emitter in the LF scenario, but a net carbon sink in the AD-LF scenario, in which it receives the residual waste stream. In the LF scenario, LFG emissions dominate net GWP as a result of rapidly-degrading food waste producing methane that is released prior to installation of the LFG collection system. In the AD-LF scenario, LFG emissions are reduced because most of the food waste has been diverted, and the remaining degradable materials (mostly cardboard and paper products) degrade more slowly, so more of the gas is collected and treated. Since the remaining materials degrade to a lesser extent than food waste, they also have higher carbon storage. This demonstrates the importance of modeling each component of the entire waste stream individually (e.g., HFW-ICI waste in this study). The use of a unit mass of HFW-ICI as a functional unit and modeling each waste component individually makes it possible to capture changes that may occur in the broader SWM system as a result of food waste management choices. Studies that do not use a mixed waste functional unit or do not model each waste component separately when studying food waste management may unintentionally omit changes in the performance of facilities from which the food waste is diverted.

The disaggregated results indicate that waste collection is a relatively minor contributor to the performance of each scenario, and that the addition of a separate collection scheme for food waste increases the GWP only marginally. This is true under a wide range of assumptions as shown in Section 3.5 of Appendix A. While this result appears to be relevant for this study, it may not be applicable to residential food waste collection. In addition, disaggregation shows that mineral fertilizer offsets have a relatively minor impact. Use of CHP in the WTE scenario actually incurs a slight GWP penalty compared to generating only electricity under the base case model assumptions (Figures 8.b, 8.d), which are relatively conservative in that recovered usable heat offsets operation of a natural gas- rather than coal-fired boiler. Energy recovery from LFG, on the other hand, has a major impact on net GWP for all scenarios involving the landfill, as shown in the shift between beneficial use and no beneficial use cases in Figure 5.

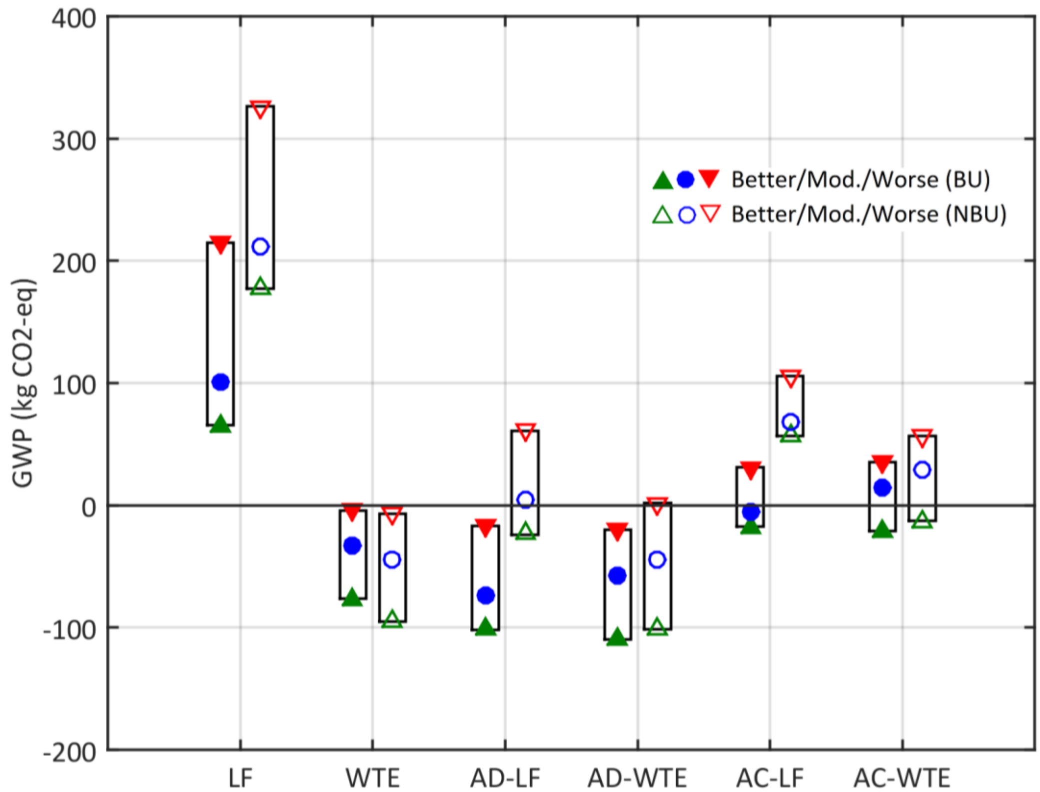
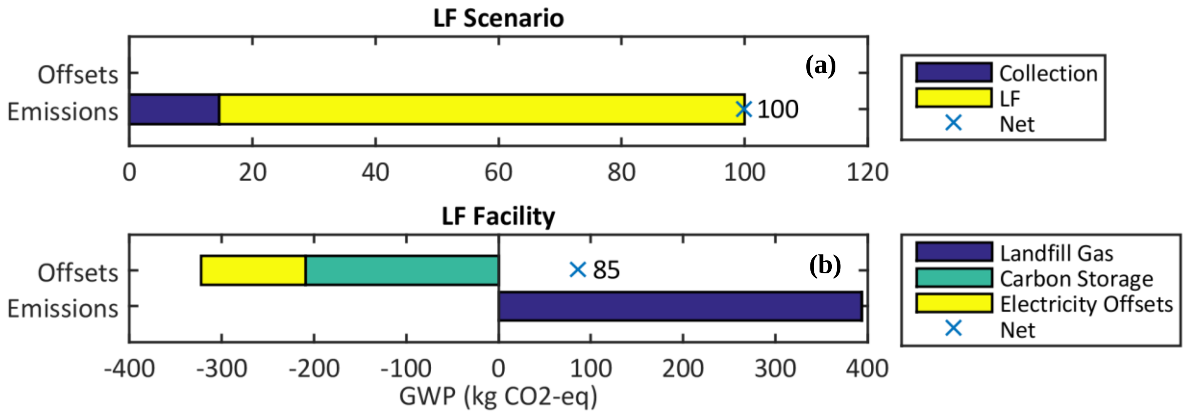
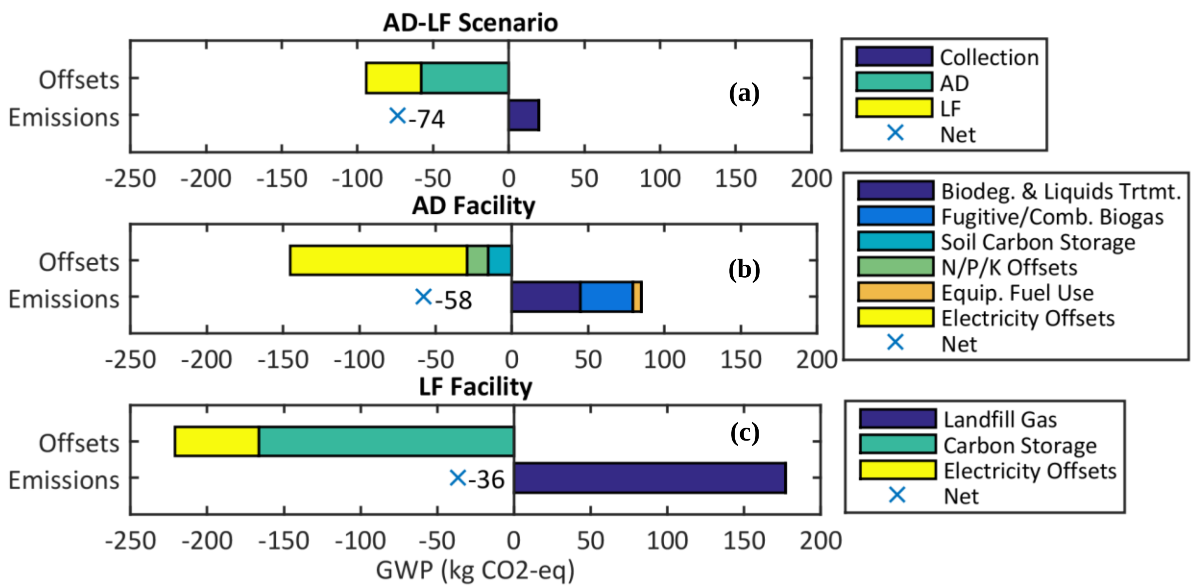


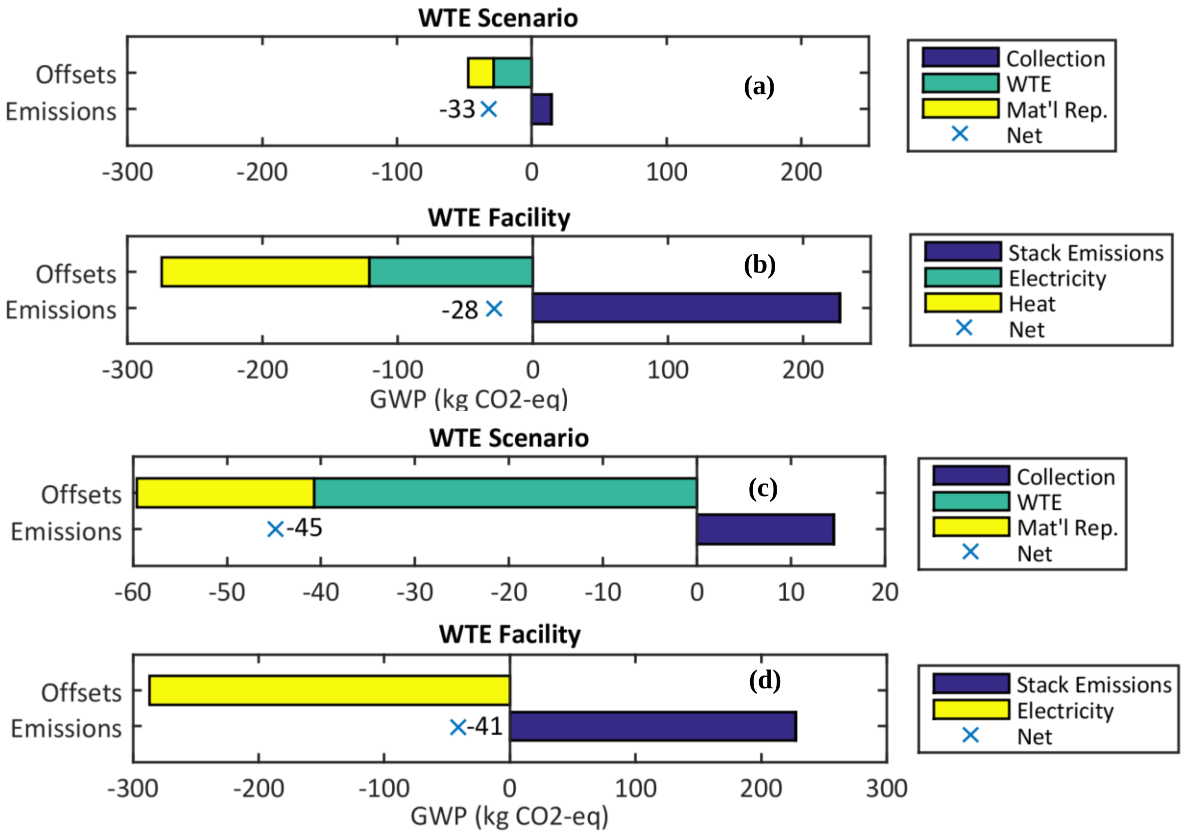
Figure 5 – Net GWP for each scenario and configuration. Note that bar outlines represent the range of values for all scenarios modeled and the individual symbols correspond to configurations described in the Modeling Approach.



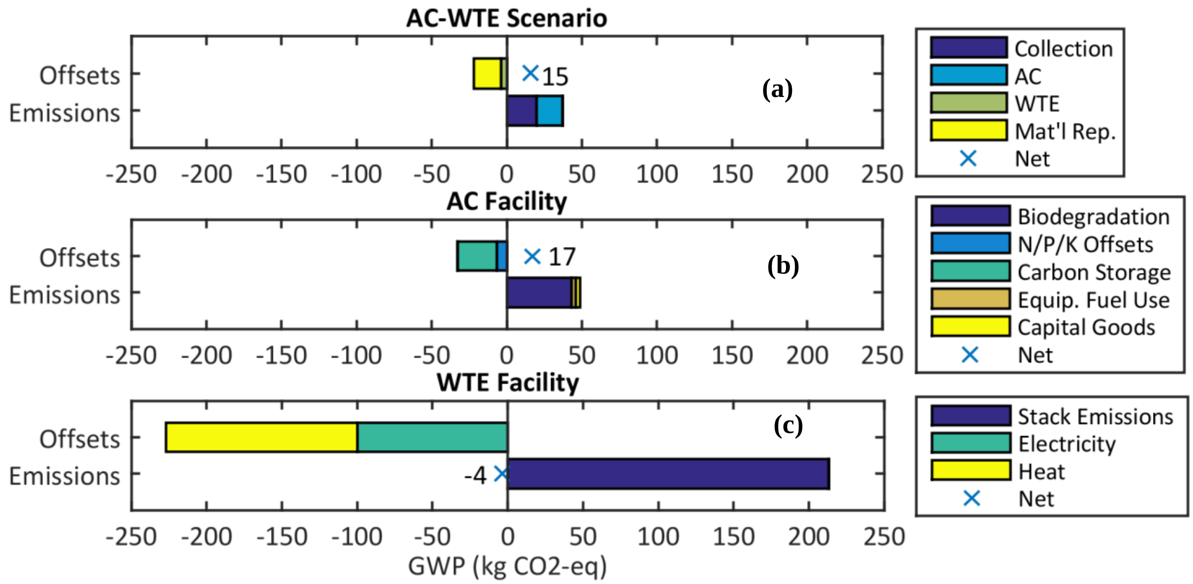
Figures 6.a-b – Contribution analysis for the LF Scenario; (a) the processes involved in the LF scenario (waste collection and landfill disposal) and (b) the landfill facility as it performs in the LF scenario. Results are based on moderate configuration, with beneficial use. Processes contributing less than 5% of gross GWP are not shown for clarity.



Figures 7.a-c – Contribution analysis for the AD-LF scenario; (a) the processes involved in the AD-LF scenario (waste collection, landfill, and AD), (b) the AD facility, and (c) the landfill facility as it performs in the AD-LF scenario. Results are based on moderate configuration, with beneficial use. Processes contributing less than 5% of gross GWP are not shown for clarity.



Figures 8.a-d – Contribution analysis for two cases of the WTE scenario; (a) the processes involved in the WTE scenario with CHP (waste collection, WTE, and material reprocessing for recovered metals), (b) the WTE facility as it performs in the WTE scenario with CHP, (c) the processes involved in the WTE scenario without CHP, and (d) the WTE facility as it performs in the WTE scenario without CHP. Results are based on moderate configuration in both cases. Processes contributing less than 5% of gross GWP are not shown for clarity.



Figures 9.a-c – Contribution analysis for the AC-WTE scenario; (a) the processes involved in the AC-WTE scenario (waste collection, composting, WTE, and material reprocessing for recovered metals), (b) the AC facility, and (c) the WTE facility as it performs in the AC-WTE scenario. Results are based on moderate configuration, with beneficial use. Processes contributing less than 5% of gross GWP are not shown for clarity.

Figure 10 shows net photochemical smog formation potential for all scenarios. Comparison of the moderate configurations for each scenario shows that LF (NBU) and AC-LF (NBU) have the lowest equivalent NO_x emissions. LF (BU) and the AD scenarios result in relatively high smog formation potential because LFG and biogas engines tend to have higher NO_x emissions. Similarly, scenarios involving the NSPS Limits and Fleet Average WTE configurations have relatively high NO_x emissions. SOTA WTE configurations include a greater level of NO_x control, which is reflected in the lower photochemical smog formation results for those configurations.

Scenario-level results for other impact categories are presented in the SI (Figures S1-S3). The rankings for the other impact categories tend to be similar to GWP, and scenarios involving WTE consistently outperformed those involving the landfill. Net acidification values ranged from approximately -92 to 53 moles H+-eq, cumulative fossil energy demand ranged from -5100 to 540 MJ-eq, and eutrophication ranged from -0.01 to 0.55 kg N.

