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Most landfill methane emissions Escape detection in EPA21 surface emission monitoring surveys

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ABSTRACT

We measured emissions from ten landfills using mobile surveys and Surface Emission Monitoring (SEM) to determine what fraction of emissions can be identified by SEM surveys. SEM is commonly used for regulatory compliance and leak detection at specific locations. However, evolving regulations emphasize the need to manage methane emissions from the entire landfill site, and the suitability of SEM for this objective remains unclear. Using mobile methane measurements and a back-trajectory attribution and rate estimation method, we measured overall site emissions and those of individual landfill components (active face, closed cells, leachate, etc.). We evaluated each component's contribution to the total emissions and compared how much of emissions captured by mobile surveys could be covered by the walking SEM survey. We found that SEM was effective for closed sites, achieving on-average 67% rate coverage. However, SEM missed relevant emission sources at open landfill sites, most notably from the active face, reducing its rate percent coverage to 17%. The limited rate coverage of SEM suggests that using SEM alone is insufficient for measurement-informed management of landfill emissions. We recommend that SEM be augmented by other methods to fill monitoring gaps and provide a more comprehensive assessment of landfill methane emissions.

1. Introduction

The waste sector is the third largest contributor to greenhouse gas emissions globally (Ritchie et al., 2020). Walking Surface Emission Monitoring (SEM) is the most widely used ground-level method for detecting methane (CH_4) leaks at landfills (Abichou et al., 2023; Bogner et al., 1997; Scheutz et al., 2009), largely due to regulatory requirements mandating monitoring of capped areas equipped with gas collection systems (U.S. EPA, 2016a; Victoria, 2018). SEM involves technicians walking in ~ 30 m grids with handheld sensors, keeping the air intake nozzle a few centimetres above the ground.

In the United States, the regulation of landfill emissions began in the 1990s under the Clean Air Act, with the New Source Performance Standards (NSPS) and Emission Guidelines (EG) for Municipal Solid Waste (MSW) landfills (Clean Air Act Amendments of 1990; U.S. EPA, 2016b). These rules, codified in 40 CFR Part 60 Subpart WWW, aim primarily to control emissions of volatile organic compounds (VOCs) and hazardous air pollutants (HAPs). The rules require landfills under certain criteria to install Gas Collection and Control Systems (GCCS) (Clean Air Act Amendments of 1990) to capture and either flare or utilize landfill gas (U.S. EPA, CFR 40, Subpart WWW). A key compliance requirement under Subpart WWW is quarterly SEM, which relies on flame ionization detectors (FIDs) to detect CH_4 concentrations above 500 ppm as a practical surrogate for VOC leaks (U.S. EPA, CFR 40, Subpart WWW; U.S. EPA 2016c). While CH_4 is not the regulated pollutant under this subpart, its monitoring is used to verify landfill surface integrity and assess GCCS performance. Methane emissions are separately reported under the EPA's Greenhouse Gas Reporting Program (GHGRP), but not controlled under that program.

However, landfill CH_4 regulation is now being developed in North America and globally, shifting from verifying gas collection system presence toward achieving measurable CH_4 emission reductions. For example, recent EPA discussion papers (U.S. EPA, 2024) indicate growing interest in outcome-based regulation aligned with national emissions targets. In Canada, landfill CH_4 rules have explicitly embraced an emissions-focused approach (Government of Canada, 2024). In both contexts, regulation is purposefully shifting toward reducing whole-site emissions to meet climate goals.

