Sustainability in Action

November 27, 2024

Submitted electronically via https://www.regulations.gov

Vasco Roma, *roma.vasco@epa.gov*
Office of Atmospheric Protection, Climate Change Division
Office of Air and Radiation
U.S. Environmental Protection Agency

Re: Use of Advanced and Emerging Technologies for Quantification of Annual Facility Methane Emissions under the Greenhouse Gas Reporting Program;
Docket ID No. EPA-HQ-OAR-2024-0350

Dear Mr. Roma:

Republic Services (Republic) appreciates the opportunity to provide comments on the Request for Information (RFI). Republic has had the opportunity to review comments submitted by the National Waste & Recycling Association (NW&RA), and we support their comments submitted on November 27, 2024.

Republic has a substantial stakeholder position in the RFI based on our significant experience in the industry and reporting for over 200 facilities since the Greenhouse Gas Reporting Program ("GHGRP") became effective in 2010. Republic is an environmental service industry leader with operations in 47 states and Canada. Republic Services is also recognized for our sustainability leadership, with 42,000 employees, 13 million customers, and more than 900 locations, including 209 active landfills, six specialty disposal facilities for hazardous waste and 76 renewable energy projects. As such, Republic Services has a significant interest in providing comments to the RFI.

As a sustainability company, we are committed to reducing methane emissions across our operations. We are the first U.S. environmental services provider to have our emissions reduction target endorsed by the Science Based Targets Initiative (SBTI). In addition, we have set an ambitious goal to reduce our absolute Scope 1 and 2 greenhouse gas emissions by 35 percent by 2030. We are also investing in facilities to capture and refine landfill gas for use as renewable natural gas (RNG). RNG can be utilized as a low-carbon fuel source that significantly reduces emissions when compared to diesel-burning vehicles.

As responsible operators, we collaborate closely with local, state, and federal agencies to ensure compliance with regulations. We continuously enhance our emissions reduction systems to advance our understanding of methane emissions and technologies.

In addition to the comments provided by NWRA, Republic offers the following comment based on our experience, data, analysis, and testing.

Evaluation of emerging measurement technology

Republic Methane Quantification Emissions Pilot

Republic has been actively involved in a methane emissions pilot to assess multiple emissions measurement technologies simultaneously for comparative emissions quantification analysis (Table 1). The pilot program began in 2022 at two sites in the United States – one in the South (South Landfill), the other in the Midwest (Midwest Landfill). Republic assessed methane quantification for whole landfill site emissions.

Table 1: Table of Quantification methods

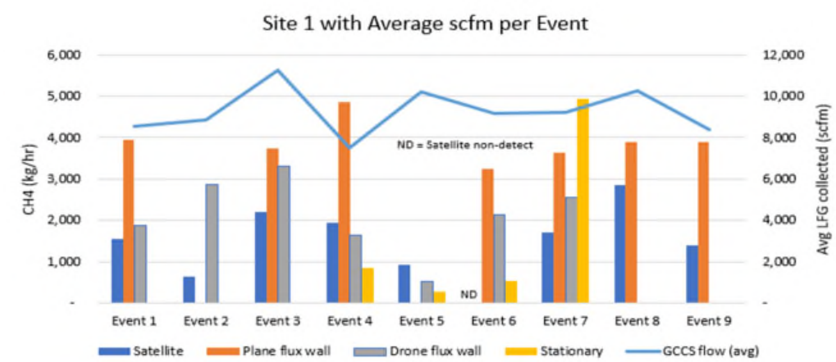
Technology	Sensor	Principle Operation	General Comments
Aircraft Mass Balance	Picaro Spectrometer	Loops, Gauss' theorem	• Very expensive & needs ideal weather conditions • 360° flux emission curtain provides a *snapshot* of emissions • Sensitive to wind speed for quantification • Includes emissions from sources beyond the landfill, such as combustion equipment or nearby methane sources
Drone Mass Balance	Tunable Diode Laser Absorption Spectrometer	Inversion Algorithms	• Lower deployment complexity • Flux emission curtain for *snapshots* of emissions • Very sensitive to wind speeds • Deployable for leak detection without quantification • Identifies large & small emission sources with precision
Satellite Spectrometer	Fabry-Perot Imaging Spectrometer	–	• Very sensitive to wind speeds and weather conditions • Diffused emissions are not detected-Provides *snapshots* of emissions • Detects larger point sources • High-altitude imaging enables broad atmospheric measurements
Stationary MOS Sensor	Metal Oxide Sensor	Machine Learning Algorithms, Triangulation	• 24/7 monitoring capability • Requires many sensors to cover an entire landfill footprint • Equipment & data subscriptions can be costly

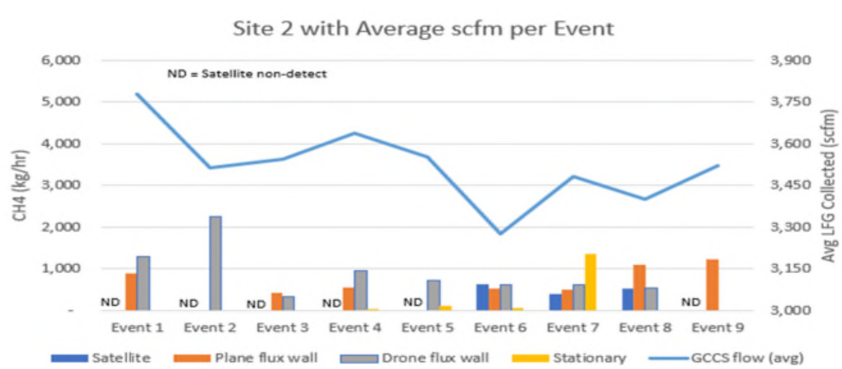
The objective of using two landfills allowed for the assessment of the technologies to be evaluated for variability in accuracy under different site conditions (e.g. topography, temperature, seasonality, wind, etc.) This research investigates methane emissions originating from the South Landfill and the Midwest Landfill. General background information on each landfill is shown in Table 2.

Table 2: Landfill Background information

Landfill	Start Accepting Waste	Area (ac)	GCCS	Gas Collectors
Site 1 – South Landfill	1972	388	Yes	>500
Site 2 – Midwest Landfill	1981	173	Yes	>180

Below is a summary of the data from the methane emissions quantification pilot study, which shows the inconsistencies across the various methane measurement technologies.





In the charts shown above, note:

- Aircraft was used only for Events 1, 3, 4, 6, 7, 8, and 9
- Stationary sensors began operating with Event 4

On average the values estimated by aircraft are higher than those estimated by drone and satellite at Site 1 –South Landfill. At the Site 2 - Midwest Landfill on average the aircraft estimates are lower than those reported by drone for the same landfill. Further, there is no strong correlation between a reduction in gas collection and an increase in gas emissions. These initial observations require further analysis and understanding.

High Level Conclusions – Technology Specific

- Satellite - detects some plumes at the larger emitting landfill but seems to be missing other portions. The satellite appears to have more success under low wind conditions when it can see plumes over heterogenous terrain. At Site 2 the satellite only detected plumes when a new cell was being built and during initial waste placement. However, once the cell was filled to ground level with partial gas collection installed, there were no detections. This could be attributed to "pooling" of the gas as the cell was below ground level. Even when the gas system was partially connected and the cell was still below ground level, methane (pooling) may still have been a part of the detected plume.

- Aircraft - consistent performer and the best understood of the technologies that were tested. At Site 2, the measurements showed some dependence on wind speed, which was not unexpected. It could be method-related and/or it could be that higher winds draw out more emissions from the landfill's pore space as storage flux. At Site 1, the aircraft was more consistent but also included sources beyond the landfill as the site has additional methane sources within the flux boundary.

- Drone - performed reasonably well. Repeatability is a potential issue, and measurement estimates were somewhat volatile at Site 1 which is larger than Site 2. Since the landfills were measured in segments for full coverage this required that winds are blowing consistently in one direction for the entire day, which will only sometimes be the case. At times when the winds shift appreciably during measurement days, the measurements are less reliable.

- Stationary sensor - this method was confusing. After evaluating with the vendor this confusion was attributed to the sensor being originally designed for oil and gas facilities with the primary objective to identify significant emission events, with priority given to avoiding false alarms. With respect to landfills, the priority is less about detecting significant events, and more about identifying trends in overall methane emission, such as reductions caused by implementing capture systems. When the sensors were first deployed, the plume model logic was identical to what is used on oil and gas facilities. The largest uncertainty in the plume model calculation is the distance between the sensor and the source, which feeds in to estimating the plume width and height. Between Events 6 and 7, a new plume logic was implemented to address the distance estimate that ultimately did not yield significantly better results. From these learnings, an improved landfill model that eliminates the source to sensor distance in calculating the plume width needs to be developed.

Overall Pilot Study Take-Aways

- No strong correlation between a reduction in gas collection and an increase in gas emissions
- Inconsistent results between the various technologies
- The equipment vendors use unique algorithms for processing, which makes it difficult to compare results
- Detection limits varied by technology
- Weather patterns (wind, clouds, rain, snow) limits
- Topography complex, which impacts emissions
- Difficult to assume yearly emissions with snapshots given construction activity and diurnal changes
- It is difficult to stack technologies on the same day

Republic recently completed the methane emissions measurement pilot. As such, the final data analysis is not completed at this time but still provides valuable insight on emerging technologies from a landfill perspective.

Specific Republic comments to the RFI questions are incorporated in Attachment A. As mentioned previously, we fully support the comments that have been provided by NWRA as they provide more detail and are also reflective of Republic's overall position of the RFI questions. As such comments submitted by NWRA are included in Attachment B for your consideration with our response.

<u>Closing remarks</u>

Republic continues to commit considerable time and resources in assessing the capabilities of emerging measurement technologies while engaging with various technology vendors, academics, and government agencies. The emerging measurement technologies may be useful as an additional resource for detecting landfill gas point sources; however, based on our experience, they are not ready to quantify landfill methane emissions. Overall, there is a lack of consistency and reliability among technologies that quantify landfill methane emissions accurately.

At this point in time, nearly all the emerging technologies available require further development and refinement when quantifying landfill methane emissions. There are significant differences between the purported algorithms employed by ground-based, fixed sensors compared to UAV technologies, compared to aerial technologies, and satellite technologies, including, but not limited to, implementation of meteorological and atmospheric data using anemometers, conversion methodologies, algorithms employed to calculate emission rates, and algorithms employed to extrapolate data into annual emission rates. Many of these algorithms are proprietary and/or still in the process of being developed.

Monitoring emissions from landfills sparks considerable debate and has been the source of misconceptions. Based on our initial findings in the pilot study we conducted on various technologies and assessment of external landfill methane measurement data, more work needs to be done on the quantification of landfill methane emissions. Landfill emissions vary throughout the day due to weather, composition, and waste age. Current measurement and reporting techniques do not consider these dynamic factors but are critical to ensure a representative assessment of landfill emissions. We remain encouraged that these technologies are improving over time. We look forward to continued collaboration opportunities to better align methane monitoring, measurement, and analysis policies.

Respectfully submitted,

Niki Wuestenberg
Senior Manager, Air Programs
Republic Services

cc: David Penoyer – Republic Services
Judith George – Republic Services

Attachment A – Republic Specific Response to RFI questions NWRA comment letter
Attachment B – NWRA comment letter

Sustainability in Action

ATTACHMENT A

RFI questions

Quantification of Annual Emission Rates

a. Detection/Quantification from Advanced Measurement Technologies (e.g., satellite, aircraft, or using continuous monitors)
    i. What technologies use transparent, open-source, and standardized methodologies?
        - Have they been demonstrated and validated?
        - Can they provide consistent, annual data for reporting?
        - Which approaches/methodologies that should/should not be considered?

Response: We are unaware of any technology currently used to quantify methane emissions from landfills that are transparent, open-source, standard, validated, and can provide consistent, annual emissions data. The current method of taking a point in time point source concentration and then extrapolating through a series of assumptions and algorithms to develop an annual emission rate should not be used until it is standardized, transparent, and validated.

    ii. What performance metrics/thresholds can be incorporated into the GHGRP? (e.g., methane detection limit, false positives/negative, levels of accuracy, measurement frequencies)

    iii. Should quantification be limited to specific methodologies (e.g., inverse analysis, mass balance) or approaches for using ancillary datasets (e.g., standardized interpolation of wind)?

Response: Based on the Republic Methane Emissions Quantification Pilot Study and those performed by others, wind speed is a significant factor and can cause large swings in estimated emissions rates. It was also noted that given the topography of the landfill, wind speed and directions are highly variable.

    iv. Are there efforts to develop standards or protocols for detection and quantification?

Response: The first step is determining whether the technology is reliable and accurate. Once that can be established, standards and protocols will need to be developed.

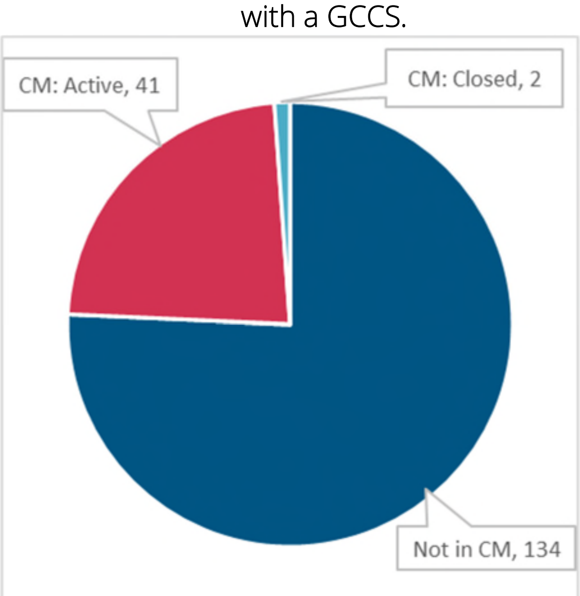
However, the technology vendors have yet to establish reliable and valid methods to address the unique nature of landfill emissions.

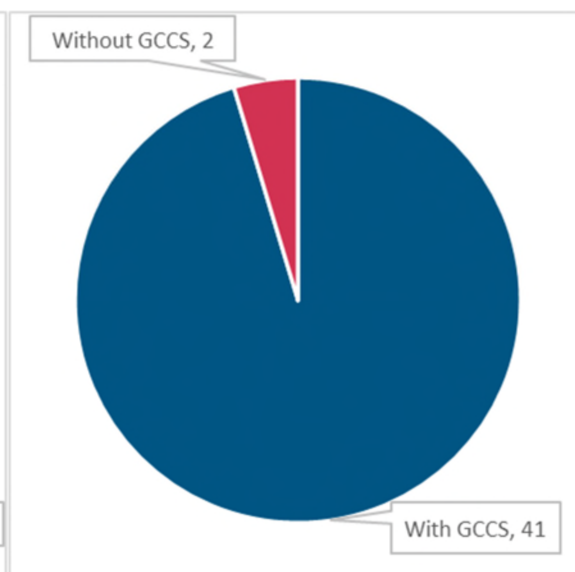
b. Extrapolating Quantified Methane to Annual Emissions given variable sampling frequencies (e.g., continuous to weekly) and durations (e.g., seconds to hours)
   i. What advanced measurement technologies are currently available that can provide annual total methane emission estimates for specific regions, facilities, processes, or equipment-level sources, that use transparent, open source, and standardized methods? Are these technologies applicable across the entire U.S. and could they provide annual data in a consistent manner for each future year of GHGRP reporting? Are there specific annual extrapolation approaches or methodologies that EPA should or should not consider?

Response: We are unaware of any advanced measurement technologies that are currently available that can provide accurate annual total methane emission estimates from landfills that are transparent, open-source, standard, validated, and can provide consistent annual reporting data. In addition, the current datasets that are being used are limited and not representative.

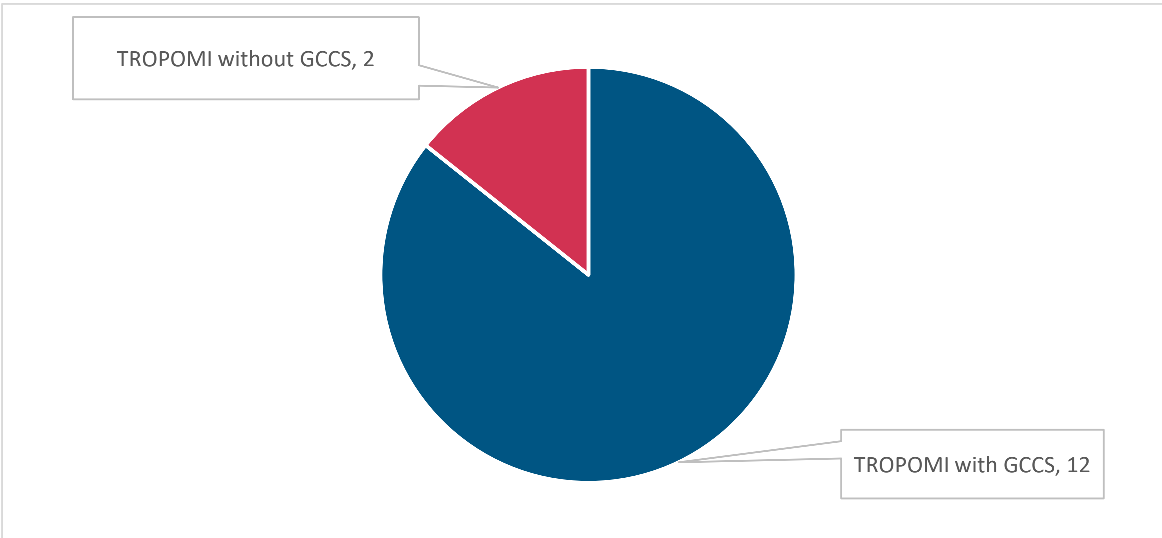
Republic reviewed the dataset compiled by the Environmental Defense Fund (EDF) [https://landfills.edf.org/]. This dataset relies heavily on the Carbon Mapper (CM) data. Using the Republic landfills as an example, the following demonstrates the very small number of sites represented in this dataset where remote methane monitoring has been conducted.

- 177 Republic Landfills in this dataset - 144 are active, and 33 are closed
- Less than 25% of the landfills have CM data; almost all are active sites and with a GCCS.

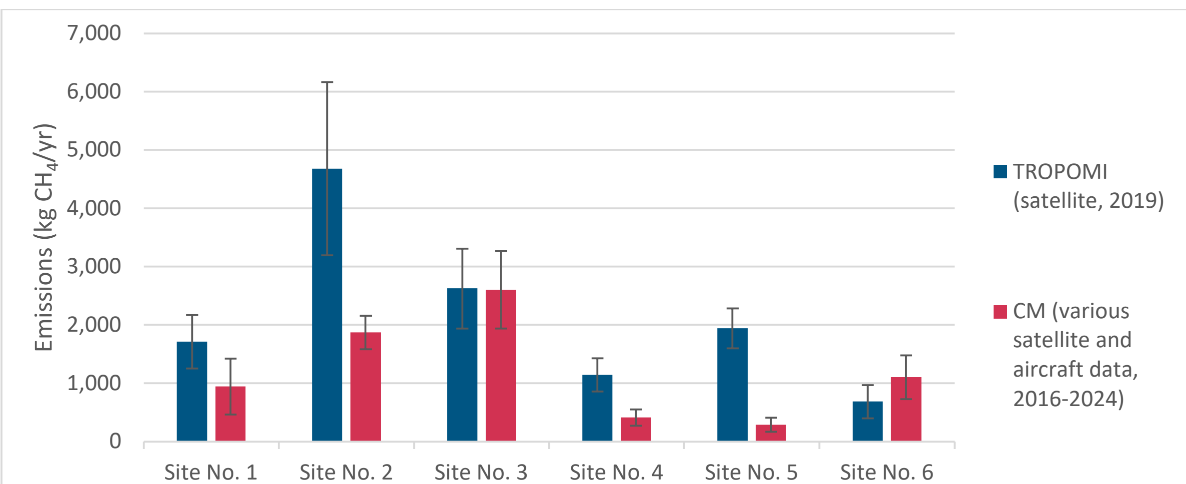




The EDF dataset also includes TROPOspheric Monitoring Instrument (TROPOMI) satellite data. This dataset is even smaller and highly weighted to active sites with a GCCS. There are 14 Republic Landfills with TROPOMI data, all active - 12 with a GCCS and 2 without a GCCS.



Only 6 Republic Landfills have data for both CM and TROPOMI. As noted in the graph below, there is no discernible correlation in the emission estimates during this period.



The limited dataset and the need for more data and research is also presented in what EPA has relied on in the paper *Cusworth et al*.[1] The conclusions in this paper support the contention that advanced measurement technologies are not primed for use in detecting, quantifying, and extrapolating annual emissions from municipal solid waste landfills without further research and development. Indeed, the article concludes that

[1] *Cusworth, et al., Quantifying methane emissions from United States landfills*. 383 Science 1499 (2024).

"direct measurements of CH4 emissions at landfills to date using surface or aircraft instruments have largely been limited to a small number of facilities due primarily to cost, which has resulted in incomplete spatial and temporal sampling. Given the diversity of operational and environmental factors driving landfill emissions, these observational limitations lead to continued uncertainty in this sector's contribution to regional, national, and global CH4 emission inventories, which can complicate assessing the efficacy of emission mitigation efforts."[2].

The RFI also asked questions about extrapolating detected methane to annual emissions. Although inappropriate, several companies, agencies, and organizations have taken satellite and aircraft point-in-time detection data and extrapolated it to hourly and annual emissions. For Example, the EDF dataset heavily relies on some of the Carbon Mapper data to compare point-in-time point source emissions in kg/hr to the overall site-wide annual emissions prepared as part of the annual GHGRP.

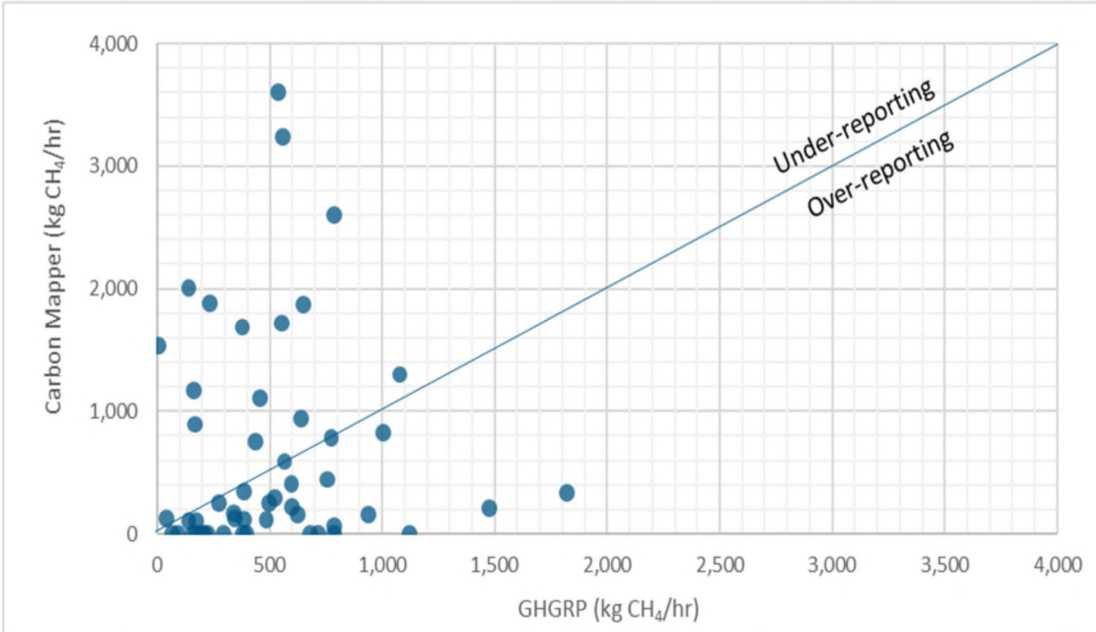
Such extrapolations appear to have been initially made and presented in ***Cusworth et al***. This paper notes that a correlation between GHGRP-reported values and values derived from remote measurements increases with increased numbers of measurements. It also concluded that "Poor correlation exists between aerial emission rates and GHGRP (R^2 = 0.07), which could be expected under sparse sampling[3]."

Representatives from EPA's ORD noted in their presentation at the Landfill Workshop and again in their November 19, 2024, webinar that moving from emissions detection to extrapolating the data to emissions quantifications is not ready for widespread deployment.

Although making such extrapolations and comparisons does not comport to reasonable science, given that the extrapolations have been performed and continue to be performed, we provide a similar comparison to refute the concept that landfills are "under-reporting" emissions and to also show that reliance on such comparisons to make regulatory changes is not appropriate at this time.

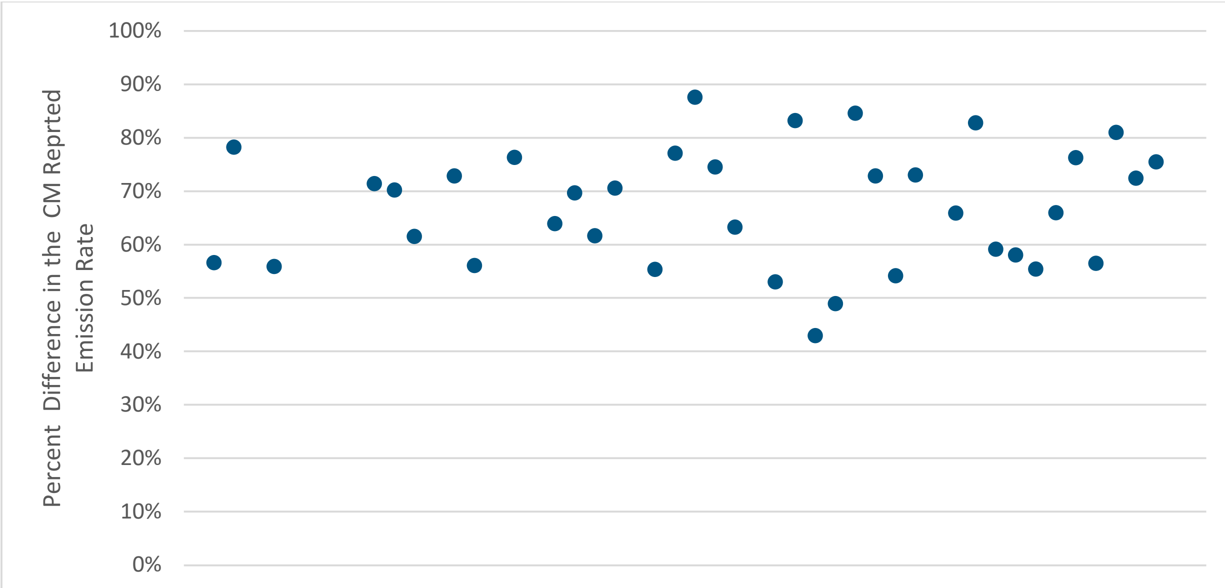
In the graph below, CM and GHGRP data from the EDF dataset for the Republic sites have been plotted. The data does not indicate that landfills are significantly "under-reporting," and that there is a need to adjust the GHGRP for landfills. In fact, more sites (twenty-five), are "over-reporting," and only eighteen sites are "under-reporting." Again, the data does not support that increasing landfill gas emissions through changes in the GHGRP are needed. This is very similar to what was found in the ***Cusworth et al*** in that the data does not correlate, and some sites are "over-reporting" and some are "under-reporting."

[2] *Cusworth, et al., Quantifying methane emissions from United States landfills*. 383 Science 1499 (2024).
[3] *Id.*



ii. What accuracy or uncertainty metrics would be appropriate for GHGRP reporting purposes? For example, what level of accuracy in reported annual methane emissions should advanced measurement technologies be required to meet? What sources of uncertainty are necessary to consider? Are there other specific quality assurance or quality control markers that should be considered to ensure that annual estimates represent the methane emissions from all operational activities throughout the reporting year, such as specific measurement frequencies or duration? What would be a feasible approach to developing these thresholds and metrics?

Response: Until there is a representative sample size of active and closed landfills in various regions of the country with and without gas systems, a determination on accuracy and uncertainty metrics is difficult to evaluate. The graph presents the percent difference based on the reported CM uncertainties for the Republic sites in the EDF database. As shown in the graph, the percent difference is extremely high and variable and would again point to how unreliable the data is at this point.



iii. To what extent should standards and protocols be specific to the type of methods and ancillary data used (e.g., statistical approaches), and to what extent should standards and protocols simultaneously consider the specific type of emission sources being sampled (e.g., large unintended vs. small routine emissions event)?

c. Quantifying Annual Methane Emissions from Sources Below Detection Limits of Advanced Measurement Technologies.

i. What methodologies are available for integrating estimates of methane emissions for sources below detection thresholds in an open-source, transparent, and standardized way? Can these methodologies provide consistent annual data? Are there approaches/methodologies that should or should not be considered?

Response: We are unaware of any available methodologies for integrating estimated methane emissions for sources below detection thresholds in an open-source, transparent, standard way.

i. Should these quantification approaches be limited to the use of specific methodologies (e.g., Monte Carlo method) or specific ancillary datasets (e.g., the use of standardized infrastructure or operator data)?

Attribution

a. What methodologies are currently available that can attribute quantified methane emission events to specific equipment types (or additionally, specific regions, facilities, or processes) using transparent, open-source, and standardized methods? Are there specific attribution approaches or methodologies that EPA should or should not consider?

Response: We are unaware of any open-source, transparent, standard currently available attribution methodologies. However, from our onsite testing and review of satellite data, we have seen how nearby sources can be incorrectly attributed to a landfill.

b. What accuracy/uncertainty is appropriate for GHGRP reporting?

Response: Proper and accurate attribution is critical. As noted in the Republic pilot study, off site sources were improperly attributed to the landfill.

c. To what extent would standards/protocols need to be specific to the type of methods and ancillary data used (e.g., infrastructure datasets) or the type of emission source sampled (e.g., large unintended vs small routine emissions event)?

Implementation

a. Structure of Approaches or Protocols
    i. What is needed for annual total, source-specific, methane emissions in a transparent and standardized way?
        (1) To what extent should standards/protocols be specific to the type of methods used (e.g., satellite, aircraft, ground-based)? Could standard methods be developed to be technology agnostic?
        (2) To what extent could standard methods be developed to be source agnostic? Would standards need to be specific to the type of equipment, process, or emission source sampled (e.g., tanks, flares, pneumatic devices, landfill working face), or could they be more broadly applicable across different GHGRP industry segments (e.g., oil and gas operations and landfills)? Alternatively, would different standards be necessary for different types of methane emission events sampled (e.g., large unintended vs small routine emissions events)?

Response: Given the unique nature of landfills and the emissions sources at landfills, it is unlikely that the methane quantification methods used at other industry segments would be accurate or representative of landfills.

b. Verification and Validation of Annual Source-specific Methane Emission Quantification Methods Using Advanced Measurement Technologies for GHGRP Reporting Purposes

    i. Are there approaches that can verify that advanced measurement technologies meet specific standards (e.g., independent blind studies, calibration standards)? Is it necessary to limit the applicability to environmental/site conditions that have been previously validated? For example, if a technology has been validated through blind control release testing during which wind speeds ranged from 0.5 to 10 m/s, should it be limited to that range? How could validity be demonstrated outside tested ranges?

ii. Are there specific types of operator- or facility-specific information that would be useful for improving or validating annual methane emissions quantification or source attribution from advanced measurement technologies?

Response: Based on our pilot study, wind speed is a significant factor when moving from detection of methane to quantification of emissions. It was also our experience that wind speed and direction are highly variable and site-specific. Our testing shows that emissions determined at one wind speed should not be extrapolated and used for annual emissions estimates.

c. Other Considerations Related to the Use of Advanced Measurement Technologies for GHGRP Reporting Purposes

i. What (if any) are the current barriers or limitations to using advanced measurement technologies beyond what is currently allowed under the GHGRP to quantify annual equipment-level methane emissions at scale in the U.S.?

ii. What are the cost considerations for implementing different advanced measurement technologies to quantify annual, equipment-, process-, or facility level methane emissions for GHGRP reporting purposes? If available, costs should be provided in a manner that can be scaled up to different implementation approaches (e.g., cost per site, cost per area covered).

iii. How are factors such as measurement and analysis cost, complexity, or time burden relevant for determining whether advanced measurement technologies may be appropriate for annual GHGRP application?

iv. Other than methane emissions detection and quantification and establishing the duration of emission events as permitted under Subpart W for Other Large Release Events, are there additional ways in which advanced measurement technologies could be used to support quantification and reporting of equipment-, process-, or facility-level methane emissions to the GHGRP (e.g., as a method to identify changes in operating conditions, to supplement specific reported data elements)?

Response: Under the current GHGRP for landfills, sites can use a generation or collection model approach for estimating annual methane emissions. It is tempting to refer to "Advanced Measurement Technologies" as a move away from a model approach to a "direct measurement" approach and although it may sound like a more "advanced" or accurate approach, the accuracy of the remote detection to quantification approach has not been established. For years, the solid waste industry has been taking site-specific direct measurements of captured methane, and then quantifying an annual emission rate with HH-8. As such, using "advanced measurement technology" and extrapolating the data to the annual emission rate is simply replacing one model for another. It has not been established in any reliable, transparent method that the transition from a bottom-up to a top-down model is more representative. The idea of using detection data from aircraft, drones, satellites, or fixed sensors and then modeling/quantifying emissions is an exciting prospect. The point-in-time measurement technologies are not appropriate to extrapolate into annual emission rates as the dataset for these technologies is still limited, and often contain hidden algorithms/models that do not consider the unique nature of landfill operations. Republic supports technology and methodology advancement and is actively involved in the research and development of these technologies. We are actively employing these technologies in a "find and fix" approach, but the extrapolation into estimated emissions rates is not ready for regulatory applications.

ATTACHMENT B

NWRA COMMENT LETTER

November 27, 2024

Submitted electronically via https://www.regulations.gov

Vasco Roma, ***roma.vasco@epa.gov***
Office of Atmospheric Protection, Climate Change Division
Office of Air and Radiation
U.S. Environmental Protection Agency

Re: Use of Advanced and Emerging Technologies for Quantification of Annual Facility Methane Emissions under the Greenhouse Gas Reporting Program;

Docket ID No. EPA-HQ-OAR-2024-0350

Dear Mr. Roma:

The National Waste & Recycling Association (NWRA) is pleased to submit the following comments to the *Request for Information on the Use of Advanced and Emerging Technologies for Quantification of Annual Facility Methane Emissions under the Greenhouse Gas Reporting Program*; Docket ID No. EPA-HQ-OAR-2024-0350 (hereinafter, the "RFI").

NWRA represents companies and professionals in the solid waste industry. NWRA is a not-for-profit trade association representing private solid waste and recycling collection, processing, and management companies that operate in all fifty states. Our members strive to deliver collection, composting, recycling, and disposal services that are protective of the environment in a safe, science-based, and technologically advanced manner. It is important that regulatory policy enables us to continue to deliver these essential services. NWRA's members own and operate municipal solid waste landfills governed by EPA's Greenhouse Gas Reporting Program ("GHGRP") rules at 40 C.F.R. Part 98, Subpart HH (hereinafter, "Subpart HH").

NWRA has long been partners with EPA in developing data, methods and best practices governing the operation of municipal solid waste landfills, including the development of emission estimates and data governing the quantification of greenhouse gas emissions associated with our members' operations. We have been active participants in the rulemaking process for Subpart HH, and likewise are pleased to participate in responding to this RFI.

I. Background to NWRA Comments

NWRA and its members have been active participants in the GHGRP since its inception in 2009. Importantly, and most relevant to the RFI, NWRA has been very engaged in providing feedback to EPA relating to the recent revisions to Subpart HH encompassed within the rule entitled *Revisions and Confidentiality Determinations for Data Elements Under the Greenhouse Gas Reporting Rule,* 89 Fed. Reg. 31802 (April 25, 2024), docket No. EPA-HQ-OAR-2019-0424 (hereinafter, the "2024 Subpart HH Revisions"). NWRA submitted comments to two Notices of Proposed Rulemakings underlying the 2024 Subpart HH Revisions; *Revisions and Confidentiality Determinations for Data Elements Under the Greenhouse Gas Reporting Rule,* 87 Fed. Reg. 36920-37119 (June 21, 2022) (hereinafter the "Data Quality Improvements Proposal"), and *Revisions and Confidentiality Determinations for Data Elements Under the Greenhouse Gas Reporting Rule,* 88 Fed. Reg. 32852 (May 22, 2023) (hereinafter the "Supplemental Proposal").

The 2024 Subpart HH Revisions are highly relevant to the subject matter of the RFI, because EPA's decision to lower default landfill gas collection efficiency values set forth in Table HH-3 in the 2024 Subpart HH Revisions was based entirely on EPA's assessment of papers and data released by environmental advocacy organizations and others asserting, based on emerging measurement technologies, that actual landfill gas emissions are higher than previously reported in the GHGRP.[1] NWRA disagrees with this assertion, and with EPA's action in lowering the landfill gas collection efficiency values in Table HH-3. NWRA's members have committed considerable time and resources in assessing the capabilities of emerging measurement technologies and in so doing have engaged with a broad suite of technology vendors, academics and agencies. While we believe that emerging measurement technologies may be useful in providing additional tools for the detection of landfill gas emissions, most of them are not yet ready for wide-scale deployment in the regulatory context, and do not meet the data quality objectives and criteria necessary for the quantification of landfill gas emissions or required use in rulemaking. For these reasons, NWRA submitted a Petition for Reconsideration in response to the 2024 Subpart HH Revisions on June 24, 2024, a copy of which is attached hereto as Exhibit 1. Importantly, EPA has granted NWRA's Petition for Reconsideration of the 2024 Subpart HH Revisions, and we look forward to working collaboratively with EPA toward the continued improvement of data quality and reporting under the GHGRP.

In reviewing NWRA's comments herein, we ask EPA to carefully consider the following overarching principles that underpin our detailed responses. Each of these is critical to a full and fair evaluation of emerging measurement technologies and their potential application to municipal solid waste landfills:

- Municipal solid waste landfill operations are unique and pose challenges that are not experienced in the oil and gas context in measuring greenhouse gas emissions. Thus, EPA's assessments and regulatory determinations for oil and gas facilities cannot be imposed upon municipal solid waste landfills without significant additional evaluations and methods development.

[1] *See* 89 Fed. Reg. at 31855–56. Notably, EPA asserted in the preamble to the RFI that EPA "did not take final action to incorporate advanced measurement technologies in the April 2024 final rule. . ." revising Subpart HH due to "limitations in existing technologies" even though its reduction of collection efficiencies were directly informed by third party advocacy using these technologies. *See* RFI, 89 Fed. Reg. at 70178.

- For the municipal solid waste landfill sector, emerging measurement methods encompass a variety of technologies that differ in approach and have shown a wide range of accuracy in detection and quantification when compared to known release rates.

- Given the nature of landfill gas emissions, emerging measurement technologies are currently incapable of detecting emissions at the same level of precision as in the oil and gas sector.

- Point in time observations cannot be appropriately or reliably quantified and compared to annualized reported emissions.

- At this time, emerging measurement technologies are not transparent, open-source or standardized.

- At this time, emerging measurement technologies can be used only as a tool to support landfill gas collection and control practices, in conjunction with site-specific data using more established means.

- Site-specific data using established methodologies are critical to the accurate quantification of landfill gas emissions and cannot be replaced by emerging measurement technologies.

In light of the importance of these principles to NWRA's response to the RFI, and to avoid overlap in our responses to EPA's individual questions in the RFI, we have organized our comments around these principles, as set forth below, and have attempted to indicate throughout this document which RFI questions are most relevant to each comment.

II. Specific Comments in Response to RFI

A. Municipal solid waste landfills, and their emissions, are unique.[2]

EPA has begun to deploy emerging measurement technologies for purposes of detecting methane emissions from oil and gas sources, including through the "Super-Emitter Program" incorporated into the New Source Performance Standards / Emission Guidelines for that sector. While the program envisions a verification and certification process for third-party measurement technologies, it is our understanding that no such technologies and third parties have completed the verification and certification process. In addition, we understand that significant challenges remain in terms of meeting EPA's objectives for this and other emerging measurement programs. Some of these challenges are addressed in a submittal by Veritas, which is an initiative developed by GTI Energy experts in collaboration with a broad range of stakeholders, to develop and refine a standardized, science-based, technology-agnostic, measurement-informed approach to calculating and reporting methane missions for the natural gas industry. Veritas identifies and

[2] The text in section is responsive and relevant to each of the questions contained in EPA's RFI. All of the questions are contained in Appendix A, attached hereto.

seeks to address current challenges relating to intermittent emissions; identification, attribution and quantification for events that are below detection limits; and standardization for quantification methodologies, among others.[3] The challenges that are identified for the oil and gas sector are even more attenuated, and must be examined closely, before any such technologies could be considered for inclusion in regulatory structures for municipal solid waste landfills.

There are several important distinctions between greenhouse gas emissions from landfills and from the oil and gas sector, all of which are important for purposes of considering the potential use of emerging technologies for detecting, measuring, and quantifying emissions in upcoming rulemakings pertaining to landfills.[4]

First, landfill gas and natural gas have different compositions and different characteristics. Landfill gas is comprised of roughly half methane and half carbon dioxide. In contrast, natural gas is comprised of 100% methane. Landfill gas is slightly heavier than air, influencing its dispersion and behavior differently than methane, which is significantly lighter than air. In addition, landfill gas emissions occur due to the decomposition of organic waste that is already a part of the carbon cycle, whereas oil and gas emissions are primarily the result of extracting, processing, and transporting fossilized carbon from underground shale areas and introducing that carbon into the carbon cycle.

Emission rates also differ significantly between landfills and oil and gas facilities. Leaks at oil and gas facilities tend to occur at a relatively constant rate under significant positive pressure. Landfill gas collection and control systems, on the other hand, are generally maintained at negative pressure, thereby causing any leaks to be released at near-atmospheric pressure. Leaks at landfills are ephemeral and can vary significantly depending on a number of factors, including construction activities, atmospheric and meteorological conditions, operational fluctuations, and diurnal and seasonal considerations.

Moreover, municipal solid waste landfills and oil and gas facilities are operated in an entirely different manner, wherein some emissions are expected and intrinsic to landfill operation. By contrast, emissions from oil and gas facilities are not intrinsic and can be mitigated and/or avoided with proper management and controls. Whereas oil and gas facilities are static, municipal solid waste landfills are continuously under construction—the working face is consistently moving, new cells are being built, old cells are being closed, and other cells are undergoing placement of intermediate cover. Accordingly, landfill gas emissions are expected to occur over the active life of the landfill as a result of such construction.

In addition to the ephemeral nature of leaks and the constant state of construction at landfills, landfill gas emissions are also highly influenced by the topographic nature of landfills. For example, landfills may have an abundance of hills, ditches, high areas, and low-lying areas, each with their own unique "micro-climate." As a result, landfill gas acts according to the micro-meteorological factors where it is emitted, including significant variance of windspeed,

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[3] *See* Veritas Comment, EPA-HQ-OAR-2024-0350-0021.

[4] Although the RFI is for the express purpose of considering emerging measurement technologies in the context of the GHGRP, NWRA is also aware of EPA's intent to commence a rulemaking process to revise the New Source Performance Standards ("NSPS") and Emission Guidelines ("EG") governing municipal solid waste landfills.

temperature, and barometric pressure at the surface of the landfill versus higher up in the atmosphere. Moreover, landfill gas tends to travel along the surface of the ground outward. As landfill gas moves downhill, it tends to pool, impinging on and complicating attempts to quantify it using aerial techniques. More specifically, when landfill gas pools, measurement technologies tend to inaccurately overestimate emissions. To further complicate the behavior of landfill gas, ground-level vegetation and other physical interferences exercise influence over the movement of landfill gas. Accordingly, landfill gas plumes behave in a non-Gaussian manner (i.e., skewed and uneven). In contrast, the topography of oil and gas exploration wells tend to be relatively uniform, allowing plumes of methane to follow Gaussian distribution (i.e., spread from a continuous point in a predictable pattern of dispersion). EPA should prioritize characterizing and evaluating the impacts of topographic conditions on landfill gas behavior, and in turn, emissions quantification.

As a result of these differences, emission detection techniques have historically differed across both industries. For roughly thirty years, landfill emissions have been calculated under the GHGRP using a *modeled* approach—the applicable formulas use: 1) the difference between the estimated landfill gas generated and the amount collected; or 2) an assumed collection efficiency is applied to the collected gas to estimate uncaptured emissions. From a work practice standpoint, under the NSPS/EG rules, fugitive emissions from covered areas are detected and mitigated by conducting Surface Emissions Monitoring ("SEM") utilizing a modified EPA Method 21 to detect a methane concentrations at the surface of the landfill. At oil and gas facilities, emissions are measured utilizing a variety of techniques including direct measurement with sensors installed at key points, such as valves and compressor stations, to continuously monitor and detect leaks. Oil and gas facilities also use Method 21, but instead of SEM, portable gas analyzers measure specific components around equipment such as pumps, valves and flanges. Accordingly, oil and gas facilities are able to directly *measure* emissions, due entirely to the fact that their facilities are constructed and operated in a manner that imposes little to no uncertainty with respect to detecting, measuring, and quantifying emissions directly.

For all of the above reasons, the approaches to detecting, quantifying and reducing emissions from landfills and from oil and gas facilities must likewise differ. These differences have directly informed NWRA members' experience with emerging measurement technologies and our comments to the RFI questions set forth below.

B. Emerging measurement technologies are being evaluated at municipal solid waste landfills.[5]

NWRA and its members have been deeply engaged in the evaluation of various emerging measurement technologies, including fixed sensor, handheld equipment, drone, aircraft and satellite. These types of technologies may utilize various detection techniques, as follows:

- Mobile Gaussian Plume Assessment ("MGPA") utilizes a high-performance methane analyzer deployed in a vehicle and carried along transects at the fenceline or further downwind, alongside geolocated wind speed and direction measurements.

[5] The text included in this section is responsive to RFI Question 1.a.i.

- Mobile Tracer Correlation Emission Assessment ("MTCEA") involves a controlled release of a non-reactive gas, such as sulfur hexafluoride or acetylene, that is easy to detect and distinguish from other gases emitted by the landfill, so that correlation can be made with target gases and the tracer gas can be used to estimate emissions of the target gases.

- Gas mapping light detection and ranging ("LiDAR") uses a pulse beam of radiation that reflects off the ground surface, and back to the aircraft where a specialized receiver detects and analyzes the special signature of light absorbed or scattered by methane in the atmosphere, with a resulting column measurement that can be used for detection or quantification.

- UAV Column Sensor Emission Assessment ("UCSEA") is a UAV-mounted Tunable Diode Laser that emits a narrow beam of light at a wavelength appropriate to detect methane by using its special signature. The laser is carried on the underside of the UAV and is directed towards the ground. The laser beam reflects off the ground and back to the UAV. During its travel, the beam interacts with the gas molecules and some of the light is absorbed at specific wavelengths corresponding to the molecular absorption lines of methane. The technology is often called TDLAS, Active TDLAS, or a "column-type" sensor. Measurements are retrieved in ppm*m.

- UAV Point Sensor Emission Assessment ("UPSEA") uses a drone with a mounted TDLAS, MOS, or other point measurement sensor for landfill gas quantification. In the method, the UAV flies repeated horizontal transects perpendicular to the wind direction and repeats the measurements at different altitudes to paint in a screen or curtain. Sometimes called a "flux plane" measurement, the method sees wind speed, temperature and pressure values interpolated across the plane, after which the interpolated values are used in a mass balance equation to solve for emission rate.

- Airborne Point Sensor Emission Assessment ("APSEA") uses high-performance gas analyzer mounted in a small aircraft. Flying stacked orbits at a radius slightly larger than the site. Orbits are repeated at progressively higher altitudes until the aircraft reaches the top of the surface-mixed layer. Wind values may be measured in the air, or wind estimates are procured from databases. The wind and methane concentration are interpolated onto a flux screen around the site, and the flux rate is solved using mass balance equation.

- Remote Point Sensor Emission Assessment ("RPSEA") consists of freestanding stations around the landfill perimeter in which various environmental sensors are used to measure wind speed, wind direction, temperature, pressure, and humidity. Methane detection is done using a metal oxide (MOS) sensor. Another type uses an open path Fourier Transform infrared (FT-IR) spectrometer. Algorithms are used to continually assess facility emission using an inverse source dispersion model, or similar.

- Satellite Imaging Sensor Emission Assessment ("SISEA") uses a satellite-mounted sensor to take a series of images and collect methane column measurements for individual pixels. The images are merged, and an interference pattern is created which allows the quantification and detection of methane emissions at facility scale.

- Lagrangian Emission Assessment ("LEA") combines the type of truck-based sampling used in MGPA but pairs the measurements with a different post-processing algorithm. Lagrangian models are commonly used to predict source location probabilities and can be used to calculate emission rates for either point or area-based sources. Normally, Lagrangian models are applied to tower-based measurements, but can be adapted to a mobile setting, as if the tower were moving through the domain.

See, *Hossian* et. al., *A Controlled Release Experiment for Investigation Methane Measurement Performance at Landfills* (2024) ("First EREF Controlled Release Study").[6]

Each of these technologies was evaluated in a comprehensive landfill study by the Environmental Research & Education Foundation ("EREF") at the Petrolia Landfill in Canada between November 6, 2023, and November 14, 2023. The following technologies and platform types were assessed in the study:

Table 1: Summary of methodologies that participated in the controlled release study

Technology Identifier	Technology Type	Platform Type	Sensor	Method	R&D ?
A	Quantification/ Detection	Truck	LGR	MGPA	No
B	Quantification	Truck	LICOR	MGPA	No
C	Quantification/ Detection	Drone	TDLAS	UPSEA	No
D	Quantification	Drone	Mid-IR LDS	UPSEA	No
E	Quantification	Truck	Picarro	MTCEA	No
F	Quantification	Aircraft	Picarro	APSEA	No
G	Quantification/ Detection	Helicopter	LiDAR	LiDAR	No
H	Quantification/ Detection	Satellite	Spectrometer	SISEA	No
I	Quantification	Fixed	EM27	RPSEA	Yes
J	Quantification	Fixed	Metal Oxide	RPSEA	Yes
K	Quantification	Fixed	Metal Oxide	RPSEA	Yes
L	Detection	Drone	TDLAS/ Laser Falcon	UCSEA	No
M	Detection	Drone	TDLAS/ Laser Falcon	UCSEA	No
N	Quantification/ Detection	Truck	LGR	LEA	Yes

[6] A copy of the First EREF Controlled Release Study is attached hereto as Exhibit 2.