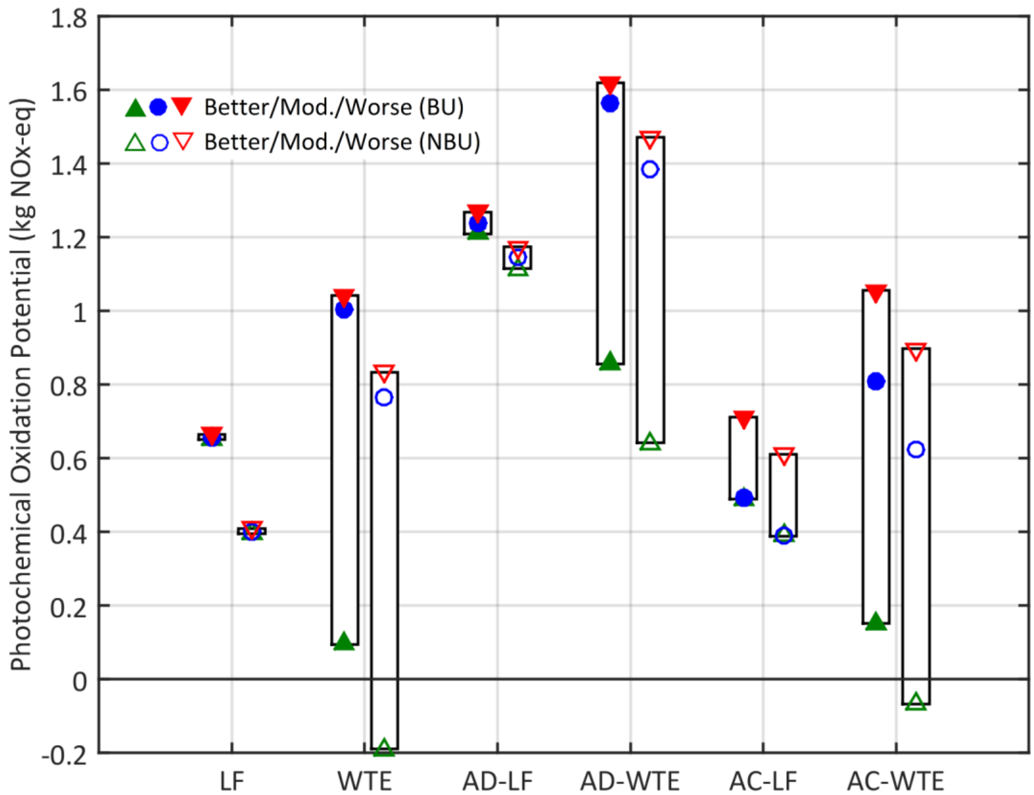


Figure 10 – Net photochemical oxidation potential for each scenario and configuration. Note that bar outlines represent the range of values for all scenarios modeled and the individual symbols correspond to configurations described in the Modeling Approach. Filled symbols represent beneficial use while open symbols represent no beneficial use.

The results are consistent with earlier work in showing that AD typically outperforms composting in terms of GWP (Levis & Barlaz 2011b). Laurent, Bakas, et al. (2014) showed a consensus among studies reviewed that AD was comparable to WTE, both outperformed composting, and landfilling was the least preferable option for food waste. Morris et al. (2013)

showed that, based on the median of studies reviewed, WTE performed about the same as composting and that landfilling performed worst among alternatives considered but it is difficult to compare the Morris summary to this study given the divergent functional units and process assumptions. Bernstad & Jansen (2012) suggested that differences in relative rankings of alternatives among food waste management LCA studies were largely due to methodology inconsistencies and divergent input assumptions across studies. Sensitivity analyses are presented in the following section to evaluate the robustness of the initial results.

3.2 Sensitivity Analysis

Electricity offsets are major contributors to net GWP in all scenarios involving WTE, AD, or LF (BU) (Figures 6-9). The base case assumes that each unit of electricity produced avoids one unit of electricity from the U.S. national average grid. Since New England has several states with regulations limiting landfilling of food waste (including Massachusetts, where the regulation also explicitly prohibits combustion of food waste), sensitivity of the scenario-level results to electricity grid characteristics was tested using the Northeast Power Coordinating Council (NPCC) regional grid as a test case. The NPCC regional grid and the U.S. national average GHG intensities are approximately 0.42 and 0.71 kg CO2-eq/kWh, respectively, with NPCC being the least carbon-intensive regional grid in the U.S., based on the results of a model developed for this work. Resulting GWP for all scenarios for the NPCC case are shown in Figure 11, with comparisons to base case results.

As expected, Figure 11 shows that all scenarios that involve electricity generation (all except LF (NBU) and AC-LF (NBU)) result in higher net GWP compared to the base case. Interestingly, the rankings also change. While LF (NBU) is still the worst performer, the GWP ranges of AD-WTE (NBU) and AC-WTE (NBU) increased and partially overlap with LF (BU). In the NPCC case, the potential benefit of CHP for a WTE facility is realized, as avoiding natural gas use in a boiler is preferable when grid electricity has low carbon intensity. Again excluding the WTE with CHP configurations, AD-LF and AC-LF scenarios performed best, meaning that without CHP, separate treatment of food waste and landfilling of residuals is the best option. Composting coupled with landfilling became a relatively attractive option in the

NPCC case, whereas it was not in the base case. As in the base case, if an existing WTE facility is receiving HFW-ICI waste, there is a GWP penalty for diverting the food waste to composting, while continuing to combust the residuals. However, in the NPCC case, there is also a GWP penalty for diverting food waste from WTE to AD, whether the WTE facility has CHP or not. The results suggest that WTE can be a beneficial alternative for HFW-ICI management, but more detailed case studies of specific jurisdictions would be required to comprehensively address that question.

Results assuming avoided electricity emissions are all from coal generation showed that a more carbon-intensive grid resulted in greater benefits to scenarios that produce electricity, particularly AD-WTE (both) and WTE (NBU) (Figure A6). The grid change was sufficient for AD-WTE (NBU) to become the most beneficial scenario, outperforming the second-ranked alternative, WTE (NBU), by 10%. While scenarios involving AD performed best in all electricity grid cases tested, the benefits of diversion vary depending upon the current destination of food waste. The relative GWP benefits of composting also vary significantly with regional electricity grid. As electricity generation becomes less carbon intensive over time, which could occur due to a variety of factors including the availability of natural gas, growth of wind and solar generation capacity, development of cap-and-trade or other regulatory programs (i.e. the Regional Greenhouse Gas Initiative and California AB 32), or other factors, regions may correspond more to this study's NPCC case rather than the base case.

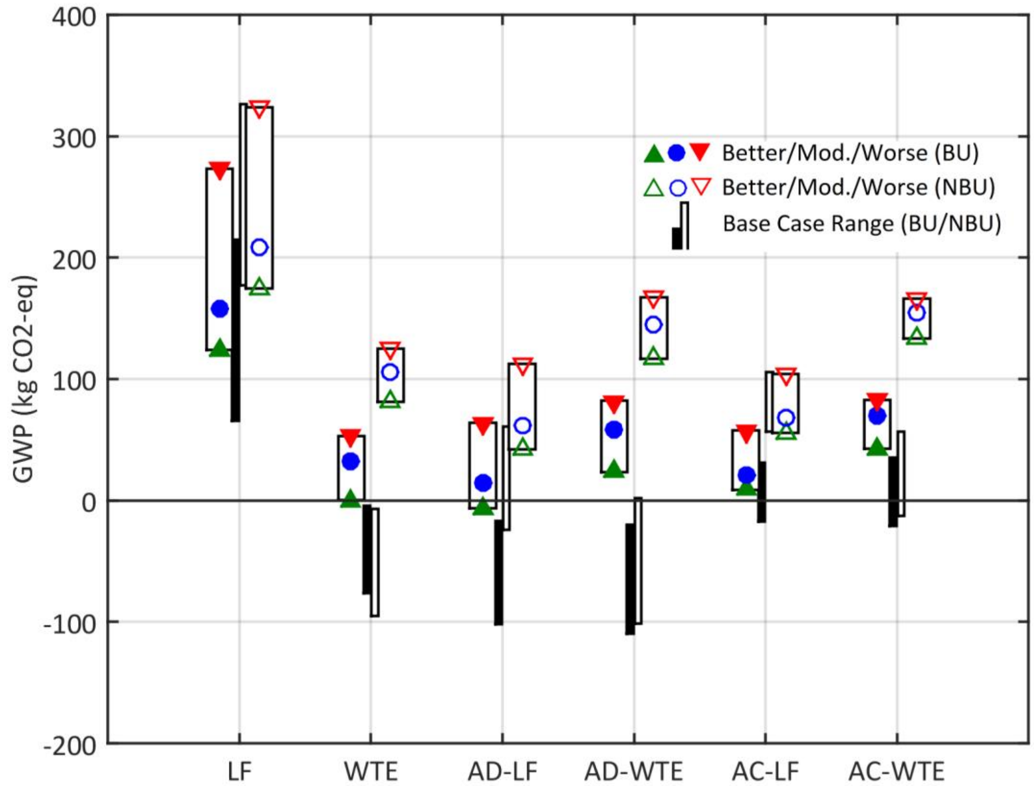


Figure 11 – Net GWP for each scenario and configuration under the NPCC case (0.42 kg CO_2e/kWh). Wide bar outlines present the range of values for all scenarios modeled and the individual symbols correspond to configurations described in the Modeling Approach.

Sensitivity to a set of food waste material properties was tested by varying the proportional mix of vegetable and non-vegetable food waste from the default of 80% vegetable content. Moisture content, nutrient content, and lower heating value were changed together to evaluate model sensitivity to food waste characteristics. Results for the vegetable case, assuming no non-vegetable food, are shown in Figure A9. While the effects of changing from the base assumption to the vegetable case are marginal, they show a trend of landfill facilities performing better and WTE facilities performing worse. Both results are most directly tied to the moisture content. Moisture is important because mass flows are reported on wet weight basis though the methane yield and heating content reflect the solids content. Thus, a higher moisture content reduces the methane yield and energy content per mass of wet food waste, and the reduced effective LHV reduces WTE performance. In the vegetable case, there is a larger benefit associated with diverting food waste from WTE to AD. To further test the impact of moisture content, the vegetable case was extended to a "wet" vegetable case by changing the moisture content to 85%. The wet vegetable case confirmed trends seen in the vegetable case, and it was one of only two cases in which the LF (BU) scenario outperformed both WTE scenarios. An all non-vegetable food waste case (drier, higher LHV, higher nutrient content) has the opposite effect (Figure 12). The non-vegetable case results show that the WTE scenarios perform best, and there is no GWP benefit associated with food waste diversion from WTE. Food waste diversion from the landfill remains beneficial. These results suggest that scenario-level GWP performance is strongly dependent upon food waste material properties. It may be appropriate for regulators to consider these properties in determining diversion requirements from particular categories of establishments or of particular materials.

Additional sensitivity analysis was performed, with results presented in Appendix A. Summary rankings for sensitivity cases are provided in Table 10, based on the moderate configurations for all scenarios. The difference between first- and second-ranked alternatives is also shown in Table 10 as one indicator of the degree to which the top ranked scenario outperforms others. In addition to the electricity grid cases already described, the energy system was further varied by changing the source of avoided heat production from the default of natural gas to coal, and a 50% coal, 50% natural gas mix. As expected, these changes increased the benefits associated with CHP, and made the WTE (BU) scenario the second ranked choice (10% behind AD-WTE (BU)) in the 100% coal heat case. Beyond the vegetable, wet vegetable, and non-vegetable cases that varied food waste material properties, the methane yield of food waste was tested at 250 and 500 m^3/dry Mg compared to the base case assumption of 400 m^3/dry Mg. Low methane yield reduced the benefits of AD, which made the WTE scenarios and composting more competitive alternatives. High methane yield did not significantly alter scenario rankings, though the LF scenarios performed notably worse. There is significant variation in reported methane yields of food waste, which will significantly impact the performance of LF and AD scenarios.

Sensitivity of the results to composition was tested by two means. First, the source-separation effectiveness of food waste was varied from the base assumption of 80% to 70% and then to 100%, such that no food waste is present in the residual stream. Separation effectiveness of all other waste components remained at 5% (e.g. 5% of plastic, etc. is directed into the food waste stream, where it is a contaminant). The 70% source separation case did not significantly change the scenario rankings in terms of GWP (Figure A15). The 100% source separation case improved all scenarios involving AD and improved all scenarios that send residual to the landfill, since there was no rapidly-degrading food waste in the residual stream. As a result, the AD-LF (NBU) scenario improved to the third rank behind AD-LF (BU) and AD-WTE (BU) (Figure A14). This suggests that where diversion of food waste to AD is practiced, maximizing source separation effectiveness is important to maximize GWP benefits. The second means of testing composition was replacing the HFW-ICI composition with a statewide as-discarded MSW composition from Minnesota (Burns & McDonnell 2013). Importantly, only composition was changed for this sensitivity case- the modeled collection system was not altered to represent inclusion of other sectors. The MSW composition case caused the most dramatic change in rankings due to the improvement of landfill and worsening of WTE facilities in terms of GWP (Figure A13). The top ranked scenarios for the MSW composition case were AD-LF (BU), followed by AC-LF (BU), then LF (BU). These results are due to (1) the relatively higher proportion of plastics in MSW (18.5% vs. 8.6% in HFW-ICI), which increased the fossil CO_2 stack emissions from the WTE facility, (2) the simultaneous large reduction in food waste (18.4% vs. 58.8% in HFW-ICI), which contributed to reducing LFG emissions by approximately 57% in the LF scenario, and (3) the higher proportion of paper products (25.2% vs. 20.7% in HFW-ICI), which contributed to increasing carbon storage by approximately 48% over the base case. These changes all highlight the importance of composition in the LCA of SWM systems, and further highlight the importance of using a mixed waste functional unit for food waste LCA studies.

The net GWP results shown in Table 10 reveal several trends that remain consistent across sensitivity cases. With only one exception (the non-vegetable case, where drier, high-LHV food made WTE most beneficial), the top-performing scenario in all cases included AD.

In most cases, AD-LF (BU) was the top performer, though the next best scenario was less consistent and varied with energy system, food waste material properties, and composition-related factors. In about two-thirds of the cases presented, the difference in net GWP between first-and second-ranked scenarios as a percent of the range for that case was approximately 10% or less, which is likely within model accuracy. However, over one third of the cases had a more pronounced best option. The LF scenarios perform poorly in all cases except when changing the input composition to MSW, but performed slightly better when food waste methane yield was reduced.

The final sensitivity analysis examined whether the latest IPCC methodology for estimation of GWP changed the relative rankings. In the 2013 standard, the 100-year GWP of methane was increased to 34 from 25 kg CO_2-eq in the IPCC 2007 methodology. Since methane is a major contributor to net GWP in several scenarios using IPCC 2007 methodology (Figure A4), it is even more significant with the updated impact factor. As a result, LF scenarios perform worse, and all scenarios involving WTE rank relatively higher in the IPCC 2013 case. As the IPCC methodology changes, new interpretations may be necessary when considering regulations that aim to limit GWP.

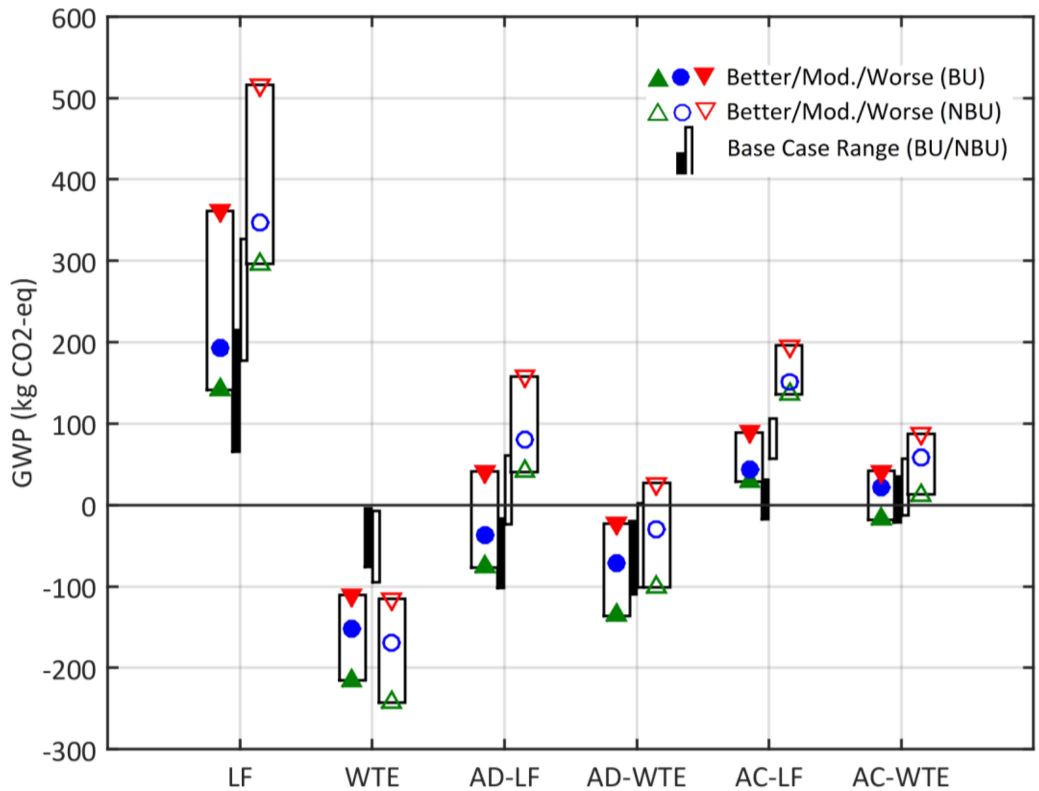


Figure 12 – Net GWP for each scenario and configuration under the non-vegetable case. Wide bar outlines present the range of values for all scenarios modeled and the individual symbols correspond to configurations described in the Modeling Approach.

