Niki Wuestenberg

Please see attached comments from Republic Services.

REPUBLIC SERVICES

Sustainability in Action

April 17, 2026

Via Electronic Submittal

Clerks' Office
California Air Resources Board
1001 I Street, Sacramento, California 95814
Electronic submittal: https://ww2.arb.ca.gov/lispub/comm/bclist.php

Dear Clerk,

This letter shall constitute the public comment of Republic Services on the "Proposed Amendment to the Regulation on Methane Emissions from Municipal Solid Waste Landfills" circulated by the California Air Resources Board for public comment on April 2, 2026.

We thank you for the opportunity to provide this comment on the draft regulation. Please let us know if we can answer any questions or if you have any requests for further information on these comments.

1. Surface Monitoring Exceedances (§ 94569(a)(1)(D) and (a)(2)(D))

The proposed language stipulates that any surface monitoring exceedance found by an inspector constitutes an immediate violation, subjecting the operator to "no-fault" civil penalties, assessed daily, until the "leak" is considered remediated, and even subjecting the operator to potential misdemeanor charges. (Health and Safety Code §§ 42404, 42400.) Historically, landfill methane rules have treated surface emissions monitoring exceedances as performance indicators requiring corrective action rather than strict-liability violations absent an opportunity to cure. This is a significant shift from the previous sanction, which simply required a return to quarterly monitoring.

- Active landfills are required by state regulations to use twelve inches of compacted intermediate soil cover over areas of the landfill that are not currently active but have not yet reached final permitted fill elevations. (17 CCR § 20700(a).) This intermediate soil cover is subject to voids, cracking, and depressions due to exposure to the elements, including rain, wind erosion, earthquakes, settlement, barometric pressure changes, and other natural conditions that are unpredictable and occur spontaneously. Therefore, surface exceedances can and do occur sporadically and without notice, even under best management practices. The emission will often occur between quarterly or even monthly surface monitoring events. That is why the regulation specifies what corrective action should be taken by the operator where such surface "leaks: are found. **By replacing the "return to quarterly monitoring" corrective action pathway and replacing it with immediate daily violations and civil penalties, the rule becomes purely punitive rather than remedial**.

- Furthermore, under § 95470(b)(5), operators must provide CARB with a 15-day advance notice of scheduled monitoring. If CARB performs a compliance inspection before that window lapses and identifies an exceedance, the operator is penalized without a cure period. Controlled-release testing studies demonstrate that walking surface monitoring methodologies based on portable hydrocarbon detectors are problematic and sensitive to meteorology, ground conditions, survey-grid spacing, operator path selection, and interpretation variability. Because these tools are screening-level work-practice methods rather than quantitative emissions measurements, they should not serve as automatic strict-liability enforcement triggers without confirmatory evaluation. There are well-known and substantial questions regarding the efficacy and variability of surface monitoring using a portable hydrocarbon detector. See, "*Simplex-Landfill Methane Controlled-Release Study: Measurement Performance From the Second Experimental Campaign,*" Fluxlab and Tarek Abichou, March 2026. The following quotations are taken from this article, which is attached for your review.

> *In most cases, the walking MGSEM* [handheld hydrocarbon detector surface emission monitoring] *methodology failed to detect active emission sources or incorrectly localized detected emissions. (p. 12) <u>False positives were common in the MGSEM results, where the participant detected concentrations above threshold when there was no source within 15 m.</u> (p. 13) The regulatory EPA Method 21 MGSEM work practice (500 ppm threshold and 30 m spacing) did not perform well, <u>consistent with longstanding concerns</u>. Despite rapid advances in UAV-based detection technologies, MGSEM exhibited the lowest detection performance among the methodologies evaluated across the past two years. Field observations and modeling together suggest that, under real-world conditions, MGSEM detections are largely probabilistic—occurring when the survey path happens to intersect an emission source—or dependent on operator skill and interpretation of audio, visual, and olfactory cues. <u>These factors can produce variable and non-equivalent outcomes</u> <u>across sites and users</u>. Consequently, MGSEM performance using 200- or 500-ppm thresholds is expected to depend strongly on meteorology, ground conditions, survey-grid design, path spacing, and operator aptitude. (p. 19)*
> [Emphasis added.]

Recommendation: Where an operator is duly performing quarterly or monthly surface monitoring, where applicable, and is promptly repairing any exceedances found during the operator's inspections, exceedances discovered during compliance inspections should trigger a corrective-action period rather than immediate daily violations. This approach maintains alignment with emissions-reduction objectives while preserving consistency with established landfill methane regulatory frameworks.

2. Grid Assessment Requirements (§ 94569(a)(4)(A))

This section requires both a collection system assessment and a cover integrity assessment on **all adjacent grids** whenever a single grid shows recurring exceedances. The requirement to conduct both collection system assessments and cover integrity assessments on all adjacent grids whenever a single grid experiences recurring exceedances introduces investigation requirements that are disproportionate to the localized nature of most surface emission exceedances.

Surface methane exceedances typically arise from localized settlement, isolated well performance variation, temporary cover disturbance, intermediate cover desiccation, or localized gas migration pathways rather than system-wide performance issues. Because landfill surface monitoring programs are resource-intensive and weather-dependent, expanding assessment obligations beyond affected grids may unintentionally reduce monitoring efficiency by diverting personnel and equipment away from targeted corrective actions.

- Assessing every adjacent grid creates an exponential increase in workload based on a localized issue and will likely detract from the regulatory goal of allowing the operator to focus its resources on the grids that require corrective action.

Recommendation: Adjacent grids should not be subject to automatic collection system and cover integrity assessments.

3. High Temperature/CO Wells (§ 94569(d)(3)(C) and (e)(4)(E) & (F))

Regarding Section 94569(d)(3)(C), we recognize the intent of CARB wishing to see additional data on warmer wells, but if a well is warm due to biological or abiotic conditions and the heat is not the result of a subsurface oxidation (SSO), collecting additional carbon monoxide readings weekly is not useful. Carbon monoxide is a byproduct of early-stage methanogenesis and it is commonly found in warm and elevated temperature landfill gas when methane concentration is low, carbon dioxide is elevated, and hydrogen is present. If those conditions are present, while the presence and concentrations of CO may be interesting or a point of curiosity, monthly data are not useful in terms of guiding the management of the well. Therefore, we propose that if a warm or elevated temperature condition is not the result of an SSO, that CO monitoring be required weekly for 4 events in order to provide baseline data, and that semi-annual readings be taken thereafter to provide a more useful body of data.

Daily civil penalties should not be assessed on a "no fault" basis when the operator cannot feasibly correct the high temperature condition.

- <u>Inability to Correct Some High-Temperature Wells</u>. Not all high-temperature wells can be brought below the 145^o threshold. High temperature conditions can be caused by a variety of factors beyond the operator's reasonable control, which cannot be feasibly corrected, including abiotic heat generation due to waste composition, and biologically produced heat due to normal waste degradation mechanics. The corrective action required in these circumstances should be to encourage the operators to increase heat removal via gas and liquid extraction from the waste mass. The collection of additional data on a frequency that does not enhance decision-making processes only serves to divert resources from the task that should be front-and-center, which is gas and, if present, liquid removal to reduce the buildup of heat within the waste mass.

It is also important to note that if warm or elevated temperature conditions exist, even with aggressive heat removal efforts, those warm conditions are likely to persist for years (up to 15 to 20 years as reported for some landfills). This further highlights that unnecessarily frequent data collection only results in a multitude of data that will not shorten the duration of the situation, nor drive a different result.

- Furthermore, for wells with high temperatures as defined in the regulation, there is a logical inconsistency between subsections E and F that needs clarification. Subsection (E) suggests it is a violation if a well over 145° F cannot be corrected, period. However, Subsection (F) triggers a violation if corrective action for a well over 170°F is not completed within 15 days. What happens if corrective action is initiated when temperatures are over 145 °F or 170 °F but the efforts prove unsuccessful? Is the operator in violation despite a good-faith effort to correct the issue?

Recommendation: If a warm or elevated temperature condition is not the result of an SSO, CO monitoring should be required weekly for 4 events in order to provide baseline data. Semi-annual readings should be taken thereafter. Also, civil penalties should not be assessed for conditions beyond an operator's reasonable control. This "strict liability" approach for subsurface conditions is punitive and fails to account for the technical realities of landfill gas management. So long as an operator is timely performing good faith efforts to correct a well's high temperature, a violation with resulting daily civil penalties should not be assessed. Otherwise, an operator could be placed in a state of perpetual non-compliance with the regulation, with no ability to correct the violation. This would raise serious legal concerns regarding fundamental fairness, a lack of due process, and the imposition of excessive fines and penalties.

4. Collection System Assessment (§ 95471(j))

The proposed text states that if "a collection system component is determined to be pinched, broken, or otherwise compromised it shall be repaired or a replacement well shall be installed…" We ask CARB to focus on whether the well is functioning (i.e., producing landfill gas), not on whether the down-hole conditions have changed from when the well was originally installed. A cracked or sheared well, particularly if the well casing is PVC or CPVC, does not necessarily stop providing value just because the pipe is “compromised” particularly if the crack or shear is in the perforated pipe section. The same can be said of other well casing materials, but the explanation is more nuanced.

If a well is still providing gas flow and, coupled with other wells nearby, the focus should be on surface emission prevention. A “compromised” well, could still provide value either in terms of gas collection or liquid removal and a landfill owner/operator should not be forced to abandon the well simply because the well is deemed by one definition or another as “compromised.” Also, the regulation does not provide clarity on the degree to which a well may be considered “pinched, broken, or otherwise compromised " before replacement is required.

Recommendations: Repair or replacement of collection system components should be required only where monitoring results demonstrate that the component is no longer contributing effectively to methane collection or surface emissions control performance. We request that CARB delete the requirement to abandon and replace a well if it is “pinched, broken, or otherwise compromised”, and instead focus on the performance of the system relative to preventing surface emissions of landfill gas.

5. Cover Integrity Assessment and Corrective Action (§ 95471(k)(1)-(5))

The proposed cover integrity assessment provisions introduce prescriptive soil sampling and classification requirements that fall within landfill construction oversight already regulated under Title 27 and administered by Local Enforcement Agencies and CalRecycle.

Methane emissions performance is already directly evaluated through instantaneous surface emissions monitoring, integrated surface emissions monitoring, wellhead monitoring, and gas collection system performance metrics. Soil classification testing does not provide equivalent emissions-performance verification.

Daily cover is temporary by design, routinely disturbed as part of landfill operations, and not intended to function as a methane containment layer. Applying methane-rule integrity-monitoring requirements to daily cover areas imposes documentation burdens unrelated to methane-control performance.

In addition to concerns regarding daily cover, the proposed cover integrity assessment requirements as applied to intermediate cover introduce prescriptive expectations that are already comprehensively addressed under California’s solid-waste regulatory framework and landfill facility permit conditions administered pursuant to Title 27.

Intermediate cover serves multiple purposes within landfill engineering practice, including:

- limiting precipitation infiltration
- maintaining slope stability
- controlling vectors

- supporting operational traffic
- protecting underlying waste mass
- facilitating staged filling operations

Intermediate cover is not designed or regulated as a primary methane containment barrier layer, and its construction specifications are already governed through:

- Title 27 performance standards
- Local Enforcement Agency inspection programs
- CalRecycle oversight
- site-specific landfill permit requirements

Therefore, introducing additional soil classification and sampling requirements under the proposed LMR rule duplicates or may conflict with these existing regulatory controls without improving methane-emissions verification capability.

Impractical Requirements:

- The requirements to obtain any number of samples per acre and to classify the cover soil is unnecessary. The intent should be that whatever cover soil is put in place should be of adequate character and quality to prevent the escape of landfill gas and prevent the infiltration of oxygen into the waste mass. This can be accomplished with a thinner layer of highly impermeable material or a thicker layer of more permeable material. Either way, the end-goal of emissions control remains the same and therefore adding soil testing requirements is unnecessary.

- Landfills often do not have a consistent source of material for cover soil; it can vary from day to day from on and off-site sources based on supply limitations and other practical considerations. Therefore, the testing requirements add an unrealistic expectation and burden. As long as the soil (or other material) that is used for cover accomplishes the goal of preventing landfill gas emissions and oxygen infiltration, the landfill owner should be afforded the ability to make the operational decision on what material to utilize.

- The rule suggests replacing Alternative Daily Cover (ADC) with soil, or daily cover with intermediate cover. At many landfills, replacing ADC with soil is unfeasible due to availability of soil and may create operational issues such as creating permanent barriers in the waste mass to the proper operation of collection wells and the leachate collection system.

- Supply Concerns: There is no guarantee that soil meeting the regulation's specific technical specifications will be available on-site or even locally when needed.

Recommendation: Revise § 95471(k)(1)–(5) to remove prescriptive soil classification and sampling requirements and clarify that cover integrity assessments supports—but does not replace—surface emissions monitoring performance verification.

6. CO Measurement Methods (§ 95471(o)(C) & (D))

We encourage CARB to add provisions for the use of colorimetric (e.g., Draeger, etc.) tubes to measure carbon monoxide concentrations in the field. Colorimetric detection tubes such as Draeger tubes are widely used throughout the landfill industry as screening-level diagnostic tools for evaluating subsurface conditions and guiding operational decisions.

In addition, colorimetric tubes are quick to use and provide data “on the spot”. Immediate field data availability allows field and management teams to evaluate and make direct operational decisions, which is particularly important when evaluating elevated temperature conditions or potential subsurface oxidation indicators. Directionally accurate and immediately available data should be preferred over “perfect” data that can slow decision-making.

