6. LANDFILLING

This chapter presents estimates of GHG emissions and carbon storage from landfilling the materials considered in this analysis. For this study, EPA estimated the CH_4 emissions, transportation-related CO_2 emissions, and carbon storage that will result from landfilling each type of organic waste and mixed MSW. The analysis is based on three key GHG accounting principles:[1]

- When food discards, yard trimmings, paper, and wood are landfilled, anaerobic bacteria degrade the materials, producing CH_4 and CO_2. CH_4 is counted as an anthropogenic GHG, because even though it is derived from sustainably harvested biogenic sources, degradation would not result in CH_4 emissions if not for deposition in landfills. The CO_2 is not counted as a GHG in this context because if it were not emitted from landfills, it would be produced through natural decomposition. Because metals and glass do not contain carbon, they do not generate CH_4 when landfilled. Plastics, carpet, PCs, clay bricks, concrete, fly ash, and tires do not biodegrade measurably in anaerobic conditions, and therefore do not generate any CH_4.
- Transportation of waste materials to a landfill results in anthropogenic CO_2 emissions, due to the combustion of fossil fuels in the vehicles used to haul the wastes.
- Because food discards, yard trimmings, and paper are not completely decomposed by anaerobic bacteria, some of the carbon in these materials is stored in the landfill. Because this carbon storage would not normally occur under natural conditions (virtually all of the organic material would degrade to CO_2, completing the photosynthesis/respiration cycle), this is counted as an anthropogenic sink. However, carbon in plastic that remains in the landfill is not counted as stored carbon, because it is of fossil origin.

EPA developed separate estimates of emissions from (1) landfills without gas recovery systems, (2) those that flare CH_4, (3) those that combust CH_4 for energy recovery, and (4) the national average mix of these three categories. The national average emission estimate accounts for the extent to which CH_4 will be flared at some landfills and combusted onsite[2] for energy recovery at others.[3]

From the standpoint of postconsumer GHG emissions, landfilling some materials—including newspaper and phonebooks—results in net storage (i.e., carbon storage exceeds CH_4 plus transportation energy emissions) at all landfills, regardless of whether gas recovery is present. At the other extreme, office paper, textbooks, and food discards result in net emissions regardless of landfill gas collection and recovery practices. The remaining materials have net postconsumer emissions that are either very low (all materials have transportation-related emissions of 0.01 MTCE per ton, regardless of whether gas collection is present) or borderline, depending on whether the landfill has gas recovery (e.g., mixed MSW has net emissions at landfills without gas recovery, but net carbon storage at landfills with gas recovery).

[1] These principles are described in broad terms in Section 1.4 of this report.

[2] Although gas from some landfills is piped to an offsite power plant and combusted there, for the purposes of this report, the assumption was that all gas for energy recovery was combusted onsite.

[3] Currently, most landfill CH_4 recovery in the United States—both for flaring and electricity—is occurring in response to a 1996 EPA rule that requires a well-designed and well-operated landfill gas collection system at landfills that (1) have a design capacity of at least 2.5 million metric tons and 2.5 million cubic meters; (2) are calculated to emit more than 50 metric tons of non-CH_4 organic compounds per year; and (3) received waste on or after November 11, 1987 (*Federal Register*, Vol. 61, No. 49, p. 9905, March 12, 1996). For the year 2003, an estimated 59 percent of landfill CH_4 was generated at landfills with landfill gas recovery systems subject to these requirements or installed on a voluntary basis (U.S. Environmental Protection Agency, 2005. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003*).

6.1 CH_4 GENERATION AND CARBON STORAGE FOR ORGANIC MATERIALS

This section starts with a review of the principal processes that influence the fate of organic carbon in the landfill environment and then describes the experimental basis for and derivation of the estimates of CH_4 emissions and carbon storage used in this report.

6.1.1 Carbon Stocks and Flows in Landfills

Exhibit 6-1 shows the carbon flows within a landfill system. Carbon entering the landfill can have one of several fates: exit as CH_4, exit as CO_2, exit as volatile organic compounds (VOCs), exit dissolved in leachate, or remain stored in the landfill.[4]

After entering landfills, a portion of the organic materials decomposes and eventually is transformed into landfill gas and/or leachate. Aerobic bacteria initially decompose the waste until the available oxygen is consumed. This stage usually lasts less than a week and is followed by the anaerobic acid state, in which carboxylic acids accumulate, the pH decreases, and some cellulose and hemicellulose decomposition occurs. Finally, during the methanogenic state, bacteria further decompose the organic material into CH_4 and CO_2.

The rate of decomposition in landfills is affected by a number of factors, including: (1) waste composition; (2) factors influencing microbial growth (moisture, available nutrients, pH, temperature); and (3) whether the operation of the landfill retards or enhances waste decomposition. Most studies have shown the amount of moisture in the waste, which can vary widely within a single landfill, to be a critical factor in the rate of decomposition.[5] As a result, there is increasing interest in the operation of landfills as bioreactors, in which leachate and possibly other liquids are recirculated to enhance decomposition and gas production.[6] Bioreactor technologies, which optimize landfill moisture content in order to accelerate waste decomposition, have emerged as a leading technology for facilitating rapid decomposition of organic wastes and cost-effective CH_4 collection.

Of the various components of the landfill carbon system, by far the most research to date has been conducted on the transformation of landfill carbon into CH_4.[7,8] This interest has been spurred by a number of factors, including EPA's 1996 rule requiring large landfills to control landfill gas emissions (40 Code of Federal Regulations Part 60, Subparts Cc and WWW), the importance of CH_4 emissions in GHG inventories, and the market for CH_4 as an energy source. CH_4 production occurs in the methanogenic stage of decomposition, as methanogenic bacteria break down the fermentation products from earlier decomposition processes. Since CH_4 emissions result from waste decomposition, the quantity and duration of the emissions is dependent on the same factors that influence waste degradability (e.g., waste composition, moisture).

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[4] The exhibit and much of the ensuing discussion are taken directly from Freed, J.R., K. Skog, C. Mintz, and N. Glick. 2004. "Carbon Storage due to Disposal of Biogenic Materials in U.S. Landfills." *Proceedings of the Third Annual Conference on Carbon Sequestration*, U.S. Department of Energy. Available at www.carbonsq.com.