Table 10 – Summary of net GWP and scenario rankings by sensitivity case.[a]

Scenarios		AD-LF (BU)	AD-WTE (BU)	WTE (NBU)	AD-WTE (NBU)	WTE (BU)	AC-LF (BU)	AD-LF (NBU)	AC-WTE (BU)	AC-WTE (NBU)	AC-LF (NBU)	LF (BU)	LF (NBU)	GWP Spread[b]
Base Case	Rank	1	2	3	4	5	6	7	8	9	10	11	12	5.9%
	GWP	*-74*	*-57*	*-45*	*-44*	*-33*	*-5*	*4*	*15*	*29*	*69*	*100*	*212*	*286*
NPCC Electricity	Rank	1	4	8	9	3	2	5	7	10	6	11	12	3.6%
	GWP	*14*	*59*	*106*	*145*	*33*	*21*	*62*	*70*	*154*	*68*	*158*	*209*	*195*
100% Coal Electricity	Rank	4	3	2	1	6	9	7	8	5	11	10	12	10%
	GWP	*-211*	*-239*	*-281*	*-339*	*-135*	*-47*	*-87*	*-70*	*-166*	*71*	*9*	*216*	*555*
50/50 Coal, Nat. Gas Heat	Rank	3	1	5	6	2	7	8	4	9	10	11	12	3.5%
	GWP	*-74*	*-131*	*-45*	*-44*	*-119*	*-5*	*4*	*-56*	*29*	*69*	*100*	*212*	*343*
100% Coal Avoided Heat	Rank	4	2	5	6	1	7	8	3	9	10	11	12	0.0%
	GWP	*-74*	*-205*	*-45*	*-44*	*-205*	*-5*	*4*	*-127*	*29*	*69*	*100*	*212*	*417*
Vegetable Food Waste	Rank	1	2	6	3	7	4	5	8	9	10	11	12	11%
	GWP	*-83*	*-54*	*-14*	*-47*	*-3*	*-18*	*-15*	*13*	*21*	*48*	*77*	*178*	*261*
"Wet" Veg. Food Waste	Rank	1	3	6	4	9	2	5	7	8	10	11	12	22%
	GWP	*-66*	*-20*	*10*	*-18*	*20*	*-28*	*-8*	*17*	*19*	*28*	*31*	*110*	*176*
Non-Vegetable Food Waste	Rank	4	3	1	5	2	7	9	6	8	10	11	12	3.5%
	GWP	*-37*	*-71*	*-170*	*-30*	*-152*	*44*	*80*	*22*	*59*	*151*	*192*	*347*	*517*
Low Methane Yield	Rank	2	5	1	6	3	4	10	7	9	11	8	12	3.2%
	GWP	*-40*	*-6*	*-45*	*7*	*-33*	*-20*	*30*	*15*	*29*	*49*	*25*	*109*	*154*
High Methane Yield	Rank	1	2	4	3	5	7	6	8	9	10	11	12	1.4%
	GWP	*-87*	*-82*	*-45*	*-72*	*-33*	*5*	*-8*	*15*	*29*	*83*	*151*	*281*	*368*
MSW Composition	Rank	1	8	6	7	9	2	4	12	11	5	3	10	17%
	GWP	*-148*	*-30*	*-50*	*-39*	*-29*	*-125*	*-84*	*-10*	*-20*	*-64*	*-101*	*-28*	*138*
100% FW Source-Sep.	Rank	1	2	5	4	7	6	3	8	10	9	11	12	16%
	GWP	*-119*	*-65*	*-45*	*-46*	*-33*	*-34*	*-50*	*26*	*46*	*32*	*100*	*212*	*331*
70% FW Source-Sep.	Rank	2	1	3	4	5	6	9	7	8	10	11	12	0.4%
	GWP	*-52*	*-53*	*-45*	*-43*	*-33*	*9*	*31*	*10*	*20*	*88*	*100*	*212*	*265*
IPCC 2013 Method	Rank	5	1	3	4	2	7	9	6	8	10	11	12	0.7%
	GWP	*17*	*-14*	*-7*	*13*	*-11*	*64*	*84*	*42*	*68*	*129*	*252*	*344*	*357*

a. Each scenario is represented by its moderate configuration.

b. Bottom value represents range of net GWP across scenarios for each case. Top number represents difference in net GWP between first and second ranked alternatives, as a percent of range.

4.0 CONCLUSIONS

The results showed that in most cases, it was beneficial to divert food waste from the landfill to AD or composting, and from WTE to AD, but not composting. AD outperformed composting in terms of GWP in most cases, but the treatment options were more comparable when electricity produced at AD offset less GHG-intensive NPCC electricity, when food waste methane yields were low, or when examining an alternate waste composition with more paper, plastic, and less food. With a few exceptions (carbon-intensive energy system, non-vegetable food waste, low methane yield, 70% source separation effectiveness, and IPCC 2013 methodology), the AD-LF (BU) scenario was the leading alternative in terms of GWP. Energy recovery at the landfill provided large GWP benefits over the flare cases. Waste collection was shown to be a relatively minor contributor, even when considering scenarios with separate food waste collection. The nutrient value of the solids from biologically-treated food waste, and potential benefits of avoided mineral fertilizer production, were minor in terms of GWP, but important in determining eutrophication impacts.

In the NPCC regional electricity grid case, there was a GWP penalty for diverting food waste from WTE to AD or to composting, while there were GWP benefits to diverting food waste from the landfill. This result challenges the assumption that food waste diversion always provides a GWP benefit. In particular, a future case study could evaluate the Massachusetts commercial food waste diversion regulation, which requires diversion of commercial organics from combustion facilities. Results of sensitivity analysis on food waste material properties suggest that certain properties have a notable impact on the relative ranking of scenarios. Moisture content, LHV, and nutrient content, which were modeled as changing as a group, affected all scenarios, and methane yield affected AD and landfill facilities.

Based on the possible changes to overall SWM system results, it would be appropriate to consider requiring food waste diversion based upon food waste characteristics (e.g., moisture content, nutrient content, or percent volatile solids), regional energy system carbon intensity, and potentially based on the relative performance of locally relevant waste treatment facilities. These conclusions are in large part based on moderate configurations for all scenarios. Comparing better with worse configurations, for example, could produce a different set of results and rankings, which indicates that it is important to evaluate actual or site-specific facility performance when making comparisons and recommendations.

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APPENDICES

APPENDIX A: SUPPLEMENTAL INFORMATION

1.0 WASTE COMPOSITION CALCULATIONS

MSW is a heterogeneous mixed material, so defining its composition is critical to any study involving its management. This study examines waste produced by industrial, commercial, and institutional (ICI) entities for which food waste is the largest component of the waste stream. For the purposes of this study, these entities are collectively referred to as high-food waste ICI (HFW-ICI) generators and include grocery stores, restaurants, food manufacturers, and other types of entities shown in Table A1.

A two-step procedure was developed to calculate a representative average HFW-ICI as-discarded waste composition. First, facility-level food waste generation information was extracted from Connecticut's Organics Mapping Project dataset (Connecticut Department of Energy & Environmental Protection 2012) and used to estimate the total mass of food waste generated from each type of HFW-ICI facility. The Connecticut data were extrapolated and supplemented with a secondary source (Draper/Lennon Inc. 2001) where appropriate, as shown in Table A1.

In the second step, the initial set of eleven generator types was condensed to four: 1) Conference Facilities & Resorts, 2) Food & Beverage Manufacturing/Processing, 3) Grocery Stores and Supermarkets, and 4) Restaurants. Then as-discarded waste composition datasets for the condensed set of business types were selected from a California statewide report (Cascadia Consulting Group 2006) and a U.K.-based report for food processors (Jacobs 2011). The aggregate HFW-ICI composition was calculated from a weighted average of the four individual waste compositions, based on the fraction of total solid waste produced by each of the four groups.

Table A1 – Summary of Connecticut waste generation data with estimated generation profile by generator type.

	Reported Annual FW Generation (t) from Facilities Generating at least:[a]			Avg. Annual FW Gen. (t), Facilities over 104 t/yr [a,b]	Number of FW Generating Facilities[a,c]		Percent	Estimated Annual FW Generation from Facilities Generating at least 104 t/yr (t)			Estimated FW Generation Profile by Generator Type	
Generator Type	0 t/yr	52 t/yr	104 t/yr		Total	Reporting	Reporting:	Scaled[d]	D/L Report[e]	Combined[f]	Type	Grouped[g]
Conference Facilities & Resorts	5,458	4,618	4,012	669	159	45	28%	14,176	14,843	14,843	9%	19%
Colleges & Universities	6,509	6,130	5,418	258	54	49	91%	5,971	-	5,971	4%	
Food & Beverage Manufacturers/Processors	-	-	-	184[e]	347	0	0%	-	58,359	58,359	37%	37%
Grocery Stores & Supermarkets	62,027	61,191	58,011	235	348	338	97%	59,727	-	59,727	37%	37%
Hospitals	5,853	5,630	5,077	254	34	33	97%	5,231	-	5,231	3%	
Other Health Care Facilities	12,071	3,476	839	120	365	355	97%	863	-	863	1%	
Independent Schools	520	60	0	-	17	17	100%	0	-	0	0%	
Prisons/Correctional Facilities	3,175	3,175	3,028	216	17	16	94%	3,217	-	3,217	2%	
Restaurants	68,414	29,269	9,725	137	1,717	1,717	100%	9,725	-	9,725	6%	6%
Venues	-	-	-	-	37	0	0%	-	-	-	0%	
Wholesale Food Distributors	-	-	-	-	234	0	0%	-	1,592	1,592	1%	
Total	164,027	113,549	86,110	248[h]	3,329	2,570	77%	-	-	159,528	100%[i]	100%[i]

a. Generation and Facility data extracted from Connecticut Organics Mapping Project spreadsheet (Connecticut Department of Energy & Environmental Protection 2012).

b. Average food waste generation per facility obtained by dividing generation from facilities generating at least 104 t/yr by the number of facilities meeting this threshold.

c. Not all food waste generating facilities were required to report waste generation rates to Connecticut.

d. “Scaled” generation tonnage is an extrapolation from reported generation to total generation, scaled by percent reporting. Assumes non-reporting facilities have generation characteristics similar to those that reported.

e. Supplemental values obtained from an organic waste recycling report for the State of Connecticut to supplement generator types with no data (Draper/Lennon Inc. 2001).

f. “Combined” generation tonnage includes values from “Scaled” or “D/L Report” based on data availability.

g. Generator types are aggregated into groups based on assumed similar as-discarded waste compositions. Restaurants, Grocery Stores & Supermarkets, and Food & Beverage Manufacturers/Processors are maintained separate, while all other generator types are added and classified as Conference Facilities & Resorts.

h. Weighted average based on estimated generation profile.

i. Totals may not sum to 100% due to rounding.

Table A2 – Composition by generator type groups and final calculated HFW-ICI composition.

Waste Component	Waste Composition (percent of discarded mixed waste)				
	Conference Facilities & Resorts[a]	Food & Beverage Manufacturing/ Processing[b]	Grocery Stores & Supermarkets[a]	Restaurants[a,c]	Calculated HFW-ICI Aggregate
Yard Trimmings, Leaves	3.9	1	1	0.05	1.8
Yard Trimmings, Branches	0.2		0.2	0.05	0.1
Food Waste[d]	36.4	75	63.1	58.75	58.3
Textiles	1.1	1	0.1	0.45	0.7
Rubber/Leather	2		0.6	0.25	0.8
Newsprint	9		1.1	2.25	3.3
Corr. Cardboard	3.2	3	3.9	4.35	3.5
Office Paper	5.2	1	0.7	0.65	2.2
Magazines	1		0.2	0.2	0.4
Paper Bags	0.3		0.5	0.2	0.3
Mixed Paper	5.6		1.6	14.6	3.2
Paper - Non-recyclable	7.9	6	10.6	2.9	8
HDPE - Translucent Containers	0.3		0.1	0.5	0.2
HDPE - Pigmented Containers	0.5		0.4	0.3	0.3
PET - Containers	0.8		0.2	0.35	0.3
Mixed Plastic	0.5		0.3	0.4	0.3
Plastic Film	3.7	6	5.7	5.25	5.2
Plastic - Non-Recyclable	3.8		2.9	2.7	2.3
Ferrous Cans	0.5	0.5	0.3	1.15	0.5
Ferrous Metal - Other	0.6	1	0.8	0.15	0.8
Aluminum Cans	0.2		0	0.05	0.1
Aluminum - Other	0.1		0	0.05	0
Ferrous - Non-recyclable	0.4	0.5	0.2	0.15	0.3
Al - Non-recyclable	2		0	0.15	0.6
Glass - Brown	0.9		0.1	0.45	0.3
Glass - Green	1.4		0.1	0.45	0.5
Glass - Clear	2		0.4	0.65	0.8
Glass - Non-recyclable	0.3		0	0.05	0.1
Misc. Organic	3.7		4.1	0.6	2.6
Misc. Inorganic	1.1	5	0.9	1.4	2.2
E-waste	0.4		0	0.05	0.1
Total	100[e]	100[e]	100[e]	100[e]	100[e]

Table A2 (continued)

Waste Component	Waste Composition (percent of discarded mixed waste) Conference Facilities & Resorts[a]	Food & Beverage Manufacturing/ Processing[b]	Grocery Stores & Supermarkets[a]	Restaurants[a,c]	Calculated HFW-ICI Aggregate
Generation Profile, Food Waste Basis (%)	19	37	37	6	100[e]
Total Food Waste Content (%)	36.4	75	63.1	58.75	58.3
Generation Profile, Mixed Waste Basis (%)	30	29	35	6	100[e]

a. Values adapted from California statewide as-discarded compositions to match SWOLF waste components. Relevant dataset names from California study are "Large Hotels," "Food Stores," "Fast Food Restaurants," and "Full Service Restaurants" (Cascadia Consulting Group 2006).
b. Food & Beverage Manufacturing/Processing composition estimated by the author, informed by a study of waste generation in the UK (Jacobs 2011).
c. Arithmetic average of "Fast Food" and "Full Service" restaurant data sets. Assumes these two types of restaurants produce equal shares of total restaurant as-discarded waste.
d. Food waste is treated as one component in composition data sources, but later split into two components (80% vegetable and 20% non-vegetable, consistent with Petersen & Domela (2003)) to develop its HFW-ICI material properties.
e. Totals may not sum to 100% due to rounding.

The resulting aggregate HFW-ICI composition is used directly in analyses where a mixed waste stream is evaluated in the study, specifically the LF and WTE scenarios. Waste component mass and compositions for the source-separated food waste and residual waste streams were estimated for the separate collection schemes inherent in the AD and composting configurations as shown in Table A3. No data were available for specific waste component separation percentages, so a nominal estimate of 5% was applied uniformly across all non-food components. The resulting separated food waste composition includes a total of approximately 4% non-food contaminant material, which is reasonable when compared with Washington State regulations requiring compost facility operators to reject or pre-process feedstock containing more than 5% contaminant material (WAC 173-350-220 Sec. 4.f.iii.C).