The primary findings from the First EREF Controlled Release Study can be summarized as follows:

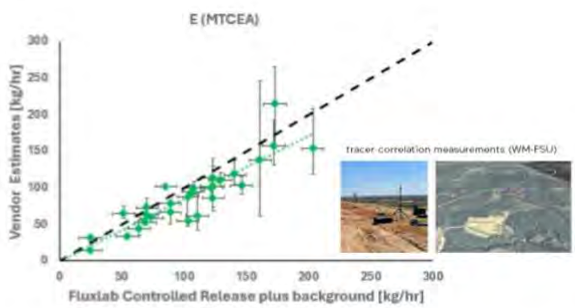
- MTCEA provided good quantification estimates while being flexible to operate in various weather conditions.
  - One vendor evaluated
  - Average uncertainty of ± 20%
- Gas Mapping LiDAR can detect source leaks to 1-3 kg/hr with 90% probability
  - One vendor evaluated
  - Average uncertainty of ± 45%
- UPSEA can only operate in conditions with no precipitation and windspeed below 12 m/s.
  - Two vendors evaluated
  - Combined average uncertainty of ± 48%
- UCSEA reported high number of false positives (False positive fraction > 0.79) with limited visibility when measuring active emission points on slopes
  - Two vendors evaluated
  - Leak detection only
- RPSEA has not been validated by any other studies for use in landfill applications.
  - Three vendors evaluated
  - Average uncertainty of ± 39% in the best-case scenario
- MGPA methodologies were limited by a compressed timeline. Further studies are required to include necessary time for replication.
  - Two vendors evaluated
  - Average uncertainty of ± 43%
- APSEA consistently underestimated emission rates with low bias where predicted emission rates were only 52% of actual values and required meteorological conditions (*i.e.*, low cloud cover, windspeed from 2-6 m/s, good solar insolation) that allowed for a plume to rise and disperse.
  - One vendor evaluated
- SISEA can detect large emission events at or above 300 kg/hr and requires little to no cloud cover and wind speeds less than 10 m/s
  - One vendor evaluated
- LEA overestimated emissions in most cases and is a methodology typically applies in a tower-based system
  - One vendor evaluated

The First EREF Controlled Release Study evidences variability across technology types and even across vendors within specific technology types. The study provided insight on how these technologies operated and performed at a closed landfill setting and provides a baseline for future controlled release studies. Pictorial depictions of the First EREF Controlled Release Study results are shown in the following:

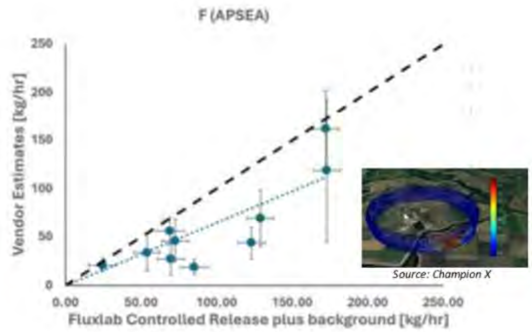
EREF 1st Controlled Release Study

Quantification Results: Mobile Tracer Correlation and Aircraft Mass Balance

Mobile Tracer Correlation– good alignment with true release rates but complex and limited by accessible roads



Aircraft Mass Balance– some alignment but limited by weather conditions and cost



*Aerial Point Sensor (APS)

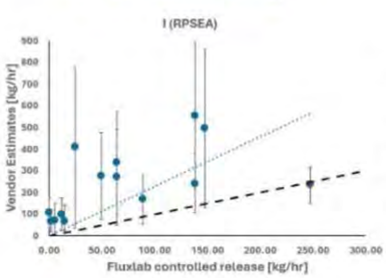
EREF 1st Controlled Release Study

Fixed sensor quantification results varies between vendors

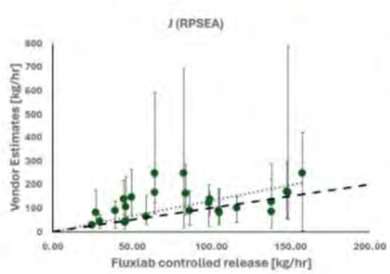
Algorithms were developed for Oil and Gas and still under development for landfills
Take-away: fixed sensors aren't there yet; deeper dive needed into vendors

Source: Champion X

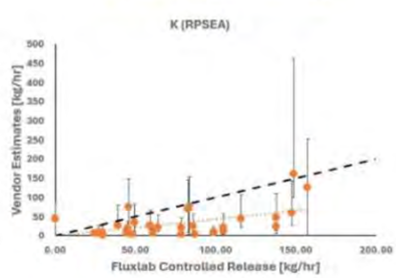
Over-estimating



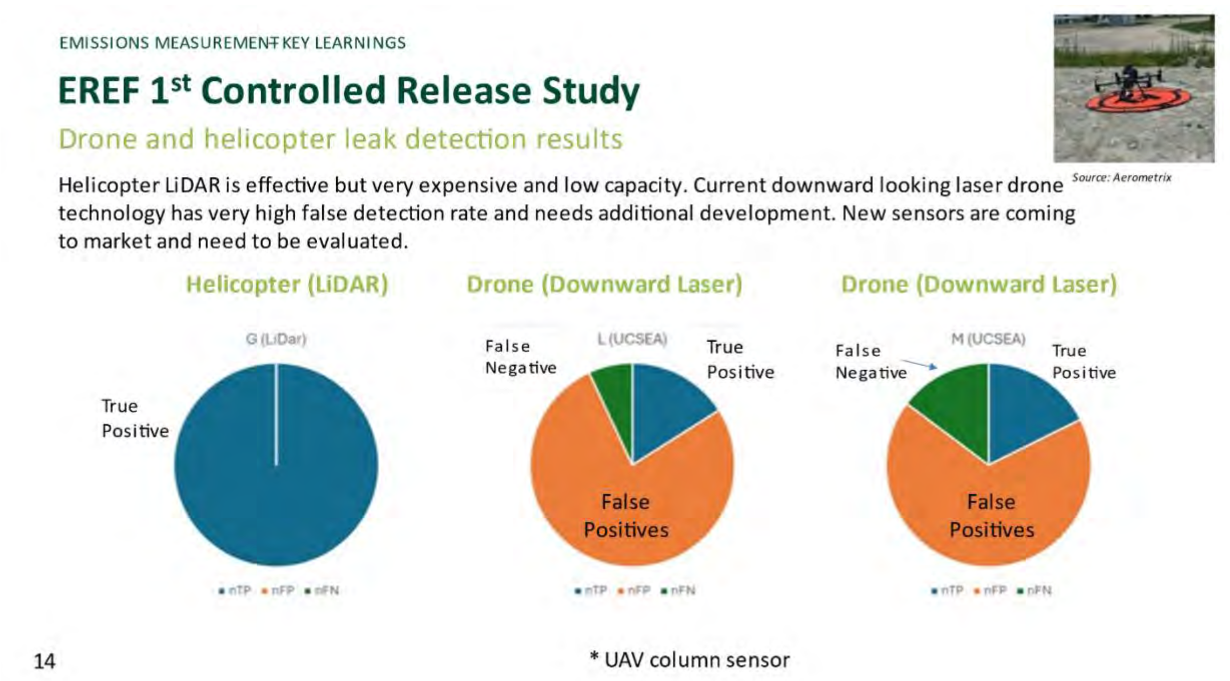
Aligns Generally



Under-estimating



 * Remote point sensor emission assessment



A second controlled release study is underway at the closed Petrolia Landfill to further evaluate these technologies and their vendors. The infrastructure to support releases was improved prior to the second study in order to allow multiple future controlled release studies and allow greater access to vendors to the area of the release. In particular, burying gas-piping intended to allow foot patrols of the area, and ground-based follow-up observations that are a part of some vendor service offerings. Additional invitations to vendors, and adjustments to the study protocol (e.g., higher rates for some planned release windows) were completed to allow more technology vendors to participate. The primary objectives of this Second Controlled Release Study are listed as follows:[7]

- Conduct a comparative assessment of multiple landfill emissions measurement technologies at a single site simultaneously;
- Determine the accuracy of these technologies via controlled, known release of methane;
- Assess annualized costs of utilizing these technologies at different frequencies on sites of different size;
- Evaluate variability in accuracy under different site conditions (.e.g. weather, temperature, season, etc.) *(NOTE: this objective may be considered optional or as a 2nd phase effort depending on additional cost/time needed to complete it)*.

In addition to the technologies studied by EREF, several of NWRA's member companies have engaged directly with technology vendors to evaluate the use and accuracy of satellite, aerial, drone and fixed measurements on a site-specific basis. Some findings are summarized below, but overall highlight a current lack of consistency and reliability among technologies, and an understanding that no one technology can be useful without contemporaneous site operational

[7] NWRA will share the Final Report of the Second EREF Controlled Release Study when it becomes available. NWRA will similarly share the details and reports regarding a third controlled release event scheduled to occur in the spring of 2025.

data to accurately quantify emissions.

Finally, EPA hosted a Municipal Solid Waste Landfill Technology Workshop ("Technology Workshop") in October 2024 in Research Triangle Park. With over 100 participants, the Technology Workshop highlighted both the potential future promise but also the current gaps in readiness of these technologies to be deployed as regulatory compliance monitoring tools. Although the Technology Workshop materials have not yet been made public, NWRA urges EPA to closely evaluate them in context of the RFI.

C. Emerging technologies are currently incapable of detecting emissions at municipal solid waste landfills with the same level of precision as in the oil and gas sector.[8]

Due to the differences described above, emerging measurement technologies are currently incapable of detecting municipal solid waste landfill emissions at the same level of precision or certainty as in the oil and gas sector.

Oil and gas sector emissions are generally easier to detect than landfill gas emissions. First, as noted earlier, oil and gas emissions themselves tend to be either: routine or continuous leaks from processing equipment that (as an equipment class) can be known to leak (*i.e.*, compressor shaft seals, flange connections, etc.); or some kind of non-routine, episodic failure in a location that may or may not be prevalent. For the first type, routine methane detection of processing equipment and flange attachments would likely identify any emission points, leading to precise corrective action, as they are required to do. Because these emissions usually happen as part of a mechanical process at relatively stable and continuous process status, their emission rate can be relatively easily quantified. *See infra* Section II.D. For episodic emissions, monitoring—such as continuous fence line and periodic drone, plane, or satellite scanning—can give some assurance that these events will be detected, or that no non-routine emissions have occurred. But again, because the oil and gas operations are happening at known/recorded process status, once identified the leak event can be somewhat readily quantified. These types of monitoring are also useful due to the geographic nature of oil and gas operations; there are many facilities that are not regularly manned, so fence line and aerial campaigns can collect data very efficiently.

Landfill emissions, however, are neither so reliably detected nor quantified. First, there are generally two areas of landfill emissions: emissions that are recently referred to by EPA as "intrinsic" emissions, such as those that relate to the landfill working face, maintenance activities, and diffuse emissions through landfill cover; [9] and discrete emission sources such as cover system failures, gas extraction issues, and infrastructure leaks, flare issues, or venting due to malfunctions (including both install and failure).[10]

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[8] The text included in this section is responsive to RFI Questions 1.a. and 2.

[9] Members of EPA's Office of Research and Development ("ORD") have referred to these emissions as "intrinsic" or "expected" in that they can be partially controlled but never eliminated. *See e.g.*, EPA webinar materials, *Airborne Survey-Methane from U.S. Landfills*, at slide 13, attached hereto as Exhibit 3.

[10] ORD has referred to these emissions as "fugitive" in that they are more easily dealt with via the "find-and-fix" method. *Id*.

Intrinsic emissions are ephemeral and vary significantly depending on a number of factors, including construction activities, topography, weather, barometric pressure, and diurnal and seasonal considerations. Due to the diffuse and variable nature of landfill emissions, fence line type sensors can have variable reliability in detecting and locating, and low emissions rates are challenging for plane and satellites to detect. Episodic "fugitive" emissions can be somewhat easier to locate, as operators are typically immediately aware of or become aware of discrete infrastructure failures through olfactory and visual inspection as well as routine gas collection and control system monitoring.

Aerial and satellite methodologies are limited by diurnal and seasonal considerations and fail to account for micro-climate fluctuations that occur as a result of topographic differences across landfills. The following figure evidences the behavioral impact that complex topography has on landfill gas emissions:

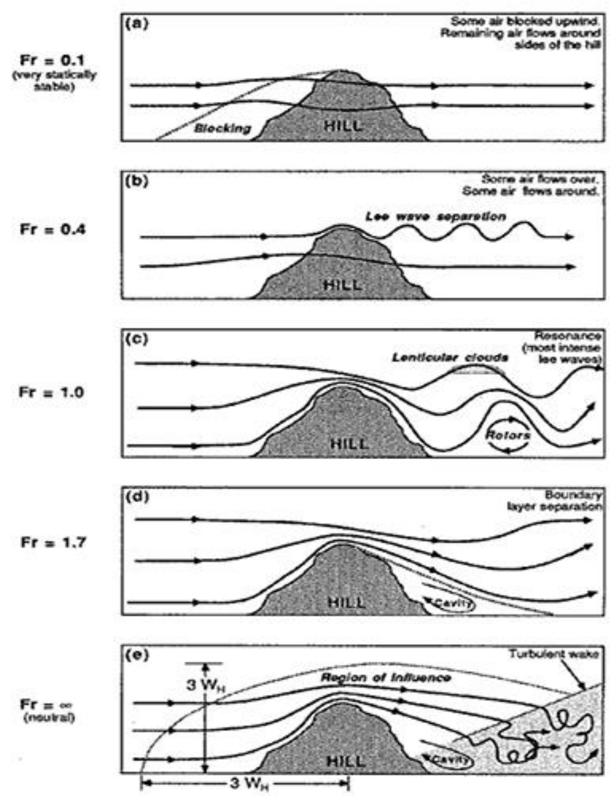

Figure 3: Idealized flow over an isolated hill. Different stability conditions are defined by the values of the Froude number Fr=U/(NL), where U is the wind speed, N the Brunt-Vaisala frequency and L is the length scale of the hill (from Stull, 1988, p. 602, fig. 14.4). [Reprinted with kind permission from Kluwer Academic Publishers]

See Finardi, et al., *Wind Flow Models over Complex Terrain for Dispersion Calculations*, at 8 (1997).

EPA has also acknowledged that aerial and satellite technologies are limited in their detection capacity, particularly with respect to "diffuse area sources."[11] Moreover, remote sensing technologies are limited by cloud cover and surface reflectivity anomalies as well as wind speed and direction. Satellite orbital hours vary by season and geographic location—for example, the orbital schedule for nine satellites over Colorado in November 2024 were all within a 5-hour window. In addition, aircraft flights must be "carefully planned and operated" in order to "capture plumes accurately," making them unsuitable for unpredictable landfill emissions and putting them directly at odds with the very nature of landfills, whose working face is constantly moving and whose cells are constantly under construction. Direct in-situ aerial sampling is similarly situated. Though it is capable of capturing both point sources and diffuse area sources, flight and sampling conditions must be "ideal"—that is, wind speed and direction are moderate and steady and turbulence and precipitation are limited—in order to achieve the greatest accuracy. Both remote and direct in situ technologies are hindered by their threshold detection capabilities.[12]

UAV technologies, including UCSEA and UPSEA, were evaluated in the First EREF Controlled Release Study, but have not been validated for use in the oil and gas sector. The study concluded, with respect to UCSEA, that because "[m]ost of the laser beam's transit is of course through atmospheric air containing relatively little methane," "a strong methane enhancement at the surface is diluted by the air above and can be difficult to detect, unless the sensor has very high precision, or flight altitude is reduced."[13] Vendors at the Technology Workshop indicated that the detection and quantification capabilities of UAV technologies is dependent on suitable wind and meteorological conditions.

Ground-based measurement technologies also have detection limitations. In particular, certain sensor vendors have indicated that sensors cannot account for the complex topography of landfills and typically employ dispersion models that assume flat ground. Additionally, vendors have indicated that additional research is necessary to better understand how their sensor can detect and quantify landfill gas plumes that stay close to the surface of the landfill, as distinct from oil and gas plumes. While fixed, ground-based sensors appear to have promising detection capabilities at 0.1 kg/hr or below, the vendors have acknowledged that their capabilities also depend on ideal wind and meteorological conditions during daytime hours.[14]

While certain of the existing advanced measurement technologies are able to attribute landfill emissions, including UAV technologies, satellite technologies are incapable of attributing detected plumes to specific equipment types, facilities, or processes in an automated manner. Carbon Mapper describes its attribution process as one considering two criteria: "high concentration—typically a spatially tightly constrained area of maximal constrained area of maximal concentration, indicative of a large gas release," and "plausible RGB/GIS

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[11] EPA, Whitepaper No. 6: *Aerial Monitoring for Examining Landfill Methane Emissions*, at 6 (Oct. 2024) ("Remote sensing technologies like AVRIS-NG and GAO are tuned to detect larger point sources and typically cannot detect the lower concentration, diffuse area sources; thus, remote sensing technologies typically do not encapsulate those diffuse emissions into their emission estimates from a site.").
[12] *Id.* at 8.
[13] Exhibit 2, First EREF Controlled Release Study, at 19.
[14] *Id.* at 64.

infrastructure."[15] Carbon Mapper then attributes plumes to "sectors," rather than specific areas within the site.

D. *Point in time observations cannot be appropriately or reliably quantified and compared to annualized reported emissions*[16]

1. General Quantification Difficulties

Existing advanced measurement technologies cannot provide quantified methane emission rates for municipal solid waste landfills using transparent, open-source, and standardized methodologies at this point in time. In fact, no standardized quantification methodologies currently exist for solid waste landfills. As evident from the Technology Workshop, technology vendors apply their own unique—and in many cases proprietary—quantification algorithms in quantifying detected emissions, though it is unclear whether their algorithms can be adjusted to account for the factors unique to municipal solid waste landfills.

In the recently updated NSPS/EG applicable to oil and gas facilities, EPA implemented a "Super Emitter Program."[17] The Super Emitter Program is based on third party detection and reporting of leaks and releases of 100 kg/hr or more of methane from affected facilities (individual well sites, centralized production facilities, compressor stations, and natural gas processing plants). Although the Super Emitter Program envisions an EPA verification and certification process for third-party observers and their technologies, no third parties have been certified for the purposes of the Super Emitter Program, so no lessons can be learned yet from its implementation. Indeed, the National Institute of Standards and Technology ("NIST") has since recognized that there is an "[a]bsence of consistent definitions, best practices, and protocols for plume identification, data quality control, emissions analysis, and independent validation" with respect to greenhouse gas emissions from "energy exploitation and waste" facilities.[18]

EPA's "Super Emitter" requirements for the oil and gas sector are not directly transferrable to landfills because of the differences between oil and gas facilities and landfills. As mentioned earlier, oil and gas emissions tend to happen at physical locations where process data is available, or at least relatively easily approximated. For routine emissions, release quantification is relatively straight forward. Further, oil and gas emissions are predominantly methane. Methane is, by itself, lighter than air, and once released forms a Gaussian plume more easily due to the underlying assumption about gas buoyancy of Gaussian plumes. More specifically, Gaussian dispersion "applies to neutrally buoyant dispersion of gases in which the turbulent mixing is the dominant feature of the dispersion" which is "typically valid only for a distance of 0.1-19 km from the release point."[19] Further, oil and gas infrastructure has limited topographical impacts, allowing wind to help "form" the plume. This means that for episodic emissions, determining where to put fence line monitors is more readily discernable, and aerial

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[15] *See* Carbon Mapper Quality Control Description Document, at 5–6.
[16] The text in this section is responsive to RFI Questions 1.a and 1.b.
[17] *See Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review*, 89 Fed. Reg. 16820, 16876–81 (March 8, 2024).
[18] *See* NIST, *Workshop Report: Methane Super-Emitter Consensus Standards Workshop*, at 1 (July 2024).
[19] DANIEL CROWL & JOSEPH LOUVAR, CHEMICAL PROCESS SAFETY: FUNDAMENTALS WITH APPLICATIONS 194 (Andreas Acrivos et al., eds., 2nd ed. 2002).

campaigns have a more predictable "success" rate of quantification. Once identified, the plume can be tied to operational data for straightforward calculation.

In contrast, landfill gas emissions are not so easily detected. For intrinsic emissions, the large size of landfills (often >100 acres) and their topographical features make predicting where fence line monitors should reliably be able to pick up emissions very difficult. Furthermore, because the fence line is usually "far" away, significant dilution occurs and back-tracking to the diffuse emission would be quite difficult without mountains of site-specific topographical modeling and discrete wind data. SEM can more reliably find diffuse emissions but using Method 21 or OTM 51 to quantify or model intrinsic emissions from large areas simply has not been done consistently or reliably. Second, landfill gas is a dense gas that behaves differently than pure methane from oil and gas facilities:

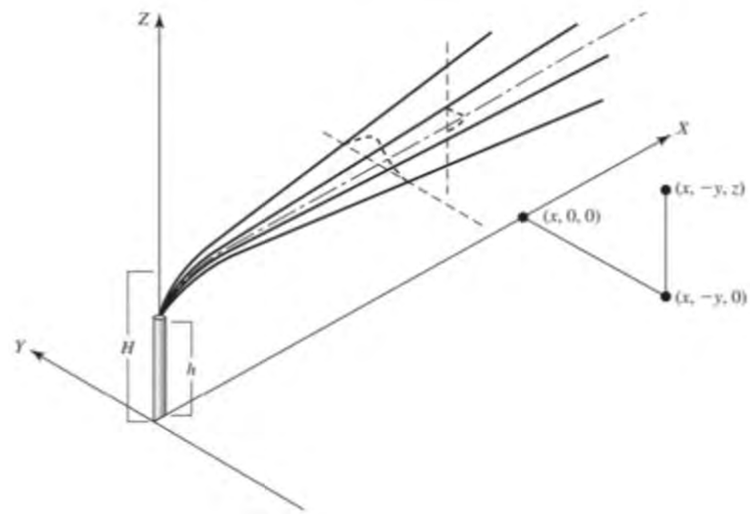
> *Following a typical puff release, a cloud having similar vertical and horizontal dimensions (near the source) may form. The dense cloud slumps toward the ground under the influence of gravity, increasing its diameter and reducing its height. Considerable initial dilution occurs because of the gravity-driven intrusion of the cloud into the ambient air. Subsequently, the cloud height increases because of further entrainment of air across both the vertical and the horizontal interfaces. After sufficient dilution occurs, normal atmospheric turbulence predominates over gravitational forces and typical Gaussian characteristics are exhibited.*[20]

Accordingly, emissions detection and quantification will be limited by the behavior of dense landfill gas, which is also heavily influenced by topographic, atmospheric, and meteorological elements, as described and depicted *supra* in Section II.A.

These topographic, atmospheric, and meteorological elements limit the use of technologies whose algorithms employ or assume Gaussian dispersion exists in all detected plumes. The figures below illustrate the difference in dispersion between Gaussian plumes and puff releases:

[20] CROWL & LOUVAR, at 195.

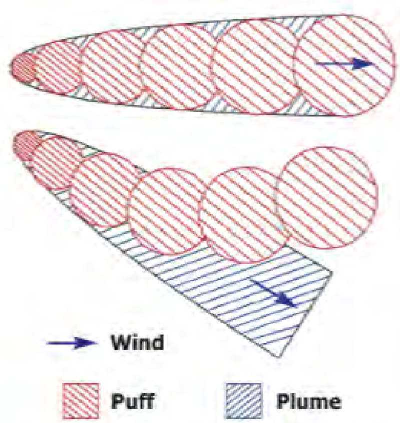
Figure 1. Orientation of the Gaussian plume model.



See Lucas Monteiro Nogueira, [*Air Pollution and the Gaussian Plume Model*]() (Nov. 15, 2020).

Puff vs. Plume

A preliminary consideration on the advantages of puff models over plume models should be based on the following modeling requirements:



A schematic depicting the tracking differences of a puff and a plume model

- Whether the straight-line steady-state assumptions on which a plume model is based are valid
- Transport distances
- Potential for temporally and/or spatially varying flow fields due to influences of complex terrain
- Non-uniform land use patterns
- Coastal effects
- Calm winds and stagnation conditions
- Variable wind directions

For cases involving a high degree of spatial variability of the flow within the boundary layer, such as up-slope or down-slope flows or flows along a winding river valley, the straight-line steady state assumption may not be valid beyond even a few kilometers, and a puff model may be more appropriate.

Different than a plume model, a puff model releases emissions independent of the source, allowing the puff to respond to the meteorology immediately surrounding it. This also allows puffs to be tracked across multiple sampling periods until it has either completely diluted or has tracked across the entire modeling domain and out of the computational area.

See CALPUFF View, Lake Environmental.

Aerial measurements that rely on Integrated Mass Enhancement (IME) are reported to be less sensitive than Gaussian reverse dispersion calculation; however IME remains sensitive to low wind speeds. The documented approaches to estimating the effective wind speed used for emission rate calculations in literature do not account for landfill topography, surface roughness, and other micrometeorological impacts that may cause low local windspeeds, poor dispersion, and accumulation of methane over time. The accumulated methane will be observable to the aerial and satellite sensors but the assumptions related to wind and related methane dispersion have uncharacterized uncertainty that would bias measurements. Characterizing the these affects, the magnitude of the bias introduced, and strategies for meteorology data collection, limitations on monitoring approaches to avoid bias, or effective measures to overcome bias are a key research priority.

While existing drone campaigns include discrete methane and wind data, with some success, there is a general consensus that additional studies must be conducted to better understand the capabilities of drone detection and quantification. At this time, ORD has recognized the need to supplement all measurements with site-specific operations, meteorological, topographic data, etc. to get the full picture. However, different vendors have their own unique methodologies of incorporating such data, some of which are proprietary, others of which are applicable to oil and gas leak detection and not readily transferrable to landfill emissions.

Detection of episodic or "fugitive" emissions from landfills are subject to the same behavioral and environmental influences as intrinsic landfill emissions. In addition, episodic emissions happen at variable and unpredictable times and locations. Current detection technologies are not rapidly deployable and requisite wind data may not be readily available to track these emissions. Unlike oil and gas pipelines, where process data is readily available, landfills do not possess the granular data at this point in time to apply where such emissions may occur, such as for example, a header break.

Aerial and satellite detection of emissions from municipal solid waste landfills will be limited in accordance with the detection threshold of the relevant technology. Vendors have indicated that satellite technologies cannot detect emissions at rates below 100 kg/hr.[21]

2. Extrapolating point-in-time measurements into hourly and annual emission rates is inappropriate.

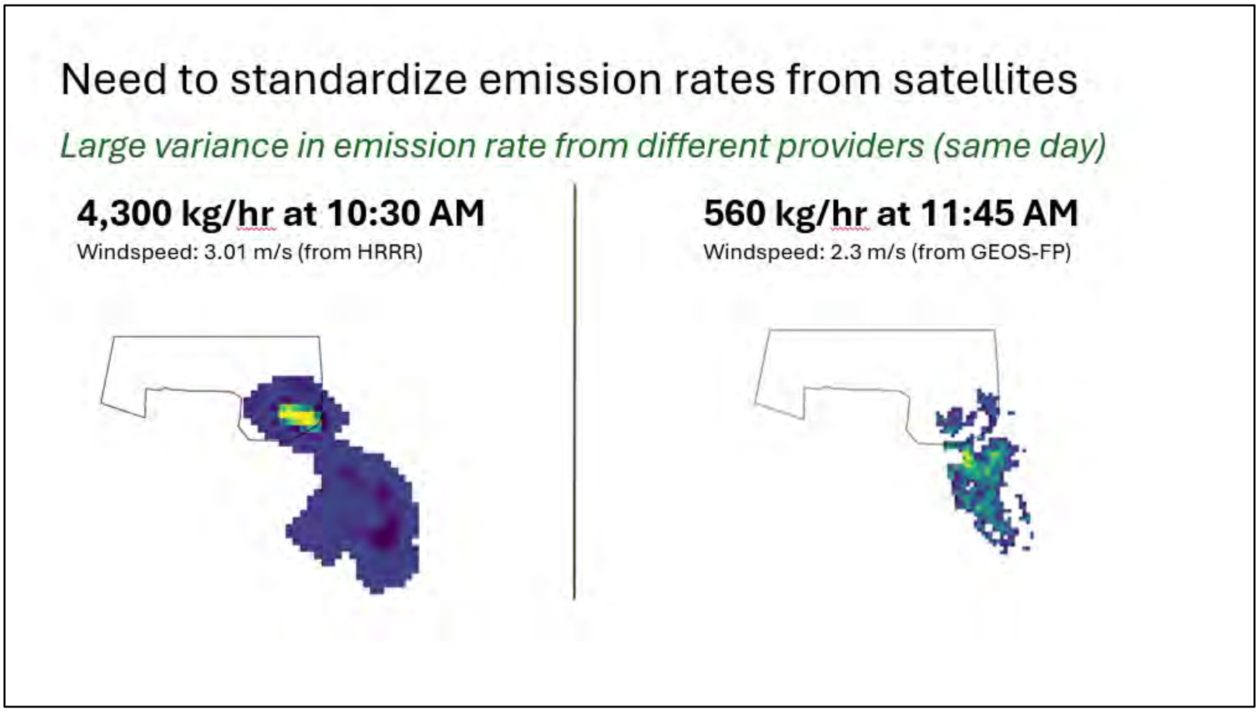
Though emerging measurement technologies purport to be capable of providing hourly and annual total methane emission estimates for specific municipal solid waste landfill facilities, there are shortfalls to their approach: (1) the approach does not differentiate between quantification methods for municipal solid waste landfills and oil and gas facilities; (2) the technologies cannot quantify point-in-time emissions rate with great enough certainty; and (3) the methodologies used to extrapolate point-in-time measurements into annual emission rates do not accurately capture emissions from individual facilities.

Vendors of fixed-sensor and UAV drone-based technologies have indicated their ability

[21] These threshold limitations may be resolved with a "stacked" approach, described in further detail *infra* in Section II.F.1. However, additional research and development is necessary to understand the capabilities of such an approach before its use in any regulatory determinations.

to calculate whole-site emissions using a mass balance approach. However, both fixed sensors and UAV technologies have spatial limitations that lead to unacceptable levels of uncertainty. Moreover, vendors of these technologies have not indicated that their approach in detection and quantification is unique to landfills, except for the use of site-specific data—however, how such data is utilized is generally proprietary and likely differs amongst vendors. Republic Services conducted a pilot study to evaluate the capabilities of metal oxide fixed sensors, a type of ground-based continuous emissions monitoring sensor. The specific metal oxide fixed sensors were originally designed for oil and gas facilities with the primary objective to identify significant emission events, with priority given to avoiding false alarms. With respect to landfills, the priority is less about detecting significant events, and more about identifying trends in overall methane emission, such as reductions caused by implementing capture systems. When Republic first deployed metal oxide fixed sensors, the plume model logic was identical to what is used on oil and gas facilities. The largest uncertainty in the plume model calculation is the distance between the sensor and the source, which feeds in to estimating the plume width and height. In February, Republic tested a new implementation of that distance estimate that ultimately did not yield significantly better results. From these learnings, an improved landfill model that eliminates the source to sensor distance in calculating the plume width needs to be developed and will take several months to deploy to assess the effectiveness of the changes.

With respect to satellite technologies, both Carbon Mapper and GHGSat have made their detection and quantification processes publicly available. However, neither indicate that they use an approach specific to landfills. Moreover, the approaches are not the same, and are therefore unlikely to yield the same results, indicating the need for better standardization amongst the same technologies. This issue has played out in practice when comparing emission rates estimated by one or more vendors evaluating the same plume. For example, as depicted below, at one landfill site, two measurements taken at very close points in time by different satellite measurement vendors were used to calculate very different emission rates. Despite being observed at nearly identical points in time, Vendor 1 calculated an emission rate of 4,300 kg/hr while Vendor 2 calculated an emission rate of 560 kg/hr.



Although extrapolation of point in time measurements to hourly and annual emission rates has been done by advocacy organizations using satellite and aerial data, NWRA does not believe that such extrapolation is accurate or appropriate. For example, a landfill methane emission map made available on EDF's website[22]would suggest large discrepancies between GHGRP reported emissions and emissions quantified using aerial and satellite measurements. However, a close review of the data reveals several points which tend to undermine these conclusions.

EDF extrapolated data from Carbon Mapper and TROPOMI to calculate hourly annual emission rates, without disclosing its calculations and methodology and explaining its decision not to include additional publicly available data from Carbon Mapper's database (e.g., EMIT data). Moreover, the very process of extrapolating point-in-time measurements to calculate an hourly annual emission rate irreconcilably clashes with the nature of emissions reported under the GHGRP. In particular, the emissions reported under the GHGRP are not annualized hourly emission rates, nor does the nature of landfill emissions lend itself to an assumed hourly rate. Further, there is limited value in reducing one or more remote observations to an assumed hourly emission rate based on a very limited data set - as the limited data set itself is evidence that more observations would likely lead to more agreement between reported and observed values.[23]

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[22] Environmental Defense Fund, *America's Hidden Landfill Emissions*, https://landfills.edf.org/interactive/ (last visited Nov. 22, 2024).

[23] As generally noted by *Cusworth, et al*., correlation between GHGRP reported values and values derived from remote measurements increase with increased numbers of measurements. Cusworth, et al., *Quantifying methane emissions from United States landfills*. 383 SCIENCE 1499, 1503 (2024) ("On average, aerial emission rates were a factor of 2.7 higher than GHGRP for all landfills and a factor 1.4 higher for landfills with 10+ unique overpasses.").

Moreover, there are several unexplainable transcription errors between the underlying data and the public-facing aspects of the map that have resulted in the display of emission rates that cannot be made sense of. And finally, even if the comparison of derived emission rates are taken at face value, the map would tend to show that many landfills are overreporting data when detection-derived values are compared to GHGRP reported values.

Thus, while particular vendors may have applicable internal standardization processes that would enable them to calculate annual emission rates, such calculations may not be meaningful where the applied processes and algorithms are not verifiable or consistent amongst technologies and are not transferrable among various sites. Quantification approaches for municipal solid waste landfills, if used for any regulatory purpose, for consistency should be limited to use of specific methodologies depending on the type of technology being deployed catering specifically to municipal solid waste landfills (*i.e.*, is not source agnostic). Until a consistent standardization process for each technology type exists that is unique to municipal solid waste landfills, these technologies are not ready for implementation into the municipal solid waste landfill regulations.

a. Too much uncertainty exists with respect to the detection and quantification abilities of emerging technologies to justify any regulatory switch from a modeled quantification approach to a measured one.

Under the GHGRP, as well as for other regulatory purposes, landfills have applied a modeled approach to emissions quantification. The modeled approach has been periodically updated; most recently in the 2024 Subpart HH Revisions. The finalized updates to Subpart HH are scheduled to become effective on January 1, 2025, and include revisions to emissions calculation equations applicable to landfills so as to account for periods of time where facilities' gas collection and control systems are not operating "normally." Accordingly, emissions of landfill gas that will occur as a result of operational inconsistencies and "large release events"—which EPA's ORD has referred to as "fugitive" or episodic emissions—will be accounted for within the updated modeled approach under the GHGRP. *See* Supplemental Proposal, 88 Fed. Reg. at 32877. These revisions will be implemented within 40 C.F.R. § 98.343, which includes several equations used to model methane emissions from municipal solid waste landfills. Equation HH-6 is used to "calculate CH4 emissions from the modeled CH4 generation and measured CH 4 recovery":

$$\text{Emissions} = \left[\left(G_{CH4} - \sum_{n=1}^{N} R_n\right) \times (1 - OX) + \sum_{n=1}^{N} \left\{R_n \times \left(1 - \left(DE_n \times f_{Dest,n}\right)\right)\right\}\right] \qquad \text{(Eq. HH-6)}$$

$F_{Dest,\,n}$ was revised to mean the following:

> Fraction of hours the destruction device associated with the nth measurement location was operating during active gas flow calculated as the annual operating hours for the destruction device divided by the annual hours flow was sent to the

destruction device. *The annual operating hours for the destruction device should include only those periods when flow was sent to the destruction device and the destruction device was operating at its intended temperature or other parameter indicative of effective operation. For flares, times when there is no flame present must be excluded from the annual operating hours for the destruction device.*

See 2024 Subpart HH Revisions, 89 Fed. Reg. at 31939 (emphasis added).

Similarly, Equations HH-7 and HH-8 are used to "calculate CH4 generation and CH4 emissions using measured CH4 recovery and estimated gas collection efficiency":

$$MG = \left[\frac{1}{CE}\sum_{c=1}^{C}\left[\frac{\sum_{x=1}^{X} R_{x,c}}{f_{Rec,c}}\right] \times (1 - OX)\right] \qquad \text{(Eq. HH–7)}$$

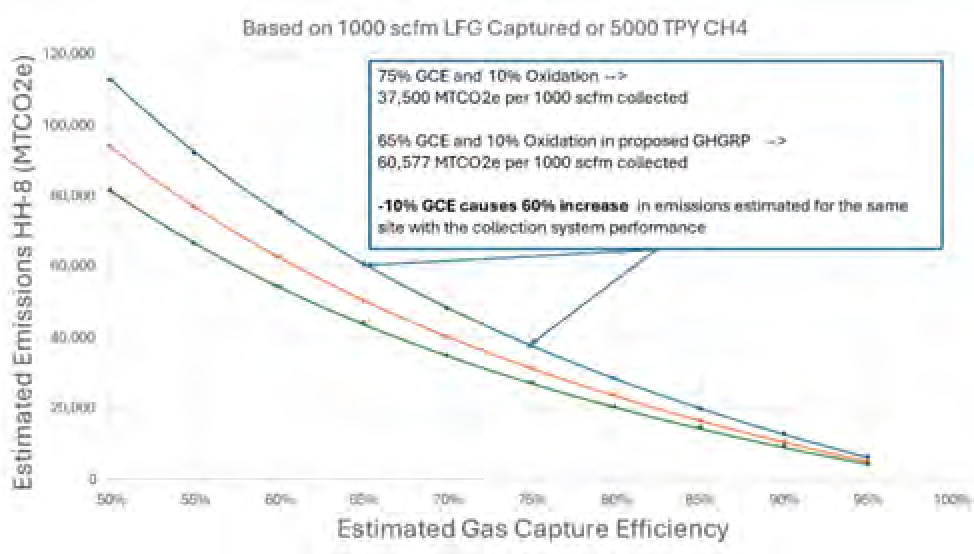
$$\text{Emissions} = \left[\left(\frac{1}{CE}\sum_{c=1}^{C}\left[\frac{\sum_{x=1}^{X} R_{x,c}}{f_{Rec,c}}\right] - \sum_{n=1}^{N} R_n\right) \times (1 - OX) + \sum_{n=1}^{N}\left\{R_n \times \left(1 - \left(DE_n \times f_{Dest,n}\right)\right)\right\}\right] \qquad \text{(Eq. HH–8)}$$

EPA updated the definition of $f_{Dest,n}$ as it pertains to HH-7 and HH-8 in the same way as it pertains to HH-6. Moreover, $f_{Rec,c}$ was updated to mean the following:

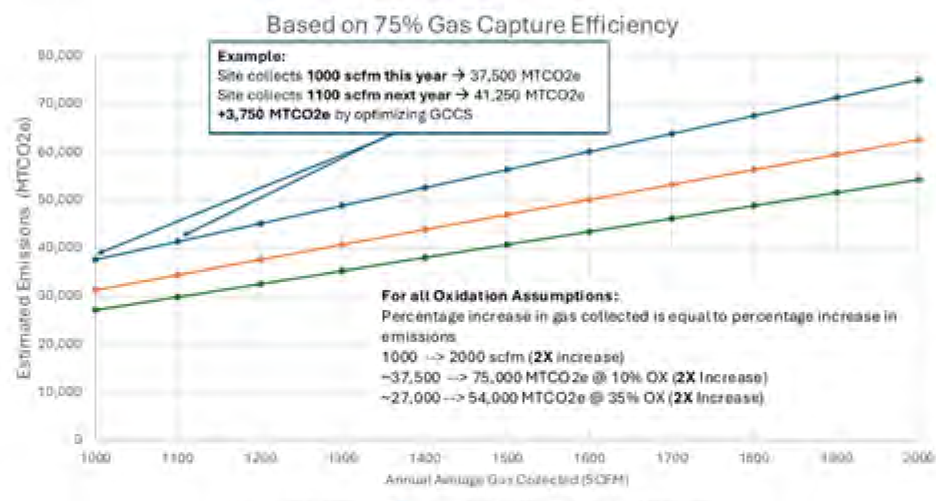
> Fraction of hours the landfill gas collection system "c" *was operating normally* (annual operating hours/8760 hours per year or annual operating hours/8784 hours per year for a leap year). *Do not include periods of shutdown or poor operation, such as times when pressure, temperature, or other parameters indicative of operation are outside of normal variances, in the annual operating hours.*

See 2024 Subpart HH Revisions, 89 Fed. Reg. at 31939 (emphasis added).

Accordingly, both the revised definitions of $f_{Dest,n}$ and $f_{Rec,c}$ are intended to account for periods of operational anomalies, so as to reflect when gas collection was reduced and/or when emissions were greater than typical. To the extent that EPA believes that emerging measurement technologies would account for emissions that occur as a result of operational anomalies, it is imperative that EPA understand that those events are already accounted for by the modeled structure under Subpart HH. Indeed, by reducing Table HH-3 collection efficiency values based on assumptions derived from emerging measurement technologies, EPA has vastly overcorrected the perceived impacts of these so-called "large release events," and in so doing, has unfairly penalized landfill owners and operators by removing their ability to demonstrate reductions in emissions correlated with improved performance. As depicted below, the 10% mandated reduction in collection efficiency in GHGRP calculations results in an increase of 60% in reported emissions.



NWRA does not agree with this result or the basis on which it was determined, and believes that the mandated use of a "one-size-fits-all" reduced collection efficiency will tend to undermine, rather than support, incentives for improved site-specific performance. This is due in part to the assumption included in the finalized version of Equations HH-7 and HH-8: where gas collection increases, so does gas production and therefore, gas emissions. Under this assumption, the percentage increase in emissions becomes equal to the percentage increase in gas collected, as shown in the figure below:



In this respect, the 2024 Revisions to the GHGRP actually disincentivize greater gas collection, thereby disincentivizing investment in GCCS and impeding NWRA members' abilities to meet their emission reduction goals.

NWRA pointed out in its Petition for Reconsideration of the 2024 Subpart HH Revisions that satellite technologies currently involve too much uncertainty to justify their use in the regulatory realm.[24] For example, in the *Nesser* study cited by EPA in 2024 Subpart HH Revisions, the authors alleged that 77% of observed landfills underreported GHG emissions. However, 15 of 38 of the observed municipal solid waste landfills with gas collection and control systems were within the reported range of uncertainty.[25] While academic and advocacy papers do include uncertainty values in their supporting data, this detail and its import is often lost in the public-facing messaging surrounding this data, and likewise appears to not have been duly considered by EPA. In short, such large uncertainty values evidences the need for a more accurate approach to calculating annual rates.

Further, as discussed above, the uncertainties associated with each technology evaluated as part of the First EREF Controlled Release Study are varying and too large for justification within a regulatory program. Accuracy and certainty are of the utmost importance in the event EPA seeks to transition to a measured approach and away from the decades-old, modeled approach. EPA should feel justified in doing so only to the extent that emerging technologies prove that they can achieve the required degree of certainty, and can "quantify annual methane emissions under the GHGRP in a robust, transparent, accurate, standardized, and verifiable way."[26]

E. *At this time, emerging technologies are not transparent, open-source, or standardized*[27]

To the extent that academic papers have attempted to evaluate and quantify municipal solid waste landfill emissions using emerging measurement technologies, their conclusions are not well-founded or technically accurate and therefore cannot support the inclusion of such technologies into regulatory reporting or other requirements. For example, EPA cited to *Nesser*, et al. for the general proposition that "recent aerial studies indicate methane emissions from landfills may be considerably higher than bottom-up emissions reported under subpart HH for *some* landfills" and further noted that such higher emissions may be attributable to "poorly operating gas collection systems or destruction devices and leaking cover systems." [28] However, the *Nesser* study only observed 38 landfills using 2019 satellite (TROPOMI) data at approximately 25 x 25 km resolution to estimate methane emissions for grid cells in the contiguous United States with 2012 reported methane emissions larger than 0.1 Mg /(km year).[29] The study used low spatial resolution satellite data, which makes attributing emissions to specific landfills very difficult.[30] Moreover, the inversion model was not strongly sensitive to landfill

[24] *See* Exhibit 1, Petition for Reconsideration, at 26.

[25] *Id.* (discussing Nesser et al., *High-resolution US methane emissions inferred from an inversion of 2019 TROPOMI satellite data: contributions from individual states, urban areas, and landfills*, ATMOSPHERIC CHEMISTRY & PHYSICS 5069 (2024).

[26] *See* RFI, 89 Fed. Reg. at 70178.

[27] The text in this subsection is responsive and relevant to all of the questions contained in the RFI.

[28] 2024 Subpart HH Revisions, 89 Fed. Reg. at 31854 (emphasis added).

[29] *Nesser*, et al., at 2, 4. NWRA's concerns regarding the *Nesser* paper can be found in greater detail in its Petition for Reconsideration. *See* Exhibit 1, at 25–28.

[30] Oil and gas researchers have cautioned against using TROPOMI, and satellites generally, for point-in-time measurements. Dubey, et al., *Minimum detection limits of the TROPOMI satellite sensor across North America and their implications for measuring oil and gas methane emissions*, 872 Science of the Total Env't, 2 (2023). ("Due to the quantity of emissions that can be captured in a single overpass, TROPOMI, and satellites in general, should be

emissions, and the authors rely on the 2012 inventory as the default emissions if not enough data was available to produce an optimized estimate. This approach ignores any changes that occurred at individual facilities between 2012 and 2019—potentially leading to the mis-attribution of emissions from sources that did not report in 2012. EPA also cited a paper by *Oonk* et al. to support its contention that "subpart HH underestimates the actual methane emissions released from landfills."[31] But *Oonk* et al. observed landfills in Holland, presented very little site-specific information on the observed landfills, and used the emissions measurement methods that were not well developed at the time, including modeled gas generation, which introduces additional uncertainty.[32] Similarly, EPA's reliance on a paper by *Duan* et al. is misplaced, as the study focused on 23 landfills in Denmark, and noted significant differences between Danish landfills and those in the U.S.[33]

Another paper by *Balasus*, et al. used wind-rotated oversampling of TROPOMI observations for each year from 2019 to 2023 to construct annually averaged methane plumes with 1 × 1 km2 resolution from four large Southeast U.S. landfills using the cross-sectional flux method (*Varon* et al. 2018) to quantify total annual emissions and uncertainties from the individual landfills.[34] The paper concludes that the generation-first model under the GHGRP conforms more with the measured results from the TROPOMI observations but that landfills with gas collection and control systems prefer to utilize the recovery-first model which "yields emissions that are one-quarter of those from the generation-first model[.]"[35] However, the conclusions from *Balasus*, et al. mischaracterize the relationship between Equations HH-6 and HH-7 and 8. The paper fails to acknowledge that landfills cannot use the recovery-first model under Equations HH-7 and HH-8 unless they have GCCS. Landfills do not have a GCCS until there is sufficient waste in place. Equation HH-6 is based on tonnage, which means that calculated emissions will ramp up quickly during initial operation.

Landfills generally begin installing GCCS infrastructure when they reach intermediate grades and elevations. Upon and after installation of GCCS infrastructure, landfills, of course, begin gas capture. When a landfill develops sufficient GCCS coverage across its footprint, Equations HH-7 and HH-8 can be appropriately used to calculate fugitive methane emissions. Considerable thought is taken as to when it becomes appropriate to transition away from the use

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used with caution. There is little use in using TROPOMI for a single measurement, but sustained measurements over a long period of time have great benefit. This optimal use of TROPOMI should be reflected in the policies that are developed moving forward.").

[31] 2024 Subpart HH Revisions, 89 Fed. Reg. at 31855.

[32] Oonk, H., *Efficiency of landfill gas collection for methane emission reduction. Greenhouse Gas Measurement and Management*, 129 (2012), https://doi.org/10.1080/20430779.2012.730798.

[33] NWRA commented extensively in its Petition as to the issues associated with EPA's reliance on the *Duan* et al. paper. *See* Exhibit 1, at 28–30 (discussing Duan, Z., et al., *Efficiency of gas collection systems at Danish landfills and implications for regulations*, 139 WASTE MANAGEMENT 270 (2022).

[34] Balasus, N., et al., *Satellite monitoring of annual US landfill methane emissions and trends* (Pre-publication) (2024).

[35] *Id.* at 1. It is important to reiterate that TROPOMI uses a low spatial resolution satellite data, making attribution to specific landfills difficult. Studies geared toward the oil and gas sector have stated that TROPOMI is less suitable for quantifying emissions from individual facilities than another satellite. Dubey, et al., *Minimum detection limits of the TROPOMI satellite sensor across North America and their implications for measuring oil and gas methane emissions*, 872 SCIENCE OF THE TOTAL ENV'T, 2 (2023). Moreover, TROPOMI is in sun-synchronous orbit so sites are observed as a single, non-representative time of day.

of HH-6 and to the use of Equations HH-7 and HH-8, in order to avoid grossly underreporting a recovery-first value. While there is a discrepancy between the results of Equation HH-6 versus Equation HH-8, it is not as distinct as *Balasus* alleges. And while another study by *Stark* et al. iterates the position that more operators "preferentially select the [Equation HH-8] method over the [Equation HH-6] method," the study acknowledged that "the purpose within GHGRP for having two different emissions estimation methods is to give the operators flexibility if good operating practices are employed that would likely result in decreased emissions from the site." *Stark* et al. also opined that the "default values for many of the parameters of the [Equation HH-6 approach]" themselves "retain high uncertainty."[36]

Moreover, as landfills start to reach maturity, incoming tonnage remains consistent, thereby causing the results of Equation HH-6 to "level off" to some extent, reducing the discrepancy between the results of Equation HH-6 and HH-8. As landfills reach final capacity, incoming tonnage begins to decrease, causing the results of HH-6 to "ramp down." As gas flows remain constant for a number of years post-closure, the results of Equation HH-8 do not decrease significantly—as a result, the use of Equation HH-8 causes overreporting compared to HH-6.

Balasus et al. wrongfully assumes that landfill operators simply pick the equation leading to lower resulting emissions. In reality, operators use site-specific knowledge to utilize the equations in the way that most appropriately comports with the actual conditions at the landfill. Often times, operators chose the more conservative outcome. For example, a WM landfill that stopped accepting waste five years ago and is fully capped, still reports significant calculated emissions due to gas production under Equation HH-8, despite the fact that HH-6 would result in nonexistent or even negative emissions. In addition, *Balasus* et al. used a method for quantifying emissions based on oversampling the low-resolution data—and this method has *not* been validated in any setting, particularly via controlled release or with other site-specific methods. The *Balasus* et al. study was also purposely conducted at four isolated landfills, to avoid interference of emissions from other, nearby sources. But this approach fails to acknowledge the realities facing many existing, operational landfills: namely, that emissions from nearby sources may indeed be misallocated to landfills.[37] There are agricultural sources of methane adjacent to one or more landfills that are contributing to the methane observations that are not discussed in the paper. Accordingly, EPA should not rely on *Balasus* et al. when considering whether and how to alter the modeling scheme under the GHGRP or dispense with it entirely by switching to a measured approach.

EPA has also indicated its intent to rely on a paper by *Cusworth*, et al.[38] But the conclusions in *Cusworth*, et al. support the contention that advanced measurement technologies are not primed for use in detecting, quantifying, and extrapolating annual emissions from municipal solid waste landfills without further research and development. Indeed, *Cusworth*, et al. concludes that "direct measurements of CH4 emissions at landfills to date using surface or aircraft instruments have largely been limited to a small number of facilities due primarily to

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[36] *See* Stark et al., *Investigation of U.S. landfill GHG reporting program methane emission models*, 186 WASTE MANAGEMENT 86-93, at 87-88 (2024).
[37] *See* Nesser, et al. at 5079 (stating that some emissions from "co-located" oil and gas facilities may have been "misallocated" to the studied landfill).
[38] Cusworth, et al., *Quantifying methane emissions from United States landfills*. 383 SCIENCE 1499, 1499 (2024).

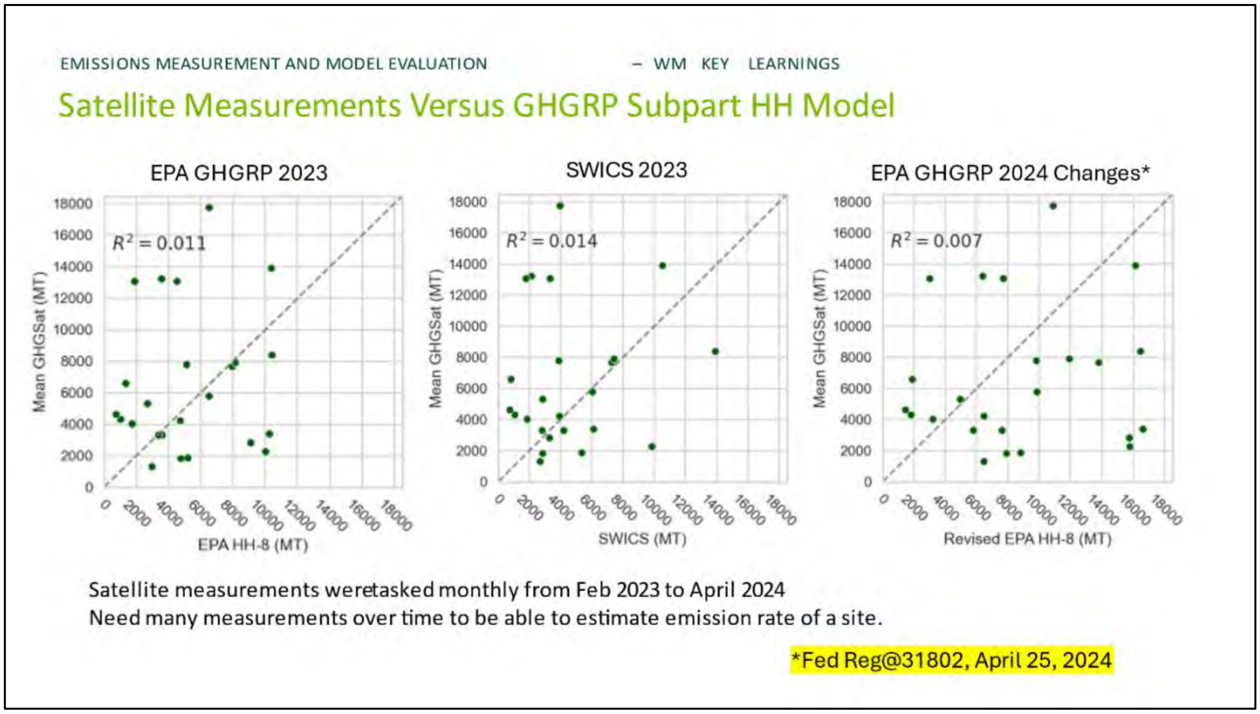
cost, which has resulted in incomplete spatial and temporal sampling. Given the diversity of operational and environmental factors driving landfill emissions, these observational limitations lead to continued uncertainty in this sector's contribution to regional, national, and global CH4 emission inventories, which can complicate assessing the efficacy of emission mitigation efforts."[39]

Each of these studies tended to focus on larger landfills above certain emission rates; they are therefore not representative of the national body of existing landfills subject to regulation under the GHGRP or NSPS/EG. For example, the *Nesser*, et al. paper does not include landfills with reported 2019 emissions below 300 kg.hr—approximately half of the landfills reporting under the GHGRP fall within this category.

Site-specific studies by NWRA members have also demonstrated the limitations of emerging measurement technologies for landfill gas emission quantification. In one example, WM undertook a twenty-five landfill study, using satellite measurements taken monthly from February 2023 to April 2024, to compare emissions quantified under pre-2024 GHGRP method, using the collection efficiencies required by the 2024 Subpart HH Revisions, and using Solid Waste Industry for Climate Solutions ("SWICS") Methodologies.[40] The comparison showed mixed results in terms of correlation, including that some sites would be overreporting, and some underreporting relative to both GHGRP methods. As a general matter however, the 2024 Subpart HH Revisions tended to result in more overreporting than underreporting when compared to data derived from emerging measurement technologies. In addition, of the three methodologies, SWICS was most consistent with data derived from satellite measurements, and as explained below is most responsive to real-time operational observations at municipal solid waste landfills. WM's study results are depicted below.

[39] *Id.*

[40] The SWICS model is discussed in greater detail *infra* in Section II, Subsection I.



F. At this time, emerging technologies can be used as a tool to support landfill gas collection and control practices, in conjunction with site-specific data.[41]

1. A "stacked" or "tiered" approach to the use of emerging technologies would allow for research and development as well as a better understanding of landfill emissions.