- **Operational Impact:** Draeger tubes provide immediate, cost-effective field results. Transitioning to gas chromograph will likely require third-party lab analysis or expensive on-site equipment, increasing costs and, more importantly, delaying response times.

Recommendation: CARB should explicitly add provisions to allow the use of colorimetric tubes as an acceptable screening-level carbon monoxide monitoring method for landfill gas.

Conclusion

We appreciate CARB’s continued engagement with stakeholders during this rulemaking process and respectfully request consideration of the revisions proposed in these comments to support implementation clarity, regulatory consistency, and effective methane emissions reduction outcomes.

Respectfully submitted,

Niki Wuestenberg

Niki Wuestenberg, Senior Manager Air Programs

Attachment: *Simplex-Landfill Methane Controlled-Release Study: Measurement Performance From the Second Experimental Campaign,*" Fluxlab and Tarek Abichou, March 2026

cc: Mike Caprio, Director Government Affairs - CA
David Penoyer, Senior Manager Landfill Gas Operations
Judith George, Senior Corporate Counsel

ATTACHMENT

***Simplex-Landfill Methane Controlled-Release Study: Measurement Performance From the Second Experimental Campaign,*" Fluxlab and Tarek Abichou, March 2026**

SIMFLEX-LANDFILL METHANE CONTROLLED-RELEASE STUDY: MEASUREMENT PERFORMANCE FROM THE SECOND EXPERIMENTAL CAMPAIGN

PREPARED BY [1]FLUXLAB AND [2]TAREK ABICHOU
[1]ST. FRANCIS XAVIER UNIVERSITY, CANADA
[2]FLORIDA STATE UNIVERSITY, USA
MARCH 2026

For questions or to learn more, contact the Environmental Research & Education Foundation at irp@erefdn.org.

EREF
ENVIRONMENTAL RESEARCH
& EDUCATION FOUNDATION™
erefdn.org

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Methane emissions from landfills remain a significant concern for the solid waste sector. To support mitigation efforts, new technologies for detecting and quantifying methane emissions continue to emerge, although many have not yet been rigorously evaluated in landfill environments. Controlled-release studies provide an effective framework for tracking methodological progress and assessing real-world performance.

In this study, multiple methane detection and quantification approaches were evaluated during 31 controlled-release experiments conducted between 20 and 29 November 2024 at a closed landfill in Petrolia, Ontario, Canada. This work builds on a prior controlled-release campaign at the same site conducted in 2023 (EREF, 2024; Hossain et al., 2026). The 2024 campaign emphasized new and modified measurement approaches, including fixed-point sensor systems, drone-based surface emission measurements, and walking surveys. Controlled-release rates were also increased relative to 2023 to better evaluate satellite-scale detection capabilities.

Fixed-point sensor systems using the Remote Point Sensor Emission Assessment (RPSEA) approach showed clear improvement relative to 2023. In 2024, both participating RPSEA systems underestimated emissions only slightly to moderately (1.8% to 37%), with variability ranging from ±52% to ±143%. Although individual measurements exhibited variability, the continuous and high-frequency nature of RPSEA observations enables temporal averaging, which can reduce uncertainty in longer-term emission inventories.

UAV Column Sensor Emission Assessment (UCSEA) systems demonstrated substantial gains in detection and localization performance compared with 2023. The two UCSEA participants produced no false positives and achieved true-positive detection rates of 88% and 100%, respectively. These improvements are attributed to refined operational work practices and updated sensor configurations introduced in 2024.

Manual Ground Surface Emission Monitoring (MGSEM), consistent with EPA Method 21 regulatory practice, showed limited detection sensitivity. Walking surveys conducted at 500 ppm detected no true positives, while surveys at 200 ppm detected only a single true positive across 15 active sources in five emission scenarios. Under the same conditions, UCSEA systems detected 13–15 of 15 sources, indicating substantially higher sensitivity than MGSEM and lower detection capability relative to modern remote-sensing approaches.

Satellite observations were not successfully retrieved during the 2024 campaign due in part to persistent cloud cover that limited the number of clear-sky opportunities, and therefore no satellite performance results are presented despite increased controlled-release rates.

Key Takeaways

- RPSEA continuous sensor systems showed improved and operationally relevant quantification performance in 2024.
- UCSEA drone-based systems achieved high detection sensitivity with zero false positives.
- MGSEM walking surveys demonstrated substantially lower detection capability than modern remote-sensing approaches.
- Satellite validation was not possible due to cloud cover, highlighting environmental constraints on satellite monitoring.
- Controlled-release testing remains essential for objectively evaluating emerging landfill methane measurement

INTRODUCTION

As methane landfill gas emission concerns have risen, new methane measurement techniques for the waste sector are quickly being developed. Many of these techniques were originally designed for the oil and gas sector and few have been rigorously validated for waste sector applications. Only one of the new methods is formally recognized in US regulatory language. Once properly validated for waste sector use, newer approaches could transform how landfill operators understand their emissions and meet emissions reduction targets.

Recognizing the potential benefits of modernizing landfill methane monitoring, the Environmental Research & Education Foundation (EREF) launched a program to assess existing and emerging emissions measurement methods, evaluating accuracy, precision, and practicality under real-world conditions. The FluxLab research group conducted this research at the Simulation Facility for Landfill Emission Experiments (SIMFLEX) in Ontario, Canada which was built explicitly for this purpose. Dr. Dave Risk (FluxLab) provided scientific leadership in collaboration with Dr. Tarek Abichou of Florida State University.

This report presents results from the second round of methodology testing conducted in November 2024. The 2024 experiments followed significant upgrades to the SIMFLEX infrastructure, including newly buried pipelines that allowed researchers to move safely and efficiently across the site during controlled release experiments. In addition, improvements to the release technology allowed for higher release rates to assess satellite systems. The site modifications required a nearly complete re-install of the testing infrastructure that included digging almost 1 km of shallow trenches for the buried pipelines.

In the November 2023 inaugural study, the truck-based Tracer Correlation method delivered the most accurate quantified emission rates, with ±20% uncertainty. In the 2023 study, the drone flux-plane approaches performed well, although this approach was more sensitive to weather. Truck Gaussian methods underestimated emissions, whereas aircraft and aerial LiDAR methods showed upward biases that improved when local meteorology was considered. Satellite sensors failed to detect emissions, highlighting their limitations with regards to dispersed landfill sources. For leak detection, aerial LiDAR was highly sensitive, but drone column sensors, intended as a replacement for walking surveys, were far less effective than expected and were prone to false positives. In 2023, several continuous sensor systems were evaluated on an R&D basis, with only one delivering reasonable results, exhibiting an uncertainty of ±39.1% of the release rate. Although some methods were highly accurate, they were not necessarily suited for developing robust site-level inventories because inventories depend on repeated measurements and technology choice. In addition, highly accurate methods are often costly and require much effort. A detailed report of the 2023 study is available on the EREF website and in Hossain et al., 2026.

In our 2024 experiments, a new SIMFLEX program addressed gaps in participation and addressed questions that arose from the 2023 inaugural experiments. The goals for the 2024 study were:

- To assess surface emissions monitoring (SEM) methods, especially regulated walking surveys methods, and assess repeated testing of drone- and truck-based sensors to see whether improving work practice and/or changing the sensor hardware from 2023 materially improved detection outcomes.
- To assess aerial imaging and satellite capabilities. These measurement systems have been very important in shaping the landfill emissions narrative.
- To assess how well remote point sensor systems quantified rates, detected intermittency, and provided frequent estimates.
- To assess mobile point sensors for repeatability across a range of emission magnitudes and spatial patterns.

MEASUREMENT SOLUTIONS AND PARTICIPANTS FOR 2024

Table 1 lists the 14 participants and their measurement solutions. All groups self-funded their involvement and travel to the field site. Because the focus of the SIMFLEX experimental program is scientific and focusses on evaluating and, potentially, improving measurement methods, participants we assigned anonymized identifiers.

Table 1. Summary of controlled release study participants

Participant Identifier	Solution Type	Platform Type	Sensor	Method	R&D?
A	Quantification	Truck	LGR	MGPA	No
B	Quantification/Localization	Fixed	TDLAS	RPSEA	No
C	Localization	Drone	Mid-IR LDS	UGSEM	Yes
D	Quantification/Localization	Fixed	Metal Oxide	RPSEA	No
E	Localization	Drone	TDLAS	UCSEA	No
F	Localization	Drone	TDLAS	UCSEA	No
G	Quantification/Localization	Satellite	Spectrometer	SISEA	Yes
H	Quantification/Localization	Satellite	Spectrometer	SISEA	No
I	Quantification/Localization	Satellite	Spectrometer	SISEA	Yes
J	Quantification/Localization	Drone	TDLAS	UCSEA	Yes
K	Localization	Walking	TDLAS	MGSEM	Yes
L	Quantification	Truck	TDLAS	RMSEA	Yes
M	Quantification/Localization	Fixed	TDLAS	RPSEA	Yes
N	Quantification/Localization	Walking	TDLAS	MGSEM	Yes

A brief description of each methodology is provided here. Longer descriptions are available at the end of this document as supplementary information. The acronym UAV is used for unmanned aerial vehicles, i.e., drones.

- **UCSEA (UAV Column Sensor Emission Assessment):** A drone-mounted laser system that measures methane along a single beam path (ppm·m), offering fast coverage but limited sensitivity due to atmospheric dilution.
- **MGSEM (Manual Ground Surface Emission Measurement):** Walking surveys with handheld methane sensors across 30 m grids; effective but labor-intensive and depends highly on operator skill.
- **UGSEM (UAV Ground Surface Emission Measurement):** A system with a drone-borne intake tube (as per EPA OTM 51 guidelines) that mimics walking surveys with faster, safer coverage; still unvalidated in controlled release studies.
- **SEM2Flux:** Uses surface methane concentration data from SEM surveys and simplified inverse dispersion models to estimate total site emissions by optimizing source configurations.
- **RPSEA (Remote Point Sensor Emission Assessment):** Fixed stations with methane and meteorological sensors that continuously (~hourly) estimate emissions using inverse dispersion; lacks validation for landfill settings.
- **SISEA (Satellite Imaging Sensor Emission Assessment):** Satellite-based imaging that detects strong point sources at facility scales but struggles with diffuse landfill emissions due to column dilution.
- **RMSEA (Remote Mobile Sensor Emission Assessment):** Vehicle-mounted methane analyzers driven along fenceline transects to estimate emissions using dispersion models; correlates well with gold standards of measurement but typically underestimates totals.

RESULTS AND DISCUSSION

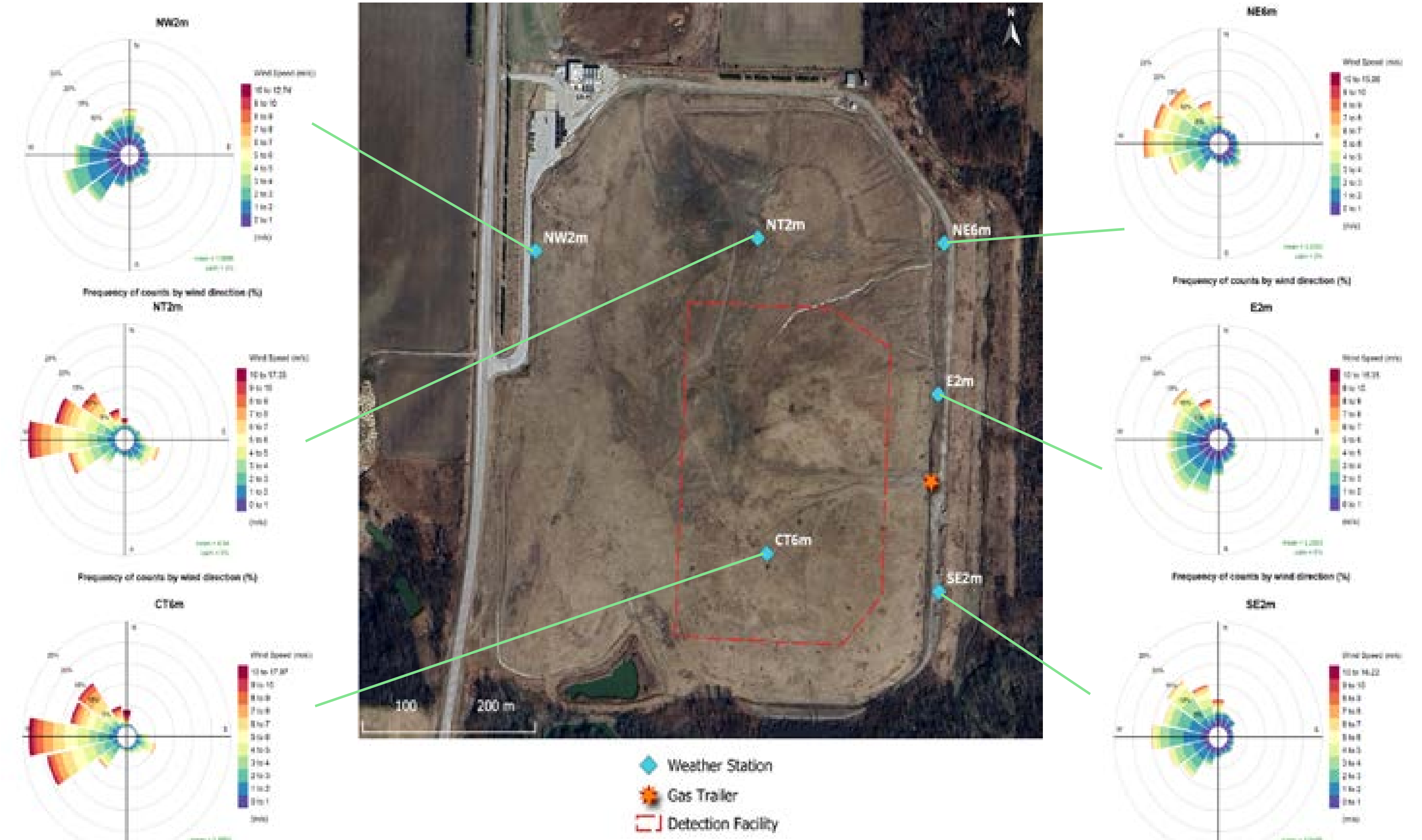
Experimental Conditions

The releases were conducted in late November 2024, with quantification and localization measurements occurring at the same time. Table S1 lists methodology and participation by day. Once measurements were complete, participants had several weeks to submit measurement estimates. Most participants submitted measurement reports within the expected time. Table S2 lists the report submission dates. After participants provided their initial estimates, they received the on-site weather station data and informed release data. Then, participants had the opportunity to resubmit their estimates. For complete details on controlled release methodology and experimental protocol, please see the Supplemental Information.