Table A3 – Separated waste stream masses and compositions.[a]

Waste Component	Aggr. HFW-ICI (mixed waste) Comp.[b] (%)	Aggr. HFW-ICI (mixed waste) Mass[c] (kg)	Source Separation into FW Stream (%)[d]	Separated Food Waste Mass[c] (kg)	Separated Food Waste Comp.[b] (%)	Residual Waste Mass[c] (Mg)	Residual Waste Comp.[b] (%)
Yard Trimmings, Leaves	1.83	18.3	5	0.9	0.2	17.4	3.4
Yard Trimmings, Branches	0.13	1.3	5	0.1	0.0	1.3	0.2
Food Waste - Vegetable	46.63	466.3	80	373.0	76.6	93.3	18.2
Food Waste - Non-Vegetable	11.66	116.6	80	93.3	19.1	23.3	4.5
Textiles	0.69	6.9	5	0.3	0.1	6.5	1.3
Rubber/Leather	0.84	8.4	5	0.4	0.1	7.9	1.5
Newsprint	3.27	32.7	5	1.6	0.3	31.1	6.1
Corr. Cardboard	3.47	34.7	5	1.7	0.4	32.9	6.4
Office Paper	2.16	21.6	5	1.1	0.2	20.5	4.0
Magazines	0.39	3.9	5	0.2	0.0	3.7	0.7
Paper Bags	0.28	2.8	5	0.1	0.0	2.6	0.5
Mixed Paper	3.16	31.6	5	1.6	0.3	30.0	5.9
Paper - Non-recyclable	8.02	80.2	5	4.0	0.8	76.1	14.8
HDPE - Translucent Containers	0.16	1.6	5	0.1	0.0	1.5	0.3
HDPE - Pigmented Containers	0.31	3.1	5	0.2	0.0	3.0	0.6
PET - Containers	0.34	3.4	5	0.2	0.0	3.2	0.6
Mixed Plastic	0.28	2.8	5	0.1	0.0	2.7	0.5
Plastic Film	5.16	51.6	5	2.6	0.5	49.1	9.6
Plastic - Non-Recyclable	2.34	23.4	5	1.2	0.2	22.2	4.3
Ferrous Cans	0.47	4.7	5	0.2	0.0	4.5	0.9
Ferrous Metal - Other	0.76	7.6	5	0.4	0.1	7.2	1.4
Aluminum Cans	0.06	0.6	5	0.0	0.0	0.6	0.1
Aluminum - Other	0.03	0.3	5	0.0	0.0	0.3	0.1
Ferrous - Non-recyclable	0.34	3.4	5	0.2	0.0	3.3	0.6
Al - Non-recyclable	0.62	6.2	5	0.3	0.1	5.9	1.1
Glass – Brown	0.34	3.4	5	0.2	0.0	3.2	0.6
Glass – Green	0.49	4.9	5	0.2	0.1	4.7	0.9
Glass – Clear	0.79	7.9	5	0.4	0.1	7.5	1.5
Glass - Non-recyclable	0.09	0.9	5	0.0	0.0	0.9	0.2
Misc. Organic	2.60	26.0	5	1.3	0.3	24.7	4.8
Misc. Inorganic	2.17	21.7	5	1.1	0.2	20.6	4.0
E-waste	0.13	1.3	5	0.1	0.0	1.2	0.2
Total[e]	100.00	1000.0	-	486.2	100.0	513.8	100.0

a. The number of significant figures provided in this table is larger than typically appropriate for waste compositions because many small but non-negligible components are produced by source separation.
b. Composition of each waste stream.
c. Mass values are calculated based on the functional unit of 1 Mg of HFW-ICI waste.
d. Percent of HFW-ICI mixed waste stream diverted at generation source for separate food waste management. Values based on assumption
e. Sum of individual components may not match totals due to rounding.

2.0 WASTE COMPONENT MATERIAL PROPERTIES

Table A4 – Waste component material properties.[a]

Waste Component	Moisture Content	VS (%TS)	LHV (MJ/ dry kg)	Methane Yield [b] (m3/dry Mg)	Field Decay Rates[c] k = 0.04 (yr-1)	Carbon Storage Factor[d] (kg C/dry Mg)	Biogenic C Content (%TS)	Fossil C Content (%TS)	N Content (%TS)	P Content (%TS
Yard Trimmings, Leaves	38.2	90.2	13.4	65.3	0.114	470	48.6	0.9	0.9	0.20
Yard Trimmings, Branches	42.5	96.6	19.0	62.6	0.010	380	48.1	0.9	0.1	0.20
Food Waste - Vegetable	77.0	96.4	10.7	400	0.096	80	47.7	0.2	1.9	0.23
Food Waste - Non-Vegetable	57.1	94.2	21.5	400	0.096	80	56.5	1.1	7.0	1.00
Textiles	6.0	96.6	19.8	46.4	0.020	10	39.1	13.0	3.2	0.23
Rubber/Leather	6.8	89.3	25.2	0	0.000	10	30.9	30.9	0.3	0.03
Newsprint	13.0	92.7	17.1	74.3	0.022	420	44.6	0.2	0.1	0.01
Corr. Cardboard	16.5	89.0	15.1	195	0.013	260	40.7	0.2	0.1	0.01
Office Paper	8.8	87.8	12.5	264	0.020	50	37.3	0.2	0.1	0.00
Magazines	6.2	76.7	11.5	84.4	0.081	270	34.0	0.2	0.1	0.02
Paper Bags	22.3	88.8	15.0	185	0.013	260	40.9	0.2	0.2	0.01
Mixed Paper	16.6	88.1	15.3	164	0.021	240	51.5	0.6	0.2	0.03
Paper - Non-recyclable	25.1	91.5	17.2	174	0.081	100	43.0	1.4	0.4	0.06
HDPE - Translucent Containers	10.5	93.8	36.5	0	0		0.4	76.8	0.1	0.03
HDPE - Pigmented Containers	10.5	93.8	36.5	0	0		0.4	76.8	0.1	0.03

Table A4 (continued)

Waste Component	Moisture Content	VS (%TS)	LHV (MJ/ dry kg)	Methane Yield [b] (m3/dry Mg)	Field Decay Rates[c] k = 0.04 (yr-1)	Carbon Storage Factor[d] (kg C/dry Mg)	Biogenic C Content (%TS)	Fossil C Content (%TS)	N Content (%TS)	P Content (%TS
PET - Containers	10.5	93.8	36.5	0	0		0.4	62.5	0.1	0.03
Mixed Plastic	8.0	95.6	37.3	0	0		0.4	72.4	0.3	0.32
Plastic Film	14.1	95.8	40.1	0	0		0.4	81.6	0.2	0.02
Plastic - Non-Recyclable	7.1	94.9	32.0	0	0		0.4	70.6	0.5	0.56
Ferrous Cans	13.2	0		0	0		0	0	0	0.02
Ferrous Metal - Other	13.2	0		0	0		0	0	0	0.02
Aluminum Cans	8.3	0		0	0		0	0	0	0.01
Aluminum - Other	18.8	21.8	6.8	0	0		15.0	0.2	0.4	0.06
Ferrous - Non-recyclable	13.2			0	0		0	0	0	0.02
Al - Non-recyclable	18.8			0	0		15.0	0.2	0.4	0.06
Glass - Brown	5.0			0	0		0	0	0	0.01
Glass - Green	3.4			0	0		0	0	0	0.01
Glass - Clear	12.0			0	0		0	0	0	0.01
Glass - Non-recyclable	10.3			0	0		0	0	0	0.01
Misc. Organic	31.6	91.3	15.1	124	0.059	244	44.1	2.8	1.0	0.11
Misc. Inorganic	36.6	3.4	0.00	0	0	0	0.7	0.7	0	0.01
E-waste										

a. Material properties obtained from Riber et al. (2009) except where otherwise noted.
b. Methane yield estimates are based on the default values used in the U.S. EPA's MSW-DST and WARM models, as updated in 2014 (Appendix B).
c. As estimated in De la Cruz & Barlaz (2010) for a landfill with a bulk MSW decay rate of k=0.04.
d. Carbon storage factor values obtained from Barlaz (1998).

3.0 MODELING PARAMETERS

3.1 Landfill

Table A5 – Selected input parameters common to all landfill configurations.

Parameter	Units	Value
Landfill Construction, Operations, and Closure		
Liner Type	-	Single Composite
Percent of Landfill Site not using daily cover	%	0
Percent of daily cover that is soil	%	100
Percent of airspace that is daily cover	%	10
Operating fuel use, including daily cover	L/Mg	1.17
Density of gas collection wells	wells/ha	2.5
Average length of vertical wells	m	13
Length of additional HDPE connection	m	30
Combined thickness of soil, sand, clay in final cover	m	1.05
Fuel use during closure	L/Mg	0.07
Leachate Production and Management		
Annual Precipitation	mm	900
Percent of precip that becomes leachate (year 1)	%	20
Percent of precip that becomes leachate (year 2-5)	%	13.3
Percent of precip that becomes leachate (year 6-10)	%	6.6
Percent of precip that becomes leachate (year 10-100)	%	0.04
Percent of leachate transported to WWTP	%	100
WWTP distance	km	40
Leachate treatment electricity consumption	kWh/kg BOD removed	1
Landfill Gas Production and End Use		
Landfill decay rate	-	0.04
Methane oxidation rate without gas collection or final cover	%	10
Methane oxidation rate with gas collection, before final cover	%	20
Methane oxidation rate with final cover	%	35
LFG methane content	%	50
Lower heating value of methane	MJ/m3	37.7
Energy recovery method (turbine, IC engine, boiler)	-	IC Engine
Energy recovery efficiency (electrical)	%	36.5

a. Electrical efficiency is based on numerical average of manufacturer's specified efficiency for two typical internal combustion engines, rated approximately 1 MW: CAT G3516A+ (Caterpillar 2013) and Jenbacher Type 320, low NO_x (GE Energy 2010).

Table A6 – Parameters differentiating landfill configurations.

Parameter	SOTA	US Nat’l Avg.	NSPS Limits
Time until initial gas collection (yr)	0.5	2	5
Initial gas collection efficiency (%)	50	50	50
Time to intermediate cover (yr)	3	5	5
Gas collection efficiency under intermediate cover (%)	75	75	75
Time to increased gas collection efficiency (yr)	15	15	15
Increased gas collection efficiency (%)	82.5	82.5	82.5
Time from final waste placement to final cover (yr)	1	1	1
Gas collection efficiency under final cover (%)	90	90	90
Energy recovery cuton time (yr)	5	5	5
Energy recovery cutoff time (yr)	52	52	52
Energy recovery downtime (%)	3	3	3

3.2 Mass Burn Waste-to-Energy Combustion (WTE)

Table A7 – Selected input parameters for WTE configurations.

Parameter	SOTA[a]	Fleet Avg.[b]	Worse[c]
Energy Recovery Parameters			
Net Electrical Efficiency without CHP (%)	24.4	20.9	18.2
Net Electrical Efficiency with CHP(%)	10.3	8.8	7.6
Net Thermal Efficiency with CHP (% of waste input LHV recovered as heat)	37.5	33.0	30.6
Non-metal Stack Emissions (ppmv @ 7% oxygen, dry, unless otherwise noted)			
Sulfur dioxide	2	8	10
HCl	2	10	12.5
NO_x	35	150	150
CO	20	30	37.5
Methane	1.1	1.1	1.375
Nitrous Oxide	1.3	1.3	1.625
Ammonia	2	4	5
Hydrocarbons	1	1	1.25
PM (mg/dscm @ 7% oxygen, dry)	1.5	3	3.75
Dioxins / Furans (ng/dscm @ 7% oxygen, dry)	1.5	4	5
Metal Recovery Rates from Ash (%)			
Ferrous	90	90	90[d]
Aluminum	65	35	35[d]
Copper	0	0	0

a. State-of-the-art. Parameters in this column based on information obtained from Covanta (M. Van Brunt, pers. comm.) describing best currently feasible facilities (unless otherwise noted).
b. Covanta fleet average. Parameters in this column based on information obtained from Covanta describing average emissions and performance data in their operating facilities (unless otherwise noted).
c. New source performance standards. Parameters in this column obtained from Title 40 CFR §60.52b and §60.53b unless otherwise specified.
d. Values adopted from fleet average.

3.3 Aerobic Composting

All model inputs used to describe the composting configurations in this study are based on Levis & Barlaz (2013b), unless otherwise noted. Capital goods for the compost facility are represented using the global market for open compost facility from the ecoinvent database (Weidema et al. 2013).

Table A8 – Selected input parameters common to all composting configurations.

Facility Operating Parameters	**Units**	**Value**
Time spent at tipping floor	Mg/day	1
Active composting time	Days	70
Curing time	Days	30
Office Area required per ton per day of material	m^2/Mgpd	7.03E-03
Energy required to power an office	kWh/m^2-yr	290
Target material properties		
Wet weight moisture content after active composting	-	0.5
Wet weight moisture content after curing	-	0.45
Equipment fuel and electricity use parameters		
Grinder power rating.	kWh/Mg	10.6
Grinder fuel consumption	L/kWh	0.25
Windrow turner power rating	kWh/Mg	0.24
The fuel consumption of a windrow turner	L/kWh	0.127
Turning frequency	1/day	0.33
Energy required per wet weight of post- screened material	kWh/Mg	0.9
Frequency of turning during curing phase	1/day	0.14
Front end loader energy required per wet weight flow of material	MJ/Mg	1.20
Front end loader specific fuel consumption	L/kWh	0.26
General equipment fuel consumption.	L/kWh	0.26
Turner throughput	Mg/hr	1500
Carbon and Nitrogen Balance During Composting		
Proportion of incoming C emitted	-	0.58
Proportion of emitted C emitted as CH_4	-	0.017
Proportion of incoming N emitted as NH_3	-	0.04
Proportion of emitted N emitted as N_2O	-	0.004
Land Application Parameters		
Distance to application site[a]	km	20
Payload of truck to land application	Mg	7.3
Percent of applied N evaporated as N_2O	%	1.5
Percent of Ammonia that evaporates[b]	%	15
Percent N that is Ammonia	%	50
Percent of N that runs off as nitrate[b]	%	14
Cured solids application diesel use	L/Mg solids	0.80
Percent of carbon in solids remaining after 100 years	%	10

a. Assumed.
b. Based on difference between land application of biologically treated solids and reference case of mineral fertilizer (Hansen et al. 2006).

Table A9 – Parameters differentiating composting configurations.

Parameter	Units	Open Windrow	Windrow Under Roof w/ biofilter
Biofilter CH_4 removal efficiency	%	N/A	0.15
Biofilter NH_3 removal efficiency	%	N/A	48
Biofilter N_2O removal efficiency	%	N/A	0
Biofilter VOC removal efficiency	%	N/A	18
Motor efficiency	kW-in/kW-out	N/A	1.54
Odor control air flow required	m^3/hr	N/A	1.26
Time spent under odor control	Days	N/A	1

Table A10 – Parameters differentiating composting beneficial use cases.

Parameter	No Beneficial Use	Beneficial Use
Humus Formation Factor	0	0.19
Mineral fertilizer equivalent for nitrogen	N/A	0.4
Mineral fertilizer equivalent for phosphorus	N/A	1.0
Mineral fertilizer equivalent for potassium.	N/A	1.0
Ratio of compost required to meet P demand to N demand.	N/A	1.0
Ratio of compost required to meet K demand to N demand.	N/A	0.74

3.4 Anaerobic Digestion

All model inputs used to describe the AD configurations in this study are based on (Levis & Barlaz 2013a), unless otherwise noted. Capital goods for the AD facility are represented using the global market for biowaste anaerobic digestion plant from the ecoinvent database (Weidema et al. 2013).

Table A11 – Selected input parameters common to all AD configurations.

Digester Operating Parameters	**Units**	**Value**
Reactor moisture content.	-	0.92
Facility specific electricity usage.[a]	kWh/Mg	58
Biogas leakage rate	-	0.03
Proportion of gas that is flared without electricity generation.	-	0.05
Digestate Liquids Management		
Digestate density	kg/L	1
Amount of BOD in digestate	kg/L	0.0023
Total N	kg/L	0.00135
Percent of total N that is NH_3	%	50
Distance to liquids treatment facility	km	0
Electricity used per pound of BOD removed.	kWh/kg	1
BOD removal efficiency.	-	0.92
Mass of biogenic CO_2 emitted per pound of BOD removed	kg CO_2/kg BOD	3.6
Digestate Solids Curing		
Digestate moisture content after dewatering	-	0.6
Retention time in windrows	days	21
Turning energy required per ton of compost	kWh/Mg	0.24
The fuel consumption of a windrow turner	L/kWh	0.13
Turning frequency	1/days	0.43
Proportion of emitted C emitted as CH_4	-	0.017
Proportion of emitted N emitted as NH_3	-	0.04
Proportion of emitted N emitted as N_2O	-	0.004
VS reduction of digestate during curing	-	0.3
Land Application Parameters		
Distance to application site[b]	km	20
Payload of truck to land application	Mg	7.3
Percent of applied N evaporated as N_2O	%	1.5
Percent of Ammonia that evaporates	%	15
Percent N that is Ammonia	%	50
Percent of N that runs off as nitrate	%	14
Cured solids application diesel use	L/Mg solids	0.80
Percent of carbon in solids remaining after 100 years	%	10

a. Adopted from Sanscartier et al. (2012).
b. Assumed.

Table A12 – Parameters differentiating AD configurations.

		Best Case	Typical	Worst Case
Parameter	Units	Value	Value	Value
Energy Recovery Electrical Efficiency	%	32.9	36.5	40.2

a. Electrical efficiency for "Typical" case is based on numerical average of manufacturer's specified efficiency for two typical internal combustion engines, rated approximately 1 MW: CAT G3516A+ (Caterpillar 2013) and Jenbacher Type 320, low NO_x (GE Energy 2010). Values for best and worst cases are calculated as 90% and 110% of the typical case.

Table A13 – Parameters differentiating AD beneficial use cases.

Parameter	No Beneficial Use	Beneficial Use
Humus Formation Factor	0	0.19
Mineral fertilizer equivalent for nitrogen	N/A	0.4
Mineral fertilizer equivalent for phosphorus	N/A	1.0
Mineral fertilizer equivalent for potassium.	N/A	1.0
Ratio of compost required to meet P demand to N demand.	N/A	1.0
Ratio of compost required to meet K demand to N demand.	N/A	0.74

3.5 Waste Collection and Transport

All inputs used to represent the waste collection processes in this study are based on the model and commercial sector default parameters described in Jaunich et al. (2015), unless otherwise noted. Capital goods for the collection process are represented using the global market for waste collection lorry from the ecoinvent database (Weidema et al. 2013).

Table A14 – Selected input parameters and default values for waste collection and transport common to all collection schemes.

