GREENHOUSE GAS EMISSION FACTORS FOR MANAGEMENT OF SELECTED MATERIALS IN MUNICIPAL SOLID WASTE

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Waste management practices can impact greenhouse gas (GHG) emissions by affecting energy consumption, methane generation, carbon sequestration, and non-energy-related manufacturing emissions. This paper examines GHG emissions and sinks, from a life-cycle perspective, for selected paper, glass, metal, and plastic materials comprising about one-third of municipal solid waste (MSW) generated in the US. Material-specific emission factors are provided for four MSW management practices: source reduction, recycling, combustion, and landfilling. Manufacturers, solid waste decision-makers, and others interested in the GHG implications of MSW management may use this information for voluntary reporting of GHG emission reductions associated with waste management practices and to develop strategies to reduce GHG emissions. Each of the waste management options provides opportunities for GHG reductions for one or more materials.

Introduction. In 1993, the U.S. issued its Climate Change Action Plan (CCAP), which outlines over 50 voluntary initiatives to reduce GHG emissions in the US. Initiative 16 of the Plan calls for *accelerated source reduction and recycling of municipal solid waste*[1] through combined efforts by the US Environmental Protection Agency (EPA), the Department of Energy, and the Department of Agriculture. To support EPA's efforts on this initiative, a research project was launched to develop material-specific emission factors for MSW management practices.[2]

1. Method for Analyzing GHG Emissions From Municipal Waste Management. We selected ten materials for analysis, based on an initial screen for the quantity of waste generated, the potential to increase source reduction or recycling of the material, and the difference in energy used to manufacture the product from virgin inputs rather than recycled inputs. The ten materials are: newspaper; office paper; corrugated cardboard; mixed paper; aluminum cans; steel cans; glass containers; high density polyethylene (HDPE) plastic; low density polyethylene (LDPE) plastic; and polyethylene terephthalate (PET) plastic These materials constitute 31 percent of municipal solid waste in the US, as shown in Table 1.[3]

We examined those stages of the life cycle that have the potential to affect GHG emissions as materials are converted from their raw states to products, and then disposed as waste. Figure 1 shows the steps in the life cycle in which GHGs are emitted, carbon sequestration is affected, and electric utility energy is displaced (reducing utility GHG emissions).[4] At

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[1] Source reduction is defined as making less of a product, and may be the result of (1) "lightweighting" (e.g., producing less glass or plastic because bottles are made thinner and lighter), (2) more efficient use of a material (e.g., double-sided photocopying), (3) extending the life of a product, or (4) material substitution (e.g., substituting cans for bottles, or vice versa). Recycling is defined as remanufacturing a material to make more of the same material, or a different material (e.g., office paper can be recycled to make office paper or tissue paper).

[2] A complete description of the research results is available on the internet at http://www.epa.gov/ epaoswer/non-hw/muncpl/ghg.htm

[3] Mixed paper is a term used in the recycling industry; it does not correspond directly to paper grades as generated, and thus does not appear in Table 1.

[4] EPA's Office of Research and Development (ORD) is performing a more extensive application of life cycle assessment for various waste management options for MSW. ORD's analysis will inventory a broader set of emissions (air, water, and

each of these points, we also considered transportation-related energy emissions. We did not analyze the GHG emissions associated with consumer use of products, but believe them to be negligible for the selected materials.

Raw material acquisition and manufacturing GHGs were compared to a baseline of acquiring raw materials and manufacturing products using the current mix of virgin and recycled inputs. Similarly, the projected stock of carbon in forests and harvested forest products, under existing recycling policies and projected market conditions, was the reference case against which changes in forest carbon were estimated. Table 2 summarizes the GHG sources and sinks for each MSW management option. Throughout the analysis, we used methods consistent with guidance from the Intergovernmental Panel on Climate Change on accounting and estimating techniques for GHG emissions and sinks.[5]