Most solutions listed in Table 1 quantify methane release rates, and a few focus on localization. Several solutions have both functionalities. Quantification solution participants submitted their estimated emission rates 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 in which they participated. Localization solution participants submitted estimated leak coordinates (longitude and latitude) and measurement time. Some participants also participated in the research and development (R&D) stream which allowed more flexibility in reporting timelines. Participant methodologies in the R&D stream were up and coming or wanting to enter the methane monitoring market.

Figure 1 shows the six positions where wind velocities were logged during the experiments. Two of the locations were at the highest point of the landfill, whereas four were positioned at the bottom. The anemometers were deployed at heights of 2 m or 6 m. For the duration of the experiments, the measured winds were moderate and considered normal for November with an average wind speed of about 5 m/s (~18 km/hr) and with substantial variability throughout the experiment. On some afternoons, wind speeds exceeded 10 m/s (~36 km/hr) at the highest point of the landfill. Wind roses are also shown in Figure 1.

Significant differences were observed in wind speed and directional variability between the highest point and the bottom of the landfill. On average, wind speeds at the bottom of the landfill were about half the magnitude of the wind speed observed at the highest point of the landfill, implying that emissions from the top or flank of the landfill might be exposed to, and transported by, winds of different speed. Wind directions were, on average, similar between the top of the landfill and its bottom, but the anemometers at the bottom measured very high directional variability. On some days, one or more anemometers at the bottom recorded almost every possible wind direction for one day, reflecting eddy flows and creating potentially un-mixed areas.



Google maps

Figure 1. Wind Conditions During Experiments. Note scales.

This spatiotemporal variability in the wind reflects the complexity of the landfill’s topography. For some participants, these winds could exceed ideal field conditions, and for some quantification methodologies, the complex winds could amplify uncertainties and measurement variability. These complex wind observations emphasize why controlled release experiments should be conducted using landfill-like topography. The full meteorological datasets from November 2024 will be in the public domain for those who wish to validate Computational Fluid Dynamics (CFD) modelling or other studies of the site.

Heavy rain fell during points of the campaign. Impacts to the number measurement days was minimal but significant overland flows damaged equipment which caused our field team to have to repair instruments overnight. Ground conditions were generally damp for the entire campaign.

This report presents results only from methodologies that completed successful performance assessments. While the inaugural 2023 study included a larger number of quantification participants and approaches, the 2024 campaign yielded assessable results from three quantification methodologies (two RPSEA and one MGSEM) and five detection and localization methodologies (two RPSEA, two UAV UCSEA, and one MGSEM evaluated at two concentration thresholds). These reductions primarily reflected technical limitations encountered during field deployment.

Several participants were unable to complete full assessments. Participant A experienced analyzer leaks that could not be resolved during the experiment, Participant C encountered early technical failures that prevented continuation, Participant J did not submit sufficient estimates for quantification or localization evaluation, and Participant L did not complete enough measurements to generate quantification results. Participant M deployed 13 fixed sensors and provided time-stamped methane concentration data (ppm) for each location, which will be archived in the St. Francis Xavier University Dataverse for the November 2024 controlled releases. However, because no quantification (kg/hr) or localization estimates were submitted, this methodology could not be evaluated using the study’s performance metrics.

Satellite participation was also limited. Cloud cover frequently prevented retrieval of satellite observations, and even during clear-sky conditions no satellite quantifications were achieved. The relatively small and spatially dispersed emission footprint of the controlled-release site likely produced column methane enhancements below satellite detection sensitivity, highlighting a potential mismatch between controlled-release geometry and typical satellite measurement requirements.

Additional experimental constraints influenced participation and interpretation. Permitting requirements and logistical limitations meant that some release locations were visible to certain participants, preventing fully blind testing in all cases. Heavy rainfall also damaged equipment and restricted the achievable range of controlled-release scenarios, resulting in gaps within the intended emission-rate matrix.

Quantification Performance Assessments

Quantification of total methane emissions was evaluated as a primary performance metric during the controlled-release experiments. Quantification performance could be assessed for three methodologies: RPSEA systems (Participants B and D) and MGSEM (Participant N). As noted previously, quantification could not be evaluated for Participants A, J, and L. Table 2 summarizes linear-regression statistics and average percent error for the assessed methodologies, based on the results reported by each participant.

The regression slope and bias factor indicate whether a methodology systematically under- or overestimates emission rates, with slopes <1 representing underestimation and slopes >1 representing overestimation. Variability in emission estimates relative to the regression trendline is represented by the standard deviation of residual percent error, where lower values indicate more consistent quantification. Replicate measurements increase statistical power and therefore reduce uncertainty in variability estimates. Experiments yielding 0 kg/hr estimates were excluded from residual calculations because percent error relative to near-zero true release rates is undefined.

Table 2. Statistical summaries of quantification performance for B, D, and N.

Technology Identifier/ Participant	Slope (1st sub)	R^2 (1st sub)	Slope (2nd sub)	R^2 (2nd sub)	Bias Factor 1/slope	Standard Deviation residuals %	Deviation from true in %	Number of estimates (n)
B	0.4840	0.7313	-	-	2.0661	52	6-138	31
D(1st)	0.8113	0.8481			1.2326	122	2-407	14
D (2nd)	-	-	1.0993	0.8404	0.9097	144	2-407	9
N	0.4383	0.8918	-	-	2.2815	21	18-72	5

Quantification performance of the remote point sensor (RPSEA) systems improved relative to 2023, when only one of three participants approached the acceptability threshold defined as the percentage of estimates within a factor of three of the true emission rates. In the 2024 study, parity plots for RPSEA methodologies (Participants B and D; Figure 2) show strong agreement between quantified and controlled-release emissions using dense sensor networks of 14 and 12 nodes, respectively.

Participant D achieved particularly high quantification accuracy, with 93% and 89% of estimates within a factor of three for dispersion trajectories of 2 min and 5 min, respectively. The 5-min solutions underestimated emissions by 9.7% with an uncertainty of ±122%, whereas the 2-min solutions underestimated by only 1.8% with an uncertainty of ±143%. These large uncertainty values (>100%) reflect both the limited number of submitted estimates and substantial variability in quantification error (absolute QE% ranging from 2% to 407%). Sensor coverage also influenced performance. In terms of bias, these results were comparable to Truck Tracer Correlation and UAV curtain-type measurements reported in the 2023 study, although variability remained higher than Truck Tracer Correlation. The continuous nature of RPSEA sensing provides the advantage of repeated measurements, which can improve statistical confidence and better capture temporal variability in landfill emissions, an advantage not fully represented in short-duration controlled-release experiments.

Participant D's measurements were selective, with only 9 (2-min) and 14 (5-min) estimates submitted out of 31 possible experiments (Figure 2; green and orange dotted lines for 2- and 5-min dispersion, respectively). This selectivity reflected internal quality-assurance requirements for sufficient spatial coverage of potential release locations before reporting whole-site quantification. Specifically, an experiment was required to achieve full coverage across the footprint of at least five release locations, or partial coverage of eight or more. All participants knew the total number of release locations

(10), yet only seven experiments achieved full coverage across all potential locations required to meet Participant D's reporting threshold. As a result, the 12-node sensor network produced fewer than one acceptable quantified result per day. Nevertheless, such performance could remain operationally valuable if comparable low-bias measurements were sustained through continuous, long-term monitoring.

Participant B, applying the same RPSEA methodology with a larger sensor network, underestimated emissions by an average of 37% with an overall uncertainty of ±52%. A total of 81% of estimates fell within a factor of three of the true emission rates, despite absolute quantification error (QE%) values ranging from 6% to 138%. Unlike Participant D's selective reporting, Participant B submitted quantification estimates for all 31 experiments, demonstrating the capability for continuous multi-day emission monitoring under the participant's sensor coverage and modeling framework (Figure 2). Participant B's accuracy is consistent with findings from controlled-release validation of continuous sensors in oil-and-gas settings (Cheptonui et al., 2025). Participant notes indicated that wind conditions were sub-optimal for some estimates; however, complete reporting provided insight into the potential performance envelope of RPSEA networks operating without strict quality-assurance filtering. Examination of the parity plots shows that the overall underestimation bias was strongly influenced by approximately six data points. If these had been excluded under a quality-assurance protocol similar to that used by Participant D, the resulting bias would likely have approached the lower-bias performance observed for Participant D. Damage to flowmeter equipment during the study limited the range of achievable controlled-release emission rates, constraining regression evaluation. Regression relationships may therefore have been clearer had the full emission-rate range been available.

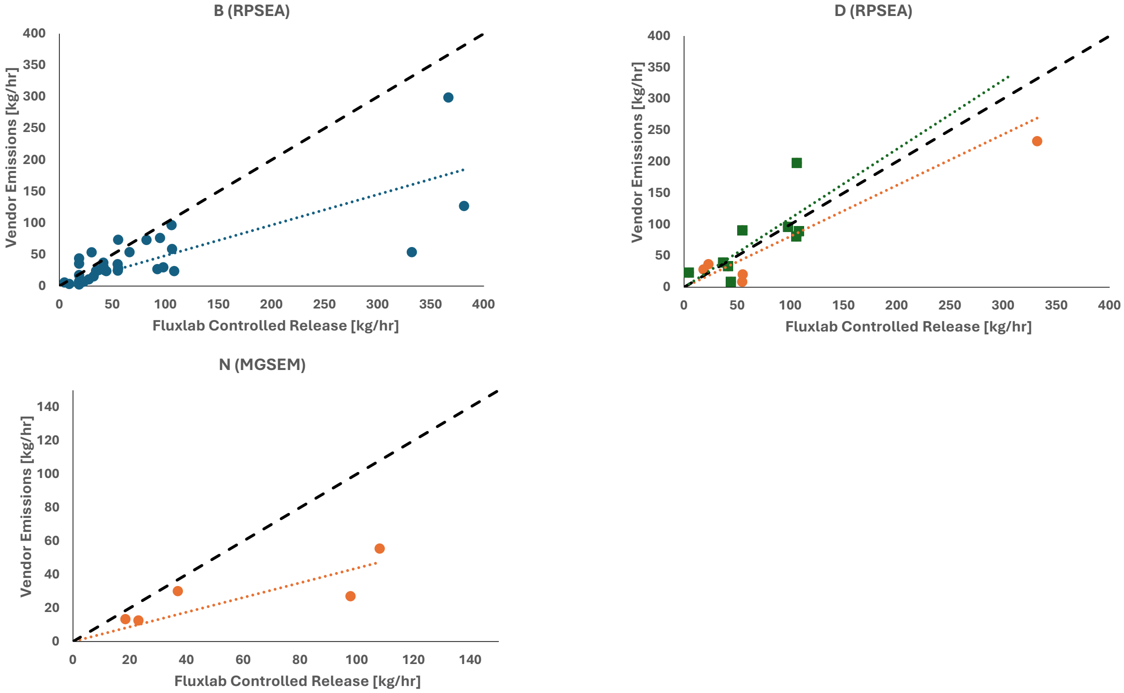


Figure 2. Parity plots for quantification assessments. Dashed line = 1:1.

Overall, RPSEA system performance in 2024 improved substantially relative to the 2023 study, which produced poor emission estimates and high uncertainty. The contrasting approaches of the two participants highlight the importance of quality-assurance frameworks in determining quantification outcomes. Continuous sensor systems were originally developed for oil and gas applications, where rapid detection and alarm generation for spontaneous emission events are critical. In landfill environments, however, emission sources typically evolve more gradually and exhibit more predictable magnitudes, reducing the relative importance of alarm functionality. For the waste sector, a more valuable objective may therefore be refinement of quality-assurance frameworks that prioritize low-bias, inventory-quality quantification.

Sensor network density represents an additional practical consideration. The RPSEA networks deployed in this study were relatively dense, exceeding 0.5 devices per acre and approaching 1 device per acre - levels that could be cost-prohibitive for large landfill sites. However, both participants indicated that such densities would not be required in operational deployments. Evidence from the 2023 study supports this view, as Participant D achieved the lowest quantification bias among continuous monitoring systems using a network of only three devices.

Important questions remain regarding best practices for RPSEA deployment at landfill sites, including the number of sensors required to achieve inventory-quality quantification and whether fewer, higher-performance sensors located farther from emission sources could provide equivalent or improved results compared with dense near-source networks. These findings highlight the strong potential of RPSEA systems while identifying key priorities for future research.

