Understanding the Inventory of U.S. Greenhouse Gas Emissions and Sinks and the Greenhouse Gas Reporting Program for Landfills: Methodologies, Uncertainties, Improvements and Deferrals

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ABSTRACT

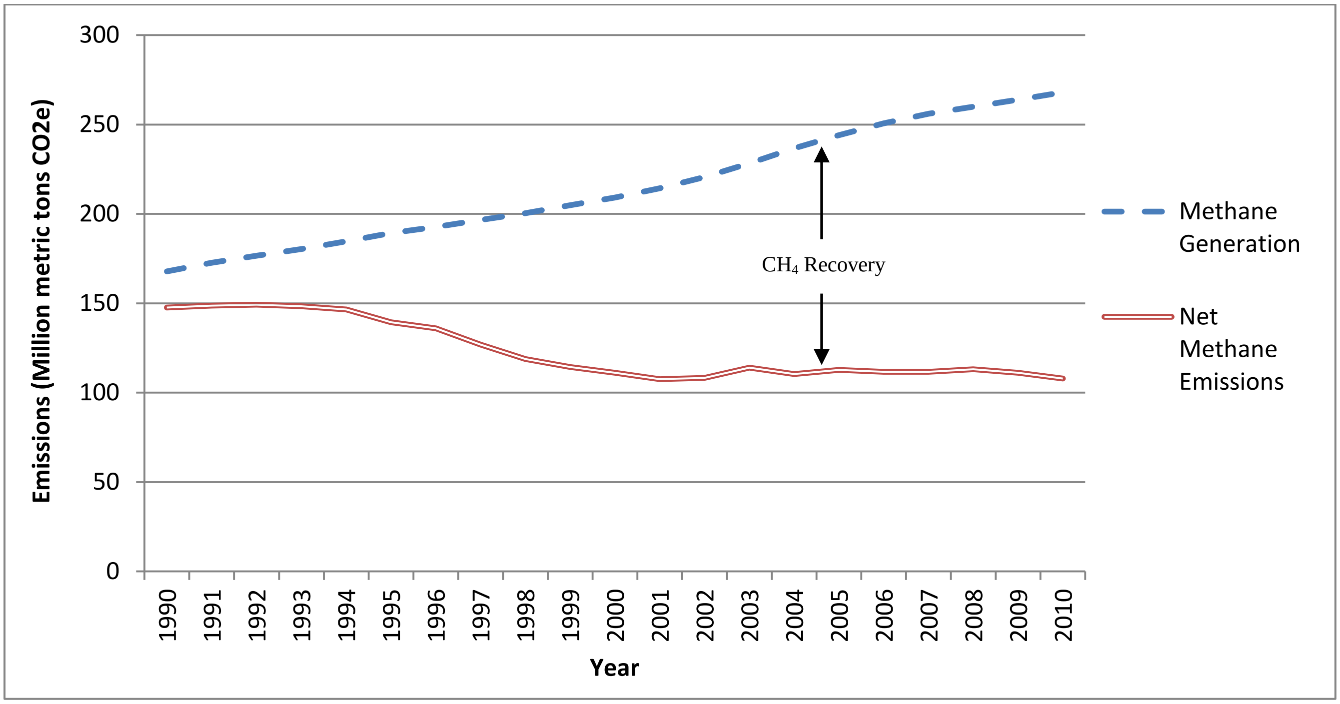
The Inventory of U.S. Greenhouse Gas Emissions and Sinks is a top down emissions inventory that estimates nationwide greenhouse gas emissions including methane emissions from municipal solid waste and industrial waste landfills using the 2006 Intergovernmental Panel on Climate Change Guidelines. A combination of datasets is used as inputs to the landfill section of the Inventory. Methane generation, recovery, and net emissions are estimated using data from these datasets at the national level, along with default values for certain parameters. The Greenhouse Gas Reporting Program (GHGRP), on the other hand, requires individual landfills meeting the applicability threshold to report detailed landfill characteristics and landfill methane emissions using a consistent methodology.

There are several differences between the Inventory and the GHGRP, including the methodology and data inputs used to determine net methane emissions. This paper provides an overview of each program and seeks to explain the differences between the methodologies. By using the GHGRP data, the Inventory may be improved to provide a more complete picture of greenhouse gas emissions from landfills in the United States. The GHGRP data elements that may be the most useful in terms of improving the Inventory's estimates have been deferred from reporting until 2013. However, once the deferral expires, the GHGRP data may help reduce uncertainties associated with the Inventory's emissions estimates.