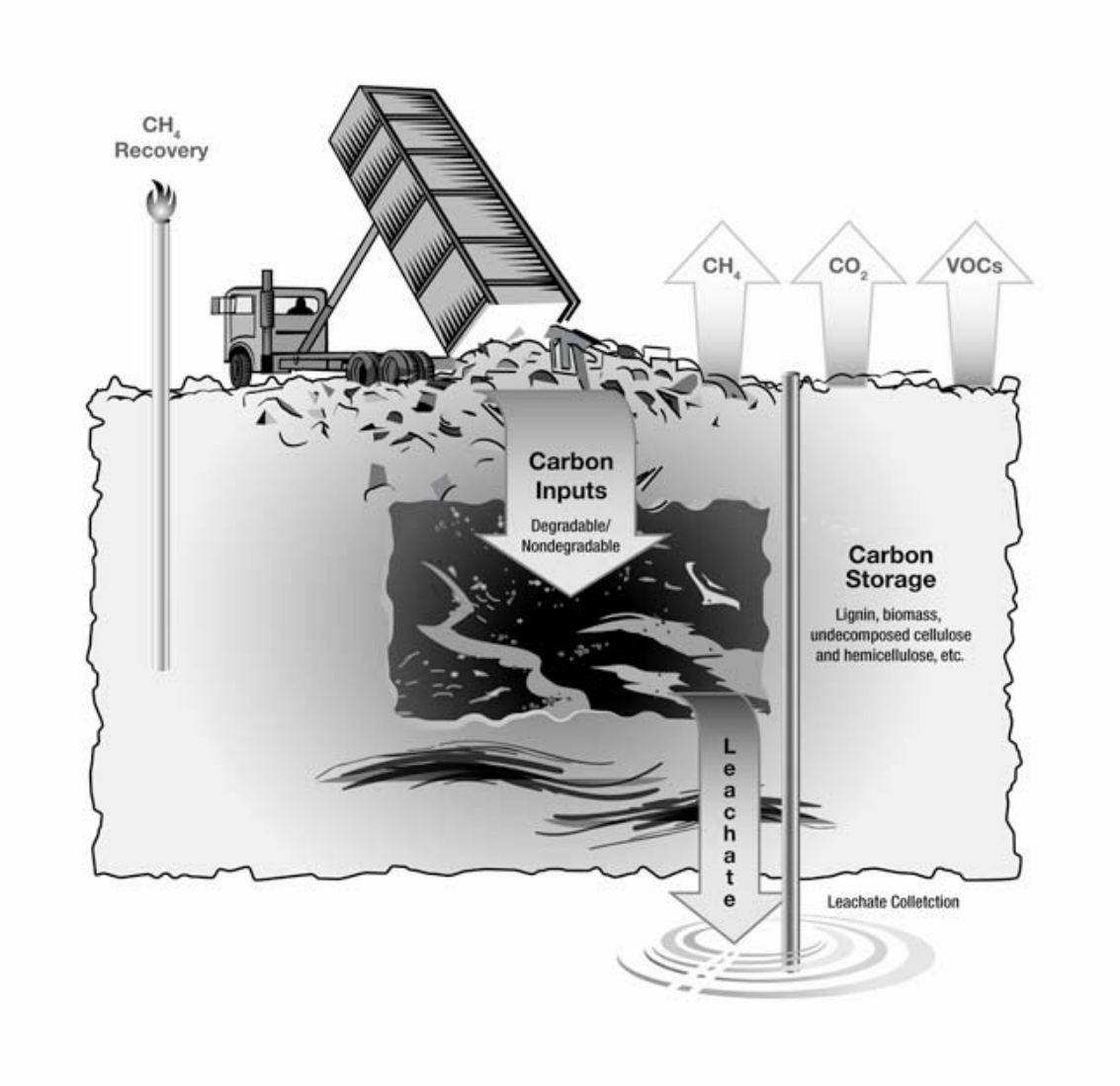
[5] Barlaz, M. A., R.K. Ham, and D.M. Schaefer. 1990. "Methane Production From Municipal Refuse: A Review of Enhancement Techniques and Microbial Dynamics," *Critical Reviews in Environmental Control, 19(6):557.*

[6] Pacey, J., D. Augenstein, R. Morck, D. Reinhart, R. Yazdani. 1999. The Bioreactive Landfill. *MSW Management*, September/October 1999.

[7] Bingemer, H G. and P J Crutzen, 1987. "The Production of Methane from Solid Wastes." *Journal of Geophysical Research* 90(D2): 2181-2187.

[8] Barlaz, M., W. Eleazer, W. Odle, X. Qian, Y. Wang. 1997. "Biodegradative Analysis of Municipal Solid Waste in Laboratory-Scale Landfills," U.S. Environmental Protection Agency 600/R-97-071.

Exhibit 6-1 Landfill Carbon Mass Balance



Carbon dioxide is produced in the initial aerobic stage and anaerobic acid stage of decomposition. However, relatively little research has been conducted to quantify CO_2 emissions during these stages. Emissions during the aerobic stage are generally assumed to be a small proportion of total organic carbon inputs, and a screening level analysis indicates that less than 1 percent of carbon is likely to be emitted through this pathway.[9] Once the methanogenic stage of decomposition begins, landfill gas *as generated* is composed of approximately 50 percent CH_4 and 50 percent CO_2.[10] But landfill gas *as collected* generally has a higher CH_4 concentration than CO_2 concentration (sometimes as much as a 60 percent:40 percent ratio), because some of the CO_2 is dissolved in the leachate as part of the carbonate system ($CO_2 \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- \leftrightarrow CO_3^{2-}$).

To date, very little research has been conducted on the role of VOC emissions in the landfill carbon mass balance. Given the thousands of compounds entering the landfill environment, tracking the biochemistry by which these compounds ultimately are converted to VOC is a complex undertaking. Existing research indicates that ethane, limonene, *n*-decane, *p*-dichlorobenzene, and toluene may be

[9] Freed et al. 2004. Op cit.
[10] Bingemer, H. G. and P. J. Crutzen, 1987. Op. cit.

among the most abundant landfill VOCs.[11] Hartog (2003) reported non-CH_4 volatile organic compound concentrations in landfill gas at a bioreactor site in Iowa, averaging 1,700 parts per million (ppm) carbon by volume in 2001 and 925 ppm carbon by volume in 2002.[12] If the VOC concentrations in landfill gas are generally of the order of magnitude of 1,000 ppm, VOCs would have a small role in the overall carbon balance, as concentrations of CH_4 and CO_2 will both be hundreds of times larger.

Leachate is produced as water percolates through landfills. Factors affecting leachate formation include the quantity of water entering the landfill, waste composition, and the degree of decomposition. Because it may contain materials capable of contaminating groundwater, leachate (and the carbon it contains) is typically collected and treated before being released to the environment, where it eventually degrades into CO_2. However, leachate is increasingly being recycled into the landfill as a means of inexpensive disposal and to promote decomposition while the containment system is operating at peak efficiency.[13] Research shows that this recirculation can increase the mass of organics collected by the system and consequently enhance aqueous degradation.[14] Although a significant body of literature exists on landfill leachate formation, little research is available on the carbon implications of this process. Based on a screening analysis, Freed et al. (2004) found that loss as leachate may occur for less than one percent of total carbon inputs to landfills.

