Estimates of solid waste disposal rates and reduction targets for landfill gas emissions

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1. Greenhouse Gas Reporting Program Data Queries

Data from the U.S. EPA’s Greenhouse Gas Reporting Tool portal were obtained to examine landfill facility-level information, including facility-level emissions data and associated metadata. This necessitated multiple custom data queries to ensure data sets for the full population of reporting facilities were available. The address of the portal to run a customized query is http://www.epa.gov/enviro/facts/ghg/customized.html. Only data for municipal landfills (located in the Greenhouse Gas Reporting Rule’s Subpart HH Subject “Municipal Solid Waste Landfills”) were explored. Data tables for Municipal Solid Waste Landfills and Facility Information were requested. Details of the key queries run to obtain the necessary data for years 2010, 2011, 2012, and 2013 are presented below.

1. Query 1: Landfill information. Information includes:

   a. Unique landfill ID (this number is consistent through all years of reporting)

   b. Reporting Year

   c. Landfill Name

   d. Year that the landfill will close (i.e., stop accepting waste). This number is typically based on the permitted capacity and projected waste acceptance rate for the facility.

   e. First year that the landfill accepted waste.

   f. The degree that the landfill recirculates leachate. Leachate is the liquid that drains to the bottom of landfills, which originates either from rainwater that percolates through the waste or from liquid that drains out from waste that is placed in the landfill. Some landfills “recirculate” their leachate, which means they either pump it back into the landfill using pipes or they use a spray irrigation type of system. Landfills will recirculate as a low-cost method of managing leachate since it is often less expensive than hauling the leachate to a wastewater treatment plant. Landfills may also recirculate leachate to speed up acceleration of waste in the landfill. This concept is similar to composting, and a large body of landfill research focuses on so-called “bioreactor” landfills, which deliberately attempt to accelerate organic waste decomposition in the landfill itself. The accelerated waste decomposition results in a faster rate of landfill gas production and has been considered a more sustainable method of managing waste.

   g. Whether or not the landfill is open and actively accepting waste.

   h. Whether or not the landfill has an active landfill gas collection system. A rule in the U.S. Clean Air Act (40 CFR Part 60, Subpart WWW, New Source Performance Standards for Municipal Solid Waste Landfills) requires landfills that reach a certain size (2.5 million tonnes of waste in place or 2.5 million m$^3$ of waste in place) to use active systems to collect landfill gas that is produced unless the site can demonstrate that their emissions are below a defined threshold.
i. The maximum capacity of the landfill, expressed in units of metric tons.

j. The total surface area of the site that contains waste, in units of m². This number differs from the total property that comprises the “landfill facility”, which are often much larger than the actual area containing waste because of planned buffer areas, access roads, administrative and support facilities.

k. Annual modeled CH₄ generation. This is a figure calculated based on the following equation (Eqn. 1-1) as published in the GHG reporting rule:

\[
G_{CH_4} = \left[ \sum_{x=S}^{T-1} \left( W_x \times MCF \times DOC \times DOC_f \times F \times \frac{16}{12} \times \left( e^{-k(T-x-1)} - e^{-k(T-x)} \right) \right) \right]
\]

Eqn. 1-1

Where: \( G_{CH_4} \) is the modeled CH₄ generation rate for the given year (tonnes CH₄); \( X = \) year in which waste was disposed; \( S = \) the start year of the calculation; \( T = \) reporting year for which emissions are calculated; \( W_x = \) quantity of waste disposed in the landfill in year \( X \) based on measurement data or other approved means (tonnes, wet weight); \( MCF = \) methane correction factor (fraction); \( DOC = \) degradable organic carbon from U.S. EPA Table HH-1 or available measurement data (tonne carbon/tonne waste); \( DOC_f = \) Fraction of DOC dissimilated (default = 0.5); \( F = \) Fraction by volume of methane in landfill gas from measurement data on a dry basis, if available (fraction); \( 16/12 = \) constant; \( k = \) rate constant from U.S. EPA Table HH-1 (yr⁻¹), the \( k \) value most applicable to the past 10 years or landfill operating life must be selected.

l. Indicators to show how the CH₄ fraction value was obtained and the CH₄ fraction value itself.

m. Latitude, longitude, and US state where the facility is located.

