

## LANDFILLING

This chapter presents an overview of landfilling as a waste management strategy in relation to the development of material-specific emission factors for EPA's Waste Reduction Model (WARM). Estimates of the net greenhouse gas (GHG) emissions from landfilling most of the materials considered in WARM and several categories of mixed waste streams (e.g., mixed paper, mixed recyclables and mixed municipal solid waste (MSW)) are included in the chapter.

### 1. A SUMMARY OF THE GHG IMPLICATIONS OF LANDFILLING

When food waste, yard trimmings, paper and wood are landfilled, anaerobic bacteria degrade the materials, producing methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>). CH<sub>4</sub> is counted as an anthropogenic GHG because, even if it is derived from sustainably harvested biogenic sources, degradation would not result in CH<sub>4</sub> emissions if not for deposition in landfills. The CO<sub>2</sub> is not counted as a GHG because it is considered part of the natural carbon cycle of growth and decomposition; for more information, see the text box on biogenic carbon in the [Introduction & Background](#) chapter. The other materials in WARM either do not contain carbon or do not biodegrade measurably in anaerobic conditions, and therefore do not generate any CH<sub>4</sub>.

In addition to carbon emissions, some of the carbon in these materials (i.e., food waste, yard trimmings, paper and wood) is stored in the landfill because these materials are not completely decomposed by anaerobic bacteria. Because this carbon storage would not normally occur under natural conditions (virtually all of the biodegradable material would degrade to CO<sub>2</sub>, completing the photosynthesis/respiration cycle), this is counted as an anthropogenic sink. However, carbon in plastics and rubber that remains in the landfill is not counted as stored carbon because it is of fossil origin. Fossil carbon (e.g., petroleum, coal) is already considered "stored" in its natural state; converting it to plastic or rubber and putting it in a landfill only moves the carbon from one storage site to another.

EPA developed separate estimates of emissions from (1) landfills without gas recovery systems, (2) those that flare CH<sub>4</sub>, (3) those that combust CH<sub>4</sub> 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<sub>4</sub> will not be managed at some landfills, flared at some landfills, and combusted onsite for energy recovery at others.<sup>1</sup> The assumed mix of the three landfill categories that make up the national average for all material types are presented in Exhibit 1. These estimates are based on the amount of CH<sub>4</sub> recovered by U.S. landfills, as cited in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2012* (EPA 2014b). WARM assumes that construction and demolition landfills do not flare or collect CH<sub>4</sub>.

**Exhibit 1: Percentage of CH<sub>4</sub> Generated from Each Type of Landfill**

Material/Product	Percentage of CH <sub>4</sub> from Landfills without LFG Recovery	Percentage of CH <sub>4</sub> from Landfills with LFG Recovery and Flaring	CH <sub>4</sub> from Landfills with LFG Recovery and Electricity Generation (%)
Construction and Demolition Materials	100%	–	–
All Other Materials	18%	38%	44%

– = Zero Emissions.

<sup>1</sup> Although gas from some landfills is piped to an offsite power plant and combusted there, for the purposes of WARM, the simplifying assumption was that all gas for energy recovery was combusted onsite. This assumption was made due to the lack of information about the frequency of offsite power generation, piping distances and losses from pipelines.

## 2. CALCULATING THE GHG IMPACTS OF LANDFILLING

The landfilling emission factors are made up of the following components:

1. CH<sub>4</sub> emissions from anaerobic decomposition of biogenic carbon compounds;
2. Transportation CO<sub>2</sub> emissions from landfilling equipment;
3. Biogenic carbon stored in the landfill; and
4. CO<sub>2</sub> emissions avoided through landfill gas-to-energy projects.

As mentioned above, WARM does not calculate CH<sub>4</sub> emissions, stored carbon or CO<sub>2</sub> avoided for materials containing only fossil carbon (e.g., plastics, rubber). These materials have net landfilling emissions that are very low because they include only the transportation-related emissions from landfilling equipment. Some materials (e.g., newspaper and dimensional lumber) result in net storage (i.e., carbon storage exceeds CH<sub>4</sub> plus transportation energy emissions) at all landfills, regardless of whether gas recovery is present, while others (e.g., food waste) result in net emissions regardless of landfill gas collection and recovery practices. Whether the remaining materials result in net storage or net emissions depends on the landfill gas recovery scenario.

### 2.1 CARBON STOCKS AND FLOWS IN LANDFILLS

Exhibit 2 shows the carbon flows within a landfill system. Carbon entering the landfill can have one of several fates: exit as CH<sub>4</sub>, exit as CO<sub>2</sub>, exit as volatile organic compounds (VOCs), exit dissolved in leachate, or remain stored in the landfill.<sup>2</sup>

After entering landfills, a portion of the biodegradable material 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 biodegradable material into CH<sub>4</sub> and CO<sub>2</sub>.

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 that the amount of moisture in the waste, which can vary widely within a single landfill, is a critical factor in the rate of decomposition (Barlaz et al., 1990).

Among the research conducted on the various components of the landfill carbon system, by far the most to date has focused on the transformation of landfill carbon into CH<sub>4</sub>. 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<sub>4</sub> emissions in GHG inventories, and the market for CH<sub>4</sub> as an energy source. CH<sub>4</sub> production occurs in the methanogenic stage of decomposition, as methanogenic bacteria break down the fermentation products from earlier decomposition processes. Since CH<sub>4</sub> 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). The CH<sub>4</sub> portion of each material type's emission factor is discussed further in section 2.2.

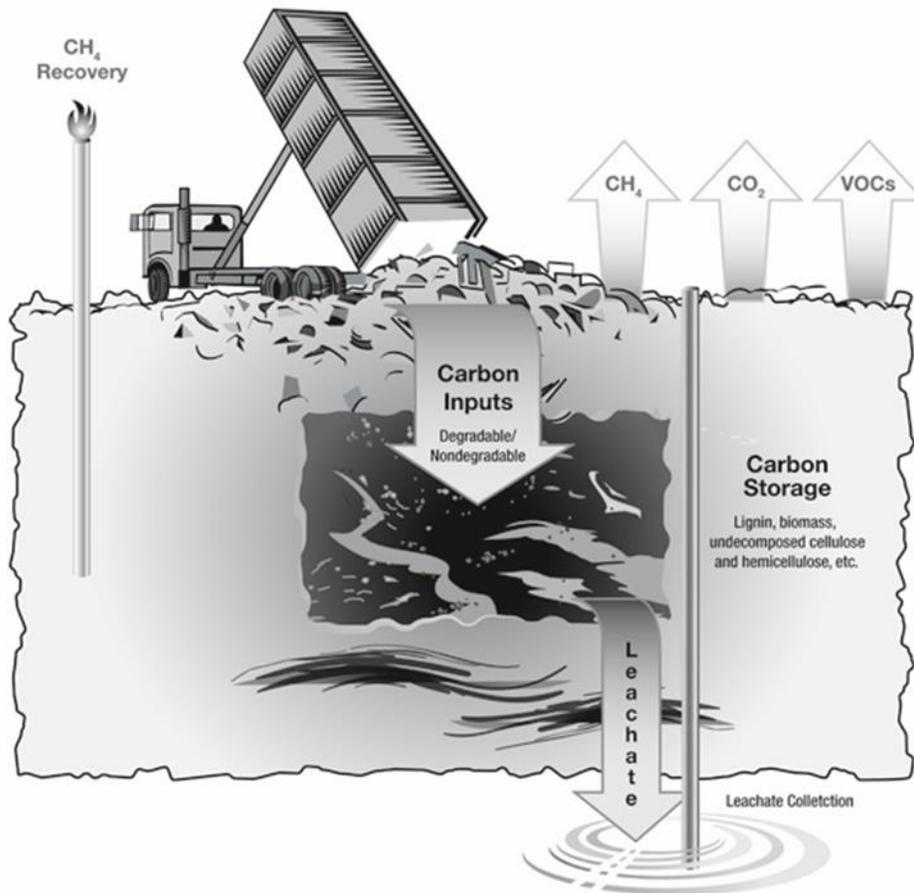
Carbon dioxide is produced in the initial aerobic stage and in the anaerobic acid stage of decomposition. However, relatively little research has been conducted to quantify CO<sub>2</sub> emissions during these stages. Emissions during the aerobic stage are generally assumed to be a small proportion of total

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<sup>2</sup> The exhibit and much of the ensuing discussion are taken directly from Freed et al. (2004).

organic carbon inputs, and a screening-level analysis indicates that less than 1 percent of carbon is likely to be emitted through this pathway (Freed et al., 2004). Once the methanogenic stage of decomposition begins, landfill gas *as generated* is composed of approximately 50 percent CH<sub>4</sub> and 50 percent CO<sub>2</sub> (Bingemer and Crutzen, 1987). However, landfill gas *as collected* generally has a higher CH<sub>4</sub> concentration than CO<sub>2</sub> concentration (sometimes as much as a 60 percent: 40 percent ratio), because some of the CO<sub>2</sub> is dissolved in the leachate as part of the carbonate system (CO<sub>2</sub> ↔ H<sub>2</sub>CO<sub>3</sub> ↔ HCO<sub>3</sub><sup>-</sup> ↔ CO<sub>3</sub><sup>2-</sup>).

