The Evolution of Methane Emissions Measurements at Landfills: Where are We Now?

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ABSTRACT

Landfill methane measurement methods have evolved over the past 40+ years since the first landfill air regulations were enacted in California in the early 1980's, yet despite technological advances and increasingly sophisticated measurement methods, obtaining accurate data of emissions flux or rate remains a challenge. Although research has been conducted on a variety of methods, no method has risen to the top of the hierarchy or has been accepted as representative the most accurate methane emissions measurements. None have received regulatory acceptance except for surface emissions monitoring required in federal, state, and local air regulations, and a limited number of alternative test methods approved by the U.S. Environmental Protection Agency (EPA). Without a definitive method that can be accepted as providing accurate methane flux numbers, it is difficult to study new methods because there is no "official" value to which emission numbers can be compared for accuracy.

This paper was developed to compare and contrast the various methods for methane: (1) emissions estimation, (2) surface emissions monitoring, and (3) flux measurement; in addition to some general observations regarding relative cost, implementation issues, and potential areas of uncertainty. This includes the specific technology that is used to measure methane concentrations (e.g., infrared, lasers, flux chambers, field instruments, etc.), the monitoring/sampling mechanisms used for the measurements (e.g., hand-held, towers, drones, aircraft, satellites, etc.), and the methods used to calculate flux or emission rate from the concentration values (e.g., models, algorithms, etc.).

The goal of this review is to provide a summary of the current status of the landfill industry in terms of methane measurement methods while at the same time identifying which methods offer the best opportunity for accurate emission measurements. Since the research in this field is ongoing, the paper is intended to show which methods have the most promise for future research, development, and improvements.

INTRODUCTION

Methane emissions measurement methods at landfills have changed substantially over time, starting with “hot spot” monitoring for methane concentrations using hand-held devices, which subsequently evolved to a variety of sophisticated technologies and methods. However, despite these advances, accurate measurements of emissions flux have been difficult to obtain because of the unique nature of the source. Landfills are large area sources with variable emission rates across large surface areas. The emissions are generally diffuse, but can be affected by hot spot locations of more significant leaks, which can drastically change the site-wide emissions. Landfill methane emissions are also affected by the presence and effectiveness of landfill gas (LFG) collection systems, piping or equipment leaks, downtime for the LFG collection system, cracks in the landfill surface or poor cover practices or materials, barometric pressure changes, landfill settlement, and other landfill practices. As a result, one-time measurements do not accurately portray a landfill’s long-term emissions.

To this day, landfills are still using hand-held monitoring of methane “hot spots” for compliance purposes, while relying on models to estimate LFG emissions. Although technological developments in optical remote sensing and other methods offer significant promise as they improve the ability to measure actual surface emissions from landfills, no single technology or method has risen to the top of the scientific hierarchy, gained universal acceptance, or achieved regulatory approval. Clearly, the technological advances have provided more comprehensive methods for measuring methane concentration, identifying methane hot spots and leaks, and providing better coverage of the entire landfill surface. Technology falls short in its ability to provide accurate, consistent, and repeatable methane flux or emissions measurements. As monitoring technology evolves, so have the various ways we take measurements, from source level, low flying drones, and high-altitude aircraft, to satellites.

Specifically, this paper will summarize and provide details on the following methods:

- First order decay (FOD) modeling for landfills without active LFG collection systems.
- Non-FOD modeling for landfills without active LFG collection systems.
- FOD modeling with measured LFG collection.
- Non-FOD models with various site-specific data input.
- Measured LFG collection with estimated collection efficiency.
- Surface emission monitoring (SEM) for compliance purposes.
- Ground-based or low-altitude imaging for concentration or hot spot measurement.
- Satellite and aerial imaging for concentration or hot spot measurement.
- Flux chamber testing.
- Ground-level plume measurement.
- Micrometeorology.
- Stationary path measurement.
- Reverse air dispersion modeling.
- Tracer studies.
- Low or high-altitude imaging.
- Hybrid methods.

The review will include a discussion of relative cost, implementation issues, and potential areas of uncertainty.

EMISSION ESTIMATION METHODS

Landfill methane emission estimation determines the landfill methane emissions without direct measurement of those emissions. Landfill methane estimation methods should be discussed separately for landfills without active[1] LFG collection and control systems (GCCS), and for sites with an active GCCS. This separate discussion is necessary because landfills without a GCCS typically lack a way to measure LFG flow (the amount of LFG that is collected), while sites with an active GCCS are able to measure the flow and methane content of collected LFG. This measurement provides a reference that can be used to determine methane generation and emission.