2. **Query 2: LFG collection system information. This query includes:**

a. Unique landfill ID

b. Reporting year

c. Facility name

d. Annual average CH₄ concentration (% by volume). This value is measured at a central collection point at each site using a calibrated instrument. The measurement frequency can vary per the requirements of the rule, but generally reflects measurements taken at least monthly.

e. Gas collection system efficiency. A higher efficiency reflects better system performance. The efficiency is calculated by the Greenhouse Gas Reporting Tool based on inputs provided to the system by each landfill site.
f. Gas collection system capacity (standard cubic feet per minute). This reflects the overall capacity of the gas collection system to remove gas from the landfill, and can be a quick indicator for the overall gas collection system’s size.

g. Gas collection system annual operating hours. This value shows the number of hours that each facility’s gas collection system operated for the given reporting year (maximum = 8,760). Each landfill with a gas collection system is required to have a data recording system that monitors whether or not the gas collection system is on and these data are uploaded to the GHG reporting program’s online portal.

h. Number of gas collection wells. This shows how many individual devices are installed within the landfill and are actively inducing a vacuum on the waste mass to collect gas.

i. Latitude, longitude, and US state where the facility is located.

3. **Query 3: Waste disposal quantity data. Information includes:**

   a. Unique landfill ID
   b. Reporting year
   c. Quantity of waste disposed of during the reporting year (tonnes)
   d. Facility name
   e. Latitude, longitude, and US state where the facility is located.

2. **Examination of Landfill Disposal Quantity and Available Landfill Capacity in the U.S.**

The data from Query 3 were organized by reporting year (2010, 2011, 2012, and 2013) and the amount of waste disposed of for each year was calculated by summing the waste disposal quantity for each site for each year as shown in Eqn. 2-1:

\[
M_{\text{Disposed},T} = \sum_{i=1}^{n} M_i
\]

**Eqn 2-1**

Where \(M_{\text{Disposed},T}\) is the total mass of waste disposed of in all landfills in a given year (tonne); \(i\) is an index; \(n\) is the total number of landfills that reported to the GHG reporting program in a given year, and \(M_i\) is the mass of waste reported to be disposed of at a given site in a given year. The results were provided in the manuscript in Figure 1. These disposal estimates likely represent a more accurate portrayal compared to previously-reported estimates that rely upon a materials flow analysis approach like the US EPA’s annually-published municipal solid waste facts and figures report, particularly because of GHG reporting rule’s requirement that facilities with certified scales submit waste quantities based on the scale data. The GHG Reporting Rule also sets forth scale accuracy requirements that all reporters must follow.
Previous estimates that relied upon surveying individual US states have reported larger waste disposal quantities than the routinely-published US EPA figure\(^2\), but the methodology used in the current study has several advantages compared to the material flow analysis and survey method:

1. Uniform reporting requirements for all facilities. Landfills subject to the GHG reporting rule must report annual waste disposal quantities using a uniform set of procedures in a common unit (tonnes). Certified scales must be used to weigh incoming waste loads if scales are present. If no scale is present or if a scale cannot be used, the US EPA outlines a procedure to estimate the capacity of the vehicle. In contrast, the state survey method necessitates normalizing data since most states did not require landfills to report disposal quantities (15 states had such requirements in 2008)\(^5\). State reporting requirements have differences which are difficult to account for. Another published survey that apparently gathered data by directly contacting each landfill in the U.S.\(^3\) reflects a reported average daily disposal rate, which can be a source of error when extrapolated to an annual amount – this error is discussed further below. Material flow analysis approaches are broad, do not capture facility-level data, and can also be subject to fairly large error.

2. Every facility subject to the GHG reporting rule must certify all submitted data as true and accurate, including waste disposal data. It is unknown how many of the 15 states requiring annual reporting from active landfills also have similar certification or attestation requirements.

3. The waste quantity data from the GHG reporting program are produced annually, thus permitting aggregate year-to-year and granular site-to-site analysis. The survey-based studies require substantial time and effort to gather and may not be available every year (the BioCycle survey was last published with 2008 data). Unlike the Waste Business Journal data set, the GHG reporting data are freely available. Our methodology and the GHG reporting data can thus be used in subsequent studies when analyses dependent on accurate waste disposal figures are required, such as management of specific waste components\(^4\).  