INTRODUCTION

Atmospheric methane (CH_4) levels have tripled since pre-industrial times, and although there is less CH_4 in the atmosphere compared to carbon dioxide (CO_2), CH_4 is 21 to 25 times more potent as a greenhouse gas (GHG).[1] The majority of CH_4 emissions result from anthropogenic sources including natural gas activities, agricultural sources, and landfills.[2] Organic waste placed in municipal solid waste (MSW) or industrial waste landfills generates CH_4 and CO_2 emissions at approximately equal proportions as the waste decays over time. In 1990, landfills were one of the largest sources of CH_4 emissions according to the U.S. Inventory of Greenhouse Gases and Sinks (the Inventory). Despite an increase in waste generation, net CH_4 emissions from landfills decreased by approximately 27 percent over the 1990 to 2010 time frame (see **Figure 1**) due to increased landfill gas recovery and increased composting of organic wastes. In 2010, landfill CH_4 emissions totaled approximately 107.8 million metric tons of carbon dioxide equivalents (million MT CO_2e), or 5,135 MT of CH_4, representing the third largest source of CH_4 emissions in the United States, behind natural gas systems and enteric fermentation[2].

Figure 1. Methane emissions from MSW and industrial waste landfills from 1990 to 2010 (million MT CO_2e).[2]



Over 1,900 landfills currently operate in the U.S. with a small number of the largest landfills receiving most of the waste and generating the majority of CH_4 emissions.[3] Technologies, policies, and management programs exist to reduce CH_4 generation and emissions from landfills. A recent United Nations Environment Programme (UNEP) report presented 16 fast-action climate change mitigation measures that, if fully implemented across the globe, could save close to 2.5 million lives a year, avoid crop losses and deliver near-term climate protection of about half a degree by 2040.[4] Seven measures to specifically mitigate CH_4 emissions are identified, including the capture of landfill gas. Accurately quantifying landfill CH_4 generation and emissions through models and emission inventories is a key factor in evaluating and implementing CH_4 reduction strategies. Two ways that the United States quantifies CH_4 emissions from landfills include the Inventory and the Greenhouse Gas Reporting Program (GHGRP).

Since 1990, the EPA has prepared and the U.S. Government has submitted the U.S. Inventory of Greenhouse Gases and Sinks annually to the United Nations Framework Convention on Climate Change (UNFCCC) to meet its reporting requirements for a variety of source categories, including landfills. Adopted in 1992, the UNFCCC sets an overall framework for intergovernmental efforts to tackle the challenges posed by climate change. The submitted GHG emission inventories are considered impartial and policy-neutral mechanisms to compare relative GHG contributions between countries. Therefore, countries use recommended methodologies (i.e., the IPCC 2006 Guidelines) to create emissions inventories for pre-defined source categories over a defined timeline (1990 to current year) to promote consistency and comparability. As part of the Inventory, the EPA estimates CH_4 emissions from waste management activities, specifically MSW and industrial waste landfills.

The GHGRP is a relatively new EPA program that requires certain MSW and industrial waste landfills to report CH_4 emissions and landfill-specific characteristics under subpart HH (MSW landfills) or subpart TT (industrial waste landfills). Beginning in 2010, all MSW landfills that accepted waste on or after January 1, 1980 and generate CH_4 in amounts equivalent to 25,000 MT or more of CO_{2e} are subject to the GHGRP under subpart HH. The first annual GHG reports were due by September 30, 2011 and are required to be submitted annually thereafter. The subpart HH source category consists of the landfill, landfill gas collection system, and landfill gas destruction devices including flares. Not all landfills in the U.S. are required to report under subpart HH, but the program does apply to the largest landfills with the greatest CH_4 generation. Industrial waste landfills are also subject to this program beginning in 2011 if the landfill accepted waste on or after January 1, 1980 and is located at a facility whose total landfill design capacity is greater than or equal to 300,000 MT and the facility has combined GHG emissions equal to or greater than 25,000 MT CO_2e. The first annual GHG reports are due by September 30, 2012 and are required to be submitted annually thereafter. An industrial waste landfill is not subject to the program if it is a dedicated construction and demolition waste landfill, or a landfill that receives only inert waste materials (as defined in the subpart) such as coal combustion residue (e.g., fly ash), cement kiln dust, rocks and/or soil, glass, non-chemically bound sand (e.g., green foundry sand), clay, gypsum, pottery cull, bricks, mortar, cement, furnace slag, refractory material, or plastics.

This paper seeks to briefly describe the similarities and differences between the methodologies used by these two EPA programs, their uncertainties, and improvements that could be made to the Inventory using data reported under the GHGRP. The timeline for implementing these improvements is also discussed as it depends on several data elements that have been deferred from reporting under the GHGRP.

