Estimating Landfill Greenhouse Gas Emissions from Measured Ambient Methane Concentrations and Dispersion Modeling

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ABSTRACT

Since municipal solid waste (MSW) landfills emit significant amounts of methane, a potent greenhouse gas, there is considerable interest in quantifying surficial methane emissions from landfills. The authors propose a new and easier method by which to estimate methane emissions. The technique uses hundreds of ambient air VOC measurements taken within a landfill, as receptors, and solves the standard Gaussian dispersion equations by matrix methods, to determine the methane emission rates at hundreds of locations throughout a MSW landfill. The method was tested on a Central Florida MSW landfill using various scenarios with differing source and receptor locations.

Once accurate methane emissions throughout a MSW landfill are determined, they can be used as surrogates for odor emissions to predict downwind odor concentrations via a more sophisticated dispersion model such as ISC, AERMOD or CALPUFF. Other beneficial uses from this research include: determination of existing gas collection system efficiencies, calculation of fugitive greenhouse gas emissions from MSW landfills, and improved landfill gas management. The material in this paper is of interest to scientists, policy makers, landfill managers, and those concerned with global climate change, greenhouse gas inventory, and environmental management practices.

INTRODUCTION

Methane Emissions in the United States

Methane is emitted from a variety of natural and human sources. Natural sources of methane include wetlands, termites, oceans, freshwater bodies, and wildfires. Human-related activities that produce methane include fossil fuel production, domestic livestock ranching/farming, manure management, rice cultivation, biomass burning, and waste management. It is estimated that 60% of global methane emissions are related to human-related activities\(^1\). Table 1 represents the largest sources of methane emissions in the United States from 1990 to 2003 in teragrams (Tg) of CO\(_2\) equivalents.
Table 1 U.S. Methane Emissions by Source\textsuperscript{1} (TgCO\textsubscript{2} Equivalents)

<table>
<thead>
<tr>
<th>Source Category</th>
<th>1990</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
</tr>
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<tbody>
<tr>
<td>Landfills</td>
<td>172.2</td>
<td>130.7</td>
<td>126.2</td>
<td>126.8</td>
<td>131.2</td>
</tr>
<tr>
<td>Natural Gas Systems</td>
<td>128.3</td>
<td>132.1</td>
<td>131.8</td>
<td>130.6</td>
<td>125.9</td>
</tr>
<tr>
<td>Enteric Fermentation</td>
<td>117.9</td>
<td>115.6</td>
<td>114.5</td>
<td>114.6</td>
<td>115</td>
</tr>
<tr>
<td>Coal Mining</td>
<td>81.9</td>
<td>56.2</td>
<td>55.6</td>
<td>52.4</td>
<td>53.8</td>
</tr>
<tr>
<td>Manure Management</td>
<td>31.2</td>
<td>38.1</td>
<td>38.9</td>
<td>39.3</td>
<td>39.1</td>
</tr>
<tr>
<td>Wastewater Treatment</td>
<td>24.8</td>
<td>34.3</td>
<td>34.7</td>
<td>35.8</td>
<td>36.8</td>
</tr>
<tr>
<td>Other</td>
<td>45.8</td>
<td>43.5</td>
<td>41.7</td>
<td>39.6</td>
<td>39.8</td>
</tr>
<tr>
<td><strong>Total for U.S.</strong></td>
<td><strong>605.3</strong></td>
<td><strong>554.2</strong></td>
<td><strong>546.7</strong></td>
<td><strong>542.3</strong></td>
<td><strong>544.9</strong></td>
</tr>
</tbody>
</table>

Note: 1 Tg = 10\textsuperscript{12} grams

**Methane Emissions in Municipal Landfills**

There are currently 2,300 active landfills in the United States\textsuperscript{1}. As seen from Table 1, landfills are the largest human-related source of methane in the U.S., accounting for 34\% of all methane emissions\textsuperscript{1}. In landfills, the natural process of anaerobic decomposition of biodegradable waste creates biogas. Biogas is roughly composed of 45-60\% methane (CH\textsubscript{4}), 40-60\% carbon dioxide (CO\textsubscript{2}), and trace chemical species\textsuperscript{2-4}. The amount of biogas produced in landfills is a function of waste quantity, type, and age, landfill moisture content, temperature, and management practices at the site.