Landfills Without Active GCCS

Landfills require an active GCCS to monitor methane generation or emission without a sampling event. Options for sampling programs are discussed in the methane measurement and monitoring sections below. The only way to estimate methane emissions from a landfill without an active GCCS, and therefore no means of measurement of methane collection or emission, is to model methane generation or emission. SCS identified the following modeling methods for landfills without a GCCS:

- First order decay (FOD) modeling.
- Non-FOD modeling.

FOD Models

FOD modeling, the preferred method for estimating methane generation, is used to estimate greenhouse gas (GHG) emissions from landfills by EPA as part of the GHG Reporting Program (GHGRP), the California Air Resources Board (CARB) as part of the Landfill Methane Control Measure (LMCM), and the Intergovernmental Panel on Climate Change (IPCC). The FOD modeling approach to determining methane generation in landfills dates back to the mid-1970s.

FOD models are advantageous for their easy-to-understand inputs (e.g. waste tonnage, decay rate, methane generation potential) and user's ability to customize the level of sophistication of the calculation method. This modification was evident when FOD models were first used over fifty years ago, as the Scholl Canyon model used a single decomposition stage and rate, while the Sheldon Arleta and the Palos Verdes models used multiple decomposition stages and rates. FOD models are a viable method for estimating methane emissions from landfills.

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[1] "Active" means a GCCS with a blower that creates a pressure differential to draw LFG out of the waste area. It is not a system where gas movement is only driven by pressure gradients created through the generation of LFG (i.e. a passive GCCS).

Table 1. Critical FOD Model Parameters

Source	Waste Type	K (YR-1)	L_0 (M^3 /Mg Waste)
LandGEM	MSW	0.02-0.04	100
GHGRP	MSW	0.02-0.57	101
	C&D	0.02-0.04	41
	Inert	0	0
	Food	0.06-.185	76
	Garden	0.05-.1	101
	Paper	0.04-0.06	203
	Wood and straw	0.02-0.03	218
	Textiles	0.04-0.06	122
	Diapers	0.05-0.1	122
	Sludge	0.06-0.185	0
	Industrial waste	0.08-0.1	76
California LMCM	MSW	0.02-0.057	68-110
	Greenwaste	0.02-0.057	63
	Sludge	0.02-0.057	25
IPCC	Food	0.1–0.2	76
	Garden	0.06–0.1	101
	Paper	0.05–0.07	203
	Wood and straw	0.02–0.04	218
	Textiles	0.05–0.07	122
	Nappies	0.06–0.1	122
	Sludge	0.1–0.2	25
	Industrial waste	0.08-0.1	76

The FOD model has been adopted for landfill generation modeling by state-level, federal-level and international governments, as well as regulatory agencies. In recent history, the two most significant adaptations of the FOD model are the EPA's LFG Emission Model (LandGEM), and the IPCC Solid Waste Disposal model. California utilizes a state-specific implementation of the IPCC model.

Parameters critical to the function of the FOD model are the decay rate (k), along with the potential of waste to generate methane (L_0 or a combination of other factors that are functionally equivalent to L_0). For the purpose of brevity and simplicity, this evaluation will use "L_0" when discussing the parameter that represents the potential to generate methane. Simple implementations of the FOD model based both the k and L_0 value on municipal solid waste

(MSW), while more complex implementations (e.g. the IPCC model) use a separate k and L_0 value for each waste type. Table 1, above, presents a summary of k and L_0, or equivalent values, from models and literature.

Once the FOD model determines methane generation e, methane emissions can be estimated by deducting methane oxidation in the landfill cover or methane destruction in passive destruction systems from methane generation, assuming the remainder is emitted into the atmosphere.

In 2011 and 2012, the Solid Waste Industry for Climate Solutions (SWICS), an industry stakeholder group, presented the EPA with results from SWICS studies, which resulted in modification of the GHGRP regulation to include a straight 10% oxidation value, in addition to a flux-based approach to determine oxidation. In the late 2000s, SWICS worked with academics to develop better estimations of methane oxidation in landfill cover, and proposed the use of oxidation rates that depend on the flux rate of methane through the landfill cover (SWICS 2009).