BODY

Methane Generation and Emissions from Landfills

When waste is placed in a landfill, it is initially decomposed by aerobic bacteria, which produce CO_2. After the landfill environment becomes anaerobic (i.e., the available oxygen is consumed), anaerobic microorganisms will break down the organic matter contained in the waste material into cellulose, amino acids, and sugars. Through fermentation, these substances are further broken down into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. Through this series of complex biological transformations, the anaerobic bacteria convert the fermentation products into stabilized organic materials and biogas, a mixture consisting mainly of CH_4 and CO_2. Landfill gas is typically assumed to contain approximately 45 to 55 percent CH_4 and 45 to 55 percent CO_2 (considered biogenic) with less than 1 percent consisting of other trace gases.[5] Negligible amounts of N_2O are generated from MSW landfills unless cover soils are amended with sewage sludge or aerobic and/or semi-aerobic landfilling practices are implemented.[6,7] Few studies have tried to quantify N_2O emissions aside from Zhang et al.[7,8]

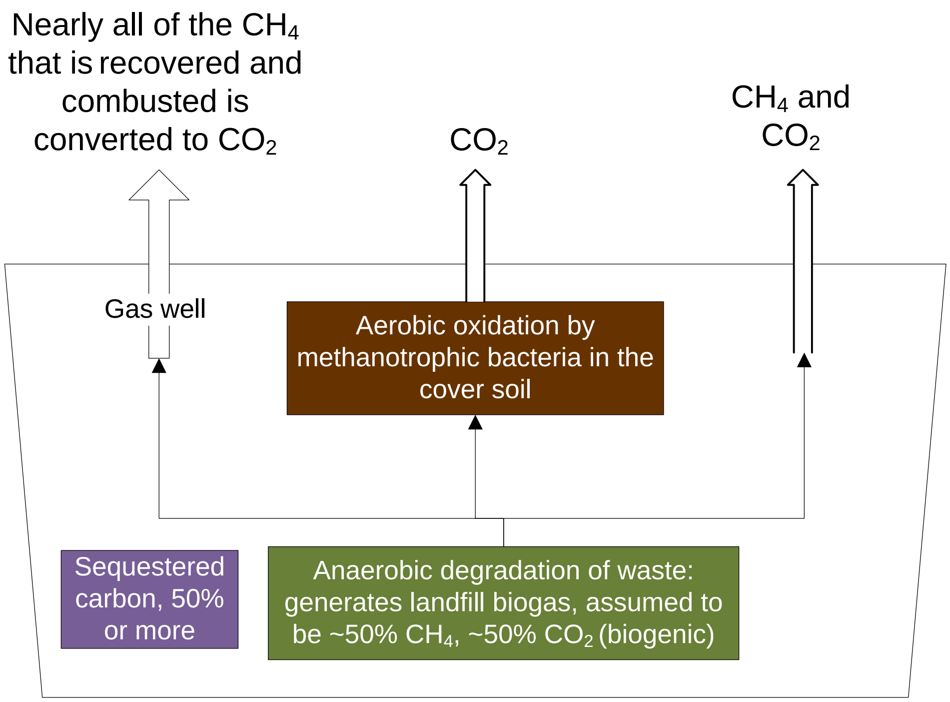
The amount of landfill gas generated and emitted depends on several factors, including:

- Composition of the landfilled waste (e.g., the amount and types of degradable [food, yard trimmings, paper, etc.] versus non-degradable wastes [plastics, metals, glass, etc.])
- Amount of waste landfilled
- Age of the landfilled waste (i.e., the year it was disposed)
- Environmental physico-chemical conditions (e.g., rainfall, temperature, pH, depth of waste, etc.)

- Presence and efficiency of the landfill gas collection system, and
- Cover type (e.g., sand, clay, geomembrane).

The CH_4 generated in the landfill may be emitted directly to the atmosphere, or collected and then flared or combusted to produce electricity or heat, converting the CH_4 to CO_2. Methane that is not collected will diffuse through the cover soil which contains adequate oxygen for aerobic degradation. A portion of the CH_4 will be oxidized to CO_2 as it diffuses through the soil surface. **Figure 2** presents a simplified mass balance for a typical landfill.

Figure 2. Simplified Mass Balance of a Typical Landfill (adapted from Bogner et al., 2007 [6]).



Emission Estimation Methodologies

Because an accepted method for direct measurement of CH_4 emissions from landfills is not currently available, CH_4 generation estimates are based on the IPCC first order decay (FOD) model (see Equation 1) where the rate of CH_4 generation is proportional to the quantity of degradable waste placed in the landfill. The IPCC FOD model is used to estimate CH_4 generation for the Inventory and subparts HH and TT.

Equation (1)

$$G_{CH4} = \left[\sum_{x=S}^{T-1}\left\{W_x \times DOC_x \times MCF \times DOC_F \times F \times \frac{16}{12} \times \left(e^{-k(T-x-1)} - e^{-k(T-x)}\right)\right\}\right]$$

where

G_{CH4} = amount of CH_4 generated (metric tons/year)
X = Year in which waste was disposed
S = Start year of calculation
T = Reporting year for which emissions are calculated

W_x = Quantity of waste disposed in the landfill in year X (metric tons, as received [wet weight])
DOC_x = Degradable organic carbon for waste disposed in year X (fraction [metric tons C/metric ton of waste]).
DOC_F = Fraction of DOC dissimilated (fraction)
MCF = Methane correction factor (fraction)
F = Fraction by volume of CH_4 in generated landfill gas (fraction, dry basis).
k = Decay rate constant (yr^{-1})

The key terms affecting CH_4 generation are the decay rate (k) and the amount of degradable organic carbon (DOC). In the Inventory, W_x in Equation 1 represents the total amount of waste generated in all 50 states multiplied by a disposal factor representing the fraction of waste generated that is disposed of in a landfill. Waste generation and disposal data are obtained from the BioCycle State of Garbage reports which are published every two years. Unlike the site-specific information reported through the GHGRP, the Inventory models three types of landfills based on climate (dry, moderate, and wet) using a national quantity of waste disposed and default values for parameters in the FOD equation. For the GHGRP, W_x is the quantity of waste landfilled in a given year at a specific facility.