#### Exhibit 2: Landfill Carbon Mass Balance



Source: Freed et al. (2004).

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 among the most abundant landfill VOCs (Eklund et al., 1998). Hartog (2003) reported non-CH<sub>4</sub> 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. 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<sub>4</sub> and CO<sub>2</sub> 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<sub>2</sub>. However, leachate is increasingly being recycled into the landfill as a means of inexpensive disposal and to promote decomposition, increasing the mass of biodegradable materials collected by the system and consequently enhancing aqueous degradation (Chan et al., 2002; Warith et al., 1999). 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 1 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 (Hilger and Barlaz, 2001). Although the degradation of cellulose and hemicellulose in landfills is well documented, lignin does not degrade to a significant extent under anaerobic conditions (Colberg, 1988). Landfills in effect store some of carbon from the cellulose and hemicellulose and all of the carbon from 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 (Barlaz et al, 1990). These variables and their effects on each material type's emission factor are discussed further below.

## **2.2 ESTIMATING EMISSIONS FROM LANDFILLS**

As discussed in section 2.1, when biodegradable materials such as wood products, food wastes and yard trimmings are placed into a landfill, a fraction of the carbon within these materials degrades into CH<sub>4</sub> emissions. The quantity and timing of CH<sub>4</sub> emissions released from the landfill depends upon three factors: (1) how much of the original material decays into CH<sub>4</sub>, (2) how readily the material decays under different landfill moisture conditions, and (3) landfill gas collection practices. This section describes how these three factors are addressed in WARM.

### **2.2.1 Methane Generation and Landfill Carbon Storage**

The first step is to determine the amount of carbon contained in degradable materials that is emitted from the landfill as CH<sub>4</sub>, and the amount that remains in long-term storage within the landfill. Although a large body of research exists on CH<sub>4</sub> generation from mixed solid wastes, only a few investigators—most notably Dr. Morton Barlaz and colleagues at North Carolina State University—have measured the behavior of specific waste wood, paper, food waste and yard trimming components. The results of their experiments yield data on the inputs—specifically the initial carbon contents, CH<sub>4</sub> generation and carbon stored—that are required for calculating material-specific emission factors for WARM.

Barlaz (1998) 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). Each waste component (e.g., grass, branches, leaves, paper) was 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). 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 food waste only) protein content. The carbon in these residual components is assumed to represent carbon that would remain undegraded over the long term in landfills: that is, it would be stored.

Based on these components, Dr. Barlaz estimated the initial biogenic carbon content of each waste material as a percent of dry matter. For some materials, the carbon content estimates have been

updated to reflect more recent studies or to better reflect changes in material composition in recent years. Exhibit 3 shows the initial carbon contents of the wastes analyzed by Barlaz (1998) and Wang et al. (2011).

**Exhibit 3: Initial Biogenic Carbon Content of Materials Tested in Barlaz (1998) and Wang et al. (2011)**

Material	Initial Biogenic Carbon Content, % of Dry Matter	Source
Corrugated Containers	47%	Barlaz (1998)
Newspaper	49%	Barlaz (1998)
Office Paper	32%	Barlaz (1998) <sup>a</sup>
Coated Paper	34%	Barlaz (1998)
Food Waste	51%	Barlaz (1998)
Grass	45%	Barlaz (1998)
Leaves	46%	Barlaz (1998)
Branches	49%	Barlaz (1998)
Mixed MSW	42%	Barlaz (1998)
Gypsum Board	5%	Barlaz (1998)
Dimensional Lumber	49%	Wang et al. (2011)
Medium-density Fiberboard	44%	Wang et al. (2011)
Wood Flooring <sup>b</sup>	46%	Wang et al. (2011)

<sup>a</sup> Based on 2014 discussions with Dr. Morton Barlaz, the carbon content of office paper has been updated to account for an average calcium carbonate (CaCO<sub>3</sub>) content of 20 percent in office paper in recent years.

<sup>b</sup> Based on an average of carbon content values for red oak and plywood in Wang et al. (2011).

The principal stocks and flows in the landfill carbon balance are:

- Initial carbon content (Initial C);
- Carbon output as CH<sub>4</sub> (CH<sub>4</sub><sup>C</sup>);
- Carbon output as CO<sub>2</sub> (CO<sub>2</sub><sup>C</sup>); and
- Residual carbon (i.e., landfill carbon storage, LF<sup>C</sup>).

The initial carbon content, along with the other results from the Barlaz (1998), Wang et al. (2013), Wang et al. (2011), and Levis et al. (2013) experiments are used to estimate each material type's emission factor in WARM. The Barlaz (1998), Wang et al. (2013), Wang et al. (2011), and Levis et al. (2013) experiments did not capture CO<sub>2</sub> emissions in the carbon balance; however, in a simple system where the only carbon fates are CH<sub>4</sub>, CO<sub>2</sub> and carbon storage, the carbon balance can be described as

$$\text{CH}_4^{\text{C}} + \text{CO}_2^{\text{C}} + \text{LF}^{\text{C}} = \text{Initial C}$$

If the only decomposition is anaerobic, then CH<sub>4</sub><sup>C</sup> = CO<sub>2</sub><sup>C</sup>.<sup>3</sup> Thus, the carbon balance can be expressed as

$$= \text{Initial C} \times 2 \times \text{CH}_4^{\text{C}} + \text{LF}^{\text{C}} = \text{Initial C}$$

Exhibit 4 shows the measured experimental values, in terms of the percentage of initial carbon for each of the materials analyzed, the implied landfill gas yield, and the sum of outputs as a percentage of initial carbon (Barlaz, 1998; Wang et al., 2013; Wang et al., 2011; Levis et al., 2013). As the sum of the

<sup>3</sup> The emissions ratio of CH<sub>4</sub> to CO<sub>2</sub> is 1:1 for carbohydrates (e.g., cellulose, hemicellulose). For proteins, the ratio is 1.65 CH<sub>4</sub> per 1.55 CO<sub>2</sub>; for protein, it is C<sub>3.2</sub>H<sub>5</sub>ON<sub>0.86</sub> (Barlaz et al., 1989). Given the predominance of carbohydrates, for all practical purposes, the overall ratio is 1:1.

outputs shows, the balance between carbon outputs and carbon inputs generally was not perfect. This imbalance is attributable to measurement uncertainty in the analytic techniques.

**Exhibit 4: Experimental Values for CH<sub>4</sub> Yield and Carbon Storage<sup>a</sup>**

(a) Material	(b) Measured CH <sub>4</sub> Yield as a % of Initial Carbon	(c) Implied Yield of Landfill Gas (CH <sub>4</sub> +CO <sub>2</sub> ) as a Proportion of Initial Carbon (c = 2 × b)	(d) Measured Proportion of Initial Carbon Stored	(e) Output as % of Initial Carbon (e = c + d)
Corrugated Containers	17%	35%	55%	90%
Newspaper	8%	16%	85%	100%
Office Paper	29%	58%	12%	70%
Coated Paper	13%	26%	79%	100%
Food Waste	32%	63%	16%	79%
Grass	17%	34%	53%	88%
Leaves	5%	10%	85%	95%
Branches	7%	14%	77%	91%
Mixed MSW	16%	32%	19%	50%
Gypsum Board	0%	0%	55%	55%
Dimensional Lumber	1%	3%	88%	91%
Medium-density Fiberboard	1%	1%	84%	85%
Wood Flooring	2%	5%	99%	100%

<sup>a</sup> The CH<sub>4</sub>, CO<sub>2</sub>, and carbon stored from these experiments represents only the biogenic carbon in each material type.

To calculate the WARM emission factors, 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 to account for exactly 100 percent of the initial carbon:

- For most materials where the total carbon output is less than the total carbon input (e.g., corrugated containers, office paper, food waste, grass, leaves), the “missing” carbon was assumed to be emitted as equal quantities of CH<sub>4</sub><sup>C</sup> and CO<sub>2</sub><sup>C</sup>. In these cases (corrugated containers, office paper, food waste, grass, leaves), the CH<sub>4</sub><sup>C</sup> was increased with respect to the measured values as follows:

$$\frac{\text{Initial C-LF}^{\text{C}}}{2} = \text{CH}_4^{\text{C}}$$

This calculation assumes that CO<sub>2</sub><sup>C</sup> = CH<sub>4</sub><sup>C</sup>. In essence, the adjustment approach was to increase landfill gas production, as suggested by Dr. Barlaz.

- For coated paper, newspaper, and wood flooring, where carbon outputs were greater than initial carbon, the measurements of initial carbon content and CH<sub>4</sub> 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 × CH<sub>4</sub><sup>C</sup>).

The resulting adjusted CH<sub>4</sub> yields and carbon storage are presented in Exhibit 5.

- For branches, dimensional lumber, medium-density fiberboard, and mixed MSW, the measured CH<sub>4</sub> yield as a percentage of initial carbon was considered to be the most realistic estimate for methane yield, based on consultation with Dr. Barlaz. Therefore, no adjustment was made for these materials.