FOD models are known to be inaccurate when estimating landfill methane generation for individual sites, as several demonstrate methane recovery of more than twice what the FOD modeled generation predicted, and the model can similarly over predict methane generation by a factor of more than two for individual sites. In addition, in the "Compilation of Air Pollutant Emission Factors" document (AP-42, Section 2.4, 1998), the EPA estimates that the predicted (i.e., modeled) methane emissions varied from 38 to 492% of actual emissions. While this inaccuracy can be reduced by robust characterization of the waste stream at each landfill, the required level of characterization is more detailed than standard industry practice in the U.S.

The use of the FOD model for calculating methane generation is appropriate for landfills of all sizes. However, the cost of modeling is independent of the size of the landfill, so the relative cost will be greater for small landfills. Costs for using FOD models will be in the high hundreds of dollars to low thousands of dollars. There are no logistical limitations associated with this method; however, understanding the inherent uncertainty with FOD models is critical.

Non-FOD Models Without Gas Collection

The use of non-FOD modeling to determine landfill methane emissions is relatively uncommon. The only non-FOD model that is in use is the California Landfill Methane Inventory Model (CALMIM), which was established for use in California, but its development is supported by the EPA. CALMIM is a one-dimensional transport and oxidation model for landfill methane. Non-FOD models are a viable method for estimating methane emissions from landfills, but typically require different inputs, such as the amount of organic matter in cover materials and detailed climate information. CALMIM calculates methane emissions based on modeled methane transport in the landfill cover materials and methane oxidation in the landfill cover. CALMIM was also vetted internationally as a potential reporting method for the IPCC (Bogner et. al. 2011) and the organization concluded that CALMIM is a Tier III methodology for determining landfill methane emissions.

Similar to FOD models, the use of a non-FOD model for calculating methane generation is also appropriate for landfills of all sizes. The cost of modeling is independent of the size of the landfill, so the relative cost is greater for small landfills. Non-FOD models require data that is outside of what landfills typically record and maintain, and they are more complicated to use, so costs for using non-FOD models to estimate methane emissions tend to be higher than costs for using FOD models. Costs for using non-FOD models will be in the low thousands of dollars to low tens of thousands of dollars, depending on the amount of additional data collection. There are no logistical limitations associated with this method; however, the additional data collection needs must be considered.

Landfills With Active GCCS

Landfills with active LFG collection can measure the flow and methane concentration in the collected LFG. This additional measurement data results in the following methane emission estimation methods:

- FOD modeling with measured LFG collection.
- Non-FOD Models.
- Measured LFG collection with estimated collection efficiency.

FOD Modeling With Measured LFG Collection

In this process, methane generation is demonstrated using an FOD model. Measured methane recovery is deducted from the methane passing through the landfill cover as fugitive emissions. Recovered methane emissions are measured and calculated as per a stationary combustion device or other process. The general form of the emission calculation is shown in Equation 1 below.

Equation 1: $Emissions = (Gen - Recovery)x(1 - Oxidation)$

As calculated by the FOD model, where "Emissions" is the mass of methane emitted, and "Gen" is the mass of methane generated, "Recovery" is the measured methane recovered by the active GCCS, and "Oxidation" is the fraction of methane oxidized in the landfill cover. FOD modeling with methane recovery is a viable method for estimating methane emissions from landfills. The EPA's GHGRP uses this method for calculating GHG emissions under Equation HH-6. This method is also included in the IPCC Solid Waste Disposal inventory method.

However, this method for methane emission estimation relies on FOD modeling as the basis for estimating methane emissions and inherits the inaccuracy, uncertainty and limitations of the FOD modeling discussed above. This inaccuracy can become apparent when the recovered methane exceeds modeled methane generation. When the model overpredicts methane generation, there is no obvious discrepancy, but the model is also known to overpredict methane generation for individual sites, as well, particularly in arid climates.

Costs for this method are higher than FOD modeling alone, due to additional costs associated with monitoring and processing methane recovery data. Costs for this method will be in the low to mid thousands of dollars. Costs will have some scaling associated with the number of methane measurement locations/methane destruction devices. Facilities that are operating an active GCCS do not have logistical limitations associated with this method.

Non-FOD Models With LFG Collection

The presence of an active GCCS may limit some of the non-FOD models use for methane emission estimates, but CALMIM can be used for sites with a GCCS. CALMIM enables users to input the area of the landfill with an active GCCS, and calculates the methane emissions based on the area with coverage. CALMIM does not require information about the amount of annual landfill waste or the amount of methane collected by the GCCS.