Parameter	Units	Value [a]
General Parameters		
Working days per week	days/week	5
Working hours per day [b]	hours/vehicle-day	9
Usable vehicle capacity [b]	yd^3	30
Fuel Parameters		
Fraction of stops serviced by diesel vehicles	-	1
Fraction of stops serviced by CNG vehicles	-	0
Fuel usage while traveling	miles/gal	5
Fuel usage between collection stops	miles/gal	2
Fuel usage while idling	gal/hour	1
Operating Times		
Lunch time	min/day-vehicle	30
Break time	min/day-vehicle	30
Time from garage to 1st collection stop	min/day-vehicle	20
Time from unloading site to garage	min/day-vehicle	20
Driving Distances		
Distance between unloading site and garage	miles	11.7
Distance between garage and collection route	miles	11.7

a. Default values adopted from SWOLF waste collection model (Jaunich et al. 2015) unless otherwise noted.
b. Selected using judgment, informed by recent Biocycle articles (Goldstein 2014b; Goldstein 2013; Goldstein 2014a).

Table A15 – Parameters differentiating waste collection and transport schemes.

Parameter	Units	Combined Collection [a]	Residual Collection [a]	Food Waste Collection [b]
As-discarded waste generation rate [c]	lb/week-location	19400	9900	9500
Effective in-truck density [d]	kg/m3	550	430	800
Vehicle capacity (weight) [b]	tons	15	15	15
Vehicle capacity (volume) [b]	yd3	30	30	30
Volume utilization factor	occupied yd3/ usable yd3	0.8	0.8	0.8
Collection frequency [b]	1/week	2	1	2
Loading time at one collection stop	min/stop	5	5	5
Time at unloading site	min/trip	15	15	15
Travel time between collection stops	min	1.5	1.5	3
Distance between collection stops	miles	0.25	0.25	1
Travel time between collection route and unloading site	minutes	20	20	30
Distance between collection route and unloading site	miles	10	10	20

a. Default values adopted from MSW-DST commercial collection model (Curtis et al. 2000) unless otherwise noted.
b. Food waste collection values and collection frequencies chosen using judgment, informed by Goldstein (2014c) and Goldstein (2014b).
c. Based on Connecticut data, see Table A1. 248 t/y, 52 wk/y, 2000 lb/t. Combined based on separated FW mass fraction of 0.49 (Table A3).
d. Density values estimated based on composition-weighted average of waste component in-truck densities obtained from WRAP (2010).

Using the input parameters described in Tables A14 and A15, a set of unit fuel use parameters was estimated. Mixed waste, separate food waste, and residual collection services were estimated to require 3.4, 5.3, and 4.3 L of diesel fuel per Mg of waste, respectively. There is a significant amount of uncertainty related to travel time and distance between collection stops. Facility availability in a given region may result in a wide range of distances between collection route and waste destination. Further, informal conversation with food waste generators and haulers has indicated significant variability in collection frequency, vehicle capacity, and generation rate. A parametric sensitivity analysis was conducted to explore the impact of these parameters on fuel use associated with food waste collection.

Increasing both distance and time from collection to unloading by a factor of two increased food waste collection unit fuel use from 5.3 L/Mg to 9.7 L/Mg. Similarly, increasing distance and time between collection stops to 5 miles and 12 minutes, respectively, increased food waste collection unit fuel use from 5.3 L/Mg to 8.7 L/Mg. Increasing food waste collection frequency from 2 to 5 times per week increased fuel use to 7.1 L/Mg. Decreasing truck capacity to 20 cubic yards increased fuel use to 7.4 L/Mg while increasing capacity to 40 cubic yards decreased fuel use to 4.3 L/Mg. Decreasing total waste generation per stop by 50% increased fuel use by 4%, while increasing generation by 50% decreased fuel use by 26%. Further decreases in generation (which may be relevant as food waste regulatory thresholds are reduced) result in larger increases in collection fuel use.

Truck size and collection frequency are management decisions that should be optimized by waste haulers, based on generation rates of their clients. Current state regulations also set a maximum on distance to waste receiving facilities. As a result, it should be feasible for a commercial food waste collection system to operate with fuel use below 10 L diesel/Mg. If 10 L/Mg was required for separate food waste collection rather than the 5.3 L/Mg estimated for this study, fuel use (which contributes the vast majority of impacts associated with collection) for the entire collection scheme would increase by less than 50%, since the food waste stream comprises less than 60% of total mixed HFW-ICI waste. In the context of system-level results presented in this study, collection would remain a minor contributor even with higher fuel use requirements.

3.6 Inter-Facility Transportation

Some mass flows in the food waste management scenarios require transportation between facilities described by SWOLF process models (e.g. ash from WTE to Ash landfill, AD process residual to WTE). For simplicity, all inter-facility distances are assumed to be 20 km, one way loaded, and one way empty. Emission factors are adapted from the ecoinvent database (Weidema et al. 2013) for medium-heavy duty and heavy-heavy duty trucks.

4.0 SUPPLEMENTAL RESULTS AND DISCUSSION

4.1 Base Case Results for Other Impacts

Net acidification potential, eutrophication potential, and cumulative fossil energy demand (CED-fossil) for each scenario in the base case are shown in Figures A1-A3. Acidification potential is lowest for the WTE scenarios (Figure A1), as greater electricity production leads to large offsets from conventional electricity generation. This also contributes to low net cumulative fossil energy demand for the WTE scenarios (Figure A3).

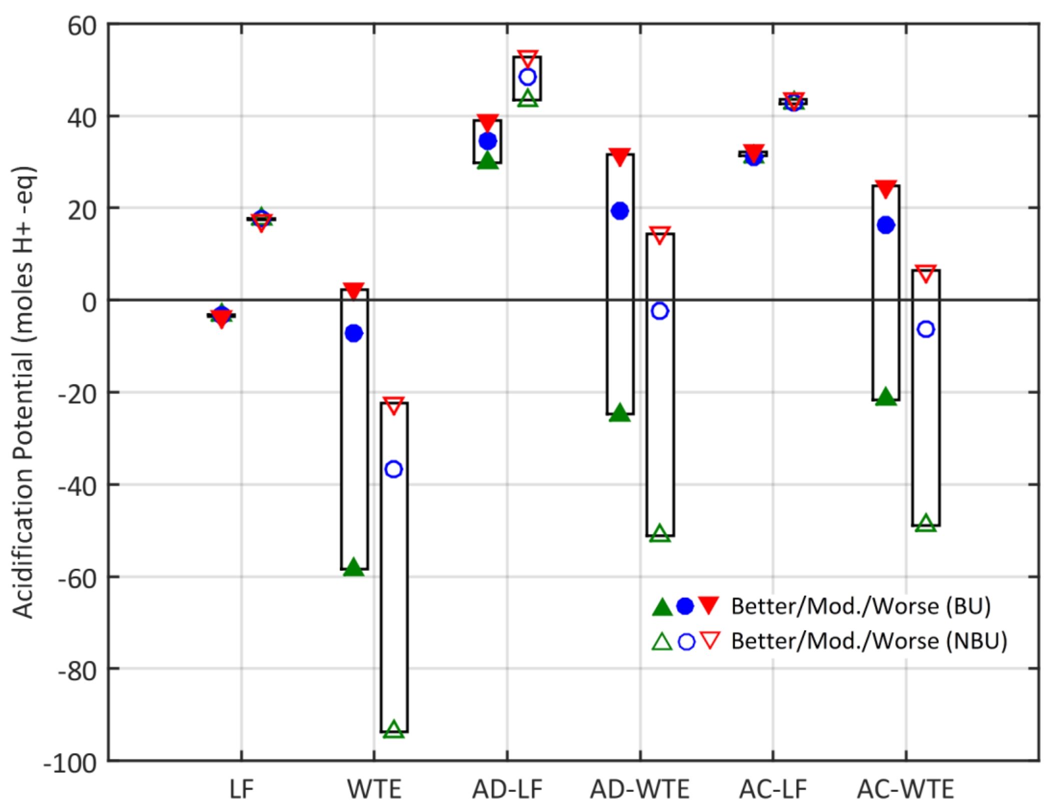

Figure A1 – Net acidification potential for each scenario and configuration. Note that bar outlines represent the range of values for all scenarios modeled and the individual symbols correspond to configurations described in the Modeling Approach.

Net eutrophication potential is lowest for the WTE and LF scenarios, neither of which involves land application of treated food waste (Figure A2). The amount of nitrate runoff to surface water is critical in determining the eutrophication potential of a given system, and scenarios involving AD tended to have higher eutrophication than those that did not. This study did not focus on developing ranges of environmental performance for land application of compost or digestate solids, but additional research in this area would be beneficial.

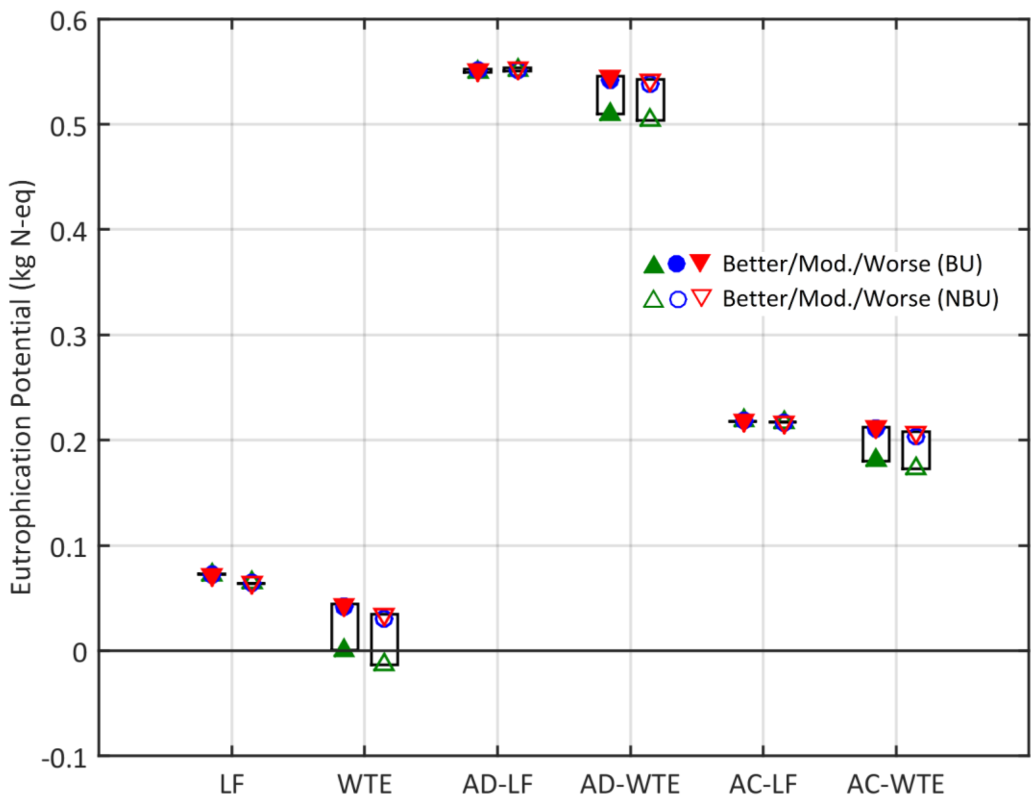

Figure A2 – Net eutrophication for each scenario and configuration. Note that bar outlines represent the range of values for all scenarios modeled and the individual symbols correspond to configurations described in the Modeling Approach.

Cumulative fossil energy demand is lowest for scenarios which produce the most electricity, in particular AD-WTE, WTE, and AC-WTE (Figure A3).

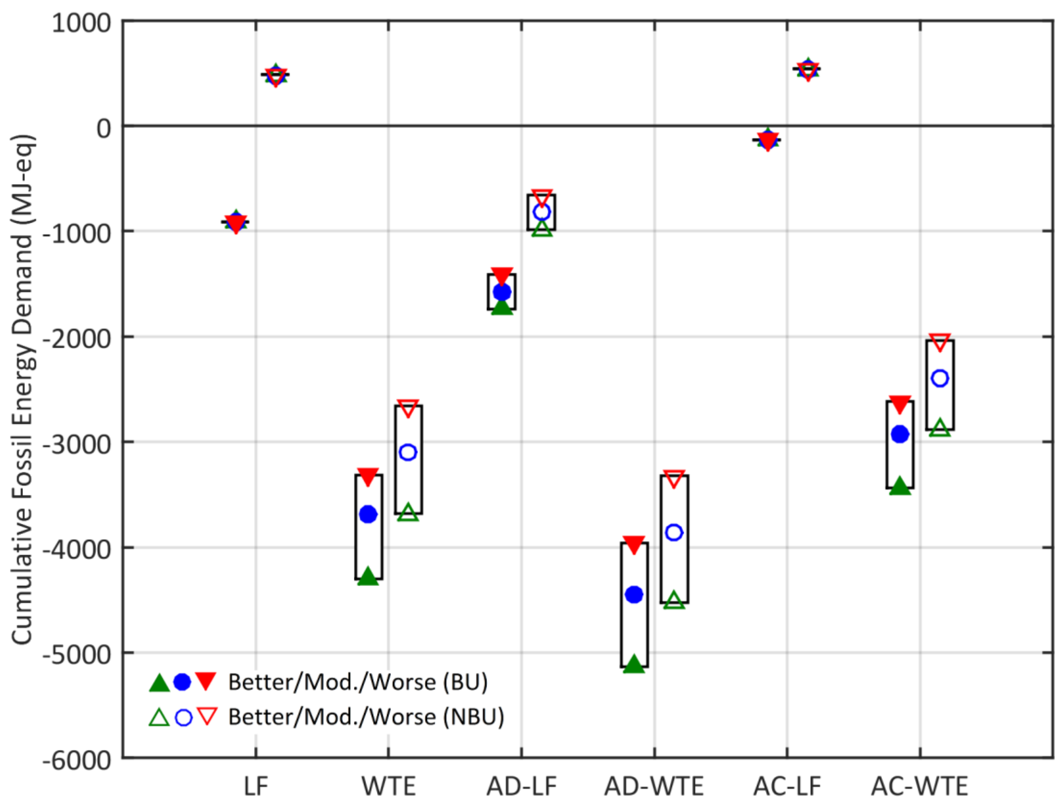

Figure A3 – Net CED-fossil for each scenario and configuration. Note that bar outlines represent the range of values for all scenarios modeled and the individual symbols correspond to configurations described in the Modeling Approach.

4.2 Selected Life-Cycle Inventory Results

The following tables (A16-A21) provide selected life-cycle inventory results for the moderate configuration and BU case for all scenarios. In these tables, carbon dioxide from fossil sources (CO_2-f) and biogenic sources (CO_2-b) are reported separately. Carbon dioxide from soil storage (CO_2-s) is also counted separately, and negative CO_2-s values indicate stored CO_2. Figures A4-A5 show how particular substances contribute to net GWP. Figure A4 highlights the fact that methane is a major contributor to net GWP in all scenarios that involve a landfill, while nitrous oxide (N_2O) is a smaller, but significant contributor to net GWP in all AD- and AC- scenarios. As shown in Figure A5, N_2O contributes most of the biodegradation-related emissions for AD, while methane produces approximately 50% of net GWP for composting biodegradation.

Table A16 – Selected emissions by process and sub-process for the LF scenario.[a]

	CO_2-f	CO_2-b	CO_2-s	CH_4	N_2O	NO_x	SO_2
Collection (net)	13.9			0.02		0.16	0.017
Landfill (net)	**-93.8**	**314.3**	**-208.9**	**15.37**	**0.00**	**0.44**	**-0.533**
Materials	3.7	0.1		0.01		0.02	0.013
Landfill Gas		316.4		15.56		0.52	
Leachate							
Carbon Storage			-208.9				
Equip. Fuel Use	9.1			0.01		0.11	0.010
Transport	0.6			0.00		0.00	0.001
Electricity Offsets	-107.2	-2.1		-0.21		-0.21	-0.556
LF Scenario Net	-79.9	314.4	-208.9	15.39	0.00	0.60	-0.507

a. All emissions values have units of kg emission per Mg HFW-ICI waste. Where values are not reported, emissions were negligible. Values may not sum to process net subtotals or scenario net total due to rounding.

Table A17 – Selected emissions by process and sub-process for the WTE scenario.[a]

	CO_2-f	CO_2-b	CO_2-s	CH_4	N_2O	NO_x	SO_2
Collection (net)	13.9			0.02		0.16	0.017
WTE (net)	**-16.0**	**598.9**	**0.0**	**-0.55**	**0.00**	**0.89**	**-0.953**
Stack Emissions	224.4	601.0		0.00	0.01	1.12	0.083
Materials	10.3	0.2		0.01		0.01	0.011
Eq. Fuel Use	2.6					0.03	0.003
Transportation	0.9						0.001
Capital Goods	4.5	0.1		0.01		0.01	0.010
Electricity	-114.0	-2.3		-0.23		-0.22	-0.591
Heat	-144.6	-0.1		-0.35		-0.06	-0.470
Ash Landfill (net)	0.1		-0.2				
Material Reprocessing (net)	-18.2	-0.1		-0.02		-0.04	-0.038
WTE Scenario Net	-20.0	598.8	-0.2	-0.56	0.00	1.01	-0.974

a. All emissions values have units of kg emission per Mg HFW-ICI waste. Where values are not reported, emissions were negligible. Values may not sum to process net subtotals or scenario net total due to rounding.