Representatives from EPA's ORD noted in their presentation at the Landfill Workshop that emerging measurement technologies are poised for a "stacked" or "tiered" approach at this time. This conclusions reflects those of recent scientific studies.[42] When asked what the "ideal" stacked approach would look like, ORD's representatives stated that satellite images should be supplemented with ground-level data from continuous sensors and UAV devices.

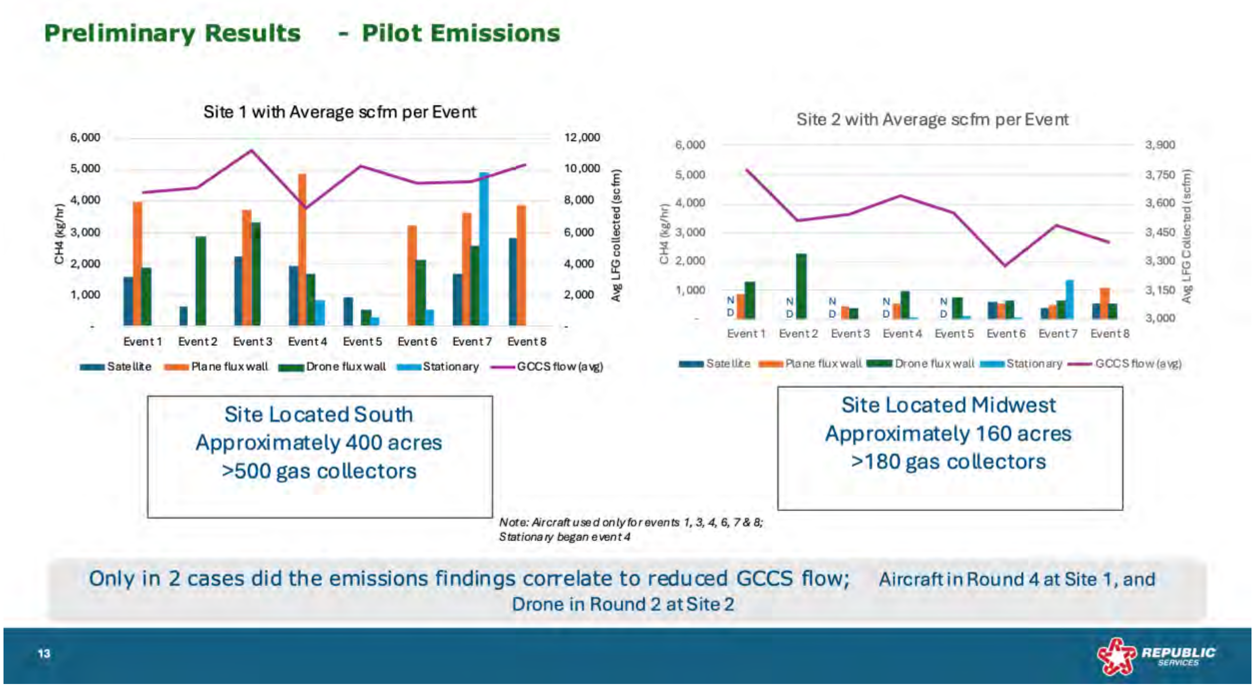
At this time, it remains unclear how a stacked or tiered approach could be implemented into the various regulatory programs, and whether and how remote sensing or direct measurement aerial technologies would be used for specific purposes—*i.e.*, to replace the use of Method 21; to detect large emission events; to quantify annual emission rates for reporting purposes. To the extent that these technologies could be utilized in the near-term, such uses should comport with existing work practices under applicable rules, particularly as means to replace or bolster Method 21 for SEM. This approach aligns with ORD's indication that the

[41] The text in this section is responsive to RFI Questions 1.c; 3.b; and 3.c.

[42] *See Cusworth, et al.*, at 1503 ("On average, aerial emission rates were a factor of 2.7 higher than GHGRP for all landfills and a factor 1.4 higher for landfills with 10+ unique overpasses. Consistent with this study, independent assessments of US emission inventories have indicated a needed 1.25 to 1.5 scaling of waste emissions to reconcile inventories with in situ ground-based measurements and coarse resolution satellite observations.")

technologies are poised to aid in the understanding of fugitive or episodic emissions in the near-term, and intrinsic emissions in the long-term.[43] NWRA agrees that the technologies may be useful for find-and-fix approaches, wherein Method 21 could be supplemented with UAV devices to help identify the origin of fixable emissions so as to apply a timely response and correction. This approach would fit more squarely within the NSPS/EG realm of regulations, rather than the GHGRP.

A stacked approach could be valuable for understanding annual emissions, but additional research and development is necessary to understand how it could fit within the regulatory scheme of the GHGRP and to what extent, if any, such stacked data could be utilized to quantify emissions. As indicated by ORD representatives, UAV and ground-based devices could be used to verify the emissions detected by satellite and aerial images. To account for the detection threshold limitations of satellite devices—which typically cannot identify emissions events less than 100 kg/hr—UAV and ground-based technologies could be used to collect more consistent data at lower detection thresholds. However, the protocol, algorithms, and procedures would be needed to integrate estimates of methane emissions for sources emitting below detection thresholds, and would need to produce correlated data. Such correlation has not yet been observed by NWRA and its members. As one case in point, Republic Services sought to correlate contemporaneous data collected at two sites by various technologies, and saw wide disparities in the resulting estimates, as depicted below:



These disparities are attributable to the lack of standardized methods, detection limits that vary by technology, unique algorithms for processing atmospheric data, and challenges posed by weather, topography, diurnal impacts and ongoing construction. Initial findings also indicate the

[43] *See* Exhibit 3, EPA webinar materials, *Airborne Survey-Methane from U.S. Landfills*, at slide 13.

size of the landfill may impact the uncertainty of the emissions.

Ultimately, researchers have concluded that a "method that can measure both the diffuse and point-source emissions from landfills" does not exist and "is needed to validate or refute the current GHGRP approaches."[44] And, rather than shift entirely from a modeled to measured approach, researchers suggest that the emerging technologies be developed to "improve the models" instead.[45] This idea—that " a combination of technologies (i.e., on-site sensors and possibly satellite or aerial platforms) are needed to better quantify annual emissions from MSW landfills"—comports with ORD's indication that technologies are only poised for a "stacked" approach at this time.[46]

G. EPA's verification process of advanced measurement technologies should comport with the standards applicable to Other and Alternative Test Methods.[47]

EPA currently employs a multi-step process for standardizing regulatory test methods. Test methods must first be designated as an Other Test Method ("OTM"), and then an Alternative Test Method, before EPA can point to it as a Reference Method for compliance purposes within the NSPS or NESHAP programs. To go from an OTM to an Alternative Test Method, the EPA must be assured that the test method alternative provides "a determination of compliance status at the same or greater stringency as the test method specified in the applicable regulation," which should be shown by including the results of a Method 301 (Validation of Pollutant Measurement Methods from Various Waste Media) validation and justification for not using the regulation's specified method, which compares the test method against a validated reference test method to determine the method's bias and collecting multiple or co-located simultaneous samples to determine the method's precision.

The only methodologies currently approved as Alternative Test Method to Method 21 so as to satisfy the SEM requirements under the NSPS/EG is ALT-150/OTM-51: *Approval to Use Unmanned Aerial System Application as an Alternative to Method 21 for Surface Emission Monitoring of Landfills*. Because ALT-150 was approved in accordance with EPA's procedures, its implementation is the only transparent, open-source, standardized option that exists among the new advanced measurement technologies. However, Method 21 is applicable to SEM requirements under the NSPS/EG, rather than as a means to quantify emissions for the purpose of calculating annual emissions.[48]

EPA should continue to employ this or a similar process with respect to other technologies that it into future rulemakings, so as to provide clarity on how the technologies should be deployed and what they aim to achieve from a regulatory standpoint. Namely, EPA should employ a similar multi-step approval process for any technologies purporting to (1) be a viable alternative to Method 21 for SEM; (2) be capable for use in detecting large-scale

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[44] *Stark et al.*, at 91.
[45] *Id.*
[46] *Id.* at 92.
[47] The text under this section is responsive to RFI Questions 3.a and 3.b.
[48] OTM-58A is in draft form and uses a mass balance approach to quantify whole site emissions. NWRA applauds EPA on its collaboration with Champion X in developing additional test methods; however, OTM-58A is not scalable, and a scalable methodology should be high priority for landfills.

emissions events, or (3) be suitable for quantifying emissions and/or calculating an annual emission rate. EPA developed a streamlined process applicable to oil and gas facilities, which can be found under 40 C.F.R. § 60.5398b(d). If EPA intends to move forward with new technologies for landfills, EPA must consider developing a similar process, which would allow for the qualification of "alternative" test methods that can be utilized for compliance purposes even after the rule has become effective. This process allows for the continued development of appropriate technologies without rushing to implement emerging technologies into regulatory programs before they are sufficiently ready. In establishing this process, EPA should prioritize its goal to "peer review of all scientific and technical information that is intended to inform or support Agency decisions is encouraged and expected."[49] This is especially important for verifying and standardizing technologies for emissions detection, quantification, and extrapolation into annual emission rates as no current validated reference method exists.

Further, standards and protocols implemented to ensure that emerging measurement technologies provide annual total, source-specific, methane emissions in a transparent and standardized way should not be source or technology agnostic. As stated above, there are stark, important differences between oil and gas facilities and municipal solid waste landfills. These differences would make source agnosticism among standardized methods wholly inappropriate, as the detection and quantification of oil and gas emissions from landfills is subject to a different set of considerations than methane emissions from oil and gas facilities. As an example, Carbon Mapper has indicated that it cannot automate source attribution when evaluating its satellite and aerial images, and must do so manually in order to distinguish emissions from oil and gas facilities versus those from landfills.[50] Accordingly, without the capability to distinguish between and attribute emissions from landfill and oil and gas facilities, source agnosticism is not an appropriate option. In fact, TROPOMI satellite research has shown that the imaging may attribute emissions from oil and gas facilities to nearby landfills: "[o]ur landfill attribution approach, which relies on a prior estimate from 2012, may therefore misallocate emissions to the Puente Hills Landfill instead of to co-located oil and gas operations." [51] As such, the development and standardization of advanced technologies must be made as specific as possible to municipal solid waste landfills in order to be primed for regulatory use.

Standards and protocols should be specific to the type of method used rather than be technology agnostic. At this point in time, nearly all of the emerging technologies available require further development and refinement. There are significant differences between the purported algorithms employed by ground-based, fixed sensors compared to UAV technologies, compared to aerial technologies, compared to satellite technologies including, but not limited to, implementation of meteorological and atmospheric data using anemometers, conversion methodologies, algorithms employed to calculate emission rates, and algorithms employed to extrapolate data into annual emission rates. Many of these algorithms are proprietary and/or still in the process of being developed. Moreover, until it becomes clear whether and how EPA intends to implement advanced technologies into the regulatory programs, a comment on technology agnosticism is inherently incomplete.

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[49] EPA. *Peer Review and Peer Involvement at the U.S. Environmental Protection Agency*, (Jan. 2006) https://www.epa.gov/sites/default/files/2015-01/documents/peer_review_policy_and_memo.pdf
[50] *See* Carbon Mapper Quality Control Description Document, at 5–6.
[51] *Nesser*, et al., at 5079.

H. Other limitations relating to the use of advanced technologies for GHGRP reporting purposes [52]

The greatest limitation to using advanced measurement technologies under the GHGRP would be the transition from a modeled to measured approach of emissions quantification. This transition would require reconciling the bottom-up emissions estimates that the industry has utilized since the beginning of the GHGRP with the top-down approach that would be applied in a measured system, the limitations of which are set out at length above.

Costs present another major barrier and limitation to switching to a measured approach under the GHGRP. In directing EPA to create the GHGRP, Congress stated that a "comprehensive and effective national program of mandatory market-based limits and incentives on emissions of greenhouse gases" should be implemented to "slow, stop, and reverse" emissions in such a way which does not "significantly harm the United States economy."[53] Congress issued an accompanying joint statement directing EPA to use its existing authority under the federal Clean Air Act, 42 U.S.C. § 7401 *et seq.*, to develop the mandatory greenhouse gas reporting rule. EPA finalized its first version of the GHGRP on October 30, 2009, utilizing its information-gathering authority under Section 114 of the Clean Air Act.[54]

Accordingly, in issuing and revising the GHGRP, EPA has traditionally considered costs of compliance. Costs of compliance will depend on whether and how EPA implements the use of advanced technologies into regulatory determinations. For example, if EPA provides that certain technologies can be used as alternatives to Method 21 to conduct quarterly SEM, then cost of compliance could consider the baseline estimates in accordance with the dollar amounts revealed in the First EREF Controlled Release Study, set forth below:[55]

MGPA 1	$5,000/day
MGPA 2	$5,000/day
UPSEA 1	$5,000-8,000/day
UPSEA 2	$5,000-8,000/day
MTCEA	$5,000/day
APSEA	$14,000/day
LiDAR	$14,000/day
SISEA	$3,000-6,500/package
RPSEA 1	$7,000-30,000/year
RPSEA 2	$7,000-30,000/year
RPSEA 3	$7,000-30,000/year
UCSEA 1	$5,000-8,000/day

[52] The text in this section is responsive to RFI Question 3.c.
[53] 121 Stat. 1844, 2152, Pub. Law 110-116 (Dec. 26, 2007).
[54] *Mandatory Reporting of Greenhouse Gases*, 74 Fed. Reg. 56260, 56264 (Oct. 30, 2009).
[55] It is important to note that these rates were estimated particular to the study and may not be transferrable to practical implementation in the regulatory context. Moreover, the costs listed fail to account for vendor-specific context. For example, one drone may be able to fly a single site in one day, whereas another vendor may take five days to fly the same site.

UCSEA 2	$5,000-8,000/day
LEA	$5,000/day

However, as stated previously, the correlation between the GHGRP reported emissions and emissions quantified using aerial and satellite technologies increases with additional measurement events.[56] Thus, it is unclear, at this point, how often municipal solid waste landfills could be subject to utilizing such technologies for the purposes of calculating annual emission rates. The costs could become exorbitant and unreasonable. For the purposes of calculating annual emission rates under the GHGRP, until it becomes clearer whether any technologies can be capable of detecting and quantifying emissions with an acceptable degree of accuracy and certainty, and how often measurements would be necessary to capture a substantiated and trusted annual emission rate, NWRA cannot speculate further on costs. Regardless, landfills provide an essential public service and should not be subject to unwarranted, unreasonable costs associated with advanced measurement technologies until and unless the compliance methodologies using such technologies proves to be certain and accurate enough to justify the accompanying costs.

I. Site-specific data is critical to the quantification of landfill gas emissions, and cannot be replaced by emerging measurement technologies.[57]

The members of NWRA are proposing a tool that relies on readily available site-specific information to calculate annual emissions inventories that would be sensitive to the implementation of good practices to reduce emissions. The Solid Waste Industry for Climate Solutions (SWICS) represents a group of practitioners that most recently worked to update the guidance document titled *Current MSW Industry Position and State-of-the-Practice on LFG Collection Efficiency, Methane Oxidation, and Carbon Sequestration in Landfills Version 2.2*, Revised January, 2009, and the *Methane Oxidation Addendum 2012* dated November, 2012. The updated version of guidance and associated excel tool is expected to be available in late 2024 or early 2025.

The guidance document describes how the proposed values for collection efficiency, methane oxidation, and methane destruction could be used to replace the current CARB and USEPA default values for collection efficiency (75%), methane oxidation (10, 25, 35% based on cover), methane destruction (98 - 99%). This document also provides the best estimates of carbon storage in landfills although it is not used as part of the model for estimation of methane emissions.

An important element of this update is the proposed excel tool or landfill emissions model (LEM) rating matrix which is an effort to standardize (e.g., quantify) the professional judgement using operations parameters that are typically collected and available at landfills with a GCCS. In order to use previous versions of the SWICS guidance on emission calculations the user was required to use professional judgement (aka qualified judgement) to indicate whether the performance of the GCCS cover area was high, medium, or low performance The GCCS rating matrix for each cover area utilizes four gas operations parameters and a specific rating to

[56] *See* Cusworth, et al., *Quantifying methane emissions from United States landfills*. 383 SCIENCE 1499, 1499 (2024).
[57] The text in this section is responsive to RFI Question 3.

be used for each to determine a total score which correlates to collection efficiency value. Defining the bins for each operations parameter allows tuning of the LEM to determine which landfills cover areas will be represented by one of five categories of performance, High, med-hid, medium, med-low, and low.

The SWICS Team assessed gas operations data from 399 landfills throughout the United States to determine the parameters to be included in the GCCS rating matrix and developed a scoring system derived from statistical analysis of the selected parameters combined with the professional judgement of practitioners from the contributing members of SWICS.

The rating system utilizes the following four gas operation parameters:

- Well Field Density (wells per waste footprint);
- Surface Emission Monitoring Exceedances at/over 500 ppmv methane (exceedances/acre);
- Percentage of Wellfield Positive Pressure Readings (positive readings divided by total readings *100); and
- Percentage of GCCS Uptime (running hours divided by total hours).

It is expected that the output of the LEM will be more comparable across the sector based on organizations and practitioners using the collective professional judgement of the group assembled for this effort and applied through the matrix. Refinements to the scoring bins are expected in future versions of the LEM based upon published evaluations of the operations parameters and GCCS performance.

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NWRA very much appreciates the Agency's consideration of these comments. Should you have any questions about this letter, please contact me at agermain@wasterecycling.org.

Very truly yours,

Anne M. Germain
Chief of Technical & Regulatory Affairs

Attachments:
Appendix A: RFI questions
Exhibit 1: NWRA June 24, 2024 Petition for Reconsideration
Exhibit 2: Fluxlab July 9, 2024 final report on controlled release
Exhibit 3: EPA March 19, 2024 webinar slides

Appendix A:
RFI Questions

1. *Quantification of Annual Emission Rates*
    a. *Detection and Quantification of Atmospheric Methane Emission Events from Advanced Measurement Technology*
        i. What advanced measurement technologies are currently available that can provide quantified methane emission rates using transparent, open-source, and standardized methodologies?
            1. What are the specific quantification approaches that have been used with these technologies and how have these methodologies been demonstrated and validated?
            2. How can these technologies and quantification methodologies be used to provide annual data in a consistent manner for each future year of GHGRP reporting?
            3. Are there specific detection and quantification approaches or methodologies that EPA should or should not consider?
        ii. What performance metrics and thresholds related to quantification would be appropriate to apply to advanced measurement technologies for their incorporation into the GHGRP? What would be a feasible approach for developing these thresholds and metrics?
        iii. Should quantification approaches be limited to use of specific methodologies (*e.g.*, inverse analysis, mass balance) or specific approaches for using ancillary datasets (*e.g.*, standardized interpolation of wind field products)?
        iv. Are there ongoing efforts outside of EPA to develop standards or protocols for methane emissions detection and quantification from advanced measurement technologies that would address any of the questions raised in this RFI?

    b. *Extrapolating Quantified Methane Emission Rates to Calculate Annual Emissions for GHGRP Reporting Purposes*
        i. What advanced measurement technologies are currently available that can provide annual total methane emission estimates for specific regions, facilities, processes, or equipment-level sources, that use transparent, open-source, and standardized methods?
            1. Are these technologies applicable across the entire US and could they provide annual data in a consistent manner for each future year of GHGRP reporting?
            2. Are there specific annual extrapolation approaches or methodologies that EPA should or should not consider?
        ii. What accuracy or uncertainty metrics would be appropriate for GHGRP reporting purposes?
            1. What level of accuracy in reported annual methane emissions should advanced measurement technologies be required to meet?
            2. What sources of uncertainty are necessary to consider?
            3. Are there other specific quality assurance or quality control markers that should be considered to ensure that annual estimates represent the methane emissions from all operational activities

throughout the reporting year, such as specific measurement frequencies or duration?

4. What would be a feasible approach for developing these methods and thresholds?

iii. To what extent should standards and protocols be specific to the type of methods and ancillary data used (*e.g.*, statistical approaches), and to what extent should standards and protocols simultaneously consider the specific type of emission sources being sampled (*e.g.*, large unintended vs. small routine emissions event)?

c. Quantifying Annual Methane Emissions from Emissions Sources Below Detection Limits of Advanced Measurement Technologies

i. What methodologies are currently available for integrating estimates of methane emissions for those sources emitting below technology detection thresholds in an open-source, transparent, and standardized way? Can these methodologies provide annual data in a consistent manner for each future year of GHGRP reporting? Are there specific approaches or methodologies that EPA should or should not consider?

ii. Should these quantification approaches be limited to the use of specific methodologies (*e.g.*, Monte Carlo method) or specific ancillary data sets (*e.g.*, the use of standardized infrastructure or operator data)?

2. Attribution

a. What methodologies are currently available that can attribute quantified methane emission events to specific equipment types (or additionally, specific regions, facilities, or processes) using transparent, open-source, and standardized methods? Are there specific attribution approaches or methodology trees that EPA should or should not consider?

b. What accuracy or uncertainty metrics would be appropriate for GHGRP reporting purposes? For example, what level of confidence in the source attribution would be necessary for advanced measurement technologies to meet GHGRP reporting purposes? What would be a feasible approach to developing these thresholds?

c. To what extent would standards and protocols need to be specific to the type of methods and ancillary data used(*e.g.*, infrastructure data sets) or the type of emission source sampled (*e.g.*, large unintended versus small routine emissions event)?

3. Implementation

a. Structure of Approaches or Protocol

i. What form would standard methods or protocols need to take to ensure that advanced measurement technologies provide annual total, source-specific, methane emissions in a transparent and standardized way? For example –

1. To what extent should standards and protocols be specific to the type of methods used (e.g., satellite, aircraft, ground based)? Would different standards or protocols be necessary for sampling

approaches using single platform versus multi platform measurements? Could standard methods be developed to be technology agnostic?

2. To what extent could standard methods be developed to be source agnostic? For example would standards need to be specific to the type of equipment, process, or emission source sampled (e.g., tanks, flares, pneumatic devices, landfill working face), Or could a set of standards be developed to be more broadly applicable across different GHGRP industry segments?

b. *Verification and Validation of Annual Source-Specific Methane Emission Quantification Methods Using Advanced Measurement Technologies for GHGRP Reporting Purposes*
   i. Are there approaches currently available that could be used to verify that advanced measurement technologies meet specific standards (*e.g.*, independent blind studies, deployment of calibration standards, others)?
   ii. Is it necessary to limit the applicability of advanced measurement technologies to environmental and site conditions that have been previously validated? For example, if an advanced measurement technology has been validated through blind control release testing during which wind speeds ranged from 0.5 to 10 m/s should the technology be limited to measurements within this range of wind speeds? What form of validation could be used to demonstrate whether a technology is applicable across environmental conditions outside of their tested ranges?
   iii. Are there specific types of operator- or facility-specific information that would be useful for improving or validating annual methane emissions quantification or source attribution from advanced measurement technologies?

c. *Other Considerations Related to the Use of Advanced Measurement Technologies for GHGRP Reporting Purposes*
   i. What (if any) are the current barriers or limitations to using advanced measurement technologies beyond what is currently allowed under the GHGRP to quantify annual equipment-level methane emissions at scale in the U.S.?
   ii. What are the cost considerations for implementing different advanced measurement technologies to quantify annual, equipment-, process-, or facility-level methane emissions for GHG RP reporting purposes? If available, cost should be provided in a manner that can be scaled up to different implementation approaches (*e.g.*, cost per site, cost per area covered).
   iii. How are factors such as measurement and analysis cost, complexity, or time burden relevant for determining whether advanced measurement technologies may be appropriate for annual GHGRP application?

iv. Other than methane emissions detection and quantification, and establishing the duration of [large release events] are there additional ways in which advanced measurement technologies could be used to support quantification and reporting of equipment process or facility level methane emissions to the GHGRP (*e.g.*, as a method to identify changes in operating conditions, to supplement specific reported data elements)?

EXHIBIT 1

National Waste & Recycling Association[SM]
Collect. Recycle. Innovate.

June 24, 2024

Via Electronic Mail and Hand Delivery

The Honorable Michael S. Regan
Administrator
U.S. Environmental Protection Agency
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Re: **Petition for Reconsideration: Greenhouse Gas Reporting Program Subpart HH, Municipal Solid Waste Landfills**

Dear Administrator Regan and Associate General Counsel Srinivasan:

Enclosed please find attached a Petition for Reconsideration submitted by the National Waste & Recycling Association (NWRA) with respect to the rule entitled *Revisions and Confidentiality Determinations for Data Elements Under the Greenhouse Gas Reporting Rule*, 89 Fed. Reg. 31802 (April 25, 2024), docket No. EPA-HQ-OAR-2019-0424. NWRA's Petition for Reconsideration is limited to Subpart HH of the Greenhouse Gas Reporting Rule, which is applicable to Municipal Solid Waste Landfills, and EPA's determination therein to reduce default landfill gas collection efficiency values for reporters under the rule.

NWRA appreciates EPA's consideration of this Petition and hopes to work cooperatively with EPA toward improvements in the accuracy of landfill sector emissions reporting. Please feel free to contact the undersigned at agermain@wasterecycling.org, or outside counsel for NWRA, Carol McCabe at cmccabe@mankogold.com or Matt Morrison at matthew.morrison@pillsburylaw.com, with any questions you may have.

Respectfully submitted,

Anne Germain
Chief Operating Officer and Senior Vice President of Technical and Regulatory Affairs
National Waste & Recycling Association

Enclosure

cc: Jennifer Bohman, EPA Office of Atmospheric Programs (via electronic mail)
Julius Banks, EPA Greenhouse Gas Reporting Branch (via hand delivery)
Carol F. McCabe, Manko, Gold, Katcher & Fox (via electronic mail)
Kelly A. Hanna, Manko, Gold, Katcher & Fox (via electronic mail)
Matthew W. Morrison, Pillsbury, Winthrop, Shaw, Pittman (via electronic mail)
Steve R. Brenner, Pillsbury, Winthrop, Shaw, Pittman (via electronic mail)

The National Waste & Recycling Association's
Petition for Reconsideration of The Final Rule:
Revisions and Confidentiality Determinations for Data Elements
***Under the Greenhouse Gas Reporting Rule*,**
89 Fed. Reg. 31802 (April 25, 2024)
Docket No. EPA-HQ-OAR-2019-0424

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PETITION FOR RECONSIDERATION TO THE U.S. ENVIRONMENTAL PROTECTION AGENCY

I. Introduction

On April 25, 2024, the United States Environmental Protection Agency ("EPA") finalized updates to the Greenhouse Gas Reporting Program rules ("GHGRP"), codified under Title 40, part 98 of the Code of Federal Regulations and effective January 1, 2025 ("Final Rule").[1] The Final Rule is a culmination of two Notices of Proposed Rulemakings: the Data Quality Improvement Proposal and the 2023 Supplemental Proposal.[2] In finalizing the respective changes across part 98, EPA articulated its two overarching goals: (1) improving the quality of data collected from municipal solid waste ("MSW") landfills; and (2) strengthening applicable reporting requirements. The Final Rule includes updates to subpart HH of the GHGRP, applicable to MSW landfills, including unanticipated changes to methane emissions calculation methodologies that form the subject of this Petition for Reconsideration.

Specifically, in the Final Rule, EPA unexpectedly reduced the collection efficiency values contained in Table HH-3 and applied in equations HH-7 and HH-8 to calculate methane emissions from MSW landfills subject to the GHGRP ("Reporters").[3] As proposed in the 2023 Supplement, the lowered collection efficiencies would have applied only to "non-regulated" Reporters who are not required to and opt not to conduct surface methane emissions monitoring ("SEM") under applicable federal rules. EPA proposed to retain the same, higher collection efficiencies applicable to "regulated" landfills that are required to, or opt to, conduct SEM.

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[1] *Revisions and Confidentiality Determinations for Data Elements Under the Greenhouse Gas Reporting Rule*, 89 Fed. Reg. 31802 (April 25, 2024) ("Final Rule").
[2] *Revisions and Confidentiality Determinations for Data Elements Under the Greenhouse Gas Reporting Rule*, 87 Fed. Reg. 36920 (June 21, 2022) ("Data Quality Improvements Proposal"); *Revisions and Confidentiality Determinations for Data Elements Under the Greenhouse Gas Reporting Rule*, 88 Fed. Reg. 32852 (May 22, 2023) ("2023 Supplemental Proposal").
[3] 2023 Supplemental Proposal, 88 Fed. Reg. 32861.

Relatedly, EPA proposed to impose a new "correction term" within equations HH-6, HH-7, and HH-8 for landfills conducting SEM to adjust emissions values based on the number of locations with concentration above 500 parts per million above background identified during surface measurement periods. Taken together, EPA's proposal expressly coupled collection efficiency adjustments with SEM practices. In its Final Rule, however, EPA took an impermissible and unanticipated U-turn, decoupling collection efficiency from SEM and site-specific performance measures and imposing significantly reduced collection efficiencies across all Reporters, without adequate prelude or justification. Moreover, by requiring Reporters to apply a reduced collection efficiency irrespective of whether they are conducting SEM, EPA is effectively requiring the majority of Reporters to overstate their greenhouse gas emissions. These changes do nothing to achieve EPA's two stated goals of improving data quality and strengthening reporting requirements.

The Petitioner is the National Waste & Recycling Association ("NWRA" or "the Petitioner"). NWRA is the leading voice of the North American waste and recycling industry on advocacy, education, and safety. The industry provides essential services that benefit our local communities and businesses by assisting our customers in achieving their environmental and sustainability aspirations. NWRA supports and promotes regulatory advancements and policies that benefit the solid waste industry and improve the quality of life for all Americans. Association members operate in all 50 states and the District of Columbia and can be found in most, if not all, U.S. congressional districts. Waste and recycling facilities number nearly 18,000 scattered throughout the U.S., mirroring population centers. Our nearly 700 members are a mix of publicly traded and privately owned local, regional and Fortune 500 national and international companies. NWRA represents approximately 70 percent of the private sector waste and recycling market.

Members of NWRA are directly and adversely affected by EPA's promulgation of the Final Rule, which cannot plausibly be considered the logical outgrowth of the 2023 Supplemental Proposal. NWRA and other interested parties were not afforded adequate notice of EPA's ultimate decision to reduce existing collection efficiencies identified in subpart HH of the GHGRP for all landfills, irrespective of whether a landfill was conducting SEM. While NWRA shares EPA's stated objective of ensuring accurate quantification and reporting of greenhouse gas emissions, the Agency's finalized approach undermines that shared objective by adopting a methodology that will overestimate methane emissions, despite an abundance of scientific evidence that more closely aligns with EPA's proposed approach to base emission estimates on site-specific factors like SEM. The Final Rule will also cause reporting under the GHGRP to be at odds with other federal reporting and permitting programs, as well as the landfill sector's established practices regarding sustainability and GHG reporting.

Since EPA's decision to lower collection efficiencies in subpart HH of the Final Rule is procedurally flawed and substantively unwarranted, NWRA respectfully requests that EPA reconsider this important aspect of subpart HH of the Final Rule.[4]

II. Background to the Final Rule

In its Fiscal Year 2008 Consolidated Appropriations Act,[5] Congress directed EPA to promulgate regulations requiring "mandatory reporting of greenhouse gas emissions above appropriate thresholds in all sectors of the economy of the United States."[6] Congress articulated,

[4] NWRA has also filed a petition for judicial review of the Final Rule in the United States Court of Appeals for the District of Columbia Circuit.
[5] 121 Stat. 1844, Pub. Law 110-116 (Dec. 26, 2007).
[6] *Id.* at 2128.

in light of the "growing scientific consensus" that humans were contributing to the accumulation of greenhouse gases in the atmosphere, leading to increased global temperatures, that a "comprehensive and effective national program of mandatory market-based limits and incentives on emissions of greenhouse gases" should be implemented to "slow, stop, and reverse" emissions in such a way which does not "significantly harm the United States economy."[7] Congress issued an accompanying joint statement directing EPA to use its existing authority under the federal Clean Air Act, 42 U.S.C. § 7401 *et seq.*, to develop the mandatory greenhouse gas reporting rule.

In accordance with this Congressional directive, EPA finalized its first version of the GHGRP on October 30, 2009, utilizing its information-gathering authority under Section 114 of the Clean Air Act.[8] The original GHGRP Rule included MSW landfills that generated over 25,000 metric tons of carbon dioxide equivalent or more per year as a source category and was promulgated under Title 40 of the Code of Federal Regulations, part 98, subpart HH.[9]

Since 2009, the GHGRP has been updated numerous times.[10] On June 21, 2022, EPA published a Notice of Proposed Rulemaking ("NPRM") in the Federal Register proposing certain updates to the GHGRP, referred to as the Data Quality Improvements Proposal.[11] Thereafter, EPA issued another NPRM to supplement the Data Quality Improvements Proposal—the 2023 Supplement[12] (collectively, the "Proposed Rules")—once again seeking comment from interested parties regarding proposed changes geared toward improving the quality of data

[7] *Id.* at 2152.
[8] *Mandatory Reporting of Greenhouse Gases*, 74 Fed. Reg. 56260, 56264.
[9] *See id.* at 56267.
[10] *Rulemaking Notices for GHG Reporting*, EPA (last updated May 31, 2024), https://www.epa.gov/ghgreporting/rulemaking-notices-ghg-reporting.
[11] Data Quality Improvements Proposal, 87 Fed. Reg. 36920 (June 21, 2022).
[12] 2023 Supplemental Proposal, 88 Fed. Reg. 32852 (May 22, 2023).

collected from MSW landfills and strengthening reporting requirements. The 2023 Supplement included proposed changes to several methodologies within subpart HH used to calculate methane emissions from MSW landfills subject to the rule.

On April 25, 2024, EPA finalized its updates to the GHGRP, including changes to collection efficiency values in table HH-3. However, the finalized collection efficiencies differed starkly from those in the Proposed Rules, specifically the 2023 Supplement. Interested parties, including the Petitioner, were completely surprised by and unprepared for this change.

A. <u>The Proposed Rules</u>

In the 2023 Supplemental Proposal, EPA proposed several changes to the GHGRP that it said would lead to more accurate emissions calculations, based on its conclusion that high emission events may be occurring where there is "a leaking cover system due to cracks, fissures, or gaps around protruding wells."[13] In order to address this concern, EPA proposed two ways in which collection efficiency or emission estimates would be adjusted, both related to SEM. First, EPA proposed to amend Equations HH-6, HH-7, and HH-8 for regulated reporters (those that are subject to SEM requirements), by adding a "correction term." Equation HH-6 is used to calculate methane emissions using modeled methane generation and measured methane recovery, while equations HH-7 and HH-8 are used in tandem to calculate methane generation and emissions using methane recovery and estimated gas collection efficiency.[14] EPA noted that the three equations did not "directly account for periods where surface issues reduce the gas collection efficiency and/or reduce the fraction of methane oxidized."[15] To address that concern, EPA

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[13] *Id.* at 32877–78. EPA also proposed other measures in the 2023 Supplemental Proposal to address a "poorly operating or non-operating gas collection system" and a "poorly operating or non-operating destruction device." NWRA commented on these proposed measures, which are not addressed in this petition.
[14] *See* 40 CFR 98.343(c)(3)(i).
[15] 2023 Supplemental Proposal, 88 Fed. Reg. 32878.

proposed a way to correct the estimated methane emissions based on monitored exceedances at the surface of the landfill. This proposed correction was based on conclusions from a study cited by EPA, *Heroux*, et al., and its internal citations, which suggested that methane "flux" (*i.e.*, the exchange of methane emissions and naturally occurring substances between Earth's surface and its atmosphere) is proportional to the measured methane concentration at six centimeters above the ground.[16] The proposed correction term would require Reporters subject to SEM to input the "leak duration days" (the number of days since the last monitoring event at the specified location) and the "surface methane concentration for the mth measurement that exceeds 500 parts per million above background."[17] The proposed correction term accounted for the fact that regulated landfills must record as a monitored exceedance, and take corrective action to address, any location with a reading of 500 ppm or more above background. EPA proposed to allow non-regulated landfills to elect to conduct SEM as well, so as to avail themselves of the use of the correction term when calculating their methane emissions using equations HH-6, HH-7, and HH-8.[18]

The second method by which EPA considered an adjustment of collection efficiency based on SEM was a proposed adjustment to the gas collection efficiency values in Table HH-3, as utilized in equations HH-7 and HH-8, applicable *only* to landfills that are not required to conduct SEM under other federal provisions or decline to elect to conduct SEM pursuant to proposed 40 CFR § 98.346(g)(7).[19] Specifically, EPA proposed to include a new set of gas

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[16] *Id.*
[17] *Id.* at 32931. "Regulated" landfills are subject to such SEM requirements under the NSPS program, 40 CFR part 60, WWW or XXX; the EG program, subparts Cc or Cf; or Federal plans, 40 CFR part 62, subparts GGG or OOO. *Id.* at 32877–78.
[18] *See id.* at 32932 (proposing to implement elective surface-emissions monitoring for landfills with landfill gas collection systems that are not required to conduct such under an existing federal program under a new subsection, 40 CFR § 98.346(g)(7)).
[19] *Id.* at 32879.

collection efficiency values in Table HH-3, applicable to landfills that do not conduct SEM, that are "10 percent lower than the current set of collection efficiencies."[20] EPA proposed that the current set of collection efficiencies would be retained, and would "only be applicable for landfills that are conducting [SEM] according to the landfills rule requirements." [21] Since the vast majority of landfills conduct surface emission monitoring,[22] EPA's proposal would have lowered the collection efficiencies for *only* a relatively small subset of Reporters.

EPA's proposal rested on the conclusions of a study by the Environmental Integrity Project ("EIP Study")[23] that collection efficiencies of non-regulated landfills were 20% lower, on average, than regulated landfills. In discussing the EIP study conclusion relating to SEM, EPA stated: "These results make sense because the objective of the surface methane concentration measurements are to ensure proper gas collection and non-regulated landfills that do not conduct these measurements would not necessarily have such checks in place and may be expected to have higher emissions."[24] The EIP study results focused on a limited number of landfills in the state of Maryland that, when compared to the values reported under subpart HH, showed collection efficiencies that were 10% lower than regulated landfills under the GHGRP.

EPA specifically requested comment on: its proposal to lower collection efficiencies for landfills with gas collection systems that do not conduct SEM; the selection of a 10 percent collection efficiency reduction rather than the 20 percent reduction for those non-regulated landfills; and whether EPA should select an alternative value for non-regulated landfills based on

[20] *Id.*
[21] *Id.*
[22] EPA-HQ-OAR-2019-0424-0256, Attachment A.
[23] EIP, *Greenhouse Gas Emissions from Maryland's Landfills* (2021), https://environmentalintegrity.org/wp-content/uploads/2021/06/MD-Landfill-Methane-Report-6.9.2021-unembargoed_with-Attachments.pdf).
[24] 2023 Supplemental Proposal, 88 Fed. Reg. at 32878.

the supporting data.[25] NWRA provided comment with respect to these proposed changes.[26] In addition to comments noting the technical and substantive inadequacy of the EIP Study, NWRA also noted that EPA's proposal and reliance on the EIP Study failed to account for other major factors that are more influential with respect to collection efficiencies at regulated and non-regulated landfills, including federal requirements to provide comprehensive controls, meet prescriptive timelines, and limit system downtime. NWRA also incorporated by reference the comments of Morton Barlaz, who likewise noted that EPA failed to identify all the factors that can affect collection efficiency, such as the type of cover and well density.[27] NWRA further noted that the equation HH-8 methodology accounts for these differences already, obviating the need for reduced collection efficiencies as proposed.

NWRA also provided comment on the proposed correction term, asking EPA to consider other studies that show significant variability in the correlation between surface emissions exceedances and methane flux. Specifically, we noted that the *Heroux*, et al. study EPA used to support the purported correlation was conducted over 20 years ago based on data from a single landfill in Canada.

Importantly, NWRA asked that EPA delay the finalization of any of the proposed revisions to subpart HH until the Solid Waste Industry for Climate Solutions ("SWICS") finalized its revisions to the third version of its white paper entitled *Current MSW Industry Position and State-of-the-Practice on LFG Collection Efficiency, Methane Oxidation, and Carbon Sequestration in Landfills*. The SWICS White Paper is a compilation of peer-reviewed data and studies relating to a broad range of MSW landfills, and it was undertaken for the

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[25] *Id.* at 32879.
[26] *See* EPA-HQ-OAR-2019-0424-0255.
[27] NWRA incorporated by reference the comments of Morton Barlaz. *See* EPA-HQ-OAR-2019-0424-0286.

express purpose of creating a methodology that would result in more accurate inventories of methane from landfills. In relevant part, NWRA noted that the SWICS paper will "move toward a more quantified basis for GCCS collection efficiency assessment….and a revisit on the current state-of-the-practice on collection efficiencies, oxidation, carbon storage, methane generation in landfills and destruction efficiencies."[28]

B. Final Rule

In the Final Rule, EPA stated that, "[f]ollowing the consideration of comments received, we are not taking final action on the surface-emissions monitoring correction term that was proposed. *Instead*, we are finalizing the proposed lower collection efficiencies in table HH-3 to subpart HH but applying the reduced collection efficiencies for *all* reporters under subpart HH."[29] In making this decision, EPA conceded, consistent with NWRA's comments, that the *Heroux*, et al. study was insufficient, alone, to support the implementation of the correction term, because it was over two decades old and focused on one landfill in Canada.[30] Upon review of the additional studies identified by commenters, including those identified by NWRA, EPA agreed that there was indeed significant variability in measured surface concentrations and methane emissions flux across different landfills.[31] Due to "high uncertainty," EPA indicated that it is reassessing the appropriateness of a correction term and "evaluating other direct measurement technologies for assessing more accurate, landfill-specific gas collection efficiencies."[32]

With respect to the proposed collection efficiencies, EPA concluded that it "expected that the surface emissions correction factor would result in lower emissions than those calculated

[28] *See* EPA-HQ-OAR-2019-0424-0255.
[29] Final Rule, 89 Fed. Reg. at 31853 (emphasis added).
[30] *Id.* at 31855.
[31] Final Rule, 89 Fed. Reg. at 31855.
[32] *Id.*

using the 10-percentage point decrease in collection efficiency[.]"[33] Based on EPA's review of other studies correlating surface methane concentrations with methane flux," EPA stated its belief that a "more central tendency correlation factor is projected to yield emissions similar to a 10-percentage point decrease in collection efficiency."[34] EPA went on to state that "all the measurement study data" reviewed suggests that current collection efficiencies are overstated on average by 10-percentage points or more.[35] In making this point, EPA cited two studies that were not included in either the preamble or the docket for the Proposed Rules: *Duan et al.*, 2022 and *Nesser et al.*, 2023.[36] EPA asserted that the *Nesser* study, which observed 38 landfills subject to SEM requirements, provides evidence that most observed landfills had lower or similar measured collection efficiencies to those reported under subpart HH.[37] EPA further concluded that "[s]imilar low average collection efficiencies were noted by *Duan* et al.," and that those efficiencies justified its decision to finalize the lower default collection efficiencies for all landfills.[38]

III. Requested Reconsideration of the Collection Efficiency Values

Pursuant to Section 307(d)(7)(B) of the Clean Air Act, EPA "shall convene a proceeding for reconsideration of [a] rule and provide the same procedural rights as would have been afforded had this information been available at the time the rule was proposed" so long as the party seeking reconsideration can demonstrate: (1) "that it was impracticable to raise such

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[33] *Id.* at 31856.
[34] *Id.*
[35] *Id.*
[36] *Id.* (citing Duan, Z., et al., *Efficiency of gas collection systems at Danish landfills and implications for regulations*, 139 WASTE MANAGEMENT 269–78 (2022), https://doi.org/10.1016/j.wasman.2021.12.023.; Nesser, H., et al., *High-resolution U.S. methane emissions inferred from an inversion of 2019 TROPOMI satellite data: contributions from individual states, urban areas, and landfills*, EGUSPHERE [preprint] (2023), https://doi.org/10.5194/egusphere-2023-946; and supplement https://egusphere.copernicus.org/preprints/2023/egusphere-2023-946/egusphere-2023-946-supplement.pdf.
[37] Final Rule, 89 Fed. Reg. at 31856.
[38] *Id.* at 31856.

objection" during the public comment period or that "the grounds for such objection arose after the period for public comment (but within the time specified for judicial review)"; and (2) "such objection is of central relevance to the outcome of the rule." 42 U.S.C. § 7607(d)(7)(B).

The Petitioner could not practicably raise procedural and substantive objections to EPA's finalization of Table HH-3's reduced collection efficiencies by 10 percentage points, applicable to *all* Reporters under subpart HH, because EPA did not afford adequate notice of this change to interested parties prior to the public comment period. As such, the change to collection efficiency in HH-3 applicable to all Reporters under the Final Rule is not the "logical outgrowth" of the Proposed Rules. EPA is required to convene proceedings for reconsideration, so that interested parties may raise relevant substantive objections that are of central relevance to the outcome of the rule.

A. EPA did not afford interested parties with adequate notice of the lowered collection efficiencies applicable to all Reporters; therefore, the Final Rule is not the "logical outgrowth" of the Proposed Rules.

The practicability of raising an objection during the public comment period is dependent on EPA providing adequate notice of the changes it purports to finalize. The Clean Air Act incorporates the notice requirements set forth in the Administrative Procedure Act, by stipulating "[i]n the case of any federal rule to which this subsection applies, notice of a proposed rulemaking shall be published in the Federal Register, as provided under Section 553(b) of Title 5[.]" § 7607(b)(3). The APA's notice requirements are designed (1) to ensure that agency regulations are tested via exposure to diverse public comment, (2) to ensure fairness to affected parties, and (3) to give affected parties an opportunity to develop evidence in the record to support their objections to the rule and thereby enhance the quality of judicial review." *Int'l Union, United Mine Workers of America v. Mine Safety & Health Admin.*, 407 F.3d 1250, 1259

(D.C.Cir.2005). Notice, courts have recognized, must come from the agency's Notice of Proposed Rulemaking. *Chesapeake Climate Action Network v. EPA*, 952 F.3d 310, 320 (D.C. Cir. 2020). Because agencies "do not quite have the prerogative of obscurantism reserved to the legislatures," they must adhere to a "high standard of articulation" in expressing the "data [of] critical degree" in their Notices of Proposed Rulemakings. *United States v. Nova Scotia Food Prod. Corp.*, 568 F.2d 240, 252 (2d Cir. 1977). Notice, therefore, cannot be "bootstrap[ped]" from a comment received during the comment period after a Notice of Proposed Rulemaking has been published. *Fertilizer Inst. v. EPA*, 935 F.2d 1303, 1312 (D.C.Cir.1991). In this respect, if agencies "fail[] to disclose to interested persons the factual material upon which the agency was relying," the elements of fairness which are "essential to any kind of administrative action" are vitiated by preventing agencies from submitting comments of "cogent materiality." *Nova Scotia*, 568 F.2d at 249, 252.

Moreover, without adequate notice, it is widely recognized that a final rule does not equate to the "logical outgrowth" of the proposal. *See, e.g.*, *Envtl. Integrity Project v. EPA*, 425 F.3d 992, 996 (D.C. Cir. 2005); *Northeast Md. Waste Disposal Auth. v. EPA*, 358 F.3d 936, 951-52 (D.C. Cir. 2004); *Alon Ref. Krotz Springs, Inc. v. EPA*, 936 F.3d 628, 648 (D.C. Cir. 2019) (stating that the "impracticability prong" of Section 307(d)(7)(B) covers "instances when the final rule was not a logical outgrowth of the proposed rule"). A final rule is the "logical outgrowth" of a proposed rule only if interested parties "should have anticipated that the change was possible, and thus reasonably should have filed their comments on the subject during the notice-and-comment period." *Env't Integrity Project v. EPA*, 425 F.3d 992, 996 (D.C. Cir. 2005).

In contrast, agencies cannot justify changes implemented in a final rule by placing an "unreasonable burden on commentors not only to identify errors in a proposed rule but also to contemplate why every theoretical course of correction the agency might pursue would be inappropriate or incorrect." *Chesapeake Climate Action Network*, 952 F.3d at 320 (holding that a party's ability to comment on an *issue* generally does not in and of itself demonstrate sufficient notice from EPA). While an agency "need not subject every incremental change in its conclusions after each round of notice and comment to further public scrutiny before final action," *Sierra Club v. Costle*, 657 F.2d 298, 352 (D.C. Cir. 2981), interested parties must be able to anticipate that the change was possible, and could have submitted comments relating to such. *Northeast Md. Waste Disposal Auth.*, 358 F.3d at 952 (finding that a final rule which collapses the proposed rule's three categories into two is the logical outgrowth of the proposed rule); *Envt'l Integrity Project*, 425 F.3d at 996 ("The Court will refuse to all agencies to use the rulemaking process to pull a surprise switcheroo on the regulated entities.").

Here, the Petitioner did not have adequate notice of EPA's decision to impose lower collection efficiencies upon *all* Reporters. Rather, the Petitioner had notice that EPA was considering an adjustment to collection efficiencies and emission calculations tied to SEM practices; EPA indicated that it may lower collection efficiencies by 10% for those MSW landfills not conducting SEM and by a correction term for those that do conduct SEM and for which surface emissions were detected above defined thresholds. EPA did not indicate anywhere in the Proposed Rules that it was considering an across the board lowering of collection efficiencies regardless of SEM practices and results. Indeed, the very basis for EPA's proposal in the first instance was a concern about accurately accounting for "methane emissions from large release events that are currently not quantified under the GHGRP" including those that may result from "emissions from leaking cover systems due to cracks, fissures, or gaps around protruding wells"[39]—issues that would be detectable by SEM. EPA's decision in the Final Rule had nothing to do with SEM at all—in fact, as discussed above, EPA pivoted away from SEM and in its place adopted an across-the-board reduction in collection efficiencies based in large part on newly identified data.

While it is true that EPA is not obligated, and cannot be reasonably expected, to subject "every incremental change in its conclusions" to additional rounds of notice and comment before final action, this change is not incremental. *See Sierra Club*, 657 F.2d at 352. The Petitioner could not and did not anticipate EPA's final action, especially given that EPA requested comment regarding: (1) the "new set of proposed collection efficiencies for landfills with gas collection systems that do not conduct surface methane concentration measurements"; (2) EPAs "selection of 10 percent lower collection efficiencies for landfills that are not monitored for surface methane rather than selecting a 20 percent lower value as suggested by the commenters that referenced the [EIP Study] data" [40]; and (3) supporting data on whether EPA should select an "alternative collection efficiency value than the proposed 10 percent difference or the 20 percent difference[.]"[41] Based on these requests for comment, the Petitioner reasonably expected EPA to: finalize the collection efficiencies as proposed for non-regulated Reporters; lower the values applicable to non-regulated Reporters in accordance with the percentages identified in the EIP Study; retain the status quo; or, if commenters pointed to scientific data that supported some "alternative" value for non-regulated landfills, subject interested parties to another round and notice and comment on a different proposed value based on the new scientific data. *See United*

[39] 2023 Supplemental Proposal, 88 Fed. Reg. at 32877–78.
[40] *Id.* at 32878; EIP, *Greenhouse Gas Emissions from Maryland's Landfills* (2021), https://environmentalintegrity.org/wp-content/uploads/2021/06/MD-Landfill-Methane-Report-6.9.2021-unembargoed_with-Attachments.pdf).
[41] 2023 Supplemental Proposal, 88 Fed. Reg. at 32879.

States v. Nova Scotia Food Prod. Corp., 568 F.2d 240, 252 (2d Cir. 1977). In no event did EPA suggest that it was evaluating a collection efficiency reduction for all Reporters as a standalone measure, uncoupled from SEM as a factor on which that value should be based.

NWRA submitted comments in accordance with EPA's requests, in part because we disagree that SEM is a strong indicator of overall collection efficiency, especially as extrapolated to a quantification of annualized emissions. Further, NWRA disagreed with the technical information proffered by EPA to support its proposal. Specifically, the Petitioner's comments questioned the adequacy of the EIP Study on the basis that it was not properly peer-reviewed in accordance with EPA's General Assessment Factors[42] and Peer Review Policy.[43] NWRA also commented that the EIP Study, which focused on 14 landfills in Maryland only, was not representative of MSW landfills subject to subpart HH across the entire United States. In addition, NWRA pointed out that the equation HH-8 methodology, as-is, adequately accounts for the factors which legitimately and substantially influence the difference in collection efficiencies between landfills conducting SEM and landfills not conducting SEM. Accordingly, NWRA asked that EPA either maintain the status quo or await publication of comprehensive, representative data in the updated version of the SWICS White Paper, a document that EPA has relied upon in the past. NWRA's comments were also substantially influenced by the proposed "correction term," which EPA proposed in tandem with the lowered collection efficiencies. Though we objected to lowering collection efficiencies at all, we at least recognized that, coupled with the correction term, there existed an incentive for non-regulated landfills to conduct

[42] Summary of General Assessment Factors for Evaluating the Quality of Scientific and Technical Information (June 2003) (available at https://www.epa.gov/sites/default/files/2015-01/documents/assess2.pdf).
[43] Peer Review Handbook (4th Edition 2015) (available at https://www.epa.gov/sites/default/files/2020-08/documents/epa_peer_review_handbook_4th_edition.pdf).

SEM, consistent with the original goals articulated by Congress in directing EPA to establish the GHGRP.[44]

If the Petitioner had been on notice of the remote possibility that EPA would finalize lower collection efficiencies applicable to *all* Reporters, without regard to SEM, the Petitioner certainly would have submitted corresponding comments, outlining the broad range of scientific reasons why EPA should not do so. But since EPA failed to provide such notice, EPA's finalized collection efficiencies cannot permissibly be considered the "logical outgrowth" of its original proposal.