Unlike RPSEA approaches, Participant N applied a quantification algorithm to walking SEM survey measurements. This method, SEM2Flux (Abichou et al., 2023), combines surface methane concentration measurements with concurrent wind data to infer landfill methane emission rates and identify the origin of elevated concentrations. In the 2024 study, this approach underestimated emissions by an average of 45% with an uncertainty of ±21%. The number of points shown in the parity plot in Figure 2 corresponds to the number of walking surveys completed on site. During these surveys, Participant N generally evaluated lower emission rates than those typically assessed by off-site measurement technologies and conducted surveys using 30 m path spacing. It remains uncertain how quantification accuracy or precision would change under tighter survey spacing or alternative survey configurations.

Detection and Localization Performance Assessments

For all participants, detection and localization were inherently coupled because detections were expected to be actionable and associated with a known source type. In traditional walking surveys, for example, technicians not only identify elevated emissions but also determine the origin of the release so that corrective action can follow. Accordingly, the detection trials evaluated both the ability to identify emissions and the ability to associate those emissions with specific source locations.

During detection and localization trials, participants searched for emission points across the landfill surface during pre-determined controlled-release experiments. In most trials, five to seven emission nodes were active simultaneously; however, rain-related damage occasionally reduced the number of active sources to three while repairs were completed. Individual active sources emitted between approximately 1 and 60 kg/hr, with total emissions limited to no more than 120 kg/hr. Inactive decoy points were also included within the search area. Most experiments ran for approximately 1.5 hours, providing sufficient sampling duration for statistically meaningful evaluation.

Three types of participating methodologies detected and localized emissions. Figure 3 shows the proportion of true and false positives and negatives logged for Participants B and D (RPSEA), and E and F (column sensor UAV – UCSEA), and Participant K’s walking surveys (EPA Method 21 SEM - MGSEM), with 30 m serpentine paths and thresholds of 200 and 500 ppm.

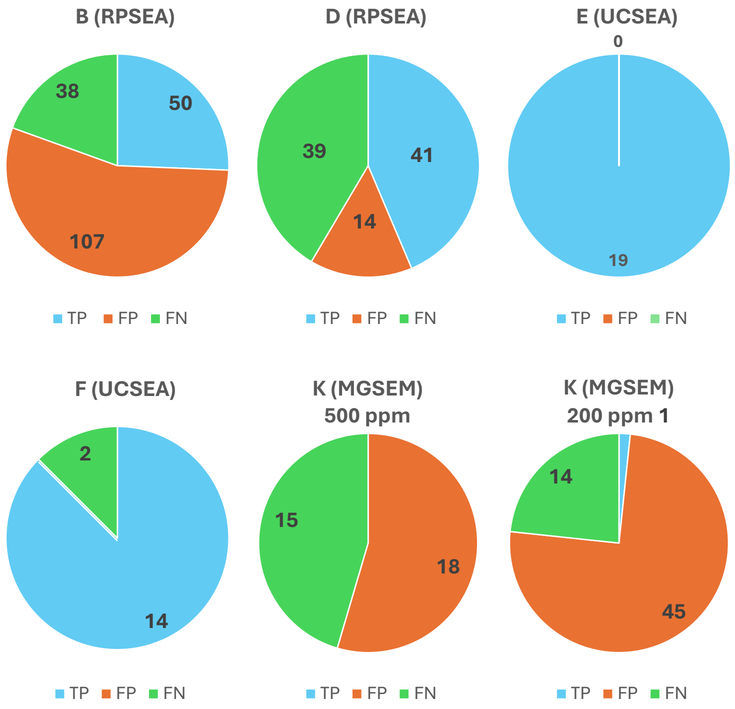


Figure 3. Detection category charts for participants using fixed sensors (B and D), UAV column sensors (E and F), and walking surveys (MGSEM) with 200- and 500-ppm thresholds. True negatives are not shown, to focus on detections only.

Unfortunately, no satellite detections were made despite different participants making several attempts. Skies were not often clear, and the system was limited by rain damage, so it was not possible to greatly exceed emission rates of 400 kg/hr. It seems the large footprint of the study's release system was an issue because under point-source release conditions, satellites should be able to detect concentrations of 400 kg/hr. The absence of detections suggest that the area-based releases in this study were too dispersed/diffuse for satellites to detect.

Walking SEM surveys were conducted across five controlled-release scenarios encompassing 15 active emission sources, with individual source rates ranging from 4.59 to 52.79 kg/hr. Detection performance was evaluated using a 15 m buffer distance combined with concentration thresholds of 200 ppm and 500 ppm. The 15 m buffer exceeds the 10 m distance typically used in regulatory practice. Under this scoring framework, detections were classified as true positives (TP) when measured concentrations exceeded the threshold within 15 m of an active source, false negatives (FN) when the survey path passed within 15 m of an active source without exceeding the threshold, and false positives (FP) when threshold exceedances occurred outside the 15 m buffer.

Walking surveys conducted using the 500-ppm threshold did not successfully locate emission points in any experiment, yielding no true positives. Threshold exceedances at either 200 ppm or 500 ppm occurred only once across the five controlled-release scenarios. In most cases, the walking MGSEM methodology failed to detect active emission sources or incorrectly localized detected emissions.

For these walking SEM experiments, the participant used a rapid response (~1s) laser-based sensor (Axetris) pumped at 2 L/min, with the inlet being 5 cm to 10 cm above the ground. The sensor has a precision of 0.1 ppm, and data were logged at 1 second intervals to provide a spatial map of methane concentrations at ~1.5 m resolution along the walking path. The speed, measurement precision, and logging rate exceeded the performance of some regular systems, which should have provided some advantage. However, an important distinction from normal walking methodologies was that the participant kept to the grid and could not follow cues such as dead vegetation (as described in regulations) because the emissions at the site originated from built infrastructure. Nor could the participant use human senses and intuition to find leak sources as they would in real-life scenarios. False positives (see orange in Figure 3) were common in the MGSEM results, where the participant detected concentrations above threshold when there was no source within 15 m. These false positives represented sources that could possibly have been found, given time, inclination, and skill. The green portion of Figure 3 represents non-detects, where a source was present within 15 m upwind, but concentration thresholds were not exceeded. Results show that the survey work practice (sensor, spacing, threshold) was not sensitive, and that the success of walking surveys would largely rely on the surveyor's experience and sensory cues.

In 2024, UAV column-sensing systems detected nearly all controlled emission sources across experiments, yielding a very high true-positive rate (shown in blue in Figure 3). This represents a substantial improvement relative to 2023, when UAV column sensors produced detection outcomes comparable to the walking SEM results observed in 2024. During the 2023 controlled-release study, approximately 80% of reported UAV detections were false positives, localization accuracy averaged 0.21 (with values closer to 1.0 preferred), and the minimum detection limit corresponding to a 90% probability of detection (POD) was 101.88 kg/hr. False-positive and false-negative fractions in 2023 both exceeded 0.5, indicating limited sensitivity to leaks and weak source attribution. In 2023, both UAV participants operated with 30 m flight-path spacing and concentration thresholds of 200 or 500 ppm·m.

Poor 2023 performance was partly attributed to sensor configuration, including the absence of gimbal integration and the use of non-nadir laser paths, which may have increased noise and reduced signal quality, particularly over sloped terrain. In 2024, Participant E returned with a new sensor incorporating gimbal stabilization, while Participant F used the same sensor configuration as in 2023 without a gimbal. The differing 2024 performance between these two configurations highlights the importance of both hardware stabilization and complementary operational factors.

Flight design also differed substantially between campaigns. In 2023, both participants flew at approximately 20 m altitude with relatively wide serpentine spacing. In 2024, narrower path spacing was adopted, with Participant E flying at 7.5 m spacing and Participant F at 15 m spacing. Participant F additionally reduced flight altitude to 10 m, which may have improved signal strength given the relatively low laser power of the sensor, whereas Participant E flew at 30 m using a higher-power system. These methodological refinements likely contributed to improved plume sampling and detection sensitivity.

Data-analysis strategy also evolved between campaigns. Participant E retained a broadly similar analytical framework to 2023 but eliminated fixed concentration thresholds and manual plume-identification approaches, instead applying improved plume interpretation methods. This change corresponded with markedly improved detection outcomes in 2024 (Figure 4): the true-positive rate increased from 21% to 100%, false positives decreased from 79% to 0%, and false negatives decreased from 50% to 0%. The 90% POD minimum detection limit decreased by 94% from the 2023 value to 5.7 kg/hr.

Collectively, these results demonstrate the rapid advancement of UAV-based methane detection capabilities and highlight the critical roles of hardware stabilization, flight methodology, and data-analysis refinement in improving real-world system performance.

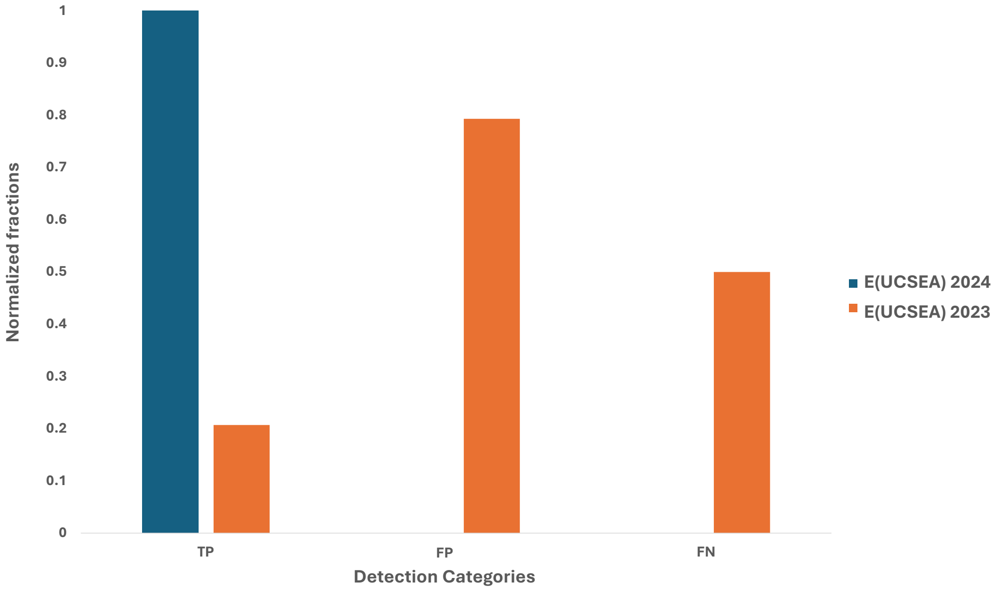


Figure 4. Difference in detection category fractions for Participant E (UCSEA) for the 2024 and 2023 studies.

Despite achieving generally good quantification performance in 2024, with more than 80% of emission estimates falling within a factor of three of the true release rates, RPSEA systems (Participants B and D) showed comparatively limited localization accuracy. True emission point sources were localized in approximately 25%–50% of detections, reflecting the fraction of estimates that satisfied stated spatial-precision criteria. Reported localization uncertainties, often on the order of tens of meters, were therefore less precise than those achieved by UAV systems evaluated using a 10 m tolerance. The relatively high number of false positives associated with RPSEA systems primarily resulted from situations in which emissions were correctly detected but could not be localized with sufficient spatial precision to meet scoring requirements. Table 3 summarizes detection, localization, and quantification performance metrics for each participant.

Table 3. Statistical summaries of quantification performance for B, D, and N.

Method	False Positive Fraction	False Negative Fraction	Localization Accuracy	Survey Time (mins)
B	0.68	0.68	0.57	-
D	0.25	0.25	0.60*	-
E	0.00	0.00	1.00	40
F	0.00	0.00	0.88	60
K	1.00	1.00	0.00**	60
N	0.82	0.82	0.13	60

*Adjusted for device coverage information provided.
**Using 500 ppm threshold.

Detection Sensitivity

Figures 5 and 6 present the 90% POD curves for Participants B and D (RPSEA systems) and Participants E and F (UAV UCSEA systems). Walking MGSEM did not produce a sufficient number of true positive detections to permit construction of a POD curve. For each participant, detections were grouped into equal emission-rate bins (e.g., 0–5, 5–10, 10–15 kg/hr), and POD was calculated within each bin as POD = $n_{TP} / (n_{TP} + n_{FN})$, where n_{TP} and n_{FN} represent the numbers of true positives and false negatives, respectively. The mean release rate within each bin was paired with the corresponding POD value to generate discrete POD data points.