Table A18 – Selected emissions by process and sub-process for the AD-LF scenario.[a]

	CO_2-f	CO_2-b	CO_2-s	CH_4	N_2O	NO_x	SO_2
Collection (net)	19.0			0.02		0.22	0.022
AD (net)	**-107.5**	**174.7**	**-15.4**	**1.26**	**0.11**	**0.76**	**-0.545**
Biodeg. & Liquids Trtmt.		23.5		0.14	0.14		
Fugitive/Comb. Biogas		155.6		1.37		0.93	0.034
Soil Carbon Storage			-15.4				
N/P/K Offsets	-5.8	-2.2		-0.05	-0.02	-0.03	-0.026
Equip. Fuel Use	5.1			0.01		0.06	0.006
Transport	0.4						
Capital Goods	1.9					0.01	0.006
Electricity Offsets	-109.1	-2.2		-0.22		-0.21	-0.566
Landfill (net)	**-44.3**	**146.4**	**-167.4**	**6.91**	**0.00**	**0.22**	**-0.255**
Materials	2.0			0.01		0.01	0.007
Landfill Gas		147.4		7.00		0.25	
Leachate							
Carbon Storage			-167.4				
Equip. Fuel Use	5.0			0.01		0.06	0.005
Transport	0.3						
Electricity Offsets	-51.6	-1.0		-0.10		-0.10	-0.268
AC-LF Scenario Net	-132.6	321.1	-182.8	8.20	0.11	1.20	-0.774

a. All emissions values have units of kg emission per Mg HFW-ICI waste. Where values are not reported, emissions were negligible. Values may not sum to process net subtotals or scenario net total due to rounding.

Table A19 – Selected emissions by process and sub-process for the AD-WTE scenario.[a]

	CO_2-f	CO_2-b	CO_2-s	CH_4	N_2O	NO_x	SO_2
Collection (net)	19.0			0.02		0.22	0.022
AD (net)	**-107.5**	**174.7**	**-15.4**	**1.26**	**0.11**	**0.76**	**-0.545**
Biodeg. & Liquids Trtmt.		23.5		0.14	0.14		
Fugitive/Comb. Biogas		155.6		1.37		0.93	0.034
Soil Carbon Storage			-15.4				
N/P/K Offsets	-5.8	-2.2		-0.05	-0.02	-0.03	-0.026
Equip. Fuel Use	5.1			0.01		0.06	0.006
Transport	0.4						
Capital Goods	1.9					0.01	0.006
Electricity Offsets	-109.1	-2.2		-0.22		-0.21	-0.566
WTE (net)	**10.4**	**374.4**	**0.0**	**-0.48**	**0.00**	**0.61**	**-0.830**
Stack Emissions	220.9	376.3			0.01	0.82	0.061
Materials	5.6	0.1				0.01	0.006
Eq. Fuel Use	1.4					0.02	0.002
Transportation	0.5						0.001
Capital Goods	2.4			0.01		0.01	0.006
Electricity	-97.2	-1.9		-0.19		-0.19	-0.504
Heat	-123.3	-0.1		-0.30		-0.05	-0.401
Ash Landfill (net)	0.1		-0.2				
Material Reprocessing (net)	-18.2	-0.1		-0.02		-0.04	-0.038
AD-WTE Scenario Net	-95.9	549.6	-15.7	0.78	0.12	1.56	-1.392

a. All emissions values have units of kg emission per Mg HFW-ICI waste. Where values are not reported, emissions were negligible. Values may not sum to process net subtotals or scenario net total due to rounding.

Table A20 – Selected emissions by process and sub-process for the AC-LF scenario.[a]

	CO_2-f	CO_2-b	CO_2-s	CH_4	N_2O	NO_x	SO_2
Collection (net)	19.0			0.02		0.22	0.022
Composting (net)	**3.6**	**38.0**	**-26.0**	**0.88**	**0.06**	**0.03**	**0.002**
Biodegradation		39.1		0.90	0.07		
N/P/K Offsets	-2.8	-1.8		-0.04	-0.01	-0.01	-0.013
Carbon Storage			-26.0				
Equip. Fuel Use	2.5					0.03	0.003
Transport	0.7						0.001
Capital Goods	2.8	0.6		0.01		0.01	0.009
Electricity Use	0.4					0.00	0.002
Landfill (net)	**-41.7**	**137.4**	**-164.9**	**6.46**	**0.00**	**0.21**	**-0.240**
Materials	1.9			0.01		0.01	0.007
Landfill Gas		138.3		6.54		0.23	
Leachate							
Carbon Storage			-164.9				
Equip. Fuel Use	4.7			0.01		0.06	0.005
Transport	0.3						
Electricity Offsets	-48.6	-1.0		-0.10		-0.10	-0.252
AC-LF Scenario Net	-19.1	175.4	-190.9	7.36	0.06	0.46	-0.212

a. All emissions values have units of kg emission per Mg HFW-ICI waste. Where values are not reported, emissions were negligible. Values may not sum to process net subtotals or scenario net total due to rounding.

Table A21 – Selected emissions by process and sub-process for the AC-WTE scenario.[a]

	CO_2-f	CO_2-b	CO_2-s	CH_4	N_2O	NO_x	SO_2
Collection (net)	19.0			0.02		0.22	0.022
Composting (net)	**3.6**	**38.0**	**-26.0**	**0.88**	**0.06**	**0.03**	**0.002**
Biodegradation		39.1		0.90	0.07		
N/P/K Offsets	-2.8	-1.8		-0.04	-0.01	-0.01	-0.013
Carbon Storage			-26.0				
Equip. Fuel Use	2.5					0.03	0.003
Transport	0.7						0.001
Capital Goods	2.8	0.6		0.01		0.01	0.009
Electricity Use	0.4					0.00	0.002
WTE (net)	**6.9**	**361.7**	**0.0**	**-0.47**	**0.00**	**0.59**	**-0.804**
Stack Emissions	211.0	363.5			0.01	0.79	0.059
Materials	5.3	0.1				0.01	0.006
Eq. Fuel Use	1.3					0.02	0.001
Transportation	0.4						0.001
Capital Goods	2.3			0.01		0.01	0.005
Electricity	-94.1	-1.9		-0.19		-0.19	-0.488
Heat	-119.4	-0.1		-0.29		-0.05	-0.388
Ash Landfill (net)	0.1		-0.2				
Material Reprocessing (net)	-17.3	-0.1		-0.02	0.00	-0.04	-0.036
AC-WTE Scenario Net	12.4	399.7	-26.4	0.41	0.06	0.81	-0.816

a. All emissions values have units of kg emission per Mg HFW-ICI waste. Where values are not reported, emissions were negligible. Values may not sum to process net subtotals or scenario net total due to rounding.

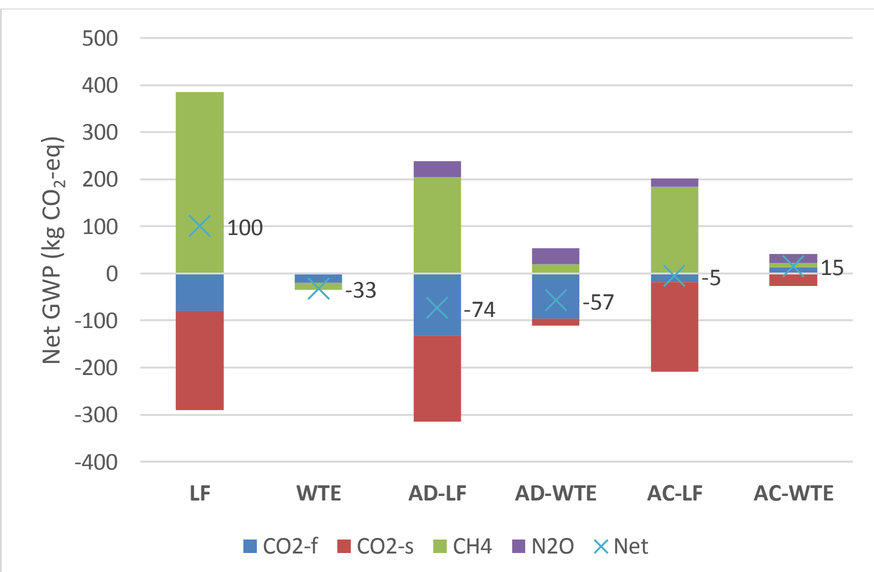

Figure A4 – Contributions to net GWP by selected net emissions. Based on emissions reported in Tables A16-A21, and assuming IPCC 2007 GWP impact factors.

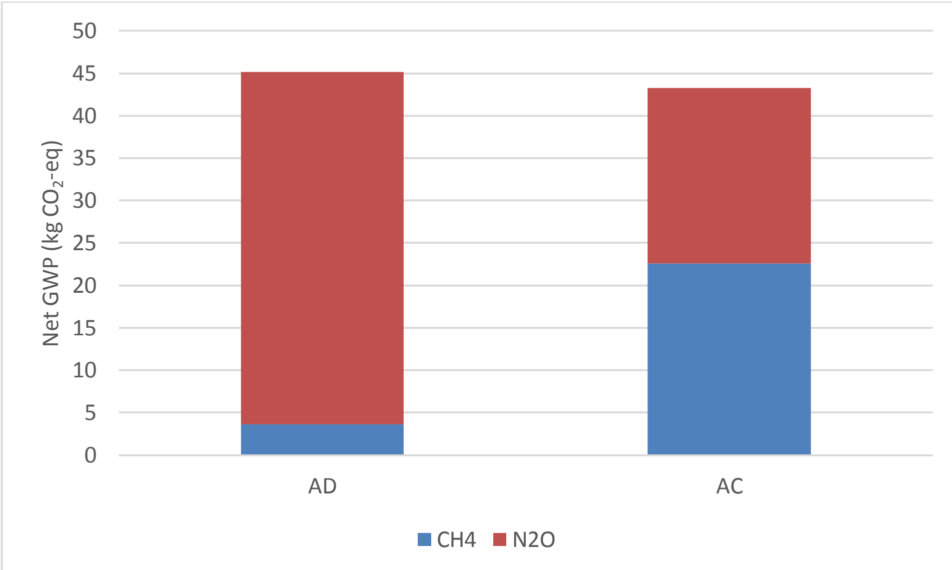

Figure A5 – Contributions of CH_4 and N_2O to biodegradation-related GWP. Based on data from Tables A18 and A20, and assuming IPCC 2007 GWP impact factors.

4.3 Sensitivity Cases

Full scenario-level net GWP results for all sensitivity cases are presented in Figures A6-A16, in addition to those provided in the main body. Results assuming a hypothetical electricity grid of 100% coal generation showed that a more carbon-intensive grid resulted in greater benefits to scenarios that produce electricity, particularly AD-WTE (both) and WTE (NBU) (Figure A8). The grid change was sufficient for AD-WTE (NBU) to become the most beneficial scenario, outperforming the second-ranked alternative, WTE (NBU), by 10%. Production of electricity rather than heat at WTE facilities is an even greater advantage in this case than in the base case.

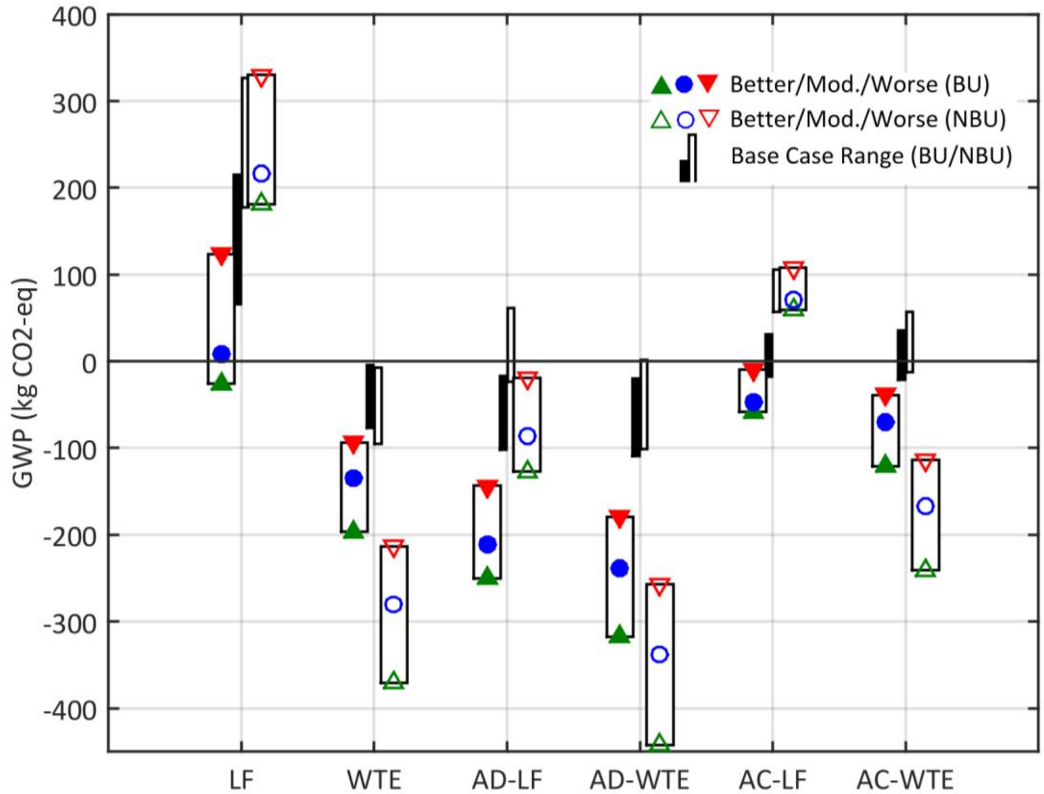

Figure A6 – Net GWP for each scenario and configuration under the 100% coal electricity case (1.3 kg CO_2e/kWh). Wide bar outlines represent the range of values for all scenarios modeled and the individual symbols correspond to configurations described in the Modeling Approach.

Figure A7 represents a case in which heat production at the WTE facilities avoids heat production from a mix of 50% coal-fired and 50% natural gas-fired boilers. Compared to the base case assumption of 100% natural gas heat, this assumption causes scenarios involving CHP to perform better.

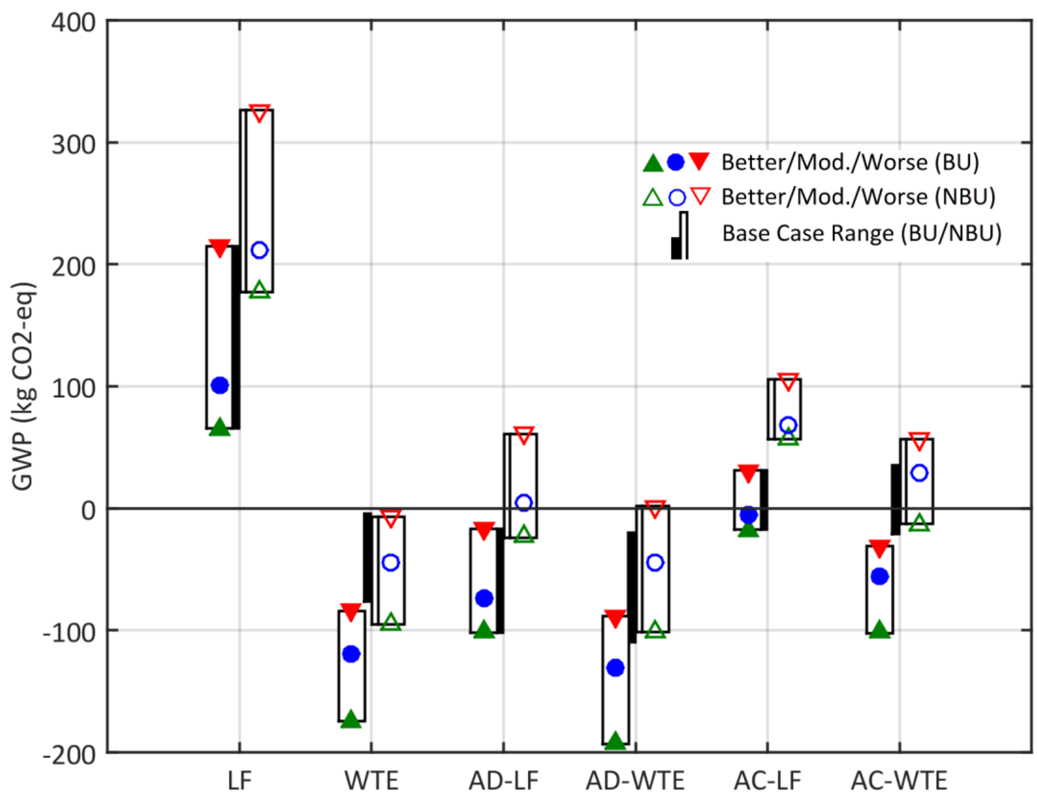

Figure A7 – Net GWP for each scenario and configuration under the 50% coal, 50% natural gas avoided heat case. Wide bar outlines represent the range of values for all scenarios modeled and the individual symbols correspond to configurations described in the Modeling Approach.