In general, most landfills lack site-specific data, particularly those that are no longer active[6]. Therefore, default values for the variables DOC_x, DOC_F, MCF, F, and k are used in Equation 1 by the Inventory and are used for some, but not all variables in the GHGRP, depending on the program requirements. A brief description of these variables is provided below.

- DOC_x – The DOC is the organic carbon in the waste stream that is accessible to biochemical decomposition. DOC is determined from the waste composition and can be calculated from a weighted average of the DOC value of various components of the waste stream. The Inventory uses an average DOC value determined from landfill gas recovery data from representative landfills across the country and an assumed collection efficiency of 75 percent. The GHGRP includes default values by waste category and specific waste types, which are based on the default value used by the Inventory and the default values provided in Table 2.4 from Chapter 2 of the IPCC 2006 Guidelines.

- MCF – The MCF accounts for the fact that unmanaged, shallow solid waste disposal sites produce less CH_4 from a given amount of waste than an anaerobically managed site (i.e., a modern landfill). Both the Inventory and GHGRP use the same MCF value of 1.

- DOC_F – DOC_F is an estimate of the fraction of carbon that is ultimately degraded and released from landfills. It reflects the fact that some DOC does not readily degrade under anaerobic conditions in the landfill. The DOC_F value depends on many factors including waste composition, temperature, moisture, and pH. Both the Inventory and GHGRP use the same DOC_F value of 0.5.

- F – The fraction of CH_4 in generated landfill gas is typically assumed to be 50 percent and only waste materials containing significant amounts of fat or oil generate landfill gas with a higher percentage of CH_4 (IPCC, 2006). Both the Inventory and GHGRP use the same F value of 0.5.

- k – The decay rate constant depends on many factors including the waste composition, the climatic conditions of the waste disposal site, and waste disposal practices. Warm, wet climates yield higher decay rates (approximately 0.2, or a half life of 3 years) while cool, dry climates yield lower decay rates (approximately 0.02, or a half life of 35 years). The Inventory uses three different k values to model CH_4 generation for the three different landfill climates. The GHGRP allows facilities to choose the k value that is most applicable to conditions and waste composition at their facility.

Net CH_4 emissions from landfills without gas collection systems are calculated as shown in Equation 2.

Equation (2) $$Net\ CH_4\ emissions = G_{CH4} \times (1 - OX)$$

where

G_{CH4} = the amount of CH_4 generated using Equation 1 (metric tons)
OX = the oxidation factor (percent)

The oxidation factor represents the amount of CH_4 in the landfill that is oxidized in the soil or other material covering the waste. Methane is oxidized by methanotrophic microorganisms to a certain extent depending on the type, thickness, moisture content and other physical properties of the cover material[5]. A value of 10 percent is used as the default value for OX in both the Inventory and GHGRP. A recent literature review found that oxidation rates range greatly between individual landfills and that modern landfills with active gas collection systems tend to have a higher factor of oxidation.[9] The Inventory uses a value of 10 percent because it is within the range recommended IPCC 2006 Guidelines while the GHGRP requires 10 percent be used for the oxidation factor for all landfills based on the data available at the time the program requirements were developed and because it is at the upper range of oxidation factors recommended by the 2006 IPCC Guidelines.

There are significant differences between how the amount of CH_4 recovered by landfill gas collection systems (R) is calculated by the Inventory and the GHGRP for landfills with gas collection systems. To determine R, the Inventory uses a combination of three databases (discussed in more detail in the next section of this paper), resulting in large uncertainties with the recovery estimates. The GHGRP, on the other hand, requires direct measurements of flow rates and CH_4 concentration of recovered landfill gas at landfills with gas collection systems. The GHGRP provides two different methodologies to estimate landfill CH_4 emissions and facilities reporting under subpart HH or TT must assess and report their emissions using both methodologies. Equation 3 presents the equation used to calculate net CH_4 emissions for the GHGRP. The Inventory uses a similar equation, with the only difference being the absence of the term f_{Dest} (i.e., f_{Dest} is assumed to be 1).

Equation 3 as applied by the GHGRP (also expressed by Equation HH-6 in the GHGRP) relies primarily on the modeled CH_4 generation rates determined from the mass of waste disposed of in the landfill using Equation 1 (i.e., Equation HH-1 in the GHGRP, which is the FOD model that is also used by the Inventory). The second methodology (expressed by Equation HH-8 in the GHGRP and in this paper as Equation 4) relies primarily on the measured quantity of gas recovered and an estimate of the collection efficiency of the gas collection system.