In mass balance terms, carbon storage can be characterized as the carbon that remains after accounting for the carbon exiting the system as landfill gas or dissolved in leachate. On a dry weight basis, municipal refuse contains 30–50 percent cellulose, 7–12 percent hemicellulose, and 15–28 percent lignin.[15] Although the degradation of cellulose and hemicellulose in landfills is well documented, lignin does not degrade to a significant extent under anaerobic conditions.[16] In fact, although cellulose and hemicellulose biodegradation does occur, the extent of decomposition varies with landfill conditions, and these materials do not appear to completely degrade based on a number of excavation studies.[17] In addition, the presence of lignin actually prevents some cellulose and hemicellulose biodegradation. Thus, landfills in effect store some of the cellulose and hemicellulose and all of the lignin that is buried initially. The amount of storage will vary with environmental conditions in the landfill; pH and moisture content have been identified as the two most important variables controlling decomposition.[18]

6.1.2 Measured and Estimated CH_4 Generation and Carbon Storage

The focus of this report is on comparing waste management options for specific materials within the solid waste stream. Although a large body of research exists on CH_4 generation from mixed solid wastes, only a few investigators—most notably Dr. Morton Barlaz and coworkers at North Carolina State University—have measured the behavior of specific waste wood, paper, food waste, and yard trimming components.

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[11] Eklund B., E. Anderson, B. Walker, and D. Burrows.1998. "Characterization of landfill gas composition at the Fresh Kills municipal solid-waste landfill." *Environ Sci Technol* 32:2233-2237.

[12] Hartog, C.L. 2003. The Bluestem Bioreactor. Briefing presented at the Bioreactor Workshop, sponsored by USEPA, Feb 27-28, 2003, Arlington, VA.

[13] Chan G., L. Chu, and M. Wong. 2002. "Effects of leachate recirculation on biogas production from landfill co-disposal of municipal solid waste, sewage sludge and marine sediment." *Environmental Pollution* 118(3). 393–399.

[14] Warith, M. A., W. Zekry, and N. Gawri. 1999. "Effect of leachate recirculation on municipal solid waste biodegradation," *Water Quality Research Journal of Canada* Volume 34, No. 2, pp. 267–280.

[15] Hilger, H., and M. Barlaz. 2001. "Anaerobic decomposition of refuse in landfills and methane oxidation in landfill cover soils," *Manual of Environmental Microbiology*, 2nd Ed., Am. Soc. Microbiol., Washington, D. C., pp. 696–718.

[16] Colberg, P.J. 1988. "Anaerobic microbial degradation of cellulose lignin, oligolignols, and monoaromatic lignin derivatives." p. 333–372. *In* A.J.B. Zehnder (ed.) Biology of anaerobic microorganisms. New York: Wiley.

[17] Ham, R.K., and Bookter T.J. 1982. "Decomposition of solid waste in test lysimeters." *J.Env. Eng*. 108: 1147.

[18] Barlaz, M. A., R. Ham, and D. Schaefer. 1990. Op cit.

Barlaz[19] developed a series of laboratory experiments designed to measure biodegradation of these materials in a simulated landfill environment, in conditions designed to promote decomposition (i.e., by providing ample moisture and nutrients). Specific waste components (e.g., grass, branches, leaves, paper) were dried, analyzed for cellulose, hemicellulose, and lignin content, weighed, placed in two-liter plastic containers (i.e., reactors), and allowed to decompose anaerobically under moist conditions (Eleazer, et al. 1997).[20] The reactors were seeded with a small amount of well-decomposed refuse containing an active population of microorganisms. Phosphate and nitrogen concentrations were maintained at sufficient levels to assure that they were not limiting factors for biodegradation. The reactors were allowed to run until either no more CH_4 was produced or an extrapolation of gas production data indicate that the reactors had produced 95 percent of the CH_4 that would ultimately be emitted if allowed to run forever. At the end of the experiment, the contents of the reactors were dried, weighed, and analyzed for cellulose, hemicellulose, lignin, and (in the case of grass only) protein content. The carbon in these residual components is assumed to represent carbon that would remain undegraded over the long term in landfills; i.e., it would be stored.

Thus, these experiments provide three key outputs on a material-by-material basis: initial carbon content (namely, the sum of carbon in the cellulose, hemicellulose, lignin, and protein components), cumulative CH_4 emissions (over the course of the experiment), and carbon stored (as of the end of the experiment).[21]

As described in the preceding section, the principal elements in the landfill carbon balance are:

- Initial carbon content;
- Carbon output as CH_4 (CH_4-C);
- Carbon output as CO_2 (CO_2-C); and
- Residual carbon (i.e., landfill carbon storage, LF C).

Of these elements, the only one missing in the Barlaz experiments is CO_2 emissions. In a simple system where the only carbon fates are CH_4, CO_2, and carbon storage, the carbon balance can be described as

$$CH_4 - C + CO_2 - C + LF\ C = Initial\ C$$

If the only decomposition is anaerobic, then CH_4-C = CO_2-C.[22] Thus, the carbon balance can be expressed as

$$2 \times CH_4 - C + LF\ C = Initial\ C$$

Exhibit 6-2 shows the measured experimental values, in terms of the percentage of initial carbon, for each of the materials analyzed (see columns "b" and "d"). The exhibit also displays the implied biogas yield (= $2 \times CH_4$ - C, column "c"), and the sum of outputs (= $2 \times CH_4$ - C + LF C) as a percentage of initial carbon (see column "e"). As column "e" shows, the balance between carbon outputs and carbon inputs generally was not perfect; the imbalance ranges from 0 percent of initial carbon for newsprint to 34 percent of initial carbon for office paper, and is attributable to measurement uncertainty in the analytic techniques.

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[19] Barlaz, M.A., 1998. "Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills." *Global Biogeochemical Cycles* 12 (2), 373-380.

[20] Eleazer, W.E., W.S. Odle, III, Y.S. Wang, and M.A. Barlaz. 1997. "Biodegradability of municipal solid waste components in laboratory-scale landfills." *Env. Sci. Tech.* 31(3):911–917.

[21] It should be noted that VOCs are also emitted, but are estimated to account for less than one percent of carbon flux from landfills. (Freed, J.R., K. Skog, N. Glick, C. Mintz. 2004. *Carbon Storage due to Disposal of Biogenic Materials in U.S. Landfills*. Proceedings of the Third Annual Conference on Carbon Sequestration. U.S. Dept of Energy, National Energy Technology Lab.)

[22] The molar ratio of CH_4 to CO_2 is 1:1 for carbohydrates (e.g., cellulose, hemicellulose). For proteins, the molar ratio is 1.65 CH_4 per 1.55 CO_2; for protein it is $C_{3.2}H_5ON_{0.86}$ (Barlaz et al. 1989). Given the predominance of carbohydrates, for all practical purposes, the overall ratio is 1:1.