- For gypsum board, the sulfate in wallboard is estimated to reduce methane generation, as bacteria use sulfate preferentially to the pathway that results in methane, as suggested by Dr. Barlaz. As such, methane yield from gypsum board is likely to be negligible and is therefore adjusted to 0% in WARM.

**Exhibit 5: Adjusted CH<sub>4</sub> Yield and Carbon Storage by Material Type**

Material	Adjusted Yield of CH <sub>4</sub> as Proportion of Initial Carbon	Adjusted Carbon Storage as Proportion of Initial Carbon
Corrugated Containers <sup>a</sup>	22%	55%
Newspaper <sup>b</sup>	8%	84%
Office Paper <sup>a</sup>	44%	12%
Coated Paper <sup>b</sup>	13%	74%
Food Waste <sup>a</sup>	42%	16%
Grass <sup>a</sup>	23%	53%
Leaves <sup>a</sup>	8%	85%
Branches <sup>c</sup>	7%	77%
Mixed MSW <sup>c</sup>	16%	19%
Gypsum Board <sup>d</sup>	0%	55%
Dimensional Lumber <sup>c</sup>	1%	88%
Medium-density Fiberboard <sup>c</sup>	1%	84%
Wood Flooring <sup>b</sup>	2%	95%

<sup>a</sup> CH<sub>4</sub> yield is adjusted to account for measurement uncertainty in the analytic techniques to measure these quantities. For corrugated containers, office paper, food waste, grass, leaves, the yield of CH<sub>4</sub> was increased such that the proportion of initial carbon emitted as landfill gas (i.e., 2 × CH<sub>4</sub>) plus the proportion that remains stored in the landfill is equal to 100% of the initial carbon.

<sup>b</sup> For coated paper, newspaper, and wood flooring, the proportion of initial carbon that is stored in the landfill is decreased such that the proportion of initial carbon emitted as landfill gas (i.e., 2 × CH<sub>4</sub>) plus the proportion that remains stored in the landfill is equal to 100% of the initial carbon.

<sup>c</sup> For branches, dimensional lumber, medium-density fiberboard, and mixed MSW, the measured CH<sub>4</sub> yield as a percentage of initial carbon and measured proportion of initial carbon stored shown in columns b and d, respectively of Exhibit 4 was considered to be the most realistic estimate for methane yield. Therefore, these values were not adjusted.

<sup>d</sup> For gypsum board, the sulfate in wallboard is estimated to reduce methane generation; thus, the methane yield from gypsum board is likely to be negligible and is therefore adjusted to 0%.

Dr. Barlaz's experiment did not test all of the biodegradable material types in WARM. EPA identified proxies for the remaining material types for which there were no experimental data. Magazines and third-class mail placed in a landfill were assumed to contain a mix of coated paper and office paper and were therefore assumed to behave like an average of those two materials. Similarly, phone books and textbooks were assumed to behave in the same way as newspaper and office paper, respectively. Results from two studies by Wang et al. were used for dimensional lumber, medium-density fiberboard, and wood flooring (Wang et al., 2013; Wang et al., 2011). For wood flooring, the ratio of dry-to-wet weight was adjusted to more accurately represent the moisture content of wood lumber (Staley and Barlaz, 2009). Drywall was assumed to have characteristics similar to gypsum board. Exhibit 6 shows the landfill CH<sub>4</sub> emission factors and the final carbon storage factors for all applicable material types.

**Exhibit 6: CH<sub>4</sub> Yield for Solid Waste Components**

Material/Product	Initial Biogenic Carbon Content	Adjusted Yield of CH <sub>4</sub> as Proportion Of Initial Carbon	Final (Adjusted) CH <sub>4</sub> Generation, MTCO <sub>2</sub> E/Dry Metric Ton <sup>a</sup>	Final (Adjusted) CH <sub>4</sub> Generation (MTCO <sub>2</sub> E /Wet Short Ton) <sup>b</sup>
Corrugated Containers	47%	22%	3.48	2.62
Magazines/Third-Class Mail	33%	28%	3.11	2.59
Newspaper	49%	8%	1.33	1.05
Office Paper	32%	44%	4.71	3.89
Phone Books	49%	8%	1.33	1.05
Textbooks	32%	44%	4.71	3.89
Dimensional Lumber	49%	1%	0.24	0.17
Medium-Density Fiberboard	44%	1%	0.08	0.06
Food Waste	51%	42%	7.13	1.75
Yard Trimmings				
Grass	45%	23%	3.48	0.57
Leaves	46%	8%	1.17	0.65
Branches	49%	7%	1.12	0.85
Mixed MSW	42%	16%	2.23	1.62
Drywall	5%	0%	0	0
Wood Flooring	46%	2%	0.35	0.24

<sup>a</sup> Final adjusted CH<sub>4</sub> generation per dry metric ton is the product of the initial carbon content and the final percent carbon emitted as CH<sub>4</sub> multiplied by the molecular ratio of carbon to CH<sub>4</sub> (12/16).

<sup>b</sup> CH<sub>4</sub> generation is converted from per dry metric ton to per wet short ton by multiplying the CH<sub>4</sub> generation on a dry metric ton basis by (1 – the material's moisture content) and by converting from metric tons to short tons of material.

**2.2.2 Component-Specific Decay Rates**

The second factor in estimating material-specific landfill emissions is the rate at which a material decays under anaerobic conditions in the landfill. The decay rate is an important factor that influences the landfill collection efficiency described further in the next section. Although the final adjusted CH<sub>4</sub> yield shown in Exhibit 6 will eventually occur no matter what the decay rate, the rate at which the material decays influences how much of the CH<sub>4</sub> yield will eventually be captured for landfills with collection systems.

Recent studies by De la Cruz and Barlaz (2010) found that different materials degrade at different rates relative to bulk MSW rates of decay. For example, one short ton of a relatively inert wood material—such as lumber—will degrade slowly and produce a smaller amount of methane than food waste, which readily decays over a much shorter timeframe. Materials will also degrade faster under wetter landfill conditions. Consequently, the rate at which CH<sub>4</sub> emissions are generated from decaying material in a landfill depends upon: (1) the type of material placed in the landfill, and (2) the moisture conditions of the landfill.

De la Cruz and Barlaz (2010) measured component-specific decay rates in laboratory experiments that were then scaled to field-level, component-specific decay rates based on mixed MSW field-scale decay rates published in EPA (1998) guidance.

To scale the laboratory-scale, component-specific decay rate measurements to field-scale values, De la Cruz and Barlaz (2010) assumed that the weighted average decay rate for a waste mixture of the same composition as MSW would be equal to the bulk MSW decay rate. They also related a lab-scale decay rate for mixed MSW to the field-scale decay rate using a scaling factor. Using these two

relationships, the authors were able to estimate field-scale decay rates for different materials based on the laboratory data. The following equations were used to estimate the component-specific decay rates:

**Equation 1**

$$f \times \sum_{i=1}^n k_{lab,i} \times (wt. fraction)_i = decay rate$$

**Equation 2**

$$k_{field,i} = f \times k_{lab,i}$$

where,

- $f$  = a correction factor to force the left side of the equation to equal the overall MSW decay rate
- $k_{lab,i}$  = the component-specific decay rate calculated from lab experiments
- $k_{field,i}$  = the component-specific decay rate determined for the field
- $i$  = the  $i^{th}$  waste component

Based on the results from De la Cruz and Barlaz (2010), the Excel version of WARM allows users to select different component-specific decay rates based on different assumed moisture contents of the landfill to estimate the rate at which CH<sub>4</sub> is emitted for each material type (or “component”). The five MSW decay rates used are:

1.  $k = 0.02/\text{year}$  (“Dry”), corresponding to landfills receiving fewer than 20 inches of annual precipitation: based values reported in EPA (2010)
2.  $k = 0.04/\text{year}$  (“Moderate”), corresponding to landfills receiving between 20 and 40 inches of annual precipitation: based values reported in EPA (2010)
3.  $k = 0.06/\text{year}$  (“Wet”), corresponding to landfills receiving greater than 40 inches of annual precipitation: based values reported in EPA (2010)
4.  $k = 0.12/\text{year}$  (“Bioreactor”), corresponding to landfills operating as bioreactors where water is added until the moisture content reaches 40 percent moisture on a wet-weight basis: based on expert judgment using values reported in Barlaz et al. (2010) and Tolaymat et al. (2010)
5.  $k = 0.052/\text{year}$  (“National Average”), corresponding to a weighted average based on the share of waste received at each landfill type: based on expert judgment using values reported in EPA (2010)

The final waste component-specific decay rates as a function of landfill moisture conditions are provided in Exhibit 7.