As discussed above, the methodology for determining the waste disposal estimate, as well as the estimate itself, holds several advantages compared to other methods or estimates. There are, however, potential limitations with the GHG reporting disposal data that must be highlighted here. Specifically, the limitations regard the population of sites that are subject to the GHG reporting program and the nature of the waste disposed of in landfills subject to the GHG reporting program.

The GHG Reporting Program requires sites emitting greater than 25,000 Mt CO\(_2\)-eq to report. The number of open or active landfills in the US based on the GHG reporting data were as follows: 939 (2010), 942 (2011), 943 (2012), and 947 (2013). A study published by Waste Business Journal (WBJ)\(^3\), which has landfill survey data corresponding to the year 2011, was reviewed to estimate the quantity of waste disposed of at sites that are not subject to the GHG reporting program. The WBJ data set reported 1,872 active municipal landfills in the US.

Since the US EPA uses a GHG emissions quantity as a cutoff for reporting, an ideal comparison would involve comparing the reported GHG emissions from the GHG reporting rule data set to GHG emissions from the WBJ data set. This would require information such as current disposal rate.
quantity, historical disposal amounts, and waste-specific data such as gas generation rates.

However, GHG emissions are not reported in the WBJ data set, and the only available factor in this data set that would contribute to a GHG estimate is the disposal quantity in 2011. Given that disposal quantity is the only common value available in both data sets, the disposal amount for each site was compared to approximate the amount of MSW disposed not captured by sites subject to the GHG Reporting Rule. Table SI-1 summarizes this comparison.

Table SI-1. Comparison of Number of Landfills and Total Disposal Quantity from the GHG Reporting Rule Data and the WBJ Data for Year 2011

<table>
<thead>
<tr>
<th>Disposal Quantity Range (Tonne)</th>
<th>GHG Reporting Rule Data</th>
<th>WBJ Data</th>
<th>Relative Percent Difference in Waste Disposal Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of Landfills</td>
<td>Total Quantity of Waste Disposed</td>
<td>Number of Landfills</td>
</tr>
<tr>
<td>&lt;5,000</td>
<td>13</td>
<td>3,389</td>
<td>379</td>
</tr>
<tr>
<td>5,000 &lt; x &lt; 10,000</td>
<td>6</td>
<td>46,535</td>
<td>130</td>
</tr>
<tr>
<td>10,000 &lt; x &lt; 50,000</td>
<td>105</td>
<td>3,707,634</td>
<td>419</td>
</tr>
<tr>
<td>50,000 &lt; x &lt; 100,000</td>
<td>187</td>
<td>14,125,713</td>
<td>239</td>
</tr>
<tr>
<td>100,000 &lt; x &lt; 200,000</td>
<td>242</td>
<td>35,590,252</td>
<td>249</td>
</tr>
<tr>
<td>200,000 &lt; x &lt; 500,000</td>
<td>249</td>
<td>78,909,399</td>
<td>308</td>
</tr>
<tr>
<td>500,000 &lt; x</td>
<td>140</td>
<td>130,542,801</td>
<td>148</td>
</tr>
<tr>
<td>TOTALS</td>
<td>942</td>
<td>262,925,723</td>
<td>1872</td>
</tr>
</tbody>
</table>

Note: Relative percent difference calculated as 100 x (W_{WBJ} – W_{GHG})/W_{GHG}

As shown in Table SI-1, a series of waste disposal quantity bin sizes were established to identify the largest disparities between the GHG reporting rule data set and the WBJ data set. A relative percent difference in waste disposal quantity upon comparing the GHG reporting rule data set and the WBJ data set was calculated as shown in Table SI-1. Table SI-1 shows a large relative percent difference in the first three disposal quantity bin sizes, which sum to approximately 12.6 million tonnes for the WBJ data set, compared to 3.7 million tonnes in the GHG Reporting Rule data set. Thus, for smaller landfills, the approximate amount of waste disposed that is unaccounted for in the GHG Reporting Rule data set is about 8.9 million tonnes.