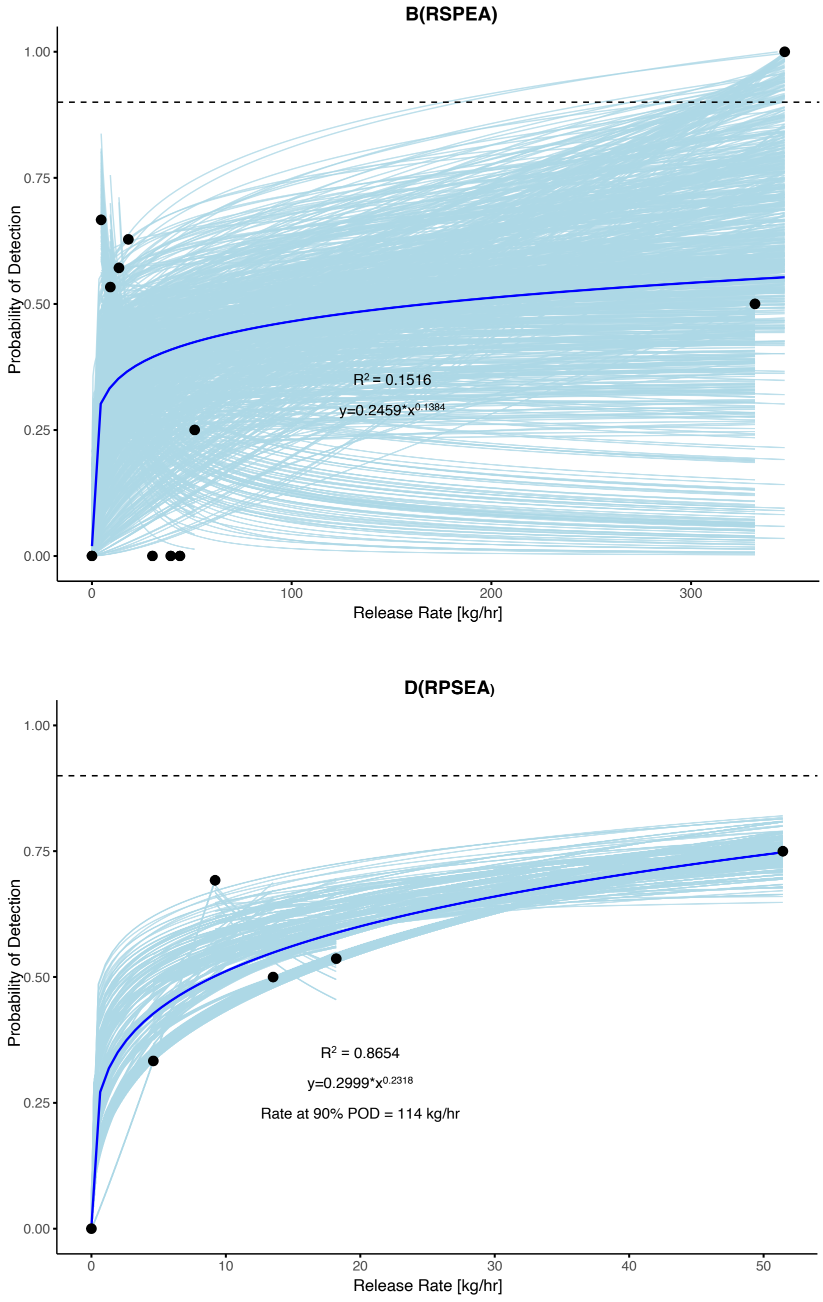


Figure 5. 90% POD curves for the RPSEA participants (B and D). Thin blue lines represent logistic models fitted to individual bootstrap resamples, illustrating POD uncertainty, while the bold blue line shows the median bootstrap curve. For Participants B and D, the 90% POD intersection is not observed because the tested release rates did not extend to values high enough to reach this threshold.

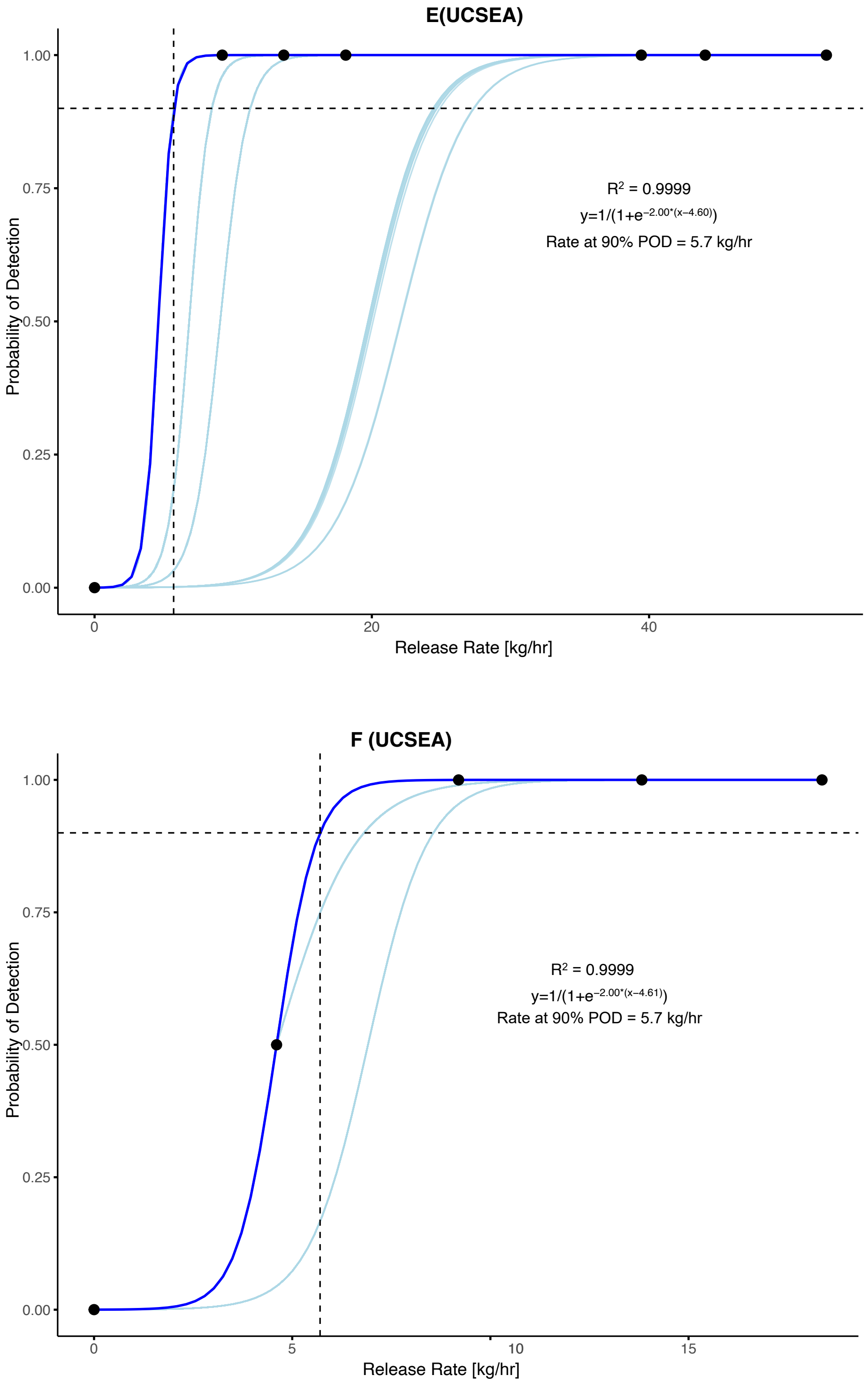


Figure 6. Probability of detection curves for the UCSEA participants (E and F). Thin blue lines represent logistic models fitted to individual bootstrap resamples, illustrating POD uncertainty, while the bold blue line shows the median bootstrap curve. The horizontal dotted line denotes POD = 0.90, and the vertical dotted line marks the release rate at which the curve reaches POD = 0.90 (the 90%-POD MDL).

Uncertainty in these estimates was evaluated using bootstrap resampling to produce a distribution of possible POD curves. Logistic ($y=1/(1+e^{-k(x-x_0)})$) and power-law ($y=kx^n$) functions were then fitted to the resampled data to obtain smooth best-fit relationships. From these fitted curves, the emission rate corresponding to a 90% POD was identified as the minimum detection limit (MDL). Accordingly, the POD curves represent the lower reliable bound of source-detection sensitivity expressed in kg/hr.

In 2024, the 90% POD for UAV-based UCSEA column-sensing systems was 5.7 kg/hr, representing approximately an order-of-magnitude improvement relative to their 2023 performance (Table 4). This improvement is attributed to refinements in work practice and data analysis that moved away from approaches designed to replicate walking surveys. In 2023, the most sensitive detection and localization methodology evaluated was gas-mapping LiDAR, which achieved a 90% POD of approximately 1 kg/hr. Thus, within one year, UAV column-sensing systems advanced from limited effectiveness to the second-highest detection sensitivity among evaluated technologies, behind LiDAR.

These results should be interpreted with caution, as the estimated 90% POD of 5.7 kg/hr in 2024 corresponds to the lowest emission scenario tested following the poor detection performance observed in 2023. The true 90% POD may therefore be either higher or lower than this estimate. Future controlled-release studies should include lower emission-rate scenarios to more rigorously evaluate detection sensitivity and to determine whether gas-mapping LiDAR–level performance can be achieved.

Table 4. Summary of 90% POD rate for UCSEA methodologies that surveyed as full participants

UCSEA Methodologies	90% POD rate [kg/hr]
L (2023)	95.34
M (2023)	101.88
E (2024)	5.7
F (2024)	5.7

RPSEA systems exhibited reduced performance under the 90% POD metric, largely driven by a high number of false positives, many of which reflected failures to meet stated localization precision rather than an absence of detection sensitivity. The intrinsic emission-rate sensitivity of RPSEA systems is expected to be high; however, the experimental evaluation rubric penalizes detections classified as false positives when reported source locations do not satisfy required spatial precision criteria. Independent observations of off-site sources in the 2-5 kg/hr range indicate that RPSEA systems are capable of detecting emissions at rates lower than implied by the POD metric alone.

These systems must balance localization and quantification objectives, requiring operators to determine acceptable spatial precision under varying conditions. Ongoing analysis of controlled-release data is expected to further constrain achievable localization accuracy. At present, no evaluated system can simultaneously achieve high-accuracy quantification and precise localization across all conditions. However, the results of this study indicate that RPSEA systems retain a practical advantage over UAV column-sensing systems in their ability to quantify emissions while also providing limited detection capability, even when localization precision is not consistently achieved.

Modeling Detection to Explain Outcomes

Because walking surveys conducted using the regulatory Method 21 work practice did not detect any controlled releases, numerical modeling was used to better understand the scenarios under which SEM could detect methane leaks. Modeling enabled simulation of a range of realistic SEM survey configurations, allowing evaluation of key work-practice drivers such as path spacing sensitivity. Modeled SEM performance was also compared with modeled UAV UCSEA performance. Probability of detection was estimated for methane leaks across a range of emission rates and survey configurations for both systems.

Landfill domains up to 120 × 120 m were simulated with methane emission sources at known locations and controlled emission rates ranging from 1 to 100 kg/hr in 1 kg/hr increments. Atmospheric dispersion was represented using a Gaussian plume formulation with variability introduced through wind speed and atmospheric stability class (Pasquill A-D). Four representative conditions were modeled: stability class A with 2 m/s wind, class B with 3 m/s wind, class C with 5 m/s wind, and class D with 8 m/s wind.

Surface emission monitoring surveys were simulated at knee height (0.5 m), reflecting detection at remote positions relative to emission sources, where concentrations are not expected to differ substantially from ground level. Walking surveys were represented using a speed of 5 km/hr and a sampling frequency of 1 Hz, with serpentine path spacings of 1, 3.2, 7.5, 15, 22.5, and 30 m. Detection exceedance thresholds ranging from 50 to 500 ppmv were evaluated. For UAV simulations, plume fields were vertically integrated to correspond with ppm·m measurements under otherwise identical conditions.

These simulations were intended to evaluate theoretical detection behavior rather than reproduce exact field concentrations or detection probabilities. Accordingly, sensor noise, surface roughness, vegetation effects, and topographic variability were not included. Select simulation outcomes are presented in Figure 7.

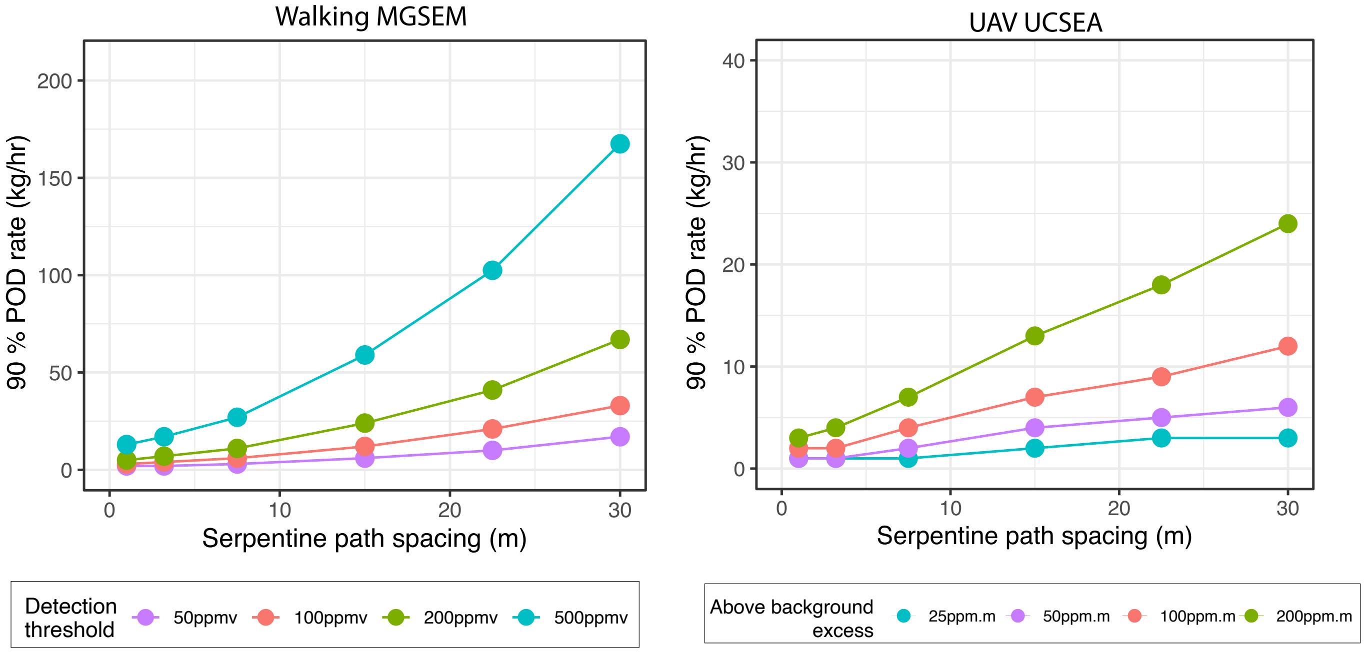


Figure 7. Walking MGSEM (left) and UAV UCSEA (right) modelled 90% POD rates for simulated plumes under Pasquill C and wind speed of 5 m/s. Colors correspond to different simulated detection thresholds. Note, the drone method should be inherently more sensitive at similar spacings because of vertical integration if concentrations could be measured with similar levels of noise.