Figure A8 shows a case that continues in the direction of increasing GHG-intensiveness of avoided heat begun in Figure A7. In Figure A8, avoided heat is assumed to be 100% coal boiler. The value of CHP increases significantly in this case, to the point where the scenarios involving CHP stand alone as the best options.

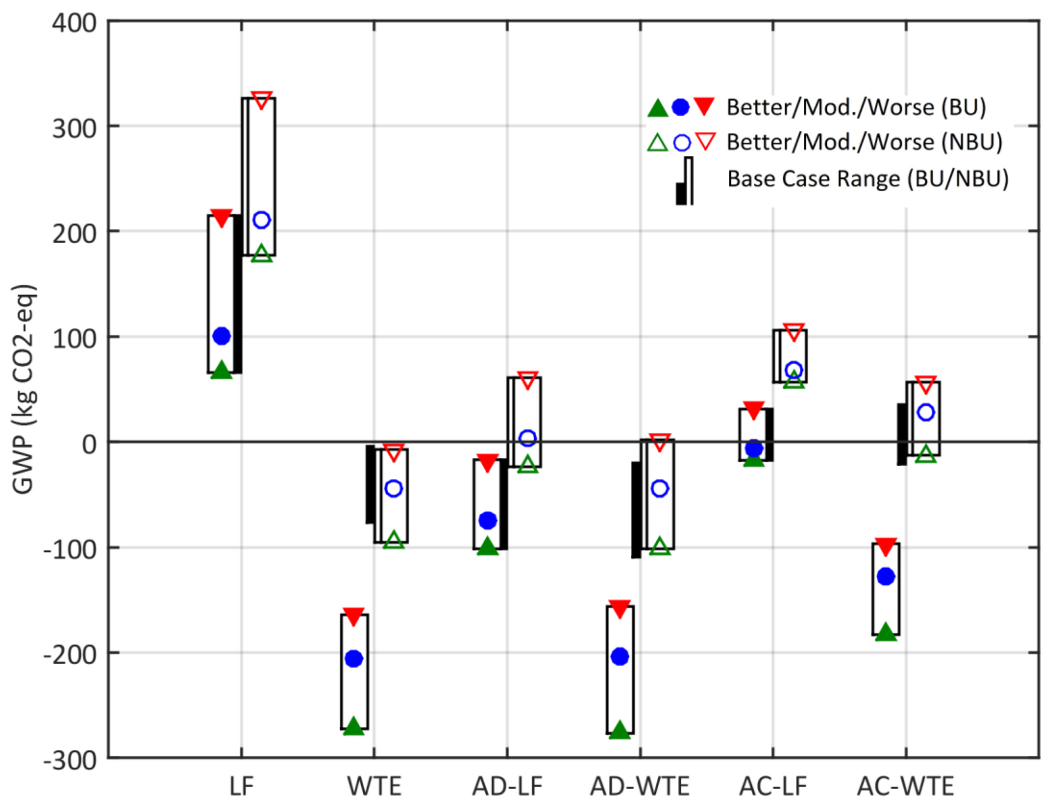

Figure A8 – Net GWP for each scenario and configuration under the 100% coal avoided heat case. Wide bar outlines represent the range of values for all scenarios modeled and the individual symbols correspond to configurations described in the Modeling Approach.

Results for the vegetable case, assuming no non-vegetable food, are shown in Figure A9. While the effects of changing from the base assumption to the vegetable case are marginal, they show a trend of landfill facilities performing better and WTE facilities performing worse.

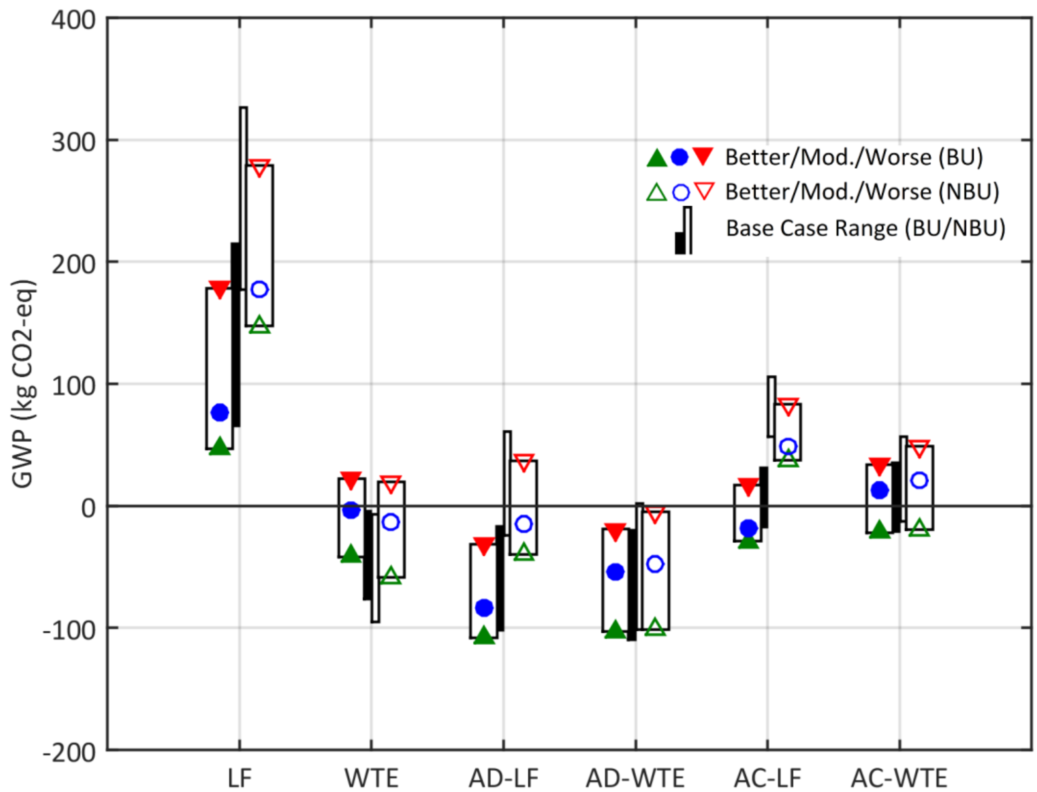

Figure A9 – Net GWP for each scenario and configuration under the vegetable case. Wide bar outlines represent the range of values for all scenarios modeled and the individual symbols correspond to configurations described in the Modeling Approach.

Figure A10 shows results for a case in which the vegetable case is extended by increasing the moisture content of vegetable food waste from 77% to 85%. This situation continues the trends shown in Figure A9, but the impact of increased moisture content is more pronounced. Specifically, scenarios involving the landfill improve, while those involving the WTE facility worsen in terms of GWP. This is one of only two cases in which the LF (BU) scenario outperformed both WTE scenarios

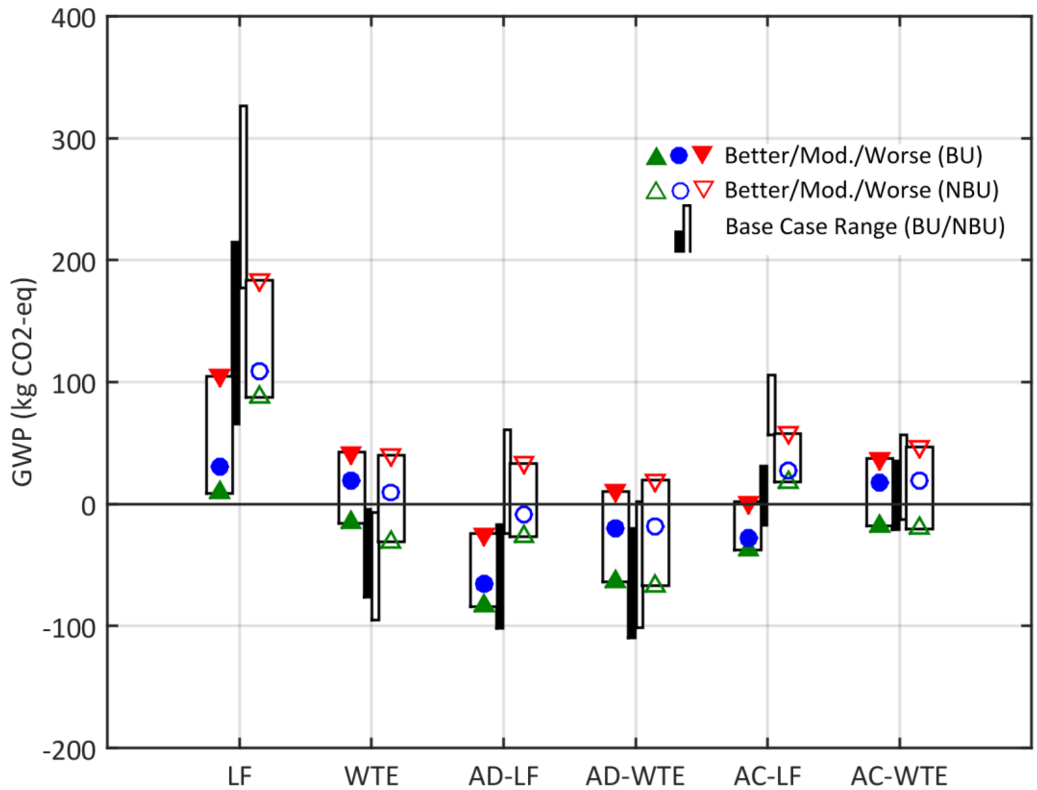

Figure A10– Net GWP for each scenario and configuration under the wet vegetable case. Wide bar outlines represent the range of values for all scenarios modeled and the individual symbols correspond to configurations described in the Modeling Approach.

The methane yield of food waste was tested at 250 and 500 m^3/dry Mg compared to the base case assumption of 400 m^3/dry Mg. Low methane yield reduced the benefits of AD, which made the WTE scenarios and composting more competitive alternatives (Figure A11). Scenarios involving the landfill also performed better, as the reduced methane yield of food waste reduced methane emissions. High methane yield did not significantly alter scenario rankings, though the LF scenarios performed notably worse (Figure A12).

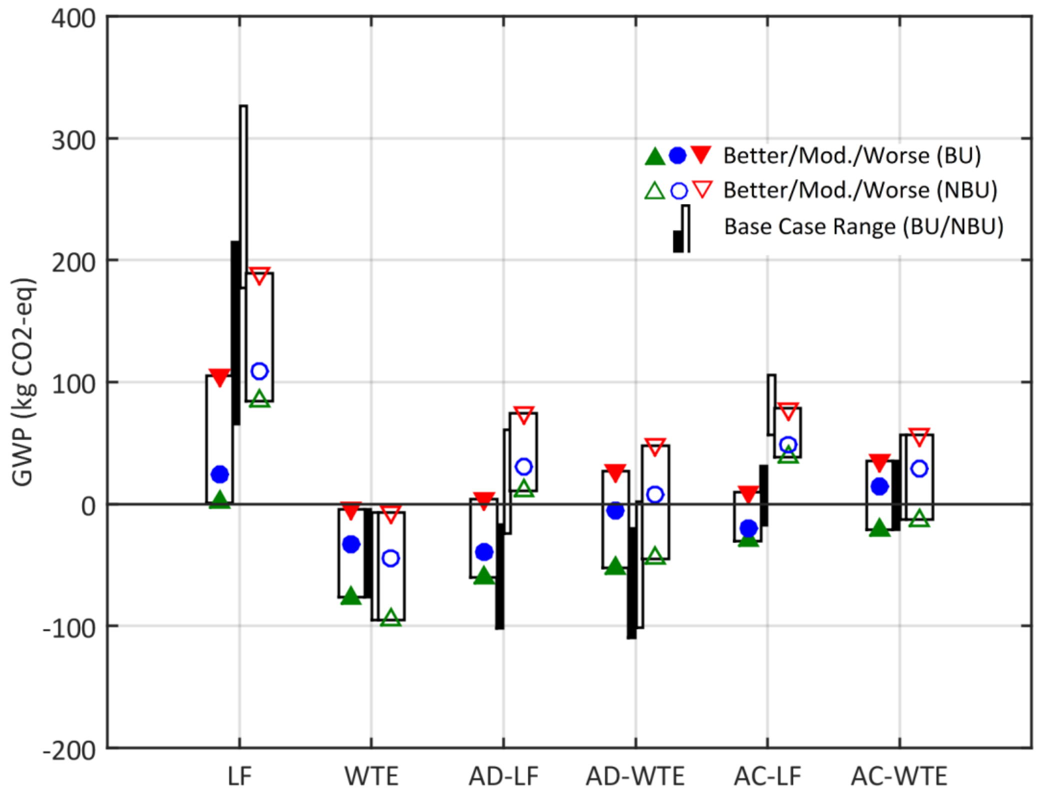

Figure A11 – Net GWP for each scenario and configuration under the low methane yield case (250 m^3/dry Mg). Wide bar outlines represent the range of values for all scenarios modeled and the individual symbols correspond to configurations described in the Modeling Approach.

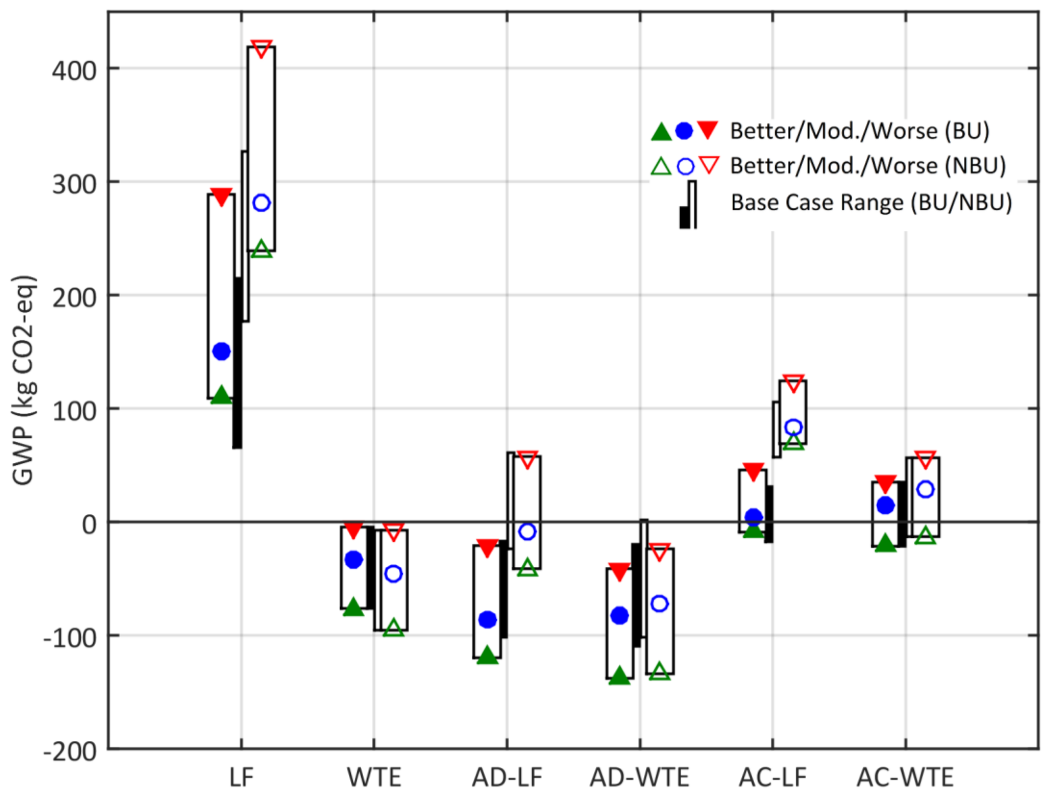

Figure A12 – Net GWP for each scenario and configuration under the high methane yield case (500 m^3/dry Mg). Wide bar outlines represent the range of values for all scenarios modeled and the individual symbols correspond to configurations described in the Modeling Approach.

Sensitivity to composition was tested by replacing the HFW-ICI composition with a statewide as-discarded MSW composition from Minnesota (Burns & McDonnell 2013). Importantly, only composition was changed for this sensitivity case- the modeled collection system was not altered to represent inclusion of other sectors. The MSW composition case caused the most dramatic change in rankings due to the improvement of landfill and worsening of WTE facilities in terms of GWP (Figure A13). The top ranked scenarios for the MSW composition case were AD-LF (BU), followed by AC-LF (BU), then LF (BU). These results are due to (1) the relatively higher proportion of plastics in MSW (18.5% vs. 8.6% in HFW-ICI), which increased the fossil CO_2 stack emissions from the WTE facility, (2) the simultaneous large reduction in food waste (18.4% vs. 58.8% in HFW-ICI), which contributed to reducing LFG emissions by approximately 57% in the LF scenario, and (3) the higher proportion of paper products (25.2% vs. 20.7% in HFW-ICI), which contributed to increasing carbon storage by approximately 48% over the base case.