Equation (3) $$Net\ CH_4\ emissions = [G_{CH4} - R] \times (1 - OX) + R \times (1 - (DE \times f_{Dest}))]$$

where

G_{CH4} = amount of CH_4 generated using Equation 1 (or Equation HH-1, or Equation HH-4 of the GHGRP, whichever is greater to avoid a negative value for net emissions) (metric tons)
R = quantity of CH_4 recovered from Equation HH-4 of the GHGRP (metric tons)
OX = oxidation factor (percent)
DE = destruction efficiency (percent)

f_{Dest} = fraction of hours the destruction device was operating; this term is not used (or assumed to be 1) in the Inventory methodology (percent)

Equation (4) $$Net\ CH_4\ emissions = [\left(\frac{R}{CE \times f_{REC}} - R\right) \times (1 - OX) + R \times \left(1 - (DE \times f_{Dest})\right)]$$

where

- R = quantity of CH_4 recovered from Equation HH-4 of the GHGRP (metric tons)
- CE = collection efficiency estimated at the landfill, taking into account system coverage, operation, and cover system materials from Table HH-3 of the GHGRP. If area by soil cover type information is not available, the default value of 0.75 should be used. (percent)
- f_{REC} = fraction of hours the recovery system was operating (percent)
- OX = oxidation factor (percent)
- DE = destruction efficiency (percent)
- f_{Dest} = fraction of hours the destruction device was operating (fraction)

Data Sources Used to Estimate Emissions in the Inventory

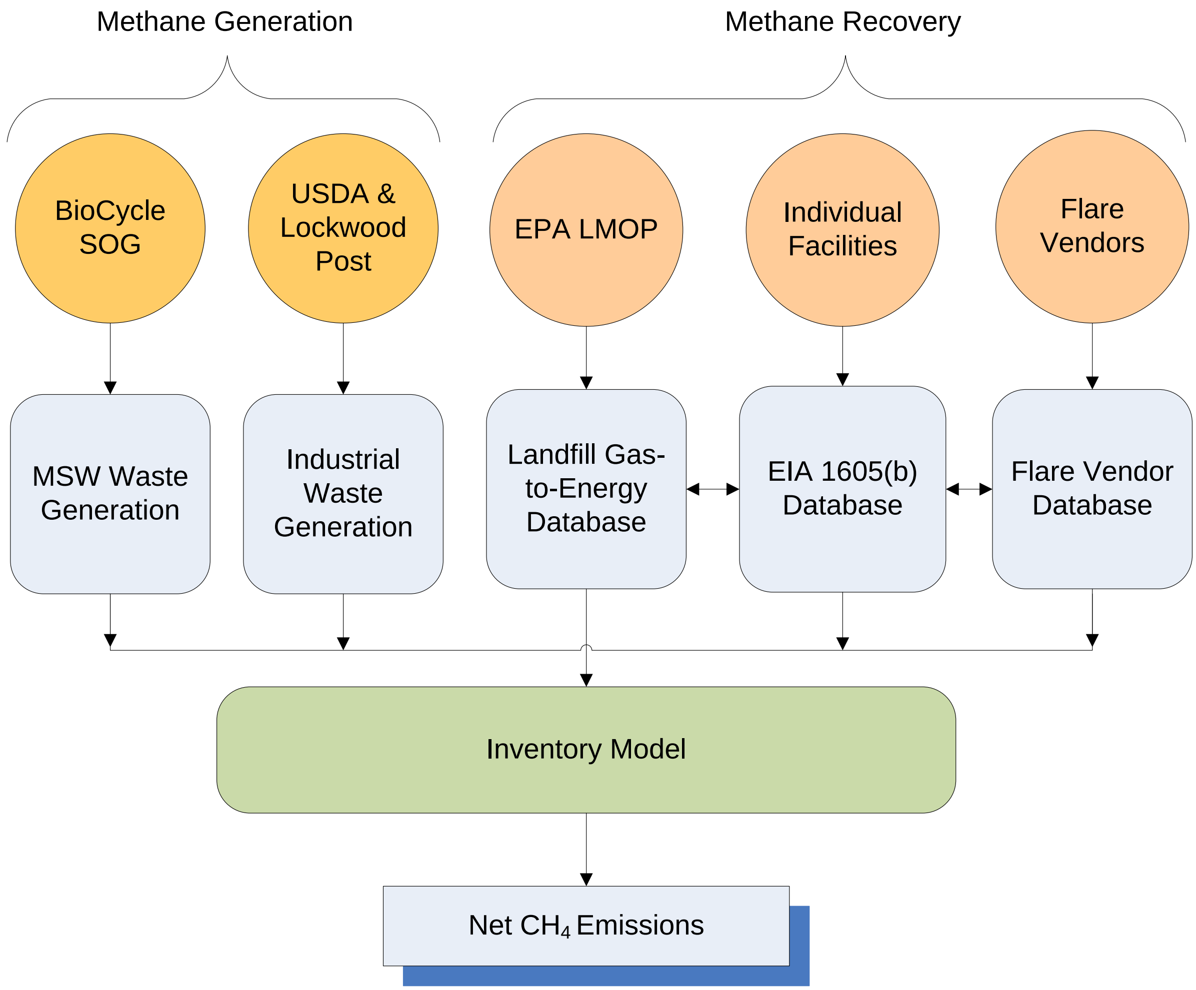
Unlike the GHGRP, the Inventory uses a combination of secondary data sources as shown in **Figure 3**. Briefly, the amount of waste generated nationally is used to estimate the amount of CH_4 generated nationally, to which the amount of CH_4 recovered and oxidized is subtracted. This methodology assumes that the landfills represented by the databases described below include all of the landfills with gas collection systems in the United States.