For simulated walking MGSEM surveys, detection performance was strongly influenced by survey spacing and exceedance threshold. Only configurations with spacing ≤15 m and thresholds ≤100 ppmv achieved a 90% POD for emission rates below 15 kg/hr, which are already relatively large leaks. Detection performance further degraded under stable atmospheric conditions, where elongated plumes increased the likelihood of multiple serpentine-path intersections and introduced ambiguity for survey technicians.

In contrast, simulated UAV UCSEA performance showed substantially greater sensitivity under equivalent conditions. Vertical integration of plume concentrations enhanced plume contrast against background conditions while still fully sampling near-ground emissions within the 30 m integration height. As with MGSEM, tighter spacing and lower thresholds improved detection; however, the UAV UCSEA system maintained 90% POD for emission rates below 15 kg/hr across nearly all configurations, except where spacing exceeded 22.5 m combined with a 200 ppm·m threshold. Collectively, these results demonstrate that walking SEM detection is highly sensitive to work-practice parameters, whereas UAV UCSEA detection is more robust across survey configurations.

CONCLUSIONS

In November 2024, a controlled-release study was conducted to evaluate how 14 participant–methodology combinations detected and quantified methane emissions across 31 controlled-release experiments. Overall, quantification methods performed well during the 2024 study. Fixed-sensor systems showed mild to moderate underestimation, with emission-rate parity plot slopes ranging from 0.4 to 0.8. Detection performance improved substantially for UAV UCSEA systems relative to the 2023 campaign, achieving a 90% probability of detection (POD) at 5.7 kg/hr, representing approximately an order-of-magnitude increase in sensitivity. The 2024 results further emphasized the importance of aligning methodological capability with appropriate work practices, particularly for UAV UCSEA systems. Compared with 2023, the standard UAV UCSEA approach substantially increased the likelihood of leak detection and warrants continued evaluation in future studies.

In contrast, walking SEM demonstrated poor sensitivity, consistent with previously documented limitations including incomplete spatial coverage of total emissions (Omidi et al., 2025). The regulatory EPA Method 21 MGSEM work practice (500 ppm threshold and 30 m spacing) did not perform well, consistent with longstanding concerns. Despite rapid advances in UAV-based detection technologies, MGSEM exhibited the lowest detection performance among the methodologies evaluated across the past two years. Field observations and modeling together suggest that, under real-world conditions, MGSEM detections are largely probabilistic—occurring when the survey path happens to intersect an emission source—or dependent on operator skill and interpretation of audio, visual, and olfactory cues. These factors can produce variable and non-equivalent outcomes across sites and users. Consequently, MGSEM performance using 200- or 500-ppm thresholds is expected to depend strongly on meteorology, ground conditions, survey-grid design, path spacing, and operator aptitude. The results instead suggest that MGSEM may be most appropriate in limited spatial contexts, such as delineating and investigating leaks after their approximate locations have already been identified.

The 2024 study provided insight into how different monitoring solutions operate in a landfill environment and identified several areas requiring further investigation. One priority is the validation of satellite-based methane measurements, which are gaining increasing attention as remote-sensing capabilities expand. Although the upgraded downstream pipeline was designed to achieve emission rates exceeding 1000 kg/hr, levels generally considered detectable by current satellite systems, site flooding limited the maximum controlled-release rate to 381 kg/hr by increasing gas-transport resistance within dispersed source sections and damaging flow-measurement infrastructure. In the area-source configuration, flooding further constrained release rates to approximately 60 kg/hr, compared with a typical maximum of ~118 kg/hr under normal operating conditions.

These constraints highlight an important experimental outcome: successful satellite detection depends not only on emission magnitude but also on environmental and operational conditions, including weather, surface saturation, and achievable release stability. Validation of satellite-based methane measurements will likely require controlled-release experiments conducted during periods of low to no cloud cover and stable operating conditions, potentially at sites that allow longer-duration or repeatable releases. To support this objective, development of a dedicated controlled-release site is underway. Such configurations would enable evaluation of minimum detection thresholds as a function of wind speed, emission rate, and plume footprint, as well as improved assessment of quantification accuracy through experimental replication.

The 2024 study provides evidence to support more informed decision-making by operators and regulators regarding landfill emission measurement techniques. In addition, the results offer participating technology developers' actionable data to refine their methodologies and improve service to the waste management sector, with the overarching goal of reducing landfill methane emissions.

SUPPLEMENTAL INFORMATION ON METHODS

Simulation Facilities for Landfill Emissions Experiments (SIMFLEX) Site Description

Facility Description

The Simulation Facilities for Landfill Emissions Experiments (SIMFLEX) is on the Petrolia Landfill site at 4052 Oil Heritage Road, Petrolia, Ontario (42°52'19"N 82°7'14"W; Figure S1), near Sarnia, Ontario, Canada. The landfill is a closed landfill that was once owned and operated by the Town of Petrolia and is now operated by Waste Management (WM) Canada.The Petrolia landfill entered the permitting process in 1982 under Schedule A of the issued Environmental Compliance Approval (ECA), with a total approved capacity of 4,749,000 m³. The site opened in 1990 and ceased accepting new waste in June 2016, although it continues to operate as a transfer station for WM Canada. The facility covers approximately 41.23 ha, of which 26.02 ha were used for waste disposal during operations. Reported annual fill rates were approximately 365,000 tonnes per year, including about 65,000 tonnes per year of municipal solid waste from municipalities within Lambton County and 300,000 tonnes per year of institutional, commercial, and industrial waste from across Ontario. Incoming waste was deposited into excavated cells below ground level in the local clay soil. Figure S2 shows a layout of the Petrolia Landfill. The site is currently capped, top-soiled, and seeded.

Figure S1. Petrolia Landfill location. The blue marker indicates the position of the landfill in Ontario, Canada. In the inset, the landfill perimeter is outlined in orange. The location of a known cluster of oil and gas batteries is highlighted in green.

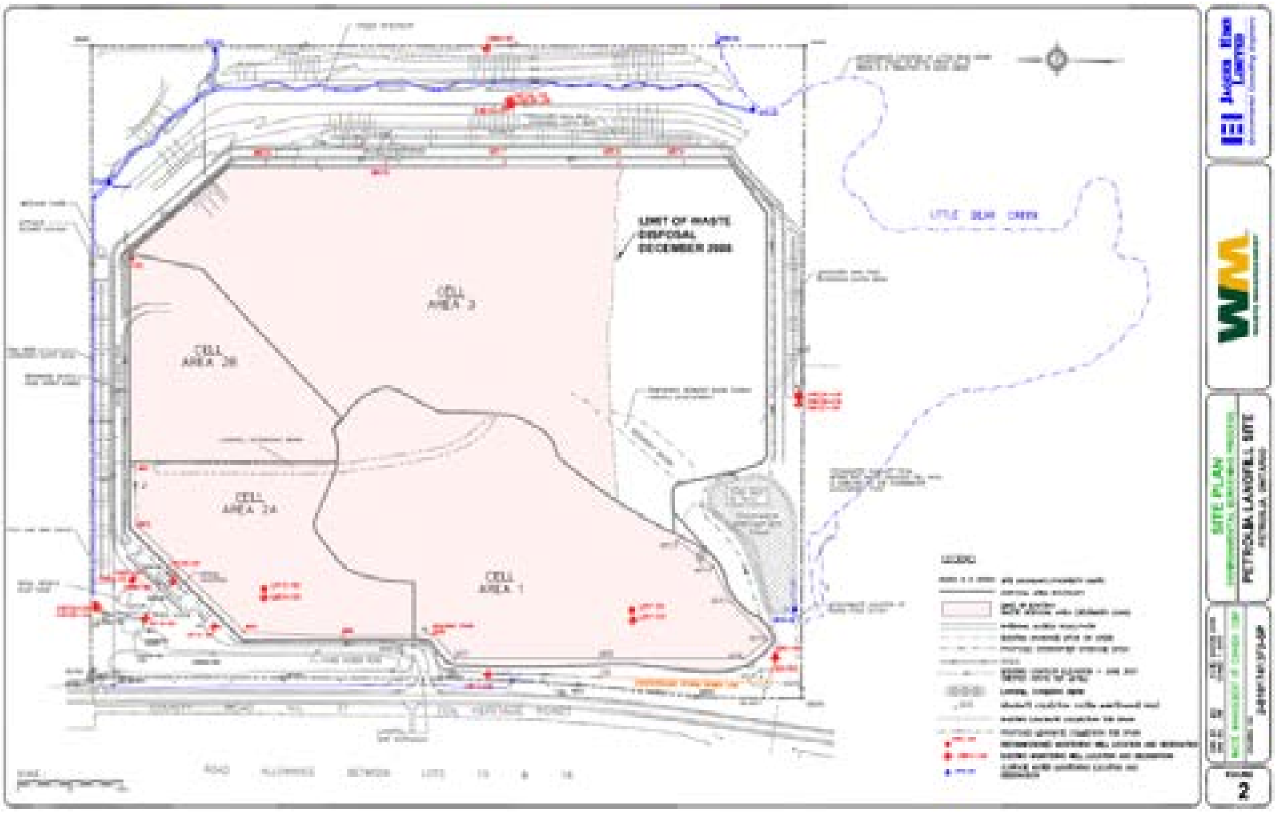


Figure S2. Petrolia Landfill site layout

The landfill collects contaminated runoff from precipitation and moisture, known as leachate, and conveys it via sewer lines to the Petrolia wastewater treatment plant for off-site treatment. The site is also equipped with a double cap system incorporating both clay and geomembrane layers. This site has a Landfill Gas (LFG) Collection and Flaring system. In 2010, the landfill commenced operating a landfill gas-to-energy project, converting methane gas into enough energy to power 2,500 homes (up to 3.2 megawatts of electricity, a WM Canada projected number from 2009). Bluewater Power Generation continues to generate electricity at the Petrolia Landfill, even though the landfill has stopped accepting waste. From the 2020-2021 Ministry of the Environment, Conservation and Parks (MECP) Report, 2,710 tonnes CH_4 per year were recovered in 2021, and all of the methane was utilized (none was flared).

We required two permits to conduct our controlled release study at the Petrolia 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). Ontario’s Technical Standards and Safety Authority (TSSA), which is the public safety provincial regulator for various devices and equipment, issued this permit. Our study was assessed by the Fuels Division, and we secured a variance approval in relation to CSA code B149.1, which outlines the installation code for natural gas propane and was used as our reference for the variance application. The TSSA approved the gas release system and inspected the system on several occasions. The second permit covered the environmental and public impact of conducting the experiments at the landfill and releasing methane and acetylene as a tracer gas. The Ministry of Environment, Conservation, and Parks (MECP) issued this Environment Compliance Approval (ECA). Because our study used a buried pipeline system, we had to follow a regular environmental compliance approval process. In addition to submitting permit applications, we contacted immediate neighbors of the landfill property and observed a 30-day consultation period.

The Petrolia site's topography was moderately complex and typical of a landfill (Figure S3). The cells were like hills that sloped away from the center. The highest point of the landfill was about 35m above the landfill’s outer edges and the surrounding areas which were flat and used as croplands or were covered with trees.