**Problem Identification**

People are now facing a serious environmental threat. Global climate change is predicted to produce negative global effects such as: more frequent and more powerful hurricanes, rising sea level and flooding, altered rainfall patterns resulting in major changes in agriculture, more insect infestations, and loss of glaciers\textsuperscript{5}. Global climate change is due in large part to the emission of human generated greenhouse gases into the atmosphere. Carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons (CFCs) are the main greenhouse gases which absorb and retain infrared energy; thus changing the world’s overall energy balance.

Biogas, composed mainly of methane and carbon dioxide are both greenhouse gases; however, methane is more of a concern. Methane has a global warming potential of twenty three over a hundred year time horizon, as compared to carbon dioxide with a global warming potential of one\textsuperscript{6}. Since methane is a key greenhouse gas and landfills produce a significant amount of methane, there is considerable interest in quantifying surficial methane emissions from landfills.

**40 CFR Part 60, Subparts WWW**

Under the 1996 EPA New Source Performance Standards and Emission Guidelines for Municipal Solid Waste Landfills (40 CFR Part 60, Subparts WWW), landfills with the potential to emit more than 50 Mg/year of nonmethane volatile organic compounds (NMVOC are typically less than 1\% of landfill gas or roughly 2\% of methane emissions) must collect and combust landfill gas. Combusting or flaring landfill biogas reduces odors, safety concerns, and methane emissions.
To ensure that the landfill biogas collection systems are operating properly, quarterly surface VOC monitoring is required, as specified in 40 CFR 60.755 (c) and (d), and 40 CFR 60, Appendix A, Method 21. These regulations require air monitoring around the perimeter of and within the area of a landfill gas collection system to determine compliance. Exceedance of 500 ppm above background requires remedial action, and may imply that something is wrong in the gas collection system.

**Existing Methane Emission Techniques**

Numerous techniques exist for the measurement of methane emissions from landfills. The most popular methane emissions techniques are the chamber techniques, either closed or open. Both chamber techniques have their own advantages and disadvantages. For example, the open or dynamic flux chamber simulates field conditions better than the closed flux chamber; however, the open chamber may create artificially high fluxes due to its sensitivity to pressure changes inside the chamber. In contrast, the closed or static flux chamber is much easier to use and cheaper to operate than the open chamber; however, the closed chamber tends to underestimate the gas fluxes because of pressure buildup with time that distorts the gas flow pathways in the soil and decreases the flow into the chamber. Overall problems with a flux chamber include labor intensity, time consumption, point measurements, and highly variable results.

Methane production rates can be estimated by any of several biogas production models. The Environmental Protection Agency (EPA) Landfill Gas Emissions Model (LandGEM) is an automated estimation tool used to estimate emission rates from municipal solid waste landfills. LandGEM is based on a first-order decomposition rate equation for quantifying emissions from the decomposition of biodegradable waste. LandGEM is used to estimate uncontrolled emission rates for total landfill gas, methane, carbon dioxide, nonmethane organic compounds, and individual air pollutants from landfills.

Another biogas production model is MICROGEN-MGM. By simulating the basic biological and physicochemical processes that take place inside a landfill, MICROGEN can estimate the methane production rate for a landfill. MICROGEN utilizes Monod microbial growth based equations to describe the dynamics of the landfill ecosystem. LandGEM and MICROGEN, as well as other biogas production models, involve many assumptions and mathematical limitations. A few problems with biogas production models are that they are only theoretical, a good record of waste deposits is needed, and the models can not estimate the percentage of landfill gas captured versus that emitted.

The measurement of pollutant mass emissions from an entire area source can be calculated using a ground-based optical remote sensing (ORS) method. The ORS method uses open-path Fourier transform infrared (OP-FTIR) spectroscopy to obtain path-integrated pollution concentration information along multiple plane-configured optical paths. The source emissions can be determined after processing the pollutant concentration information and wind vector information with a plane-integrating computer algorithm. Problems with optical remote sensing methods are that they are expensive, time and labor intensive, depend on wind orientation, and produce only one integrated emission rate for the whole landfill.
Proposed Methane Emission Technique

The authors propose a methane emissions technique that uses hundreds of ambient air VOC measurements taken within a MSW landfill (as required by 40 CFR Part 60, Subparts WWW). These measurement locations are set as receptors, and numerous other locations are chosen as sources. The standard Gaussian dispersion equations are solved by matrix methods, to determine the methane emission rates throughout the landfill.