The situation here is unlike other cases in which the D.C. Circuit has found that the final rule was a "logical outgrowth" of a proposed rule. For example, in *Northeast Maryland Waste Disposal Authority v. EPA*, the Circuit Court held that a final rule which collapses the proposed rule's three categories into two *is* the logical outgrowth of the proposed rule. 358 F.3d 936, 953 (D.C. Cir. 2004). Rather, EPA's action here is akin to situations where the Circuit has found a lack of logical outgrowth. In *International Union*, for example, the agency's proposed rule provided that "[a] minimum air velocity of 300 feet per minute must be maintained" to ventilate underground coal mines.[45] The final rule, however, provided that "[t]he maximum air velocity in the belt entry must be no greater than 500 feet per minute, unless otherwise approved in the mine ventilation plan."[46] The D.C. Circuit vacated the final rule because, although "[t]here were some comments during the hearings urging the Secretary to set a maximum velocity cap," the Agency "did not afford a ... public notice of its intent to adopt, much less an opportunity to comment on, such a cap." *International Union*, 407 F.3d at 1261. Like the concept of air velocity in

[44] 121 Stat. 1844, Pub. L. 110-116 (Dec. 26, 2007).
[45] 68 Fed. Reg. 3936, 3965 (Jan. 27, 2003).
[46] 69 Fed. Reg. 17,480, 17,526 (Apr. 2, 2004).

International Union, the general concept of collection efficiency may have been raised in the 2023 Supplement, but the Final Rule's across the board decrease in collection efficiencies for all landfills is not consistent with the Proposed Rules, nor was it foreseeable from the Proposed Rules. EPA's final action here "finds no roots in the agency's proposal," *Kooritzky v. Reich*, 17 F.3d 1509, 1513 (D.C. Cir. 1994), equating to an impermissible "surprise switcheroo." *Envt'l Integrity Project v. EPA*, 425 F.3d 992, 996 (D.C. Cir. 2005).

EPA has attempted to support its collection efficiency "switcheroo" by citing two new scientific studies that allegedly support the lowering of collection efficiencies as applicable to *all* Reporters, without regard to SEM. Specifically, EPA states that "[a]ll the measurement study data [] reviewed suggests that current GHGRP collection efficiencies are overstated on average by 10-percentage points or more," citing to *Duan et al.*, 2022[47] and *Nesser et al.*, 2023.[48] As explained below, neither these studies nor the EIP Study support EPA's final decision.

Further, from a notice standpoint, EPA did not cite to either the *Duan* or *Nesser* studies in the Proposed Rules. The *Nesser* study was advanced by the paper's co-author, Hannah Nesser, in her comment in response to EPA's 2023 Supplement. [49] The paper itself was published online on June 13, 2023, only a few weeks before the close of the public comment period on July 22, 2023. The information contained therein was not even publicly available so as to inform EPA's proposals advanced on May 22, 2023, in the 2023 Supplement. In relying on entirely new data within the *Nesser* paper, EPA attempts to impermissibly "bootstrap" notice from a comment. *See*

[47] Duan, Z., et al., *Efficiency of gas collection systems at Danish landfills and implications for regulations*. 139 WASTE MANAGEMENT 269–78 (2022), https://doi.org/10.1016/j.wasman.2021.12.023.
[48] Nesser, H., et al., *High-resolution U.S. methane emissions inferred from an inversion of 2019 TROPOMI satellite data: contributions from individual states, urban areas, and landfills*. EGUSPHERE [preprint] (2023), https://doi.org/10.5194/egusphere-2023-946.
[49] EPA-HQ-OAR-2019-0424-0306. The paper was published online on June 13, 2023, only a few weeks before the close of the public comment period on July 22, 2023.

Fertilizer Inst. V. EPA, 935 F.2d 1303, 1312 (D.C.Cir.1991). EPA cannot reasonably assert that the final collection efficiencies are the "logical outgrowth" of the 2023 Supplement by relying on a study introduced via comment, without providing other interested parties the opportunity to review and comment on the study as well, for the purpose for which it is offered. *See, e.g.*, *United States v. Nova Scotia Food Prod. Corp.*, 568 F.2d 240, 251 (2d Cir. 1977).

Even more unacceptable is EPA's reliance on the *Duan* study. EPA did not cite or refer to *Duan* in either proposed rule; nor was it cited by an interested party during the public comment process. EPA's sudden reliance on *Duan* appears to be a post-hoc rationalization for its Final Rule, rather than appropriately identified support for a proposal that was properly noticed. Indeed, in this rulemaking, EPA has expressly acknowledged that newly cited studies introduced during the comment period warrant the agency's further consideration. As described *supra*, EPA proposed to implement a "correction term" to equations HH-7 and HH-8 that it hoped would more accurately quantify emissions by "account[ing] for periods where surface issues reduce the gas collection efficiency and/or reduce the fraction of methane oxidized."[50] In NWRA's comments on the proposal, we objected to the addition of the correction term on the basis that EPA's cited sources, namely *Heroux, et al.* and its internal sources, do not "adequately capture the complexity of the attempted correlation between surface emission exceedances and methane flux."[51] We asked that EPA consider other studies which show significant variability in the alleged correlation. In response, EPA stated that it would "continue to review additional information on existing and advanced methodologies and new literature studies and consider ways to effectively incorporate these methods and data in future revisions under subpart HH[.]"[52]

[50] 2023 Supplemental Proposal, 88 Fed. Reg. at 32878.
[51] EPA-HQ-OAR-2019-0424-0319.
[52] Final Rule, 89 Fed. Reg. at 31855.

EPA also indicated that it would take time to further consider the implementation of a correction term in light of newly advanced data, without taking any action in the Final Rule.[53] Consistent with its response to comments on the correction term, EPA should have acknowledged that more study of collection efficiency values is needed and should have subjected the 10-percent across-the board reduction collection efficiencies to an additional round of notice-and comment. *See, e.g.*, *Mexichem Specialty Resins, Inc. v. EPA*, 787 F.3d 544, 554 (D.C. Cir. 2015) (EPA may determine that affording a party seeking reconsideration the "same procedural rights" requires the initiation of rulemaking to gather additional data" to inform its decision).

B. <u>The finalized collection efficiencies should be reconsidered because the Petitioner's objections are of "central relevance to the outcome of the rule."</u>

An objection is of central relevance if it "provides substantial support for the argument that the regulation should be revised." *Coal. For Responsible Regulation v. EPA*, 684 F.3d 102, 125 (D.C. Cir. 2012); *Kennecott Corp. v. EPA*, 684 F.2d 1007, 1019 (D.C. Cir. 1982) ("Because the reasonableness and accuracy of the forecast data is critical to whether a smelter can qualify for [a nonferrous smelter order], Asarco and Magma's objections to that data, if well-founded, would clearly have been "'of central relevance.'").

The finalized collection efficiencies should be reevaluated and revised because they were central to the proposed and Final Rules. Indeed, emissions calculations are the crux of the GHGRP. EPA has articulated its over-arching goal to increase the accuracy of emissions calculations, so that Reporters, and more broadly the public at large, can understand whether and to what extent an entity is contributing to greenhouse gas emissions.[54] Universal required

[53] *Id.*

[54] Final Rule, 89 Fed. Reg. at 31884 ("[T]ransparent, standardized public data on emissions allows for accountability of polluters to the public who bear the cost of the pollution. The GHGRP serves as a powerful data resource and provides a critical tool for communities to identify nearby sources of GHGs and provide information to state and local governments.").

changes in calculation methodologies, therefore, should be considered carefully by EPA, especially where it has added a new methodology that overestimates emissions across the reporting sector. At a minimum, the "central relevance" requirement for reconsideration is satisfied in circumstances such as this, where there are well-founded objections pertaining to "critical" portions of the rule. *See Kennecott*, 684 F.2d at 1019.

Indeed, EPA's finalization of understated collection efficiencies, and the lack of support thereof, undermine the very purpose and objective of the GHGRP—to promote the accurate and comprehensive collection and reporting of greenhouse gas emission data. These failures will, in turn, harm the Petitioner's members. The finalized collection efficiencies will result in discrepancies among state and federal programs that require methane emissions reporting. With respect to federal programs, EPA has used GHGRP data on MSW landfills to "inform the development of the 2016 NSPS and EG for landfills." [55] Similarly, the "benefits of improved reporting also include enhancing existing voluntary programs, such as the Landfill Methane Outreach Program (LMOP)."[56] Moreover, EPA recognizes that "[s]everal states use GHGRP data to inform their own policymaking."[57] GHGRP emission estimates will also be at odds with EPA's own emissions factors in AP-42, as well as state permitting programs, which allow for a range of collection efficiencies and the recognition that higher collection efficiencies may be achieved at some sites that are designed and engineered to collect and control landfill gas.[58]

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[55] *Id.*
[56] *Id.*
[57] *Id.*
[58] *See* AP-42, at 2.4-6, https://www3.epa.gov/ttnchie1/ap42/ch02/final/c02s04.pdf

> "To estimate controlled emissions of CH4, NMOC, and other constituents in landfill gas, the collection efficiency of the system must first be estimated. Reported collection efficiencies typically range from 60 to 85 percent, with an average of 75 percent most commonly assumed. Higher collection efficiencies may be achieved at some sites (i.e., those engineered to control gas emissions). If site-specific collection efficiencies are available (i.e., through a comprehensive surface sampling program), then they should be used instead of the 75 percent average."

Without accuracy and consistency across these programs, Reporters and agencies will not be able to appropriately identify and address emissions-related issues at affected facilities.

To the extent that GHGRP reported emissions are overestimated compared to reported emissions under other programs, such discrepancies will also add complexity to sustainability reporting and permitting, negatively impacting and complicating information provided to shareholders and third parties, and subjecting Reporters to risk. As a practical matter, the lowered collection efficiencies will have a compounding effect across multi-facility companies and may act as a disincentive to increase gas collection given that EPA's final rule now assumes inefficiencies among Reporters using HH-8. This is because HH-8, in general, assumes that emissions are directly proportional to the amount of landfill gas that is recovered and destroyed. Thus, the lowered collection efficiencies in the new rule could disincentivize higher actual collection.

Moreover, absent reconsideration, the final rule may have broad unintended consequences on policies designed to reduce greenhouse gas emissions. EPA's Renewable Fuel Standard ("RFS") program, for example, requires gasoline and diesel producers to incorporate renewable fuels into the Nation's transportation fuel supply.[59] Congress sought to accomplish this mandate in large part by encouraging the increased production and use of cellulosic biofuels—including renewable natural gas derived from landfill biogas—with the goal of achieving lower costs for consumers, reduced GHG emissions, better air quality, and greater energy independence.[60] Other policies have built upon the success of the RFS program, offering

[59] *See* 40 C.F.R. § 80, subpart M.
[60] *Renewable Fuel Standard (RFS) Program: Standards for 2023–2025 and Other Changes*, 88 Fed. Reg. 44468, 44471 (July 12, 2023).

additional incentives for landfill methane capture, which waste sector stakeholders rely on in making business decisions around the installation of bio gas processing equipment.

States such as California, Oregon, Washington, and New Mexico have also developed Clean Fuel Standard programs[61] to encourage the use of low-carbon transportation fuels by providing credit to renewable fuel producers on a sliding scale based on the carbon intensity of each fuel. Unfortunately, the finalized collection efficiencies will have a negative impact on the carbon intensity scores of fuels sourced from landfill-derived biogas, resulting in reduced financial incentives for the production of renewable natural gas and potentially disincentivizing projects aimed at capturing methane emissions from waste sector operations. Congress has similarly incentivized the implementation of clean energy projects under the Inflation Reduction Act of 2022 ("IRA")[62], making tax credits available to taxpayers using a "technology-neutral" approach. The IRA specifically included a suite of tax credits designed to reward renewable fuel producers for lowering the carbon intensity scores of their fuels.[63] Similar to the negative impacts of the final rule associated with the aforementioned Clean Fuel Standard programs, EPA's finalized collection efficiencies will reduce the value of various tax credits for the production or generation of renewable natural gas, clean hydrogen, renewable electricity, and sustainable aviation fuel—potentially resulting in lost opportunities to capture landfill methane for beneficial use. Finally, to the extent that future legislative actions would contemplate a "carbon tax" or similar financially based implications for greenhouse gas emissions, it is

[61] Cal. Code Regs. tit. 17, § 95480; Or. Admin. R. 340-253-0000; Wash. Rev. Code Ann. § 70A.535.005; New Mexico House Bill 41 (requiring the Environmental Improvement Board to promulgate regulations to initiate the program no later than July 1, 2026).
[62] 136 Stat. 1818, Pub. L. 117–169 (Aug. 16, 2022).
[63] *See* 26 U.S.C. § 6426.

imperative that the quantification of such emissions is reliable and accurate. EPA should set a high standard under the GHGRP for such accuracy.

C. EPA lacks adequate technical justification for the finalized reduction in collection efficiencies.

As finalized, the lowered collection efficiencies are technically unjustified, and the proffered bases do not support EPA's change in position.

An agency action is arbitrary and capricious if there does not exist a "rational connection between the facts found and the choices made." *Motor Vehicle Mfrs. Ass'n of U.S., Inc. v. State Farm Mut. Auto. Ins. Co.*, 463 U.S. 29, 43 (1983). A rational connection between the facts found and the choices made does not exist if, among other reasons, the agency failed to consider an important aspect of the problem or the agency offers an explanation for its decision that runs counter to the evidence. *Id.* Both shortcomings are present here. In the 2023 Supplement, EPA purported to address "methane emissions from large release events" and focused on whether landfills were using SEM to address "leaking cover systems due to cracks, fissures or gaps around protruding wells" as a basis on which to adjust collection efficiency.[64] But in the Final Rule, EPA dismissed SEM as a consideration and relied only on study papers, including two that were newly cited, to support an across the board reduction in collection efficiencies, rather than focusing on methane emissions from large release events as it did in the 2023 Supplemental Proposal. In so doing, EPA prevented comment that would have addressed overall collection efficiencies across the MSW landfill sector rather than emissions associated with large release events, including those that occur via cover problems that are addressed by SEM. Such material comments would have advanced arguments falling within the "relevant factors" that EPA is

[64] 2023 Supplemental Proposal, 88 Fed. Reg. at 32877–78.

required to consider before finalizing a regulation. Without consideration of such important input, EPA ignored "important aspects of the problem" relating to landfill collection efficiency and greenhouse gas emissions. *Motor Vehicle Mfrs. Ass'n of U.S., Inc. v. State Farm Mut. Auto. Ins. Co.*, 463 U.S. 29, 43 (1983). While reviewing courts are generally deferential with respect to decisions involving agency expertise, *Logic Tech. Dev. LLC v. FDA*, 84 F.4th 537, 549 (3d Cir. 2023); *GenOn REMA, LLC v. EPA*, 722 F.3d 513, 526 (3d Cir. 2013), agencies are forbidden from reaching "whatever conclusions [they] like" and defending such positions "with vague allusions to [their] own expertise." *Sierra Club v. EPA*, 972 F.3d 290 (3d Cir. 2020) ("Although EPA has offered vague allusions to the inability of unspecified plants to meet a lower standard, the agency has deprived us of the ability to review its decision by showing its work."). Put simply, an agency action must be "reasonable and reasonably explained." *FCC v. Prometheus Radio Project*, 592 U.S. 414 (2021). This was not.

In the Final Rule, EPA acted arbitrarily by relying on scientific data that was not presented in either of the Proposed Rules. Just as importantly, EPA also failed to adequately explain how the scientific conclusions of the studies on which it relied—which involved the use of remote sensing data to quantify landfill emissions—support the final collection efficiencies without regard to SEM. In fact, in the Final Rule EPA underscored the dangers of relying on such technologies at this juncture. There, EPA stated that it was "not taking final action at this time regarding the incorporation of other direct measurement technologies" such as satellite imaging, aerial measurements, vehicle mounted measurement or continuous sensor networks because "most top-down facility measurements are taken over limited durations (a few minutes to a few hours) typically during the daylight hours when specific meteorological conditions exist (*e.g.*, no cloud cover for satellites; specific atmospheric and wind speed ranges for aerial measurements)."[65] EPA further recognized that these methods of measurement "may not be representative of the annual CH_4 emissions from a facility, given that many emissions are episodic."[66] Consequently, EPA concluded, "[e]xtrapolating from limited measurements to an entire year therefore creates risk of either over or under counting actual emissions."[67] In this respect, EPA's decision to heavily rely upon *Nesser* and similar studies, whose findings are the result of satellite imaging, in supporting a broad-based and unqualified reduction in collection efficiency values, is puzzling. EPA makes no effort to explain this discrepancy in logic, which has resulted in a Final Rule that runs counter to the agency's own findings.[68]

1. <u>The Nesser Study does not support EPA's collection efficiency determination.</u>

EPA cites the *Nesser* study for the general proposition that "recent aerial studies indicate methane emissions from landfills may be considerably higher than bottom-up emissions reported under subpart HH for *some* landfills" and further notes that such higher emissions may be attributable to "poorly operating gas collection systems or destruction devices and leaking cover systems."[69] But EPA fails entirely to explain how the *Nesser* study, which was based on its review of only 38 landfills, supports a broad-based collection efficiency reduction applicable to

[65] Final Rule, 89 Fed. Reg. at 31856.
[66] *Id.*
[67] *Id.*
[68] This petition focuses on the introduction of scientific data from Nesser, et al., 2023 and Duan et al., 2022. EPA also referenced two additional studies: Oonk, H., *Efficiency of landfill gas collection for methane emissions reduction*, 2 GREENHOUSE GAS MEASUREMENT AND MANAGEMENT, 129–145 (2012) https://doi.org/10.1080/20430779.2012.730798; and Arcadis, *Quantifying Methane Abatement Efficiency at Three Municipal Solid Waste Landfills; Final Report*. Prepared for U.S. EPA, Office of Research and Development, Research Triangle Park, NC. EPA Report No. EPA/600/R–12/ 003. (Jan. 2012). https://nepis.epa.gov/Exe/ZyPDF.cgi/P100DGTB.PDF?Dockey=P100DGTB.PDF.
It is unclear whether EPA relies on these studies to support its assertion that historical collection efficiencies are overstated, because EPA fails to adequately explain the relevance of these studies and how they support the finalization of the lowered collection efficiencies. Final Rule, 89 Fed. Reg. at 31856.
[69] Final Rule, 89 Fed. Reg. at 31854 (emphasis added).

the more than 1,000 landfills[70] that are subject to reporting under the GHGRP.[71] Just as critically, EPA does not explain the basis on which such collection efficiencies can be appropriately or accurately measured with satellite imagery—a key concern for the Petitioner.

The *Nesser* study uses 2019 satellite (TROPOMI) data at approximately 25 x 25 km resolution to estimate methane emissions for grid cells in the contiguous United States with 2012 reported methane emissions larger than 0.1 Mg /(km year).[72] *Nesser* alleges that landfill emissions are 51% higher than the Greenhouse Gas Inventory ("GHGI") indicates.[73] The study compared optimized emissions for 73 individual landfills to those reported under the GHGRP and alleges to have found a median 77% increase in emissions relative to reported values.[74] Of the 73 studied landfills, 38 of the facilities recovered gas and reported an average efficiency of 0.5 (0.33 – 0.54) compared to the reported average of 0.61.[75] However, the collection efficiency reported in the 2019 GHGI was either within or higher than the author's reported uncertainty range for 15 of the 38 landfills.[76] Moreover, the study found no correlation (R2 = 0.00) between GHGRP emissions and the landfill estimates. The correlation did not improve when considering only facilities that do or do not capture landfill gas.[77] In summary, NWRA believes that the *Nesser* study introduces several uncertainties, which, taken separately or collectively, undermine its use as a basis for EPA's action:

- The range reported is not a credible (confidence) interval for the estimated emissions but is the range of the eight members of the ensemble. This range only accounts for

[70] EPA-HQ-OAR-2019-0424-0256, Attachment A.
[71] Final Rule, 89 Fed. Reg. at 31856.
[72] *Nesser*, *et al.*, at 2, 4.
[73] *Id.* at 26.
[74] *Id.*
[75] *Id.* at 19.
[76] *Id.*
[77] *Id.*

the uncertainty introduced by the optimized boundary conditions, bias correction, and regularization factor, and does not account for the uncertainty in the measurements, transport model or and source attribution methods.

- Emission sources not included in the 2012 GHGI are not accounted for. The source aggregation approach assumes that the 2012 reported fractional sectoral contributions are correct in each 25 x 25 km grid cell.
- The study only quantified 70 of the 1297 landfills that reported to the GHGRP in 2019.
- Satellite data can only be collected during clear daytime conditions, so landfills in areas with snow or high cloud cover were less likely to be quantified. With a low (3%) success rate, TROPOMI data may be as few as 12 measurements over the course of a year for a given site, biased toward clear summertime conditions.
- The study does not discuss whether readings occurred during landfill operating hours.
- It is our understanding that TROPOMI is an open-source satellite in geosynchronous orbit, meaning that measurements are taken at the same time each day, thus failing to account for key differences in nighttime values. EPA's own work discusses that 99% of landfills have more negative temporal pressure during days compared to the rest of the time leading to overestimating methane emission. While not published, EPA should be aware of work done within its own agency regarding this topic.

Indeed, even the authors acknowledge the risks inherent in relying on such data: "[o]ur landfill attribution approach, which relies on a prior estimate from 2012, may therefore misallocate emissions to the Puente Hills Landfill instead of to co-located oil and gas operations".[78] Further, the study goes on to say, "[c]ompared to TROPOMI, both the prior and posterior GEOS- Chem simulations produce similar coefficients of determination (R2) and root-mean-square errors (RMSEs)," indicating that using the authors' estimated emission rates fail to explain any additional variability in the satellite measurement compared with the 2012 reported values.[79]

By not accounting for all the sources of uncertainty in the model and measurements in the reported uncertainty range, the authors have failed to demonstrate that the difference between the observed and reported collection efficiencies is statistically significant. The variation in observed collection efficiencies and significant sources of uncertainty in the observations do not provide sufficient justification for a 10% reduction in collection efficiency across the board.

2. The Duan Study does not support EPA's collection efficiency determination.

EPA similarly fails to explain how the conclusions of the *Duan, et al.*, 2022 study support its decision to lower collection efficiencies and uncouple collection efficiency from SEM. In fact, the conclusions set forth in the *Duan* study more closely *support* EPA's 2023 Supplement proposal to tie collection efficiency to SEM.

The *Duan* study observed 23 Danish landfills using a tracer gas dispersion method.[80] Gas collection efficiencies were calculated by taking the collected methane gas and dividing it by the sum of collected methane, methane emitted into the atmosphere, methane oxidized in cover soil, methane migrated laterally, and methane stored in the landfill body.[81] As a result, the study concluded that Danish landfills, on average, have lower collection efficiencies than other

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[78] *Id.*
[79] *Id.* at 13.
[80] Duan, Z., et al., *Efficiency of gas collection systems at Danish landfills and implications for regulations*, 139 WASTE MANAGEMENT 270 (2022), https://doi.org/10.1016/j.wasman.2021.12.023.
[81] *Id.*

countries, and suggested that such was the result of shallow wells, lack of gas collection in some areas, and low recovery due to minimal production.[82] The study based its conclusions on "whole-site methane," even when collection systems did not cover the site. Sites that had discontinuous GCCS operations had high collection efficiencies (94-95%) when the system ran, but lower collection efficiencies when the GCCS was turned off, leading to lower average collection efficiencies.[83]

Notably, the *Duan* study acknowledged the complexity associated with quantifying gas production, emissions, and collection efficiency.[84] The study stated, "[a]t landfills with well-designed liner and cover systems and aggressive gas collection approaches, efficiency can be as high as above 90%, as observed in previous studies (e.g. UK-J and Redwood landfills) based on whole-site emissions measurements."[85] Further, the study noted "[i]f gas collection has not been established in every cell at a landfill—for example, if no gas collection occurs at active cells—using average efficiency will underestimate the actual gas collection efficiency in closed cells."[86] Based upon the complexity of calculation and landfill-dependent factors, the study actually suggests coupling collection efficiency with SEM.[87] This acknowledgment better comports with EPA's proposal in the 2023 Supplement, rather than what was finalized in the Final Rule. In sum, the *Duan* study agrees that a one-size-fits-all approach is inappropriate when it comes to landfill collection efficiency—an implication that is directly at odds with EPA's decision to

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[82] *Id.* at 277.
[83] *Id.* at 274.
[84] *Id.* at 275 ("Landfill gas production and emissions are determined by many factors, such as waste composition, waste age, disposed waste amount, landfill design and operation, lack meteorological conditions, etc."); *see also id.* at 276 ("Gas collection efficiency depends on the phase of the landfills, design, and management of the LFG collection system, the presence or type of top cover, etc.").
[85] *Id.* at 270.
[86] *Id.* at 276.
[87] *Id.* Specifically, it states that "surface methane concentration screening could be conducted to identify significant release points or areas, following which any identified major leaks should be repaired."

lower default collection efficiencies across the board. With little more than a few sentences supporting EPA's use of this study in the Final Rule, EPA has failed to establish a rational connection between *Duan* and lowered default collection efficiency values irrespective of SEM.

Further diminishing any justification for reliance on the *Duan* study is the fact that it pertains to Danish landfills that are not representative of landfills across the United States. EPA has agreed with NWRA's contention that the data the agency used to support the proposed correction term—which rested on an analysis conducted using a dynamic flux chamber covering a surface area of 0.2 m^2 over 20 years ago at one landfill in Canada—could not adequately support the proposal.[88] Similarly, here, EPA should not rely on a study evaluating Danish landfills, especially where the authors state that there are stark differences between U.S. and Danish landfills. Specifically, the study states that the "measured emissions normalized to the disposed waste mass and areas of the landfills in Denmark are *significantly* lower than" normalized emissions of U.S. landfills, which may be the result of Denmark's 1997 ban on landfilling organic waste.[89] Consequently, relying on the *Duan* study is unacceptable, especially in light of EPA's outward refusal to rely on studies not found to be "nationally representative" of MSW landfills.[90]

3. **<u>The EIP and Duren Studies do not support EPA's collection efficiency determination.</u>**

Although EPA cites to both the EIP Study and the *Duren et al.*, 2019[91] study in the 2023 Supplement, EPA fails to adequately explain how either of these studies support its decision to

[88] Final Rule, 89 Fed. Reg. at 31855.
[89] *Duan et al.*, at 276.
[90] Data Quality Improvements Proposal, 87 Fed. Reg. at 37009.
[91] Duren et al., *California's Super Emitters*. 575 NATURE 180¬84. 7 (2019), https://doi.org/10.1038/s41586-019-1720-3.

lower collection efficiencies by 10% across all categories of affected landfills. As such, EPA's decision, which relies on these papers, is not supported.

EIP's findings rest on their discovery of a math error in the State of Maryland's methane emissions calculation for landfills. The study pointed out that the Maryland Department of the Environment calculated emissions as 10% of uncollected gases and 90% oxidized instead of 90% uncollected and 10% oxidized. From there, the study discussed how few landfills have gas collection and control systems—21 out of 40—with only four subject to federal requirements under the New Source Performance Standards program. EIP ultimately suggests two solutions: (1) more widespread implementation of gas collection systems, and (2) organics diversion. It compares collection efficiencies of facilities with gas collection and control systems that are subject to NSPS (76% collection efficiency) and those that voluntarily install such systems (55% collection efficiency): "EPA estimates that the average collection system harnesses 75% of the gas generated in the waste heap." However, EIP then notes that Maryland landfills have system collection efficiencies that range from 5-95%, with an average of 59%.

As stated in NWRA's comments to the 2023 Supplement, Maryland landfills are not representative of landfills across the United States and represent a low number of federally regulated landfills. Therefore, the data from this study should not be extrapolated to other landfills in the U.S. for comparing subpart HH collection efficiencies and LandGEM modeling-based collection efficiency. EPA exacerbated this misplaced reliance by failing to consider key variables in its analysis, including differences in waste disposal streams (and associated differences in potential methane generation capacity), calculation methodologies for collection efficiencies based on reported collection volumes, and the significance of federal expansion timelines and downtime limitations over the performance of SEM.

In addition, EPA failed to articulate a rational explanation with respect to how the study's conclusions support the across-the-board reductions in collection efficiencies seen in the Final Rule, and failed to address the concerns raised by NWRA in its comments. Ultimately, EPA went from using the EIP Study to support reduced collection efficiencies for facilities not conducting SEM, to reducing collection efficiencies for all Reporters regardless of SEM. Interestingly, EPA could not cite this study, or any other for that matter, to "support further reductions in gas collection efficiencies for voluntary gas collection systems."[92] Even in light of EPA's scientific and technical expertise, the use of the EIP Study to support the finalized changes is not "reasonable [or] reasonably explained." *FCC v. Prometheus Radio Project*, 592 U.S. 414 (2021).

To the extent that EPA's finalized collection efficiencies were promulgated using conclusions from *Duren et al.*, 2019, such reliance is likewise misguided. The *Duren* study conducted five campaigns between 2016 through 2018 to survey more than 272,000 "infrastructure elements" in California using an airborne imaging spectrometer that the authors alleged "can rapidly map methane plumes."[93] However, the *Duren* study conceded "[t]he fact that we did not detect a larger population of smaller methane point sources across the landfill sector suggests that most of those facilities emit methane as area sources that cannot be detected with this method."[94] EPA similarly acknowledged this shortcoming in its Technical Support Memo:

> *It is important to note that only landfills with anomalous emissions could be quantified by the aerial methods used by Duren, et. al., (2019) and that these emissions only occurred at 7 percent of the surveyed landfills. However, when these anomalous emissions occur, the CH4 emissions reported to the EPA under Subpart HH are consistently lower than the measured emission rates extrapolated to annual*

[92] Final Rule, 89 Fed. Reg. at 31856.
[93] *Duren, et al.*, at 180.
[94] *Id.* at 182.

estimates……… Because the California aerial study of Duren, et. al., (2019) could not quantify the emissions from 93% of the landfills that did not have anomalous emissions, this study does not provide evidence that the Subpart HH methodologies are inaccurate or unbiased under typical conditions that exist for most landfills.[95]

The *Duren* study also failed to discuss diurnal issues or times of flights (*e.g.*, whether flights were conducted during the daylight hours), and it relied on a "persistence" factor that is inappropriate for multiple reasons. In this original publication, *Duren* gave landfills a blanket "100%" persistence factor, meaning that it extrapolated estimated emissions results to the entire year, which EPA has recognized as inappropriate.[96] Moreover, use of this persistence factor is inappropriate because the authors filtered their runs to weed out flights where they didn't get a detection, or the detection was unreliable for various QA/QC reasons.

Further, the *Duren* study never addresses whether the same plume may have been detected on multiple flyovers. This information is important, because it could either exaggerate or undermine the 100% persistence concept that is fundamental to emission quantification based on such remote observations. For example, different plumes would have different calculated emissions, with no one plume being appropriate for extrapolation. Further, the reality of variable emissions points reflect the variable nature of emissions over time. Assuming continuous emissions could easily overlook low- or even no-emissions days, in direct conflict with the notion of "100% persistence."

As another example, *Duren*'s methodology for calibrating wind data also relies on the work done by others in the Four Corners region, which is a very flat, desert type area that is inappropriate for other types of topography, including the canyon-topography landfills located in

[95] EPA-HQ-OAR-2019-0424-0256 Technical Support for Supplemental Revisions to subpart HH; Municipal Solid Waste Landfills, at 3.
[96] *See discussion supra* in Section III.C.1.

California. These calculations are highly sensitive to accurate wind modeling, making *Duren*'s use of a wide geographic NOAA data area questionable. In particular, *Duren's* approach was to use NOAA data, and subdivide the area around the landfill into 3 km squares, averaging the 9 closest squares into the "average site windspeed and direction" and applying that to the detected concentrations.[97] But plumes are not formed in that manner in challenging topographical areas. As with the point above, more recent publications from *Duren* and others, as well as other industry presentations, recognize that canyon landfills are notoriously difficult from which to quantify emissions.

Like *Nesser*, which utilized satellite data to support its findings, the integrity of the aerial measurements collected in *Duren* cannot provide adequate support for the lowered collection efficiencies across the entire MSW landfill sector for the same reasons.[98]

4. **<u>Other papers and emerging studies do not support EPA's reduction in collection efficiency determination.</u>**

EPA, industry participants, and third parties continue to actively assess the value of remote sensing techniques for landfill emission quantification. While there is great interest and optimism around this topic, specific conclusions around collection efficiency values are premature. For example, in its comments to the 2023 Supplemental Proposal, Carbon Mapper has pointed out that there is "no existing system to validate or revise GHGRP reporting" based on "observed emissions rates using remote sensing."[99] Instead, Carbon Mapper suggested an multi-tiered monitoring approach to validate reported annual emissions by using a system to quantify "total site-wide emission sources" using "high-frequency to continuous monitoring."[100]

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[97] *Duren* et al., at 181.
[98] *See supra*, Section III.C.1.
[99] EPA-HQ-OAR-2019-0424-0324, at 5.
[100] *Id.* at 5.

In addition, in responding to EPA's stated concern in the 2023 Supplemental Proposal about large release events, Carbon Mapper recommended the use of site-specific data to aid in assessing these events to avoid double counting, including "construction periods and locations, type of GCCS and combustion devices, any use of automated well tuning, monitoring methods used (including non-regulatory, voluntary monitoring), and cover types used."[101]

To the extent that EPA intended to rely on top-down, direct measurement technologies to support the reduction in collection efficiencies, EPA improperly extrapolated data that, if collected on a continual basis, would tend to prove the opposite conclusion. For example, a study by *Cusworth*, et al. found that "[o]n average, aerial emission rates were a factor of 2.7 higher than GHGRP for all landfills and a factor 1.4 higher for landfills with 10+ unique overpasses. Consistent with this study, independent assessments of US emission inventories have indicated a needed 1.25 to 1.5 scaling of waste emissions to reconcile inventories with in situ ground-based measurements and coarse resolution satellite observations."[102] These findings emphasize even the Nesser authors' direct acknowledgement that the average of more point-in-time observations for a single site tends to agree more closely with annual inventory estimates; providing evidence that there is not enough data to support the extrapolated claim that observations are more representative than annual inventory estimates. The recency of the *Cusworth* publication reinforces the imperative raised by the Petitioners in their comments: that EPA should wait to promulgate changes to subpart HH in anticipation of forthcoming data that will provide more appropriate support for comprehensive changes.

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[101] *Id.* at 5.
[102] Cusworth, et al., *Quantifying methane emissions from United States landfills*. 383 SCIENCE 1499 (2024).

As discussed *supra* in Sections III.C.1 and III.C.2, remote sensing measurements using satellite and aircraft systems like TROPOMI and AVIRIS-NG, described in *Nesser*, et al., 2024 and *Duren*, et al., 2019, can only be made during daylight hours, causing landfill emission rates derived from these approaches to be biased high because the measurements are made during active landfilling operations and do not capture the period when the landfill is not receiving waste. Another study, *Delkash*, et al., 2022, used eddy covariance ("EC") measurements to assess diurnal variations in methane emissions and "showed that short-term tracer correlation method ("TCM") measurements conducted between 12:00 and 18:00 overestimate diurnal emissions estimated by the EC tower up to 73% at this site."[103] The EC methodology is able to operate continuously to capture concentration measurements to support emissions estimates over longer durations in a wide range of meteorological conditions and atmospheric stability classes. The study reported significant diurnal variation in methane flux at one landfill where EC and TCM were deployed over three seasons, and found that daytime methane flux rates were up to 23 times higher than nighttime fluxes.[104] Moreover, the daily average of EC observations presented a lower estimated emission rate when compared to tracer correlation method observations, a methodology similar to that used in the *Duan*, et al., 2019 study. While the *Delkash* study included only one landfill, its findings point to the potential bias of relying on daytime only measurements to determine landfill emissions rates, particularly when those rates will then be compared to annual rates like the GHGRP. The study, therefore, stands for the same conclusion articulated above: assessing the accuracy of the GHGRP modeled rates requires measurement methods that continuously monitor both point-source and diffuse emissions so as to better

[103] Delkash, et al., *Diurnal landfill methane flux patterns across different seasons at a landfill in Southeastern US*, 144 WASTE MANAGEMENT 76, 85 (2022).
[104] *Id.* at 76.

understand diurnal and seasonal variations to compare point-in-time observations to annual emissions inventory estimates.[105]

IV. Basis for Relief and Proposed Next Steps

Overall, EPA does not articulate a rational connection between the scientific and technical evidence relating to landfill collection efficiency and the decision to stray from its proposal and apply a uniform approach to collection efficiency values uncoupled from SEM. While NWRA did not support the SEM-based approach advanced by the 2023 Supplemental Proposal for the reasons expressed in our comments, we acknowledge the importance of site-specific design and performance factors in assessing collection efficiency. EPA's Final Rule is the opposite of a site-specific approach, based on SEM or otherwise. We expected the Final Rule to be the logical outgrowth of the proposal to tie collection efficiency adjustments to SEM. We also recognized that the proposed coupling of collection efficiencies and SEM served as an incentive for "non-regulated" landfills to implement SEM to avail themselves of the higher collection efficiencies. Lowering collection efficiency regardless of SEM now may have an unintended effect—if Reporters know that they can never achieve greater than 85% efficiency in estimating emissions under the GHGRP, there is little incentive to increase efficiency. EPA's simple explanation that lowered collection efficiencies are warranted in light of the agency's review of "direct measurement data for landfills" leaves an unfillable gap in reasoning and logic, warranting reconsideration.

NWRA and its members recognize the importance of developing technologies and ongoing studies and analyses of direct measurements and remote sensing data. The MSW landfill sector is deeply engaged in this work, in partnership with EPA's Office of Air and Radiation as

[105] *Id.* at 85; *see also* Stark, et al., *Investigation of U.S. landfill GHG reporting program methane emission models*, 186 WASTE MANAGEMENT, 86, 86, 91 (2024).

well as its Office of Research and Development, Carbon Mapper, GHG Sat, RMI and others. Through SWICS and company-specific data analyses, NWRA anticipates that it will have a substantial set of data to share with EPA in the very near term, after appropriate quality control and assessment is complete. The data will consist of direct measurements, correlated with site-specific SEM and operational conditions, and evaluations of resulting emission impacts. NWRA will share this data with EPA in the proposed reconsideration period to help inform EPA's perspective on collection efficiencies. Most importantly, to the extent that these advancements assist in the strengthening of emission quantification and information, and thereby provide avenues for improvements in methane capture, the GHGRP should be structured to acknowledge and account for such improvements. The Final Rule unfortunately has the opposite effect, by imposing reduced collection efficiencies across the board, based on overgeneralized and qualitative theories that do not support the determination that was made.

As set forth at length above, NWRA requests that EPA grant reconsideration of the reduced collection efficiencies set forth in Table HH-3 of the Final Rule. Interested parties were not afforded the opportunity to comment on EPA's finalized collection efficiencies because they were not a "logical outgrowth" of the Proposed Rules.

To the extent that EPA declines to grant reconsideration on the bases set forth in Section 307(d)(7)(B) of the Clean Air Act, the Petitioner asks that EPA treat this submittal as a petition for rulemaking under the Administrative Procedure Act, 5 U.S.C. § 553(e), which is a "procedural right." *Massachusetts v. EPA*, 415 F.3d 50, 53 (D.C. Cir. 2005) *rev'd and remanded on other grounds by* 549 U.S. 497, 527 (2007); *Friends of the Earth v. EPA*, 934 F. Supp.2d 40, 54 (D.D.C. 2013) ("EPA is required to respond to a citizen petition for rulemaking.").

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EXHIBIT 2

A Controlled Release Experiment for Investigating Methane Measurement Performance at Landfills

Final report

Revised on July 9, 2024

Fluxlab

St. Francis Xavier University

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Executive Summary

A large-scale controlled release study was performed at a closed landfill in Petrolia, Ontario Canada between November 6, 2023, and November 14, 2023. During this time, 16 combinations of vendors and methodologies were assessed for their performance of quantification and detection of methane during 71 experiments.

For quantification performance, ground and aerial methodologies were used. Fenceline truck-based measurement systems using the Mobile Gaussian Plume Assessment (MGPA) method underestimated emission measurements, on average by 47% and with an uncertainty of ± 43%. Uncertainty around MGPA measurements reduces with better atmospheric factors, but timing constraints led to lack of replicates. Mobile Tracer Correlation Emission Assessment (MTCEA) on average underestimated emissions by 11% and had an uncertainty of ±20%. The drone-based UAV Point Sensor Emission Measurement (UPSEA) vendors displayed tendencies to both over- and underestimate. The UPSEA method provided good quantification estimates – vendor C reported very few outliers, with vendor D having a greater spread. Vendor C on average overestimated emissions by 14 % and had an uncertainty of ±34%, while vendor D on average underestimated emissions by 11% and had an uncertainty of ±62% but demonstrated sensitivity to atmospheric stability and reported fewer than other vendors (n<10). Aerial-based Light Detection and Ranging (LiDAR) systems improved when they were revised using onsite weather data, resulting estimates on average overestimated by 45% with an uncertainty of ± 45%. Remote Point Sensor Emission Assessment (RPSEA)offers a low maintenance option for measuring emissions with uncertainty of ± 39% in the best-case scenario. RPSEA is currently in the early development stages, with variability across vendors.

MTCEA, LiDAR, and UPSEA delivered minimal bias and generally delivered low variability. However, all are relatively specialized tools requiring specialized equipment and knowledge and may not be useful or available to all sites. Although trucks tended to under-estimate and were more volatile, they delivered estimates that were on average within a reasonable margin of the actual values and would therefore be reasonable alternatives for some applications like rapid screening, in suitable conditions. LiDAR had the best detection performance; it was able to detect 100% of the emitting sources, without false positives.

For detection performance, UAV Column Sensor Emission Assessment (UCSEA) systems detected dispersed source releases above 10 kg/hr on even ground. However, the detection performance deteriorated when scanning on slopes, with either very limited or no detections reported. The two UCSEA systems reported false positives fractions of 0.79 and 0.83, which is the ratio of false positives to total reported detections. LiDAR-based detection systems are very sensitive to emissions and detect emissions as low as 1 kg/hr. UCSEA can improve with changes in work practice and more testing and may eventually be capable of replacing walking surface emissions measurement.

This study highlights the need for further research in several areas related to methane emission quantification in a landfill setting. Validation of the Satellite Imaging Sensor Emission Assessment (SISEA) method is of high priority and will require future controlled release configurations of over 300

kg/hr during low cloud cover months. Studying methane emission rates during day and night cycles and variability among methodologies are important factors to advance landfill methane measurements. A permanent or long-term, buried underground release setup would facilitate frequent research and validation opportunities.

Contents

AGL	Above Ground Level
CGU	Canadian Geophysical Union
CMOS	Canadian Meteorological and Oceanographic Society
CNG	Compressed Natural Gas
CSA	Canadian Standards Association
ECA	Environment Compliance Approval
ECCC	Environment Climate Change Canada
ELARS	Eastern Landfill Atmospheric Research Station
ERA5	5^{th} gen. European Centre for Medium-Range Weather Forecasts Reanalysis
HRDEM	High Resolution Digital Elevation Model
ICI	Infrared Cameras Incorporated
LEA	Lagrangian Emission Assessment
LFG	Landfill Gas
LiDAR	Light Detection and Ranging
MDL	Minimum detection limit
MECP	Ministry of the Environment, Conservation and Parks
METEC	Methane Emissions Technology Evaluation Center
MGPA	Mobile Gaussian Plume Assessment
Mid-IR	Mid-infrared
MOS	Metal Oxide Sensor
MTCEA	Mobile Tracer Correlation Emission Assessment
NETL	National Energy Technology Laboratory
OTM51	Other Test Methods-51
PD	Probability of Detection
PRS	Pressure reduction system
RPSEA	Remote Point Sensor Emission Assessment
SISEA	Satellite Imaging Sensor Emission Assessment
TDLAS	Tunable diode laser absorpotion spectroscopy
TSSA	Technical Standards and Safety Authority
UAS	Unmanned Aircraft Systems
UAV	Unmanned Aerial Vehicle
UCSEA	UAV Column Sensor Emission Assessment
UPSEA	UAV Point Sensor Emission Assessment
WM	Waste Management

1. Introduction

Landfills contribute approximately 16% of the anthropogenic methane emission in the United States (Delkash et al., 2022). There are several methane measurement methodologies available; however, few are validated, and none are recognized as an international reference method. Main challenges in measuring methane emissions from landfills is the temporal and spatial variability. Emission rates can vary by up to 7 orders of magnitude within few meters, which is primarily caused due to cracks or holes in the soil cover, this causes emission hotspots or elevated levels of methane concentration (Mønster et al., 2019). However, landfill operators lack reliable information on measurement tools that will provide data to meet Environmental, Social, and Governance (ESG) criteria, requirements imposed on publicly traded companies to disclose verified emissions, or measurement requirements that may be part of future governmental regulations. As the urgency of the climate crisis has grown, so too has the array of measurement technologies and methodologies used to evaluate emissions. These methodologies can help operators better understand their emissions and meet emission reduction targets, if their accuracy is validated.

This controlled methane release study was conducted at a closed landfill in Petrolia, Ontario between November 6 and 14, 2023. The selected site was, in many ways, an ideal controlled release test site insofar as both FluxLab and ECCC (Environment Climate Change Canada) conducted past measurements there, providing a solid baseline understanding of the characteristics of the landfill. Additionally, this site has the appropriate morphology, low emissions, and no interfering neighboring methane sources.

All the methodologies tested in this study can survey landfills for emissions, but each has different dependencies, costs, speeds, and uncertainties. We assembled a varied group of methodologies to assess their performance under controlled conditions to help educate landfill operators and regulatory bodies about the benefits and drawbacks of different measurement methodologies. Results are also meaningful to the renewable natural gas sector.

Unlike oil and gas sources, landfill emissions are highly variable. Methodologies used to measure landfill emissions are, therefore, likewise varied and offer different capabilities. For this reason, we divided the participating methodologies into three groups. One group specializes in localization capabilities, meaning they can identify where emissions are coming from. The second group consisted of methodologies that specialized in quantification, meaning they can identify how much is being emitted. The third methodology group had both localization and quantification capabilities.

The study sought answer three main questions:

1. How do different methodologies perform in various meteorological conditions?
2. What are the quantification accuracies of different methodologies?
3. What are the localization accuracies of different methodologies?

2. Methods

2.1. Facility Selection

The Petrolia landfill located at 4052 Oil Heritage Road, Petrolia, Ontario (42°52'19"N 82°7'14"W; Figure 1), near Sarnia, is a closed landfill once owned and operated by the Town of Petrolia and by Waste Management (WM) Canada since 1990. The site closed its gates to new garbage in June 2016 after decades of operation (approval signed in 1982) but still operates as a transfer station for a nearby WM waste collection facility. The site is approximately 41.23 ha, and 26.02 ha was used for the disposal of municipal, industrial, and commercial solid wastes. It was approved for a total capacity of 4,749,000 m^3 and its reported fill rate was 365,000 t/y (65,000 t/y of Municipal waste from the Municipalities within the County of Lambton and 300,000 t/y of Institutional, Commercial, and Industrial waste from the Province of Ontario). Incoming waste was deposited into excavated cells below ground level in the local clayey soil. Figure 2 shows a drawing of the layout of the Petrolia landfill. The site has now been capped, top-soiled and seeded.

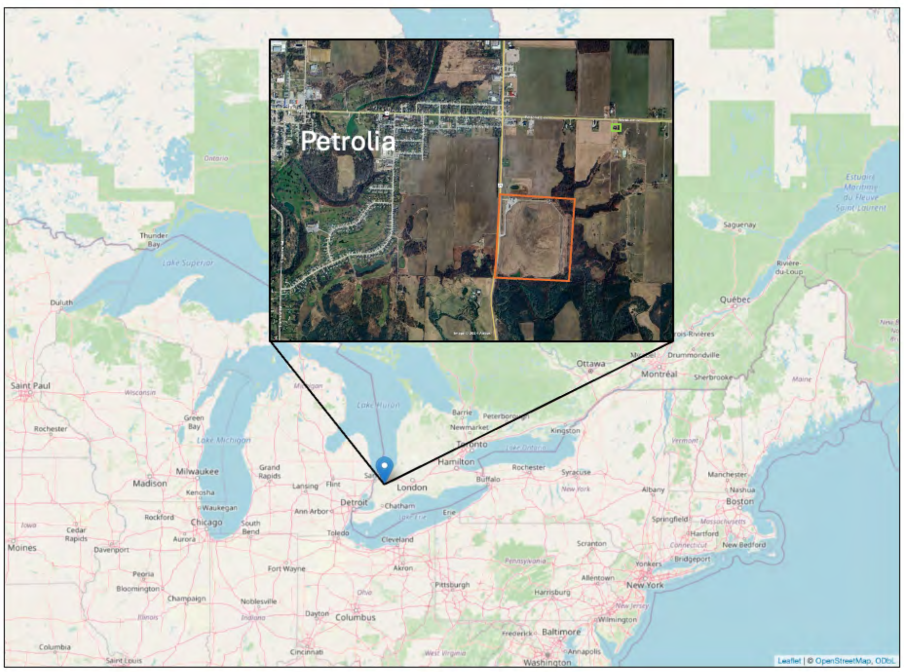

Figure 1: Petrolia landfill location. The blue marker positions the landfill in Ontario. In the inset, the landfill perimeter is outlined in orange. The location of a known cluster of oil & gas batteries is highlighted in green.

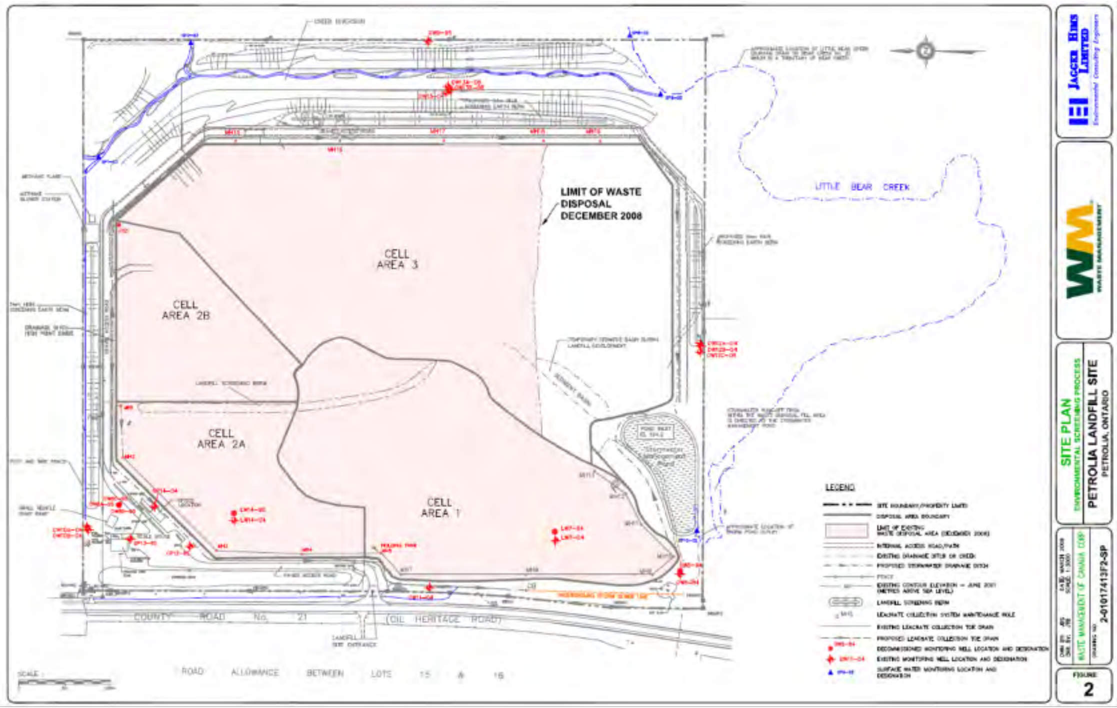

Figure 2: Petrolia Landfill Site Layout (Jagger Hims Ltd. 2009)

The landfill collects contaminated runoff from rain and moisture, known as leachate, and sends it to alternative municipal treatment facilities via sewer lines.

This site has a Landfill Gas (LFG) Collection and Flaring system. In 2010, the landfill commenced the operation of a landfill gas-to-energy project which converts methane gas into enough energy to power 2,500 homes (up to 3.2 megawatts of electricity, WM projected number, 2009). Bluewater Power Generation continues to generate electricity at the Petrolia landfill, even after the landfill stops accepting waste.

From the 2020-2021 Ministry of the Environment, Conservation and Parks (MECP) report, 2,710 tonnes CH_4/y of methane was recovered in 2021 and all of it was utilized (none was flared). This site is not reporting its emissions to the Canada Greenhouse Gas Reporting Program (GHGRP).

Environment and Climate Change Canada surveyed the site in September 2021 with a mobile laboratory and estimated emission of 19.7 kg/hr or 173 tonnes CH_4/y using a Gaussian dispersion model (Sebastien Ars (ECCC) presentation on June 7th, 2022, at CGU/CMOS joint-meeting). Using the same measurement technique and processing, FluxLab surveyed this site in July 2022 and obtained a similar emission rate: 20kg/h or 175 tonnes CH_4/y. The landfill methane emission rate was also estimated prior to the releases in November 2023 using a tracer-based method (labeled as technology E in this study) and determined to be 24.44 kg/hr or 214 tonnes CH_4/y.

The site's topography is moderately complex and typical of a landfill (Figure 3). The cells are like hills that slope away from the center. The highest point of the landfill is about 35m above the outer edges and the surrounding areas which are generally flat and used as croplands or covered with trees.