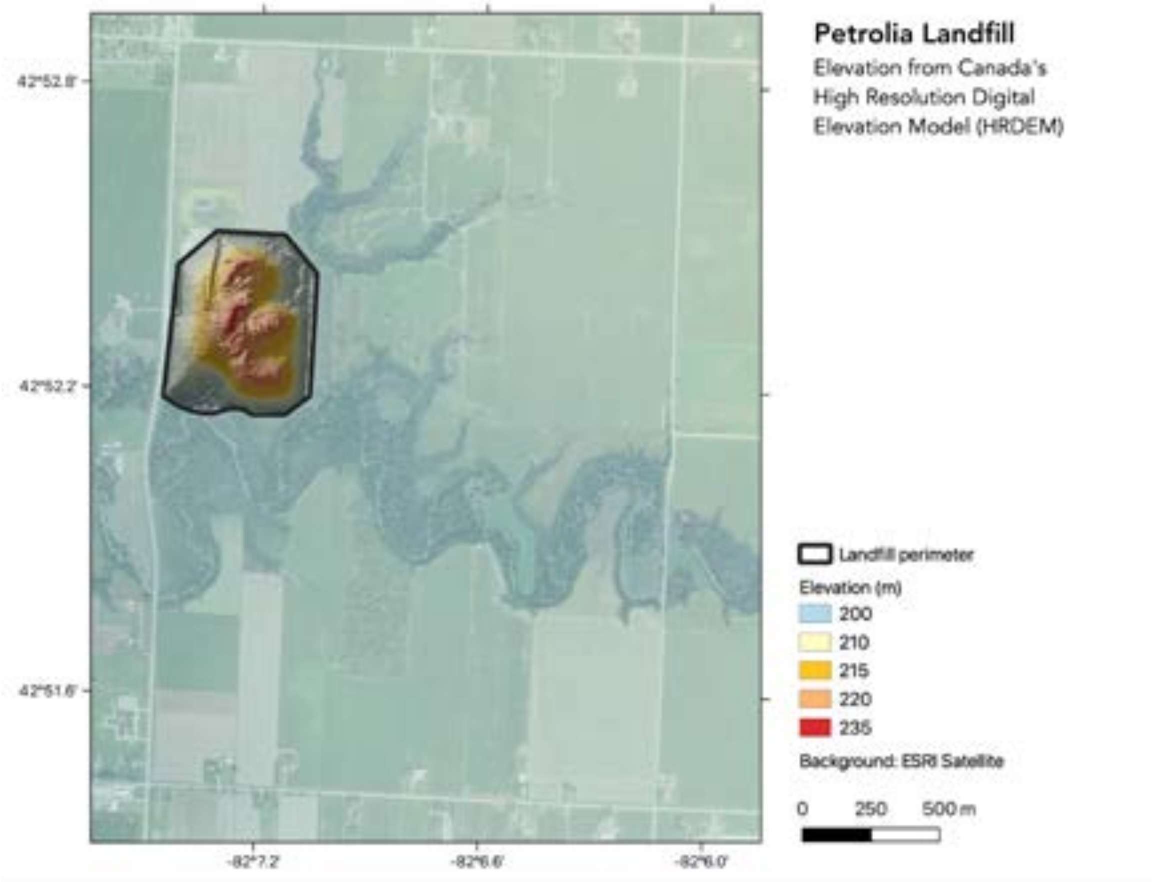


Figure S3. Petrolia Landfill and surroundings elevations

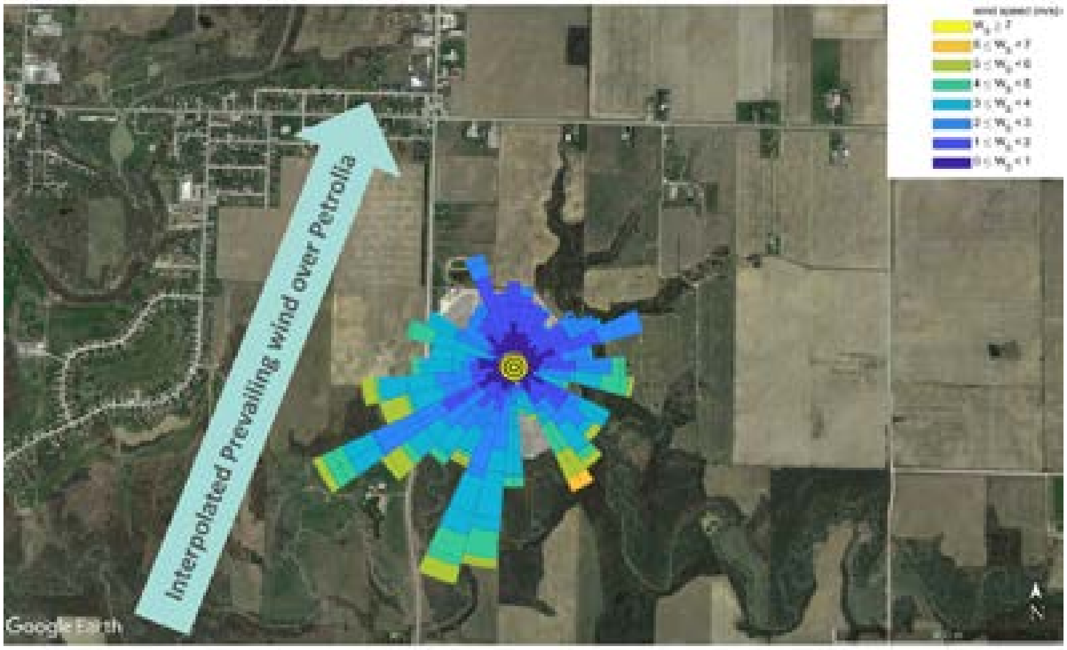


Figure S4. Wind rose patterns based on ERA5, ERA5-Land, and ECCC historical climate data from Sarnia, Ontario

The Great Lakes affect the climate at Petrolia. 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 the European Centre for Medium-Range Weather Forecasts) and historical climate data from ECCC. Our wind analysis (Figure S4) suggests that, from September to November, the prevailing winds are west-southwest and occur between 13:00 and 16:00 EST. Historical trends were a good predictor for this study, where winds were from typical directions, and within normal ranges of wind speed.

Experimental Methodology for the Participants

We based the experimental protocol for the 2024 study on the Methane Emissions Technology Evaluation Center (METEC) survey protocol from Colorado State University. The base protocol validated oil and gas emission measurement solutions. Adapting the METEC method mostly relied on the fact that, in the oil and gas sector, the main METEC method components are point sources. However, landfill emissions come from multiple sources or areas. The rate of emission from a landfill tends to be much higher than for oil and gas sites. Nevertheless, many publications have applied 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) focused on active face emission in landfills.

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

1. Classifying point and area source releases
2. Recording meteorology measurement details
3. Simplifying experiment cycles
4. Removing oil and gas measurement-specific analysis (e.g., classifying detections on equipment units)

The METEC protocol emphasized the need for transparent documentation without revealing proprietary information. The first step included documenting the configuration of survey solutions, such as system components, software revisions, methodology, and personnel involved. In the next step, participants conducted emission detection within defined facility boundaries, documenting controlled releases and survey data. The process involved establishing experimental design points, conducting surveys, and submitting data to the test center. The final step required participants to report experiment and detection data, including survey summaries and facility quantification data that included essential details such as experiment and facility IDs, survey start/end times, and emission rates. In our case, some of the participants used the same solutions. Therefore, where appropriate, we refer to testing methodologies instead of using “solution” or “participant” in this report.

One of the key protocol features was having separate evaluations for emission quantification and localization. The primary metrics for each involved different sets of assessments. The emission rates and location for the controlled release points were the true values for the evaluation of the participants’ systems.

Classifying the detection involved categorizing detections as true positive or false positive based on how accurately the solution identified the controlled releases. The metrics for detection we used were as follows:

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

For localization techniques and models, primary metrics focused on the how precisely and accurately the systems pinpointed the emission points identified by the detections. The precision of the instruments or the error percentage of the method of analysis introduced the uncertainty in finding the sources.

For further evaluation, we used secondary metrics: 1) quantification accuracy evaluated how accurate the reported emission rates were compared to metered rates, in absolute and relative terms; 2) quantification precision assessed the precision of the reported emission rates, providing insights into the consistency of the measurements, and 3) localization accuracy and precision assessed how accurate and precise the reported coordinates or bounding boxes were, offering detailed insights into the spatial accuracy of detections.

We evaluated survey efficiency, survey speeds, and annualized costs based on actual survey reports submitted, offering practical insights into the efficiency of each survey operation.

Overall, these metrics comprehensively evaluated the detection systems' performance, considering factors such as accuracy, precision, efficiency, and environmental conditions.

Two weeks after the data collection phase, participants were required to submit their estimates. Quantification methodology providers were instructed to provide their estimated rates in kg/hr and localization methodology providers were instructed to provide coordinates of leak estimates. After the first round of submissions, we provided the participants with on-site weather data and allowed participants to resubmit estimates. Releases were not classified as a quantification/ localization-type release during the 2024 campaign. Instead in 2024, releases were assigned a scenario depending on the spatial configuration and magnitude of releases. Most experiments lasted for approximately 90 mins and satellite specific releases lasted for approximately 15 mins. Between experiments, there was a break of 10 to 15 mins. Except for the satellite specific releases, most releases were below 100 kg/hr.

We compared the participants’ rate estimates in kg/hr with the sum of the average flowmeter values. The results are displayed using parity charts with linear regression values listed in a table. For the analysis of the methodologies that performed measurement off site, we compared participants’ estimates with the total site emission rate, which we calculated by adding the background emission rate and total gas release rate. In 2023, we determined the background emission rate to be 24.44 kg/hr (standard deviation of 8.88 kg/hr) using the Tracer Correlation method (EREF 2024, Hossain et al., 2026). For analysis of methodologies that performed onsite measurements (near the border of the release area), we compared participants’ estimates with the total gas release rates.

We assessed the localization methodologies by classifying leak estimates provided by participants into three categories: true positive, false positive, and false negative. The participants mapped their leak coordinates and the release point/area coordinates using Google Earth Pro. We compared the active emitter locations with participants’ coordinate estimates to assess how well systems located the release points.

We defined a 10 m radius bounding circle with the release point at the center for active release points. We considered participant leak coordinates that fell within the bounding area to be true positives, and leak coordinates outside of the bounding area to be false positives. False negatives were active leak points that were not detected. Using the categorized leak estimates, we assessed the methodologies for the POD, false positive, and negative fractions. Equations 1 to 4 list the primary factors we used to assess localization performance.

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

where PD is the POD, n_{TP} is the number of true positives, and n_{FN} is the number of false negatives.

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

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.

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

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.

$$\boldsymbol{LA} = \frac{\boldsymbol{N}_{\mathbf{TP}}}{\boldsymbol{N_{RD}}} = \frac{\boldsymbol{N_{TP}}}{\boldsymbol{N_{TP}} + \boldsymbol{N_{FP}}} \quad \text{...(4)}$$

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.

We calculated the quantification error percentage for each quantification estimate using the equation below. Error percentages determined the deviation of the estimates from actual release rates.

$$\text{Quantification Error} = \frac{|\text{Measured Emission Rate} - \text{Controlled Release Rate}|}{\text{Controlled Release Rate}} \times 100$$

Controlled release system configuration

We upgraded the controlled release system from the 2023 study by burying a pipeline network of polyethylene and metal pipes placed 40 cm underground on an approximately 20-acre (8- hectare) section of the landfill. We placed the release points at various elevations of the landfill, and a CNG trailer, connected to a small pressure reduction trailer, held the source of methane. With combined release rates ranging from 1 kg/hr to 381 kg/hr, we released a total of 2,172.79 kg methane from point and diffused sources between 20 November and 29 November.

The field team initially mowed sections of the landfill to stubble length on areas where the pipeline lay on the ground. Using manual and mechanical methods, the team dug sections of the landfill. The technicians made the connections between polyethylene and metal pipes and covered the sections near the polyethylene fittings with soil. The team placed Alicat MCR series flow controllers in black metal enclosures buried 40 cm underground and connected the controllers to the pipeline network. The manufacturer had calibrated the flow controllers before we deployed them. The standard accuracy of a reading was ± 0.6% or ± 0.1% of full scale. The flow rate data was recorded at 1 s intervals. Wiring work involved connecting the flow controllers to a console which allowed gas to be released remotely.

A connected laptop monitored the flow controllers' performance. We compared flow rate data from the flow controllers to the end-of-day gas use report from Certarus which was generated by the pressure reduction system trailer software. Gas flow performance was monitored from the pressure reduction trailer and the remote-control center. We used the mass flow values from the flow controllers for our analyses. The flowmeters have an uncertainty of 0.6%, and we calculated the error propagation with the root sum of squares. We give the average flowmeter readings for each experiment in the data stack (see "Datasets Access" section below for details).

Basemap: Google Maps
CRS: NAD83(CSRS) UTM Zone 17N

Figure S5. Map of experimental search area (red) and locations of the meteorological stations

The controlled release setup had eight point and two dispersed sources. We modified one of the dispersed sources to directly release from the pressure reduction trailer, bypassing the flow controller, to allow higher release rates for validating the satellite methodologies. The point source releases simulated emissions from membrane tears and wells, whereas dispersed source releases simulated emissions from a landfill's active face. The point sources had elevated metal nozzles with a release rate up to 19.7 kg/hr. For the dispersed sources, we used a perforated tube spread over 40 cm of soil covering an area of about 144 m^2 and 107 m^2. The dispersed sources released methane up to118.3 kg/hr when the gas passed through a flow controller and 346 kg/hr when the gas was directly released from the pressure reduction trailer. Flow controllers recorded flow in standard litres per minute. ATEX-certified Alicat flow controllers regulated and monitored each release source in real time. We installed the Alicat flow controllers, in their black boxes, at the end of each downstream branch of the pipeline. A Certarus' online platform monitored the overall flow into the downstream piping.

Certarus supplied the methane gas, which we sourced from Enbridge. For the 2024 study, we used a natural gas composition of 93.57% methane, 5.35% ethane, 0.24% propane, 0.51% nitrogen, and 0.26% carbon dioxide. Having the bulk CNG trailer connected to the pressure reduction trailer 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 the downstream piping.

Six weather stations collected meteorological data as shown in Figure S5. We did not include the locations of the release points in the figure so that we could use the same release points for future blind studies to be conducted at the Petrolia site. Our weather stations used Gill Instruments weather sensors (WindUltra compact ultrasonic anemometer). The weather sensors were factory calibrated before our study. Field team members checked the weather stations daily to ensure the equipment was operating properly.

We designed the release configurations based on participating methodologies. Each experiment matched a corresponding release with distinct flow rates and active emission patterns. When possible, we ran duplicate scenarios to see if a methodology performed consistently.