For the emission factors used in this report, adjustments were made to the measured values so that exactly 100 percent of the initial carbon would be accounted for. After consultation with Dr. Barlaz, the following approach was adopted:

- For materials where carbon outputs were *less than* initial carbon, the "missing" carbon was assumed to be emitted as equal molar quantities of CH_4 and CO_2. In these cases (corrugated cardboard, office paper, food discards, leaves, branches, and mixed MSW) the CH_4-C was increased with respect to the measured values as follows:

  $$(\text{Initial C} - \text{LF C}) / 2 = CH_4 - C$$

  This calculation assumes that CO_2-C = CH_4-C. In essence, the adjustment approach was to increase biogas production. The resulting values are italicized in column "g" of Exhibit 6-2.

- For materials where carbon outputs were *greater than* initial carbon (coated paper and grass), the measurements of initial carbon content and CH_4 mass were assumed to be accurate. Here, the adjustment approach was to decrease carbon storage. Thus, landfill carbon storage was calculated as the residual of initial carbon content minus ($2 \times CH_4$-C). The resulting values are italicized in column "h" of Exhibit 6-2.

Exhibit 6-2
Experimental and Adjusted Values for CH_4 Yield and Carbon Storage.[a]

	Initial Carbon Content, % Of dry Matter a	Measured Yield as a % Of Initial Carbon b	Implied Yield Of Biogas (CH_4+CO_2) as Proportion Of Initial Carbon c (=2×b)	Measured Proportion of Initial Carbon Stored d	Output as % of Initial Carbon e (=c+d)	Adjustment Approach f	Adjusted Yield of CH_4 as Proportion Of Initial Carbon g	Adjusted Proportion Of Initial Carbon Stored h
Paper and Paperboard								
Corrugated	46%	16%	32%	55%	88%	inc biogas	*22%*	55%
Newsprint	49%	8%	15%	85%	100%	NA	8%	85%
Office Paper	40%	27%	54%	12%	66%	inc biogas	*44%*	12%
Coated Paper	34%	12%	25%	99%	124%	reduce LF C	12%	*75%*
Food Discards	50%	30%	59%	16%	75%	inc biogas	*42%*	16%
Yard Trimmings								
Grass	44%	16%	32%	71%	103%	reduce LF C	16%	*68%*
Leaves	41%	7%	14%	72%	86%	inc biogas	*14%*	72%
Branches	49%	6%	13%	77%	90%	inc biogas	*12%*	77%
MSW	42%	11%	22%	52%	74%	inc biogas	*24%*	52%

[a] CH_4 generation estimates are from Eleazer, et al. (1997), op cit. Carbon storage and initial carbon content values are from Barlaz (1998), op cit. All values for leaves (initial carbon content, CH_4 generation, and carbon storage) are from updated experiments reported in a letter report from M.A. Barlaz to J.R. Freed (of ICF Consulting) dated June 29, 2005.

Exhibit 6-3
CH_4 Yield for Solid Waste Components

Material	Initial Carbon Content (%)	Final (Adjusted) C Emitted as CH_4 (%)	Final (Adjusted) CH_4 Yield (MTCE/dry ton)	Final (Adjusted) CH_4 Yield (MTCE/wet ton)
Corrugated Cardboard	47	22	0.80	0.688
Magazines/Third-class Mail	34	12	0.32	0.278
Newspaper	49	08	0.28	0.244
Office Paper	40	44	1.35	1.198
Food Discards	51	42	1.63	0.445
Yard Trimmings				0.264
Grass	45	16	0.55	0.150
Leaves	49	14	0.44	0.281
Branches	49	12	0.44	0.355
Mixed MSW	42	24	0.76	0.580

Exhibit 6-4
Carbon Storage for Solid Waste Components

(a) Material	(b) Ratio Of Carbon Storage to Dry Weight (gm C/dry gm)	(c) Ratio Of Dry Weight to Wet Weight (dry gm/wet gm)	(d) (d = b × c) Ratio Of Carbon Storage to Wet Weight (gm C/wet gm)	(e) Amount Of Carbon Stored (MTCE per Wet Ton)
Corrugated Cardboard	0.26	0.95	0.25	0.22
Magazines/Third-class Mail	0.26	0.95	0.25	0.22
Newspaper	0.42	0.95	0.40	0.36
Office Paper	0.05	0.95	0.05	0.04
Food Discards	0.08	0.30	0.02	0.02
Yard Trimmings				0.19
Grass	0.30	0.30	0.09	0.08
Leaves	0.30	0.70	0.21	0.19
Branches	0.38	0.90	0.34	0.31
Mixed MSW	0.22	0.84	0.18	0.17

Explanatory Notes:
(1) Because MSW is typically measured in terms of its wet weight, it was required to convert the ratios for carbon stored as a fraction of dry weight to carbon stored as a fraction of wet weight. To do this conversion, EPA used the estimated ratio of dry weight to wet weight for each material. These ratios are shown in column "c" of the exhibit. For most of the materials, EPA used data from an engineering handbook.[23] For grass, leaves, and branches, EPA used data provided by Dr. Barlaz.
(2) For consistency with the overall analysis, EPA converted the carbon storage values for each material to units of MTCE stored per short ton of waste material landfilled. The resulting values are shown in column "e" of the exhibit.

The CH_4 yields in column "g" of Exhibit 6-2 can be converted to yields expressed in MTCE/short ton (to be consistent with units in the rest of the report), as shown in Exhibit 6-3. Similarly, the carbon storage proportions listed in percentages in Exhibit 6-2 are converted to MTCE/wet ton in Exhibit 6-4.

[23] Tchobanoglous, George, Hilary Theisen, and Rolf Eliassen. 1977. *Solid Wastes: Engineering Principles and Management Issues* (New York: McGraw-Hill Book Co.), pp. 58 and 60.

Dr. Barlaz's experiment did not specifically test all of the paper grades described in this report. He did evaluate four specific grades: newspaper, corrugated boxes, office paper, and coated paper. EPA identified proxies for five additional material types for which there were no experimental data. Magazines and third-class mail placed in a landfill were assumed to have characteristics similar to those observed for coated paper. Similarly, phonebooks and textbooks were assumed to behave in the same way as newspaper and office paper, respectively. Experimental results for branches were used as a proxy for dimensional lumber and medium-density fiberboard.

As discussed in Section 3.2, EPA included the following three definitions of mixed paper among the materials analyzed in this report:

- Broadly defined mixed paper, which includes almost all printing-writing paper, folding boxes, and most paper packaging;
- Residential mixed paper, which includes the typical mix of papers from residential curbside pick-up (e.g., high-grade office paper, magazines, catalogs, commercial printing, folding cartons, and a small amount of old corrugated containers); and
- Mixed paper from offices, which includes copy and printer paper, stationary and envelopes, and commercial printing.