Measured Recovery with Estimated Recovery Efficiency

In this method, methane recovery is measured, the methane recovery fraction (collection efficiency) is estimated, and the methane generation is calculated based on those factors. The difference between the calculated methane generation and recovered methane equates to what passes through the landfill surface, undergoes oxidation, and is emitted into the atmosphere. Emissions from the recovered methane are measured and calculated. The general form of the emission calculation is shown below in Equation 2.

Equation 2: $$Emissions = (\frac{Recovery}{Collection\ eff} - Recovery)x(1 - Oxidation)$$

Where "Emissions" is the mass of methane emitted, "Recovery" is the measured methane captured by the active GCCS, "Collection eff" is the estimated collection efficiency of the GCCS, and "Oxidation" is the fraction of methane oxidized in the landfill cover.

Measuring methane recovery and estimating collection efficiency is a viable way of assessing landfill methane emissions. This methane estimation method was developed by SWICS (SWICS 2009). A modified version of the SWICS method is also used in the EPA GHGRP, presented in the GHGRP regulation as Equation HH-8.

Collection efficiency is difficult to measure directly, and the uncertainty/accuracy of this method is associated with the ambiguity of that factor. Historically, the EPA projected that landfills with gas recovery collected 75% of the generated methane by default. The GHGRP contains the option for this default, but also presents the choice to use the surface area by landfill cover type (e.g. daily, intermediate, and final) to evaluate collection efficiency. Both the SWICS and EPA rely on landfill cover type to determine site specific collection efficiency, and each cover type has an associated collection efficiency. The overall facility collection efficiency is derived from the area-weighted average. However, while SWICS also recommends the consideration of monitoring results, engineering review of the comprehensiveness of the GCCS, and other site-specific data when evaluating collection efficiency for each cover type or area; this was not incorporated by the EPA into the GHGRP.

The use of a fixed or default collection efficiency should be avoided, as it can provide an incentive to reduce methane recovery. In this case, reduced methane recovery would result in lower calculated methane generation and lower calculated emissions, but actual methane emissions would be higher because actual methane generation would remain the same.

Costs for this method are similar to costs for the use of a FOD model with measured methane collection and will be in the low to mid thousands of dollars. Charges will reflect scaling associated with the number of methane measurement locations/methane destruction devices. There are no logistical limitations associated with this method.

Monitoring Methods

Landfill methane monitoring is the direct measurement of landfill methane emissions on an ongoing or recurring basis, without quantification of methane emissions. The categories summarized below are:

- Surface emission monitoring (SEM).
- Ground-based or low-altitude imaging.
- Satellite and aerial imaging.

Surface Emission Monitoring

SEM is the practice of using a portable methane meter near the landfill surface, while traversing the area of the landfill, to measure methane concentrations. SEM monitoring is required by the EPA for most landfills that generate more than 34 megagrams per year of non-methane organic compounds (NMOCs) using EPA Method 21. When methane exceeds action levels, the landfill is required to take steps to reduce methane emissions. California, Oregon, and Washington also have SEM requirements for landfills with an active GCCS, which are more stringent than those from the EPA.

The level of scrutiny applied with SEM and the cost to sites can be altered by adjusting the spacing of the traversal pathway, requiring both integrated and instantaneous monitoring, the monitoring of landfill surface penetrations, fine-tuning monitoring frequency, and correcting any methane monitoring levels that require landfills to take action. The EPA currently requires that instantaneous SEM be performed on a quarterly basis, with 30-meter spacing for a serpentine path across the landfill surface, and action taken by landfills when an instantaneous methane concentration of 500 parts per million by volume (ppmv) is detected.

For comparison, the state of California requires instantaneous and integrated SEM on a quarterly basis, with a spacing of 7.6 meters (25 feet), and requires corrective action at either 500 ppmv of instantaneous methane or 25 ppmv integrated (average concentration across a 50,000 square foot [4,645 square meter] grid) methane. Finally, requirements can include the monitoring of specific features or locations. For example, according to the newest EPA requirements, facilities must monitor at all surface penetrations, which includes wellheads, vents, and permanent posts.

The cost of implementing the California, Oregon, and Washington requirements is roughly three to four times higher than implementing EPA requirements. Detailed monitoring requirements are described in EPA regulations (40 Code of Federal Regulations [CFR] Part 60 Subparts XXX, Cf; Part 62, Subpart OOO; Part 63, Subpart AAAA), California regulations (California Code of Regulations [CCR] Title 17 Article 4, Subarticle 6), Oregon (Oregon Administrative Codes, 34-239), or Washington (Washington House Bill E2SHB 1663).