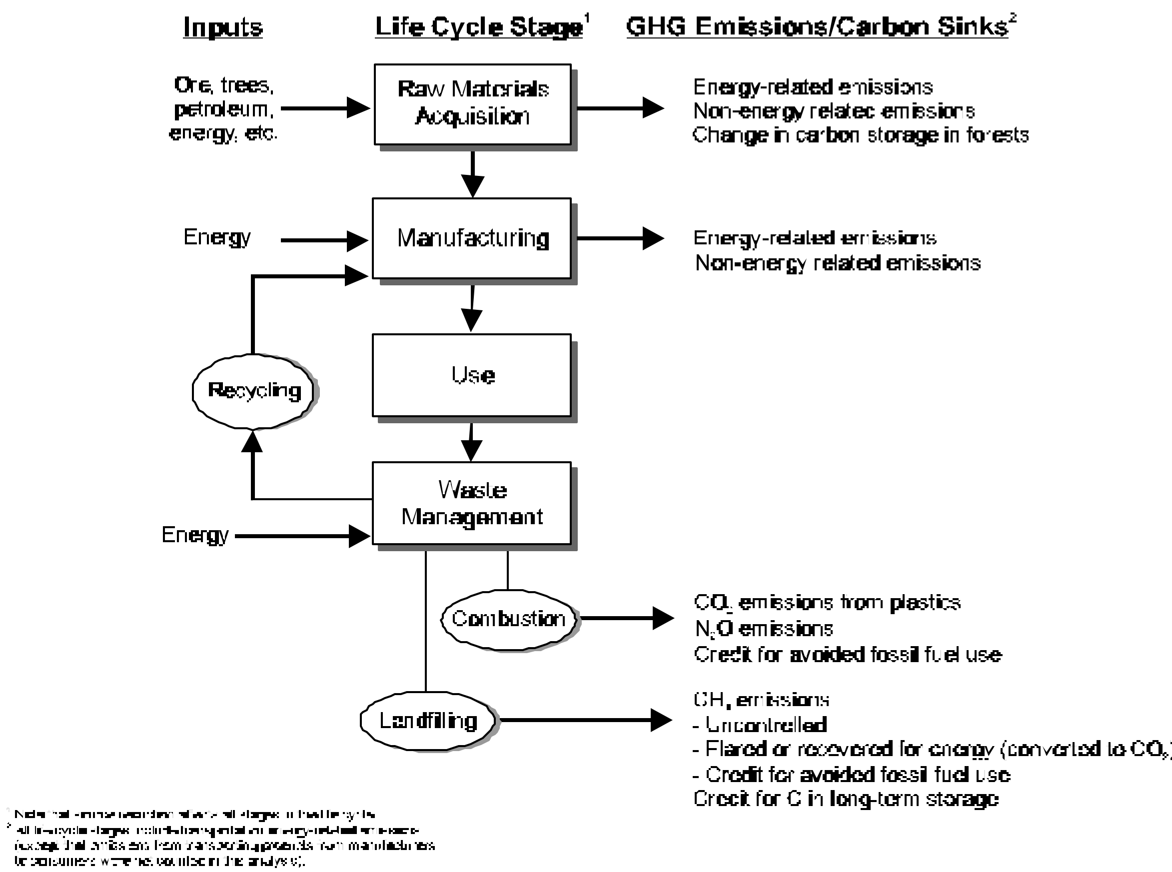
Table 1
Percentage of 1996 US Generation of MSW

Material	**Percentage of MSW Generation**
Newspaper	5.9%
Office paper	3.2%
Corrugated cardboard	13.8%
Aluminum cans	0.8%
Steel cans	1.3%
Glass containers	5.3%
HDPE plastic*	0.6%
LDPE plastic*	0.01%
PET plastic*	0.5%
Total	**31%**

*Based on blow-molded containers.

Source: USEPA, *Characterization of Municipal Solid Waste in the United States: 1997 Update***, May 1998.** EPA 530-R-98-007.

Figure 1
GHG Sources and Sinks Associated with Materials in the MSW Stream



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waste) associated with these options. For more information on this effort, go to their project web-site at http://www.epa.gov/docs/crb/apb/apb.htm.

[5] IPCC. *Guidelines for National Greenhouse Gas Inventories* (three volumes), 1997. IPCC, Hadley Centre Meteorological Office, Bracknell, England.