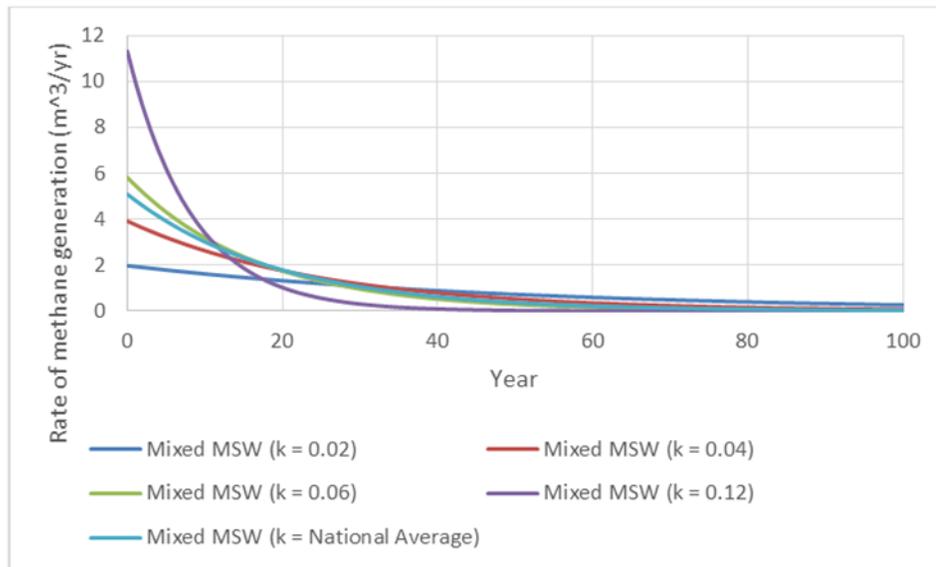
**Exhibit 7: Component-Specific Decay Rates (yr<sup>-1</sup>) by Landfill Moisture Scenario**

Material	Landfill Moisture Conditions				National Average
	Dry	Moderate	Wet	Bioreactor	
Corrugated Containers	0.01	0.02	0.03	0.06	0.03
Magazines/Third-Class Mail	0.06	0.12	0.18	0.37	0.16
Newspaper	0.02	0.03	0.05	0.10	0.04
Office Paper	0.01	0.03	0.04	0.09	0.04
Phone Books	0.02	0.03	0.05	0.10	0.04
Textbooks	0.01	0.03	0.04	0.09	0.04
Dimensional Lumber	0.04	0.08	0.12	0.25	0.11
Medium-Density Fiberboard	0.03	0.06	0.10	0.19	0.08
Food Waste	0.07	0.14	0.22	0.43	0.19
Yard Trimmings	0.10	0.20	0.29	0.59	0.26
Grass	0.15	0.30	0.45	0.89	0.39
Leaves	0.09	0.17	0.26	0.51	0.22
Branches	0.01	0.02	0.02	0.05	0.02
Mixed MSW	0.02	0.04	0.06	0.12	0.05
Drywall <sup>a</sup>	–	–	–	–	–
Wood Flooring <sup>a</sup>	–	–	–	–	–

– = Zero Emissions.

<sup>a</sup>Decay rates were not estimated since WARM assumes that the construction and demolition landfills where these materials are disposed of do not collect landfill gas.

The profile of methane emissions as materials decay in landfills over time is commonly approximated using a first-order decay methodology summarized in De la Cruz and Barlaz (2010). The CH<sub>4</sub> generation potential of landfilled waste decreases gradually throughout time and can be estimated using first order decomposition mathematics. The profile of methane emissions from landfills over time for mixed MSW is shown in Exhibit 8 as a graphic representation of the methane emissions approximated using a first-order decay equation. As Exhibit 8 shows, materials will degrade faster under wetter conditions in landfills (i.e., landfills whose conditions imply higher decay rates for materials).

**Exhibit 8. Rate of Methane Generation for Mixed MSW as a Function of Decay Rate**

Although in each landfill moisture scenario, the total final CH<sub>4</sub> yield for solid waste components (Exhibit 6) will eventually be emitted over time, the rate at which methane is emitted greatly depends on the decay rate. Finally, since different materials have very different methane emission profiles in landfills, the effectiveness and timing of the installation of landfill gas collection systems can greatly influence methane emissions, as discussed in the next section.

### 2.2.3 Landfill Gas Collection

WARM estimates the amount of methane that is collected by landfill gas collection equipment. In practice, the landfill gas collection system efficiency does not remain constant over the duration of gas production. Rather, the gas collection system at any particular landfill is typically expanded over time. Usually, only a small percentage (or none) of the gas produced soon after waste burial is collected, while almost all of the gas produced is collected once a final cover is installed. To provide a better estimate of gas collection system efficiency, EPA uses a Monte Carlo analysis to estimate the fraction of produced gas that is vented directly, flared and utilized for energy recovery while considering annual waste disposal and landfill operating life (Levis and Barlaz 2014).<sup>4</sup>

The gas collection efficiencies that WARM uses are evaluated from the perspective of a short ton of a specific material placed in the landfill at year zero. The efficiencies are calculated based on one of five moisture conditions (dry, moderate, wet, bioreactor, and national average conditions, described in section 2.2.2) and one of four landfill gas collection practices over a 100-year time period, which is approximately the amount of time required for 95 percent of the potential landfill gas to be produced under the “Dry” (k = 0.02/yr) landfill scenario. The final average efficiency is equal to the total CH<sub>4</sub> collected over 100 years divided by the total CH<sub>4</sub> produced over 100 years.

The combination of four different landfill gas collection scenarios and five different landfill moisture conditions means there are 20 possible landfill gas collection efficiencies possible for each

<sup>4</sup> This improved analysis of landfill gas collection was incorporated in June 2014 into WARM Version 13.

material in WARM. The landfill collection efficiency scenarios are described below and the assumptions for each are shown in Exhibit 9:

1. Typical collection – phased-in collection with an improved cover; judged to represent the average U.S. landfill, although every landfill is unique and a typical landfill is an approximation of reality.
2. Worst-case collection – the minimum collection requirements under EPA’s New Source Performance Standards.
3. Aggressive collection – landfills where the operator is aggressive in gas collection relative to a typical landfill; bioreactor landfills are assumed to collect gas aggressively.
4. California regulatory scenario<sup>5</sup> – equivalent to landfill management practices based on California regulatory requirements.

**Exhibit 9: WARM Gas Collection Scenario Assumptions and Efficiencies Compared to EPA AP-42 (1998) with Landfill Gas Recovery for Energy**

Scenario	Gas Collection Scenario Description	Gas Collection Scenario	Landfill Gas Collection Efficiency (%) for Mixed MSW <sup>a</sup>				
			MSW Decay Rate (yr <sup>-1</sup> )				National Average
			0.02	0.04	0.06	0.12	
AP-42	EPA default gas collection assumption (EPA 1998 AP-42) (not modeled in WARM)	All years: 75%	75.0	75.0	75.0	75.0	75.0
1	“Typical collection”, judged to represent the average U.S. landfill	Years 0–1: 0% Years 2-4: 50% Years 5–14: 75% Years 15 to 1 year before final cover: 82.5% Final cover: 90%	68.2	65.0	64.1	60.6	64.8
2	“Worst-case collection” under EPA New Source Performance Standards (NSPS)	Years 0-4: 0% Years 5-9: 50% Years 10–14: 75% Years 15 to 1 year before final cover: 82.5% Final cover: 90%	66.2	61.3	59.2	50.6	60.3
3	“Aggressive gas collection,” typical bioreactor operation	Year 0: 0% Years 0.5-2: 50% Years 3–14: 75% Years 15 to 1 year before final cover: 82.5% Final Cover: 90%	68.6	65.8	66.3	63.9	66.4
4	“California regulatory scenario”, landfill management based on California regulatory requirements	Year 0: 0% Year 1: 50% Years 2-7: 80% Years 8 to 1 year before final cover: 85% Final cover: 90%	83.6	79.5	77.4	72.9	78.8

<sup>a</sup> The values in this table are for landfills that recover gas for energy. In reality, a small share of gas recovered is eventually flared. The values provided in this table include both the gas recovered for energy and the small portion recovered for flaring.

The landfill gas collection efficiencies by material type for each of the four landfill collection efficiency scenarios and each of the five moisture conditions are provided in Exhibit 10. In addition to the gas collected, EPA also takes into account the percentage of gas that is flared, oxidized and emitted

<sup>5</sup> This additional landfill gas collection scenario was incorporated in June 2014 into WARM Version 13 to allow WARM users to estimate and view landfill management results based on California regulatory requirements.

for landfills that recover gas for energy, as described in Levis and Barlaz (2014). Some of the uncollected methane is oxidized to CO<sub>2</sub> as it passes through the landfill cover; Levis and Barlaz (2014) adapted EPA recommendations for methane oxidation (71 FR 230, 2013) to develop the following oxidation rates at various stages of landfill gas collection:

- Without gas collection or final cover: 10 percent
- With gas collection before final cover: 20 percent
- After final cover installation: 35 percent

In the EPA recommendations, the fraction of uncollected methane that is oxidized varies with the methane flux (mass per area per time) and ranges from 10 percent to 35 percent (71 FR 230, 2013). Measurement or estimation of the methane flux is possible on a site-specific basis but requires assumptions on landfill geometry and waste density to estimate flux for a generic landfill as is represented by WARM. As such, the methane oxidation values published by EPA were used as guidance for the values listed above. Landfills with a final cover and a gas collection system in place will have a relatively low flux through the cover, which justifies the upper end of the range (35 percent) given by EPA. Similarly, landfills without a gas collection system in place will have a relatively high flux, suggesting that an oxidation rate of 10 percent is most appropriate. Landfills with a gas collection system in place but prior to final cover placement were assigned an oxidation rate of 20 percent. Based on preliminary calculations for a variety of landfill geometries and waste densities, Levis and Barlaz (2014) determined that the methane flux would justify an oxidation rate of 25 percent most but not all of the time. As such, an oxidation rate of 20 percent was adopted in WARM for landfills with gas collection before final cover (Levis and Barlaz, 2014).