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However, concerns exist that SEM walking surveys do not fully cover all landfill emission sources, limiting the method's role in whole-site methane management. Studies by Ute-Röwer et al. (2016) and Mønster et al. (2019) found SEM surveys often fail to capture the heterogeneous nature of landfill covers and localized hotspots. These hotspots include active faces, gas collection infrastructure, compost, and leachate management systems—components identified as key CH_4 sources (Scheutz et al., 2011; Akerman et al., 2007; Olaguer et al., 2022). Active faces, where fresh waste is deposited (Scarpelli et al., 2024; Guha et al., 2020), can emit large CH_4 volumes due to rapid decomposition of organic waste and disturbance of underlying layers (Cusworth et al., 2024; Kumar et al., 2023; Krause et al., 2023; Manheim et al., 2023; Yeşiller et al., 2022; Cambaliza et al., 2017; Goldsmith et al., 2012). Scarpelli et al. (2024) recently found that 79 % of CH_4 emissions from U.S. landfills originated from sites where emissions were observed at the active faces.

Given the regulatory shift toward climate outcomes, monitoring approaches must also be reconsidered to assess their contribution to these goals. This study investigates the proportion of total landfill emissions detectable by SEM, evaluating its potential role within emerging climate-focused CH_4 regulations. Using mobile surveys, we mapped emissions from key landfill components across multiple sites and assessed what share of these emissions, by area and emissions rate, could be captured through SEM. Our results aim to inform policymakers and stakeholders in drafting more effective methane legislation in Canada and internationally.

2. Methodology and materials

2.1. Methodological framework

To evaluate the effectiveness of SEM in detecting CH_4 emissions at landfills, we compare SEM's areal coverage with quantitative emission estimates derived from mobile surveys. The methodology involved three main steps:

1. Mobile CH_4 Surveys and Emission Mapping
   We conducted multi-day mobile CH_4 surveys at ten landfills using vehicle-mounted analyzers and wind sensors. Methane hotspots were identified using wind-informed triangulation, and emission rates were estimated using a Gaussian plume dispersion model. Landfill components were mapped from site observations and official records and emissions were attributed to the components based on a back-trajectory method.
2. SEM Survey Coverage Assessment
   SEM surveys were conducted independently by a third-party contractor following a standard 30 × 30 m walking grid protocol. We did not use SEM data to estimate emissions. Instead, we calculated areal coverage (the proportion of component area covered by SEM) and rate coverage (the proportion of mobile-derived emissions that occurred in SEM-covered areas).
3. Coverage Analysis and Comparative Assessment
   We assessed SEM effectiveness by comparing its spatial and rate coverage across landfill components at both open and closed sites. This comparison helps determine whether SEM, as currently applied, can adequately support whole-site emission management in line with evolving regulatory frameworks.

2.2. Mobile measurements

Mobile CH_4 transect measurements using vehicle-mounted analyzers, although not yet common in landfill emission studies, have been widely applied in the oil and gas sector—particularly for emission detection and source attribution. One notable example is the U.S. EPA's Other Test Method 33A (OTM 33A) (U.S. EPA, 2020), which formalizes mobile ground-based surveys as a recognized method for CH_4 plume detection and quantification. Several large-scale North American methane source apportionment and inventory studies have used mobile platforms to map emissions at high spatial resolution and quantify fluxes using wind-informed models (Swarthout et al., 2015; Omara et al., 2024).

For our mobile laboratory, we equipped a sports utility vehicle with a Gill WindSonicM Ultrasonic Wind Sensor, compass, GPS (Garmin 18x-5 Hz GPS), and gas analyzers attached via tubing for sampling. A Los Gatos Research Ultra-Portable Greenhouse Gas Analyzer or an LGR-ICOS Microportable Gas Analyzer (GLA131 Series) with a precision of 1.4 ppb for CH_4 measured the CH_4 concentrations in ppmv. The anemometer measured wind speed with 3 % precision and wind direction with an accuracy of ± 3°. Before each daily measurement session, we calibrated the compass towards the four cardinal directions and benchmarked the gas analyzers using a standard gas cylinder to ensure data accuracy and check for any instrument drift. We also recorded the instrument's response lag before starting each measurement to guarantee the accurate location of the concentration readings.