The foundation for atmospheric dispersion calculations is the Gaussian dispersion equation as shown in equation (1) written for a nonreactive gaseous pollutant from a point source

\[
C = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp \left( -\frac{1}{2} \frac{y^2}{\sigma_y^2} \right) \left[ \exp \left( -\frac{1}{2} \frac{(z-H)^2}{\sigma_z^2} \right) + \exp \left( -\frac{1}{2} \frac{(z+H)^2}{\sigma_z^2} \right) \right]
\]

where \(C\) is the steady-state concentration (µg/m³) at a point (x,y,z), \(Q\) is the emission rate (µg/s), \(\sigma_y\) and \(\sigma_z\) are the horizontal and vertical spread parameters (m) that are functions of x-distance and atmospheric stability, \(u\) is the average wind speed at stack height (m/s), \(y\) is the crosswind distance from ground level (m), \(z\) is the vertical distance above the ground (m), and \(H\) is the effective stack height (physical stack height plus plume rise) (m). Figure 1 represents the source-receptor geometry for source \(j\) and receptor \(i\) in a landfill.

![Figure 1: Source-Receptor Geometry](image-url)
For ground-level sources and receptors \((z = 0\) and \(H = 0\)), equation (1) reduces to equation (2). Equation (2) can be written as equation (3) for each source-receptor pair \((j, i)\), where \(C_{i,j}\) represents the modeled concentration at receptor \(i\) due to source \(j\) in \((\mu g/m^3)\), \(Q_j\) is the source \(j\) emission rate in \((g/sec)\), and \(f(x, y)_{i,j}\) is the rest of equation (2) for each source-receptor pair that contains the values of wind speed, dispersion parameters, and crosswind \((y)\) distances between source \(j\) and receptor \(i\), as seen in Figure 1.

\[
C = \frac{Q}{\pi u \sigma_x \sigma_y} \exp \left( -\frac{1}{2} \frac{y^2}{\sigma_y^2} \right) 
\]  
(2)

\[
C_{i,j} = f(x, y)_{i,j} Q_j 
\]  
(3)

The horizontal and vertical dispersion spread parameters are defined by equations (4) and (5), originally developed by Martin (1976) and as shown in Cooper & Alley. The parameters \(a\), \(b\), \(c\), \(d\), and \(f\) are numerical curve-fit constants that are functions of downwind distance, \(x\) (in km), and atmospheric stability.

\[
\sigma_y = ax^b 
\]  
(4)

\[
\sigma_z = cx^d + f 
\]  
(5)

Assuming the methane background concentration is zero, the total modeled concentration \((\mu g/m^3)\), \(C_{i,\text{modeled}}\), at each receptor is the sum of all the modeled concentrations at receptor \(i\) from each of the \(n\) sources as shown in equation (6).

\[
C_{i,\text{modeled}} = \sum_{j=1}^{n} C_{i,j} 
\]  
(6)

One method for determining the best-fit methane emission rate, \(Q_j\), within a landfill involves assuming different trial sets of \(Q_j\) values, and then calculating the sum of squares of the residuals over all m receptors using equation (7). Trial and error is required to find the optimal set of \(Q_j\) to minimize \(R^2\). A more efficient method for determining the optimal set involves writing equation (7) using equivalent matrix notation. Equation (8), represented in matrix notation, shows how to minimize the 2-norm of the residual; where \(F \in \mathbb{R}^{m \times n}\) is the \((\text{real}) m \times n\) matrix of values of the function \(f(x, y)_{i,j}\), \(q \in \mathbb{R}^n\) is the \((\text{real}) n\) vector of sources, and \(c_{\text{measured}} \in \mathbb{R}^m\) is the \((\text{real}) m\) vector of measured receptor concentrations.