For landfill gas that is not collected for energy use, EPA takes into account the percentage of landfill CH<sub>4</sub> that is flared (when recovery for flaring is assumed), oxidized near the surface of the landfill, and emitted. Based on analysis by Levis and Barlaz, EPA estimated the percentage of the landfill CH<sub>4</sub> generated that are either flared, chemically oxidized or converted by bacteria to CO<sub>2</sub>, and emitted for each material type for each of the four landfill collection efficiency scenarios and each of the five moisture conditions (Levis and Barlaz, 2014).

**Exhibit 10: Waste Component-Specific Collection Efficiencies by Landfill Moisture Condition with Landfill Gas Recovery for Energy**

Material/ Product	Typical Landfill Scenario					Worst-Case Landfill Scenario					Aggressive Collection Landfill Scenario					California Regulations Collection Scenario				
	Dry	Mode rate	Wet	Bio-react or	Natio nal Avg.	Dry	Mod erate	Wet	Bio-react or	Natio nal Avg.	Dry	Mod erate	Wet	Bio-react or	Natio nal Avg.	Dry	Mod erate	Wet	Bio-react or	Natio nal Avg.
Corrugated Containers	61%	55%	54%	55%	56%	60%	54%	53%	50%	54%	61%	56%	56%	58%	57%	66%	59%	60%	62%	61%
Magazines/ Third-Class Mail	59%	55%	52%	45%	54%	55%	46%	40%	26%	43%	61%	58%	57%	51%	57%	67%	63%	61%	54%	62%
Newspaper	62%	59%	59%	57%	59%	61%	56%	55%	49%	56%	62%	59%	61%	60%	61%	67%	64%	65%	65%	65%
Office Paper	62%	58%	58%	57%	59%	61%	56%	55%	50%	56%	62%	59%	60%	60%	60%	67%	63%	64%	65%	64%
Phone Books	62%	59%	59%	57%	59%	61%	56%	55%	49%	56%	62%	59%	61%	60%	61%	67%	64%	65%	65%	65%
Textbooks	62%	58%	58%	57%	59%	61%	56%	55%	50%	56%	62%	59%	60%	60%	60%	67%	63%	64%	65%	64%
Dimensional Lumber	62%	59%	57%	50%	58%	59%	52%	48%	35%	50%	63%	61%	60%	55%	60%	68%	66%	65%	60%	65%
Medium-Density Fiberboard	62%	60%	59%	53%	59%	60%	55%	51%	40%	53%	63%	62%	62%	58%	62%	68%	66%	67%	62%	67%
Food Waste	58%	53%	50%	42%	52%	53%	43%	36%	22%	40%	59%	56%	55%	49%	55%	65%	61%	59%	51%	60%
Food Waste (meat only)	58%	53%	50%	42%	52%	53%	43%	36%	22%	40%	59%	56%	55%	49%	55%	65%	61%	59%	51%	60%
Food Waste (non-meat)	58%	53%	50%	42%	52%	53%	43%	36%	22%	40%	59%	56%	55%	49%	55%	65%	61%	59%	51%	60%
Beef	58%	53%	50%	42%	52%	53%	43%	36%	22%	40%	59%	56%	55%	49%	55%	65%	61%	59%	51%	60%
Poultry	58%	53%	50%	42%	52%	53%	43%	36%	22%	40%	59%	56%	55%	49%	55%	65%	61%	59%	51%	60%
Grains	58%	53%	50%	42%	52%	53%	43%	36%	22%	40%	59%	56%	55%	49%	55%	65%	61%	59%	51%	60%
Bread	58%	53%	50%	42%	52%	53%	43%	36%	22%	40%	59%	56%	55%	49%	55%	65%	61%	59%	51%	60%
Fruits and Vegetables	58%	53%	50%	42%	52%	53%	43%	36%	22%	40%	59%	56%	55%	49%	55%	65%	61%	59%	51%	60%
Dairy Products	58%	53%	50%	42%	52%	53%	43%	36%	22%	40%	59%	56%	55%	49%	55%	65%	61%	59%	51%	60%
Yard Trimmings	54%	47%	44%	39%	47%	47%	37%	31%	21%	35%	55%	51%	49%	44%	50%	61%	55%	52%	45%	54%
Grass	49%	43%	39%	33%	41%	39%	27%	20%	9%	25%	51%	47%	45%	39%	46%	57%	51%	48%	38%	50%
Leaves	56%	51%	47%	40%	49%	50%	40%	33%	19%	37%	58%	54%	52%	46%	53%	64%	59%	57%	48%	58%
Branches	61%	53%	51%	52%	54%	60%	52%	51%	49%	53%	61%	54%	53%	54%	55%	65%	57%	57%	58%	59%
Mixed MSW	62%	60%	60%	57%	60%	61%	56%	55%	47%	56%	63%	61%	62%	60%	62%	67%	65%	67%	65%	66%

Material/ Product	Typical Landfill Scenario					Worst-Case Landfill Scenario					Aggressive Collection Landfill Scenario					California Regulations Collection Scenario				
	Dry	Moderate	Wet	Bio-reactor	National Avg.	Dry	Moderate	Wet	Bio-reactor	National Avg.	Dry	Moderate	Wet	Bio-reactor	National Avg.	Dry	Moderate	Wet	Bio-reactor	National Avg.
Gypsum <sup>a</sup>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Wood Flooring <sup>a</sup>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

- = Zero Emissions.

<sup>a</sup>WARM assumes that construction and demolition landfills do not collect landfill gas.

### 2.3 EMISSIONS FROM TRANSPORTATION TO LANDFILLS AND LANDFILL OPERATION

In addition to CH<sub>4</sub> emissions from waste decomposition in landfills, WARM includes transportation CO<sub>2</sub> emissions from collecting MSW and running landfill operational equipment in each material type's landfill emission factor. The amount of diesel fuel required to collect a short ton of waste and operate the necessary equipment to manage the landfill was taken from FAL (1994). Exhibit 11 provides the transportation emission factor calculation.

**Exhibit 11: Transportation CO<sub>2</sub> Emissions Assumptions and Calculation**

Equipment	Diesel Fuel (gallons/ 10 <sup>3</sup> lbs of MSW landfilled)	Total Energy (Btu/10 <sup>3</sup> lb of MSW landfilled)	Total Energy (Btu/Short Ton of MSW landfilled)	MTCE (per million Btus)	Total (MTCO <sub>2</sub> E/Short Ton)
Collection Vehicles	0.90	148,300	296,600	–	–
Landfill Equipment	0.70	115,400	230,800	–	–
<b>Total</b>	<b>1.60</b>	<b>263,700</b>	<b>527,400</b>	<b>0.02</b>	<b>0.04</b>

– = Zero Emissions.

### 2.4 ESTIMATING LANDFILL CARBON STORAGE

The other anthropogenic fate of carbon in landfills is storage. As described in section 2.1, a portion of the carbon in biodegradable materials (i.e., food waste, yard trimmings, paper and wood) that is not completely decomposed by anaerobic bacteria remains stored in the landfill. This carbon storage would not normally occur under natural conditions, so it is counted as an anthropogenic sink (IPCC, 2006; Bogner et al., 2007).

The discussion in section 2.2 on initial carbon contents and CH<sub>4</sub> generation includes the measured carbon stored from the Barlaz (1998), Wang et al. (2013), Wang et al. (2011), and Levis et al. (2013) experiments. For the most part, the amount of stored carbon measured as the output during these experiments is considered the final ratio of carbon stored to total initial dry weight of each material type. For newspaper, wood flooring, and coated paper—which is used to estimate landfill characteristics for magazines and third-class mail—the amount of carbon stored is reduced because carbon outputs were *greater than* initial carbon.

To estimate the final carbon storage factor, the proportion of initial carbon stored found in Exhibit 5 is multiplied by the initial carbon contents in Exhibit 3 to obtain the ratio of carbon storage to dry weight for each material type found in Exhibit 12. These estimates are then converted from dry weight to wet weight and from grams to metric tons of CO<sub>2</sub> per wet short ton of material. The last column of Exhibit 12 provides the final carbon storage factors for the biodegradable solid waste components modeled in WARM.