We measured each landfill for a total of 5–12 days during winter and summer. During each field day, we drove all accessible areas of the landfill continuously for about seven hours, collecting about 50,000 geolocated concentrations measurements. This included both onsite and perimeter measurements, ensuring comprehensive coverage of the landfill. During each day, and between days, winds would shift, so we intercepted plumes in different locations as we travelled the accessible landfill roads, allowing us to triangulate emission sources.

Fig. 1(a) shows an example of data measured from a mobile survey of LF3's perimeter. We depicted the operational features of the landfills on landfill maps using polygons. The polygons represented the active face, closed cells with intermediate and final covers, leachate and gas collection systems, composting sites, and other infrastructure of each landfill. Any component related to wastewater such as tanks, manholes, sumps, piping, or wastewater ponds was classified as part of the leachate management system.

To identify the source of emissions and to quantify the fluxes, we attributed all peaks in our measured CH_4 time series to potential point sources, determined from triangulation, within the polygons. Starting from the location of a CH_4 concentration peak in the time series, we traced the wind direction to identify all upwind path intersections as potential origins of the plume (Omidi et al, 2024). We applied a Kernel Density Estimate (KDE) to smooth the distribution of the triangulated points, weighted by the measured concentrations, and mapped them across the landfill's geographic area ((b)).

We identified local maxima and used the Gaussian dispersion model represented in Eq. (1) at the maximum concentration to quantify the emissions (Turner, 2020). We assumed we had measured directly downwind from the emission source (y = 0):

$$C(x,y,z) = \frac{Q}{2\pi\,\sigma_y\sigma_z U}\exp\left(\frac{-y^2}{2\sigma_y^2}\right)\left(\exp\left(\frac{-(z+H)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z-H)^2}{2\sigma_z^2}\right)\right) \quad (1)$$

where$Q$ = pollutant emission rate (g s^{-1})σ_z = vertical standard deviation of the concentration distribution (m)σ_z = crosswind standard deviation of the concentration distribution (m)U = mean horizontal wind velocity at pollutant release height (m s^{-1})$C(x,y,z)$ = concentration at location (x,y,z) (g m^{-3})H = pollutant release height (m)

We estimated fluxes from the mobile transects, keeping in mind that the ground-based measurement and Gaussian estimation from truck measurement could underestimate actual emission rates (Fairley and Fischer, 2015; Hossian et al., 2024).

2.3. Surface emission monitoring surveys

For the walking SEM surveys, we engaged a third-party contractor to conduct walking surveys in ten Canadian landfills, with seven landfills