\[
\text{Minimize} : R^2 = \sum_{i=1}^{m} \left( C_{i,\text{measured}} - C_{i,\text{mod}} \right)^2 
\]  
(7)

\[
\min_q \|F \cdot q - c_{\text{measured}}\|_2^2 
\]  
(8)
Equation (8) can be solved using linear least-squares regression theory when subject to the following constraints: 1) The number of sources must be less than or equal to the number of receptors, 2) Each \( Q_j \) must be greater than or equal to zero, and 3) If any downwind distance is negative \( F \) must be set to zero because the receptor is upwind from the source. The vector \( \mathbf{q} \) that minimizes equation (8) is unique if and only if \( \mathbf{F} \) has full rank. If \( \mathbf{F} \) has full rank, \( \mathbf{q} \) can be determined using the normal equations as equation (9), where the pseudoinverse \( \mathbf{F}^+ \) is shown in equation (10).

\[
\mathbf{q} = \mathbf{F}^+ \mathbf{c}_{\text{measured}} \\
\mathbf{F}^+ = (\mathbf{F}^\text{T} \mathbf{F})^{-1} \mathbf{F}^\text{T}
\]

However, this formulation does not guarantee that each \( Q_j \) is not negative. Therefore, a more general approach, equation (11), is necessary that requires the solution of the non-negative constrained least squares problem; where \( \mathbf{I} \) is the identity matrix. The non-negative least squares (NNLS) problem can be solved numerically using a variety of available transformation, active-set, or iterative algorithms\(^{11}\).

\[
\mathbf{q} = \arg\min_{\mathbf{q}} \| \mathbf{F} \cdot \mathbf{q} - \mathbf{c}_{\text{measured}} | \mathbf{I} \cdot \mathbf{q} \geq 0 \|_2
\]

**METHODOLOGY**

The methodology below outlines the recommended methodology for determining methane emission rates from a MSW landfill.

**Step 1: Formulate Receptor Sub-Model**

Obtain ambient air VOC measurements at numerous locations within the landfill, as required by 40 CFR Part 60, Subparts WWW. If the landfill does not require quarterly ambient air VOC measurements, a walking survey with instruments (a portable FID and a GPS) is required to obtain the ambient concentrations and to link each concentration with a location. Also, the local wind speed and direction, and stability class must be determined during the time of the walking survey.

**Step 2: Formulate Source Sub-Model**

Use an aerial photo or plot plan to designate point sources throughout the MSW landfill. Recall the constraints previously defined: The number of sources must be less than or equal to the number of receptors. Locations of these sources should be chosen generally upwind of receptors, not too close nor too far away. Note that this somewhat arbitrary locating of sources will influence the final answers for individual source strengths, and may well influence the final estimate of overall emissions using this approach.

**Step 3: Formulate Matrix Dispersion Model**

Solve the standard Gaussian dispersion equations by matrix inversion methods, as previously described, to determine the methane emission rates throughout the MSW landfill. This can be done easily in MATLAB, which specializes in numerical computing and allows easy matrix manipulation.
**Step 4: Perform Sensitivity Studies**
Perform sensitivity studies to estimate the sensitivity of results to our techniques.

**Step 5: Formulate Air Dispersion Model to Test Validity**
After determining the best representation of methane point-source emission rates from the MSW landfill, run those emission rates through the steady-state Gaussian air dispersion model, ISC, to determine the VOC ambient air concentrations. ISC is utilized instead of the current EPA steady-state Gaussian air dispersion model, AERMOD, because the ISC model allows one to specify meteorological data such as local wind speed, wind direction, ambient temperature, and stability class. Compare ISC’s modeled receptor concentrations with an independent set of ambient air VOC measurements taken within the landfill to test the validity of the methane emission rates.

**CASE STUDIES**

**Simple Scenario Test Case**
Prior to using the above methodology on a landfill, a simple scenario was devised as a “test case” to determine if MATLAB could indeed predict source strengths accurately. This test case is based upon a small and simplified set of receptors and sources. Figure 2 shows the test case’s source-receptor geometry.