To identify differences between sites that are both in the GHG reporting rule and the WBJ data set, a separate analysis was conducted for all sites in the WBJ data set with a reported disposal quantity greater than 1,000,000 tonnes in 2011. A total of 54 sites were identified and subsequently matched with sites in the GHG reporting data based on available locational information. The calculated waste disposal quantity from the WBJ survey for the 54 sites was 77.4 million tonnes, which was 16% greater than the calculated disposal quantity for the same 54
sites in the GHG reporting rule data (66.9 million tonnes). The disparity likely results from the
nature of data collected by WBJ, which is an average daily disposal rate, which had to be
extrapolated to directly compare to the GHG reporting rule data. Also, details regarding data
collection methods used by WBJ are unavailable, so some uncertainty may be expected.

Based on the above analysis, a likely lower boundary for the amount of waste disposed of at sites
not subject to the GHG reporting rule is 10.5 million tonnes. In light of the disparity when
comparing a subset of the 54 largest landfills in the GHG reporting rule data and the WBJ survey
data, the total disposal estimate of 309.4 million tonnes in the WBJ data likely reflects an
overestimate of the total U.S. disposal rate. If the difference between the two data sets for the 54
sites analyzed is considered, an upper boundary for disposal at sites not subject to the rule is 36.0
million tonnes (309.4 million tonnes (WBJ estimate) – 10.5 million tonnes (over-estimate of
disposal at the largest landfills in the WBJ data) – 262.9 million tonnes (this study’s estimate for
year 2011)). Thus, the estimated total disposal quantity at MSW landfills, inclusive of all sites,
ranged from 275.5 to 298.9 million tonnes in 2011. If the disparity between the 54 matched sites
in the two databases (16%) was assumed to apply across all sites, the estimated disposal rate in
the WBJ data set would adjust to 266 million tonnes. This figure appears to be low, as it would
reflect the disposal of about 4 million tonnes at the approximately 930 sites not subject to the
GHG reporting rule in 2011.

The disposal quantity in the GHG Reporting Program data analyzed in this study reflects the
quantity of material disposed of at MSW landfills. However, other non-municipal types of waste
may be included in the disposal data in the GHG Reporting Rule data set (e.g., construction and
demolition debris or non-degradable wastes such as ash from waste-to-energy facilities).
Estimates of the quantity of these two waste streams were developed based on other available
data.

Construction and demolition debris (CDD) is typically not regulated as stringently as municipal
waste in the U.S. and is often managed in landfills dedicated to receiving only this type of waste.
However, these materials could be disposed of at municipal landfills based on where the waste
was generated, the regional cost of disposal, the availability of CDD landfills, the availability of
recycling options, or other factors. Three large-scale studies that measured the composition of
waste loads received at MSW landfills were reviewed, and the weighted average composition of
incoming materials consisting of CDD (weight basis) was 12.8%5, 6, 7.

The amount of ash disposed of in MSW landfills was calculated based on a data set for 85
municipal waste-to-energy facilities operating in the U.S. in the year 20108. The total amount of
ash generated at these facilities was 6.9 million tonnes. Although ash from municipal waste-to-
energy facilities may be disposed of at dedicated ash landfills (which may not be subject to the
GHG Reporting Rule), if it is assumed that all ash generated is disposed of at MSW landfills, this
amount would comprise 2.6% of the total disposal in the year 2010. This figure decreases when
accounting for waste disposed of at all municipal landfills, including those not subject to the
GHG Reporting Rule.

Upon estimating the total disposal quantity for years 2010 through 2013, the total landfill
capacity data were evaluated to estimate the amount of landfill capacity remaining based on data
generated from Query 1. First, a histogram was developed to examine the anticipated year of closure for all landfills, shown in Figure SI-1 – note that these data only reflect those landfills subject to the GHG Reporting Rule.

![Histogram of Landfill Closure Year for All U.S. Landfills Based on Reported Closure Year Estimates from Query 1, Reporting Year 2013](image)

**Figure SI-1. Histogram of Landfill Closure Year for All U.S. Landfills Based on Reported Closure Year Estimates from Query 1, Reporting Year 2013**

The data in Figure SI-1 show that the majority of landfills are slated to close prior to the year 2060. Multiple, very large sites show an anticipated closure year that is 100 years from now or more. Descriptive statistics of the data from Figure SI-1 are provided in Table SI-2. Note that not every landfill is required to report an anticipated year of closure – the data in Table SI-2 represents approximately one-third of all landfills subject to the rule.