**Exhibit 12: Carbon Storage for Solid Waste Components**

Material/Product	Ratio of Carbon Storage to Dry Weight (gram C/dry gram)	Ratio of Dry Weight to Wet Weight	Ratio of Carbon Storage to Wet Weight (gram C/wet gram)	Amount of Carbon Stored (MTCO <sub>2</sub> E per Wet Short Ton)
Corrugated Containers	0.26	0.83	0.22	0.72
Magazines/Third-Class Mail	0.15	0.92	0.13	0.45
Newspaper	0.41	0.87	0.36	1.19
Office Paper	0.04	0.91	0.04	0.12
Phone Books	0.41	0.87	0.36	1.12
Textbooks	0.04	0.91	0.04	0.12
Dimensional Lumber	0.44	0.75	0.33	1.09
Medium-Density Fiberboard	0.37	0.75	0.28	0.92
Food Waste	0.08	0.27	0.02	0.07
Yard Trimmings	0.31	0.46	0.16	0.54
Grass	0.24	0.18	0.04	0.14
Leaves	0.39	0.62	0.24	0.79
Branches	0.38	0.84	0.32	1.06
Mixed MSW	0.08	0.80	0.06	0.21
Drywall	0.03	0.94	0.02	0.08
Wood Flooring	0.44	0.75	0.33	1.09

## 2.5 ELECTRIC UTILITY GHG EMISSIONS AVOIDED

The CH<sub>4</sub> component of landfill gas that is collected from landfills can be combusted to produce heat and electricity, and recovery of heat and electricity from landfill gas offsets the combustion of other fossil fuel inputs. WARM models the recovery of landfill gas for electricity generation and assumes that this electricity offsets non-baseload electricity generation in the power sector.

WARM applies non-baseload electricity emission rates to calculate the emissions offset from landfill gas energy recovery because the model assumes that incremental increases in landfill energy recovery will affect non-baseload power plants (i.e., power plants that are “demand-following” and adjust to marginal changes in the supply and demand of electricity). EPA calculates non-baseload emission rates as the average emissions rate from power plants that combust fuel and have capacity factors less than 0.8 (EPA, 2014a).

EPA estimates the avoided GHG emissions per MTCO<sub>2</sub>E of CH<sub>4</sub> combusted using several physical constants and data from EPA’s Landfill Methane Outreach Program and eGRID (EPA, 2013; EPA, 2014a). The mix of fuels used to produce electricity varies regionally in the United States; consequently, EPA applies a different CO<sub>2</sub>-intensity for electricity generation depending upon where the electricity is offset. The Excel version of WARM includes CO<sub>2</sub>-intensity emission factors for non-baseload electricity generated in nine different U.S. regions as well as a U.S.-average CO<sub>2</sub>-intensity (EPA, 2014a). The formula used to calculate the quantity of electricity generation emissions avoided per MTCO<sub>2</sub>E of CH<sub>4</sub> combusted is as follows:

$$\frac{BTU_{CH_4}}{H_{LFGTE}} \times a \times E_{Grid} = R$$

Where:

- $Btu_{CH_4}$  = Energy content of  $CH_4$  per  $MTCO_2E$   $CH_4$  combusted; assumed to be 1,012 Btu per cubic foot of  $CH_4$  (EPA, 2013), converted into Btu per  $MTCO_2E$   $CH_4$  assuming 20 grams per cubic foot of  $CH_4$  at standard temperature and pressure and a global warming potential of  $CH_4$  of 21
- $H_{LFGTE}$  = Heat rate of landfill gas to energy conversion; assumed to be 11,700 Btu per kWh generated (EPA, 2013)
- $a$  = Net capacity factor of electricity generation; assumed to be 85 percent (EPA, 2013)
- $E_{grid}$  = Non-baseload  $CO_2$ -equivalent GHG emissions intensity of electricity produced at the regional or national electricity grid; values assumed for each region and U.S. average are shown in Exhibit 14
- $R$  = Ratio of GHG emissions avoided from electricity generation per  $MTCO_2E$  of  $CH_4$  combusted for landfill gas to energy recovery

Exhibit 13 shows variables in the GHG emissions offset for the national average fuel mix. The final ratio is the product of columns (a) through (h). Exhibit 14 shows the amount of carbon avoided per kilowatt-hour of generated electricity and the final ratio of  $MTCO_2E$  avoided of utility carbon per  $MTCO_2E$  of  $CH_4$  combusted (column (g) and resulting column (i)).

**Exhibit 13: Calculation to Estimate Utility GHGs Avoided through Combustion of Landfill  $CH_4$  for Electricity Based on National Average Electricity Grid Mix**

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
Metric Tons $CH_4/MTCO_2E$ $CH_4$ Combusted	Grams $CH_4/Metric$ Ton $CH_4$	Cubic Ft. $CH_4/Gram$ $CH_4$	Btu/Cubic Ft. $CH_4$	kWh Electricity Generated/Btu	Electricity Generation Efficiency	Kg Utility $CO_2$ Avoided/kWh Generated Electricity	Metric Tons Avoided Utility $CO_2/Kg$ Utility $CO_2$	Ratio of $MTCO_2E$ Avoided Utility $CO_2$ per $MTCO_2E$ $CH_4$ Combusted
0.04	1,000,000	0.05	1,012	0.00009	0.85	0.74	0.001	0.11

**Exhibit 14: Ratio of  $MTCO_2E$  Avoided Utility Carbon per  $MTCO_2E$   $CH_4$  Combusted by Region**

Region	Kg Utility $CO_2$ Avoided/kWh Generated Electricity	Ratio of $MTCO_2E$ Avoided Utility C per $MTCO_2E$ $CH_4$
Pacific	0.49	0.07
Mountain	0.78	0.11
West-North Central	1.01	0.15
West-South Central	0.61	0.09
East-North Central	0.96	0.14
East-South Central	0.85	0.13
New England	0.55	0.08
Mid Atlantic	0.73	0.11
South Atlantic	0.78	0.12
National Average	0.74	0.11

If regional avoided utility emission factors are not employed, WARM calculates U.S.-average avoided utility emission factors based on the percent of  $CH_4$  generated at landfills in the nation with landfill gas recovery and electricity production found in Exhibit 1, and assuming U.S.-average, non-baseload electricity GHG emission intensity. Exhibit 15 shows this calculation for each material type for the national average fuel mix.

**Exhibit 15: Overall Avoided Utility CO<sub>2</sub> Emissions per Short Ton of Waste Material (National Average Grid Mix)**

(a) Material	(b) CH <sub>4</sub> Generation (MTCO <sub>2</sub> E/Wet Short Ton) (Exhibit 6)	Methane from Landfills With LFG Recovery and Electricity Generation					(h) Net Avoided CO <sub>2</sub> Emissions from Energy Recovery (MTCO <sub>2</sub> E/Wet Short Ton) (h = f × g)
		(c) Percentage of CH <sub>4</sub> Recovered (Exhibit 10)	(d) Utility GHG Emissions Avoided per MTCO <sub>2</sub> E CH <sub>4</sub> Combusted (MTCO <sub>2</sub> E) (Exhibit 14)	(e) Percentage of CH <sub>4</sub> Recovered for Electricity Generation Not Utilized Due to LFG System "Down Time"	(f) Utility GHG Emissions Avoided (MTCO <sub>2</sub> E/Wet Short Ton) (f = b × (1-c) × d × (1-e))	(g) Percentage of CH <sub>4</sub> From Landfills With LFG Recovery and Electricity Generation (Exhibit 1)	
Corrugated Containers	2.62	56%	-0.11	3%	-0.16	44%	-0.07
Magazines/ Third-Class Mail	2.59	54%	-0.11	3%	-0.15	44%	-0.06
Newspaper	1.05	59%	-0.11	3%	-0.07	44%	-0.03
Office Paper	3.89	59%	-0.11	3%	-0.24	44%	-0.11
Phone Books	1.05	59%	-0.11	3%	-0.07	44%	-0.03
Textbooks	3.89	59%	-0.11	3%	-0.24	44%	-0.11
Dimensional Lumber	0.17	58%	-0.11	3%	-0.01	44%	-0.004
Medium-Density Fiberboard	0.06	59%	-0.11	3%	-0.004	44%	-0.002
Food Waste	1.75	52%	-0.11	3%	-0.10	44%	-0.04
Yard Trimmings	0.66	47%	-0.11	3%	-0.03	44%	-0.01
Grass	0.57	41%	-0.11	3%	-0.02	44%	-0.01
Leaves	0.65	49%	-0.11	3%	-0.03	44%	-0.01
Branches	0.85	54%	-0.11	3%	-0.05	44%	-0.02
Mixed MSW	1.62	60%	-0.11	3%	-0.10	44%	-0.04
Drywall <sup>a</sup>	0.00	–	–	–	–	–	–
Wood Flooring <sup>a</sup>	0.24	–	–	–	–	–	–

– = Zero Emissions.

<sup>a</sup> WARM assumes that construction and demolition landfills do not collect landfill gas.

## 2.6 NET GHG EMISSIONS FROM LANDFILLING

CH<sub>4</sub> emissions, transportation CO<sub>2</sub> emissions, carbon storage and avoided utility GHG emissions are then summed to estimate the net GHG emissions from landfilling each material type. Exhibit 16 shows the net emission factors for landfilling each material based on typical landfill gas collection practices, average landfill moisture conditions (i.e., for landfills receiving between 20 and 40 inches of precipitation annually), and U.S.-average non-baseload electricity grid mix.