![Source-Receptor Geometry](image)

**Figure 2: Test Case Source-Receptor Geometry**

Instead of obtaining ambient air VOC measurements, the test case relied on a modeling exercise, described as follows. Fifteen receptors and ten sources were judiciously placed in a grid, and their X-Y coordinates determined (see Figure 2). Source emission rates, $S_{\text{Assumed}}$, were assumed (see Table 2), and the Gaussian dispersion model, represented as equations (1-6), was programmed into an Excel spreadsheet, and solved for a specific meteorology: wind speed of 2 m/s, wind direction from 40°, and stability class C. The calculated receptor concentrations, $C_{\text{Excel}}$, are presented in Table 3.
To test the proposed algorithm using MATLAB, all geometric data and the receptor concentrations were entered, and the standard Gaussian dispersion equations were solved using the proposed matrix method in MATLAB to determine the best-fit emission rate at each source. Table 4 compares the known emission rates, $S_{\text{Assumed}}$, to MATLAB’s predicted emissions rates, $S_{\text{Predicted}}$. From Table 4, it was concluded that the Matrix Methods can perform extremely accurately.

### Table 2: Source Data

<table>
<thead>
<tr>
<th>Source Number</th>
<th>x</th>
<th>y</th>
<th>$S_{\text{Assumed}}$ (µg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>800</td>
<td>500</td>
<td>500000</td>
</tr>
<tr>
<td>2</td>
<td>1100</td>
<td>1100</td>
<td>600000</td>
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<tr>
<td>3</td>
<td>1100</td>
<td>800</td>
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<td>4</td>
<td>1200</td>
<td>700</td>
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<td>5</td>
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<td>6</td>
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<td>200000</td>
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<tr>
<td>7</td>
<td>1100</td>
<td>500</td>
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<td>1000</td>
<td>600</td>
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</tr>
<tr>
<td>10</td>
<td>1500</td>
<td>800</td>
<td>700000</td>
</tr>
</tbody>
</table>

### Table 3: Receptor Data

<table>
<thead>
<tr>
<th>Receptor Number</th>
<th>x</th>
<th>y</th>
<th>$C_{\text{Excel}}$ (µg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>600</td>
<td>400</td>
<td>33</td>
</tr>
<tr>
<td>2</td>
<td>700</td>
<td>300</td>
<td>164</td>
</tr>
<tr>
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<td>600</td>
<td>100</td>
<td>93</td>
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<td>900</td>
<td>500</td>
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<td>400</td>
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<tr>
<td>8</td>
<td>1600</td>
<td>1100</td>
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</tr>
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<td>9</td>
<td>1000</td>
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<td>648</td>
</tr>
<tr>
<td>10</td>
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<td>13</td>
<td>1400</td>
<td>600</td>
<td>41</td>
</tr>
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<td>14</td>
<td>1000</td>
<td>750</td>
<td>70</td>
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<tr>
<td>15</td>
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<td>900</td>
<td>4</td>
</tr>
</tbody>
</table>
Table 4: Comparing Given Emission Rates to Predicted MATLAB Emission Rates

<table>
<thead>
<tr>
<th>Source Number</th>
<th>$S_{\text{Assumed}}$ (µg/s)</th>
<th>$S_{\text{Predicted}}$ (µg/s)</th>
</tr>
</thead>
<tbody>
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<td>330000.3</td>
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<td>6</td>
<td>200000</td>
<td>200000.2</td>
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<td>800000</td>
<td>800000.7</td>
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<tr>
<td>9</td>
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<td>110000.1</td>
</tr>
<tr>
<td>10</td>
<td>700000</td>
<td>700000.6</td>
</tr>
</tbody>
</table>

Central Florida MSW Landfill Case Study

The methodology presented earlier was applied to an existing MSW landfill in the Central Florida area to determine methane emissions from the landfill. Figure 3 is an aerial photograph of Seminole County Landfill (recently renamed the Osceola Road Solid Waste Management Facility) showing the closed and active cells. This MSW landfill is a Class 1 Landfill, serving over 300,000 residents in seven cities and the unincorporated County. In general, the Seminole County Landfill (SCL) receives approximately 810 tons per day of waste. The total disposal area is 232 acres; currently only 127 acres have been used. Typical types of received waste include: residential, commercial, incinerator/WTE ash, treated biomedical, water treatment sludge, air treatment sludge, agricultural, asbestos, C&D debris, shredded tires, and yard trash. The landfill has two candlestick flares, and is currently constructing landfill gas fueled combustion turbines to generate electricity.