**Table SI-2. Summary Statistics of Anticipated Landfill Closure Year in the U.S. Based on Year 2013 Greenhouse Gas Reporting Data**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Number of Sites Data Were Available</th>
<th>Mean Closure Year</th>
<th>Median Closure Year</th>
<th>Inter-Quartile Range of Closure Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year of Landfill Closure</td>
<td>413</td>
<td>2065</td>
<td>2048</td>
<td>2013 - 2084</td>
</tr>
</tbody>
</table>

The mean closure year is 2065 while the median closure year is 2048 – the larger mean year of closure appears to be a function of the handful of sites with closure years that are very far into the future, and the right-skewed nature of the data. Figure SI-1 only partly conveys the available
landfill capacity – capacity can be examined by comparing the total available landfill capacity in
the U.S. (in terms of tonnes of waste that can be accepted) to the total amount of waste disposed
of on a year-to-year basis.

For this analysis, the VLOOKUP function was used in Excel to match the reported remaining
disposal capacity (tonnes) for one year to the previous year for each site (e.g., comparison of
reported capacity for 2011 was compared to 2010 to evaluate the potential change in capacity).
This procedure was used to calculate the difference in total U.S.-wide landfill capacity for years

An estimate of the total number of years of landfill capacity remaining for each year based on the
total disposal rate and total available disposal capacity was developed and the results of this
analysis are shown in Table SI-3.

### Table SI-3. Total Available U.S. MSW Landfill Capacity, Total Disposal Rate, and Years
of Capacity Remaining for Years 2010, 2011, 2012, and 2013 Based on GHG Reporting
Program Data

<table>
<thead>
<tr>
<th>Year</th>
<th>Total Landfill Capacity (Tonne)</th>
<th>Disposal Rate (Tonne/Year)</th>
<th>Calculated Remaining Capacity (Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>18,828,569,176</td>
<td>263,737,025</td>
<td>71.4</td>
</tr>
<tr>
<td>2011</td>
<td>19,472,464,612</td>
<td>262,925,724</td>
<td>74.1</td>
</tr>
<tr>
<td>2012</td>
<td>19,769,353,121</td>
<td>262,946,585</td>
<td>75.2</td>
</tr>
<tr>
<td>2013</td>
<td>21,161,641,859</td>
<td>266,401,858</td>
<td>79.4</td>
</tr>
</tbody>
</table>

The estimates provided in Table SI-3 represent the first operational data-based estimate of
nationwide landfill capacity we are aware of. The total landfill capacity has grown in each year
since GHG reporting first began in 2010, and this growth can be attributed to permitting of new
sites, capacity expansion permits for existing sites, and inclusion of new sites subject to the
reporting rule. Table SI-3 shows that the years of landfill capacity has increased each year for
the past 4 years, and the data show that 2.7 years of new landfill capacity are added for every 1
year of waste disposed.

### 3. Spatial Distribution of Open/Closed Landfills and Methane Generation

The distribution of open and closed landfills based on year 2013 data is shown in Figure SI-2 and
the relative amount of methane generation at each site (open and closed) is provided in Figure SI-3.
The data in Figure SI-2 appears to show a degree of clustering as evidenced by the number of closed
sites that do not have a proximate open site, particularly in the central portion of the U.S. Figure SI-
3 shows that large methane-emitting facilities are located throughout the U.S., with expected
clusters in higher-population areas such as California, Texas, Florida, New York, and Illinois.
Figure SI-2. Distribution of Open and Closed Landfills in the U.S. Based on Year 2013 Greenhouse Gas Reporting Data (Map generated in coordination with ©OpenStreetMap contributors © CartoDB, Attribution Provided Here)

Figure SI-3. Methane Generation at Open and Closed Landfill Sites in the U.S. in 2013 (Map generated in coordination with ©OpenStreetMap contributors © CartoDB, Attribution Provided Here)