SEM costs for small sites (smaller than 50 acres [20 hectares]) are driven by mobilization, equipment, and reporting rather than the size of the site. While the cost to perform SEM at small sites is much higher per area than for large sites, costs scale more closely with the size of the site for large sites and range from the mid thousands of dollars to low tens of thousands of dollars per event for the EPA-required SEM.

The effectiveness of the monitoring is related to the spacing of the monitoring path. Tighter pathways are less likely to miss small locations with high methane emission rates. By requiring mitigation at lower monitoring thresholds, methane emissions will also be reduced. However, tighter path spacing is closely related to the cost of monitoring. Making monitoring more effective will increase costs. As noted, the EPA requires spacing of 30-meters, California requires spacing of 7.6-meters, and the cost of monitoring in California is roughly three times to four higher. Most, but not all, of the cost difference is driven by the spacing requirement.

Ground Based or Low Altitude Imaging

Devices that are capable of seeing into frequencies that the human eye cannot detect, but in which methane is visible, are infrared (IR), tunable diode laser (TDL), or hyperspectral cameras/scanners. These types of "cameras" are widely used in the oil and gas industry to screen for leaks in pipelines and other oil and gas infrastructure, but are not commonly used in the solid waste industry, although that is beginning to change.

For landfill applications, IR cameras/scanners and TDLs are used by landfill personnel to screen for large methane emission points on the landfill surface or components of the landfill GCCS. Drone-mounted IR cameras/TDLs and gas samplers can monitor remote landfills or portions of the landfill that cannot be safely accessed for SEM. However, when high methane emissions are detected, IR cameras/TDLs may not be as good at determining the source of methane emissions and personnel may be required to investigate the source with SEM equipment.

While IR cameras or TDLs are used to comply with the EPA regulations for leak detection and repair (LDAR) in the oil and gas industry, characteristics of emission sources differ from those at a landfill. Oil and gas facility methane leaks tend to be localized hot spots, like seams and holes in equipment. While cracks and fissures in landfill cover can lead to localized hot spots, methane emissions at landfills tend to be slow, but over a large surface area. Several TDL devices have been approved under EPA Method 21, and are beginning to be used as SEM alternative at landfills.

IR cameras/TDLs can be mounted, hand held, or drone mounted. This versatility means most sites should be able to find an application of suitable IR cameras. Equipment and monitoring costs are in the mid thousands of dollars to mid tens of thousands of dollars per event, depending on the size of the site and any Federal Aviation Administration (FAA) restrictions that pertain to the surrounding area.

IR or laser imaging is expected to be moderately to highly effective at finding local areas of high methane emissions, and moderately effective at characterizing site-wide emissions. Imaging can capture a site-wide overview relatively quick and is likely to catch localized hot spots that SEM might miss. As technology improves, IR, laser, or other optical technologies may be able to see and accurately quantify low concentration leaks as this becomes more cost effective. At this time, under federal rules, drone-mounted devices have not been approved for compliance monitoring.

Satellite and Aerial Imaging

Satellite and aerial imaging use high altitude or orbital imaging to get an overall picture of methane emissions from a landfill. Aerial and orbital cameras are able to see substantial methane plumes, most notably in recent years associated with the SoCal Gas Aliso Canyon leak. Similar distant imaging is used to obtain a picture of the methane emissions at landfills according to several California and national studies. This started with a program developed by the Jet Propulsion Laboratory (JPL), and continued with private companies, including Scientific Aviation (under contract to CARB), Carbon Mapper, Climate TRACE, and others. Imaging distance can limit its utility in determining precise locations of methane emissions or hot spots, but accuracy has improved substantially over the past several years. Also, there are companies (e.g., Methane SAT) that deployed methane measuring satellites, which can be contracted for individual site events. CARB has purchased its own methane satellite and is expected to deploy it by 2024.

Aircraft and satellite-based monitoring cost and specialized equipment required is not practical for individual site owners, but it is used in research programs at sites that are cooperating. These programs continue and are expanding nationally. Private companies make it possible for an individual site to contract for flyovers separately, beyond their research program participation.