Determining background emissions

Several background emission points lie outside the 20-acre search area chosen for the study, in which the pipeline systems are installed. Numerous measurement participants only work within the perimeter of the search area. We have conducted many walking surveys in the search area and can verify that no emissions occur in that area. But many participants work from farther away, for example from the road network. For these participants, we need to account for background sources that are additive to the controlled releases from our pipeline network. The background sources consist mostly of manholes venting the leachate management system around the outside perimeter of the landfill, plus an electrical generation facility burning the collected landfill gases on the northwest corner of the property, and one localized site where a modest flux of methane gas can be detected through the cover.

In the previous November 2023 study, the background emissions were determined to be 24.4 kg/hr, which is very low for a landfill of this size because of a robust geomembrane and clay cover, and a well-tuned collection system. The background site-level emission rate was determined in two ways and was supplemented with other qualitative information.

Method 1 involved Truck-based Tracer Correlation (TruckTC) measurements, conducted repeatedly over numerous days when the controlled release system was idle. The mean of these measurements 24.4 kg/hr with a standard deviation of 8.8 kg/hr (n=9). This is a direct measurement of prevailing background conditions, and values were added to release rates when adjudicating offsite participant results.

Method 2 involved high-performing offsite systems, TruckTC and Flux-Plane AirLiDAR. We analyzed the y-intercept of linear regression fits between measured and released fluxes during the experiments, without adding or correcting for background emissions. We chose these methodologies because they performed well in the 2023 study with high correlation to the controlled release rates. The resulting y-intercepts were 19.4 and 22.0 kg/hr with a mean of 20.7 kg/hr. These rates closely matched those of direct TruckTC, suggesting they were yielding similar information.

Ultimately, we adopted the background value derived from Method 1, as the instrument used in TruckTC measurements operates at ppb-level sensitivity. However, Method 2, calculated using entirely independent data and measurement approaches, supported the reasonableness of the Method 1 estimate.

In addition to these quantitative methods, we conducted walking surveys and tripod-based monitoring across the broader site to verify that all potential background sources had been identified. Over time, measurement teams have also provided source locations and, in some cases, emission estimates that further informed site-level background understanding.

For the November 2024 study, these combined lines of evidence confirmed that no background emissions were present within the defined search area. As a result, background emission values did not need to be added when evaluating participant performance, in contrast to earlier campaigns where off-site measurements required explicit background correction.

Datasets access

As a companion to this report, a dataset publication – or informally the “data stack” – can be found in the St. Francis Xavier University Dataverse repository with permanent Digital Object Identifier (DOI): 10.5683/SP3/ZYVDC1. Dataverse is a system that universities and researchers use worldwide for publishing datasets for permanent access. A similar Dataverse repository exists for the inaugural 2023 controlled release study at the same site. Datasets from these controlled releases often useful for technology or atmospheric transport algorithm developers, as example datasets or to validate air models. Many of the participants also look forward to analyzing these datasets to drive improvement. A direct link to each study’s data stack is available on the FluxLab SIMFLEX webpage at www.fluxlab.ca/SIMFLEX, included in the description of each years’ activities. Alternatively, the datasets and their DOI links should be searchable on Google with terms such as “St. Francis Xavier University FluxLab Controlled Release Dataverse”. The data stacks contain information including digital elevation maps, release rates and timings and approximate release locations, wind speeds logged by every anemometer onsite during the experiments, some geolocated concentration measurements from participating analysis systems onsite (tripods) or circulating around the site (trucks), and/or other contributed datasets.

Participating Methodologies – Full descriptions

UAV Column Sensor Emission Assessment (UCSEA)

This solution uses a UAV-mounted Tunable Diode Laser (TDLAS) to detect methane based on its spectral signature. The laser, carried beneath a drone, sends a narrow beam toward the ground. The emitted beam of light reflects back to the UAV, and along the way, methane molecules absorb energy at their characteristic wavelengths. The system is often referred to as Active TDLAS or a “column-type” sensor. Measurements are reported in ppm·m and measurements are captured along the entire laser path. Unlike LiDAR, which scans a frame of pixels, column sensors measure only a single beam, and most of that beam travels through clean air. This means methane near the ground can be diluted by the air above, making detection difficult unless the instrument is highly precise or flown at low altitude.

Manual Ground Surface Emission Measurement (MGSEM)

Walking surveys, formally known as Surface Emissions Monitoring (SEM) or Manual Ground Surface Emission Measurement (MGSEM), were the first widespread approach for detecting landfill methane. In these surveys, operators walk the perimeter of the landfill and traverse the landfill in 30-meter grids while holding a point sensor. Regulators often provide guidance on walking speed or instrument response times and when corrective action is required; for example, if a methane reading exceeds 500 ppmv. Operators are expected to leave the grid path when they observe elevated readings and search for the source of the elevated reading. Because methane plumes disperse quickly between 30-m intervals, the effectiveness of MGSEM depends heavily on operator skill.

UAV Ground Surface Emission Measurement (UGSEM)

UAV Ground Surface Emission Measurement (UGSEM) adapts the principles of walking surveys (MGSEM) by suspending an air intake tube just 10 cm above the ground from a multicopter. Air is pumped through the tube to a methane sensor on the UAV, while automated flight plans ensure consistent coverage, even over steep or unsafe landfill terrain. The resulting surface concentration maps help pinpoint emission hot spots or leaks. UGSEM, formally adopted by the US EPA as Method OTM 51, promises faster surveys, improved reproducibility, and greater safety. However, UGSEM still follows MGSEM rules for 30 m grid spacing and has yet to be validated in controlled release experiments.

SEM2Flux

Another application of SEM survey data is SEM2Flux. This approach uses ambient-air methane concentration measurements to identify elevated methane concentrations and to infer estimates of total methane emissions from landfill sites. This approach uses simplified inverse dispersion modelling commonly used in environmental studies. Using an optimization process, where variables are the locations and emission rates, the optimization identifies the configuration of location and emission rates that best fits measured concentrations. The quality of fit of a specific configuration is evaluated by calculating the corresponding methane concentrations at the same locations where measured concentrations are available. Absolute residuals calculated for all measurement points is the primary metric that needs to be minimized as part of the optimization task.

Remote Point Sensor Emission Assessment (RPSEA)

Remote Point Sensor Emissions Assessment (RPSEA) relies on fixed point stations placed around a landfill, equipped with sensors to track wind, temperature, pressure, and humidity, alongside methane detectors. Some systems use low-cost metal oxide sensors, while other systems deploy laser spectrometers. Data from these stations are fed into algorithms, often inverse dispersion models, to produce continuous (~hourly) estimates of emissions. RPSEA has been evaluated in oil and gas controlled-release studies with mixed outcomes, but how well these results apply to landfills is unclear. Landfills are larger, more complex, and emit at higher rates of methane than oil and gas complexes. No RPSEA vendor has demonstrated validated landfill performance, though several participants trialed the method in our 2023 controlled release study. While the approach offers the appeal of automated, continuous coverage, the costs depend widely on whether vendors bundle hardware, service, or both.

Satellite Imaging Sensor Emission Assessment (SISEA)

Satellite Imaging of Surface Emissions Assessment (SISEA) uses satellite-borne sensors to capture a series of images, merging them into interference patterns that reveal methane concentrations across facility-scale pixels. These systems are best suited to detecting strong point sources, while broad, diffuse landfill emissions are more easily overlooked. Past studies have validated SISEA for high rate point sources, with Sherwin et al. (2023) showing that the most sensitive satellites can detect emissions as low as ~170 kg/hr. For area sources, however, success is less certain. Like drone-based column sensors, SISEA measurements are diluted by the overlying atmospheric column, meaning very large ground-level enhancements are required to register a signal.

Remote Mobile Sensor Emissions Assessment (RMSEA)

Remote Mobile Surface Emission Assessment (RMSEA) has long been used in the oil and gas sector, but landfill applications remain limited, with only a few published studies and just one controlled release trial. RMSEA involves mounting a high-performance methane analyzer on a vehicle and driving transects along the landfill's fenceline, or even several kilometers downwind. Methane concentrations, wind speed, and direction are logged with precise geolocation. Emission rates are estimated using Gaussian dispersion inversions by segmenting individual plumes and fitting them with models like Polyphemus or by applying computational inversion to match observed plume structures. Digital elevation data are typically incorporated to account for source height and to help localize emissions. In our 2023 study, two participants used RMSEA. Previous work by Fredenslund et al. (2019) showed that RMSEA correlated well with the gold-standard MTCEA ($R^2 = 0.765$), although RMSEA underestimated emissions when compared to MTCEA, reporting about 72% of MTCEA values.

Study Participation Timelines

Table S1. Summary of controlled release study participants

Participants; Date	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Nov 20, 2024		●	●	●	●								●	
Nov 21, 2024	●	●	●	●	●						●		●	●
Nov 22, 2024	●	●		●									●	
Nov 23, 2024	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nov 24, 2024	●	●		●	●									
Nov 25, 2024	●	●		●	●					●			●	
Nov 26, 2024		●		●									●	
Nov 27, 2024		●		●				●					●	
Nov 28, 2024		●		●			●		●				●	
Nov 29, 2024		●		●									●	

Table S2. Participation submission schedules (see Table 1 for identifiers).

Participant	Methodology	Date of 1st submission	Date of 2nd submission
A	MGPA	-	-
B	RPSEA	Jan 09, 2025	-
C	UGSEM	-	-
D	RPSEA	Dec 23, 2025	Jan 22, 2025
E	UCSEA	Jan 13, 2025	Feb 02, 2025
F	UCSEA	Dec 20, 2024	-
G	SISEA	-	-
H	SISEA	-	-
I	SISEA	-	-
J	UCSEA	Jan 10, 2025	Mar 10, 2025
K	MGSEM	Jan 22, 2025	-
L	RMSEA	Feb 03, 2025	-
M	RPSEA	Feb 07, 2025	-
N	MGSEM	Mar 12, 2025	-

REFERENCES

Abichou, T., Bel Hadj Ali, N., Amankwah, S., Green, R., Howarth, E.S., 2023. Using Ground- and Drone-Based Surface Emission Monitoring (SEM) Data to Locate and Infer Landfill Methane Emissions. Methane 2, 440–451. https://doi.org/10.3390/methane2040030

Bell, C., Ilonze, C., Duggan, A., Zimmerle, D., 2023. Performance of Continuous Emission Monitoring Solutions under a Single-Blind Controlled Testing Protocol. Environmental Science & Technology 57, 5794–5805. https://doi.org/10.1021/acs.est.2c09235

Cheptonui, F., Emerson, E., Ilonze, C., Day, R., Levin, E., Fleischmann, D., Brouwer, R., Zimmerle, D.J., 2025. Assessing the performance of emerging and existing continuous monitoring solutions under a single-blind controlled testing protocol. Elementa: Science of the Anthropocene 13, 00020. https://doi.org/10.1525/elementa.2025.00020

Day, R.E., Emerson, E., Bell, C., Zimmerle, D., 2024. Point Sensor Networks Struggle to Detect and Quantify Short Controlled Releases at Oil and Gas Sites. Sensors 24, 2419. https://doi.org/10.3390/s24082419

EREF, 2024. A Controlled Release Experiment for Investigating Methane Measurement Performance at Landfills. Available at: https://erefdn.org/product/a-controlled-release-experiment-for-investigating-methane-measurement-performance-at-landfills/

Fredenslund, A.M., Mønster, J., Kjeldsen, P., Scheutz, C., 2019. Development and implementation of a screening method to categorise the greenhouse gas mitigation potential of 91 landfills. Waste Management 87, 915–923. https://doi.org/10.1016/j.wasman.2018.03.005

Hossain, R.I., Buntov, P, Dudak, Y., Martino, R., Fougère, C., Naseridoust, S., Bourlon, E., Lavoie, M., Khaleghi, A., Hall, C., Risk, D., 2026. A Controlled Release Experiment for Investigating Methane Measurement Performance at Landfills. Elementa: Science of the Anthropocene, 14(1), 00048. https://doi.org/10.1525/elementa.2025.00048

Ilonze, C., Emerson, E., Duggan, A., Zimmerle, D., 2024. Assessing the Progress of the Performance of Continuous Monitoring Solutions under a Single-Blind Controlled Testing Protocol. Environmental Science & Technology 58, 10941–10955. https://doi.org/10.1021/acs.est.3c08511

Mbua, M., Riddick, S.N., Kiplimo, E., Shonkwiler, K.B., Hodshire, A., Zimmerle, D., 2025. Evaluating the feasibility of using downwind methods to quantify point source oil and gas emissions using continuously monitoring fence-line sensors. Atmospheric Measurement Techniques 18, 5687–5703. https://doi.org/10.5194/amt-18-5687-2025

Omidi, A., Bourlon, E., Khaleghi, A., Tarakki, N., Martino, R., Stuart, J., Risk, D., 2025. Most landfill methane emissions Escape detection in EPA21 surface emission monitoring surveys. Waste Management 207, 115104. https://doi.org/10.1016/j.wasman.2025.115104

Sherwin, E.D., Rutherford, J.S., Chen, Y., Aminfard, S., Kort, E.A., Jackson, R.B., Brandt, A.R., 2023. Single-blind validation of space-based point-source detection and quantification of onshore methane emissions. Scientific Reports 13, 3836. https://doi.org/10.1038/s41598-023-30761-2

Sonderfeld, H., Bösch, H., Jeanjean, A.P.R., Riddick, S.N., Allen, G., Ars, S., Davies, S., Harris, N., Humpage, N., Leigh, R., Pitt, J., 2017. CH4 emission estimates from an active landfill site inferred from a combined approach of CFD modelling and in situ FTIR measurements. Atmospheric Measurement Techniques 10, 3931–3946. https://doi.org/10.5194/amt-10-3931-2017