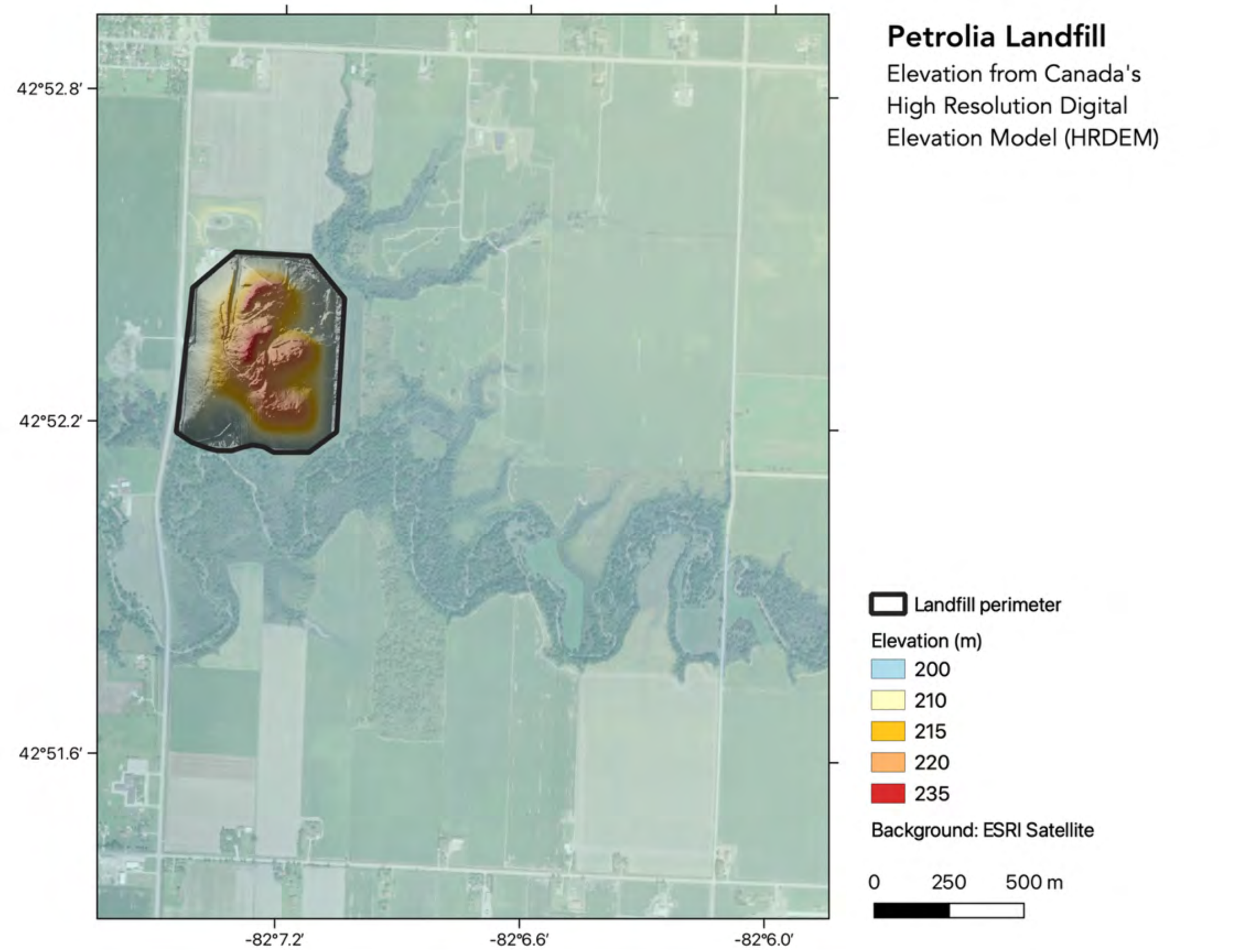

Figure 3: Petrolia landfill and surroundings elevations

A known source of methane emissions is located approximately 900m northeast of the landfill (see Figure 1). This source comprises several oil and gas tanks.

The climate of Petrolia, located in Lambton County, is tempered by the Great Lakes. Lakes contribute humidity to the atmosphere, increasing precipitation in fall and winter. Warm lake temperatures also lead to milder winters. In contrast, in summer, the cool waters of the lake temper the warm tropical air from the south. We used data from ERA5, ERA5-land (the latest climate reanalysis produced by ECMWF, the European Centre for Medium-Range Weather Forecasts) and Historical Climate data (ECCC). Our wind analysis (Figure 4) suggests that from September to November, the prevailing winds are West- Southwest and occur between 1:00 pm and 4:00 pm.

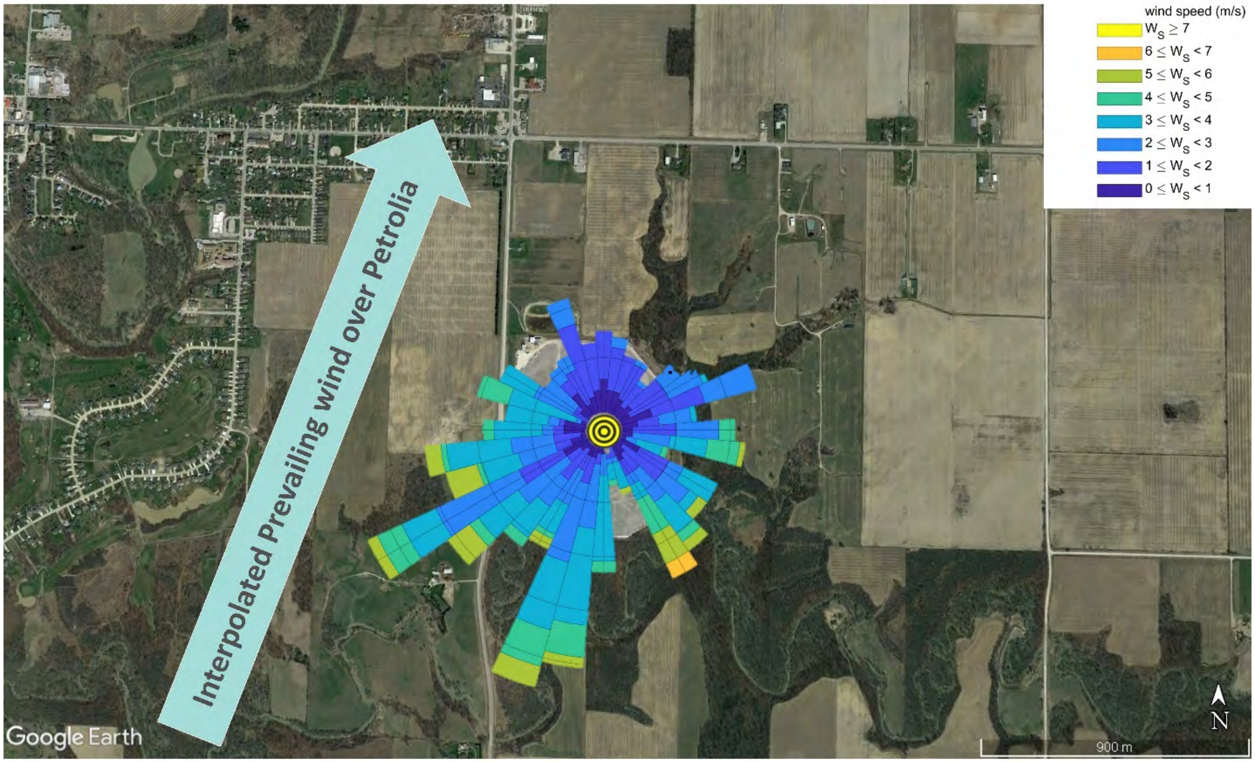

Figure 4: Wind rose patterns based on ERA5, ERA5-Land, and Sarnia historical climate data

Petrolia has several recreational facilities such as a recreation center, soccer fields, baseball diamonds, track and field, and a golf and curling club. However, all these facilities are located more than 800 meters away to the west of the Petrolia Landfill. Additionally, the site does not have public access, meaning that vendors and service providers were able to access/use the site without hindrance. Having a gas collection system, the relatively low background emission and the distance from public activities made the Petrolia site an ideal location for this study. Its central location in North America facilitated the participation of many vendors.

WM Canada generously offered the site to run this controlled release study and helped overcome various permitting and installation challenges. Two permits were required to execute the controlled release study at the site. The first was a technical permit to ensure gas transfer system safety and its compliance with guidelines set by the Canadian Standards Association (CSA). This permit was issued by the Technical Standards and Safety Authority (TSSA), which is Ontario's public safety regulator for various devices and equipment. This study was assessed by the Fuels division and a variance approval was secured, in relation to CSA code B149.1 which outlines the installation code for natural gas propane, that was used as a reference for the variance application. The TSSA approved the gas release system and inspected it on several occasions. The second permit covered the environmental and public impact of carrying out these activities at the landfill and releasing methane, and acetylene as a tracer gas (see section 2.3). This Environment Compliance Approval (ECA) was issued by the Ministry of Environment, Conservation and Parks (MECP). Since this study was using a temporary setup, a streamlined application stream was used. In addition to the application, immediate neighbors of the landfill property were contacted, and a fifteen-day consultation period was observed.

2.2. Methodology for Vendors

The experimental protocol for this study was based on METEC's survey protocol, which was built by the Methane Emissions Technology Evaluation Center (METEC) at Colorado State University. The base protocol was primarily written to validate oil and gas emission measurement technologies. The adaptation of the METEC method mostly relies on the fact that in oil and gas, the main components are point sources while landfill emissions come from multiple sources or even areas. The rate of emission from a landfill is also expected to be much higher than for oil and gas sites. Many publications used the application of the METEC method for controlled release studies (Day et al. 2024, Ilonze et al. 2024, Mbua et al. 2023, Bell et al. 2023) and among those Sonderfeld et al. 2017 were also focused on active face emission in landfills.

To reflect a landfill-based study, the main protocol changes were:

1. Classification of point and area source releases
2. Meteorology measurement details
3. Simplification of experiment cycles
4. Removal of oil and gas measurement-specific analysis (e.g. classification of detections on equipment unit)

Some vendors used the same technologies, and so where appropriate within this report we refer to testing methodologies, instead of using "technology" or "vendor". The primary experimental flow involved informing scheduled participants about the timings of the controlled releases using cellular application/ text message. Methodologies were used during their specified time. Short 5 to 15-minute breaks between releases were introduced to allow the test center to alter release configurations and vendors to prepare for the next set of releases.

The protocol emphasizes the need for transparent documentation without revealing proprietary information. The first step includes documenting the configuration of survey solutions, such as system components, software revisions, methodology, and personnel involved. In the next step, vendors conduct emission detection within defined facility boundaries, documenting controlled releases and survey data. The process involves establishing experimental design points, conducting surveys, and submitting data to the test center and the final step requires vendors to report experiment and detection data, including survey summaries and facility quantification data that includes essential details such as experiment and facility IDs, survey start/end times, and emission rates.

One of the key protocol features is having separate evaluations for emission quantification and localization. The primary metrics for each involve different sets of assessments. The emission rates and location for the controlled release points are the true values for the evaluation of the vendors' performance.

Classification of detection involves categorizing detections as true positive or false positive based on accuracy in identifying controlled releases. The metrics for detection are as follows:

1. Probability of Detection (PD): This metric evaluates the likelihood of correctly detecting emissions under different environmental conditions. It considers the number of true positive detections in relation to controlled releases.
2. False Positive Fraction: It assesses the ratio of false positive detections to total reported detections, providing insights into the rate of erroneous detections.
3. False Negative Fraction: This metric indicates the ratio of false negative detections to total controlled releases, highlighting instances where emissions were not detected.
4. Survey Time: This measures the duration of emission surveys, considering the time from the start to the end of the survey.

For localization techniques and models, primary metrics focus on the precision and accuracy of localization, particularly in pinpointing the exact emission points identified by the detections. The uncertainty in finding the sources was introduced mostly by the precision of the instruments or the error percentage of the method of analysis.

For further evaluation, secondary metrics were put in place: 1) Quantification Accuracy evaluates the accuracy of reported emission rates compared to metered rates, both in absolute and relative terms; 2) Quantification Precision assesses the precision of reported emission rates, providing insights into the consistency of measurements and, 3) Localization Accuracy and Precision delve into the accuracy and precision of reported coordinates or bounding boxes, offering detailed insights into the spatial accuracy of detections.

Survey efficiency, survey speeds, and annualized costs are evaluated based on actual survey reports submitted, offering practical insights into the efficiency of survey operations.

Overall, these metrics provide a comprehensive evaluation of detection systems' performance, considering factors such as accuracy, precision, efficiency, and environmental conditions.

Two weeks after the data collection phase, vendors were required to submit their estimates. Quantification methodology providers were instructed to provide their rate estimates in kg/hr and localization methodology providers were instructed to provide coordinates of leak estimates. After the first round of submissions, vendors were provided on-site weather data by the test center and allowed to resubmit estimates. Releases during the quantification phase of the study (1st week) ranged from 30 to 50 min releases in most cases with a greater range of release rates being used. During the localization phase of the study (2nd week) releases ranged from 60 to 90 min and the releases were usually below 100 kg/hr in most cases.

The rate estimates provided by vendors in kg/hr were compared against the sum of average flowmeter values that vendors participated in. The results are displayed using parity charts in Figures 3-5 with linear regression values listed in table 5. For the analysis of methodologies performing offsite measurements, vendor estimates were compared against the total site emission rate, which was calculated by adding the background emission rate and total gas release rate. The background emission rate was determined to be 24.44 kg/hr (Std. dev 8.88 kg/hr) using the Tracer correlation method. For analysis of methodologies performing onsite measurements (near the border of the release area), estimates were compared against only the total gas release rates.

Detection methodologies were assessed by classifying leak estimates provided by vendors into three categories, true positive, false positive and false negative. Leak coordinates provided by vendors were mapped using software (QGIS 3.34.2) along with release point/area coordinates. Active emitter locations were compared against vendor estimates to analyze localization performance.

A 15 m x 15 m bounding box was drawn with the release point at the center for active release points. Leak coordinates that fall within the bounding box are considered true positives. To account for GPS uncertainty, leak coordinates within 5 meters of the bounding box were also considered true positives. Leak coordinates outside of the bounding box are considered as false positives. Active leak points that were not detected were classified as false negatives. Figure 5 shows a detection map for one of the experiments where there were two active emission sources (shown with a bounding box) and the leak coordinates provided by the vendor (shown with a red dot). Release points are shown in a white circle with a black dot, inactive release points are shown without a bounding box. Using the categorized leak estimates, methodologies were assessed for the probability of detection, false positive and negative fractions. Equations 1-4 list the primary factors used to assess detection performance. Appendix C contains assessment summary maps for detection methodologies.

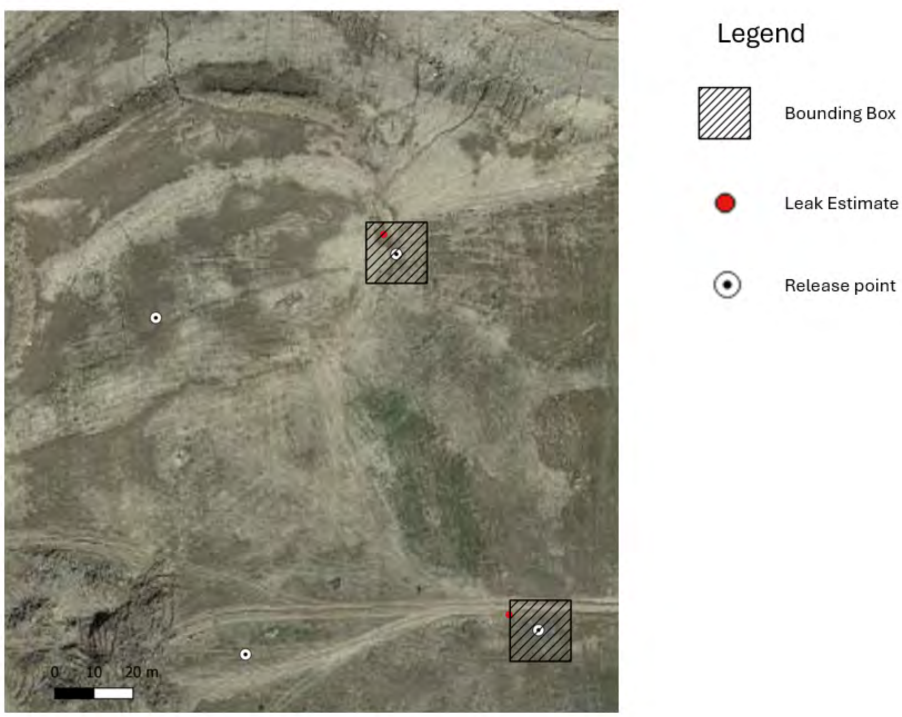

Figure 5: Sample detection map

$$PD = \frac{n_{TP}}{n_{TP} + n_{FN}} \quad ...(1)$$

Where PD is the probability of detection , n_{TP} is the number of true positives and n_{FN} is the number of false negatives.

$$FPF = \frac{N_{FP}}{N_{RD}} = \frac{N_{FP}}{N_{FP} + N_{TP}} \quad ...(2)$$

Where FPF is the false positive fraction, N_{FP} is the total number of false positives, N_{RD} is the total number of reported detections and N_{TP} is the total number of true positives.

$$FNF = \frac{N_{FN}}{N_{CR}} \quad ...(3)$$

Where FNF is the false negative fraction, N_{FN} is the total number of false negatives and N_{CR} is the total number of controlled releases.

$$LA = \frac{N_{TP}}{N_{RD}} = \frac{N_{TP}}{N_{TP} + N_{FP}} \quad ...(4)$$

Where LA is the localization accuracy, N_{TP} is the total number of true positives, N_{RD} is the total number of reported detections and N_{FP} is the total number of false positives.

$$\text{TNR} = \frac{N_{TN}}{N_{FP} + N_{TN}} \quad ...(5)$$

Where TNR is the true negative rate, N_{TN} is the total number of true negatives, N_{FP} is the total number of false positives.

3. Setup

The controlled release system for the study was a non-permanent pipeline network of mostly polyethylene pipes placed above ground on approximately a 10-acre (4 hectares) section of the landfill. Release points were set up in various elevations of the landfill. A CNG trailer was used as the source of methane for the study. With combined release rates ranging from 1 kg/hr - 300 kg/hr, methane was released from point and diffused sources. Between November 6th and 14th, 3025.81 kg of methane were released.

The field team initially mowed sections of the landfill where pipelines would be placed. Using a combination of manual and mechanical approaches, sections of the landfill were dug. G1 technicians were responsible for sourcing materials and making connections between polyethylene and metal pipes. Alicat MCR series flow controllers were placed in black plastic containers and connected to the pipeline network. Flow controllers were calibrated by the manufacturer prior to using it for this study. With a standard accuracy of ± 0.6% of reading or ± 0.1% of full scale, flow rate data was collected every 1 second. Wiring work involved connecting flow controllers to a console which allowed gas to be released remotely. A laptop was connected and used to monitor the flow controller performance. Appendix B lists the equipment used to set up the pipeline network.

The controlled release setup was designed with 8 points and 2 dispersed sources. Point source releases simulate emissions from membrane tears and wells, whereas dispersed source releases simulate emissions from landfill's active face. Elevated metal nozzles with a release rate of up to 19.7 kg/hr were used for point sources. For dispersed sources, a perforated tube spread over 10-15 cm of soil covering an area of about 170 m^2 was used. Dispersed source points were able to release methane up to118.3 kg/hr Flow controllers recorded flow in standard litres per minute (SLPM). Each release source was regulated and monitored in real time by using ATEX-certified Alicat flow controllers which were installed at the end of each downstream branch of the pipeline. During releases, participants and test center personnel did not have access to the detection facility for safety and permitting requirements.

Methane gas was sourced from Enbridge and supplied by Certarus. Natural gas with composition of 94.5% methane, 4.5% ethane, 0.09% propane, 0.4 % nitrogen, and 0.4 % carbon dioxide, was used for the study. A bulk CNG trailer was connected to a small pressure reduction trailer which decreased the pipeline inlet pressure to approximately 55 psig. The pressure reduction trailer also had a relief valve with a set pressure of 80 psig to protect downstream piping. Sections near polyethylene fittings were covered with soil and grass was cut to stubble length on areas where the pipeline lay on the ground.

Flowrate data from flow controllers was compared with the end-of-day gas use report from Certarus which is generated by the onboard pressure reduction system (PRS) trailer software. When comparing the amount of gas released between the flow controllers and PRS software there was a difference of 5 percent. Gas flow performance was monitored from the PRS trailer and the remote-control center. Mass flow values from flow controllers were used for analysis in subsequent sections. Flowmeters have an uncertainty of 0.6% and the error propagation is calculated using the root sum of squares. Average flowmeter readings for each experiment are listed in Appendix A.

Three weather stations were set up to collect meteorological data as shown in Figure 6. Onsite weather data such as windspeed, barometric pressure, wind direction, etc. were collected and later sent to vendors. Campbell Scientific weather sensors (MetSens200 and MetSens500) were used for the study (see Appendix B for specifications). Weather sensors were factory calibrated prior to the study and weather stations were checked daily by FluxLab team members to ensure equipment was in proper operating condition.

The test center designed release configurations based on participating methodologies. Each experiment was matched with a corresponding release with distinct flow rates and active emission patterns. When possible, the test center ran duplicate scenarios to assess consistency in methodology performance. Measurements taken in between releases were used to determine the background emission rate which was utilized in the assessment of methodologies taking fence line measurements.

Figure 6: Map of Controlled Release Setup

4. Participating Technologies

Table 1 lists sixteen methodologies, which were a combination of vendors and technologies, participated in the study. Appendix D summarizes methodology properties such as cost, minimum detection limit and limitations. Due to confidentiality agreements, results are arbitrarily identified by an anonymized identifier.

Table 1: Summary of methodologies that participated in the controlled release study

Technology Identifier	Technology Type	Platform Type	Sensor	Method	R&D ?
A	Quantification/ Detection	Truck	LGR	MGPA	No
B	Quantification	Truck	LICOR	MGPA	No
C	Quantification/ Detection	Drone	TDLAS	UPSEA	No
D	Quantification	Drone	Mid-IR LDS	UPSEA	No
E	Quantification	Truck	Picarro	MTCEA	No
F	Quantification	Aircraft	Picarro	APSEA	No
G	Quantification/ Detection	Helicopter	LiDAR	LiDAR	No
H	Quantification/ Detection	Satellite	Spectrometer	SISEA	No
I	Quantification	Fixed	EM27	RPSEA	Yes
J	Quantification	Fixed	Metal Oxide	RPSEA	Yes
K	Quantification	Fixed	Metal Oxide	RPSEA	Yes
L	Detection	Drone	TDLAS/ Laser Falcon	UCSEA	No
M	Detection	Drone	TDLAS/ Laser Falcon	UCSEA	No
N	Quantification/ Detection	Truck	LGR	LEA	Yes

Participants were asked to submit information about their respective solutions using a provided technology questionnaire. Most technologies in this study offer methane quantification and a few offers detection or the ability to do both quantification and detection. Quantification technology providers were instructed to submit their estimated emission rate in kg/hr, upper limit of emission rate in kg/hr, lower limit of emission rate in kg/hr and measurement time for each experiment that they participated in. Detection technology providers were instructed to submit estimated leak coordinates (longitude and latitude) and measurement time. Technologies were also allowed to participate in the research and development (R&D) stream which allowed more flexibility in reporting timelines. Technologies in the R&D stream are either up and coming or looking to enter the methane monitoring market.

The following technology overview is based on the questionnaire vendors submitted prior to participating in the controlled release study, and materials in the public domain. In this description, we include the time it takes for an average measurement, the number of replicates included, and high-level cost estimates based on vendor day rates and daily productivity in this study and/or for oil and gas methane measurement service companies in Canada's competitive and mature regulated marketplace.

4.1. Mobile Tracer Correlation Emission Assessment (MTCEA)

The Tracer correlation method is considered the gold standard for landfill quantification measurement and has been used for over two decades (e.g. Mosher et al., 1999) and its errors have been extensively probed in previous works like Fredenslund et al. (2019a). The method involves a controlled release of a non-reactive gas, such as sulfur hexafluoride or acetylene, that is easy to detect and distinguish from other gases emitted by the landfill. The data collected on tracer gas concentrations are analyzed statistically to establish correlations between the tracer gas and the target gases (e.g., methane). By understanding how the tracer gas disperses throughout and downwind of the landfill, emissions of the target gases can be estimated. No wind measurements are required. The vendor performing tracer release work at Petrolia used a Picarro dual gas analyzer, working from the public road system. This method generally takes two days at an estimated $5,000 USD/day commercial rate. One day would be used for reconnaissance and setup, and another for measurement and tear-down, and in that timeframe the vendor could deliver several replicate measurements. With an annual budget of $20,000 USD for site measurements, MTCEA measurement visits could occur every 6 months.

4.2. Gas Mapping LiDAR (LiDAR)

Methane detection by LiDAR (Light detection and ranging) is a mature technology in oil and gas and is in widespread commercial application. Numerous point-source controlled release tests have proven its ability to detect point source leaks to 1-3 kg/hr with 90% probability (Bell et al. 2002, Singh et al. 2021, Conrad et al. 2023, Rutherford et al. 2023). While the method is applicable for landfill measurement, it has seen relatively limited use. Gas mapping LiDAR uses a pulsed beam of radiation that reflects off the ground surface, and back to the aircraft where a specialized receiver detects and analyzes the spectral signature of light absorbed or scattered by methane in the atmosphere. The result is a column measurement that can be used for detection or quantification.

Unlike other column-measurement instruments, LiDAR will normally yield information on where the gases sit within the measurement column, which could be used to augment sensitivity for ground-emitted gases. For a surface leak detection scan, the helicopter flies a serpentine pattern while holding a fixed altitude. Surface leak scans can be used for quantification, by adding up quantifications for individual plumes. For a quantification scan, which is a more developmental technique, the helicopter flies transects downwind and perpendicular to the emission source of interest and solves for emission rate using mass balance. Area-based emissions are common in landfills and may prove more difficult for LiDAR to detect and quantify. The measurement generally takes one day at an estimated $14,000 USD/day commercial rate. During a flight of several hours, the vendor would deliver many replicate quantification AND leak detection scan measurements. Aircraft vendors may charge for bad weather days when the aircraft is grounded. With an annual budget of $20,000 USD for site measurements, one LiDAR measurement visit could occur.

4.3. UAV Column Sensor Emission Assessment (UCSEA)

This technology consists of a UAV-mounted Tunable Diode Laser that emits a narrow beam of light at a wavelength appropriate to detect methane by using its spectral signature. The laser is carried on the underside of the UAV and is directed towards the ground. The laser beam reflects off the ground and back to the UAV. During its travel, the beam interacts with the gas molecules and some of the light is absorbed at specific wavelengths corresponding to the molecular absorption lines of methane. The technology is often called TDLAS, Active TDLAS, or a "column-type" sensor. Measurements are retrieved in ppm*m. Relative to LiDAR, the disadvantage of a column-type sensor is that methane in each unit distance of laser beam travel is incorporated into the ppm*m measurement. Most of the laser beam's transit is of course through atmospheric air containing relatively little methane. Therefore, a strong methane enhancement at the surface is diluted by the air above and can be difficult to detect, unless the sensor has very high precision, or flight altitude is reduced. Two vendors in our study were using UCSEA technology both with flight altitudes of 20 m and 30 m spacing for serpentine paths for leak detection. UCSEA is a new technology and has not been validated in controlled release studies, or by scientists in the peer review literature, although it is in use already to replace surface emission assessments at landfills that are normally done by walking the site. The measurement would generally take 2 days at an estimated $5,000-8,000 USD/day commercial rate. In that timeframe, the vendor would deliver one leak detection scan. With an annual budget of $20,000 USD for site measurements, an UCSEA measurement visit could occur every 6-10 months.

4.4. UAV Point Sensor Emission Assessment (UPSEA)

This technology uses a drone with a mounted TDLAS, MOS, or other point measurement sensor for landfill gas quantification. Two vendors participating in the study used UPSEA. In the method, the UAV flies repeated horizontal transects perpendicular to the wind direction and repeats the measurements at different altitudes to paint in a screen or curtain. Sometimes called a "flux plane" measurement, the method sees wind speed, temperature and pressure values interpolated across the plane, after which the interpolated values are used in a mass balance equation to solve for emission rate. Both vendors using this technique carried out their work using preprogrammed flight patterns. UPSEA is a mature technology and has been validated in point-source controlled release studies at oil and gas sites (Singh et al. 2021, Ravikumar et al. 2019). In the point-source controlled release study by Ravikumar et al. 2019, the authors found reasonable correspondence between measured and known emission rates for UPSEA with R^2 of 0.42, and an upward (overestimation) bias of 27%. The measurement would generally take 2 days at an estimated $5,000-8,000 USD/day commercial rate. In that timeframe, the vendor would deliver one aggregate quantification measurement assembled from several screen measurements in different parts of the landfill, each of which might take 1-2 hours for setup and flight. With an annual budget of $20,000 USD for site measurements, an UPSEA measurement visit could occur every 6-10 months.

4.5. Mobile Gaussian Plume Assessment (MGPA)

For this quantification technology, a high-performance methane analyzer deployed in a vehicle is carried along transects driven along the downwind fenceline, or on transects even farther downwind using the road network. Measurements can be made as far away as several kilometers. Wind speed and direction are measured alongside methane concentrations, and all are geolocated. Rate quantification involves the use of a Gaussian Dispersion model inversion, with some key differences. Since individual plumes emanating from a landfill have typically not coalesced by the time they reach the fenceline, the transects must be broken into small segments each of which incorporates a distance and peak height. A human using an air quality modeling system like Polyphemus (Ars, S. et al., 2020) can fit these area-based segments. Alternatively, a computational inversion can be used to find the best fit between all measured segments, and the combination of one or more simulated site plumes of x emission rate. Source height is normally incorporated into either type of analysis from a Digital Elevation Model, and normally the method would provide some estimate of probable source location. Two vendors used the MAGPA approach in this study. Whether using area-based MGPA (near or far field applicability) or peak height-based methods (far field applicability for plumes that have coalesced), the MGPA is an old and accepted method. A comprehensive study by Fredenslund et al. (2019b) found a good correlation between MGPA and the gold standard MTCEA (R^2 = 0.765), although MGPA showed a predictable low-bias where emission rate values were normally just 72% of those measured using MTCEA. The measurement would generally take one day at an estimated $5,000 USD/day commercial rate. In that timeframe, the vendor would deliver two quantification estimates, each comprising numerous replicate transects. In this study, it should be noted that because of the very fast-changing experiments, the average number of replicate transects being used for estimates was only ~2, whereas ~12 would be more normal work practice. With an annual budget of $20,000 USD for site measurements, a MGPA measurement visit could occur every 3 months.

4.6. Airborne Point Sensor Emission Assessment (APSEA)

For this mature quantification technology, a high-performance gas analyzer is mounted in a small aircraft. The aircraft flies stacked orbits of some radius slightly larger than the site. The first orbit is at about 150 m above ground level, or the lowest permissible flight altitude in Canada, and orbits are repeated at progressively higher altitudes until the aircraft reaches the top of the surface-mixed layer. Wind values may be measured in the air, or wind estimates are procured from databases. The wind and methane concentration are interpolated onto a flux screen around the site, and the flux rate is solved using a mass balance equation. Abbadi et al. 2023 found that this technology was highly correlated to known release rates (R^2 of 0.93), but consistently under-estimated emission rates with a low bias where predicted emission rates were only 52% of actual values. The low bias could result from the downward extrapolation approach used by this vendor (Erland et al., 2022), or potentially from measurements during highly stable atmospheric conditions where the center of mass for landfill plumes sites below the initiating flight altitude (~150m). The measurement would generally take one day at an estimated $14,000 USD/day commercial rate. In that timeframe, the vendor would deliver numerous quantification measurement estimates during a flight time of several hours. Aircraft vendors may charge for bad weather days when the aircraft is grounded. With an annual budget of $20,000 USD for site measurements, an APSEA measurement visit could occur once annually.

4.7. Remote Point Sensor Emission Assessment (RPSEA)

These quantification technologies consist of freestanding stations around the landfill perimeter in which various environmental sensors are used to measure wind speed, wind direction, temperature, pressure, and humidity. Methane detection is done using a metal oxide (MOS) sensor. Another type uses an open path Fourier Transform infrared (FT-IR) spectrometer. Algorithms are used to continually assess facility emissions using an inverse source dispersion model, or similar. RPSEA technologies have been scrutinized lately in oil and gas controlled-release studies (Bell et al. 2023, Day et al. 2024), with varying results. It is difficult to understand the transferability of these results to the landfill context, where sites are large, topographically variable, and where emissions are larger. While there are many RPSEA vendors on the oil and gas market, there are none yet purporting to measure landfill emissions with accuracy, and no validation studies for RPSEA in landfill applications. Several vendors in our study used RPSEA method. These measurements are continuous (~hourly) and unfortunately costs are poorly constrained since some business models will differ widely; some focus entirely on service whereas others combine hardware and service costs. We estimate annual costs of $7,000-30,000 USD depending on the vendor and size of the landfill. With an annual budget of $20,000 USD for site measurements, a site could possibly be measured several thousand times, or RPSEA may be too expensive to do on an annual basis.

4.8. Satellite Imaging Sensor Emission Assessment (SISEA)

A satellite-mounted sensor takes a series of images and collects methane column measurements for individual pixels. The images are merged, and an interference pattern is created which allows the quantification and detection of methane emissions at facility scale. Generally, SISEA will be expected to most easily detect large point source emissions within a facility, and area-based sources could be missed. Several studies have validated SISEA for point source emissions quantification, with good results at high emission rates. Sherwin et al. (2023) found that the most sensitive present-day satellite can detect a point source emission of as little as 170 kg/hr, although expected detection success would vary for area sources. Like UCSEA, the column enhancements of near-ground methane enhancements will be diluted by the overlying column of atmospheric methane. To detect methane from a satellite, very large ground-level concentrations are needed, and landfill-type area methane sources may be difficult to detect at this magnitude. These measurements could theoretically be delivered daily under clear sky conditions, but generally, a package of images and quantification estimates at some delivery frequency would be purchased for $3,000-6,500 USD each, depending on volume. With an annual budget of $20,000 USD for site measurements, a SISEA measurement could probably be made every 2-4 months.

4.9. Lagrangian Emission Assessment (LEA)

This method combines the type of truck-based sampling used in MGPA but pairs the measurements with a different post-processing algorithm. Lagrangian models are commonly used to predict source location probabilities and can be used to calculate emission rates for either point or area-based sources. Normally, Lagrangian models are applied to tower-based measurements, but can be adapted to a mobile setting, as if the tower were moving through the domain. For landfill measurements, Lagrangian approaches can be used to infer source locations where a ground team would detect emissions when on site, and the approach can also provide whole-site quantification estimates. Although most Lagrangian models are computationally intensive, some models that use pre-calculated footprint tables are appreciably more efficient and could complete estimates faster than Gaussian inversions. Costs and timelines would be as for MGPA. For an annual budget of $20,000 USD, a measurement visit could occur every 3 months.

Costs for some of the vendors and measurement methods could drop with different business models, for example, drones stationed onsite, or sensors mounted on landfill trucks. We expect these business models to emerge over the coming years.

5. Limitations of the Study

Due to permitting requirements and other factors, experimental limitations affected participation in the study and outcomes.

- Methane releases ranged from 10 to 50 minutes in most cases. This makes replication difficult for certain methodologies that might generally survey a site for 1-3 hours (e.g. MGPA). Due to favorable weather conditions, plume development was good, and vendors were able to submit estimates with high confidence in most cases.
- Depending on the methodology used, some vendors had an advantage due to the release points being visible.
- The safety permit obtained from TSSA did not allow personnel to access the release area when gas was being released. This affected methodologies that validate potential leak sources with a ground scan which in turn resulted in a high number of false positives being reported for the detection method.
- Satellite SISEA methodology could not be validated as the distributed and area-based releases were not large enough to detect despite several attempts with high rates (up near 300 kg/hr) under clear conditions.
- Weather conditions were mostly good during the 9-day period however a couple of days had rainfall and high winds which prevented vendors from taking good measurements.
- Intermittent leaks from the south side of the landfill were identified when vendor data were being analyzed. This increased the number of false positive counts in certain cases. To account for this issue, leak estimates made by methodologies in that area were not considered as part of the performance assessment. This improved methodologies' localization accuracies in certain cases.

6. Results and Discussion

The releases were conducted in early November, with an initial focus on quantification methodologies, followed by detection methodologies. While weather conditions for the study were generally good with consistent winds, various aerial vendors were unable to deploy on certain days due to strong winds or other conditions. Schedules were modified as needed, and Table 2 shows methodology, participation by day.

Table 2:Participating methodology schedule

Date of Release	Type of emission measurement	Participating Vendors
Nov 6, 2023	Quantification	A, B
Nov 7, 2023	Quantification	A, B, C, D, E, F, H
Nov 8, 2023	Quantification	A, B, C, D, E
Nov 9, 2023	Quantification	A, B, C, D, E, F, G, H
Nov 10, 2023	Quantification	A, B, E, F, G, H
Nov 11, 2023	Detection	A, G, L
Nov 12, 2023	Detection	A, C, H, L
Nov 13, 2023	Detection	L, M
Nov 14, 2023	Detection	H, M

Once measurements were complete, vendors were provided with a specified timeline to submit measurement estimates. Most measurement reports were received within the expected timeframes. Table 3 shows report submission dates for each participating vendor. Vendor A primarily participated during the quantification phase of the study; however, they were also taking measurements during the detection phase of the study mainly for R&D purposes.

Vendors were instructed to provide their initial estimates by December 12, 2023 and a resubmission of estimates by January 12, 2024. After vendors provided their initial estimates, onsite weather station data were shared and vendors had the opportunity to resubmit their estimates if they chose to do so.

Table 3: Vendor estimates submission schedule

Vendor	Methodology	Date of 1st submission	Date of 2nd submission
A	MGPA	Jan 18, 2024	Mar 13, 2024
B	MGPA	Dec 12, 2023	Mar 15, 2024
C	UPSEA	Dec 12, 2023	-
D	UPSEA	Dec 14, 2023	-
E	MTCEA	Dec 11, 2023	-
F	APSEA	Apr 04, 2024	-
G	LiDAR	Dec 11, 2023	Jan 10, 2024
H	SISEA	Nov 29, 2023	-
I	RPSEA	Dec 12, 2023	-
J	RPSEA	Dec 12, 2023	-
K	RPSEA	Dec 12, 2023	-
L	UCSEA	Nov 22, 2023	-
M	UCSEA	Dec 08, 2023	-
N	LEA	Apr 01, 2023	-

6.1. Release Conditions

Three Atmospheric Research Stations were set up based on their location relative to the emission sources to collect meteorological data as shown in Figure 7. The stations recorded weather data including Wind Speed (m/s), Wind Direction (degrees), Barometric Pressure (mbar), Relative Humidity (%RH), Air Temperature (Celsius), and Dew Point (Celsius), which was then sent to vendors. The FluxLab team checked the weather stations daily to ensure the equipment was working correctly.

This section summarizes atmospheric measurements and controlled release conditions at the Eastern Landfill Atmospheric Research Station (ELARS). The total height above ground for weather data measurements was calculated by summing elevation relative to sea level and the height of the tripod which equaled to 1.82 meters for ELARS. ELARS was on the eastern side of the landfill to use the easterly winds for downwind testing and was the closest station to the release buffer zone. The measurement period considered here runs from November 5, 2023, at 15:20 to November 14, 2023, at 17:29, with recordings every 2 seconds. Initial data preprocessing included formatting and synchronizing timestamps, checking time continuity, correcting wind direction, interpolating missing measurements, filtering wind data, and exporting and cleaning up the data.

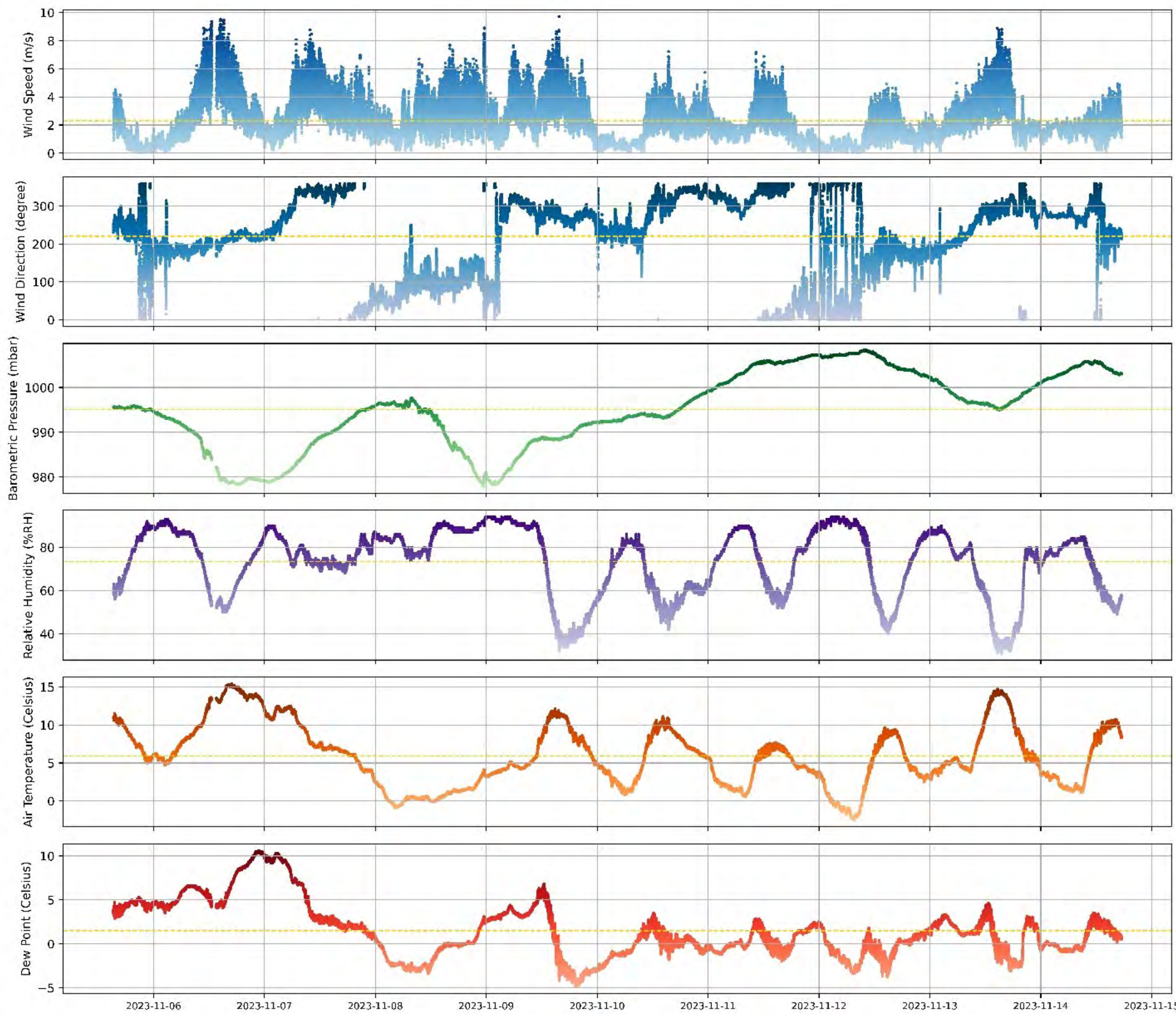

Figure 7:Time series data from the Eastern Landfill Atmospheric Research Station (ELARS) during the experimental period. From top to bottom: wind speed (m/s), wind direction (degrees), barometric pressure (mbar), relative humidity (%), air temperature (°C), and dew point (°C). The yellow line represents the mean of each series.

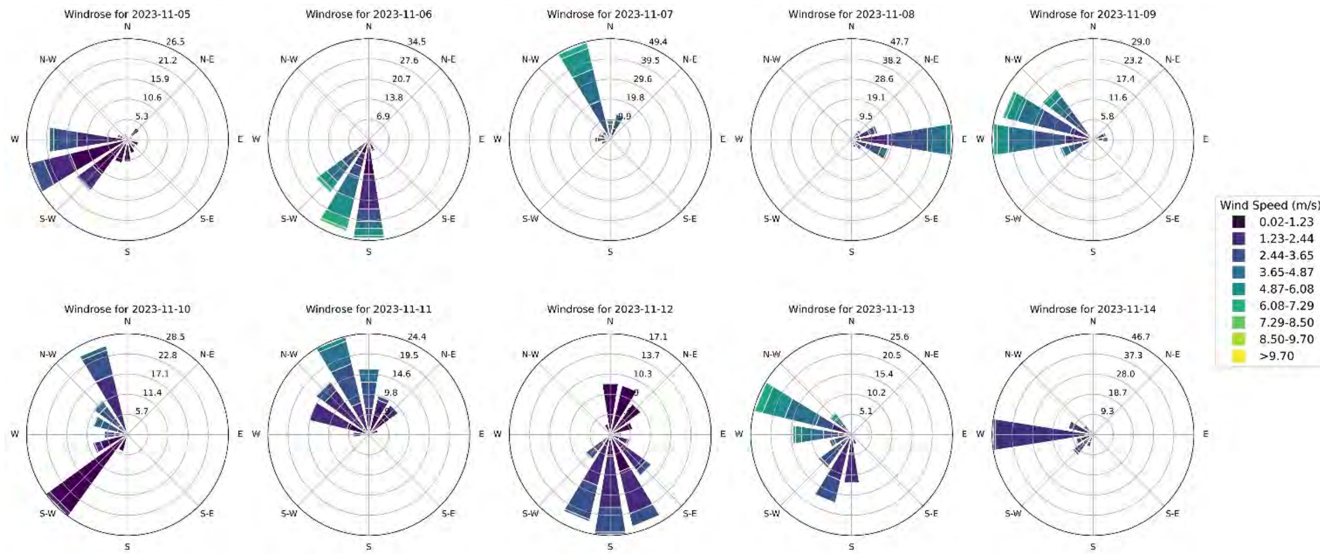

Figure 8:Daily wind roses from the Eastern Landfill Atmospheric Research Station (ELARS) during the experimental period.

The first days of the quantification experiments were mostly cloudy, but the detection test days had clearer, slightly windier conditions. Table 4 provides daily meteorological data, highlighting the most significant Pasquill Stability Classes for each day, with most days categorized as neutral (Class D) and some as slightly unstable (Class C) during the detection experiments. The cloudiness percentage time series (Figure 9) indicates that most days were partly cloudy and clear during the second round of detection experiments, increasing the likelihood of satellite measurement.

Table 4:Daily stability classes and sky conditions based on cloud cover observed during the experimental period.

Day	Statistically Significant Stability Class	Stability Level	Description
2023-11-06	D	Neutral	Calm and Partly Cloudy
2023-11-07	D	Neutral	Mostly Cloudy
2023-11-08	D	Neutral	Cloudy
2023-11-09	D	Neutral	Windy and Mostly Cloudy
2023-11-10	D	Neutral	Calm and Partly Cloudy
2023-11-11	C	Slightly Unstable	Windy and Partly Cloudy
2023-11-12	C	Slightly Unstable	Windy and Partly Cloudy
2023-11-13	C	Slightly Unstable	Windy and Clear
2023-11-14	D	Neutral	Calm and Partly Cloudy

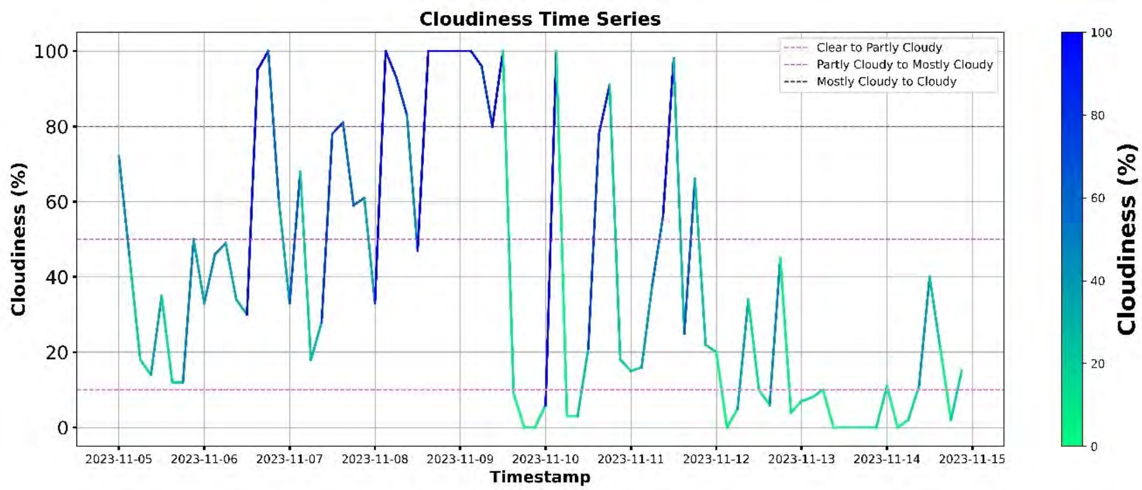

Figure 9: Daily cloudiness percentage of the study area during the experimental period, with thresholds indicating sky conditions.

6.2. Quantification Performance Assessments

6.2.1. Mobile and Drone Methodologies

Figure 10 shows performance results for MGPA, MTCEA, and UPSEA methodologies (vendors A, B, C, D & E). Vendors A and B use the same MGPA method and display a similar trend where both underestimate relative to the known release rates. As listed in Table 5, both vendors were measuring about 60% of known release rates (see Table 5), which is like a previous study in which MGPA measurements measured about 70% of known rates (Fredenslund et al., 2019). The gold-standard MTCEA measurements were very comparable to known release rates, with only minor downward bias. Vendor C uses the UAV UPSEA flux plane method, and the measurements were closer to the parity line than either of the three truck-based measurement vendors but with more spread in the measurements.

Compared to the UAV measurements, the mobile truck-based offsite methodologies (MTCEA and MGPA) offered flexibility and extended duty cycle across weather conditions and were able to report measurements on each day of the experiment, including when UAV and aerial and satellite vendors were unable to measure. Standard operating practices for these methodologies typically involve measuring emissions for several hours at a specific site. However, in this study release rates were changing on a 10 to 50-minute cycle, with very little time in between releases. Reports from vendors indicated that these conditions limited the performance of truck-based methodologies and that greater variance in measurements would be expected under the fast-changing conditions. Reported variance differed between vendors. Variance estimates from vendors A and B (MGPA) seemed unrealistically low, and few overlapped the line of best fit. Variance estimates from Vendor E, the MTCEA, were realistic and almost all overlapped the line of best fit. Vendor C using the UPSEA method also reported reasonable estimates of variance.

The performance of two UAV-based measuring systems, both using the UPSEA method, is shown in Figure 10, with varying results. Vendor C produced excellent estimates while deploying this method whereas estimates from vendor D were much less predictable. Although the regression line of best fit was statistically significant (p<0.05), we observed a substantial departure from the parity line. The levels of uncertainty for this methodology are being developed with data from this study, however, the vendor reported that an uncertainty of 5% was expected, which did not fully capture the observed uncertainty of their method in the field setting. The reason for the difference between vendors using the same method is not clear. Measurement conditions may have played a role given that the vendors performed their work at different times, but in both cases conditions were comparable. Both vendors carried high-resolution laser-based point sensors. We anticipate that differences arose primarily due to post-processing method differences and/or expertise. The UPSEA estimates from both vendors were less biased here than in previous controlled release studies where a 37% over-estimate bias was reported (Ravikumar et al., 2019) although, that study tested an earlier variant of the same methodology. Measurement estimates have improved in recent years, or else landfill controlled-release measurements are better suited to this methodology than smaller oil and gas point source releases.

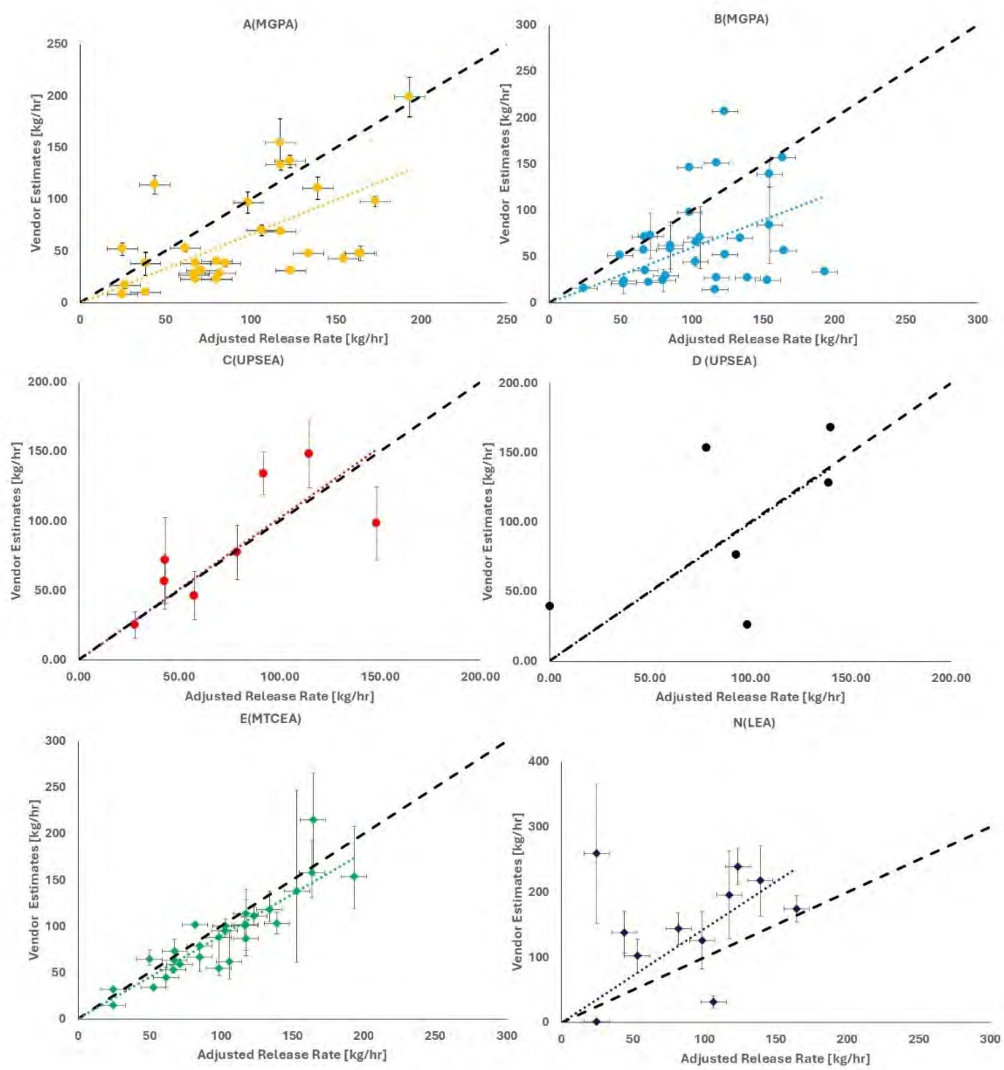

Figure 10: Parity charts of controlled release tests for truck and drone-based measurements. The dashed reference line shows the 1:1 parity relationship.