Figure 3: Aerial of the Seminole County Landfill, Florida
**Step 1, 2: Formulate Receptor and Source Sub-Models**
Quarterly surface emissions monitoring reports were obtained. Ambient air VOC measurements at 358 locations within the landfill were recorded in ppm as CH\(_4\) using a Landtec SEM 500 flame ionization detector. The local wind speed and direction at the time of measurement were estimated at 1.3 m/sec and from 40° (NE), respectively, based on records from the Orlando airport. On that day and time, the temperature was 88°F with scattered clouds, and class B stability conditions were estimated. Figure 4 shows the receptor X-Y locations for the 358 VOC readings; Figure 5 shows the 356 point sources that were selected based on the criteria listed previously.

**Step 3: Formulate Matrix Dispersion Model**
The methane emission rates throughout the SCL were determined by solving the standard Gaussian dispersion equations by matrix methods, as previously described. Figure 6 is a plot of the methane emission isopleths. Based on the MATLAB results, Phase I is emitting much less methane than Phase II; this makes sense because Phase I is closed and has a gas collection system which appears to be working properly. For Phase II, the areas of highest methane emissions may identify locations where waste was recently deposited or where a temporary soil cover might not be adequately covering the waste.

One advantage of the proposed methodology to solve for the source emission rates is the ability to remove sources that do not contribute to the matrix methods solution. For the predicted source emissions to be unique, it is necessary for \(F\) to be full rank. Numerically it is possible to determine what sources are linearly dependent, and therefore causing rank deficiency. For instance, 356 point sources were chosen by the authors, however, as MATLAB solves the Gaussian dispersion equations via matrix methods it will remove all sources that do not contribute to the linear least-squares regression solution or do not contribute to the rank of \(F\); it is for this reason that all of the cases reported below (Case 1 through Case 4) have a total number of sources less than 356.
Step 4: Perform Sensitivity Studies
A limited sensitivity study was performed on the numbers and locations of point sources. The sensitivity study included four cases:

- Case 1) Base case with 356 sources. These sources were chosen carefully to ensure that sources were in “good” positions (e.g., upwind and not too close nor too far),
- Case 2) Similar to Case 1. The same 356 sources, except that 14 of most northern (upwind) sources in the active cell were relocated to the southern part of the closed cell,
- Case 3) All of the 356 sources from Case 1 were uniformly relocated twenty (20) meters east of their original location, and
- Case 4) One hundred twenty eight (128) sources were deleted from Case 1’s initial 356 sources, while the remaining 228 sources stayed at the same locations.

Table 5 compares the calculated landfill emission inventory for each case. As previously mentioned, as MATLAB solves the matrix method Gaussian dispersion equations it will remove all sources that do not contribute to the linear least-squares regression solution. For this reason, Table 5 shows the number of sources the authors inputted into MATLAB and the resulting number of sources that MATLAB has determined to be contributing nothing.
Table 5: SCL’s Methane Emission Inventory Based on Number & Location of Sources

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Original Sources Inputted by authors</td>
<td>356</td>
<td>356</td>
<td>356</td>
<td>228</td>
</tr>
<tr>
<td>Number of Sources after processed by MATLAB</td>
<td>328</td>
<td>318</td>
<td>335</td>
<td>215</td>
</tr>
<tr>
<td>Methane Emissions Inventory (g/sec)</td>
<td>970</td>
<td>930</td>
<td>1090</td>
<td>900</td>
</tr>
<tr>
<td>Percent Difference from Case 1</td>
<td>0.0%</td>
<td>4.0%</td>
<td>12.5%</td>
<td>6.6%</td>
</tr>
</tbody>
</table>

Table 5 illustrates that the number of point sources did not significantly change the total methane emissions inventory; thus demonstrating the robustness of our new method. Comparing Case 4 (215 sources) with Case 1 (328 sources), the difference in the total methane emissions was only 6.6%.

Table 5 also illustrates that changing locations of the point sources produced variations in the emission inventory. Recall that for Case 1, source locations were chosen based on close visual inspection of where the concentration measurements had been made, and using good judgment about keeping sources upwind of receptors. Comparing Case 2 to Case 1, there was a 4.0% difference in the inventory caused by relocating the most upwind sources. However, looking at Case 3 verses Case 1, a “less intelligent” process for locating the point sources created a 12.5% difference in the landfill’s emission inventory. Please recall that for Case 3, all of the sources from Case 1 were uniformly relocated twenty meters east of their original location. Therefore using good judgment in placing sources does make a difference.