To develop estimates of CH_4 emissions and carbon storage for these three categories of mixed paper, EPA used the detailed characterization of mixed paper (shown in Exhibit 3-2) developed by FAL, and assigned analogues among the four paper grades tested by Dr. Barlaz. Exhibit 6-5 characterizes the composition of the two products made from mixed paper: boxboard (made using either a broad or a residential mix of recycled paper) and paper towels (made from recycled office paper). Emissions were calculated using these characterizations of the mixed paper grades and the values obtained from Dr. Barlaz's experiment for newspaper, corrugated boxes, office paper, and coated paper.[24]

6.2 FATES OF LANDFILL CH_4

In this analysis, EPA accounted for (1) the oxidation in the landfill of some portion of landfill CH_4 to CO_2, and (2) the capture of CH_4, either for flaring or for combustion with energy recovery (in either case, the captured CH_4 is converted to CO_2).[25] Exhibit 6-6 presents this analysis.

The exhibit begins with the CH_4 generation per wet ton of each material, which is shown in column "b" (the values were simply copied from the last column of Exhibit 6-3). Columns "c" through "k" calculate net GHG emissions from CH_4 generation for each of three categories of landfills: (1) landfills without LFG recovery; (2) landfills with LFG recovery that flare LFG; and (3) landfills with LFG recovery that generate electricity from the LFG. Columns "l" through "n" show CH_4 generation-weighted percentage for each category in 2004.[26] The final column shows the weighted average GHG emissions from CH_4 generation across all types of landfills.

To estimate MSW CH_4 emissions from each category of landfill, EPA first estimated the percentage of landfill CH_4 that is oxidized near the surface of the landfill. Based on estimates in the literature, EPA assumed that 10 percent of the landfill CH_4 generated is either chemically oxidized or

[24] Note that Exhibits 6-2 through 6-4 do not show mixed paper since this was not used as a category by Dr. Barlaz; however, mixed paper is shown in Exhibit 6-8 through Exhibit 6-10.

[25] The CO_2 that is emitted is not counted as a GHG because it is biogenic in origin (as described in "CO_2 Emissions from Biogenic Sources" in Section 1.4.2).

[26] U.S. Environmental Protection Agency, 2006. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004.*

converted by bacteria to CO_2,[27] and the remaining 90 percent remains as CH_4, and is either emitted or captured and burned.

Exhibit 6-5
Composition of Mixed Paper Categories from Barlaz Experiments (Percent)

Paper Grade	Broad Definition for Mixed Paper	Mixed Paper from Residential Sources	Mixed Paper from Offices
Corrugated Cardboard[a]	48	53	5
Magazines/Third-class Mail[b]	8	10	36
Newspaper[c]	24	23	21
Office Paper[d]	20	14	38
Total	100	100	100

Explanatory Notes:
[a] Includes virgin and recycled corrugated boxes.
[b] Includes coated free sheet paper and coated groundwood paper.
[c] Includes newspaper, uncoated groundwood paper, recycled folding boxes, and set-up boxes.
[d] Includes uncoated free sheet paper, cotton fiber paper, bleached bristols, unbleached kraft folding boxes, bleached kraft folding boxes, bleached bags and sacks, unbleached bags and sacks, and unbleached wrapping paper.

To estimate MSW CH_4 emissions from landfills with LFG recovery, EPA assumed that these landfills have an average LFG recovery efficiency of 75 percent.[28] EPA then calculated avoided utility GHG emissions from landfills where the CH_4 is used for electricity generation. Because energy recovery systems experience down time, during which CH_4 is flared rather than used to generate electricity, a 15 percent system efficiency loss was incorporated into the estimates for avoided utility emissions.[29]

EPA also estimated the percentage of CH_4 generated at each category of landfill in 2003. Research indicates that 59 percent of all landfill CH_4 was generated at landfills with recovery systems, and the remaining 41 percent was generated at landfills without LFG recovery.[30] Of the 59 percent of all CH_4 generated at landfills with LFG recovery, 53 percent (or 31 percent of all CH_4) was generated at landfills that use LFG to generate electricity, and 47 percent (or 28 percent of all CH_4) at landfills that flare LFG.[31, 32]

The results are shown in the final column of Exhibit 6-6. The materials with the highest rates of net GHG emissions from CH_4 generation, as shown in column "o"—corrugated boxes, office paper, and

[27] An oxidation rate of 10 percent is cited by Liptay, K., J. Chanton, P. Czepiel, and B. Mosher, "Use of stable isotopes to determine methane oxidation in landfill cover soils," *Journal of Geophysical Research*, April 1998, 103(D7), pp. 8243-8250; and Czepiel, P.M., B. Mosher, P.M. Crill, and R.C. Harriss. 1996. "Quantifying the effects of oxidation on landfill methane emissions," *Journal of Geophysical Research*, 101, pp. 16721-16729. The rate of 10 percent is also recommended by the IPCC.
[28] EPA. 2005. The Landfill Methane Outreach Program (LMOP) has used this figure in its most recent publications [see, for example, *U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions* (Washington, D.C.: U.S. Environmental Protection Agency) September 1999].
[29] EPA. 1999. *Landfill Gas-to-Energy Project Opportunities: Background Information on Landfill Profiles*, Office of Air and Radiation, EPA 430-K-99-002, pp. 3-13.
[30] Based on data on year 2004 MSW landfill CH_4 generation and collection data from *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004*) with an estimated landfill CH_4 recovery efficiency of 75 percent (from *U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions*).
[31] *U.S. Greenhouse Gas Emissions and Sinks: 1990-2003.*
[32] The assumption that 59 percent of landfills recovering CH_4 will use it for energy is subject to change over time based upon changes in the cost of recovery and the potential payback. Additionally, new technologies may be developed that use recovered CH_4 for purposes other than generating electricity and direct gas use.

textbooks—also have the highest gross CH_4 generation, as shown in column "b." The recovery of CH_4 at landfills reduces the CH_4 emissions for each material in proportionate amounts but does not change the ranking of materials by CH_4 emissions. Grass, leaves, branches, and the two wood products have the lowest rates of net GHG emissions from CH_4 generation.

6.3 UTILITY CO_2 EMISSIONS AVOIDED

Exhibit 6-7 presents a list of conversion factors and physical constants used to convert CH_4 combusted for electricity production to avoided CO_2 emissions. Using data on Btu per cubic feet of CH_4, kWh of electricity generated and delivered per Btu, and kilograms of utility carbon avoided per Btu delivered, EPA estimated that 0.15 MTCE is avoided per MTCE of CH_4 combusted. This figure then was incorporated into Exhibit 6-8 to estimate net GHG emissions from landfills with electricity generation. As mentioned earlier in this chapter, the analysis assumes that 31 percent of CH_4 generated in the United States comes from landfills that combust landfill CH_4 for electricity generation. EPA also assumes a 15 percent system efficiency loss, reflecting the fact that landfill gas-to-energy facilities incur some system "down-time," as shown in column 1. Landfill CH_4 is assumed to be flared during down-time periods.