6.2.2. Aerial and Satellite Methodologies

Figure 11 shows parity charts for aerial and satellite-based systems. UPSEA methods had fewer submissions due to a combination of weather factors preventing measurements and some measurements not meeting internal quality standards. Vendor D for example had eight successful attempts to scan and submitted six estimates. Weather factors such as wind speed, time of day, and cloud coverage become strong contributing factors for technologies in this group. No detections were reported from the satellite-based vendor during the study. Contributing factors include release rates not meeting the minimum detection threshold, greater cloud coverage in November, and lower elevation of the sun which resulted in reduced signals for northern sites. Discussions with the vendor confirmed that the distributed nature of emissions, where emission rates were high >300 kg/hr but distributed from 10 release points, including 2 area-based release points) over 10 hectares, would have been challenging for the SISEA method to detect. For this release configuration, the Minimum Detection Limit (MDL) cannot be predicted but is at least 300 kg/hr. With the possibility of larger future releases at the same site, we can hopefully define MDLs and other performance metrics.

Vendor F, using the APSEA method, generally underestimated compared to the actual release rates. The measurements were not classified by the vendor as high quality since their internal meteorological conditions for measurements were not met. For this approach, meteorological conditions must allow for an emission plume to rise and disperse. Conditions under Pasquill stability class B are preferred, which consist of windspeed ranging from 2-6 m/s, good solar insolation, and limited cloud cover. During scheduled measurement times for vendor F, windspeeds of 7-11 m/s and near overcast conditions were observed. This resulted in the plume flowing beneath the minimum flying altitude and not rising quickly enough for measurement purposes. Despite the poor conditions, the measurements were linearly related to the actual release rates with a strong R^2 of 0.89. The slope of the line of best fit was 0.64 (Table 5), meaning that the vendor was typically reporting only 64% of the actual emission rate. This underestimation bias is comparable to recent estimates for point source releases reported by Abbadi et al. 2023, where the measurements were strongly correlated with actual rates with an R^2 of 0.92 (see Table 5), but where they were only reporting 52% of actual emission rates. Like MPGA, this method may be prone to under-estimation and may need bias correction. The variance estimates provided by the vendor were moderately successful in overlapping the line of best fit.

Vendor G used two forms of LiDAR quantification including aggregate emissions during detection scans (G-1 in Figure 11) and aerial mass balance screens (G-2 in Figure 11) to quantify methane releases. Both techniques were successful but tended to overestimate. As shown in Table 5, the mass balance estimates were overestimated to a greater degree. After considering onsite meteorological data, the estimates were improved and closer to actual emissions values in both cases with an overestimation of 43% and 17% in the case of detection scans and screens, respectively. LiDAR quantification did not quite match the performance accuracy that can be achieved in oil and gas settings as described by Conrad et al. (2023), but the same study also points to differing performance with dark skies and shadows that can create overestimated biases – and this was potentially a factor in our study where cloud-free days were rare and clouds were rolling quickly across the site in steady winds.

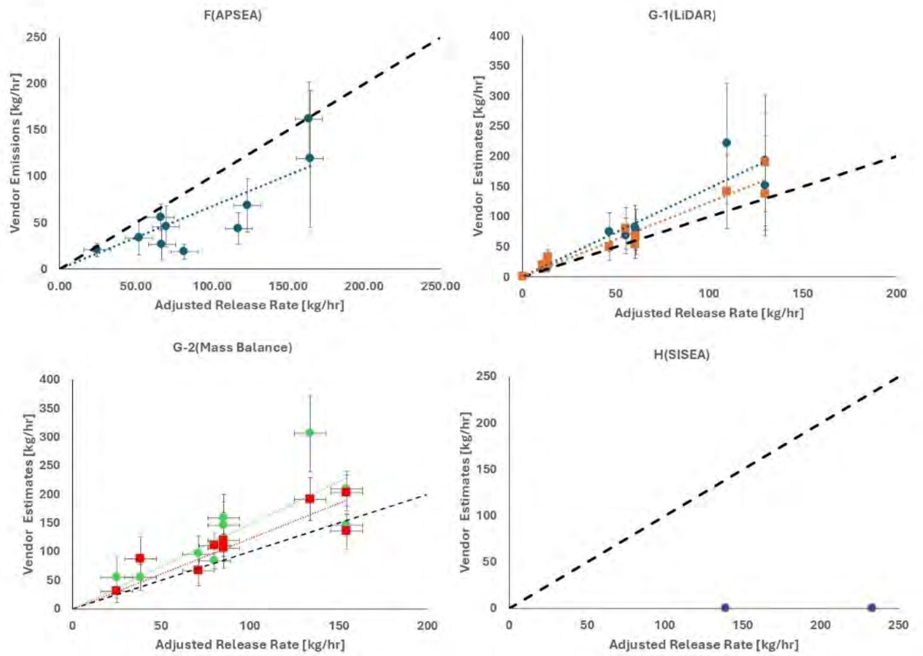

Figure 11: Parity charts of controlled release tests for aerial measurements. Plots G-1 (LiDAR) and G-2 (aerial mass balance) show two separate measurements by the vendor. Blue and green data points represent their 1st submission, and orange and red represent their revised submission after taking onsite weather data into account.

Figure 12 shows parity charts for continuous emission measurement systems (CEM) in the research and development group. Results from this study aim to further develop CEM sensors and algorithms specifically for landfill emission measurements. Estimates from vendor J provided the closest measurements to actual emission values compared to the other continuous sensors. Continuous sensors offer a low-maintenance method of measuring emissions compared to other vendors. Due to the low number of sensors available for the study, only a limited set of wind conditions were covered.

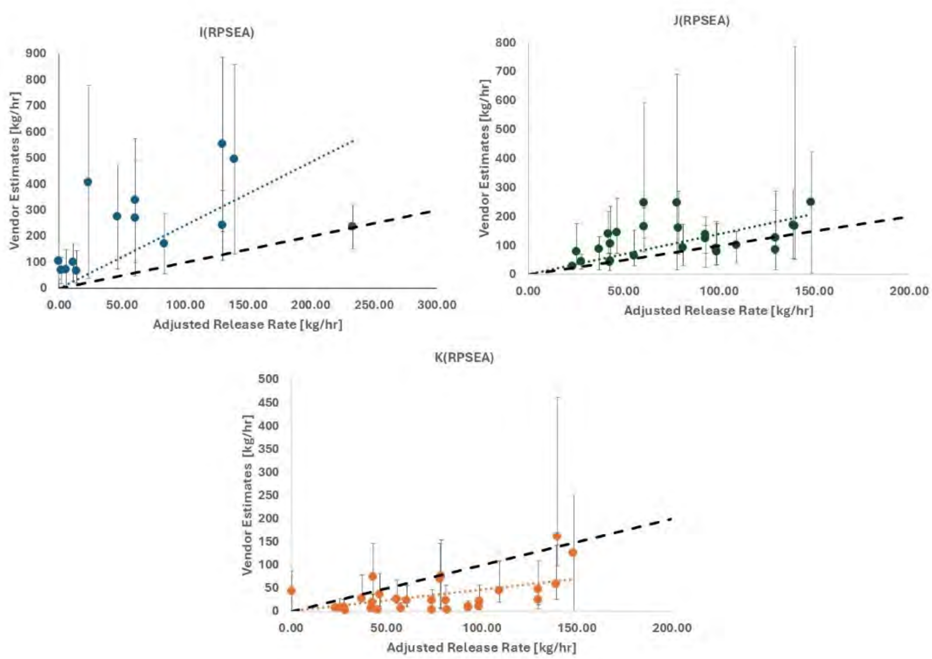

Figure 12:Parity charts of controlled release tests for CEM.

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6.2.3. Statistical Properties for Mobile, UAV, Aerial and Satellite Methodologies

Table 5 lists linear regression values and average percent recovered for quantification methodologies. The bias factor along with the value of the slope provides information whether a methodology is under or over estimating emission rates. Value of slope less than one means a technology is underestimating whereas value of slope greater than one means that a technology is overestimating. Standard deviation percentage of residuals indicates the spread of emission rate values from the trendline. Deviation from true value percentage range provides the range of deviation for quantification estimates since standard deviation represents two-thirds of a normal distribution therefore outliers lie outside of the standard deviation range. A lower standard deviation percentage is desirable as it represents a lower uncertainty in emission estimates. and methodologies with higher number of estimates submitted indicates greater statistical power. When calculating residual and deviation from true values , scenarios with 0 kg/hr were omitted since values relative to the true value is undefined when the true release value is approximately 0 kg/hr.

Table 5: Linear regression values from Figures 10,11 and 12. *Calculated using values from the second submission.

Technology Identifier	Slope (1st sub)	R^2 (1st sub)	Slope (2nd sub)	R^2 (2nd sub)	Bias Factor 1/slope	StDev residuals %	Dev. from true value %	Number of estimates (n)
A	0.6644	0.7701	-	-	1.5051	47.61	1-160	30
B	0.5670	0.6739	-	-	1.7637	39.63	1-88	31
C	1.0211	0.9021	-	-	0.9793	34.71	2-66	8
D	0.9915	0.8211	-	-	1.0086	61.98	8-96	6
E	0.8972	0.9623	-	-	1.1146	20.49	3-44	28
F	0.6781	0.8915	-	-	1.4747	23.89	1-77	10
G-1	1.4735	0.9578	1.2423	0.9725	0.8050*	44.64*	6-128*	12
G-2	1.4847	0.9043	1.2265	0.9570	0.8153*	40.67*	7-130*	9
H	0.0000	-	-	-	-	-	-	0
I	2.4248	0.6354	-	-	0.4124	975.19	1-3597	14
J	1.3959	0.7885	-	-	0.7164	96.36	2-306	25
K	0.4615	0.5959	-	-	2.1668	39.10	5-96	30
N	1.4368	0.7333	-	-	0.6960	88.34	6-215	11

Quantification error percentage was calculated for each quantification estimate using equation 5. Error percentage was plotted against pressure and windspeed values from the eastern landfill atmospheric research station weather station. The resulting R^2 and p-values are listed in Table 6.

$$Quantification\ Error = \frac{|Measured\ Emission\ Rate - Controlled\ Release\ Rate|}{Controlled\ Release\ Rate} \times 100 \qquad \ldots(5)$$

Table 6: Pressure and wind dependencies on quantification error

Vendor Identifier	Pressure Adj R^2	Pressure p-value	Windspeed Adj R^2	Windspeed p-value
A	-0.0268	0.6087	0.0794	0.0756
B	0.1419	0.0210	0.2583	0.0021
C	-0.1497	0.7758	0.3929	0.0569
D	-0.2414	0.8758	-0.0734	0.4628
E	-0.0114	0.4121	-0.0285	0.6205
F	0.0679	0.2342	0.0362	0.2807
G-1	0.3562	0.0234	0.1027	0.1637
G-2	0.6814	0.0038	-0.1236	0.7394
H	-	-	-	-
I	-0.0042	0.3501	-0.0484	0.5392
J	0.2031	0.0137	0.0338	0.1880
K	-0.0312	0.7280	-0.0226	0.5545
N	-0.1207	0.8646	-0.0.0836	0.5953

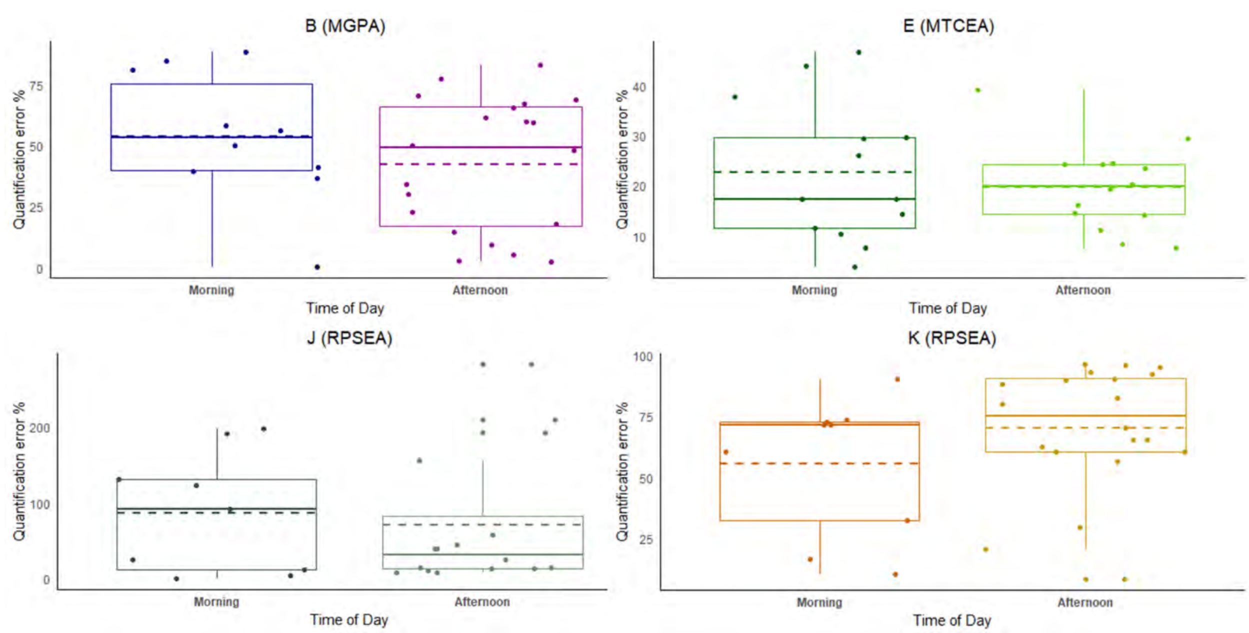

Figure 13: Boxplots of quantification accuracy of individual estimates based on time of day

Most methodologies did not show a significant dependence between error percentage and pressure and windspeed values. B (MGPA method) showed a correlation between quantification error percentage and pressure and wind speed. Vendor C's measurements (UPSEA method) showed an inverse correlation between windspeed and error percentage, with percent error decreasing as windspeed approaches 4-6 m/s. G-1 (LiDAR) displayed a significant positive correlation with barometric pressure and error %, and J (UCSEA) displayed an inverse correlation with barometric pressure.

Box plots showing quantification error during morning and afternoon measurements are shown in Figure 13 for methodologies that reported over 10 measurements during both periods of the day. The solid line indicates median quantification error percentage and dashed line indicates mean quantification error percentage for respective times of the day. Vendors B and E (MGPA and MTCEA respectively) displayed similar quantification error levels during both periods of the day, however greater variations in afternoon measurements can be observed for B (MGPA) whereas vendor E (MTCEA) displays greater variation for morning measurements. Continuous sensor vendor J(RPSEA) reported higher quantification error percentages in the morning compared to afternoon measurements and K(RPSEA) reported similar error percentages for both morning and afternoon measurements.

6.3. Discussion on Performance

Both MGPA methods (A and B) use the same methodology. The point-source Gaussian inversion method relies on various model parameters, including stability class and wind speed and direction. In a sensitivity analysis of the same technique conducted by Ars et al. (2017), it was found that the stability class contributes the most uncertainty followed by wind direction, wind speed, and source location. The overall uncertainty was estimated to be around 75%. With better constraints on atmospheric conditions, the uncertainty was reduced to 55%. In a landfill study that used the same methodology, Kumar et al. (2024) reported a level of uncertainty of approximately 30% on emission estimates from distant roads. Truck-based emission rate uncertainty was also determined to be 63% in a controlled release study described in O'Connell et al. (2019; SI). However, this last study used the Gaussian plume model differently. The measurements are likely leading to underestimated rates because the whole landfill emission might not have been fully sampled from ground-level transects on public roads. Moreover, the model does not account for plume lofting that arises from the elevated landfill surface temperature. The bias of 1.58 and 1.76 for technology A and B respectively, fit into the uncertainty range from Ars et al. (2017).

During the study, MGPA methodologies were limited by the compressed timeline. Normally MGPA requires more replication. During the study, experimental conditions and release rates were changing as often as every 30 minutes, leaving only 20 minutes for measurement. This left time for only 2 full transect passes on average per submitted measurement estimate. Numerous submitted estimates were based on a single transect pass because the plume was still increasing or subsiding during one of the passes. Normal practice for the vendor is to incorporate 6-15 full transect passes into a single measurement estimate, which might represent 2 hours of transect driving. Although various researchers over time have recommended the number of replicates required for robust Gaussian measurements, the normal recommendation is 3 at the very minimum, and ideally 10 or more. By including more replicates, the variance and volatility of individual transect estimates should reduce. Using the data submitted by vendor A, we averaged successive groups of 6 measurements from low rates to high, to simulate the effect of including 12 transects (6 measurements with 2 transects each) in a single measurement estimate (Figure 14:). As expected, the groupings decreased measurement variance substantially and more than halved average residuals (departures from the best-fit line) to 13 kg/hr across a range of 25-200 kg/hr. This indicates that under normal work practice, we might expect less variance from MGPA. Replication will help decrease variance / increase precision. Bias corrections can improve accuracy, when we multiply measurement estimates by a repeating under-estimation factor.

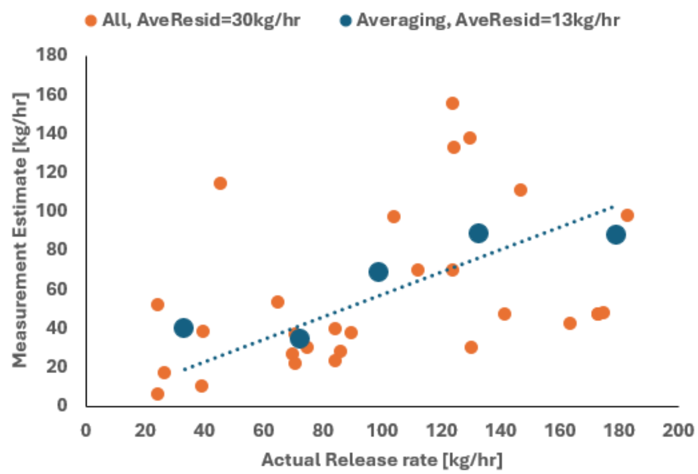

Figure 14: Simulated replicate parity chart for MGPA

Vendor E using the MTCEA method stands out with measurements closer to the parity line than other truck-based solutions, and other methodologies. We found no significant correlation between error percentage and pressure and windspeed values. Previous studies, like Foster-Witting et al. (2015) also note insensitivity of the MTCEA approach to atmospheric changes.

Consistent with a review of advanced UAS leak detection and quantification methods by Hollenbeck et al. (2021), the UPSEA method offered accurate and precise emission rate estimates but proved sensitive to atmospheric stability. In controlled release testing of flux screens derived from miniature Mid-Wave Infrared TDLAS data collected aboard a quadcopter (Corbett and Smith, 2022), the linear fit between the metered and calculated rates had an R^2 value of 0.8236, which is comparable to those of vendors C and D herein (Adj. R^2=0.9201 and Adj. R^2=0.8211, respectively). Furthermore, Corbett and Smith (2022) reported a TDLAS flux plane error range of 1.19-88.36% and a negative correlation between wind speed and absolute error. In independent single-blind controlled release testing of mobile leak detection and quantification technologies by Ravikumar et al. (2019), UAS-based TDLAS flux screens yielded exclusively true positives and true negatives, demonstrating a lower detection limit comparable to OGI and an order-of-magnitude quantification accuracy comparable to Picarro. There are fewer published controlled release studies describing Mid-IR LDS UAS flux planes, though a preprint study by Dooley et al. (2024) found a strong correlation (R^2=0.99997) between actual and estimated emissions across a wide range of release rates (0.04-1500 kg/hr) as well as systematic underestimation by their approach.

A few studies have measured methane emission fluxes from landfills using the APSEA mass balance technique (e.g., Obiminda et al. 2017; Allen et al. 2019; Gasbarra et al. 2019; Yong et al. 2024), but to our knowledge, this technology was never validated and compared in a blinded controlled methane release test in a landfill context. One controlled release test over a managed agricultural field showed that, under favorable measurement conditions, emissions from the point release source could be quantified by aerial mass balance (UAVs) with an uncertainty of 30 % (Morales et al.

2022; https://amt.copernicus.org/articles/15/2177/2022/). The authors also stated that emission rate estimates were on average slightly overestimated under optimal conditions, but lower average accuracy was observed when measurements were performed under less favorable wind conditions. In another controlled released study, also with a methane point source, Abbadi et al. (2023) showed, despite a low number of measurements, that the aerial mass balance technology was able to quantify release above 10 kg (CH_4) hr^{-1}.

Similarly, recent technologies such as satellite-based SISEA measurements using emission image capture have never been tested for detection and quantification during single-blind controlled methane release tests in a landfill context. The method has shown the ability to detect methane at landfills but with unknown accuracy. A recent study (Sherwin et al. 2023) tested several satellite methodologies with a trailer of liquefied natural gas acting as a methane point source. The authors reported that for all detected emissions from this point source, mean estimates for all satellite-team combinations were between – 68 and 110% of the release rate. It is difficult to understand how these results would translate to a landfill context where more non-point source emissions are present.

Continuous sensors show substantial promise from a cost and variability standpoint. But they are in early stages of development. A controlled release study for oil and gas detection by Chen et al. (2023) focused on detecting and quantifying methane emissions using Continuous Methane Monitoring Technologies, and while some methodologies showed good accuracy, others showed high rates of false positives. Unfortunately, the context for these oil and gas sites is very different from that of a landfill where topographic change is significant, numerous emission points are active at once, and the scale is over 100x larger. Landfill-specific controlled release testing and development must be carried out to bring these systems toward maturity for the waste sector. Given these limitations, one RPSEA methodology did perform well. Perhaps more impressively, the technology producer did not know they were participating, since a third party brought their sensor to the experiment. The technology producer may have preferred a different placement, but the results are promising. Error bars may have been overestimated.

Lagrangian footprint model has been widely used for natural sources, but using the model for emissions from anthropogenic sources is quite limited. Various studies have shown the Lagrangian footprint model's effectiveness in assessing methane emissions. Gerbig et al. (2006) used the COMET model to simulate greenhouse gas concentrations in the Netherlands and Ireland. Pisso et al. (2021) assessed methane emissions from offshore oil platforms in the Norwegian Sea, while Brunner et al. (2014) focused on methane emissions in Europe. Among these studies, none of them were focused on emissions from landfills. In this study, LEA participated as an R&D methodology, but its performance was promising given that this was a first-use trial, and the optimal work practice strongly diverged from the preference of having several hours, rather than several tens of minutes, to collect data.

Overall, the quantification results from most methodologies were promising. Table 7 lists key findings for quantification methodologies. They could all be useful, especially with replication. We observed high variability between vendors applying the RPSEA and UPSEA methods, which may indicate that standardization of operating procedures is needed. We observed very similar results between vendors applying MGPA. For MGPA, questions remain about variance under normal work practice, and these should be tested during subsequent rounds of controlled-release testing. Ultimately, there is no best vendor or methodology for quantification measurements, because the costs of these measurements may limit use to once per year. Frequent measurements can appreciably lift the value of inherently lower precision methods, and help capture temporal variation across daily, seasonal, and annual cycles. Bias corrections should potentially be applied to methodologies where we see a repeating trend of under- or over-estimation, as in this study and others.

Table 7: Summary of key findings for quantification methodologies

Technology Identifier	Method	R&D ?	Key Findings
A	MGPA	No	Reported approximately 66% of known release rates with a tendency to underestimate emission rates. Method is usually deployed over several hours and short release windows affected quantification performance. Method offered flexibility and extended duty cycle across weather conditions and was able to report measurements on each day of the experiment.
B	MGPA	No	Reported approximately 56% of known release rates with a tendency to underestimate emission rates. Method is usually deployed over several hours and short release windows affected quantification performance. Method offered flexibility and extended duty cycle across weather conditions and was able to report measurements on each day of the experiment.
C	UPSEA	No	Quantification estimates were very good with few outliers. Methodology is affected by weather conditions where measurements are not possible during rain and windspeed above 12 m/s.
D	UPSEA	No	Estimates varied greatly from true release rates with bias being less predictable. Methodology is affected by weather conditions where measurements are not possible during precipitation and windspeed above 17 m/s.
E	MTCEA	No	Quantification estimates were consistently close to true release rates with a slight downward bias. Method requires setup of tracer gas and frequent monitoring of its consumption levels. Method offered flexibility and extended duty cycle across weather conditions and was able to report measurements on each day of the experiment.
F	APSEA	No	Underestimated measurements consistently and vendor reported that estimates were not classified as high quality due to internal meteorological for measurements were not met. Requires 2-6 m/s windspeed, solar insolation and not a lot of cloud cover for good measurements.
G	LiDAR	No	Both LiDAR and mass balance methods were accurate and had a tendency to overestimate emission rates. Increase in quantification estimates were observed after onsite weather data were considered.

			Requires good visual flight rules conditions for flying aircraft. Ideal wind speed ranges from 3- 6 m/s.
H	SISEA	No	Emissions were not detected for quantification or localization purposes. Minimum detection limit expected to be at least 300 kg/hr. Cloud cover over the site and/or wind speed exceeding 10 m/s prevents emission measurement.
I	RPSEA	Yes	Overestimated emissions in most cases. Low maintenance method of quantifying estimates, due to low number of sensors only a limited set of wind conditions were covered.
J	RPSEA	Yes	Provided the closest measurements to actual emission values compared to other fixed sensors. Due to low number of sensors only a limited set of wind conditions were covered.
K	RPSEA	Yes	Underestimated emission in most cases. Due to low number of sensors only a limited set of wind conditions were covered.
N	LEA	Yes	Overestimated emissions in most cases. Lagrangian models are usually applied to tower-based systems however in this instance it was adapted to a mobile setting.

6.3.1. Detection Performance Assessments

Table 8 lists values for detection performance analysis. False positives are detections reported by methodologies that cannot be attributed to a controlled release and false positive fractions is the number of false positive detections relative to total number of detections. A false positive fraction of 0 desirable. True negative readings are instances when a methodology was able to correctly predict an inactive release point as a non- emitting source. True negative rate is the total number of true negative readings relative to the summation of true negative readings and false positive readings. A true negative value of 1 is desirable. Localization accuracy is the number of true positive detections relative so the summation of false positive readings and true positive readings. Localization accuracy of 1 is desirable.

Table 8: List of primary detection metrics

Method Identifier	False Positive Fraction	False Negative Fraction	True Negative Rate	Localization Accuracy	Survey Time (mins)
C	1	1	0.70	0	40
G	0	0	1	1	20
H	-	-	-	-	0.3
L	0.83	0.63	0.28	0.17	50
M	0.79	0.50	0.52	0.21	60
N	0.79	0.85	0.54	0.1-0.5	15

6.3.2. Analysis of Primary Detection Metrics

Table 7 lists the values obtained from equations 2 – 5 along with survey times for detection methodologies except for vendor N, which is not a leak detection technology per se but a screening that can be applied offsite. Lagrangian emission assessment is applied in a mobile setting for detection purposes in this study therefore the expectation for its assessment is different compared to other vendors. For all vendors, except N, a false positive and negative fraction closer to zero is desirable since it indicates the methodology's ability to correctly detect emissions. A true negative rate of one is desirable since it indicates the methodology's ability to classify inactive release points as a non-releasing source and it also indicates a lower false positive count. The Lagrangian model is usually not used for localization purposes, errors introduced from measurement and using the model affects resulting leak estimates. Vendor G (LiDAR) performed very well detecting active emissions 100 percent of the time without false positive readings. Vendor C provided accurate quantification estimates; however, was unable detect leaks correctly in all measurement attempts. Vendors L and M used the same drone-mounted TDLAS column sensor, and the results were similar, with a high fraction of false positives reported. Although both vendors were using identical sensors, vendor M was slightly more sensitive to leaks and we suspect that differences can be attributed to subtle differences in the work practice. It should be noted that both were unable to fully deploy their methodology, since a ground scan is usually performed to validate potential leak sources identified by the drone-mounted sensor. Vendor N was deployed from 1 km to 1.9 km from the landfill center point and was able to discern sources within ~100 m, indicating an uncertainty rate of about 15%. Since the study area could only be accessed when gas was not being released, vendors could not validate potential leak spots, which likely contributed to a much higher percentage of reported false positives. In their normal work practice vendors would manually verify using EPA21. Figure 15 illustrates the total number of true positives, false positives, and false negatives for vendors G, L, and M.

Figure 15: Classification of detection categories

6.3.3. Analysis of Probability of Detection Plots

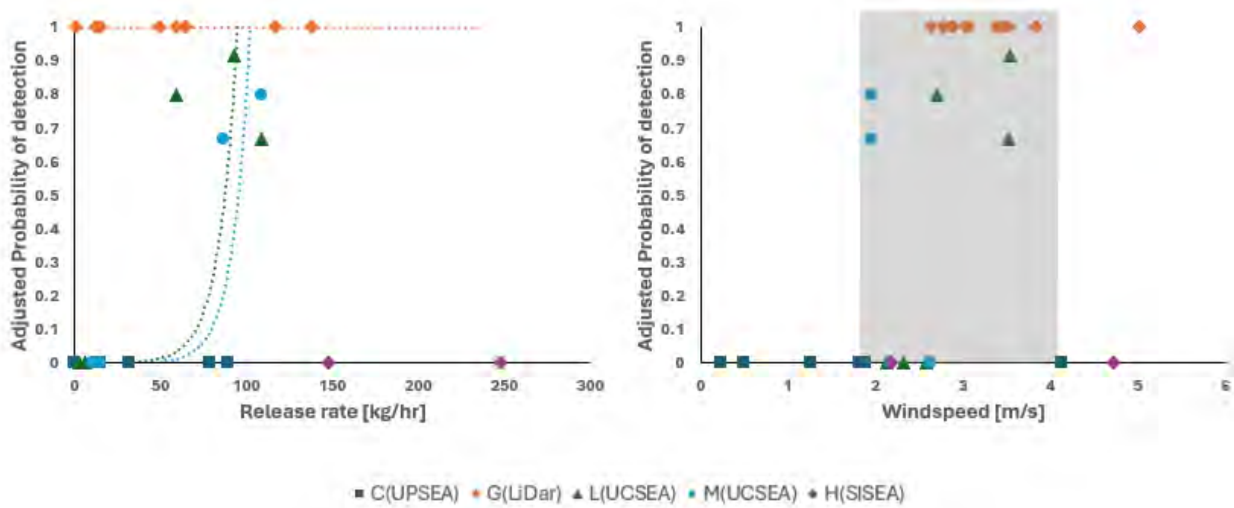

Figure 16: Adjusted Probability of Detection Curves against release rate (left) and wind speed (right)

The probability of detection curve was plotted against release rates and windspeed in Figure 16. LiDAR was very sensitive to emissions as low as 1 kg/hr. The LiDAR methodology's sensitivity is consistent with the detection analysis conducted by Bell et al. (2022) where a minimum detection limit of 0.25 (kg/hr)/(m/s) was observed at an altitude of 500 ft AGL, with 90% probability of detection. For UCSEA, the minimum detection limit was 95.34 kg/hr (vendor L) and 101.88 (vendor M), at an altitude of 20 m AGL, with 90% probability of detection. The locations of releases were a significant factor for UCSEA systems. True positive measurements were made more frequently on flat surfaces compared to slopes. When comparing the probability of detection with wind speed, most true positive detections were made between 2 and 4 m/s (shown in the shaded region in the right-hand side plot in Figure 16).

6.3.4. Detection Technology Performance Analysis

Comparison of UCSEA against previously published works is not possible since there are very few peer-reviewed papers published on the topic, and none using the sensor employed by vendors L and M. One paper by Natalie Pekney's group at NETL that describes the use of an ICI TDLAS column sensor mounted on a UAV flying the length of pipelines. A similar study by Li et al. discovered a minimum detectable release rate of 4 kg/hr in pipeline surveys with the ICI TDLAS-equipped UAV (Li, 2020). This compares favorably to the release rate-dependent probability of detection of technologies L and M, which was more than 10 times as high. There are some differences between the resolution and range specification sheets of the sensors, 1 ppm*m in Li et al. vs 5 ppm*m for vendors L and M, and respectively, 50 m vs 25 m. The sensors used in our study appear to have lower resolution by a factor of 5 and are being piloted nearer the edge of the measurement range, which may explain the differences between the results we observed, and the greater sensitivity observed by Li et al. (2020).

The only other similar controlled release experiment to UCSEA was conducted by Arain et al. (2020) using a mobile ground robot with a Sewerin TDLAS sensor to measure path-integrated methane concentrations, much like USCEA. The Sewerin sensor has a resolution and range that is virtually identical to the sensor used by vendors L and M. Arain and co-authors found a probability of detection of 56% and a 40% false positive rate. Although release rates were not disclosed, the test was conducted indoors, without wind which would have maximized the likelihood of detection. The probability of detection for vendors L and M was even lower in an outdoor environment where wind would quickly dilute concentrations. Vendors L and M returned appreciably larger false positive rates, but comparable false negative rates.

Overall, methodologies' performance in the detection component of the study was highly variable. Table 9 lists key findings for detection methodologies. One vendor (G-LiDAR) scored perfect marks in leak detection trials with no false positives and even made us aware of a malfunctioning flow controller bleeding at under 1 kg/hr. Other methodologies, at rates exceeding 90 kg/hr, could detect fewer than 20% of the releases. The difference in sensitivities between methodologies was roughly 100x in leak detection.

There is pressure to replace walking surveys with more repeatable methods that will reduce injuries incurred by walking on rough terrain. UAV surveys, and especially UCSEA, seem to fit the bill. However, there is substantial variation in the resolution of available TDLAS column sensors on the market, with some advertising as low as 1 ppm*m resolution to 100 ppm*m resolution. Even though it might not be intentional, the evolution of UCSEA, OTM51, and other UAV-based technologies mimic the sensitivity and attributes of EPA21 surface emissions monitoring walking surveys. However, EPA21 sensitivity is not well established, and until it is, it will be unclear whether these UCSEA methodologies deliver equivalent results. If industry and regulators agreed on the minimum leak rate that should be detectable in surveys sensors, work practice could be adjusted to meet rate-based outcomes, which are easy to test experimentally.

The LiDAR methodology performance was impressive, and potentially more sensitive than any landfill operator needs. While UCSEA methodologies had lower performance, they are less expensive to deploy. Based on previously published research, windspeed-specific thresholds, and work practice UCSEA has potential to improve its sensitivity. Lower-precision technology is not necessarily a poor choice for landfills, it just may need to be applied more frequently. The new US EPA OOOO/NSPS standards for oil and gas sites put forward a resolution-based frequency, where less sensitive methods must be deployed more often so they can catch larger emitters earlier – to reduce an equivalent amount of methane as an infrequently deployed higher resolution method. A similar approach could be developed for rate-based landfill leak detection sensitivity, with a move away from concentration thresholds.

Table 9:Summary of key findings for localization methodologies

Technology Identifier	Method	R&D ?	Key Findings
C	UPSEA	Yes	Methodology did not register any true positive emission estimates during the localization phase of the study.
G	LiDAR	No	Performed very well detecting active emissions 100 percent of the time without false positive readings.
H	SISEA	No	Emissions were not detected for quantification or localization purposes. Minimum detection limit expected to be at least 300 kg/hr. Cloud cover over the site and/or wind speed exceeding 10 m/s prevents emission measurement.
L	UCSEA	No	Reported high number of false positive estimates with limited visibility when measuring active emission points on slopes. Minimum detection limit at 90 % probability of detection was determined to be 95.34 kg/hr.
M	UCSEA	No	Performed slightly better than compared to other methods using TDLAS sensors. Also had high number of false positives and a minimum detection limit at 90% probability of detection of 101.88 kg/hr.
N	LEA	Yes	Reported mostly false positive estimates. Model is usually used for quantification purposes therefore is not suited for providing localization estimates.

7. Future Work

This study contributes to understandings of how different technologies operate and perform in a landfill setting, and several topics warrant further exploration. One aspect that must be further explored is the validation of satellite-based methane measurements. Satellite-based methodologies are gaining increased attention due to their expanding abilities. In future studies, a setup with the ability to release over 300 kg/hr during months with low cloud coverage will aid in validating satellite-based measurements.

Continuous fixed methane sensors offer a low-maintenance option for monitoring landfill methane emissions. During this study, fixed sensor coverage was inadequate and analysis of measurement quality over a variety of wind profiles could not be assessed. Longer release times, along with full site coverage, will allow a more accurate assessment for fixed sensors.

Certain vendors in this study were not able to fully deploy their methodologies due to permitting restrictions. In future studies vendors will be able to provide better measurement estimates if they can access the active release area, and if drone-based methodologies have a better line of sight. Having access to the release area will also allow detailed surface emission reports (SEM) to be developed for the study. Prioritizing methodologies such as OTM 51 and UCSEA will help develop standard work practices and a shift away from walking-based surveys.

Studying the rate of methane emissions during day and night cycles is another topic of interest. The ratio of maximum to minimum flux during a day-night cycle can vary between 1.81 to 23.20 as mentioned in Delkash et al. (2022). Studying the variability between day and nighttime measurements among methodologies will further advance measurement practices.

Our 2023 study utilized a temporary, above-ground pipeline setup which was later dismantled. To prevent waste and allow vendors to test new technologies, a permanent or long-term, controlled release setup buried underground can be assembled. This will allow frequent validation and research and development opportunities.

8. Summary Conclusions

A temporary controlled release setup was assembled and used to test 16 combinations of vendors and methodologies for quantification and detection performance during 71 experiments. Quantification methods performed well during the study. Truck-based systems using the Gaussian model tend to underestimate and the tracer correlation method was the most accurate among the truck-based methodologies. Using onsite weather data improved accuracy of LiDAR and should be an important consideration for vendors.

Detection methods and vendor performance varied greatly. LiDAR was very effective in localizing leaks and detecting emissions as low as 1 kg/hr. TDLAS systems, at a rate of around 80%, provided a high number of false positive leak estimates. This occurred with both vendors, who used the same technology.

Key takeaways from the study are listed below:

- MTCEA provided good quantification estimates while being flexible to operate in various weather conditions. UPSEA provided accurate quantification estimates as well , however the methodology requires good weather conditions to operate (no precipitation, windspeed below 12 m/s).
- Collecting onsite weather data is recommended as it has shown to improve quantification estimates
- LiDAR was able to detect all active emitting points including flowrates as low as 1 kg/hr.
- UCSEA reported high number of false positives (False positive fraction > 0.79) with limited visibility when measuring active emission points on slopes.
- RPSEA showed promising results; however, require further validation in a landfill setting to ensure its accuracy.

Table 10 summarizes key metrics for participating methodologies.

Table 10: Key performance metrics for all vendors

Technology Identifier	Method	Dev. from true value %	St Dev of Residuals %	Localization accuracy
A	MGPA	1-160	47.61	-
B	MGPA	1-88	39.63	-
C	UPSEA	2-66	34.71	-
D	UPSEA	8-96	61.98	-
E	MTCEA	3-44	20.49	-
F	APSEA	1-77	23.89	-
G-1	LiDAR	6-128	44.64	1
G-2	Mass Balance	7-130	40.67	-
H	SISEA	-	-	-
I	RPSEA	1-3597	975.19	-
J	RPSEA	2-306	96.36	-
K	RPSEA	5-96	39.10	-
L	UCSEA	-	-	0.17
M	UCSEA	-	-	0.21
N	LEA	6-215	88.34	0.1-0.5

This study will allow operators and regulators to make more informed decisions about landfill emission measurement techniques. Furthermore, vendors will be able to use data created during this study to further develop their methodologies and improve their services for the waste management sector, to reduce methane.

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A: Summary Data Table

Table A-1: Flowmeter data and uncertainty for all experiments. Flow rates are in kg/hr and experiment times are in Eastern time format.

Exp#	Q_A	Q_B	Q_C	Q_D1	Q_D2	Q_D3	Q_E	Q_F	Q_K4	Q_K5	Flowmeter Total	Site Total	Time Start	Time End	U_A	U_B	U_C	Q_D1	Q_D2	Q_D3	Q_E	Q_F	Q_K4	Q_K5	RSS	%U
1	2.78	4.64	2.78	0.00	0.00	6.50	0.93	1.86	0.00	0.00	19.49	43.93	2023-11-06T10:00:12.840	2023-11-06T10:40:14.723	0.006	0.006	0.006	0	0	0.006	0.006	0.006	0	0	0.000108	0.0108
2	3.71	4.64	5.57	4.64	0.00	0.00	3.70	1.86	0.00	4.38	28.50	52.94	2023-11-06T11:40:28.179	2023-11-06T12:20:57.916	0.006	0.006	0.006	0.006	0	0	0.006	0.006	0	0.006	0.000126	0.0126
3	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.00	0.00	0.30	24.74	2023-11-06T12:40:15.593	2023-11-06T13:30:35.568	0	0	0.006	0.006	0	0	0.006	0.006	0.006	0	0.00009	0.009
4	5.57	14.85	17.45	0.00	0.93	0.00	2.78	22.27	18.19	0.00	82.03	106.47	2023-11-06T13:53:12.998	2023-11-06T14:43:28.377	0.006	0.006	0.006	0	0.006	0	0.006	0.006	0.006	0	0.000126	0.0126
5	14.85	0.00	12.99	0.00	16.71	0.00	17.63	10.21	0.00	1.65	74.04	98.48	2023-11-06T15:41:01.218	2023-11-06T16:30:51.252	0.006	0	0.006	0	0.006	0	0.006	0.006	0	0.006	0.000108	0.0108
6	2.77	1.85	0.00	0.00	0.00	2.78	9.26	10.21	1.57	0.00	28.44	52.88	2023-11-07T08:16:09.775	2023-11-07T09:06:23.783	0.006	0.006	0.006	0	0	0.006	0.006	0.006	0.006	0	0.000126	0.0126
7	0.00	0.00	0.00	0.00	0.00	0.00	2.80	22.28	0.45	0.00	25.53	49.97	2023-11-07T09:40:24.157	2023-11-07T10:30:36.410	0	0	0	0	0	0	0.006	0.006	0.006	0	0.000054	0.0054
8	-0.01	-0.01	0.00	0.00	0.00	0.00	-0.01	0.25	0.02	0.00	0.25	24.68	2023-11-07T11:11:52.591	2023-11-07T12:10:46.914	0	0	0.006	0	0	0	0	0.006	0.006	0	0.000054	0.0054
9	5.55	13.87	2.78	3.70	0.00	0.00	21.33	50.11	0.00	1.54	98.87	123.31	2023-11-07T12:30:27.287	2023-11-07T13:20:41.804	0.006	0.006	0.006	0.006	0	0	0.006	0.006	0	0.006	0.000126	0.0126
10	5.54	8.32	11.11	10.19	0.00	0.00	41.71	58.47	0.00	4.64	139.98	164.42	2023-11-07T13:40:15.331	2023-11-07T14:30:28.162	0.006	0.006	0.006	0.006	0	0	0.006	0.006	0	0.006	0.000126	0.0126
11	0.10	1.08	2.06	0.00	2.95	0.00	19.92	17.74	1.66	0.00	45.50	69.94	2023-11-07T14:45:05.445	2023-11-07T15:18:11.408	0.006	0.006	0.006	0	0.006	0	0.006	0.006	0.006	0	0.000126	0.0126
12	3.71	4.64	4.64	0.00	5.57	0.00	13.91	21.35	3.71	0.00	57.53	81.97	2023-11-07T15:26:14.286	2023-11-07T15:56:16.816	0.006	0.006	0.006	0	0.006	0	0.006	0.006	0.006	0	0.000126	0.0126
13	0.00	-0.01	0.00	0.00	0.00	0.00	45.78	46.16	0.04	0.00	91.96	116.40	2023-11-08T08:13:40.905	2023-11-08T09:04:52.638	0.006	0	0	0	0	0	0.006	0.006	0.006	0	0.000072	0.0072
14	11.14	3.71	0.93	5.61	0.00	0.00	46.94	44.55	0.00	1.87	114.74	139.18	2023-11-08T09:17:03.823	2023-11-08T10:07:27.289	0.006	0.006	0.006	0.006	0	0	0.006	0.006	0	0.006	0.000126	0.0126
15	6.50	11.14	0.93	0.00	0.00	9.28	47.13	51.04	2.78	0.00	128.80	153.24	2023-11-08T10:17:27.030	2023-11-08T11:07:27.828	0.006	0.006	0.006	0	0	0.006	0.006	0.006	0.006	0	0.000126	0.0126
16	18.56	18.56	18.56	0.00	0.00	18.55	-0.15	0.32	18.56	0.00	92.97	117.41	2023-11-08T11:50:14.469	2023-11-08T12:40:19.682	0.006	0.006	0.006	0	0	0.006	0	0.006	0.006	0	0.000108	0.0108
17	12.99	18.56	16.71	0.00	18.37	0.00	34.32	52.87	14.85	0.00	168.67	193.11	2023-11-08T12:55:33.269	2023-11-08T13:45:37.403	0.006	0.006	0.006	0	0.006	0	0.006	0.006	0.006	0	0.000126	0.0126
18	0.00	-0.01	0.00	0.00	0.00	0.00	47.75	29.70	0.68	0.00	78.12	102.56	2023-11-09T08:00:22.677	2023-11-09T08:45:00.432	0	0	0.006	0	0	0	0.006	0.006	0.006	0	0.000072	0.0072
19	0.00	-0.01	0.00	0.00	0.00	0.00	48.43	29.70	0.69	0.00	78.80	103.24	2023-11-09T08:45:02.120	2023-11-09T09:20:31.461	0	0	0.006	0.006	0	0	0.006	0.006	0.006	0	0.00009	0.009
20	-0.01	0.93	1.86	2.78	0.00	0.00	19.49	16.71	1.47	0.00	43.22	67.66	2023-11-09T09:30:17.935	2023-11-09T10:15:03.745	0	0.006	0.006	0.006	0	0	0.006	0.006	0.006	0	0.000108	0.0108
21	-0.01	0.93	1.86	2.78	0.00	0.00	19.49	16.70	1.43	0.00	43.18	67.62	2023-11-09T10:15:05.662	2023-11-09T10:45:20.562	0	0.006	0.006	0.006	0	0	0.006	0.006	0.006	0	0.000108	0.0108
22	-0.01	0.00	0.00	0.00	0.00	0.00	-0.04	0.38	0.03	0.00	0.36	24.80	2023-11-09T11:00:02.155	2023-11-09T11:30:00.364	0	0	0.006	0.006	0	0	0	0.006	0.006	0	0.000072	0.0072
23	-0.01	18.56	9.28	0.00	16.71	0.00	23.20	23.20	0.00	18.56	109.50	133.94	2023-11-09T11:35:15.208	2023-11-09T12:05:16.021	0	0.006	0.006	0	0.006	0	0.006	0.006	0	0.006	0.000108	0.0108
24	-0.01	0.00	0.00	0.00	0.00	0.00	23.18	23.20	0.35	0.00	46.72	71.16	2023-11-09T12:09:59.947	2023-11-09T12:40:08.841	0	0	0.006	0.006	0	0	0.006	0.006	0.006	0	0.00009	0.009
25	18.56	18.56	9.28	4.64	0.00	0.00	-0.01	0.32	0.00	9.28	60.63	85.07	2023-11-09T12:45:14.837	2023-11-09T13:15:21.213	0.006	0.006	0.006	0.006	0	0	0	0.006	0	0.006	0.000108	0.0108
26	18.56	18.56	9.28	4.64	0.00	0.00	0.06	0.30	0.00	9.27	60.68	85.12	2023-11-09T13:20:08.104	2023-11-09T13:50:16.090	0.006	0.006	0.006	0.006	0	0	0.006	0.006	0	0.006	0.000126	0.0126
27	5.57	8.35	11.14	0.00	0.00	9.28	41.77	58.44	4.64	0.00	139.19	163.62	2023-11-09T14:20:39.444	2023-11-09T15:00:40.360	0.006	0.006	0.006	0	0	0.006	0.006	0.006	0.006	0	0.000126	0.0126
28	-0.01	0.00	1.85	0.00	0.00	2.78	19.49	16.70	1.29	0.00	42.11	66.55	2023-11-09T15:10:07.250	2023-11-09T15:40:11.989	0	0	0.006	0	0	0.006	0.006	0.006	0.006	0	0.00009	0.009