Flux Measurement Methods

Landfill methane measurement directly measures landfill methane emissions. SCS identified four categories of methane measurements in the previous annotated list, and all are substantially more expensive than methane emission estimation or monitoring methods, due to the required amount of fieldwork, equipment, and analyses used. The categories previously identified are:

- Flux chamber testing.
- Ground-level plume measurement.
- Stationary path measurement.
- Reverse air dispersion modeling.
- Tracer studies.
- Low or high-altitude imaging.
- Hybrid methods.

Many of these methods are described in Monster, et. al 2019. Each uses a specific technique to measure methane concentrations and then uses various methods to convert that into flux values.

Flux Chamber Testing

Flux chamber testing is the sampling of methane flux (mass emissions per area) at the landfill surface using flux chambers. Flux chambers are small (typically around one [1] square meter or less) chambers (typically a dome) that are placed on a surface being sampled. Sample locations are very small compared to the area of even a small landfill, so flux chamber testing must include a method of scaling the sampling results for the complete site. The EPA developed a method that includes the determination of a number of required samples and sample locations (Radian 1986). However, the number of samples required for even a small landfill is impractical. A ten (10) acre site (4 hectares) amounts to 37 sample locations, several days of fieldwork, tens of thousands in analytical costs, and days of labor to prepare the emission report. Large sites must produce more samples with proportionately larger costs.

Alternative sampling strategies have been proposed and developed, including a strategy that combines SEM with flux chamber sample location siting. Neither the method developed by the EPA or alternative methods are required for landfill regulatory compliance, but are commonly used when doing compliance source testing for composting operations. Alternatives are typically used to demonstrate emissions from a facility for academic, litigation, or other non-regulatory reasons.

Flux chambers can be used at most landfills. But sampling requires extended access to surface areas of the landfill and some landfills have large areas that cannot be sampled due to safety concerns. Flux chamber sampling should not be conducted shortly after precipitation or while the ground is covered with snow, which can limit the timeframe for sampling. Costs for flux sampling events will be in the range of mid to high tens of thousands of dollars for flux testing with SEM screening. The cost for a single flux sampling event, using the EPA statistical method, will be in the low hundreds of thousands of dollars to mid hundreds of thousands of dollars.

Ground-Level Plume Measurement

Optical plume measurement uses a ground based optical sensor to measure the methane plume released from a landfill. Plume measurements are then used to calculate the landfill's methane emission rate. At present, there is no standardized optical sensor method. The EPA published Other Test Method 10 (OTM 10), but it has generally fallen out of use and is not regarded as practical or accurate enough for regular use. The EPA does not currently recommend this method on sites they regulate.

Ground-based optical sensor methods have fallen out of favor and are not recommended for further consideration regarding plume measurement methods due to cost (i.e. high tens of thousands of dollars to mid hundreds of thousands of dollars), required specialized knowledge to operate, unknown accuracy, development of other methods (e.g. eddy covariance), poor consistency and repeatability of study results to date, and restrictive operating conditions.

Micrometeorology

Other optical sensor methods use methane concentration measurements collected along fewer paths, rather than measuring many paths to determine the size of a plume. This review will primarily discuss eddy covariance, the most common micrometeorology/stationary path method. Eddy covariance is discussed in this paper because it is well understood and monitoring commercial packages are available. Recent studies of landfills using eddy covariance have shown significant diurnal differences in methane emissions, a phenomenon not previously quantified (Delkash, et. al., 2022).

In these methods, the concentration of methane between fixed points is used to calculate the methane flux from a source. Concentration of atmospheric methane is measured by an IR or TDL. Stationary path measurements are generally superior to plume measurements because some equipment packages can remain in place to provide regular monitoring over extended periods.

There are numerous competing software packages that can be used to calculate flux using eddy covariance.

No regulations require the use of eddy covariance, but one landfill is currently being required to use eddy covariance measurement of methane emissions as part of a research permit. Similarly, there is no standard eddy covariance method from a regulatory agency. Eddy covariance is primarily used in academic research.

Eddy covariance has substantial data recording and management requirements, that benefit from more robust and less expensive storage, as well as wider cellular coverage for data transmission. Technical limitations include power and data transfer requirements. This method is also limited during heavy precipitation, and dew, snow, and frost can interfere with measurements. For these reasons, eddy covariance is best suited to arid sites with access to power and cellular data coverage, though it can be used in wetter climates. The use of battery power and manual data collection is possible at sites without power or data coverage. Some eddy covariance packages require frequent (up to daily) calibration. The knowledge and skillset required to design and implement eddy covariance monitoring is not common among landfill specialists, but many large environmental and engineering consulting companies will have monitoring groups that have the required knowledge and skills. Costs for this measurement method are in the low to mid hundreds of thousands of dollars per site.