6.4 NET GHG EMISSIONS FROM LANDFILLING

To determine the net GHG emissions from landfilling each material, the net GHG emissions from CH_4 generation, carbon storage (treated as negative emissions), and transportation CO_2 emissions were summed. The results are shown in Exhibit 6-8. The four columns under section "e" of the exhibit may be used by local MSW planners to estimate GHG emissions from MSW in a given community.

As the exhibit shows, the postconsumer results for organic materials vary widely. For some materials—in particular newspaper and phonebooks—landfilling results in substantial negative net GHG emissions. For others—including office paper, textbooks, and food discards—net emissions are significant. For the rest, net emissions and reductions are relatively small.

Exhibit 6-6
GHG Emissions from CH_4 Generation

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(l)	(m)	(n)	(o)	(p)	(q)
		CH_4 from Landfills Without CH_4 Recovery		**CH_4 from Landfills With LFG Recovery and:**						**Percentage of CH_4 from Each Type of Landfill in 2003**			**Net CH_4 Generation**	**Avoided CO_2 from Energy Recovery**	**TOTAL**
				Flaring		**Electricity Generation**									
Material	CH_4 Generation (MTCE/Wet Ton)	CH_4 Not Oxidized to CO_2	Net GHG Emissions From CH_4 Generation (MTCE/Wet Ton)	CH_4 Not Recovered (100% Minus LFG Collection System Efficiency)	CH_4 Not Recovered That Is Not Oxidized to CO_2	Net GHG Emissions From CH_4 Generation (MTCE/Wet Ton)	Utility CO_2 Emissions Avoided per MTCE CH_4 Combusted (MTCE)	CH_4 Recovered for Electricity Generation Not Utilized Due to System "Down Time"	Utility CO_2 Emissions Avoided (MTCE/Wet Ton)	CH_4 From Landfills Without LFG Recovery in 2000	CH_4 From Landfills With LFG Recovery And Flaring in 2000	CH_4 From Landfills With LFG Recovery and Electricity Generation in 2000	Net CH_4 Emissions from Landfilling (MTCE/Wet Ton)	Net Avoided CO_2 Emissions from Landfilling (MTCE/Wet Ton)	Net GHG Emissions From Landfilling (MTCE/Wet Ton)
Corrugated Cardboard	0.688	90%	0.619	25%	90%	0.155	-0.153	0.150	-0.067	41%	28%	31%	0.344	-0.021	0.323
Magazines/Third-class Mail	0.278	90%	0.250	25%	90%	0.062	-0.153	0.150	-0.027	41%	28%	31%	0.139	-0.008	0.130
Newspaper	0.244	90%	0.220	25%	90%	0.055	-0.153	0.150	-0.024	41%	28%	31%	0.122	-0.007	0.115
Office Paper	1.198	90%	1.078	25%	90%	0.270	-0.153	0.150	-0.117	41%	28%	31%	0.599	-0.037	0.562
Phonebooks	0.244	90%	0.220	25%	90%	0.055	-0.153	0.150	-0.024	41%	28%	31%	0.122	-0.007	0.115
Textbooks	1.198	90%	1.078	25%	90%	0.270	-0.153	0.150	-0.117	41%	28%	31%	0.599	-0.037	0.562
Dimensional Lumber	0.355	90%	0.320	25%	90%	0.080	-0.153	0.150	-0.035	41%	28%	31%	0.178	-0.011	0.167
Medium-density Fiberboard	0.355	90%	0.320	25%	90%	0.080	-0.153	0.150	-0.035	41%	28%	31%	0.178	-0.011	0.167
Food Discards	0.445	90%	0.400	25%	90%	0.100	-0.153	0.150	-0.043	41%	28%	31%	0.222	-0.014	0.209
Yard Trimmings	0.264	90%	0.238	25%	90%	0.059	-0.153	0.150	-0.026	41%	28%	31%	0.132	-0.008	0.124
Grass	0.150	90%	0.135	25%	90%	0.034	-0.153	0.150	-0.015	41%	28%	31%	0.075	-0.005	0.070
Leaves	0.281	90%	0.253	25%	90%	0.063	-0.153	0.150	-0.027	41%	28%	31%	0.141	-0.009	0.132
Branches	0.355	90%	0.320	25%	90%	0.080	-0.153	0.150	-0.035	41%	28%	31%	0.178	-0.011	0.167
Mixed Paper[a]															
Broad Definition	0.651	90%	0.59	25%	90%	0.146	-0.153	0.150	-0.063	41%	28%	31%	0.325	-0.020	0.305
Residential Definition	0.616	90%	0.55	25%	90%	0.139	-0.153	0.150	-0.060	41%	28%	31%	0.308	-0.019	0.289
Office Paper Definition	0.641	90%	0.58	25%	90%	0.144	-0.153	0.150	-0.062	41%	28%	31%	0.321	-0.020	0.301
Mixed MSW	0.580	90%	0.522	25%	90%	0.131	-0.153	0.150	-0.056	41%	28%	31%	0.290	-0.018	0.272

[a] The summary values for mixed paper are based on the proportions of the four paper types (corrugated cardboard, magazines/third-class mail, newspaper, and office paper) that constitute the different "mixed paper" definitions.

6.5 LIMITATIONS

Perhaps the most important caveat to the analysis of GHG emissions and storage associated with landfilling is that the results are based on a single set of laboratory experiments, those conducted by Dr. Morton Barlaz. Although researchers other than Dr. Barlaz have conducted laboratory studies that track the degradation of mixed MSW, his experiments were the only ones EPA identified that rigorously tested materials on an individual basis. Dr. Barlaz is recognized as an expert on the degradation of different fractions of MSW under anaerobic conditions, and his findings with respect to the CH_4 potential of mixed MSW are within the range used by landfill gas developers. Nevertheless, given the sensitivity of the landfill results to estimated CH_4 generation and carbon storage, EPA recognizes that more research is needed in this area.

Another important caveat relates to the estimate that 59 percent of MSW landfill CH_4 is generated at landfills with LFG recovery systems. The net GHG emissions from landfilling each material are quite sensitive to the LFG recovery rate. Because of the high GWP of CH_4, small changes in the LFG recovery rate (for the national average landfill) could have a large effect on the net GHG impacts of landfilling each material and the ranking of landfilling relative to other MSW management options. The effects of different rates of LFG recovery are shown in Exhibit 6-9. Column "b" of the exhibit shows net GHG emissions if 20 percent of waste were disposed of at landfills with recovery. The remaining columns show net GHG emissions at increasing LFG recovery rates, up to a 60 percent rate. As the exhibit shows, the net postconsumer GHG emissions for landfilling mixed MSW decline significantly as recovery increases. At the local level, the GHG emissions from landfilling MSW depend on whether the local landfill has LFG recovery, as shown in Exhibit 6-8.