4. Comparison of Factors Impacting Landfill Gas Collection Efficiency or Collected Landfill Gas Quality

A generalized linear model was developed to identify significant predictors of landfill gas collection efficiency using data from reporting year 2013. The variables included a mix of continuous and categorical variables: whether or not leachate recirculation was conducted over the past 10 years, site operating status (open and actively receiving waste or closed and no longer receiving waste), methane generation, surface area containing waste, total landfill disposal capacity, number of gas collection wells installed, and measured methane concentration. Of these
variables, the number of gas collection wells, methane generation, and landfill operating status were identified as significant (p < 0.05) predictors of gas collection efficiency. Analysis of residuals showed a significant amount of negative residuals when considering the number of gas collection wells, which reflected the very large distribution of the number of gas collection wells across sites. Some landfill sites may intentionally employ smaller-dimension wells for specific purposes (e.g., odor control), and the presence of many, smaller-capacity wells likely impacted the undesirable residuals. Interaction effects between methane generation and landfill gas collection efficiency were observed, and given the relationship between landfill gas collection efficiency and operating status in the U.S. EPA’s methodology for calculating efficiency, landfill operating status was examined further as the strongest independent predictor of LFG collection efficiency.

**Evaluation of Landfill Closure Status on Landfill Gas Collection Efficiency**

Analyses were conducted to examine the LFG collection efficiency as a function of landfill operating status. Figure SI-4 presents a series of boxplots comparing the LFG collection efficiency for all closed sites compared to all open sites for the years 2010 – 2013.

![Figure SI-4](image)

**Figure SI-4. Box Plots Comparing the LFG Collection Efficiency at Open Landfill Sites Compared to Closed Landfill Sites for Years 2010 – 2013**

Figure SI-4 shows that the year-to-year LFG collection efficiency remains quite steady for both open and closed facilities, both in the reported median values, but also the spread and apparent number of outliers. Second, and more importantly, the efficiency of LFG collection at closed sites is substantially greater when compared to open sites. To evaluate
significance of this observation, a two-sample t-test was conducted – the results for t-tests for all years (2010, 2011, 2012, and 2013) are presented in Table SI-4.

Table SI-4. Summary of Two-Sample t-tests Comparing LFG Collection Efficiency at Open and Closed Landfills

<table>
<thead>
<tr>
<th>Year</th>
<th>Landfill Status</th>
<th>Number of Sites</th>
<th>Mean LFG Collection Efficiency</th>
<th>Standard Deviation</th>
<th>95% Confidence Interval for the Difference</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Open</td>
<td>663</td>
<td>0.658</td>
<td>0.184</td>
<td>-0.2080, -0.1520</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Closed</td>
<td>216</td>
<td>0.838</td>
<td>0.181</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>Open</td>
<td>680</td>
<td>0.671</td>
<td>0.171</td>
<td>-0.2007, -0.1531</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Closed</td>
<td>224</td>
<td>0.848</td>
<td>0.152</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>Open</td>
<td>689</td>
<td>0.677</td>
<td>0.169</td>
<td>-0.1962, -0.1490</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Closed</td>
<td>232</td>
<td>0.850</td>
<td>0.155</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>Open</td>
<td>699</td>
<td>0.684</td>
<td>0.167</td>
<td>-0.1805, -0.1286</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Closed</td>
<td>217</td>
<td>0.838</td>
<td>0.171</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A review of the statistical analysis shows that in all four cases, the LFG collection efficiency at closed sites is statistically significantly different (more efficient) when compared to open landfills – p values are all < 0.001 and the 95% confidence interval (CI) for the difference in all cases does not include zero. Taking all four years of data into account, the mean LFG collection efficiency for closed sites is approximately 17.1 percentage points greater than open sites, with a standard deviation of 1.1 percentage points. The LFG collection efficiency in the GHG Reporting Rule database is not based on site measurements, but rather based on the available LFG collection system infrastructure in different areas of the landfill, coupled with the type of cover material present in those areas. The various parameters that the U.S. EPA requires reporting facilities to use for LFG collection efficiency for different areas were based on a series of field-based studies that measured efficiency under a variety of operational conditions.