Reverse Air Dispersion Modeling

Air dispersion emission calculation methodologies rely on the field measurement of methane concentration data and contemporaneous meteorology data to calculate methane emissions from the landfill using an air dispersion model such as American Meteorological Society (AMS)/EPA Regulatory Model (AERMOD), developed by EPA or CALPUFF, developed by Exponent. There is no standardized method for obtaining the field methane measurements. Methane concentration from SEM events has been used (Huitric and Kong, 2006), as well as plume measurement (Goldsmith et. al. 2012).

The air dispersion method also requires the gathering of extensive meteorological data, which must be collected contemporaneously with methane concentration data. Methane monitoring data and associated meteorology data are expensive to collect if data is not attained for other purposes, and the use of methane monitoring data from a single monitoring event is only reflective of methane emissions during that event. Ongoing monitoring (e.g. plume measurement, stationary sensors) requires sophisticated equipment and considerations for power and data management.

Determination of emission rates from air dispersion modeling is not a regulatory requirement in any jurisdiction, though it has been used to demonstrate regulatory compliance in California. No standard method for reverse modeling has been developed, but methods have been proposed (Huitric and Kong, 2006). Air dispersion methods produce generally accurate results, but regulatory models tend to over predict impacts, which can lead to under predicting emissions, and tends to be inaccurate when modeling impacts very close to area sources, such as landfills. The limitations of this method are associated with the limitations of the monitoring method used to obtain methane measurements. Air dispersion modeling costs will be in the high tens of thousands of dollars to low hundreds of thousands of dollars per event. Sampling costs are likely to scale proportionately with the size of the landfill.

Tracer Studies

Tracer gas studies have been used to verify the results of air dispersion modeling from point sources for years. The difference, regarding tracer studies on landfills, is that instead of releasing a specific tracer gas into the effluent of an emissions stack, a fixed amount of tracer gas is released at the landfill surface. Due to the dynamic composition of LFG, typically an inert, non-reactive, and easy to detect gas, such as acetylene is used as the tracer gas.

Once released at the landfill, the ratio of methane to tracer gas can be determined through sampling. When this ratio is known, the concentration of methane in ambient air, downwind of the landfill, can be determined by sampling for trace concentrations of the tracer gas at varying distances from the landfill and applying the tracer to the earlier determined methane ratio.

Due to the nature of the detection/sampling for tracer gas, this methodology is extremely sensitive to meteorological conditions (wind speed/direction, barometric pressure, etc.). However, as a promising technological advance, the EPA is currently working on an application of the tracer gas method under OTM-33B, that is being developed in coordination with WM (Green, et. al., 2012). Costs for this method can range from the high tens to low hundreds of thousands of dollars, based on the number of rounds a site conducts.

Low- and High-Altitude Imaging Flux Estimation

Using concentration data obtained from both aerial and satellite imagery, as described above, some organizations have attempted to calculate emissions rates (i.e. flux) from the observed concentrations (Cusworth, et. al., 2020). This is done through a combination of concentration measurements, wind speed measurements, and length of plume measurements, using aircraft or satellite data. Although more akin to a qualified emissions estimation methodology, scientists have presented plume emissions estimates as quantified results. However, the emissions flux estimates can have up to a 150% margin of error. The key issue with using this methodology to evaluate an area source, like a landfill, is the accuracy of the back-end algorithms that are used to convert concentration measurements into flux.

Hybrid Concepts in Development

As more landfill focused emissions estimation technologies arise, scientists and stakeholders alike have been interested in cross-evaluation of differing methodologies. For example, the solid waste industry is currently working with JPL, CARB, and Carbon Mapper to perform SEM concurrently with aerial and drone emissions estimation methodology. This approach can serve to help validate new methodologies and/or debunk some estimation methods. However, coordination between on-ground surveys and aerial/drone-based surveys has proven to be difficult due to weather-clearance, flight crew availability, and mobilization of SEM technicians on an as-needed basis. Other hybrid or modified approaches include a combination of sampling, reverse air dispersion modeling, drones outfitted with sample collection devices, and/or other types of methane sensors, in addition to lasers (Project Canary, 2021).