Exp#	Q_A	Q_B	Q_C	Q_D1	Q_D2	Q_D3	Q_E	Q_F	Q_K4	Q_K5	Flowmeter Total	Site Total	Time Start	Time End	U_A	U_B	U_C	Q_D1	Q_D2	Q_D3	Q_E	Q_F	Q_K4	Q_K5	RSS	%U
29	18.56	18.56	18.56	0.00	0.00	18.56	-0.06	0.32	18.56	0.00	93.07	117.51	2023-11-09T15:50:00.857	2023-11-09T16:30:06.796	0.006	0.006	0.006	0	0	0.006	0	0.006	0.006	0	0.000108	0.0108
30	5.57	13.92	2.78	0.00	3.71	0.00	21.33	50.11	0.00	1.28	98.71	123.15	2023-11-09T16:50:02.293	2023-11-09T17:30:04.556	0.006	0.006	0.006	0	0.006	0	0.006	0.006	0	0.006	0.000126	0.0126
31	0.00	-0.01	0.00	0.00	0.00	0.00	37.07	37.09	0.03	0.00	74.17	98.61	2023-11-10T08:09:19.152	2023-11-10T08:39:30.471	0	0	0.006	0	0	0	0.006	0.006	0.006	0	0.000072	0.0072
32	18.56	18.56	18.56	18.56	0.00	0.00	-0.10	0.32	18.56	0.00	93.03	117.46	2023-11-10T08:49:00.098	2023-11-10T09:19:03.130	0.006	0.006	0.006	0.006	0	0	0	0.006	0.006	0	0.000108	0.0108
33	0.00	-0.01	0.00	0.00	0.00	0.00	18.54	18.55	0.00	0.00	37.08	61.52	2023-11-10T09:29:12.293	2023-11-10T09:59:26.293	0	0	0.006	0.006	0	0	0.006	0.006	0.006	0	0.00009	0.009
34	16.51	16.54	16.51	16.21	0.00	0.00	-0.01	0.00	0.00	15.59	81.35	105.79	2023-11-10T10:10:01.056	2023-11-10T10:53:17.864	0.006	0.006	0.006	0.006	0	0	0	0.006	0	0.006	0.000108	0.0108
35	4.64	4.64	0.00	0.00	0.01	0.00	4.62	4.64	4.64	0.00	23.19	47.63	2023-11-10T11:02:06.039	2023-11-10T11:32:05.908	0.006	0.006	0.006	0	0.006	0	0.006	0.006	0.006	0	0.000126	0.0126
36	-0.01	0.00	0.00	0.01	0.00	0.00	27.84	27.84	0.00	0.00	55.69	80.13	2023-11-10T12:30:00.096	2023-11-10T13:10:06.739	0	0.006	0.006	0.006	0	0	0.006	0.006	0.006	0	0.000108	0.0108
37	18.56	18.56	18.56	18.56	0.00	0.00	18.55	18.56	18.56	0.00	129.92	154.36	2023-11-10T13:15:08.208	2023-11-10T13:55:03.609	0.006	0.006	0.006	0.006	0	0	0.006	0.006	0.006	0	0.000126	0.0126
38	18.56	18.56	18.56	0.00	0.00	18.56	18.56	18.56	0.00	18.56	129.94	154.38	2023-11-10T14:00:12.192	2023-11-10T14:40:13.075	0.006	0.006	0.006	0	0	0.006	0.006	0.006	0	0.006	0.000126	0.0126
39	0.00	-0.01	0.00	6.50	0.00	0.00	19.49	16.70	0.00	0.00	42.69	67.13	2023-11-10T15:05:01.397	2023-11-10T15:35:06.503	0	0	0.006	0.006	0	0	0.006	0.006	0.006	0	0.00009	0.009
40	9.28	9.28	0.00	0.00	0.01	0.00	0.01	0.01	9.28	0.00	27.86	52.30	2023-11-10T15:40:00.740	2023-11-10T16:10:06.764	0.006	0.006	0.006	0	0.006	0	0.006	0.006	0.006	0	0.000126	0.0126
41	18.56	18.56	18.56	0.00	18.49	0.00	27.83	27.84	18.56	0.00	148.42	172.86	2023-11-10T16:15:19.908	2023-11-10T16:45:20.823	0.006	0.006	0.006	0	0.006	0	0.006	0.006	0.006	0	0.000126	0.0126
42	18.56	0.00	0.00	18.56	0.00	0.00	50.22	0.01	0.00	0.00	87.36	111.80	2023-11-11T09:51:39.948	2023-11-11T10:50:10.126	0.006	0.006	0.006	0.006	0	0	0.006	0.006	0	0.006	0.000126	0.0126
43	0.00	18.56	18.56	0.00	0.00	0.00	9.27	55.68	0.00	0.00	102.08	126.52	2023-11-11T11:00:08.579	2023-11-11T12:00:12.439	0	0.006	0.006	0	0.006	0	0.006	0.006	0.006	0	0.000108	0.0108
44	0.00	0.00	0.00	0.00	0.00	0.00	0.01	9.28	0.00	0.00	9.28	33.72	2023-11-11T12:10:19.641	2023-11-11T12:40:27.410	0	0.006	0.006	0.006	0	0	0.006	0.006	0	0.006	0.000108	0.0108
45	0.00	0.00	0.00	0.00	4.64	0.00	9.24	0.01	0.00	0.00	13.89	38.33	2023-11-11T13:02:55.106	2023-11-11T13:28:55.765	0	0	0.006	0	0.006	0	0.006	0.006	0	0	0.000072	0.0072
46	0.00	0.00	0.00	4.64	0.00	0.00	9.25	0.01	0.00	0.00	13.90	38.34	2023-11-11T13:40:36.082	2023-11-11T14:09:08.330	0.006	0.006	0.006	0.006	0	0	0.006	0.006	0	0.006	0.000126	0.0126
47	9.28	0.00	0.00	0.00	0.93	0.00	0.01	0.01	0.93	0.00	11.15	35.59	2023-11-11T14:15:01.192	2023-11-11T14:40:34.068	0.006	0	0.006	0	0.006	0	0.006	0.006	0.006	0	0.000108	0.0108
48	0.00	4.64	0.00	0.00	0.00	0.00	0.01	9.27	0.00	0.00	13.92	38.36	2023-11-11T14:45:06.953	2023-11-11T15:23:18.578	0	0.006	0.006	0	0	0	0.006	0.006	0	0	0.000072	0.0072
49	9.26	0.00	0.00	0.00	0.00	9.28	9.27	18.55	9.28	0.00	55.65	80.09	2023-11-11T16:00:06.250	2023-11-11T17:00:15.344	0.006	0	0.006	0	0	0.006	0.006	0.006	0.006	0	0.000108	0.0108
50	18.56	0.00	0.00	0.00	0.00	18.56	36.98	0.01	0.00	0.00	74.11	98.55	2023-11-12T08:15:12.714	2023-11-12T08:56:17.563	0.006	0.006	0.006	0	0	0.006	0.006	0.006	0.006	0	0.000126	0.0126
51	0.00	18.56	18.56	0.00	0.00	0.00	9.27	37.12	0.00	0.00	83.53	107.96	2023-11-12T09:10:19.711	2023-11-12T09:45:23.482	0	0.006	0.006	0	0	0.006	0.006	0.006	0	0.006	0.000108	0.0108
52	0.00	0.00	0.00	0.93	0.00	0.00	0.01	9.28	0.93	0.00	11.14	35.58	2023-11-12T09:55:08.844	2023-11-12T10:33:40.553	0	0.006	0.006	0.006	0	0	0.006	0.006	0.006	0	0.000108	0.0108
53	0.00	0.00	0.00	0.00	4.64	0.00	9.26	0.01	0.00	0.00	13.91	38.34	2023-11-12T10:44:56.749	2023-11-12T11:20:37.606	0.006	0.006	0.006	0	0.006	0	0.006	0.006	0.006	0	0.000126	0.0126
54	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	24.45	2023-11-12T12:30:00.602	2023-11-12T13:00:00.389	0.006	0	0.006	0.006	0	0	0.006	0.006	0	0.006	0.000108	0.0108
55	0.00	0.00	0.00	1.86	0.00	0.00	0.01	0.00	0.00	0.00	1.87	26.31	2023-11-12T13:05:08.714	2023-11-12T14:01:43.871	0.006	0	0.006	0.006	0	0	0.006	0.006	0	0.006	0.000108	0.0108
56	18.56	18.56	18.56	18.56	0.00	0.00	47.50	92.80	18.56	0.00	233.12	257.56	2023-11-12T14:05:14.356	2023-11-12T14:11:47.965	0.006	0.006	0.006	0.006	0	0	0.006	0.006	0.006	0	0.000126	0.0126
57	0.00	0.00	0.93	0.00	0.00	0.00	0.01	4.64	0.00	0.00	5.58	30.02	2023-11-12T14:30:19.449	2023-11-12T15:30:22.073	0	0.006	0.006	0	0	0	0.006	0.006	0.006	0	0.00009	0.009
58	0.93	0.00	0.00	0.00	0.00	0.93	0.01	0.01	0.00	0.00	1.87	26.31	2023-11-12T15:41:39.323	2023-11-12T16:36:42.637	0.006	0	0.006	0	0	0.006	0.006	0.006	0	0	0.00009	0.009
59	7.42	0.00	0.00	0.00	0.00	7.43	0.00	37.10	5.97	0.00	57.92	82.36	2023-11-13T09:59:23.510	2023-11-13T10:39:29.814	0.006	0	0.006	0	0	0.006	0.006	0.006	0.006	0	0.000108	0.0108
60	7.43	0.00	0.00	0.00	0.00	7.42	0.00	37.12	7.33	0.00	59.31	83.74	2023-11-13T10:46:02.401	2023-11-13T11:15:36.063	0.006	0	0.006	0	0	0.006	0.006	0.006	0.006	0	0.000108	0.0108
61	7.42	0.00	0.00	0.00	0.00	7.42	0.01	37.09	7.41	0.00	59.36	83.80	2023-11-13T11:22:27.678	2023-11-13T11:52:23.423	0.006	0.006	0.006	0	0	0.006	0.006	0.006	0.006	0	0.000126	0.0126
62	9.28	0.93	0.00	0.00	0.93	0.00	18.52	0.00	0.00	0.00	29.67	54.11	2023-11-13T12:10:01.424	2023-11-13T12:38:47.726	0.006	0.006	0.006	0	0.006	0	0.006	0.006	0.006	0	0.000126	0.0126
63	0.93	0.00	3.71	0.00	0.00	0.00	0.01	25.98	0.00	5.54	36.17	60.61	2023-11-13T12:50:20.478	2023-11-13T13:19:27.400	0.006	0	0.006	0	0	0	0.006	0.006	0	0.006	0.00009	0.009

FLUX LAB

Exp#	Q_A	Q_B	Q_C	Q_D1	Q_D2	Q_D3	Q_E	Q_F	Q_K4	Q_K5	Flowmeter Total	Site Total	Time Start	Time End	U_A	U_B	U_C	Q_D1	Q_D2	Q_D3	Q_E	Q_F	Q_K4	Q_K5	RSS	%U
64	4.64	4.64	4.64	4.64	0.00	0.00	29.59	0.01	4.64	0.00	52.80	77.24	2023-11-13T14:30:14.232	2023-11-13T14:44:02.286	0.006	0.006	0.006	0.006	0	0	0.006	0.006	0.006	0	0.000126	0.0126
65	4.64	9.28	6.50	0.00	4.64	0.00	29.64	0.01	0.00	4.63	59.33	83.77	2023-11-13T15:59:57.197	2023-11-13T16:30:01.065	0.006	0.006	0.006	0	0.006	0	0.006	0.006	0	0.006	0.000126	0.0126
66	18.56	0.00	0.00	18.56	0.00	0.00	44.41	0.01	0.00	0.00	81.54	105.98	2023-11-14T08:15:30.074	2023-11-14T09:15:35.680	0.006	0.006	0.006	0.006	0	0	0.006	0.006	0	0	0.000108	0.0108
67	0.00	18.56	18.56	0.00	0.00	0.00	9.27	55.68	-0.01	0.00	102.07	126.51	2023-11-14T09:25:33.216	2023-11-14T10:25:39.759	0	0.006	0.006	0.006	0	0	0.006	0.006	0	0	0.00009	0.009
68	0.00	0.00	0.00	0.00	0.00	0.00	0.01	9.28	-0.02	0.00	9.27	33.71	2023-11-14T10:35:03.583	2023-11-14T11:35:10.493	0	0	0.006	0	0	0	0.006	0.006	0	0	0.000054	0.0054
69	0.00	0.00	0.00	0.00	4.64	0.00	9.21	0.00	-0.01	0.00	13.84	38.28	2023-11-14T11:44:55.704	2023-11-14T11:53:04.610	0	0.006	0.006	0	0.006	0	0.006	0.006	0	0	0.00009	0.009
70	18.56	18.56	18.56	0.00	0.00	18.56	45.90	99.64	18.56	0.00	238.34	262.78	2023-11-14T13:58:06.401	2023-11-14T14:09:07.384	0.006	0.006	0.006	0	0	0.006	0.006	0.006	0.006	0	0.000126	0.0126
71	0.00	4.64	0.00	0.00	0.00	0.00	0.01	9.28	0.00	0.00	13.93	38.37	2023-11-14T14:29:54.462	2023-11-14T15:59:55.332	0	0.006	0.006	0.006	0	0	0.006	0.006	0.006	0	0.000108	0.0108

B: Equipment List and engineering diagrams

Table B-1: List of electrical components

№	Product Name	Quantity
1	FTP 4-Pairs (FOD-CAT6-1KFT)	**305 m/ 2 pack**
2	Leakage Circuit Breaker Box, 4 Way Garage Caravan Consumer Unit 63a 30ma RCD 4MCB 2x6a 20a 32a	**1**
3	Button Switch DC 24V SPDT 5 Pin 5 Pack	**1**
4	AC/DC CONVERTER 24V 31W	**5**
5	SSR RELAY SPST-NO 15A 75-250V	**5**
6	AC/DC CONVERTER 24V 46W	**2**
7	Electriduct 3/4" Flame Retardant Polypropylene	**18**
8	Dustproof Waterproof IP65 Junction ElectricalBox (150mmx110mmx70mm)	**5**
9	Dustproof Waterproof IP65 Junction Electrical Box (200mmx155mmx80mm)	**3**
10	Uenhoy 6 Pcs NPT 1" Cable Glands Waterproof Nylon Cord Grip Cable Glands Strain Relief Cord Connectors	**6**
11	Dual Wall Heat Shrink Tubing (Dia 40mm(1.6")	**2**
12	25 Ft Extension Cord with 3 Outlets, UL Listed 16/3 SJTW, 3-Wire Grounded, 13A 125V 1625W	**1**
13	20 Inch 1 to 4 Extension Cord Splitter, 16/3 SJTW 3 Prong Power Cord.	**2**
14	PORTABLE CORD,250FT.,16 AWG, BLACK Standards - UL FlexibleCord, CSA, MSHAApproved, RoHS Compliant	**540m./7 pack2**
15	Kasonic 25 Ft Extension Cord with 3 Outlets, UL Listed 16/3 SJTW, 3-Wire Grounded, 13A 125V 1625W for Indoor/Outdoor Use - Green	**76,2m./1 pack**

Table B-2: List of Pipeline Equipment

Type	Size	Model	Certification	Quantity
Flow controller	1 1/4 inch	Alicat MCR-3000SLPM-D-485-X/5M	ATEX/CSA Class 1 Zone/Div 2 area rated	2
Flow controller	3/4 inch	Alicat MCR-500SLPM-D-485-X/5M	ATEX/CSA Class 1 Zone/Div 2 area rated	5
Ball Valve	2 inch	68AMLL-2 KITZ	CAN/CGA 3.16-M88 - 125 PSI	1
Solenoid Valve	3/4 inch	Shako PU225A-06 (FKM)	ATEX EExmIIT4 II 2G & 2D	5
PE pipe	2 inch	PE-32-250 GASTITE	CAN/CSA-B137.4	2
PE pipe	1-1/4inch	PE-20-250 GASTITE	CAN/CSA-B137.4	5
PE fitting	2 inch	PECPL-32 GASTITE	CAN/CSA-B137.4	1
PE pipe	3/4 inch	PE-12-250 GASTITE	CAN/CSA-B137.4	3
PE fitting	2 inch	PET-32	CAN/CSA-B137.4	1
PE fitting	2 1-1/4 2 inch	PERT-32-32-20	CAN/CSA-B137.4	2
PE fitting	1-1/4 3/4 1-1/4 inch	PERT-16-16-12	CAN/CSA-B137.4	3
PE fitting	2 inch	TRANS-32	CAN/CSA-B137.4	1
PE fitting	1-1/4inch	TRANS-20	CAN/CSA-B137.4	2
PE fitting	3/4 inch	TRANS-12	CAN/CSA-B137.4	11
PE fitting	2 1-1/4inch	PECPL-20-32	CAN/CSA-B137.4	2
PE fitting	1-1/4 3/4 inch	PECPL-12-20	CAN/CSA-B137.4	2

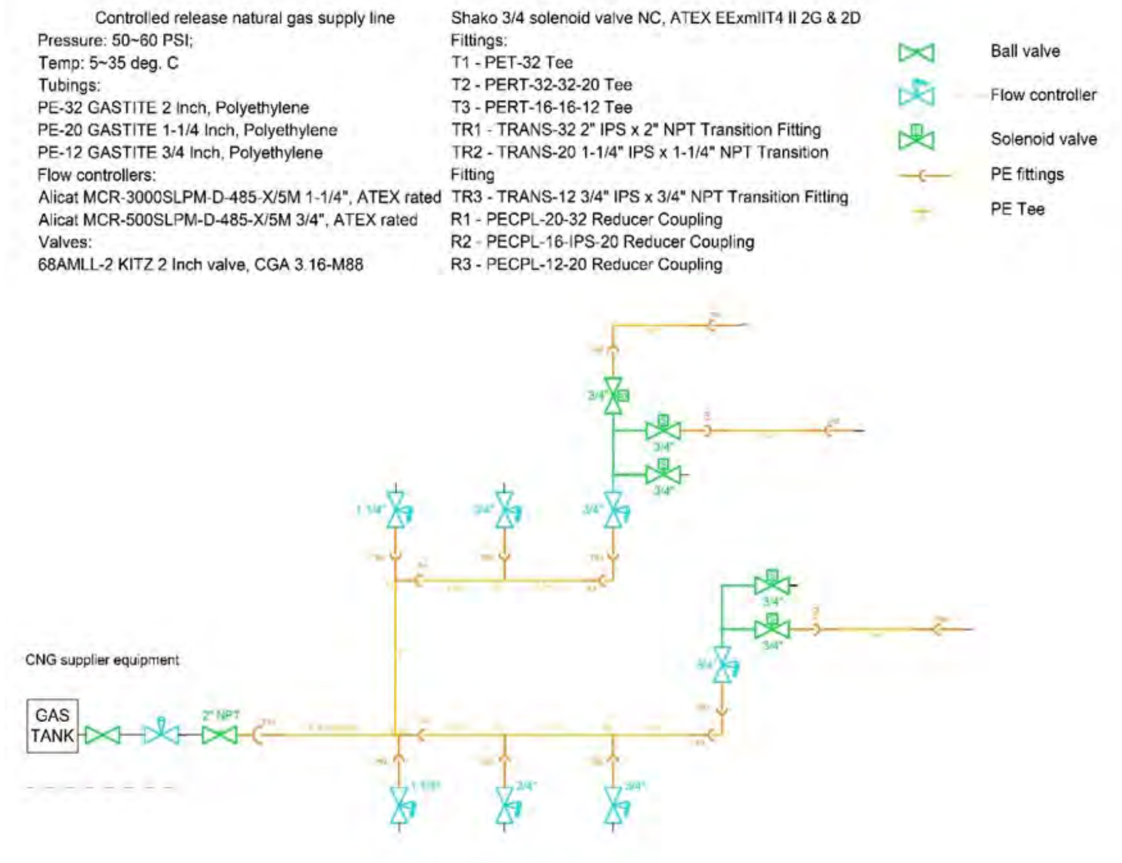

Figure B-1: Piping and instrumentation diagramf piping assembly

PRODUCT

CAMPBELL SCIENTIFIC
WHEN MEASUREMENTS MATTER

MetSens500

Compact Weather Sensor for Temperature, RH, Barometric Pressure, and Wind with Compass

Measures 5 Common Meteorological Parameters

IEC 61724-1 Compliant

Overview

The MetSens500 compact weather sensor measures wind speed and direction via an ultrasonic sensor, as well as air temperature, relative humidity, and barometric pressure, in a single, combined instrument mounted inside three double-louvered, naturally aspirated radiation shields with no moving parts. An integrated electronic compass allows the MetSens500 to provide accurate, relative wind direction measurements without being oriented in a particular way, making installation easier. WMO average wind speed and direction and gust, temperature, relative humidity, barometric pressure, absolute humidity, air density, and wet bulb temperature data are provided. The MetSens500 is compatible and easily integrated with the MeteoPV Solar Resource Platform and any Campbell Scientific data logger using SDI-12, RS-485, ModbusRS-485, or NMEA RS-232.

Benefits and Features

- Quality measurements
- Fast and simple to install
- Compact, integrated design
- Lightweight and robust

Specifications

Measurements Made	Air temperature, barometric pressure, relative humidity, wind direction, and wind speed.
Sampling Rate	1 Hz
Digital Communication Modes	Serial RS-232, RS-485, SDI-12, NMEA, Modbus, ASCII
IP Rating	66
Compliance	CE, RoHS Where applicable, all individual parameters meet or exceed specifications of IEC 61724-1 (2017, 2021).
Operating Temperature Range	-40° to +70°C
Operating Voltage	5 to 30 Vdc
Typical Current Drain @ 12 Vdc	25 mA (continuous high mode) 0.7 mA (eco-power mode; 1 hour polled)
Weight	0.7 kg (1.5 lb)

Air Temperature Measurement

Measurement Range	-40° to +70°C
Resolution	0.1°C
Accuracy	±0.3°C (@ 20°C)

Relative Humidity Measurement

Measurement Range	0 to 100%
Resolution	0.1
Accuracy	±2% @ 20°C (10 to 90% RH)

Barometric Pressure Measurement

Measurement Range	300 to 1100 hPa
Resolution	0.1 hPa
Accuracy	±0.5 hPa (@ 25°C)

Wind Speed Measurement

Measurement Range	0.01 to 60 m s^{-1}
Accuracy	±5% (up to 60 m s^{-1}) ±3% (up to 40 m s^{-1})
Resolution	0.01 m s^{-1}
Starting Threshold	0.01 m s^{-1}

Wind Direction Measurement

Measurement Range	0° to 359°
Accuracy	±3° (up to 60 m s^{-1})
Resolution	1°

Compass

Measurement Range	0 to 359°
Resolution	1°
Units of Measure	Degrees
Accuracy	±3°

PRODUCT

CAMPBELL SCIENTIFIC
WHEN MEASUREMENTS MATTER

MetSens200

Compact Weather Sensor for Wind with Compass

Measures Wind Speed and Direction

IEC 61724-1 Compliant

Overview

The MetSens200 compact weather sensor measures wind speed and direction via an ultrasonic sensor. An integrated electronic compass allows the MetSens200 to provide accurate, relative wind direction measurements without being oriented in a particular way, making installation easier. WMO average wind speed and direction and gust data are provided. The MetSens200 is compatible and easily integrated with the MeteoPV Solar Resource Platform and any Campbell Scientific data logger using SDI-12, RS-485, ModbusRS-485, or NMEA RS-232.

Benefits and Features

- Quality measurements
- Fast and simple to install
- Compact, integrated design
- Lightweight and robust

Specifications

Measurements Made	Wind direction and wind speed
Sampling Rate	1 Hz
Digital Communication Modes	Serial RS-232, RS-485, SDI-12, NMEA, Modbus, ASCII
IP Rating	66
Compliance	CE, RoHS Where applicable, all individual parameters meet or exceed specifications of IEC 61724-1 (2017, 2021).
Operating Temperature Range	-40° to +70°C
Operating Voltage	5 to 30 Vdc
Typical Current Drain @ 12 Vdc	0.7 mA (eco-power mode; 1 hour polled) 25 mA (continuous high mode)
Weight	0.5 kg (1.1 lb)

Wind Speed Measurement

Measurement Range	0.01 to 60 m s^{-1}
Accuracy	±3% (up to 40 m s^{-1}) ±5% (up to 60 m s^{-1})
Resolution	0.01 m s^{-1}
Starting Threshold	0.01 m s^{-1}

Wind Direction Measurement

Measurement Range	0° to 359°
Accuracy	±3° (up to 60 m s^{-1})
Resolution	1°

Compass

Measurement Range	0 to 359°
Resolution	1°
Units of Measure	Degrees
Accuracy	±3°

CAMPBELL SCIENTIFIC

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C: Localization assessment maps

Figures C-1 to C-4 shows localization assessment maps for methodologies C, G, L, M and N. Maps show all submitted leak estimate coordinates and active release points that vendors participated in during the study. Leak estimates are shown using circles filled with a single color. White circles with a smaller black circle show release nodes. Squares with hashed black lines indicate active release points and the bounding box is used to determine true positive leak estimates.

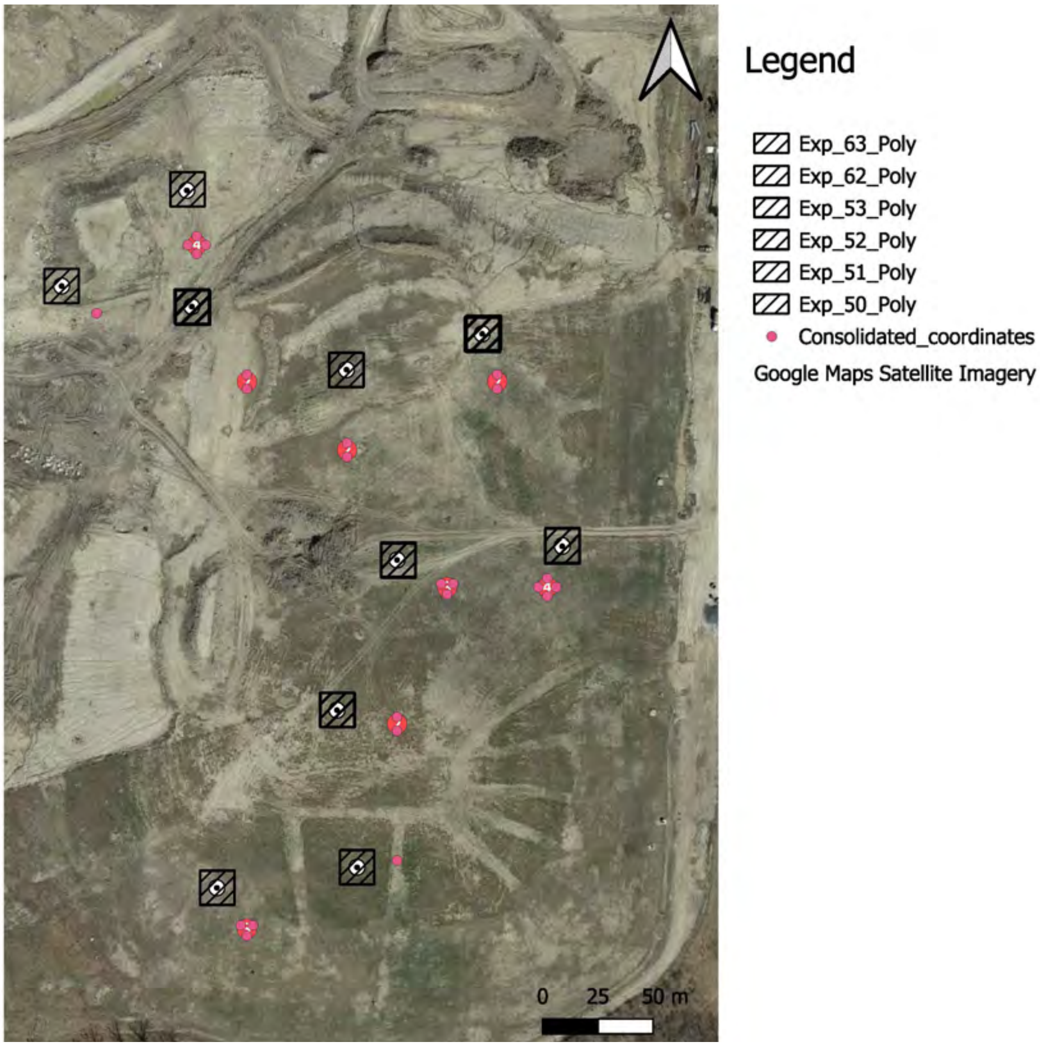


Figure C-1: Vendor C localization assessment map. Overlapping points are shown as a point cluster.

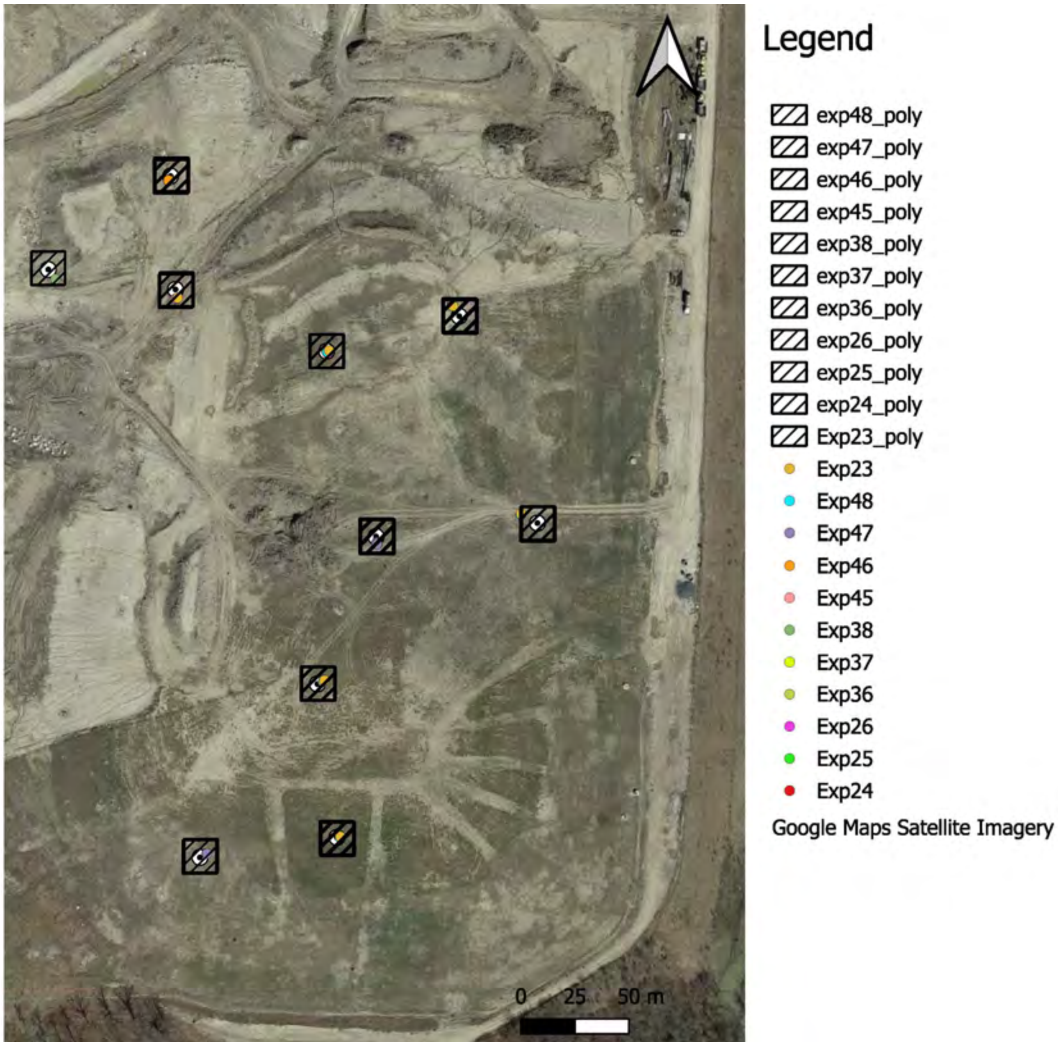


Figure C-2: Vendor G localization assessment map

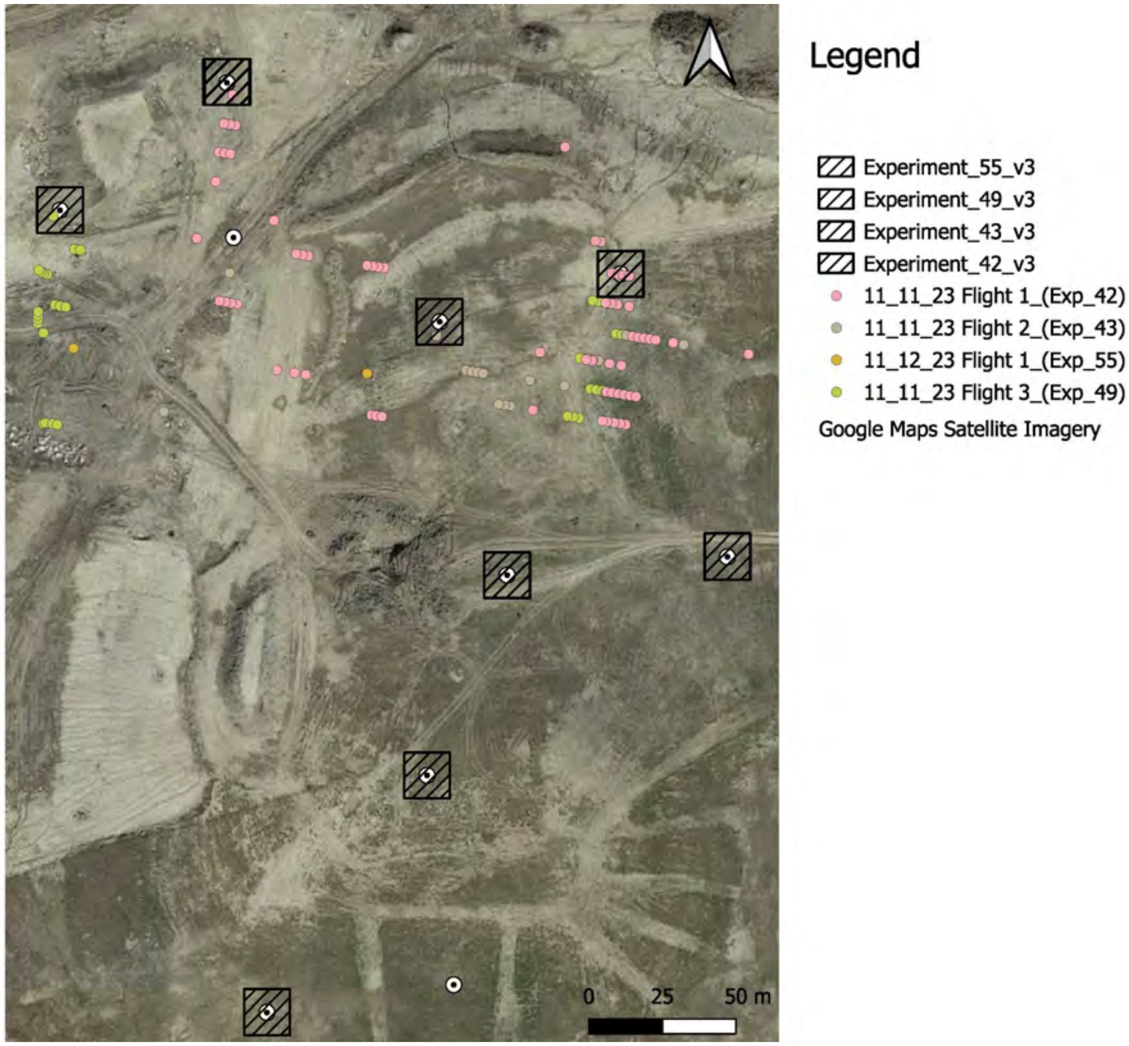


Figure C-3: Vendor L localization assessment map

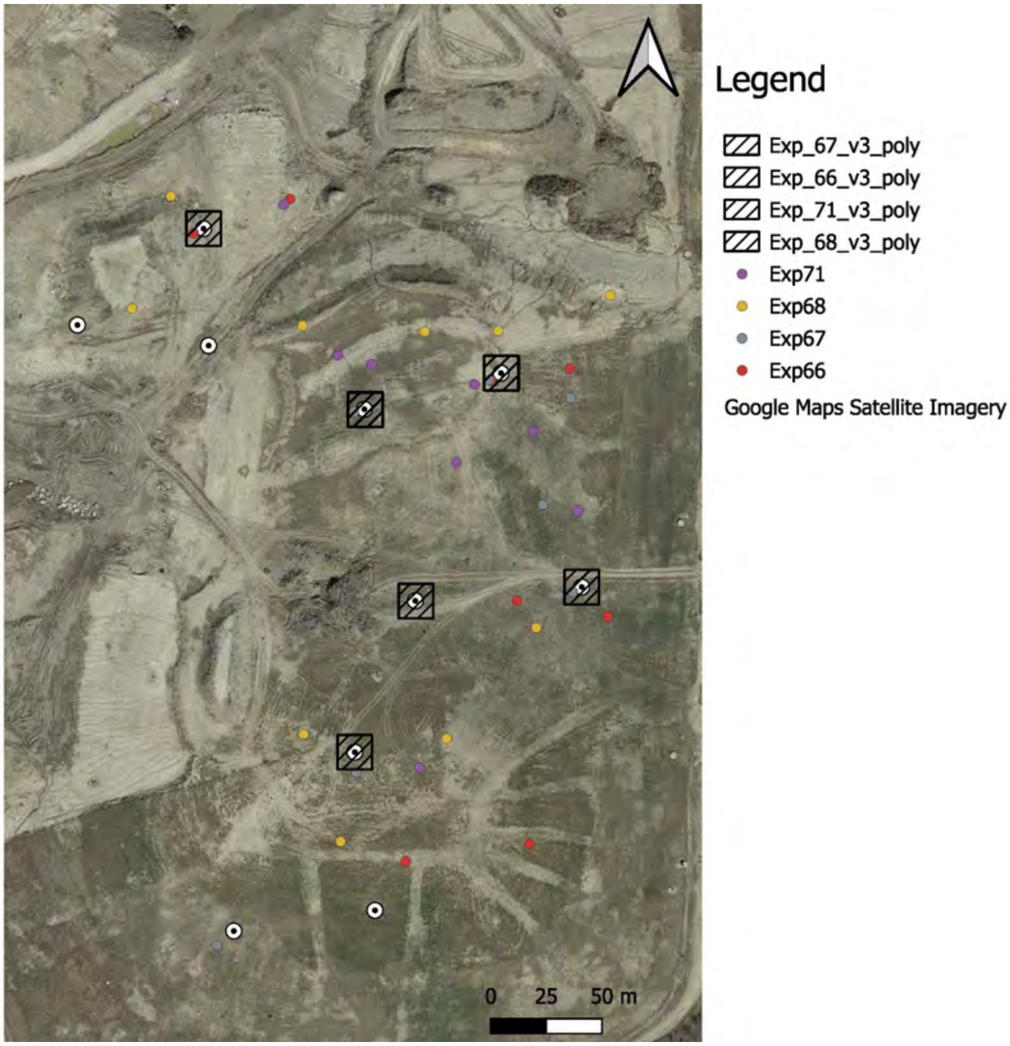


Figure C-4: Vendor M localization assessment map

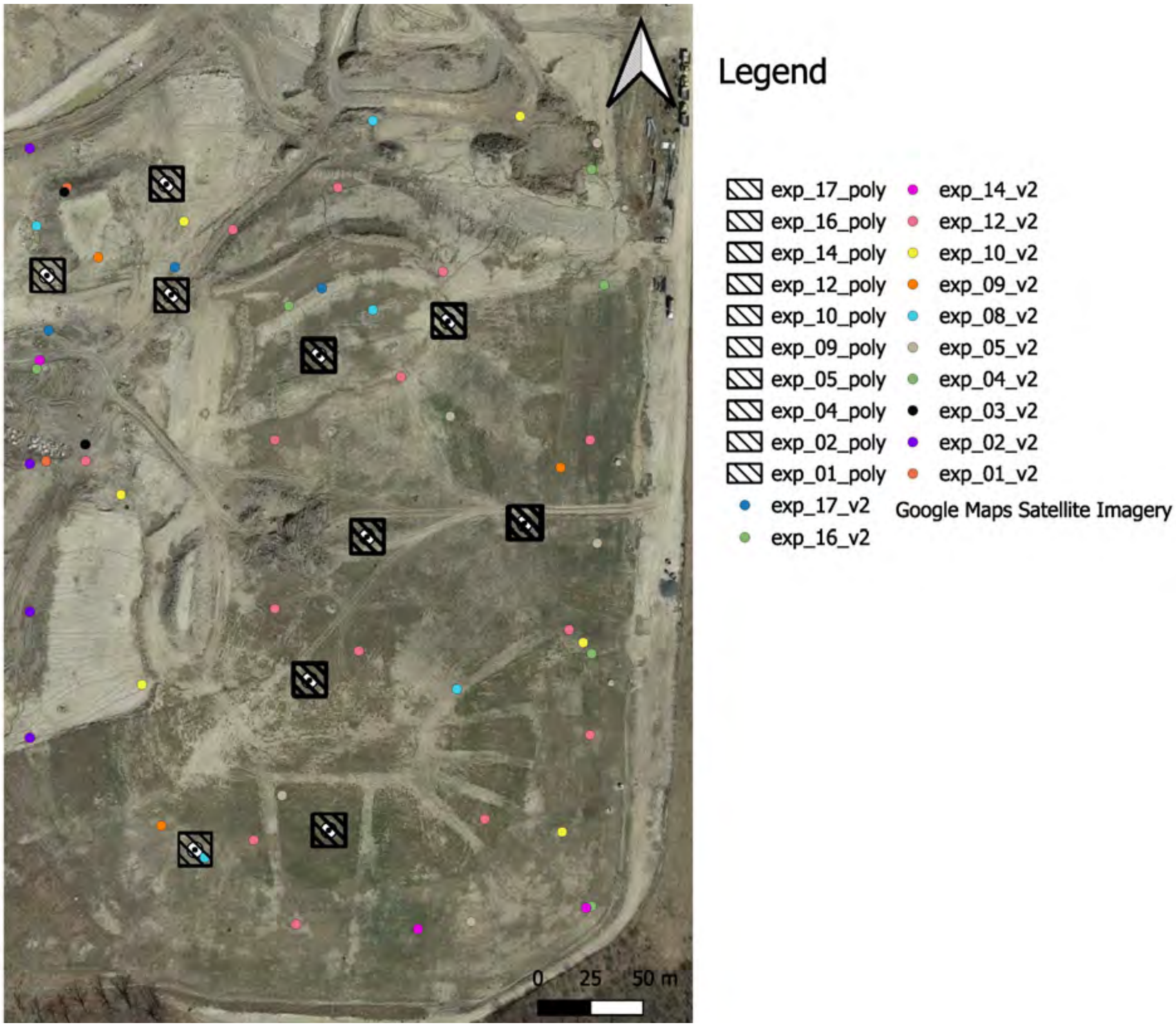


Figure C-5: Vendor N localization assessment map

D: Methodology properties

Table D-1: Methodology summary table

Technology Identifier	Method	R&D ?	Cost Estimates [USD]	Limitations	Vendor Reported minimum detection limit
A	MGPA	No	$5,000 /day	Can operate in most weather conditions. Ideal weather conditions for methane measurement around a landfill include stable and moderate wind speeds, consistent temperatures, absence of precipitation, and stable barometric pressure.	5 kg/hr
B	MGPA	No	$5,000 /day	Can operate in most weather conditions. Ideal weather conditions for methane measurement around a landfill include stable and moderate wind speeds, consistent temperatures, absence of precipitation, and stable barometric pressure.	5 kg/hr
C	UPSEA	No	$5,000-8,000 /day	Any precipitation, humidity exceeding 95%, temperature below 5 degrees Celsius or above 40 degrees Celsius and windspeed exceeding 12 m/s prevent measurements from taking place.	0.02 kg/hr
D	UPSEA	No	$5,000-8,000 /day	Any precipitation and/or windspeed exceeding 18 m/s prevents measurements from taking place.	1 ppb/s
E	MTCEA	No	$5,000 /day	Lightning and heavy rain prevent measurements from taking place.	5 kg/hr
F	APSEA	No	14,000 /day	Very stable atmospheric conditions, high winds or rapidly varying wind directions are not suitable for this method. Precipitation, extreme turbulence and conditions that does not allow visual flight to be observed	3-5 kg/hr

				prevent measurements from taking place.	
G	LiDAR	No	$14,000 /day	Conditions that do not allow visual flight rules to be observed and/or 10 m windspeed below 2 m/s or exceeding 9 m/s prevents measurements from taking place.	0.5 kg/hr
H	SISEA	No	$3,000-6,500 / package	Cloud cover over the site or wind speed exceeding 10 m/s.	100 kg/hr
I	RPSEA	Yes	$7,000-30,000 / year	Requires clear weather conditions to take measurements.	Not available
J	RPSEA	Yes	$7,000-30,000 / year	Below - 40 degrees Celsius	100 ppm at 100 meters
K	RPSEA	Yes	$7,000-30,000 / year	Below - 40 degrees Celsius	1 kg/hr
L	UCSEA	No	$5,000-8,000 /day	Precipitation, snow on ground, wind speed exceeding 6 m/s and visibility below 5 km prevent measurements from taking place.	1 ppm
M	UCSEA	No	$5,000-8,000 /day	Precipitation and windspeed exceeding 7 m/s prevent measurements from taking place.	1 ppm
N	LEA	Yes	$5,000 /day	Can operate in most weather conditions. Ideal weather conditions for methane measurement around a landfill include stable and moderate wind speeds, consistent temperatures, absence of precipitation, and stable barometric pressure.	5 kg/hr

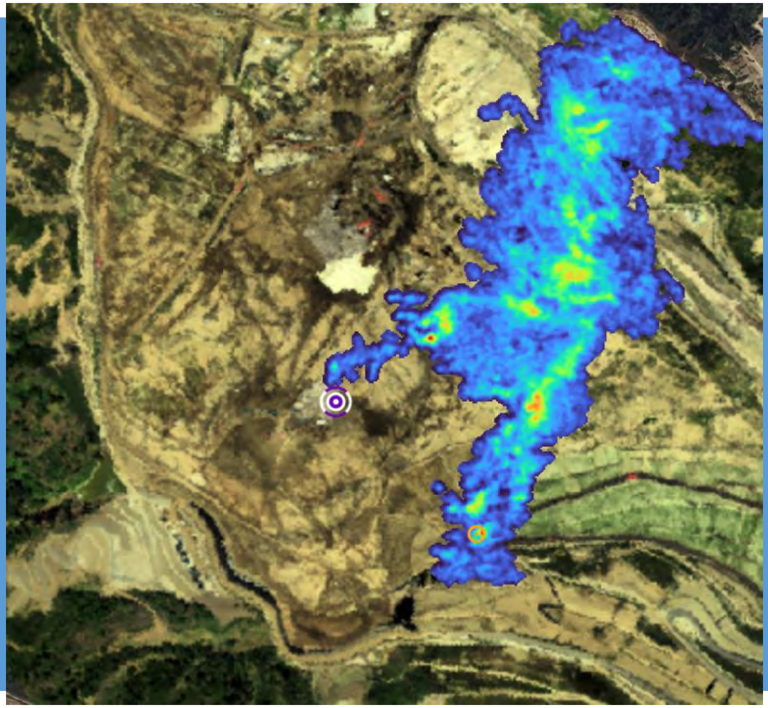
EXHIBIT 3

EPA

Air, Climate, and Energy Research Webinar Series

Hosted by EPA's Office of Research and Development

Schedule & Recordings: https://www.epa.gov/air-research/air-climate-energy-research-webinar-series



March 19, 2024 from 3:00 to 4:00 p.m. ET

Airborne Survey – Methane from U.S. Landfills

Webinar Slides: Shared through email from EPA-Webinar-ACE@icf.com.

To Ask a Question: Select **Q&A** at the bottom of the screen. Type your question in the compose box, and then select **send.** *You have the option to submit questions anonymously.*

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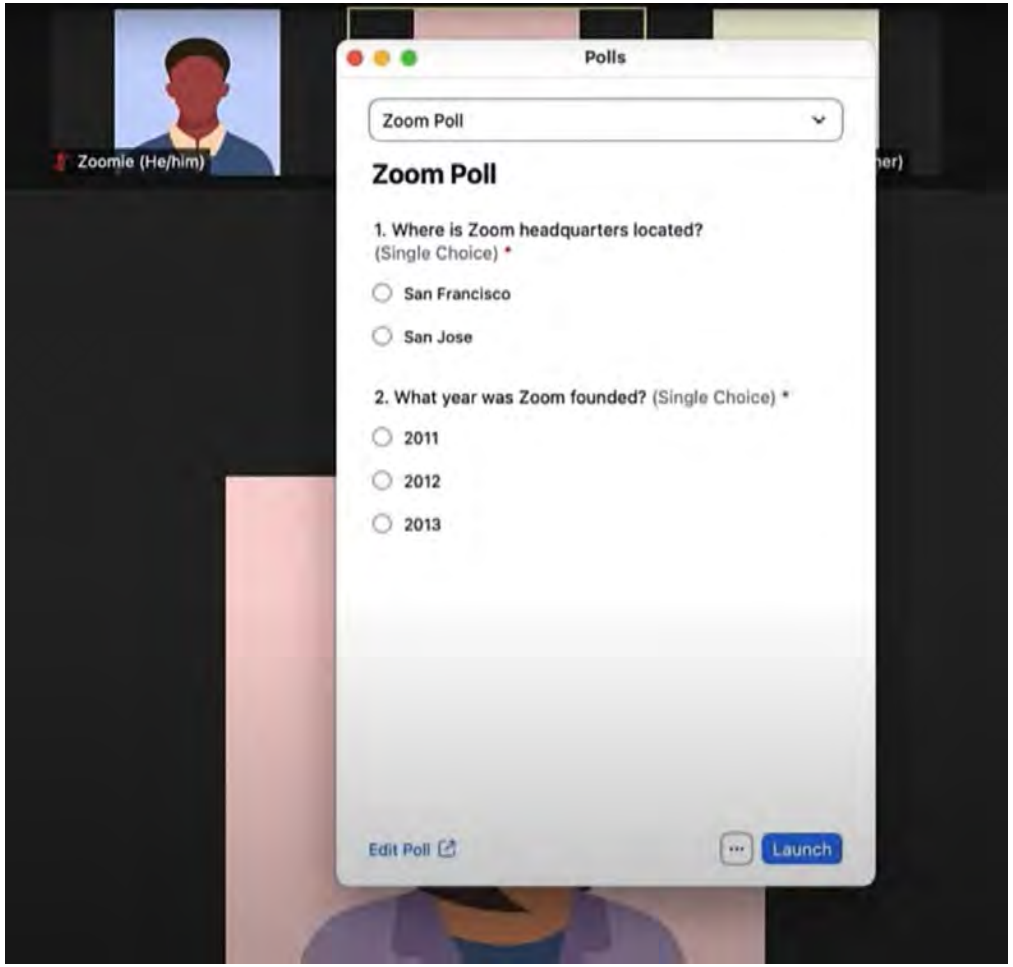
1. Find the Zoom dashboard at the bottom of the window, select the "Poll" button, and a window should pop-up separately

- *There is one question: "How many participants are viewing this webinar at your location?"*
- If you are viewing with someone registered on the same computer and would like to receive a Certificate of Attendance, email their Full Name(s) and Email(s) of the additional participants to EPA-Webinar-ACE@icf.com.



To ask a Question:

1. Select **Q&A** at the bottom of the screen.
2. Type your question in the compose box, and then select **send.** *You have the option to submit questions anonymously.*

For IT Questions:

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HABS, Hypoxia, and Nutrients Research

November 20: *Health Effects and Ecology of Anatoxin-Producing Cyanobacteria*

Registration and Additional Information

Small Drinking Water Systems

December 3: *Lead Reduction Updates and Lead Service Line Identification (LSLID) and Replacement*

Registration and Additional Information

Tools and Resources Training

December 5: *ECOTOX Knowledgebase and PFAS Updates*

Registration and Additional Information

Healthy and Resilient Communities Research

December 10: *Allostatic Load and Epigenetic Age Acceleration as Measures of Cumulative Health Impacts*

Registration and Additional Information

Emergency Response Research

December 11: *Regional Research Partnerships to Address High Priority, Near-Term Research Needs: Splash Pads & COTS Flight Simulator to Support Aerial Recon Training*

Registration and Additional Information

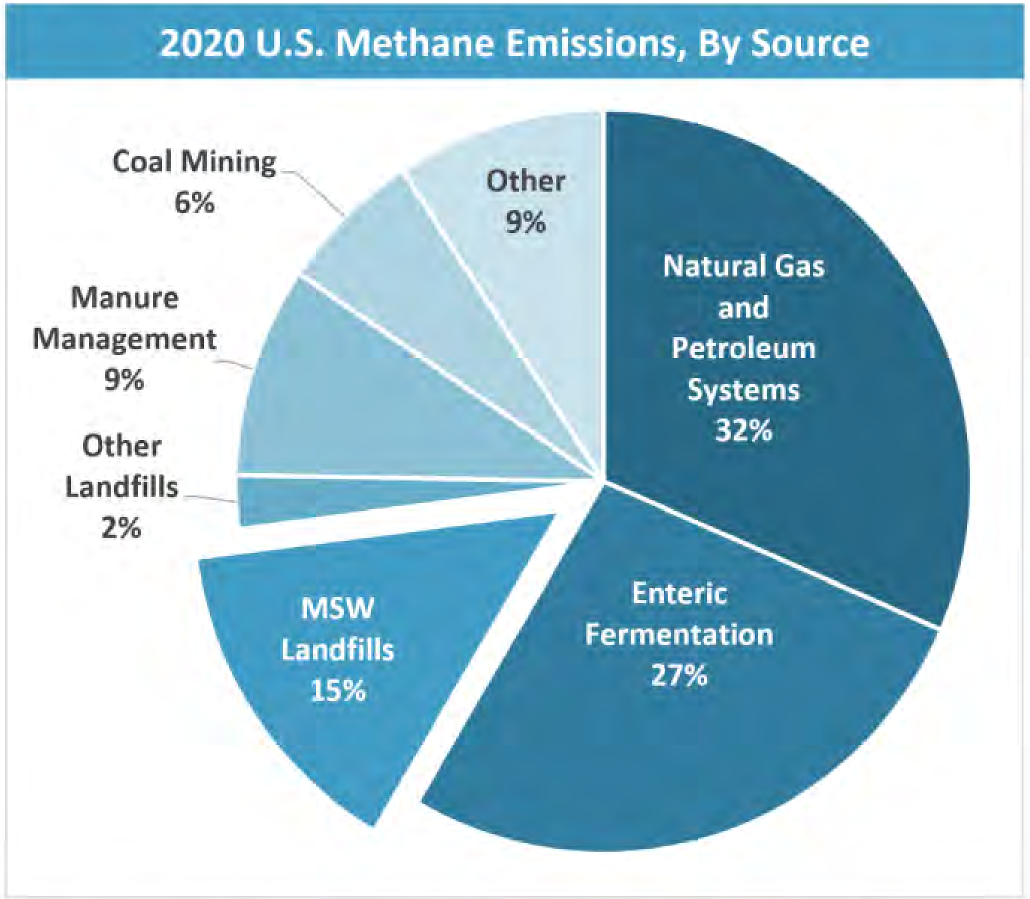
Airborne Survey - Use of Next Generation Emission Measurement (NGEM) Technology to Detect and Measure Landfill Methane Emissions

Susan Thorneloe, Senior Chemical Engineer

Disclaimer: This presentation has been subjected to review by the EPA ORD and approved for publication. Approval does not signify that the contents reflect the views of the Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

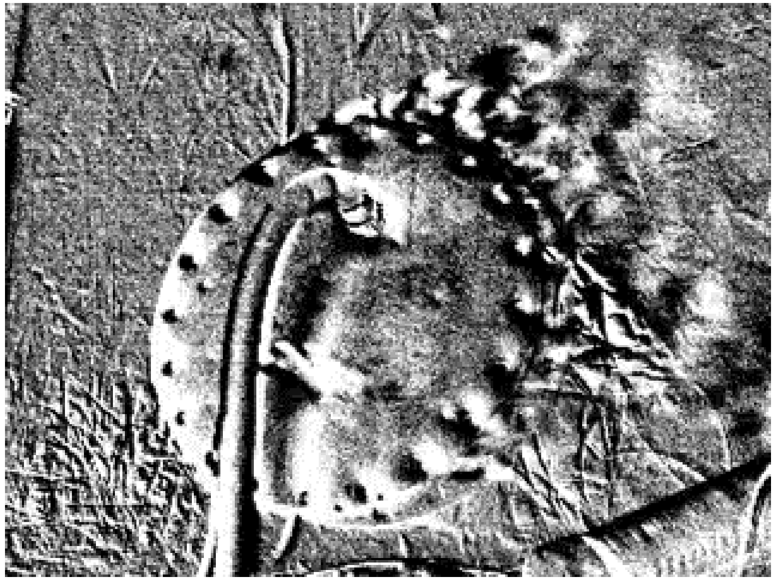
Characterization of Landfill Gas (LFG) and Pollutants

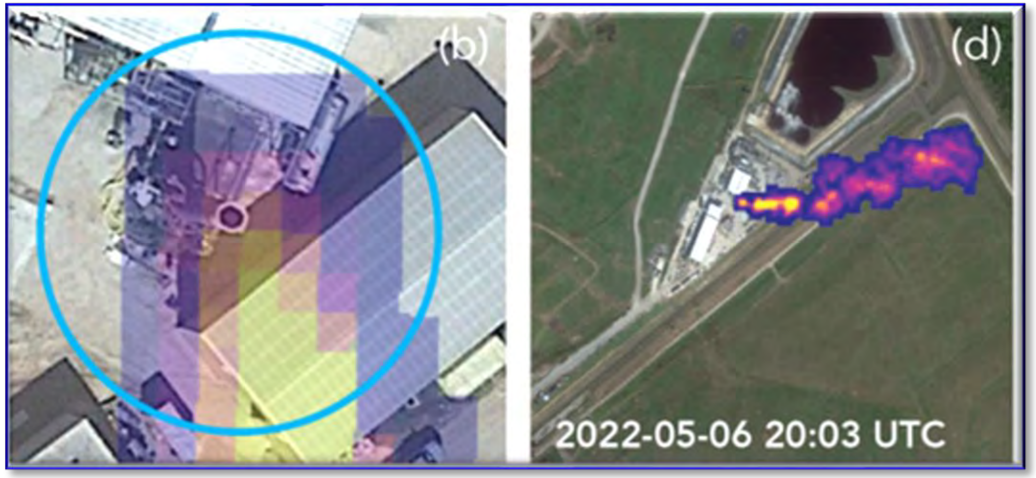
- LFG is roughly 50% methane – potent GHG
- Methane is also flammable and explosive
- VOCs contribute to air quality issues and ozone nonattainment
- HAPs and sulfur emissions affect local health & quality of life



Note: All emission estimates from the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2020.