Table 2
Components of Net Emissions for Various Municipal Solid Waste Management Strategies

Municipal Solid Waste Management Strategy	Greenhouse Gas Sources and Sinks		
	Raw Materials Acquisition and Manufacturing	Change in Forest or Soil Carbon Storage	Waste Management
Source Reduction	Decrease in GHG emissions, relative to the baseline of manufacturing	Increase in forest carbon storage (paper only)	No emissions/ sinks
Recycling	Decrease in GHG emissions due to lower energy requirements (compared to manufacture from virgin inputs) and avoided process non-energy GHGs	Increase in forest carbon storage (paper only)	Process and transportation emissions associated with recycling are counted in the manufacturing stage
Combustion	No change	No change	Nonbiogenic CO_2, N_2O emissions, avoided utility emissions, and transportation emissions
Landfilling	No change	No change	Methane emissions, long-term carbon storage, avoided utility emissions, and transportation emissions

2. GHG Emissions From Raw Materials Acquisition and Manufacturing. For this first stage of the lifecycle, we estimated the GHG emissions from fossil fuel combustion for both (1) raw materials acquisition and manufacturing, or "process energy," and (2) transportation. Transportation energy includes CO_2 emissions from transportation of raw materials, and of intermediate products to the final manufacturing or fabrication facility. For transportation of recycled inputs, we considered transportation (1) from the curbside to the materials recovery facility (MRF), (2) from the MRF to a broker, and (3) from a broker to the plant or mill.

We developed separate estimates for process and transportation energy GHG emissions for virgin inputs and recycled inputs, based on two sets of estimates: (1) the amount of each type of fuel used to make a given quantity of the material, and (2) an emission factor for each fuel. We also accounted for three additional sources of GHGs in manufacturing processes that are not related to energy use: (1) CO_2 from lime manufacture, (2) methane emissions from natural gas systems, and (3) perfluorocarbon emissions from aluminum production.

3. Forest Carbon Sequestration. When paper products are source reduced or recycled, trees that would otherwise be harvested are left standing. In the short term, this results in a larger amount of carbon remaining sequestered – in effect, resulting in “negative emissions” – because the standing trees continue to store carbon, whereas paper production and use tends to release carbon. In the long term, some of the short-term benefits disappear as market forces result in less planting of new managed forests than there would otherwise be, so that there is comparatively less forest acreage in trees that are growing rapidly (and thus sequestering carbon rapidly).

Working with US Forest Service staff, who generated outputs from Forest Service models, we estimated that recovering one metric ton of paper results in incremental forest carbon sequestration of 0.81 metric tons of carbon equivalent (MTCE). We converted the estimate for recovering any type of paper into three separate estimates for source reducing each of the three different types of paper, based on the inputs displaced by source reduction. If one assumes that source reduction displaces 100 percent virgin inputs, source reduction of any of the three types of paper results in forest carbon sequestration of approximately 0.81 MTCE, the same as for paper recovery. On the other hand, if one assumes that source reduction displaces the mix of virgin and recycled inputs currently used in manufacturing, source reduction of one metric ton of newspaper, office paper, or corrugated cardboard results in forest carbon sequestration of, respectively, 0.47, 0.55, and 0.42 MTCE.

4. Source Reduction and Recycling. Source reduction avoids energy use, and GHG emissions, in the raw materials acquisition and manufacturing stage. For paper products, source reduction also results in forest carbon sequestration.

For recycling, manufacturing from recycled inputs generally requires less energy than manufacturing from virgin inputs. Consequently, manufacturing from recycled inputs generally results in lower GHG emissions than manufacturing from virgin inputs (although changes in the fuel mix can result in higher emissions in the case of some paper products). As with source reduction of paper products, recycling of paper products also results in forest carbon sequestration.

5. Combustion. Combustion of MSW results in CO_2 and nitrous oxide (N_2O) emissions. Following IPCC guidelines, only CO_2 emitted from burning organics from nonbiogenic sources (i.e., plastics) is counted as a greenhouse gas emission. These are offset to varying degrees by GHG reductions when the heat of combustion is used to produce steam and generate electricity (thus avoiding generation from fossil fuel sources) and steel recovery (saving energy in steel manufacture). We assumed that when electricity is generated, it displaces fossil fuels in the current ratio of use in the US. Combustion of paper results in negative net emissions (the avoided fossil fuel emissions produce net benefits), whereas there are positive emissions for plastics (the CO_2 from combustion exceeds the avoided utility emissions). For mixed MSW as a whole, GHG emissions from combustion are slightly negative.

6. Landfilling. Steel and aluminum cans, glass containers, and HDPE, LDPE, and PET plastic are essentially inert in landfills. The IPCC accounting convention for carbon in plastics that are landfilled does not "count" that carbon — in essence, landfilling returns the (modified) fossil fuel back to the earth.[6] Consequently, the net GHG emissions from landfilling of metals, glass, and plastics is zero (other than small transportation CO_2 emissions). For paper, however, both methane emissions and carbon sequestration must be considered.