REFERENCES

1. U.S. Environmental Protection Agency, Office of Air and Radiation, Office of Air Quality Planning and Standards, 1998. Municipal Solid Waste Landfills. Compilation of Air Pollutant Emission Factors, Volume I: Stationary Point and Area Sources, Section 2.4.

2. IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 3 – Solid Waste Disposal.

3. Mandatory Greenhouse Gas Reporting. 40 Code of Federal Regulations, Part 98, 2016.

4. National Council for Air and Stream Improvement (NCASI), 1999. Evaluation of the EPA-Recommended Approach to Predicting Air Emissions from Pulp and Paper Industry Landfills.

5. AERMOC Modeling System: https://www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models#aermod.

6. CALPUFF Modeling System: http://www.src.com/.

7. Standards of Performance for Municipal Solid Waste Landfills that Commenced Construction, Reconstruction, or Modification after July 17, 2014, U.S. EPA. 40 CFR Part 60, Subpart XXX, August 29, 2016.

8. Methane Emissions from Municipal Solid Waste Landfills, California Air Resources Board. Title 17 CCR Article 4, Subarticle 6, Sections 95460 to 95476.

9. National Emission Standards for Hazardous Air Pollutants: Municipal Solid Waste Landfills, 40 Code of Federal Regulations, Part 63, Subpart AAAA, March 26, 2020.

10. Emission Guidelines and Compliance Times for Municipal Solid Waste Landfills, 40 Code of Federal Regulations, Part 60, Subpart Cf, August 29, 2016.

11. Federal Plan Requirements for Municipal Solid Waste Landfills That Commenced Construction on or Before July 17, 2014 and Have Not Been Modified or Reconstructed Since July 17, 2014, 40 Code of Federal Regulations, Part 62, Subpart OOO, May 21, 2021.

12. SWICS, 2012. SWICS 2.2 Methane Oxidation Addendum 2012.

13. SWICS, 2007 Current MSW Industry Position and State-of-the-Practice on LFG Collection Efficiency, Methane Oxidation, and Carbon Sequestration in Landfills.

14. SWICS, 2009. Current MSW Industry Position and State-of-the-Practice on LFG Collection Efficiency, Methane Oxidation, and Carbon Sequestration in Landfills version 2.2.

15. Bogner, Spokas, and Corcoran, 2011. A Site-Specific Process-Based Model for Landfill CH4 Emissions Inclusive of Seasonal Soil Microclimate and CH4 Oxidation.

16. Oregon State Administrative Rules, Chapter 340, Division 239, Landfill Gas Emissions.

17. Washington House Bill E2SHB 1663, An Act Relating to Reducing Methane Emissions from Landfills, March 9, 2022.

18. Radian Corp. 1986. Measurement of Gaseous Emission Rates from Land Surfaces Using an Emission Isolation Flux Chamber. User's Guide.

19. Monster, J., Kjeldsen, P., and Scheutz, C., Methodologies for Measuring Fugitive Methane Emissions from Landfills – A Review, Waste Management, Volume 87 (2019) 835-859, March 2019.

20. Delkash, M., Chow, F., and Imhoff, P., Diurnal Landfill Methane Flux Patterns Across Different Seasons at a Landfill in Southeastern US, Waste Management, Volume 144 (2022) 76-81, March 2022.

21. Huitric, R., and Kong, D. 2006. Measuring Landfill Gas Collection Efficiencies Using Surface Methane Concentrations, Solid Waste Association of North America (SWANA) 29th Landfill Gas Symposium, St. Petersburg, FL, 2006.

22. Goldsmith, Chanton, Abichou, Swan, Green, and Hater, 2012. Methane Emissions from 20 Landfills Across the United States Using Vertical Radial Plume Mapping.

23. Green, R., Swan, N., Thoma, E., Footer, T., Chanton, J., and Hater, G., Measured and Modeled Methane Emissions at Closed MSW Landfills Without Gas Collection, Global Waste Management Symposium, February 2012.

24. Cusworth, D., Duran, R., Thorpe, A., Tseng, E., Thompson, D., Guha, A., Newman, S., Foster, K., and Miller, C., Using Remote Sensing to Detect, Validate, and Quantify Methane Emissions from California Solid Waste Operations, Environmental Research Letters, Volume 15 (2020), 054012, April 2020.

25. Project Canary, A Quantitative Overview of Continuous Monitoring of Methane Emissions, Project Canary 2021.

KEYWORDS

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