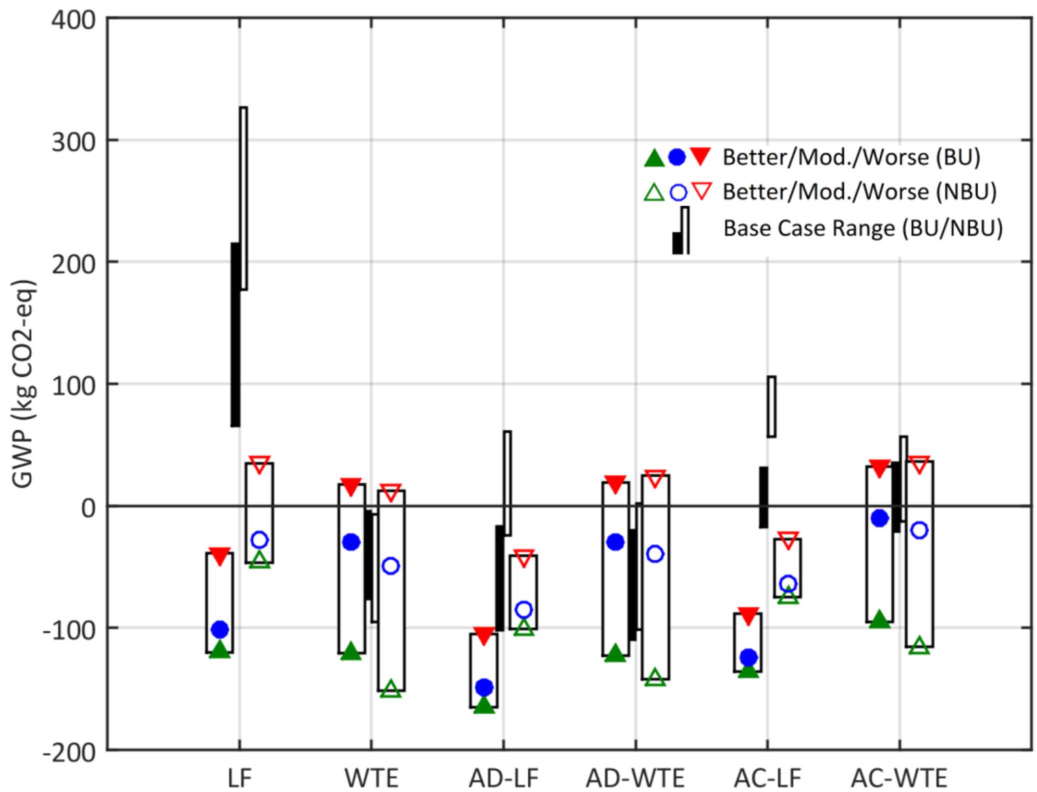

Figure A13 – Net GWP for each scenario and configuration under the MSW composition case. Wide bar outlines represent the range of values for all scenarios modeled and the individual symbols correspond to configurations described in the Modeling Approach.

Source-separation effectiveness of food waste was varied from the base assumption of 80% to 70% and then to 100%, such that no food waste is present in the residual stream. Separation effectiveness of all other waste components remained at 5% (e.g. 5% of plastic, etc. is directed into the food waste stream, where it is a contaminant). The 100% source separation case improved all scenarios involving AD and improved all scenarios that send residual to the landfill, since there was no rapidly-degrading food waste in the residual stream. As a result, the AD-LF (NBU) scenario improved to the third rank behind AD-LF (BU) and AD-WTE (BU) (Figure A14). This suggests that where diversion of food waste to AD is practiced, maximizing source separation effectiveness is important to maximize GWP benefits.

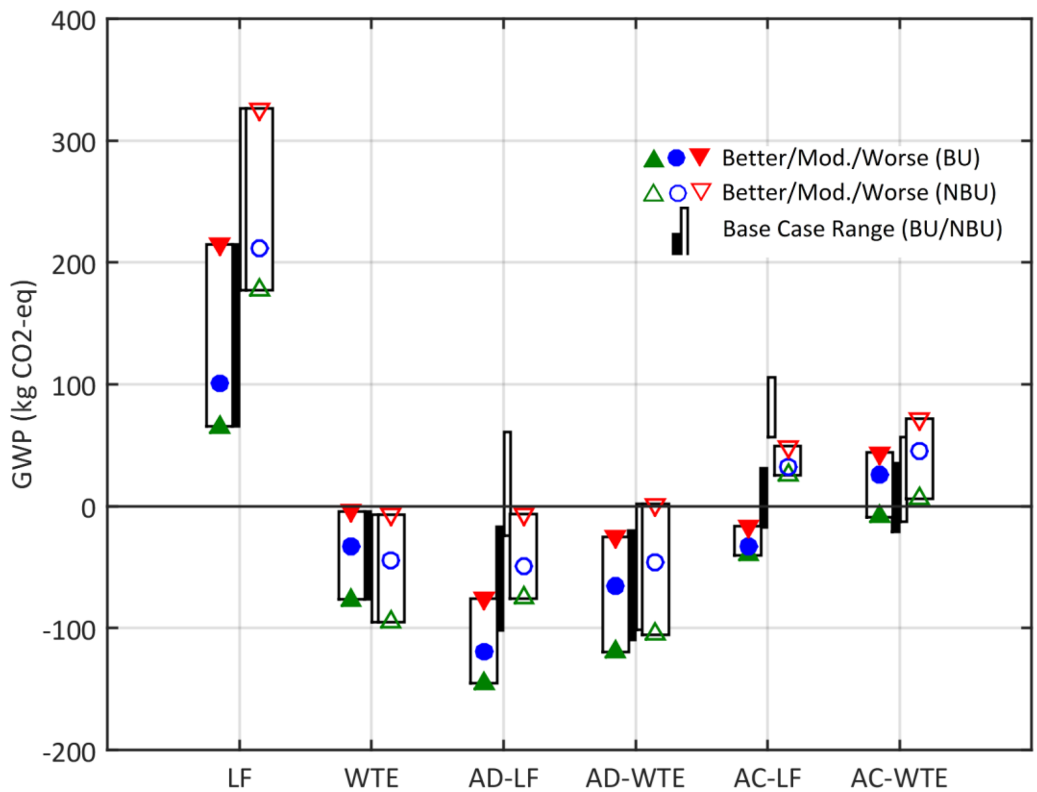

Figure A14 – Net GWP for each scenario and configuration under the 100% source separation case. Wide bar outlines represent the range of values for all scenarios modeled and the individual symbols correspond to configurations described in the Modeling Approach.

The 70% source separation case did not significantly change the scenario rankings in terms of GWP (Figure A15). However, the AD-LF and AC-LF scenarios worsen because more food waste (30% of generated food waste) is directed to the landfill in this case.

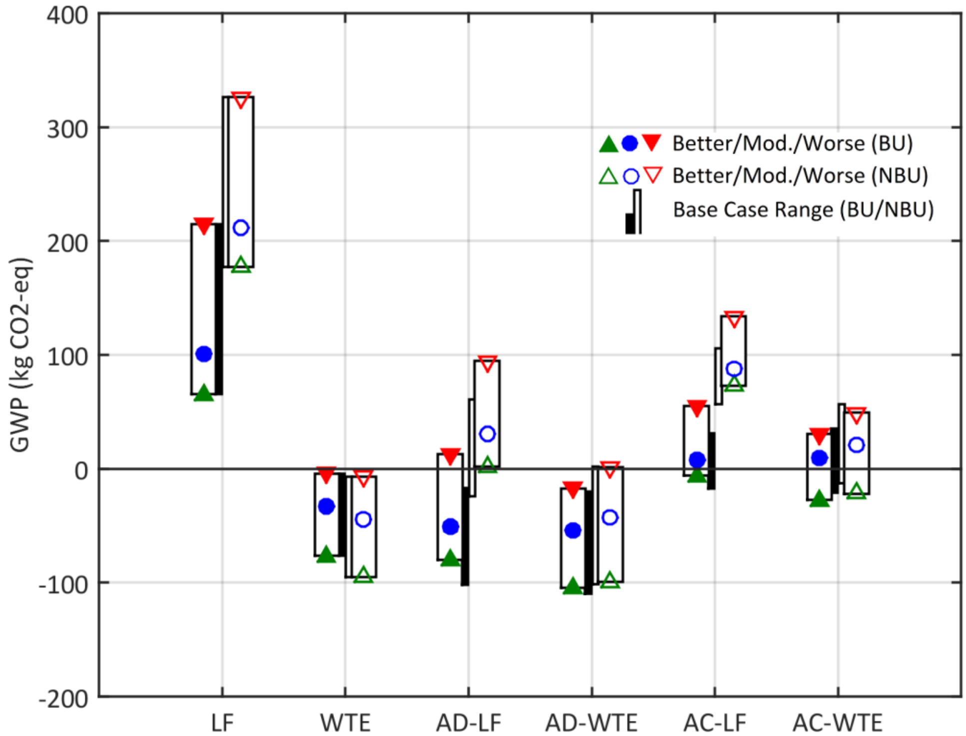

Figure A15 – Net GWP for each scenario and configuration under the 70% source separation case. Wide bar outlines represent the range of values for all scenarios modeled and the individual symbols correspond to configurations described in the Modeling Approach.

Figure A16 represents a case in which the functional unit is redefined to include only food waste (assumed 80% vegetable, 20% non-vegetable as in the base case). In this case, since full separation is assumed, only four scenarios are considered (LF, WTE, AD, AC). These scenarios perform as expected in terms of net GWP, with LF as the worst performer, AC next, and AD and WTE competing for best.

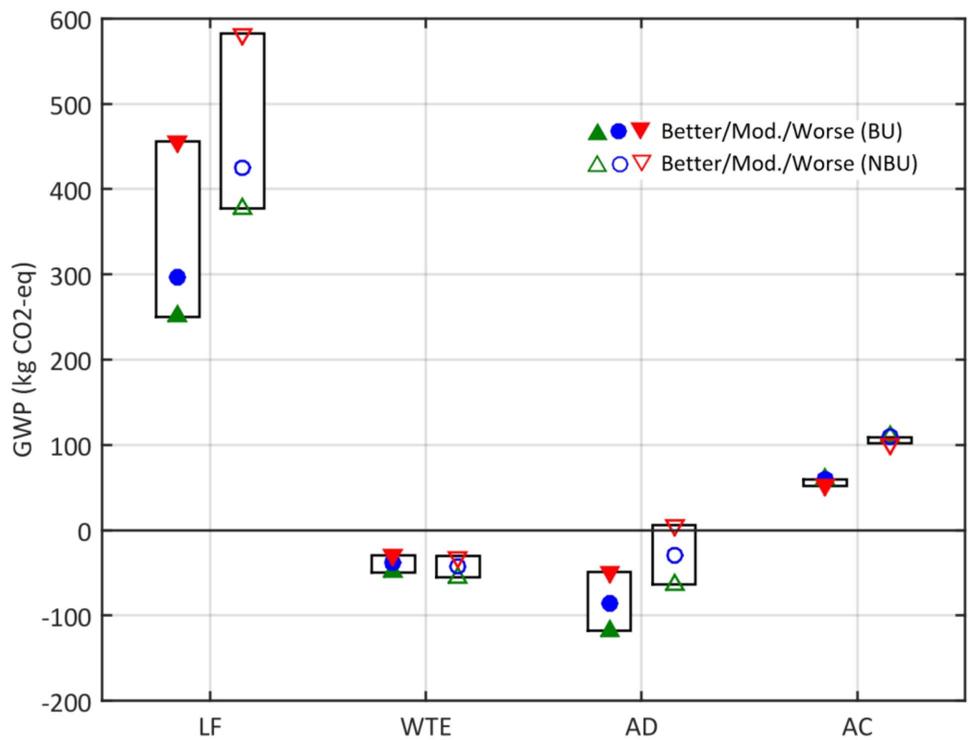

Figure A16 – Net GWP for each configuration, assuming the facility receives only food waste. Wide bar outlines represent the range of values for all scenarios modeled and the individual symbols correspond to configurations described in the Modeling Approach.

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APPENDIX B: RESEARCH NOTE ON LANDFILL GAS YIELD

The following research note was prepared by Dr. Morton A. Barlaz (North Carolina State University) on June 8, 2014. The resulting methane yields were used as default values in this study.

Documentation of Landfill Gas Yields Used in the MSW-DST

(June 8, 2014)

The objective of this note is to document updated methane yields that are used in the MSW-DST and the Waste Reduction Model (WARM) – both are solid waste life-cycle models developed by the U.S. EPA. The starting point is methane yields that were published by Eleazer et al. in 1997 and Wang et al. in 2011. These methane yields were measured in a laboratory-scale system that was designed to measure the maximum methane potential of several individual waste components. In several cases, the mass balance was imperfect, meaning that less methane was measured than would be expected on the basis of the measured loss of organic C. A yield was thus calculated by assuming that 50% of the organic C lost was converted to methane and 50% to CO_2 as is typical for carbohydrates (cellulose and hemicellulose). It is recognized that food waste will contain some protein and fats which produce a slightly higher methane to CO_2 ratio. However, the difference is small given the uncertainty of this work.

As a result of the discrepancy between measured methane and that expected on the basis of solids loss, some methane yields were adjusted on the assumption that reactors leaked. The measured methane yields, the yields adopted for use as defaults in WARM and the DST and the supporting logic are summarized in Table B1.

The calculation is illustrated below for newsprint:

The newsprint sample tested was 49.2% C and the carbon storage factor (Barlaz et al. 1998 and corrected in later memos) is 0.42 kg C stored/kg dry substrate:

0.492-0.42 = 0.072 Kg C loss per dry kg

0.072 * 0.5 kg C to CH_4/ kg C *1000 gm/kg / (12 gm/mole) * 22.4 liters/moles = 67.2 L CH_4/dry kg

Table B1 - Methane Yields for MSW Components (m^3 CH_4/dry Mg) [a]

MSW Component	Measured Methane Yield[b]	Methane Yield Calculated from C Loss	Adopted Yield	Notes
Leaves	43.7	65.3	65.3	The measured yield is the average of 30.8 and 56.8. The calculated is the average of 22.4 and 108.3. Clearly, there is considerable variability in the biodegradability of leaves.
Grass	136.0	194.8	194.8	The measured yield is the average of 144.4 and 127.6. The calculated yield is based on only one set of reactors with a yield of 144.4
Branches	62.6	106.4	62.6	The calculated value for branches is surprisingly high given the measurements for wood as reported in Wang et al. As such, we were reluctant to increase from 62.6. In ongoing work, we are measuring the methane yield of large and small diameter hardwood (red oak) and softwood (loblolly pine). Methane yields are ~20, 0, 60 and 90 for small and large diameter softwood and small and large diameter hardwood, respectively. The hardwood reactors are still producing methane and the yields are increasing.
Newspaper	74.3	67.2	74.3	We did not want to decrease the methane yield from that measured but this result emphasizes that there is also uncertainty in the calculated values.
Corrugated containers	152.3	195.1	195.1	

Table B1 (continued)

MSW Component	Measured Methane Yield[b]	Methane Yield Calculated from C Loss	Adopted Yield	Notes
Copy Paper (also referred to as office paper)	217.3	263.6	263.6	The corrected yield was multiplied by 0.8 in recognition of the fact that today's copy/office paper has about 20% inorganics in contrast to Eleazer et al which had 1.4% inorganics.
Phone books			74.3	Same as newsprint
Magazines (also known as coated paper or glossy paper)	84.4	68.1	84.4	Eleazer measured glossy paper. Same comment as for newsprint.
Textbooks			263.6	Same as copy paper
Magazines/3rd class mail			174.0	The measured yield is the average of magazines (84.4) and office paper (263.6). The adopted is the average of glossy paper (84.4) and office paper (263.6)
Food waste	300.7	399.5	399.5	Note that additional measures of food waste in Staley et al were 152.9 and 207. Mass balances were not performed in the Staley study and these values were low. The value of 380 appeared more consistent with the literature.
Wood or Dimensional Lumber[c]	13.7		13.7	Average of red oak (33), radiata pine (0.5) and spruce (7.5) as described in Wang et al. Eucalyptus (0) was excluded from the average because it is not used in the U.S. and differs considerably from other hardwoods. While radiata is not typically used in the U.S. it was judged to be similar to other pines that are used and included in the average.
Medium-density fiberboard	4.6		4.6	
Wood flooring	19.8	2.3	19.8	Average of red oak (33.3) and plywood (6.3).
Mixed MSW	125.0		125.0	Calculated assuming measured methane yield of 100 m3/wet Mg and converted assuming moisture content of 20%.

a. All methane yield data are in mL CH_4 per dry gm which is equivalent to m^3 CH_4/dry Mg where 1 Mg = 1000 kg.
b. From Eleazer et al. or Wang et al. in the case of wood.
c. Final yield for HW red oak is 33.3 (sd = 13.7)

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