To estimate methane emissions and carbon sequestration from landfilling of paper, we used data from laboratory experiments conducted by Dr. Morton Barlaz and his colleagues at North Carolina State University.[7] The experiments provided data on (1) the amount of methane generated by paper, when digested by bacteria in anaerobic conditions simulating those in a landfill, and (2) the amount of carbon remaining undecomposed (i.e., sequestered) at the end of the experiment.

An increasing number of landfills are collecting landfill gas (or LFG, which is about 50 percent CH_4), and some of the larger LFG projects are using the gas to generate electricity.[8] As with combustion, the avoided fossil fuel emissions can have a dramatic effect on total emissions for some materials. For paper, the net emissions vary widely depending on whether LFG systems are in place.

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[6] The fossil source (oil or gas) is not counted as an emission in the national GHG inventory because it is not combusted.

[7] Eleazer, William E., William S. Odle, Yu-Shen Wang, and Morton A. Barlaz, "Biodegradability of Municipal Solid Waste Components in Laboratory-Scale Landfills," *Environmental Science and Technology*, Vol. 31, No. 3, March 1997, pp. 911-917.

[8] The Landfill Methane Outreach Program, a voluntary partnership between the USEPA, state agencies, landfill gas-to-energy developers and energy users, aims to reduce landfill methane emissions by facilitating the development of landfill gas utilization projects. The program has an Internet home page (http://www.epa.gov/landfill.html), and can be reached via a toll-free hotline number (1-800-782-7937).

7. Use of Emission Factors. Table 3 displays GHG emission factors, for each of the waste management options, expressed in units of metric tonnes of carbon equivalent per wet tonne of material. These emission factors represent the cumulative emissions summed across all GHGs (after weighting each gas by its 100-year global warming potential).

Table 3
Net GHG Emissions from Waste Management Options (MTCE/Wet Tonne)

Material	Source Reduction		Recycling	Combustion	Landfilling			
	Current mix of mfgrg inputs	100% virgin mfgrg inputs			Landfills Without LFG Recovery	Landfills With LFG Recovery and Flaring	Landfills With LFG Recovery and Electric Generation	Projected US National Average
Newspaper	-1.00	-1.41	-0.94	-0.24	-0.13	-0.32	-0.36	-0.25
Office Paper	-1.13	-1.42	-0.90	-0.20	1.16	0.26	0.08	0.59
Corrugated Cardboard	-0.86	-1.22	-0.78	-0.21	0.30	-0.10	-0.18	0.04
Mixed Paper								
Broad Definition	NA	NA	-0.73	-0.21	0.34	-0.09	-0.18	0.06
Residential Definition	NA	NA	-0.73	-0.21	0.29	-0.11	-0.20	0.03
Office Paper Definition	NA	NA	-0.93	-0.19	0.42	-0.06	-0.15	0.12
Aluminum Cans	-3.29	-5.94	-4.27	0.03	0.01	0.01	0.01	0.01
Steel Cans	-0.92	-1.23	-0.63	-0.53	0.01	0.01	0.01	0.01
Glass	-0.16	-0.18	-0.09	0.03	0.01	0.01	0.01	0.01
HDPE	-0.67	-0.77	-0.40	0.23	0.01	0.01	0.01	0.01
LDPE	-0.98	-0.98	-0.54	0.23	0.01	0.01	0.01	0.01
PET	-1.08	-1.28	-0.68	0.26	0.01	0.01	0.01	0.01
Mixed MSW as disposed	NA	NA	NA	-0.03	0.11	-0.10	-0.14	-0.02

Note that more digits may be displayed than are significant.

The primary application of the GHG emission factors in this report is to support climate change mitigation analysis and accounting for waste management practices. Organizations interested in quantifying and voluntarily reporting GHG emission reductions associated with waste management practices may use these emission factors for that purpose. In conjunction with the US Department of Energy, EPA has used these emission factors to develop guidance for voluntary reporting of GHG reductions, as authorized by the US Congress in Section 1605 (b) of the Energy Policy Act of 1992. EPA also plans to use these emission factors to evaluate its progress in reducing US GHG emissions—by promoting source reduction and recycling through voluntary programs such as WasteWi$e and Pay-as-You-Throw (PAYT)—as part of the US CCAP. [9] The methodology presented in this report may also assist other countries involved in developing GHG emissions estimates for their solid waste streams.[10]

In order to apply the emission factors to a waste management strategy for a given material, one must first establish a baseline scenario and an alternative scenario. Once emissions for the two scenarios have been determined, one calculates the difference between the alternative scenario and the baseline scenario. The result represents the GHG emission reductions or increases attributable to the alternative waste management practice.