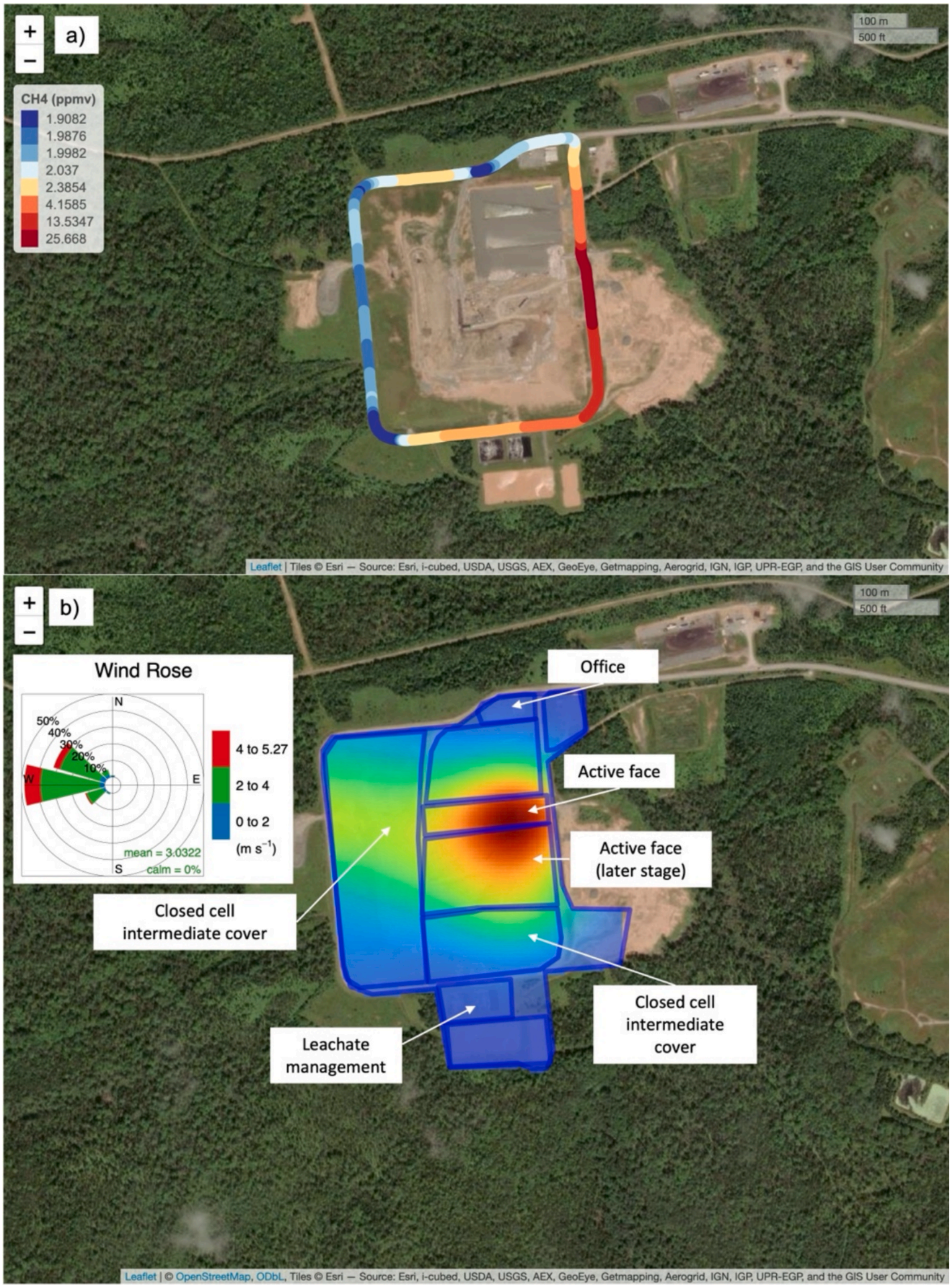

Fig. 1. (a) Examples of on site mobile measurements at LF3. The colors on the map represent different CH_4 concentrations, with red indicating the highest values and dark blue showing the lowest or background levels. (b) A map of CH_4 hotspots identified using triangulation, with landfill components tagged. A wind rose in the top-left corner illustrates wind speed and direction (mainly from the west) during the mobile measurements.

surveyed twice and three landfills surveyed once. They used two sensors for the measurement, Toxic Vaper Analyser (TVA 2020) and RKI EAGLE 2. The TVA 2020 reports CH_4 concentrations with an accuracy of $\pm$ 10 % of the readings or $\pm$ 1 ppm, whichever is greater. The RKI EAGLE 2 provides an accuracy of $\pm$ 5 % of the readings or $\pm$ 2 % of full scale, with the full scale defined as 0–100 % CH_4 by volume—corresponding to a potential error of $\pm$ 2 % absolute at any point on that scale.

Characteristics of each landfill are listed in Table 1. We provided no special instructions or requests to the contractor; we simply asked that all surveys represent industry norms and that the measurements reflect standard practice.

For each SEM survey, the CH_4 mixing ratios were recorded in parts per million by volume (ppmv) at designated grid points, with each point representing a 30×30 m^2 grid square. The contractor used a serpentine walking pattern along the predefined grid squares holding the scanner upright with the extension rod contacting the ground surface. Stationary readings were taken for at least 3 s at each grid point. In cases where the instrument did not stabilize, minimum and maximum mixing ratios

Table 1
Site Descriptions and total site emissions estimates. ECCC is Environment Climate Change Canada and GCCS stands for Gas Collection and Control System. Cumulative total waste disposal data for Site LF6 were unavailable.