Municipal solid waste generation and disposal data are obtained for MSW landfills from the BioCycle State of Garbage reports (see BioCycle, 2010 for the latest report). Industrial waste generation data are estimated based on production rates for the food industry from the United States Department of Agriculture (USDA) QuickStats and for the pulp and paper industry from the Lockwood Post Directory.

Data used to estimate CH_4 recovery comes from three sources: the EPA's voluntary Landfill Methane Outreach Program (LMOP) database of landfills and landfill gas-to-energy projects (updated annually[10]), the 2005 EIA 1605(b) database[11], and the Flare database (updated annually). The latest EIA 1605(b) database contains 2005 data about landfills and their gas collection systems (i.e., reported amounts of recovery) and is no longer updated. Information included in the Flare database includes sales records obtained annually from three of the largest flare vendors in the United States. The LMOP, the EIA 1605(b), and the Flare databases are linked to each other to avoid double counting unique landfills and their CH_4 recovery. A significant effort is made each Inventory year to check for double counting of recovered amounts of CH_4.

Currently, the EIA data are given precedence because CH_4 recovery was directly reported by facilities. LMOP data are given second priority because CH_4 recovery is estimated from the LFGTE system characteristics. The Flare database is the third priority, with CH_4 recovery estimated as 50 percent of the provided flare capacity. The uncertainty associated with these databases increases as priority decreases. However, uncertainty surrounding the amount of CH_4 recovered as reported in the EIA database increases with each passing year as it becomes more outdated.

Figure 3. Schematic of the data sources flowing into the Inventory model.



Note: SOG = State of Garbage reports; USDA = United States Department of Agriculture; LMOP = Landfill Methane Outreach Program; EIA = Energy Information Administration.

Key uncertainties Associated with the Methodologies and Emission Estimates

Several types of uncertainty are associated with the CH_4 generation estimates from the FOD model approach used by the Inventory and the GHGRP, including the FOD model itself, the changing waste composition, and other inputs to the FOD model. All models are based on a set of underlying assumptions, adding error and uncertainty to the end result. There is a high degree of uncertainty and variability associated with theoretical FOD models that assume a homogeneous waste composition and hypothetical decomposition rates in heterogeneous landfill settings[5].

The Inventory uses an average bulk MSW DOC value determined based on CH_4 generation rates measured in representative U.S. landfills equipped with gas recovery systems and assuming an average gas collection efficiency of 75 percent[2]. The average bulk MSW DOC value determined from these landfills represent average waste composition over the years 1985 to 2005 that may be outdated as waste characteristics change over time. Over the past two decades, organics have increasingly been diverted from landfills to composting facilities, contributing to changes in the average composition of waste being disposed and increasing the uncertainties surrounding the CH_4 generation estimates based on the Inventory's default DOC value. Although waste-specific default DOC values are available in the IPCC Guidelines[5], there are limited waste characterization studies available for landfills in the United States from which more accurate waste-specific DOC defaults may be derived.

While there are uncertainties with using the average bulk MSW default DOC value to estimate the cumulative CH_4 generation across thousands of landfills, there are greater uncertainties when applying the bulk MSW default DOC value to individual landfills. Estimates of DOC values for individual landfills often vary by a factor of two or more, but the average DOC value across multiple studies is fairly consistent, with uncertainties on the order of 25 to 30 percent.[12,13,14] Thus, using an assumed bulk MSW default DOC value is highly uncertain when applied to a single landfill, but is less uncertain when applied across all landfills as is done in the Inventory.

The most significant source of uncertainty in the Inventory surrounds the amount of recovered CH_4. As discussed earlier, the EIA 1605(b) database is considered to contain the most reliable recovery data compared to the LMOP and Flare databases. However, the Inventory uses the same amount of recovery reported for landfills in this dataset for 2005 and each year thereafter because 2005 was the last year this database was updated. No other comprehensive datasets have been identified to replace the 1605(b) dataset. As this dataset becomes more outdated, its uncertainty will increase. In contrast to the high uncertainties in CH_4 recovery estimates in the Inventory, the GHGRP requires direct measurement of the flow rate and CH_4 concentration in recovered landfill gas. Therefore, the CH_4 recovery estimates determined for the GHGRP are expected to have uncertainties on the order of only 5 percent.