Because the national average estimate of emissions is based on estimated year 2003 LFG recovery levels, several limitations are associated with the use of this emission factor. First, because landfill CH_4 generation occurs over time and has significant timing delays (i.e., CH_4 generation may not begin until a few years after the waste is deposited in the landfill and can continue for many years after the landfill is closed), the values listed in this chapter represent total CH_4 generated, over time, per ton of waste landfilled. To the extent that LFG recovery rates shift dramatically over time, these shifts are not reflected in the analysis. Second, landfills with LFG recovery may be permitted, under EPA regulations, to remove the LFG recovery equipment when three conditions are met: (1) the landfill is permanently closed, (2) LFG has been collected continuously for at least 15 years, and (3) the landfill emits less than 50 metric tons of non-CH_4 organic compounds per year.[33] Although the removal of LFG recovery equipment will permit CH_4 from closed landfills to escape into the atmosphere, the amounts of CH_4 emitted should be relatively small, because of the length of time required for LFG collection before LFG recovery equipment is removed. Third, several methodological issues are associated with applying the CH_4 generation estimates from the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (U.S. Inventory) to develop the national average emission factors: [34]

(1) The generation estimates in the U.S. Inventory include closed landfills (generation is modeled as a function of waste in place), whereas the estimates used in this report apply to ongoing generation (which is routed to open landfills);

(2) Likewise, both the flaring and landfill gas-to-energy estimates also include closed landfills; and

(3) The distribution of waste in place is not a perfect proxy for the destination of ongoing waste generation.

[33] *Federal Register*, 1996, Vol. 61, No. 49, p. 9907.
[34] U.S. Department of State, 2002. *U.S. Climate Action Report—2002*. Washington DC, May.

CH_4 oxidation rate and landfill gas collection system efficiency are also important factors driving results. EPA used values of 10 percent and 75 percent, respectively, as best estimates for these factors. Reviewers of previous editions of this report and sources in the literature have reported estimates ranging from about 5 percent to 40 percent for oxidation, and from about 60 to 95 percent for collection system efficiency. EPA investigated the sensitivity of the results to these assumptions, and the results are shown in Exhibit 6-10. To portray the sensitivity as a bounding analysis, EPA used the combinations of variables yielding the upper bound emission factor (5 percent oxidation, 60 percent collection efficiency) and the lower bound (40 percent oxidation, 95 percent efficiency).[35] As the exhibit shows, the materials most sensitive to these variables are those with the highest CH_4 generation potential, i.e., corrugated cardboard, office paper, textbooks, food discards, and mixed paper. Sensitivity varies: the difference between upper and lower bounds ranges from 0.05 MTCE/ton for grass to 0.42 MTCE/ton for office paper and textbooks. The postconsumer emission factors of several materials and mixed material combinations—corrugated cardboard, grass, mixed paper, and mixed MSW—change from having net storage under the lower bound to having net emissions under the upper bound.

Ongoing shifts in the use of landfill cover and liner systems are likely to influence the rate of CH_4 generation and collection. As more landfills install effective covers and implement controls to keep water and other liquids out, conditions will be less favorable for degradation of organic wastes. Over the long term, these improvements may result in a decrease in CH_4 generation and an increase in carbon storage. Moreover, Dr. Barlaz believes that the CH_4 yields from his laboratory experiments are likely to be higher than CH_4 yields in a landfill, because the laboratory experiments were designed to generate the maximum amount of CH_4 possible. If the CH_4 yields from the laboratory experiments were higher than yields in a landfill, the net GHG emissions from landfilling organic materials would be lower than estimated here.

EPA assumed that once wastes are disposed in a landfill, they are never removed. In other words, it was assumed that landfills are never "mined." A number of communities have mined their landfills—removing and combusting the waste—in order to create more space for continued disposal of waste in the landfill. To the extent that landfills are mined in the future, it is incorrect to assume that carbon stored in a landfill will remain stored. For example, if landfilled wastes are later combusted, the carbon that was stored in the landfill will be oxidized to CO_2 in the combustor.

The estimate of avoided utility GHG emissions per unit of CH_4 combusted assumes that all landfill gas-to-energy projects are electricity producing. In reality, some projects are "direct gas" projects, in which CH_4 is piped directly to the end user for use as fuel. In these cases, the CH_4 typically replaces natural gas as a fuel source. Because natural gas use is less GHG-intensive than average electricity production, direct gas projects will tend to offset fewer GHG emissions than electricity projects will—a fact not reflected in the analysis.

For landfilling of yard trimmings (and other organic materials), EPA assumed that all carbon storage in a landfill environment is incremental to the storage that occurs in a nonlandfill environment. In other words, it was assumed that in a baseline where yard trimmings are returned to the soil (i.e., in a nonlandfill environment), all of the carbon is decomposed relatively rapidly (i.e., within several years) to CO_2, and there is no long-term carbon storage. To the extent that long-term carbon storage occurs in the baseline, the estimates of carbon storage reported here are overstated, and the net postconsumer GHG emissions are understated.

[35] Exhibit 6-10 also reports two intermediate combinations, including the best estimate values.

Finally, the analysis is limited by the assumptions that were made at various steps in the analysis, as described throughout this chapter. The key assumptions that have not already been discussed as limitations are the assumptions used in developing "corrected" CH_4 yields for organic materials in MSW. Because of the high GWP of CH_4, a small difference between estimated and actual CH_4 generation values would have a large effect on the GHG impacts of landfilling and the ranking of landfilling relative to other MSW management options.

Exhibit 6-7
Calculation to Estimate Utility GHGs Avoided through Combustion of Landfill CH_4

Step	Value	Source
Metric tons CH_4/MTCE CH_4	0.17	1/((12/44) × Global warming potential of CH_4)
Grams CH_4/metric ton CH_4	1.00E+06	Physical constant
Cubic ft. CH_4/gram CH_4	0.05	1/20: 20 grams per cubic foot of CH_4 at standard temperature and pressure
Btu/cubic ft. CH_4	1,012	EPA 2005. LMOP Benefits Calculator.
kWh electricity generated/Btu	0.00009	1/11,700: EPA 2005. LMOP Benefits Calculator.
Electricity generation efficiency	0.85	EPA 2005. LMOP Net capacity factor for generation units (availability, operating load, parasitic losses).
Kg utility C avoided/kWh generated electricity	2.405E-01	0.24 kg CE/kWh generated electricity, from Exhibit 5-4. This assumes that LFG energy recovery displaces fossil fuel generation.
Metric tons avoided utility C/kg utility C	0.001	1000 kg per metric ton
Ratio of MTCE avoided utility C per MTCE CH_4	0.15	Product from multiplying all factors

Exhibit 6-8
Net GHG Emissions from Landfilling[a]