SCL’s estimated methane emissions inventory is compared to two other landfills in the United States in Table 6. Table 6 shows that our estimated methane emissions from the SCL of approximately 1000 g/sec is comparable to other estimates in the United States.

Table 6: Comparing New Method’s Estimated Methane Emission Inventory with others in the United States

<table>
<thead>
<tr>
<th>Landfill</th>
<th>Year</th>
<th>Estimated Methane Emissions (g/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seminole County, Florida</td>
<td>2007</td>
<td>Approximately 1000</td>
</tr>
<tr>
<td>Kenosha, Wisconsin(^{13})</td>
<td>2003</td>
<td>899</td>
</tr>
<tr>
<td>Central Landfill, Rhode Island(^{14})</td>
<td>1996</td>
<td>1293</td>
</tr>
</tbody>
</table>

Figure 7 compares methane emission ranges for individual sources for Case 1, Case 2, and Case 4. Theses three cases were analyzed because all three cases had 193 sources with the same x-y locations. Case 3 was not compared to the other cases because all of the source locations were different. Figure 7 shows three emission ranges: less than 5 g/s, 5-20 g/s, and greater than 20 g/s. From Figure 7, it can be seen that most of the individual sources are less than 5 g/s in all three cases. In Case 4, the number of sources in each category changed significantly.
Step 5: Formulate Air Dispersion Model to Test Validity

The predicted methane emission rates from Case 1 were input into ISC to determine modeled ambient CH$_4$ concentrations. The details of this modeling are presented elsewhere$^{12}$. Figure 8 is a scatter plot that compares the ambient air VOC measurements to ISC’s modeled concentrations.

The scatter plot shows a positive, linear correlation between the measured and the predicted VOC concentrations. The equation for the correlation between the measured and the predicted VOC concentrations has a regression coefficient, or slope of 1.04. The slope of 1.04 represents a 1:1 rate of change of the predicted VOC concentrations as a function of the measured VOC concentrations. The square of the correlation coefficient, R$^2$, is 0.65, indicating a reasonable relationship between the measured and predicted VOC concentrations; that is, 65% of the variability in the data is accounted for by the correlation equation. Ideally, for a “strong” correlation, the square of the correlation should be 80% or greater$^{15}$. 

Figure 7: Comparing Methane Emission Ranges for 193 identical locations: Case 1, Case 2, & Case 4
Figure 8: Scatter Plot of Modeled vs. Measured CH₄ Concentrations at Seminole County Landfill
CONCLUSION & RECOMMENDATIONS

The authors conclude:

(1) The proposed matrix approach can accurately solve for source strengths when provided with sufficient receptor concentration and meteorology data;

(2) Variations in the numbers of the sources in the Seminole County Landfill produced insignificant variation in landfill’s predicted methane emission inventory. This demonstrates the robustness of our methodology;

(3) One case of changing locations for a few sources produced an insignificant variation, but varying all the locations by only 20 meters, produced a significantly different result, demonstrating the importance of using good judgment in selecting source locations;

(4) Our recommended methodology was successful in determining the total methane emission rate for the Seminole County Landfill; and

(5) Our methodology shows promise for predicting spatial variation in both emission rates and VOC concentrations.

This methodology is still a work in progress. More quarters of measured SCL data should be assessed, and more landfills should be assessed. A significant modeling effort is needed to test for sensitivity to all the parameters: number of sources, errors in concentration measurements, wind speed, wind direction, and stability class. However, once the methodology is refined, this technique offers much promise to the solid waste industry. First, the calculation of a MSW landfill’s carbon footprint can be made with very little extra effort if on-site monitoring data are already available (as will be the case for many landfills). Local and national greenhouse gas inventories will improve by more accurately calculating methane fugitive emissions from a landfill. The ability to check the efficiency of existing gas collection systems will be enhanced by determining the emissions at a variety of points within a MSW landfill and identifying areas of greater than normal losses. This should also improve the design and maintenance of a landfill’s biogas collection system. The ability to assess potential health and odor impacts will increase; thus encouraging more effective land use management near landfills.

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KEYWORDS

MSW landfills; methane; greenhouse gas inventory; air dispersion modeling
REFERENCES


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