Evaluation of Landfill Closure Status on Collected Methane Content

The collected methane concentration at closed landfills was compared to open landfills using a similar procedure described in the previous section. Boxplots of the data for years 2010 – 2013 are provided in Figure SI-5. The results show steady year-to-year collected methane content both in terms of the respective median values but also the relative spread of data. Two-sample t-tests of the year-to-year values were conducted to assess the significance of the differences between open and closed landfills. The results are provided in Table SI-5.
Figure SI-5. Comparison of Collected Methane Content for Open and Closed Landfills for Years 2010 – 2013

Table SI-5. Summary of Two-Sample t-tests Comparing Collected CH\textsubscript{4} Content at Open and Closed Landfills

<table>
<thead>
<tr>
<th>Year</th>
<th>Landfill Status</th>
<th>Number of Sites</th>
<th>Mean Collected Methane Content (%)</th>
<th>Standard Deviation</th>
<th>95% Confidence Interval for the Difference</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Open</td>
<td>663</td>
<td>47.88</td>
<td>8.30</td>
<td>3.428, 6.363</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Closed</td>
<td>216</td>
<td>42.98</td>
<td>9.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>Open</td>
<td>680</td>
<td>47.77</td>
<td>8.39</td>
<td>4.167, 7.355</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Closed</td>
<td>224</td>
<td>42.0</td>
<td>11.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>Open</td>
<td>689</td>
<td>48.21</td>
<td>7.12</td>
<td>5.347, 8.153</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Closed</td>
<td>232</td>
<td>41.50</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>Open</td>
<td>699</td>
<td>48.51</td>
<td>6.84</td>
<td>5.849, 8.842</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Closed</td>
<td>217</td>
<td>41.2</td>
<td>10.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The results show a statistically significant difference in collected methane content for all years data were available at a p-value <0.001 in all cases. In contrast to the LFG collection efficiency data, the collected methane content is a value that is measured at each individual site and
reported to the U.S. EPA within the GHG Reporting Rule data portal. These results reveal that the methane content at open landfills is significantly richer than closed landfills. This result, coupled with results comparing landfill gas collection efficiency, further shows that open landfills are an obvious target for further methane emission reduction efforts. Co-benefits of reduced greenhouse gas emissions and increased opportunity for LFG-to-energy conversion projects may also be realized based on these results. The greater methane content at open landfills could be a reflection of newer waste (compared to closed landfills), which produces LFG at higher rates (but not concentrations) compared to closed landfills. So the presence of older, perhaps non-decomposing pockets of waste in closed landfills may result in lower collected methane content.

**Effect of Landfill Size on LFG Collection Efficiency**

Although two indicators of landfill size – surface area containing waste and total disposal capacity – were not found to be significant predictors of LFG collection efficiency, a separate analysis was conducted to compare the disposal rate and LFG collection efficiency for year 2013 data. A total of 690 landfills with reported LFG collection were identified (sites with missing data or a reported “zero” for waste disposal were removed from the analysis). A scatterplot of all values is provided in Figure SI-6. Although the figure appears to show slightly better efficiencies for larger sites, the data points at sites with large disposal rates are few relative to the rest of the data set. Therefore, the sites were grouped into five approximately equal-sized bins and the mean and standard deviation were calculated for each sample – the results are shown in Figure SI-7. The data show slight increases in LFG collection efficiency from the <100,000 to the 100,000 – 200,000 bin, and from the 100,000 – 200,000 to the 200,000 – 300,000 bin (approximately 4.1 and 2.7 percentage points, respectively), followed by a decline of about 1.2 percentage points to the 300,000 – 500,000 bin, and finally an approximately 3 percentage point increase to the final bin size of >500,000 tonnes.

![Figure SI-6. LFG Collection Efficiency as a Function of Waste Disposal Quantity in 2013.](image-url)
Recirculating leachate at landfills has been identified as a potentially more sustainable landfilling option relative to traditional landfilling because of the associated accelerated decomposition of waste that occurs during the operating life of the landfill\textsuperscript{12, 13}. An effect of enhanced decomposition is a greater rate of LFG production, so the data set was analyzed to identify whether any differences in LFG collection efficiency at sites that recirculate and do not recirculate leachate existed. In the GHG reporting data entry system, each facility can report the degree of recirculation based on a semi-quantitative scale:

- Not used in the past 10 years
- Used at least once per year in the past 10 years
- Used occasionally (but not every year) for the past 10 years
- Used several times a year for the past 10 years

For this analysis, the extremes of the above scale were used to examine differences in the effects of leachate recirculation on LFG collection efficiency (not used in the past 10 years (“lo recirc”) and used several times a year for the past 10 years (“hi recirc”)). A boxplot comparing the LFG collection efficiency (y-axis) based on whether the landfill recirculates frequently is provided in Figure SI-8.
Figure SI-8. Boxplots Comparing LFG Collection Efficiency at Sites that Frequently Recirculate Leachate and those That Do Not, Reporting Year 2013 Data

The boxplots appear to show that the LFG collection efficiency is slightly greater at sites that do not recirculate versus those that do. To examine the data further, a two-sample t-test was conducted and the results are summarized in Table SI-6.

Table SI-6. Summary of Two-Sample t-Tests Comparing the LFG Collection Efficiency at Landfills that Frequently Recirculate Leachate and Landfills that Do Not Recirculate Leachate

<table>
<thead>
<tr>
<th>Leachate Recirculation Frequency</th>
<th>Number of Sites</th>
<th>Mean LFG Collection Efficiency</th>
<th>Standard Deviation</th>
<th>95% Confidence Interval for the Difference</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low/None</td>
<td>525</td>
<td>0.723</td>
<td>0.184</td>
<td>-0.0644, -0.065</td>
<td>0.016</td>
</tr>
<tr>
<td>High</td>
<td>172</td>
<td>0.688</td>
<td>0.162</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The 95% confidence interval for the difference is -0.0644, -0.065, which does not contain the value of zero so the results are statistically significant (p = 0.016). Thus, the LFG collection efficiencies are statistically significantly different for these two groups.
Next, the difference in collected methane concentration for landfills that frequently recirculate leachate versus those that do not was evaluated – the results are provided in the boxplot in Figure SI-9.

![Boxplots Comparing Collected CH₄ Concentration (%)](image)

**Figure SI-9. Boxplots Comparing Collected CH₄ Concentration (%) at Landfills that Recirculate Leachate Compared to Landfills that Do Not Recirculate, Year 2013 Data**

Figure SI-9 shows that the CH₄ concentration at landfills that recirculate leachate appears to be greater than those landfills that do not recirculate leachate. To evaluate this further, a two-sample t-test was conducted on the data as summarized in Table SI-7.

**Table SI-7. Summary of Two-Sample t-Tests Comparing the Collected CH₄ Content at Landfills that Frequently Recirculate Leachate and Landfills that Do Not Recirculate Leachate**

<table>
<thead>
<tr>
<th>Leachate Recirculation Frequency</th>
<th>Number of Sites</th>
<th>Mean Collected CH₄ Content (%)</th>
<th>Standard Deviation</th>
<th>95% Confidence Interval for the Difference</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low/None</td>
<td>525</td>
<td>45.95</td>
<td>8.83</td>
<td>2.503, 4.958</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>High</td>
<td>172</td>
<td>49.68</td>
<td>6.44</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In this case, the hypothesis is that the methane concentrations are equal for the two groups, and we can see that the 95% CI for the difference ranges from 2.503 – 4.958 (i.e., does not contain zero), and the p-value for this is 0.000, so the collected methane concentration at landfills that frequently recirculate leachate is statistically significantly greater than at those sites that do not recirculate leachate.

In summary, the results for the leachate recirculation comparisons show that sites that recirculate leachate collect higher-quality methane but the overall LFG collection efficiency is less when compared to sites that do not recirculate leachate, which is a similar trend observed when comparing the collected methane content and LFG collection efficiency of open and closed landfills.

5. Mapping Landfill Fire Data

The occurrence of landfill fires was mapped based on the year 2010 fire incident reporting data, and was examined to identify any spatial trends for the year 2010 data. The number of fire incidents on a state-by-state basis is presented in Figure SI-10. The data shows the areas with the largest number of fires generally agreeing with the landfill distribution data presented in Figure SI-2, with the most frequently-reported fires occurring in California, Texas, Florida, and Illinois.

Figure SI-10. Map of Fire Incident Data in the US in the year 2010

References