(a)	(b) Net GHG Emissions from CH_4 Generation (MTCE/Wet Ton)				(c)	(d)	(e) (= b + c + d) Net GHG Emissions from Landfilling (MTCE/Wet Ton)			
Material	Landfills Without LFG Recovery	Landfills With LFG Recovery And Flaring	Landfills With LFG Recovery And Electric Generation	Year 2003 National Average	Net Carbon Storage (MTCE/Wet Ton)	GHG Emissions From Transportation (MTCE/Wet Ton)	Landfills Without LFG Recovery	Landfills With LFG Recovery And Flaring	Landfills With LFG Recovery And Electric Generation	Year 2003 National Average
Aluminum Cans	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Steel Cans	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Copper Wire	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Glass	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
HDPE	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
LDPE	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
PET	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Corrugated Cardboard	0.62	0.15	0.09	0.32	-0.22	0.01	0.41	-0.06	-0.13	0.11
Magazines/Third-class Mail	0.25	0.06	0.04	0.13	-0.22	0.01	0.04	-0.15	-0.18	-0.08
Newspaper	0.22	0.05	0.03	0.11	-0.36	0.01	-0.13	-0.30	-0.32	-0.24
Office Paper	1.08	0.27	0.15	0.56	-0.04	0.01	1.05	0.24	0.12	0.53
Phonebooks	0.22	0.05	0.03	0.11	-0.36	0.01	-0.13	-0.30	-0.32	-0.24
Textbooks	1.08	0.27	0.15	0.56	-0.04	0.01	1.05	0.24	0.12	0.53
Dimensional Lumber	0.32	0.08	0.05	0.17	-0.31	0.01	0.02	-0.22	-0.25	-0.13
Medium-density Fiberboard	0.32	0.08	0.05	0.17	-0.31	0.01	0.02	-0.22	-0.25	-0.13
Food Discards	0.40	0.10	0.06	0.21	-0.02	0.01	0.39	0.09	0.05	0.20
Yard Trimmings	0.24	0.06	0.03	0.12	-0.19	0.01	0.05	-0.12	-0.15	-0.06
Grass	0.14	0.03	0.02	0.07	-0.08	0.01	0.06	-0.04	-0.05	0.00
Leaves	0.25	0.06	0.04	0.13	-0.19	0.01	0.07	-0.12	-0.14	-0.05
Branches	0.32	0.08	0.05	0.17	-0.31	0.01	0.02	-0.22	-0.25	-0.13
Mixed Paper[b]										
Broad Definition	0.59	0.15	0.08	0.31	-0.22	0.01	0.38	-0.06	-0.13	0.09
Residential Definition	0.55	0.14	0.08	0.29	-0.23	0.01	0.33	-0.08	-0.14	0.07
Office Paper Definition	0.58	0.14	0.08	0.30	-0.18	0.01	0.40	-0.03	-0.09	0.13
Mixed MSW	0.52	0.13	0.07	0.27	-0.17	0.01	0.37	-0.03	-0.08	0.12
Carpet	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Personal Computers	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Clay Bricks	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Concrete	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Fly Ash	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Tires	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01

Explanatory Notes:

[a] Please see Exhibit 6-6 for details on calculations.

[b] The summary values for mixed paper are based on the proportions of the four paper types (corrugated cardboard, magazines/third-class mail, newspaper, and office paper) that constitute the different "mixed paper" definitions.

Exhibit 6-9
Net GHG Emissions from CH_4 Generation at Landfills with Recovery (MTCE/Wet Ton)

Sensitivity Analysis: Varying the Percentage of Waste Disposed at Landfills with CH_4 Recovery					
(a)	**(b)**	**(c)**	**(d)**	**(e)**	**(f)**
Material	**17%**	**20%**	**49%**	**55%**	**60%**
Corrugated Cardboard	0.32	0.30	0.15	0.12	0.09
Magazines/Third-class Mail	0.00	0.00	-0.07	-0.08	-0.09
Newspaper	-0.16	-0.17	-0.22	-0.23	-0.24
Office Paper	0.89	0.86	0.60	0.54	0.50
Phonebooks	-0.16	-0.17	-0.22	-0.23	-0.24
Textbooks	0.89	0.86	0.60	0.54	0.50
Dimensional Lumber	-0.03	-0.03	-0.11	-0.13	-0.14
Medium-density Fiberboard	-0.03	-0.03	-0.11	-0.13	-0.14
Food Discards	0.33	0.32	0.22	0.20	0.19
Yard Trimmings	0.02	0.01	-0.04	-0.06	-0.07
Grass	0.04	0.04	0.01	0.00	-0.01
Leaves	0.04	0.03	-0.03	-0.05	-0.06
Branches	-0.03	-0.03	-0.11	-0.13	-0.14
Mixed Paper[a]					
Broad Definition	0.29	0.28	0.13	0.10	0.08
Residential Definition	0.25	0.24	0.10	0.08	0.05
Office Paper Definition	0.32	0.31	0.16	0.13	0.11
Mixed MSW	0.29	0.28	0.15	0.12	0.10

[a] The summary values for mixed paper are based on the proportions of the four paper types (corrugated cardboard, magazines/third-class mail, newspaper, and office paper) that constitute the different "mixed paper" definitions.

Exhibit 6-10
Net GHG Emissions from CH_4 Generation at Landfills with Recovery (MTCE/Wet Ton)

Sensitivity Analysis: Varying Oxidation and Gas Collection Efficiency Rates.				
Oxidation Rate:	**40%**	**25%**	**10%**	**5%**
Collection Efficiency:	**95%**	**85%**	**75%**	**60%**
Material	**Lower-bound Emissions**	**Conservative (High) Emissions**	**Best Estimate**	**Upper-bound Emissions**
Corrugated Cardboard	0.18	0.26	0.34	0.42
Magazines/Third-class Mail	0.07	0.10	0.14	0.17
Newspaper	0.06	0.09	0.12	0.15
Office Paper	0.31	0.45	0.60	0.73
Phonebooks	0.06	0.09	0.12	0.15
Textbooks	0.31	0.45	0.60	0.73
Dimensional Lumber	0.09	0.13	0.18	0.22
Medium-density Fiberboard	0.09	0.13	0.18	0.22
Food Discards	0.12	0.17	0.22	0.27
Yard Trimmings	0.07	0.10	0.13	0.16
Grass	0.04	0.06	0.08	0.09
Leaves	0.07	0.10	0.14	0.17
Branches	0.09	0.13	0.18	0.22
Mixed Paper [a]				
Broad Definition	0.17	0.24	0.33	0.40
Residential Definition	0.16	0.23	0.31	0.38
Office Paper Definition	0.17	0.24	0.32	0.39
Mixed MSW	0.15	0.22	0.29	0.36

[a] The summary values for mixed paper are based on the proportions of the four paper types (corrugated cardboard, magazines/third-class mail, newspaper, and office paper) that constitute the different "mixed paper" definitions.