In the GHGRP, landfills without gas collection systems use only the forward calculation approach based on the FOD model (i.e., Equations HH-1 and HH-5 in the GHGRP and Equations 1 and 3 in this paper) for estimating CH_4 emissions. For landfills with gas collection systems, the GHGRP requires that net CH_4 emissions be estimated and reported using both a forward calculation approach (i.e., Equation HH-6 in the GHGRP and Equation 3 in this paper) and a back calculation approach (i.e., Equation HH-8 of the GHGRP and Equation 4 in this paper). Both of these approaches are expected to have significant uncertainties.

The forward calculation approach (either Equations HH-5 for landfills without gas collection systems or Equation HH-6 for landfills with gas collection systems) uses CH_4 generation from the FOD model. Although the GHGRP allows the use of waste-specific DOC values, it is expected that most landfills will use the average bulk MSW default. Consequently, CH_4 generation and emission estimates using the forward calculation approach are expected to have high uncertainties because the bulk MSW default DOC value is highly uncertainty when applied to individual landfills, as discussed previously.

The back calculation approach uses measured CH_4 recovery along with an estimate of the landfill gas collection efficiency to estimate CH_4 generation. The GHGRP requires the use of a series of default collection efficiencies for areas of the landfill that have “active gas collection” depending on the type of soil cover. There are uncertainties in the default collection efficiency factors as well as uncertainties in the areas assigned to each default factor. For example, there is currently no guidance for determining how close to a collection pipe one needs to be to be considered under “active gas collection” and the GHGRP relies on the assessments made by individual landfill owners and operators for these area estimates. Thus, even though the gas collection efficiency is determined on a site-specific basis for the GHGRP, there are significant uncertainties associated with these values. Using the back-calculation approach, the measured recovery is divided by the collection efficiency to estimate CH_4 generation and emissions; therefore, uncertainties in the gas collection efficiency value cause uncertainties in the back-calculated values of CH_4 emissions.

The 2010 reporting year data for subpart HH revealed that, for most landfills with gas collection systems, there are significant differences between the results of Equations HH-6 and HH-8, which are expected considering the uncertainties just discussed. The variability between the two equations in the GHGRP will be further analyzed in future reporting years. In addition, once the equation inputs are collected, starting in 2013, more detailed information on these equations will be available such that they may be even further analyzed.

Lastly, uncertainty also exists in the estimated oxidation by cover soils (i.e., the IPCC default value of 10 percent). The actual amount of oxidation is difficult to quantify outside of laboratory settings and differs from landfill to landfill. Modern landfills that actively manage their wastes may have higher oxidation rates, but older, inactive sites may not[9]. Both the Inventory and the GHGRP use the 10 percent oxidation factor, so uncertainties in the oxidation factor apply to both programs.

How Can the GHGRP Data Improve the Inventory and When?

Several potential improvements may be made to the Inventory using the GHGRP data. The site-specific data reported through the GHGRP that are most relevant to improving the Inventory emissions estimates (i.e., the net CH_4 emissions) are those related to the waste characterization and amount of recovered CH_4. Unfortunately, these data elements have been deferred from reporting until March 2013.[15] These data elements include:

- Quantity of waste disposed for each year of landfilling (for subpart TT the quantity and description of each waste stream is reported)
- Waste composition for each year in percentage by weight for the type of waste reported (for subpart HH)
- DOC value (for subpart TT, this is required by waste stream [DOC_x])
- MCF value (if the reporter used a value other than the default of 1)
- DOC_F
- Decay rate constant (k) (for subpart TT, this is required by waste stream)
- Fraction of CH_4 in landfill gas (F)
- Surface area associated with each cover type
- Operating hours and destruction efficiency for the primary and backup destruction devices used at the landfill
- Quantity of recovered CH_4 (R) calculated using Equation HH-4
- Estimated gas collection efficiency
- Surface area by cover type
- Annual operating hours of the gas collection system

Because of the deferral of reporting equation inputs, significant improvements cannot be made to the Inventory until the 1990-2013 Inventory year, which will be prepared in 2014. When the deferral expires and the data elements have been verified, they may then be used to potentially improve the Inventory dataset and estimated emissions.

The most useful data element for the Inventory will be the amount of recovered CH_4 for each reporting landfill from the GHGRP. Because the applicability threshold for the GHGRP for MSW landfills is based on CH_4 generation (without considering recovery) rather than CH_4 emissions, it is anticipated that nearly all of the landfills in the country with gas collection systems will be reporting under the GHGRP. Using measured CH_4 recovery as inputs to the Inventory as reported by individual landfills via the GHGRP is expected to be much more reliable and accurate than the data currently being used. The information reported through the GHGRP undergoes an extensive series of verification steps and will reduce uncertainties surrounding CH_4 recovery when applied to the landfills in the Inventory dataset.