Landfill ID	Operational Status	GCCS	Surface Area (~ha)	Cumulative Total Waste Disposal (Mt)	2023 ECCC Methane Generation Estimate (t yr^{-1})	Mobile Survey Estimate (t yr^{-1}) using transects
LF1	Closed	None	53	4.49	1584	1391
LF2	Open	Existing	60	2.47	3969	2160
LF3	Open	None	23	1.32	3070	3537
LF4	Open	None	47	4.46	5588	1068
LF5	Open	None	57	3.58	3759	987
LF6	Closed	None	66		6350	11,522
LF7	Open	None	107	0.60	879	924
LF8	Open	Existing	42	1.28	2610	3545
LF9	Open	Existing	27	0.95	1252	1523
LF10	Open	Existing	64	0.93	2387	4737

were recorded and averaged. Fig. 2 presents an example of measured SEM points at LF4 (details of the landfill can be found in Table 2), cross-referenced with photographs.

2.4. SEM areal and rate coverage estimation

We evaluate how effectively SEM captures high-emission sources by comparing SEM areal coverage with quantitative emission estimates from mobile surveys. Although SEM is typically used to qualitatively locate leaks, we assessed its ability to detect the most impactful sources. By linking SEM's areal coverage to the emission rates of different landfill components, we quantified its effectiveness in terms of both spatial and emission rate coverage.

We found the areal coverage ratio of component *i* measured by SEM by

$$C^i_{areal} = \frac{n_i \times 30 \times 30}{A_i};$$

where A_i is the total area of component *i* in m^2; n_i is the total number of SEM measurements; and 30 × 30 is the grid cell size in m^2.

To estimate how much the SEM data contributed to the total component emissions, we multiplied the SEM areal coverage (C^i_{areal}) by the component emission rate, measured by the mobile survey (Q^i_{mobile}). W e calculated the proportion of the total landfill emission rate covered by the SEM measurements of that component using the formula

$$C^i_{rate} = \frac{Q^i_{mobile} \times C^i_{areal}}{\sum_{i \in S} Q^i_{mobile}}$$

S represents the set of all the components of the landfill. The overall SEM emission rate coverage for the landfill was

$$C_{rate} = \sum_{i \in S} \frac{Q^i_{mobile} \times C^i_{areal}}{\sum_{i \in S} Q^i_{mobile}}$$

We compared the proportion of total landfill emissions captured by SEM measurements to the emissions estimated with mobile measurement data across all landfill components. Details of the measured components for each landfill are in Table S.1 of the Supplementary Materials.

3. Results and discussion

Table 1 contains the estimated fluxes from the mobile landfill transects. We used Gaussian dispersion models to quantify the aggregate CH_4 emission rate for each landfill.

Fewer than 1 % of the SEM sample points over all the surveys exceeded the 500 ppm regulated threshold. Given that eight of the