**Exhibit 16: Net GHG Emissions from Landfilling (MTCO<sub>2</sub>E/Short Ton)**

Material/ Product	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Landfill	Landfill CH <sub>4</sub>	Avoided CO <sub>2</sub> Emissions from Energy Recovery	Landfill Carbon Sequestration	Net Emissions (Post-Consumer)
Aluminum Cans	–	0.04	–	–	–	0.04
Aluminum Ingot	–	0.04	–	–	–	0.04

Material/ Product	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Landfill	Landfill CH <sub>4</sub>	Avoided CO <sub>2</sub> Emissions from Energy Recovery	Landfill Carbon Sequestration	Net Emissions (Post-Consumer)
Steel Cans	-	0.04	-	-	-	0.04
Copper Wire	-	0.04	-	-	-	0.04
Glass	-	0.04	-	-	-	0.04
HDPE	-	0.04	-	-	-	0.04
LDPE	-	0.04	-	-	-	0.04
PET	-	0.04	-	-	-	0.04
LLDPE	-	0.04	-	-	-	0.04
PP	-	0.04	-	-	-	0.04
PS	-	0.04	-	-	-	0.04
PVC	-	0.04	-	-	-	0.04
PLA	-	0.04	-	-	-1.66	-1.62
Corrugated Containers	-	0.04	1.19	-0.07	-0.72	0.45
Magazines/Third-Class Mail	-	0.04	1.14	-0.06	-0.45	0.67
Newspaper	-	0.04	0.46	-0.03	-1.19	-0.73
Office Paper	-	0.04	1.71	-0.11	-0.12	1.52
Phonebooks	-	0.04	0.46	-0.03	-1.19	-0.73
Textbooks	-	0.04	1.71	-0.11	-0.12	1.52
Dimensional Lumber	-	0.04	0.07	0.00	-1.09	-0.98
Medium-density Fiberboard	-	0.04	0.02	0.00	-0.92	-0.86
Food Waste	-	0.04	0.79	-0.04	-0.07	0.71
Food Waste (meat only)	-	0.04	0.79	-0.04	-0.07	0.71
Food Waste (non-meat)	-	0.04	0.79	-0.04	-0.07	0.71
Beef	-	0.04	0.79	-0.04	-0.07	0.71
Poultry	-	0.04	0.79	-0.04	-0.07	0.71
Grains	-	0.04	0.79	-0.04	-0.07	0.71
Bread	-	0.04	0.79	-0.04	-0.07	0.71
Fruits and Vegetables	-	0.04	0.79	-0.04	-0.07	0.71
Dairy Products	-	0.04	0.79	-0.04	-0.07	0.71
Yard Trimmings	-	0.04	0.32	-0.01	-0.54	-0.19
Grass	-	0.04	0.29	-0.01	-0.14	0.17
Leaves	-	0.04	0.30	-0.01	-0.79	-0.47
Branches	-	0.04	0.40	-0.02	-1.06	-0.65
Mixed Paper (general)	-	0.04	1.11	-0.07	-0.69	0.40
Mixed Paper (primarily residential)	-	0.04	1.09	-0.06	-0.72	0.35
Mixed Paper (primarily from offices)	-	0.04	1.22	-0.07	-0.49	0.69
Mixed Metals	-	0.04	-	-	-	0.04
Mixed Plastics	-	0.04	-	-	-	0.04
Mixed Recyclables	-	0.04	0.96	-0.05	-0.62	0.32
Mixed Organics	-	0.04	0.57	-0.03	-0.30	0.29
Mixed MSW	-	0.04	0.70	-0.04	-0.21	0.48
Carpet	-	0.04	-	-	-	0.04
Personal Computers	-	0.04	-	-	-	0.04
Clay Bricks	-	0.04	-	-	-	0.04

Material/ Product	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Landfill	Landfill CH <sub>4</sub>	Avoided CO <sub>2</sub> Emissions from Energy Recovery	Landfill Carbon Sequestration	Net Emissions (Post-Consumer)
Concrete	–	0.04	–	–	–	0.04
Fly Ash	–	0.04	–	–	–	0.04
Tires	–	0.04	–	–	–	0.04
Asphalt Concrete	–	0.04	–	–	–	0.04
Asphalt Shingles	–	0.04	–	–	–	0.04
Drywall	–	0.04	–	–	-0.08	-0.04
Fiberglass Insulation	–	0.04	–	–	–	0.04
Vinyl Flooring	–	0.04	–	–	–	0.04
Wood Flooring <sup>a</sup>	–	0.04	0.22	0.00	-1.09	-0.83

– = Zero Emissions.

<sup>a</sup> WARM assumes that construction and demolition landfills do not collect landfill gas

In WARM, emissions from landfills are dependent on the user selection of one of four different landfill scenarios (i.e., “Landfills: National Average,” “Landfills Without LFG Recovery,” “Landfills With LFG Recovery and Flaring,” and “Landfills With LFG Recovery and Electric Generation”) as described in section 1. The net landfilling emission factors for landfilling each material based on the default options in WARM (i.e., typical landfill gas collection practices, average landfill moisture conditions and U.S.-average non-baseload electricity grid mix) are shown in Exhibit 17.

**Exhibit 17: Landfilling Net Emission Factors in WARM Using Default Options (MTCO<sub>2</sub>E/Ton)**

Material	Landfills: National Average (Exhibit 16)	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electricity Generation
Aluminum Cans	0.04	0.04	0.04	0.04
Aluminum Ingot	0.04	0.04	0.04	0.04
Steel Cans	0.04	0.04	0.04	0.04
Copper Wire	0.04	0.04	0.04	0.04
Glass	0.04	0.04	0.04	0.04
HDPE	0.04	0.04	0.04	0.04
LDPE	0.04	0.04	0.04	0.04
PET	0.04	0.04	0.04	0.04
LLDPE	0.04	0.04	0.04	0.04
PP	0.04	0.04	0.04	0.04
PS	0.04	0.04	0.04	0.04
PVC	0.04	0.04	0.04	0.04
PLA	-1.62	-1.62	-1.62	-1.62
Corrugated Containers	0.45	1.68	0.46	-0.08
Magazines/Third-Class Mail	0.67	1.92	0.58	0.23
Newspaper	-0.73	-0.21	-0.73	-0.94
Office Paper	1.52	3.41	1.53	0.73
Phonebooks	-0.73	-0.21	-0.73	-0.94
Textbooks	1.52	3.41	1.53	0.73
Dimensional Lumber	-0.98	-0.90	-0.99	-1.01
Medium-density Fiberboard	-0.86	-0.83	-0.86	-0.87
Food Waste	0.71	1.54	0.64	0.43
Food Waste (meat only)	0.71	1.54	0.64	0.43
Food Waste (non-meat)	0.71	1.54	0.64	0.43

Material	Landfills: National Average (Exhibit 16)	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electricity Generation
Beef	0.71	1.54	0.64	0.43
Poultry	0.71	1.54	0.64	0.43
Grains	0.71	1.54	0.64	0.43
Bread	0.71	1.54	0.64	0.43
Fruits and Vegetables	0.71	1.54	0.64	0.43
Dairy Products	0.71	1.54	0.64	0.43
Yard Trimmings	-0.19	0.10	-0.21	-0.29
Grass	0.17	0.41	0.14	0.10
Leaves	-0.47	-0.16	-0.49	-0.57
Branches	-0.65	-0.26	-0.64	-0.82
Mixed Paper (general)	0.40	1.59	0.40	-0.10
Mixed Paper (primarily residential)	0.35	1.51	0.35	-0.14
Mixed Paper (primarily from offices)	0.69	2.03	0.66	0.16
Mixed Metals	0.04	0.04	0.04	0.04
Mixed Plastics	0.04	0.04	0.04	0.04
Mixed Recyclables	0.32	1.28	0.45	-0.18
Mixed Organics	0.29	0.84	0.24	0.09
Mixed MSW	0.48	1.29	0.48	0.15
Carpet	0.04	0.04	0.04	0.04
Personal Computers	0.04	0.04	0.04	0.04
Clay Bricks	0.04	0.04	0.04	0.04
Concrete	0.04	0.04	0.04	0.04
Fly Ash	0.04	0.04	0.04	0.04
Tires	0.04	0.04	0.04	0.04
Asphalt Concrete	0.04	0.04	0.04	0.04
Asphalt Shingles	0.04	0.04	0.04	0.04
Drywall	-0.04	-0.04	-0.04	-0.04
Fiberglass Insulation	0.04	0.04	0.04	0.04
Vinyl Flooring	0.04	0.04	0.04	0.04
Wood Flooring	-0.83	-0.83	-0.83	-0.83

### 3. LIMITATIONS

The landfilling analysis has several limitations associated with it; these are discussed in the following paragraphs.