Examples of **fugitive sources** (can occur on any part of the landfill)





Different fugitive sources not captured through gas capture and control (GCCS)

Cover Integrity Issues

Ground-Based Optical Remote Sensing

- EPA-ORD research helped drive some of the technology changes that we are now seeing
- In the past, site access was required – that is no longer needed thanks to use of satellites, aircraft, and drones

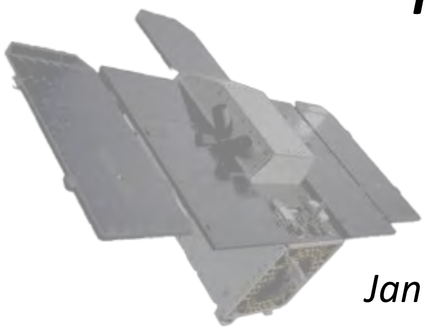
Next Generation Emission Measurement (NGEM) Technology Options for detecting and quantifying landfill methane are growing at an amazing pace

Emerging Satellite Forms

GHGSat

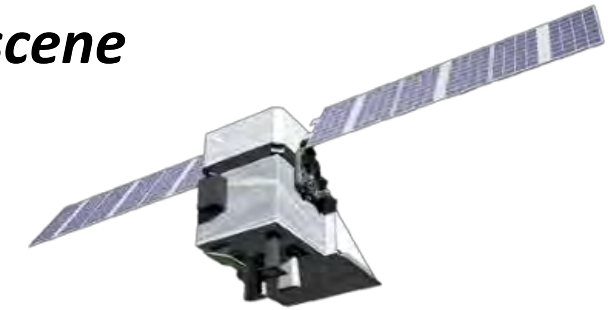
↓

New on the scene



Jan 21, 2024

Carbon Mapper

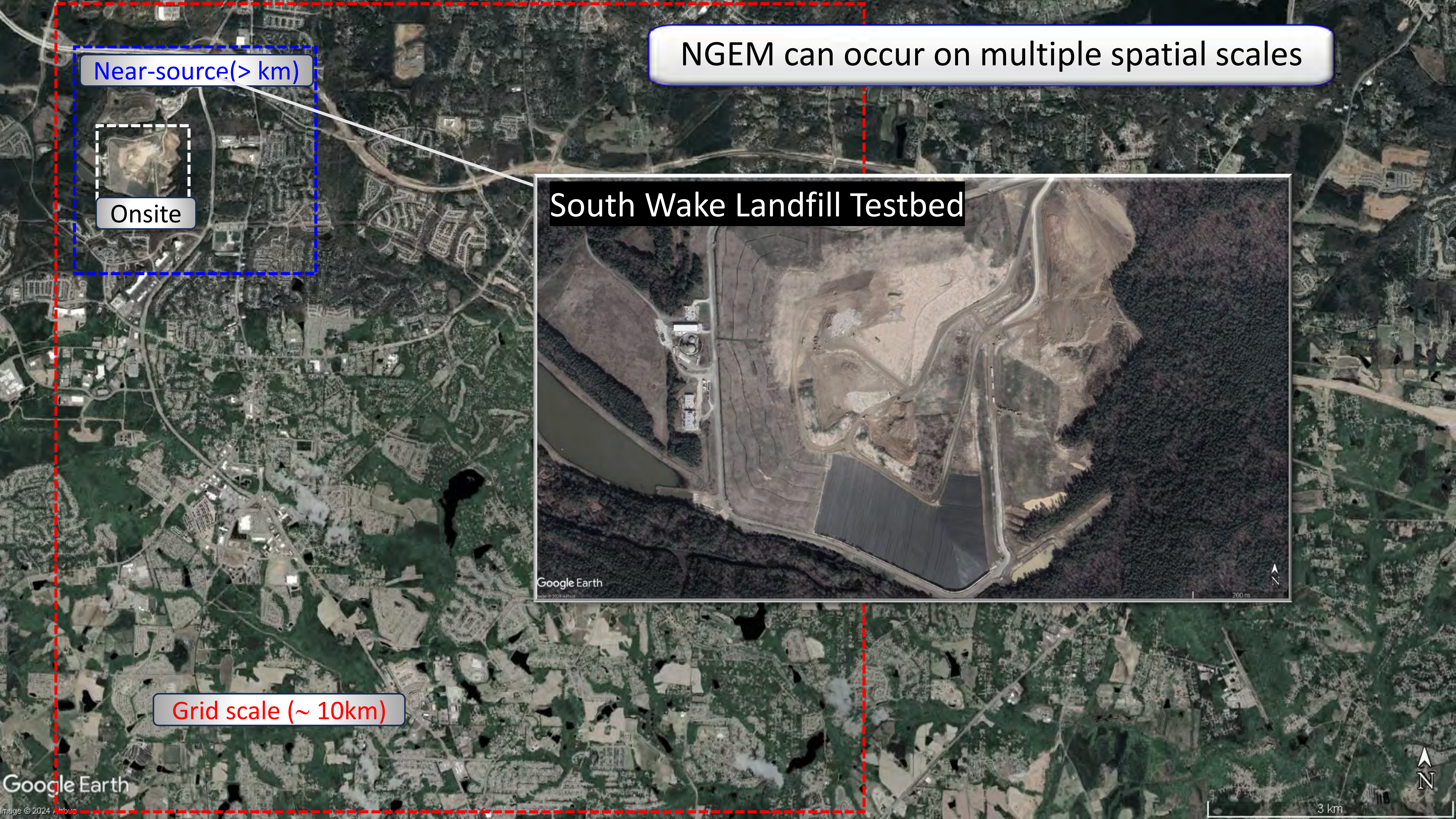


Jan 29, 2024

MethaneSAT

ORD's first look satellite landfill measurements was part of a 2023 NASA evaluation of GHGSat which generated 97 observations of 13 U.S. Landfills. Publications are in process looking at these data in a variety of ways (Max Krause lead).

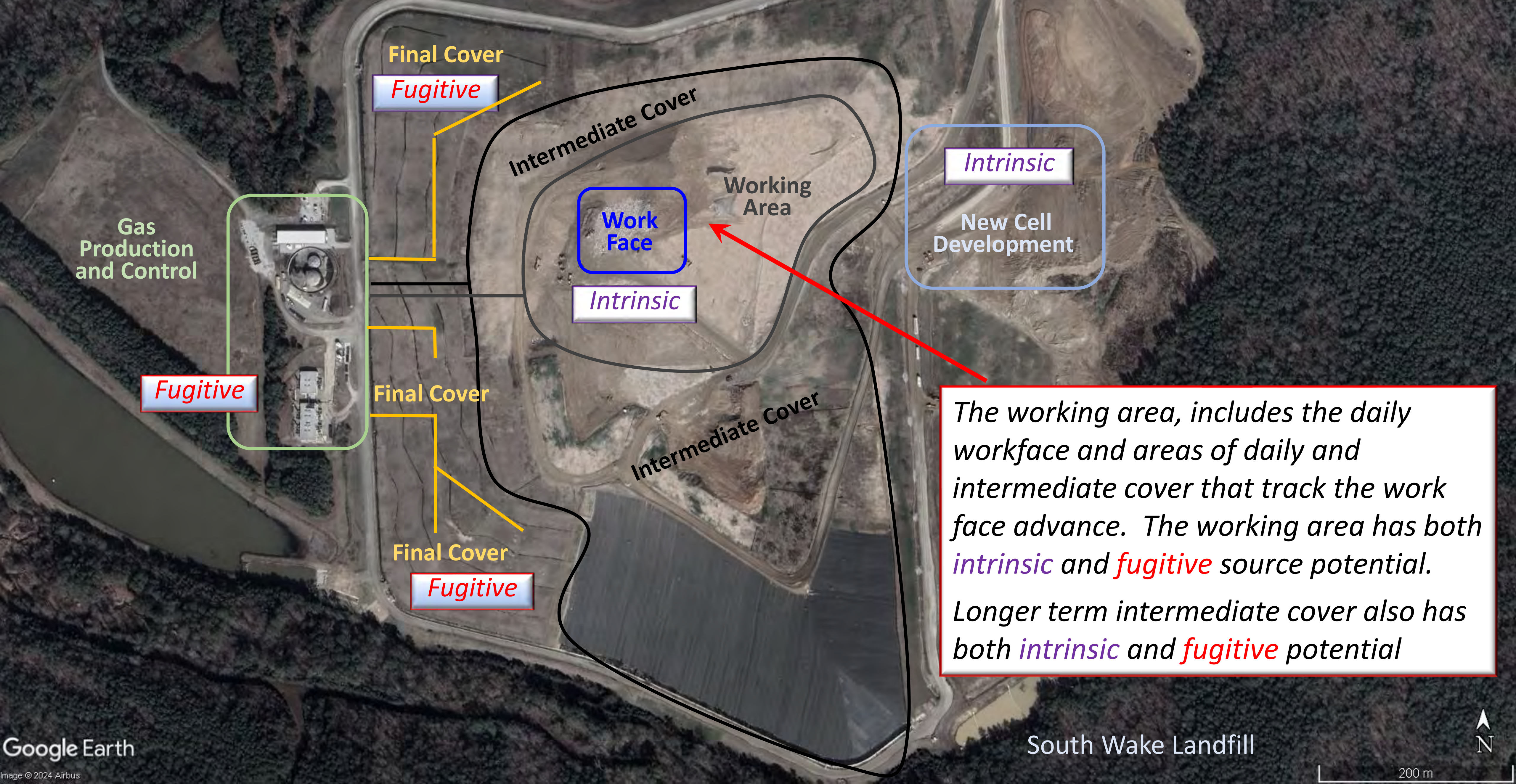
"NASA Commercial Smallsat Data Acquisition (CSDA) Evaluation of GHGSat to Measure Landfill Methane Emissions", Krause M.J., Thoma. E.D., Thorneloe, S., Valin, L., Szykman, J., NASA Report, (*in review*).


NGEM can occur on multiple spatial scales
Near-source(> km)
Onsite
South Wake Landfill Testbed
Google Earth
Grid scale (~ 10km)
Google Earth
Image © 2024 Airbus
3 km
N

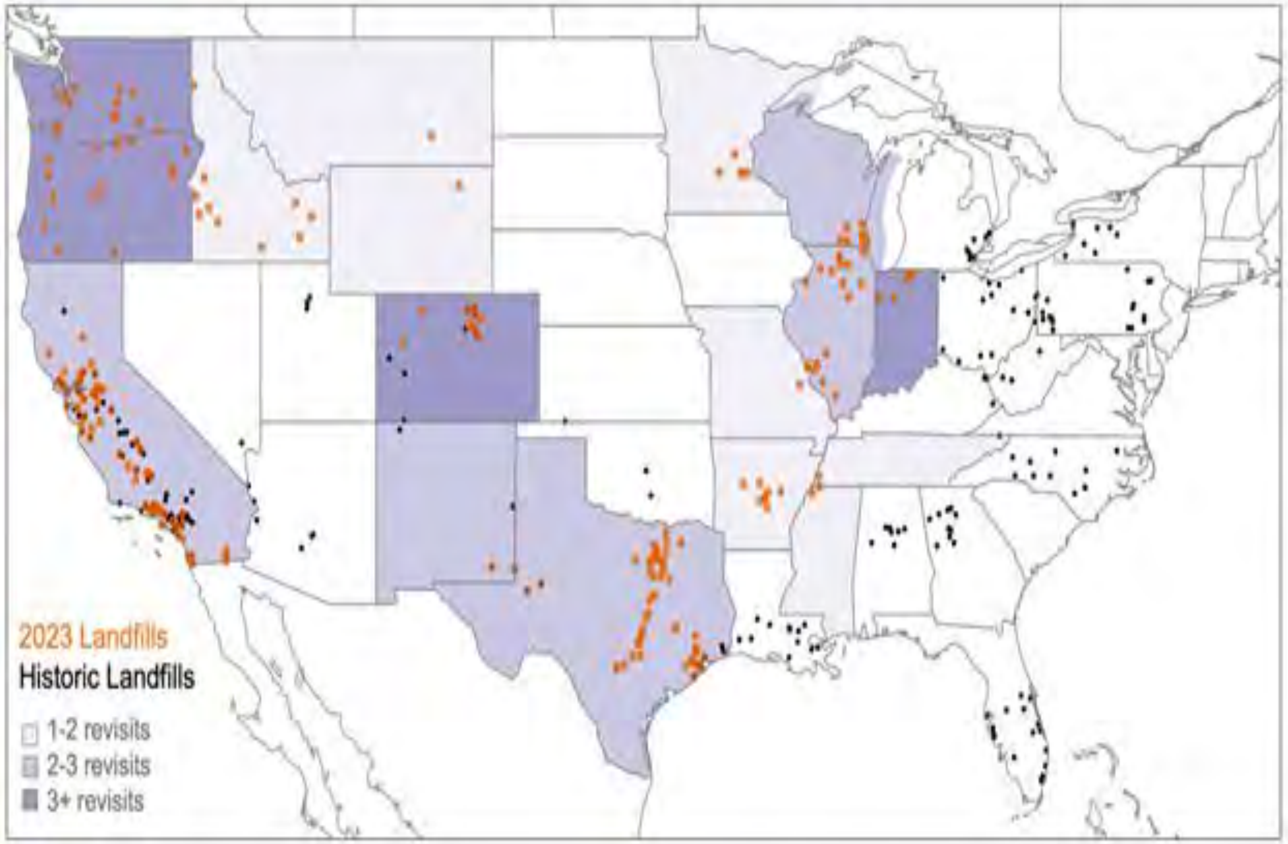
Landfill Methane - Source Types

- Landfills have both intrinsic (or expected) emissions and fugitive sources
- Intrinsic emissions are partially controlled but can't be eliminated and include:
  - Work face
  - Intact cover
  - Maintenance activity
- Fugitive sources include:
  - Cover system failure (surface leaks)
  - Gas extraction system issues (various types)
  - Infrastructure leaks, flare issues, or venting due to malfunction state
- Using NGEM to understand and reduce fugitive emissions is a near-term ORD priority
- Improved understanding and control of intrinsic sources is critical but is longer-term

What source type dominates on different areas of landfill facility?



Multi-year surveys using aircraft have produced datasets on landfill methane emissions helping to detect large leaks and quantify methane: Carbon Mapper/NASA-JPL landfill flights from 2016 - 2024



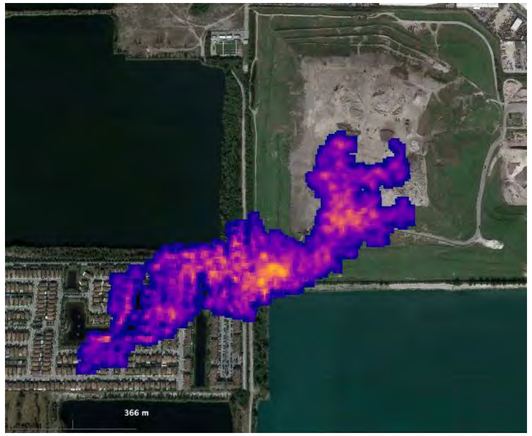
Quantifying methane emissions from United States landfills", Cusworth et al. 2023https://www.science.org/doi/10.1126/science.adi7735

Findings:

- Detection rate for "large" landfills is high: 50% of landfills had large point-source detections (compare to oil & gas where only 0.5-1% detected)
  - Emission persistence is high: 60% persistence even after 8+ flights (oil & gas ~20%)
- Correlation to the EPA Greenhouse Gas Reporting Program (GHGRP) is low. Half of sites are above GHGRP, half below. Emissions from airborne craft about 2.4 times higher than GHGRP (findings in Science publication)

High emission methane point sources observed in many regions outside California

Florida



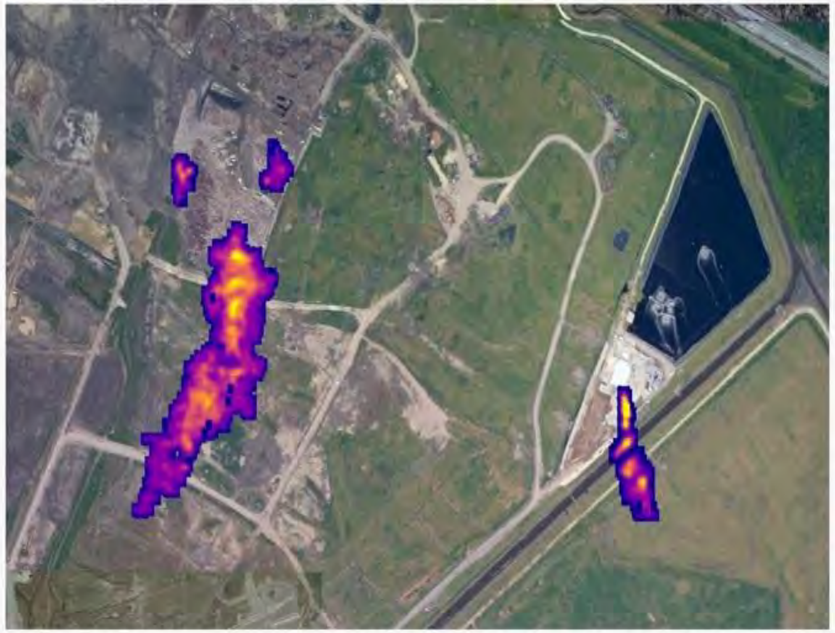
Georgia

Alabama

Louisiana

Amid reports of "super emitters," experts say getting the emissions numbers right is essential to curbing a potent climate pollutant.

By James Bruggers and Phil McKenna (Inside Climate News), Amy Green (WMFE) and Robert Benincasa (NPR)
July 13, 2021



Remote sensing of methane from high altitude aircraft reveals plumes of the gas coming from the open face, on the left, and from a vent, on the right, at the River Birch landfill outside New Orleans in April 2021. Researchers from the University of Arizona, Arizona State University, NASA's Jet Propulsion Laboratory, and Carbon Mapper calculate the rate of methane venting at approximately 2,000 kilograms per hour, which would be 48 metric tons per day. Credit: University of Arizona, Arizona State University, NASA JPL and Carbon Mapper.

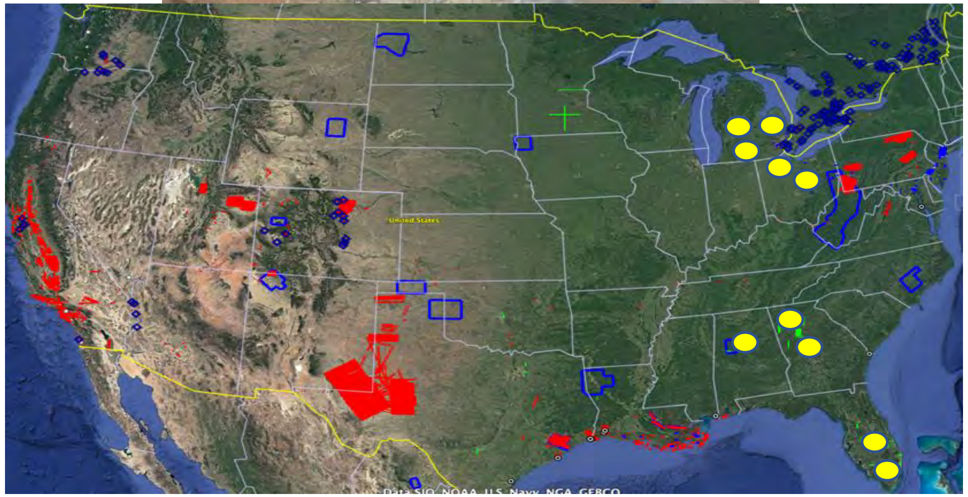
Many similar examples in CA, CO, NV, LA, MI, OH, PA

Independent Validation of the remote sensing methods from NASA-JPL and Scientific Aviation

(1) NASA-JPL researchers surveyed California landfills using a high-altitude remote sensing (aircraft). Additional observations by CM efficiently measured high-emission point sources at hundreds of landfills over large regions.

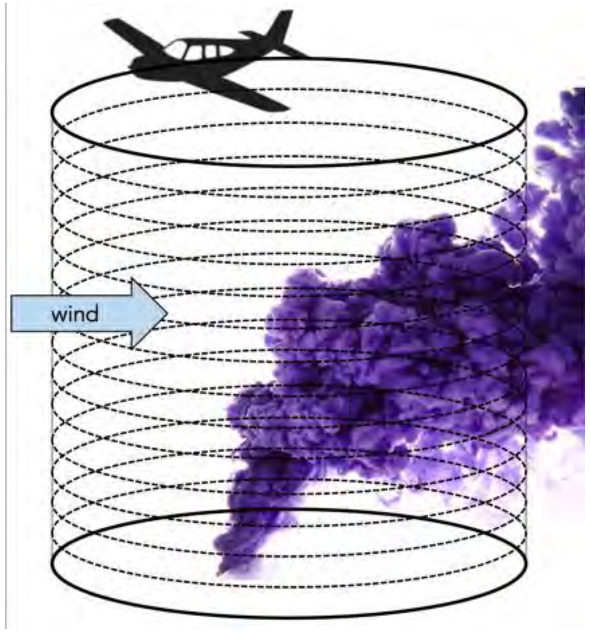
(2) Scientific Aviation (SA) was deployed to provide independent validation of the NASA-JPL/Carbon Mapper measurements using low altitude in-situ sensing aircraft that captures “total” emissions (diffuse and point sources)

Carbon Mapper has also participated in blinded controlled release experiments (Stanford)

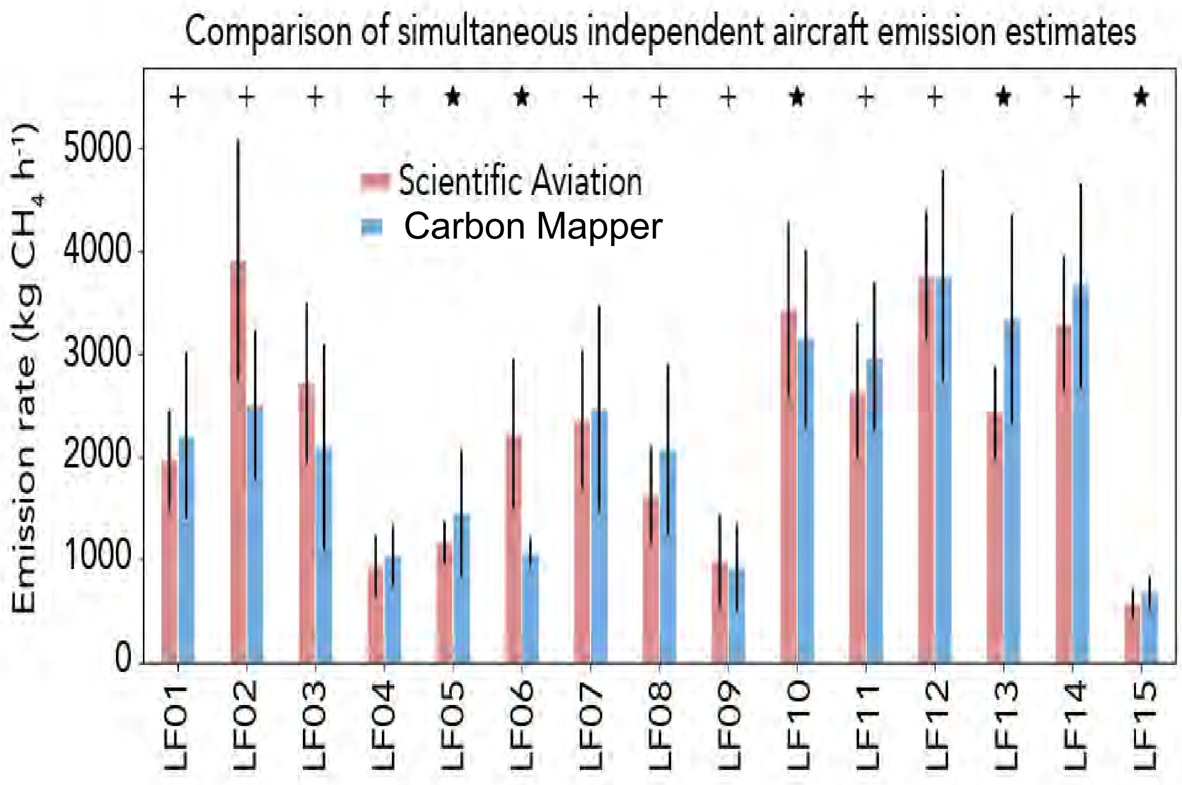


Yellow dots: coordinated validation surveys with both aircraft

Red/blue/green lines: broader regional remote sensing surveys



Results from comparison of simultaneous Carbon Mapper and Scientific Aviation Measurements

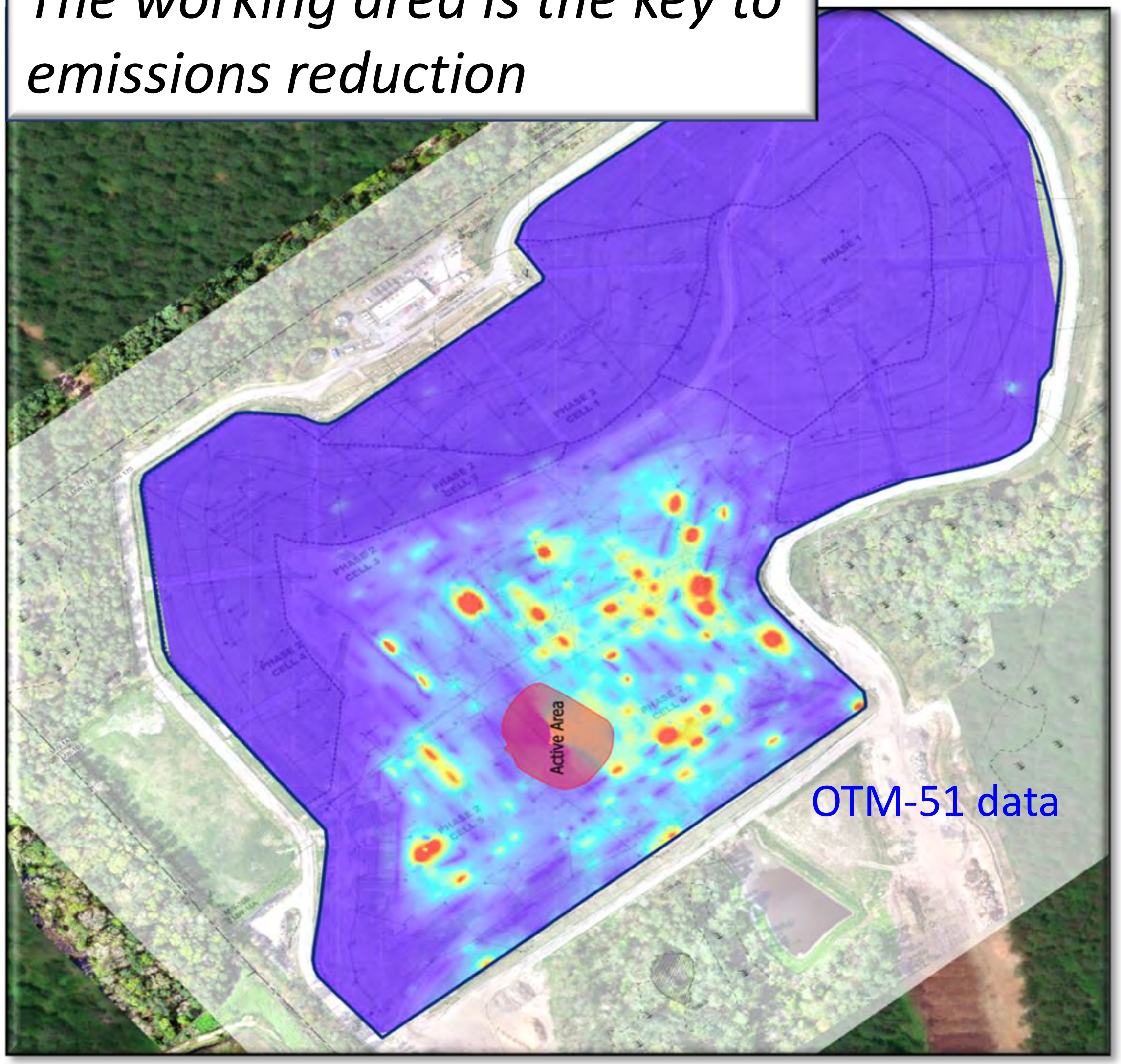


- Airborne hyperspectral imagery (Carbon Mapper) detects discrete point-like sources and general CH_4 enhancements to some degree
- Airborne flux surface (Draft OTM-58A, Champion X/ Sci. Aviation) is a whole facility measurement approach
- Currently, point-like sources appear to represent a significant fraction of whole facility emissions

Quantifying methane emissions from United States landfills", Cusworth et al. 2023https://www.science.org/doi/10.1126/science.adi7735

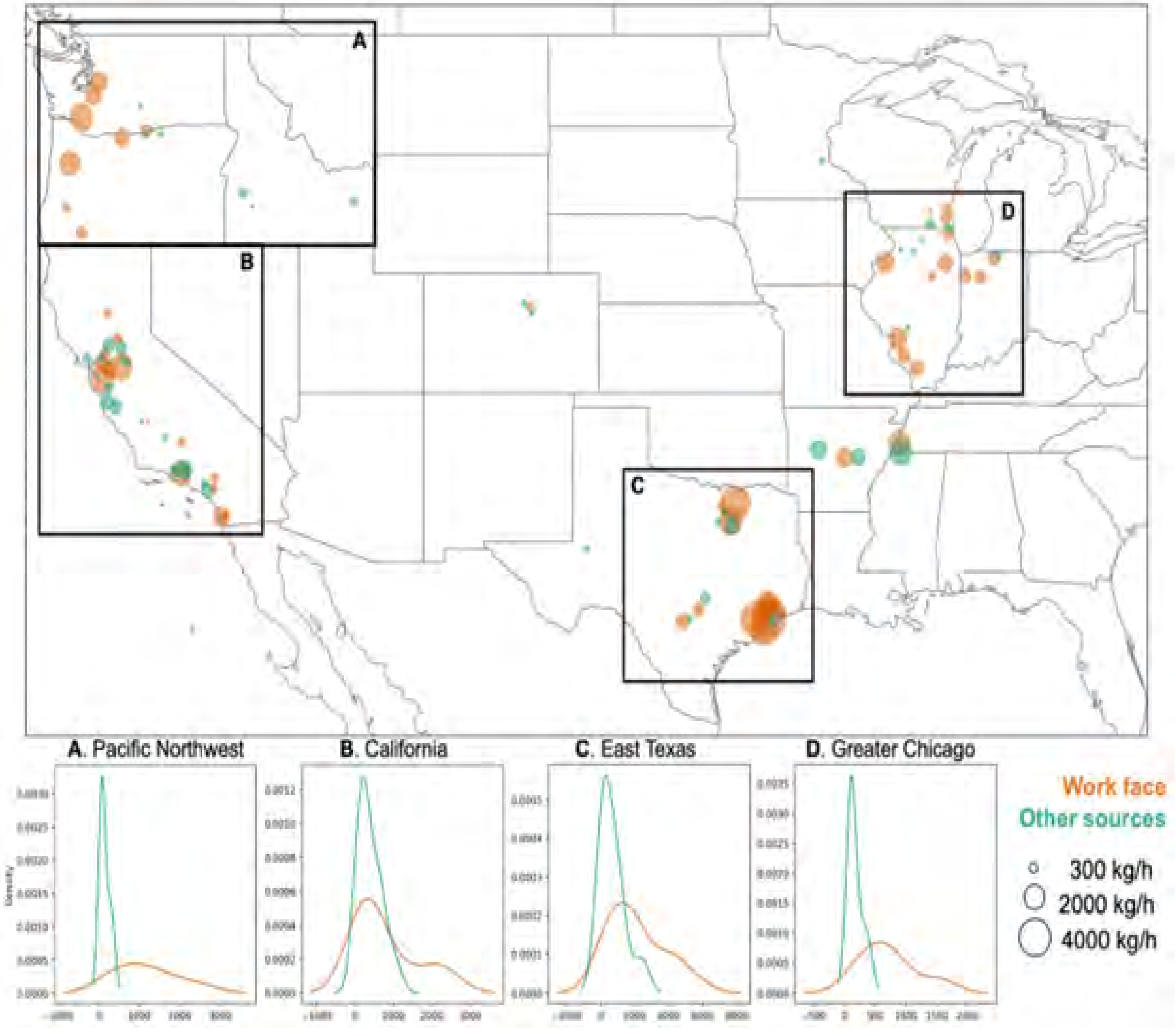
Working Face Emissions

The working area is the key to emissions reduction



"Understanding and Reducing Fugitive Landfill Emissions Using Combined Well Performance and Methane Air Monitoring", **AWMA Measurements Meeting Sims et al., 2023**

Measurements from Aircraft

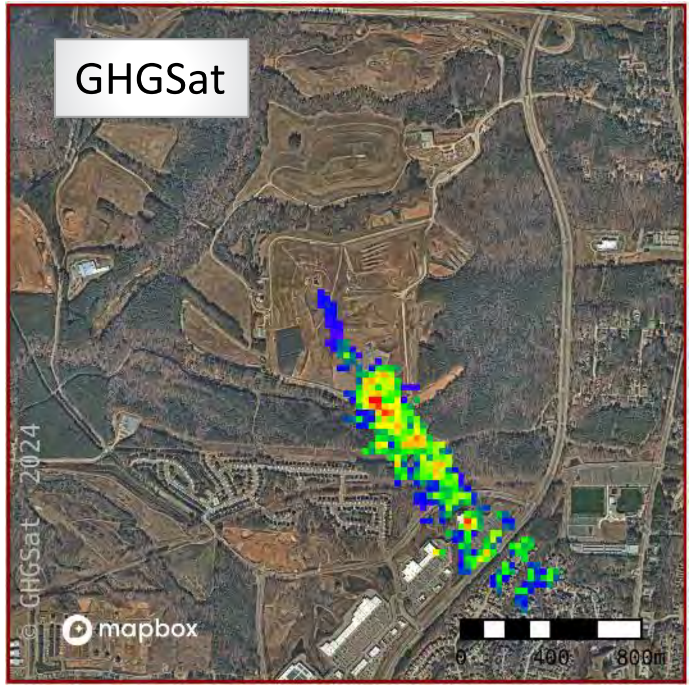


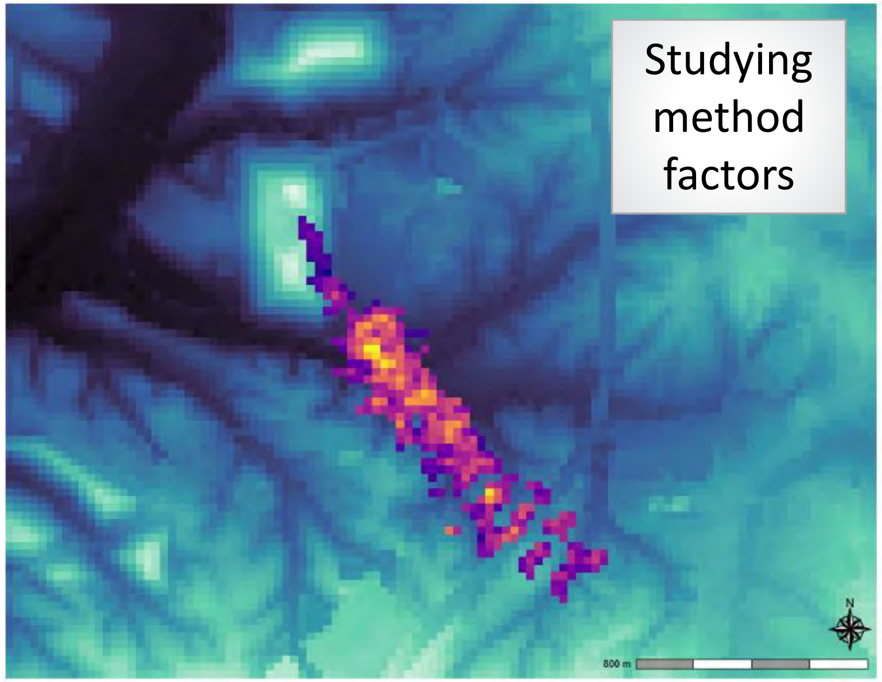
- Focus of 2nd manuscript (through partnership between EPA, Carbon Mapper, and NASA) is to investigate aircraft remote sensing data to attribute work face emissions to total fugitive landfill methane. Anticipate publication in ES&T in near future.
- Have conducted additional aircraft measurements at 14 landfills in NC, SC, and GA. Emission measurements occurred fall 2025 to further investigate landfill methane leaks and quantification.
- Time resolved GCCS data are needed along with landfill design and operating conditions that affect fugitive loss. Also need data on meteorological conditions including barometric pressure. Focus is to determine total fugitive loss versus amount of gas collected through GCCS.

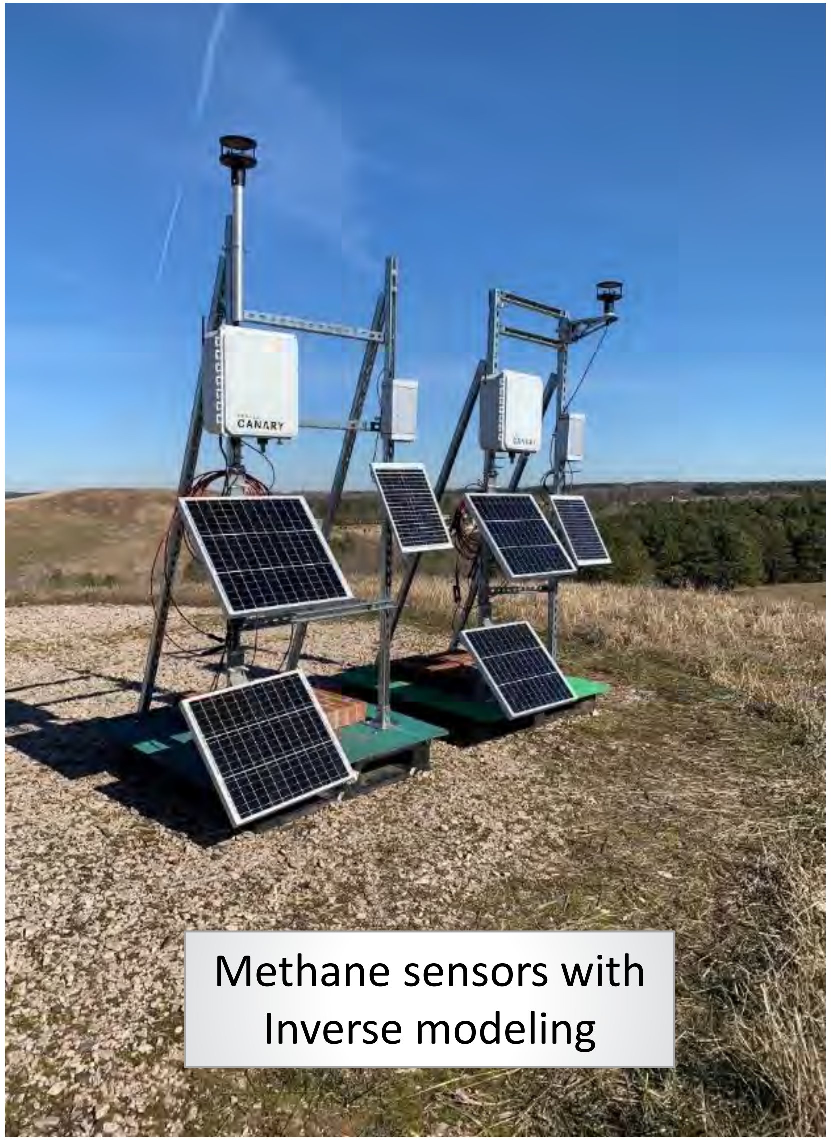
"Investigating Major Sources of Methane Emissions at US Landfills", Scarpelli et al, ES&T, accepted, in press).

Next publication will use data from fall 2024 measurements on landfills in NC, SC, and GA to further explore work face emissions.

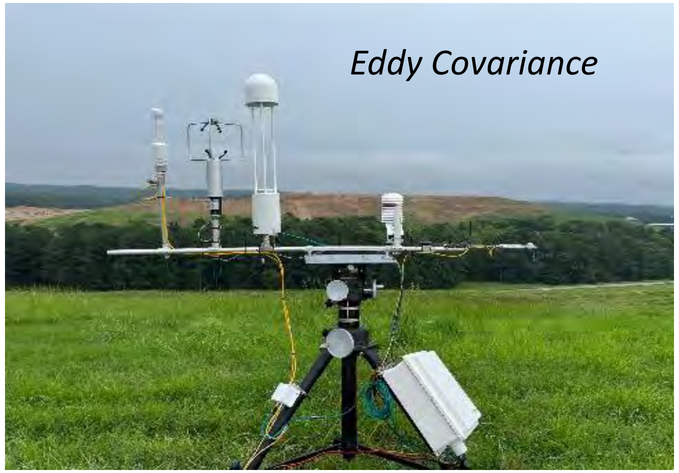
Multi-tier Method Comparisons at EPA South Wake Landfill Testbed







- 21 GHGSat observations to date
- 6 multi-unit sensor stations installed
- 8 wind measurement positions
- Future advanced wind field and Solar column methane measurements supported by parametrized CFD flow field modeling



Methane Point Sensor Trials at EPA ORD Test Range

- Cross platform reference comparisons with simulated methane plumes *(fixed placed sensors and UAV forms)*
- Conclusion: Methane sensors have come a long way in recent years. The hardware is there.

"An evaluation of commercial methane sensors using controlled release testing", Champion, W.M, et al (in preparation)

Handheld Methane Tunable Diode Lasers (TDLs)

ORD refers to this as manual column sensor emission assessment (MCSEA)

More established models

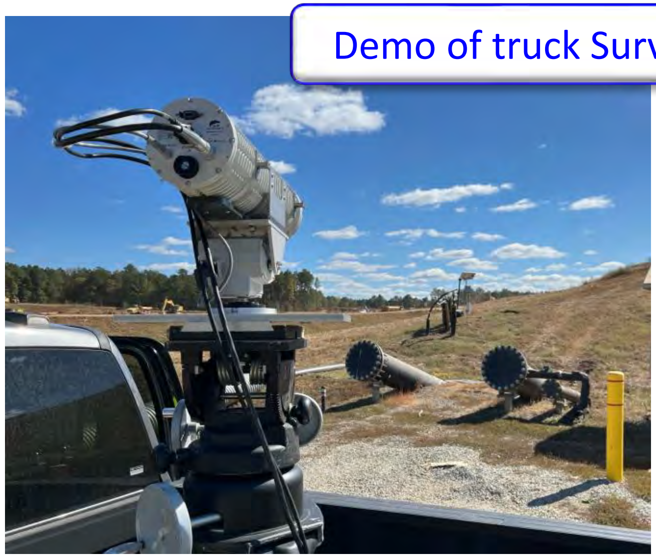
- Handheld TDLs are column sensors and variations of this tech are used on UAVs (downward looking laser)
- Handheld TDLs are mature and proven (for other applications) and have clear value for landfill fugitive emission assessment
- Collaborative near-term method development is needed

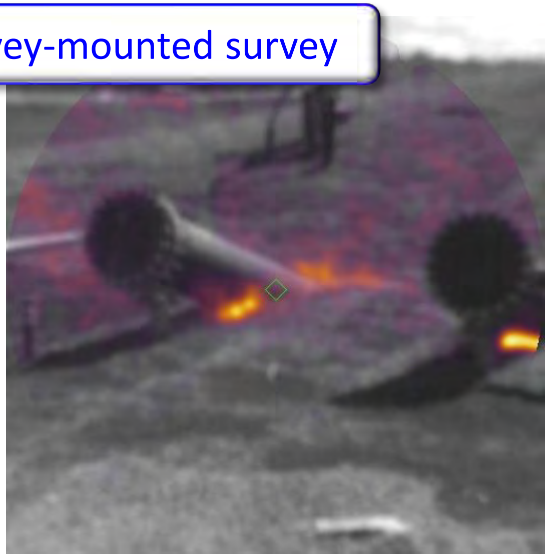
There are many sensors in this class.

What performance is needed?

Emerging Column Sensor Forms (e.g., QLM LiDAR)

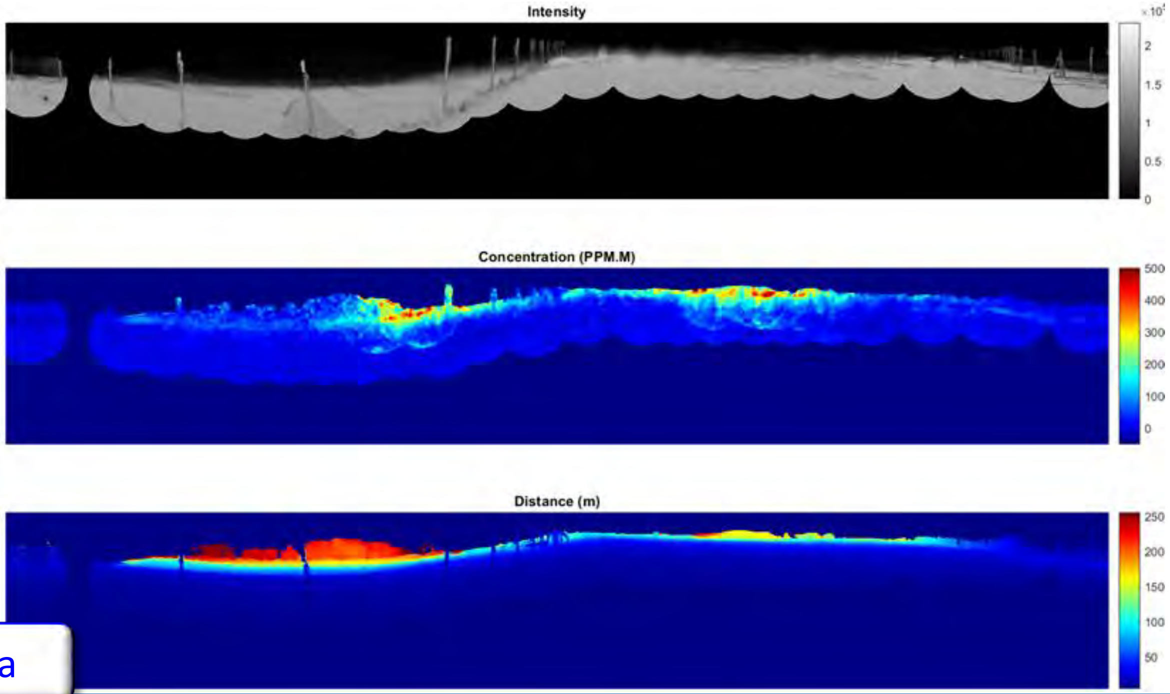
Demo of truck Survey-mounted survey





Demo of continuous scanning of large area

- A “step up” from TDLs but not as sensitive
- Companies like QLM and Bridger Photonics
- Deployed from trucks or aircraft (UAVs one day)
- Can provide 24-hr scanning for diurnal studies
- These data are from QLM pilot on 10/17/24
- Can quantify (with proper wind field data)



Added Value of Any UAV-based Approach

UAV surveys can produce valuable metadata that can be used by the operators to reduce emissions. Here are examples of aerial imagery showing problematic cover conditions.

Adapted from 2024 Sniffer Services and Solutions 20240809.pptx (with permission)

Time-resolved GCCS data (three types)

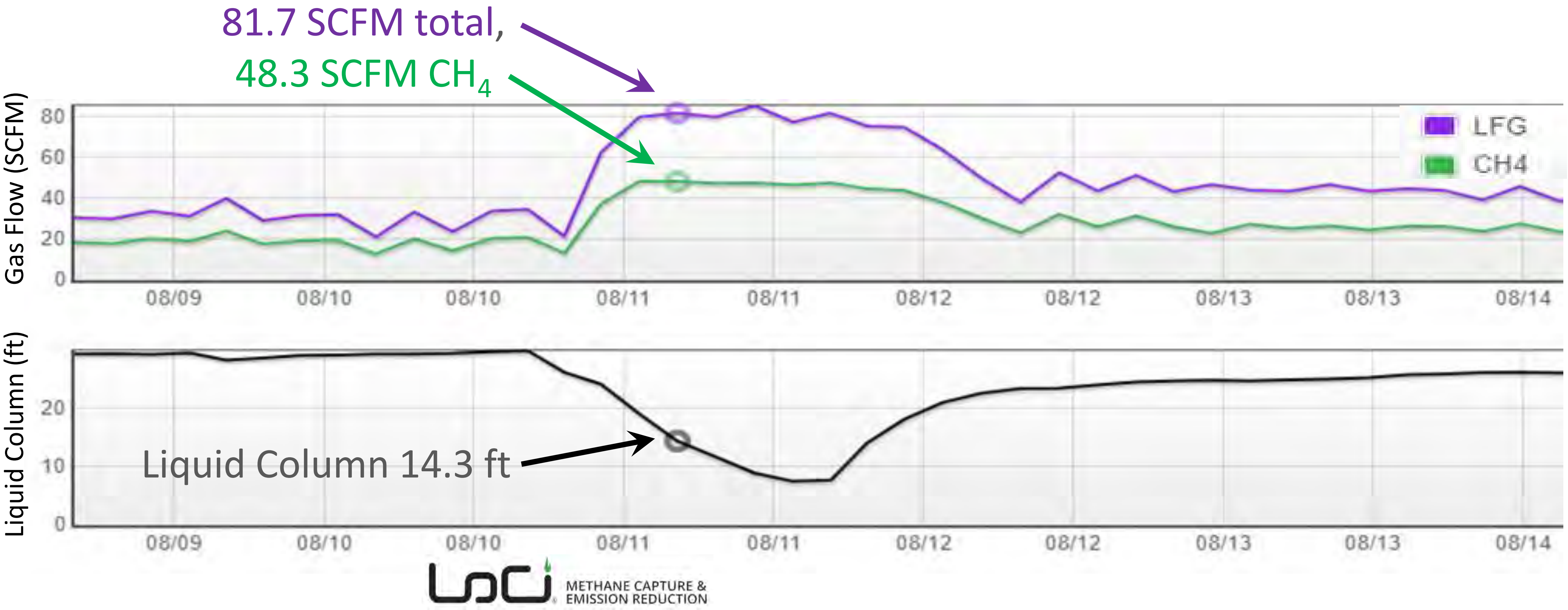
Aggregate - one location
(at flare)

Partitioned - few locations
(on header pipes)

Each well - many locations
(auto well-tuning)

Individual well data can add value

Improvement in gas collection during flooded well pump out



Environmental Research & Education Foundation (EREF), Summit on Quantification of Landfill Emissions, October 24- 25, 2023, Chicago IL, https://cfpub.epa.gov/si/, Record ID: 359503.

EPA Landfill STAR Awardees

University of Wisconsin, Jamie Schauer (Lead)

Analysis of Continuous Monitoring Data with Inverse Atmospheric Models to Improve Landfill Gas Emissions Data and Elucidate Drivers of Emissions

Five STAR Awards
4 regular, 1 early career
Total funding of $4,592,430

University of Delaware, Paul Imhoff (Coms Lead)

Evaluation and Control of Emissions from Municipal Solid Waste (MSW) Landfills: Direct Measurement and Modeling

Colorado University – Boulder, Mike Hannigan (Lead)

Integrating Measurements Across Platforms to Feasibly Assess Emissions and Mitigation of Methane and VOCs from Landfills

University of California - Berkeley, Dimitrios Zekkos (Lead)

Next-generation landfill monitoring: a multi-scale approach to measuring emissions for evaluating and financing interventions

Miami University, Jiayu Li (Early Career)

Integrating Multi-source Data for Landfill Methane Emission Quantification

For additional information on EPA STAR, please contact Serena Chung <chung.serena@epa.gov>

Next Steps

- Will be working with EPA colleagues, industry, NGOs, academia and others to evaluate what next generation measurement (NGEM) technologies work best for landfill leak detection and quantification of methane (mass emission rate).
- A multi-tier NGEM approach is likely with collection and evaluation of performance data where technology is deployed at landfills
- NGEM advancements from oil and gas applications have accelerated the pace of NGEM technology for landfill applications - However, we recognize unique characteristics and variability across landfills that make leak detection and quantification of methane more difficult.
- STAR efforts will provide landfill specific data for 9 landfills evaluating different NGEM technologies
- We thank Carbon Mapper, CARB, ECCC, EDF, EREF, NASA, industry, and others helping to advance detection of landfill leaks and methane quantification technologies that are resulting in near term carbon reduction at US landfills.