An updated national waste characterization may also be developed using the waste composition data reported in the GHGRP. The waste types disposed by each year of landfill operation that are reported, may make it possible to group the reporting landfills into the major waste composition types. Through a literature search of waste characterization studies, we could determine if different DOC values could be assigned to the landfills in each waste composition group.

Inputs to the FOD equation (i.e., Equation 1 in this paper and Equations HH-1 or TT-1 in the GHGRP) can be analyzed across the GHGRP dataset and a more up-to-date bulk MSW DOC value could be developed to replace the default value currently used in the Inventory model. Additionally, the Inventory currently uses a default MCF value of 1 and an F value of 0.5. Landfills reporting under the GHGRP must indicate if a value other than the default is used for both MCF and F, but reporting of the actual values used has been deferred. If an MCF value other than 1 is used, it is expected that the landfill has active aeration and the facility must answer a series of questions regarding the aeration system. When the deferral expires, an analysis of landfills with active aeration and deep or shallow landfills may be performed to determine whether the MCF used in the Inventory should be revised and whether a different MCF should be used for industrial waste landfills versus MSW landfills.

Other potential improvements to the Inventory using the GHGRP data are described below. These potential improvements will not specifically reduce the uncertainties surrounding the amount of calculated CH_4 generated and recovered by the Inventory model, but can create a more robust dataset to use in policy-related analyses.

- ***Create a list of reporting and non-reporting landfills***. Landfills reporting under subparts HH and TT can be matched to those landfills in the LMOP, EIA database and Flare database using the registered landfill name and/or landfill ID.

- ***Estimate emissions separately for reporting and non-reporting landfills***. If facilities without landfill gas recovery are in the LMOP and/or Flare databases, but not the GHGRP dataset, it may be possible to break out the reporting landfills from the non-reporting landfills enabling emissions to be estimated separately for reporting and non-reporting landfills. The current inventory methodology can be used for the non-reporting landfills since the Inventory model will still be relying on the LMOP, EIA 1605(b), and Flare databases. For non-reporting landfills, the landfills in the specific reporting thresholds (defined in USEPA, 2009 [16]) could be analyzed to see if the reporting landfill information could be extrapolated to the non-reporting landfills. The methodology can be improved for the reporting landfills over time as equation inputs become available.

- ***Cross-check landfill open/closed status in the LMOP, EIA, and Flare databases.*** Landfills reporting under subparts HH and TT can be cross-checked with the LMOP and EIA databases to make sure that all landfills are marked correctly as open or closed. If a closed landfill is marked open, then CH_4 emissions and destruction are being allocated erroneously. This is important for policy analyses since new policy options tend to focus on active landfills.

- ***Develop an uncertainty factor for scales versus assumed loads***. This is a possible addition to the uncertainty calculations in the Inventory. In general, landfills using scales will be reporting a more accurate estimate of waste quantities than those landfills without scales. The GHGRP data can be potentially tiered for landfills with and without scales to determine an uncertainty factor to apply for each tier, with the end result being that there is less uncertainty associated with waste quantity data reported using scales.

CONCLUSION

As the world's population increases, more waste will inevitably be generated and disposed. Landfill CH_4 emissions can be reduced through landfill gas collection and recovery projects and waste diversion measures. Better data regarding waste composition, landfill characteristics, and gas collection system operation can result in more accurate CH_4 emission inventory estimates to inform decision-makers.

The EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks for solid waste and the GHGRP subparts HH and TT are two important programs that contribute to the knowledge-base of landfill CH_4 emissions for decision-makers. The Inventory uses a top-down approach to estimate CH_4 emissions while the GHGRP requires facility-specific reporting. While the default values and assumptions used by the Inventory lead to uncertainty and may not be completely accurate or representative of all individual landfills (i.e., CH_4 may be over or underestimated at some sites), the variability in net emissions is thought to balance out overall. Despite the high amount of uncertainty associated with the Inventory, the FOD model and individual data sources, there are several advantages to the Inventory. For example, there is consistency and comparability between the other countries reporting under the UNFCCC framework, improvements are made to the methodology each year to better represent CH_4 emissions, and there is no burden on individual landfills to provide data currently being used for the Inventory.

Data obtained from the GHGRP can be used to create a more robust and complete Inventory data set and the inclusion of site-specific conditions and CH_4 recovery can reduce uncertainties in the Inventory emissions estimates. The data collected from the GHGRP can be incorporated in future Inventories (starting with the 1990-2011 Inventory year), but the most significant improvements will not occur until after the deferral of reporting of equation inputs expires in 2013. In the interim, the Inventory methodology can be improved using landfill-specific components. The key difference between the Inventory and the GHGRP methodology is related to how the amount of CH_4 recovered from landfill gas collection systems is determined. Measured CH_4 recovery data can significantly reduce the uncertainty in the CH_4 recovery value of the Inventory's emission estimates. Ultimately, the addition of this site-specific detailed data will provide a more accurate representation of GHG emissions from MSW and industrial waste landfills in the Inventory.

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KEY WORDS

Greenhouse gas, methane, landfills, emissions inventory