- The net GHG emissions from landfilling each material are quite sensitive to the LFG recovery rate. Because of the high global warming potential of CH<sub>4</sub>, 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 distribution of waste in place is not a perfect proxy for the distribution of ongoing waste generation destined for landfill.
- Ongoing shifts in the use of landfill cover and liner systems are likely to influence the rate of CH<sub>4</sub> 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

biodegradable wastes. Over the long term, these improvements may result in a decrease in CH<sub>4</sub> generation and an increase in carbon storage. Moreover, Dr. Barlaz believes that the CH<sub>4</sub> yields from his laboratory experiments are likely to be higher than CH<sub>4</sub> yields in a landfill, because the laboratory experiments were designed to generate the maximum amount of CH<sub>4</sub> possible. If the CH<sub>4</sub> yields from the laboratory experiments were higher than yields in a landfill, the net GHG emissions from landfilling biodegradable 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<sub>2</sub> in the combustor.
- The estimate of avoided utility GHG emissions per unit of CH<sub>4</sub> combusted assumes that all landfill gas-to-energy projects produce electricity. In reality, some projects are “direct gas” projects, in which CH<sub>4</sub> is piped directly to the end user for use as fuel. In these cases, the CH<sub>4</sub> 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 non-landfill environment. In other words, it was assumed that in a baseline where yard trimmings are returned to the soil (i.e., in a non-landfill environment), all of the carbon is decomposed relatively rapidly (i.e., within several years) to CO<sub>2</sub>, 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.
- The key assumptions that have not already been discussed as limitations are the assumptions used in developing “corrected” CH<sub>4</sub> yields for biodegradable materials in MSW. Because of the high GWP of CH<sub>4</sub>, a small difference between estimated and actual CH<sub>4</sub> generation values would have a large effect on the GHG impacts of landfilling and the ranking of landfilling relative to other MSW management options.

#### 4. REFERENCES

- 61 FR 49. (1996). Standards of Performance for New Stationary Sources and Guidelines for Controls of Existing Sources, Municipal Solid Waste Landfills. *61 Federal Register 49* (12 March 1996), pp. 9905-9944.
- 71 FR 230. (2013). Revisions to the Greenhouse Gas Reporting Rule and Final Confidentiality Determinations for New or Substantially Revised Data Elements; Final Rule. *78 Federal Register 230* (29 November 2013), pp. 71904-71981.

- Barlaz, M.A., Bareither, C.A., Hossain, A., Saquing, J., Mezzari, I., Benson, C.H., Tolaymat, T.M., Yazdani, R. (2010). Performance of North American bioreactor landfills. II: Chemical and biological characteristics. *Journal of Environmental Engineering-ASCE* 2010 (136), 839-853.
- Barlaz, M.A. (2008). Memorandum to Parties Interested in Carbon Sequestration from Municipal Solid Waste: "Corrections to Previously Published Carbon Storage Factors." February 27, 2008.
- Barlaz, M.A. (2005). Letter to Randy Freed, ICF International: "Decomposition of Leaves." June 29, 2005.
- Barlaz, M.A. (1998). Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills. *Global Biogeochemical Cycles*, 12 (2), 373–380.
- Barlaz, M. A., Chanton, J. P., & Green, R. B. (2009). Controls on Landfill Gas Collection Efficiency: Instantaneous and Lifetime Performance. *Journal of the Air & Waste Management Association*, 59 (12).
- Barlaz, M. A., Ham, R. K., & Schaefer, D. M. (1990). Methane Production from Municipal Refuse: A Review of Enhancement Techniques and Microbial Dynamics. *Critical Reviews in Environmental Control*, 19 (6), 557.
- Barlaz, M. A., Ham, R. K., & Schaefer, D. M. (1989). Mass Balance Analysis of Decomposed Refuse in Laboratory Scale Lysimeters. *Journal of Environmental Engineering, ASCE*, 115 (6), 1088–1102.
- Bogner, J., Ahmed, M. A., Diaz, C., Faaij, A., Gao, Q., Hashimoto, S., Mareckova, K., Pipatti, R., & Zhang, T. (2007). Chapter 10L: Waste Management. In B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, & L.A. Meyer (Eds.), *Climate Change 2007: Mitigation*. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press.
- Bingemer, H G., & Crutzen, P. J. (1987). The Production of Methane from Solid Wastes. *Journal of Geophysical Research*, 90 (D2), 2181–2187.
- Chan G., Chu, L., & Wong, M. (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.
- Colberg, P.J. (1988). Anaerobic microbial degradation of cellulose lignin, oligolignols, and monoaromatic lignin derivatives. In A. J. B. Zehnder (Ed.), *Biology of anaerobic microorganisms*. New York: Wiley, pp. 333–372.
- Czepiel, P. M., Mosher, B., Crill, P. M., & Harriss, R. C. (1996). Quantifying the effects of oxidation on landfill methane emissions. *Journal of Geophysical Research*, 101, 16721–16729.
- De la Cruz, F. B., & Barlaz, M. A. (2010). Estimation of Waste Component-Specific Landfill Decay Rates Using Laboratory-Scale Decomposition Data. *Environmental Science & Technology*, 44 (12), 4722–4728. doi:10.1021/es100240r.
- Eklund B., Anderson, E., Walker, B., & Burrows, D. (1998). Characterization of landfill gas composition at the Fresh Kills municipal solid-waste landfill. *Environ Sci Technol*, 32, 2233–2237.
- Eleazer, W.E., Odle, W. S. III, Wang, Y. S., & Barlaz, M. A. (1997). "Biodegradability of municipal solid waste components in laboratory-scale landfills." *Env. Sci. Tech*, 31 (3), 911–917.
- EPA. (2014a). eGRID2010 year 2010 aggregation file. Available online at: <http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html>.

- EPA. (2014b). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2012*. (EPA publication no. EPA 430-R-14-003.) Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs, April. Retrieved from: <http://epa.gov/climatechange/emissions/usinventoryreport.html>.
- EPA. (2013). *The Landfill Methane Outreach Program (LMOP) LFGE Benefits Calculator*. Available online at: <http://www.epa.gov/lmop/projects-candidates/lfge-calculator.html>.
- EPA. (2010). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008*. (EPA publication no. EPA 430-R-10-006.) Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs, April. Retrieved from: <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/archive.html>.
- EPA. (1998). *AP-42 Emission factors for municipal solid waste landfills – Supplement E*. Washington, DC: U.S. Environmental Protection Agency.
- FAL (1994). *The Role of Recycling in Integrated Solid Waste Management to the Year 2000*. Franklin Associates, Ltd. (Stamford, CT: Keep America Beautiful, Inc.), pp. 1-16.
- Freed, J.R., Skog, K., Mintz, C., & Glick, N. (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.
- Hartog, C. L. (2003). The Bluestem Bioreactor. Briefing presented at the Bioreactor Workshop, sponsored by USEPA, February 27–28, 2003, Arlington, VA.
- Hilger, H., & Barlaz, M. (2001). Anaerobic decomposition of refuse in landfills and methane oxidation in landfill cover soils, *Manual of Environmental Microbiology*, 2nd Ed., Washington, DC: Am. Soc. Microbiol., pp. 696–718.
- IPCC. (2006). Chapter 3: Solid Waste Disposal. In *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5: Waste (Vol. 5)*. Intergovernmental Panel on Climate Change (IPCC). Retrieved from <http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html>.
- Levis, J. and Barlaz, M.A. (2014). Landfill Gas Monte Carlo Model Documentation and Results. Available under Background Documents at <http://epa.gov/epawaste/conserves/tools/warm/SWMGHGreport.html>. June 18, 2014.
- Levis, J. W., Barlaz, M. A., DeCarolis, J. F., Ranjithan, S. R. (2013). What is the optimal way for a suburban U.S. city to sustainably manage future solid waste? Perspectives from a Solid Waste Optimization Life-cycle Framework (SWOLF). *Environ. Sci. Technol.*, submitted.
- Liptay, K., Chanton, J., Czepiel, P., & Mosher, B. (1998). Use of stable isotopes to determine methane oxidation in landfill cover soils. *Journal of Geophysical Research*, 103 (D7), 8243–8250.
- Staley, B. F., & Barlaz, M. A. (2009). Composition of Municipal Solid Waste in the United States and Implications for Carbon Sequestration and Methane Yield. *Journal of Environmental Engineering*, 135 (10), 901–909. doi: 10.1061/(ASCE)EE.1943-7870.0000032
- Tolaymat, T.M., Green, R.B., Hater, G.R., Barlaz, M.A., Black, P., Bronson, D., Powell, J. (2010). Evaluation of landfill gas decay constant for municipal solid waste landfills operated as bioreactors. *Journal of the Air & Waste Management Association*, 2010 (60), 91-97.
- Wang, X., Padgett, J. M., Powell, J. S., Barlaz, M. A. (2013). Decomposition of Forest Products Buried in Landfills. *Waste Management*, 33 (11), 2267-2276.

Wang, X., Padgett, J.M., De la Cruz, F.B., and Barlaz, M.A. (2011). Wood Biodegradation in Laboratory-Scale Landfills. *Environmental Science & Technology*, 2011 (45), 6864-6871.

Warith, M. A., Zekry, M., & Gawri, N. (1999). Effect of leachate recirculation on municipal solid waste biodegradation." *Water Quality Research Journal of Canada*, 34 (2), pp. 267–280.