Example Calculation

Given a baseline scenario of landfilling 10 metric tons of office paper and an alternative scenario of recycling the same amount, one could estimate the change in net emissions as follows. For recycling:

10 MT x -0.90 MTCE/MT = -9.0 MTCE

The net emissions of landfilling 10 MT, in the “average” landfill, is

10 MT x 0.58 MTCE/MT = 5.8 MTCE.

The change in GHG emissions for the alternate scenario, with respect to the baseline, is

–9.0 MTCE –5.8 MTCE = -14.8 MTCE,

so GHG emissions would be reduced by 14.8 MTCE.

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[9] Information on WasteWi$e and PAYT can be found on the web at http://www.epa.gov/epaoswer/non-hw/reduce/wstewise/ and http://www.epa.gov/epaoswer/non-hw/payt/, or call the hot-line at 800 EPA-WISE (372-9473).

[10] Note that waste composition and product life cycles vary significantly among countries, but the basic methodologic framework would still apply.

The life cycle GHG emissions for source reduction, recycling, and combustion are compared to the GHG emissions from landfilling in Table 4. The values in the table indicate the effect of changing management of one ton of each material from landfilling (often viewed as the baseline waste management strategy) to one of the other waste management options, based on average US conditions. GHG emissions are sensitive to some factors that vary on a local basis, and thus site-specific emissions differ from those summarized here. The WAste Reduction Model (WARM), scheduled for release on EPA's web site in late 1998, will provide the emission factors, along with the capability of incorporating key site-specific parameters to improve the accuracy of the emission factors for specific conditions.

Table 4
Greenhouse Gas Emissions of MSW Management Options Compared to Landfilling
(MTCE/Metric Ton)

Material	Source Reduction Net Emissions Minus Landfilling Net Emissions	Recycling Net Emissions Minus Landfilling Net Emissions	Combustion Net Emissions Minus Landfilling Net Emissions
Newspaper	-0.75	-0.70	0.01
Office Paper	-1.72	-1.49	-0.79
Corrugated Cardboard	-0.90	-0.81	-0.25
Mixed Paper			
Broad Definition	NA	-0.80	-0.28
Residential Definition	NA	-0.77	-0.24
Office Paper Definition	NA	-1.05	-0.31
Aluminum Cans	-3.30	-4.29	0.02
Steel Cans	-0.93	-0.64	-0.54
Glass	-0.17	-0.10	0.01
HDPE	-0.68	-0.41	0.22
LDPE	-1.00	-0.56	0.22
PET	-1.09	-0.70	0.25

Note that values reflect US national averages, and more digits may be displayed than are significant.

8. Major Limitations of the Analysis. When conducting this analysis, we used a number of analytical approaches and numerous data sources, each with its own limitations. In addition, we employed major assumptions throughout the analysis. Some of the major limitations follow:

- The manufacturing GHG analysis is based on estimated industry averages for energy usage, and in some cases the estimates are based on limited data and average values for electricity generation.
- The forest carbon sequestration analysis uses a point estimate for forest carbon sequestration, whereas the system of models predicts changing net sequestration over time.
- The combustion analysis uses US national average values for a number of parameters that may not be representative of a given combustor facility.
- The landfill analysis is based on laboratory data from a single researcher.

Many of the emissions are likely to vary considerably among sites; applying the values in this paper to specific circumstances at the site is an exercise involving considerable uncertainty. Also, many different emission estimation methodologies are being employed to measure the impact of climate change mitigation activities. While the methods and results reported here are appropriate for evaluating voluntary measures, they are not sufficiently accurate for purposes that go beyond evaluation of GHG emissions from waste management options in a voluntary setting. For a more thorough description of the limitations and assumptions that underlie the results in this paper, please see our full report, *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste.*[11]

[11] US EPA, *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste; Final Report*, Sept 1998. EPA 530-R-98-013. Published on the Internet at http://www.epa.gov/ epaoswer/non-hw/muncpl/ghg.htm