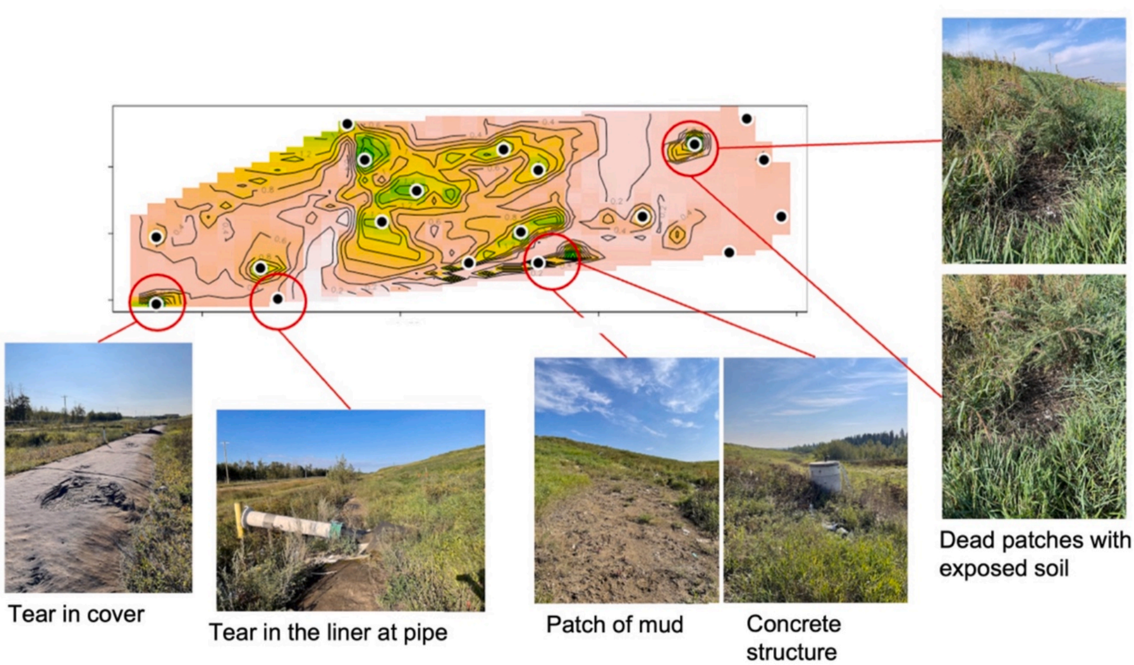

Fig. 2. Examples of source types and locations from SEM surveys of LF4.

Table 2
Summary of source contributions for open landfills, categorized by the presence or absence of GCCS. The table shows the mean emission rate per area (kg hr^{-1} ha^{-1}), the average contribution percentage of each source, and the standard deviation of these contributions. The averages and standard deviations are calculated over the measurement days, which varied from landfill to landfills ranging from 5 to 12 days. The "Others" source incorporates variable areas not commonly found across the surveyed landfills, such as compost piles, office, garbage truck garages, and forest patches, which differ from one landfill to another.

Source	Open Landfill Status	Mean Emission Rate Per Component Area (kg$hr^{-1}$$ha^{-1}$)	Average Contribution (%)	Standard Deviation of Contribution (%)
Active Face	Without GCCS	5.37	42.35	13.96
Closed Cell Intermediate Cover	Without GCCS	3.73	31.37	22.47
Compost Facility	Without GCCS	1.33	7.85	7.28
Others	Without GCCS	5.10	11.74	7.29
Leachate Management	Without GCCS	1.21	12.37	21.06
Closed Cell Final Cover	Without GCCS	0.02	0.41	–
Active Face	GCCS	14.17	69.12	22.65
Closed Cell Intermediate Cover	GCCS	2.34	16.76	13.50
Compost Facility	GCCS	2.89	7.28	7.73
Others	GCCS	0.85	3.89	4.31
Flare and Gas Collection System	GCCS	1.43	0.29	0.41
Leachate Management	GCCS	0.20	0.69	0.55
Closed Cell Final Cover	GCCS	1.82	13.86	22.37

surveyed sites were among the 270 large Canadian landfills that account for approximately 85 % of Canada's estimated landfill-related eCO_2 emissions (Canada, 2022), we expected a higher number of exceedances. For those landfills surveyed more than once, we also noticed variations in CH_4 levels between visits, indicating possible fluctuations in emissions due to seasonality and different atmospheric conditions (e.g., wind patterns).

Fig. 3 shows the mapped interpolated SEM points for both visits for some of the landfills (also Fig. S1 in Supplementary Materials). We used Akima's bivariate interpolation method (Gebhardt et al., 2022). Landfill components like composting areas, gas collection systems, and leachate/ flare systems, which showed emissions from mobile survey data, were

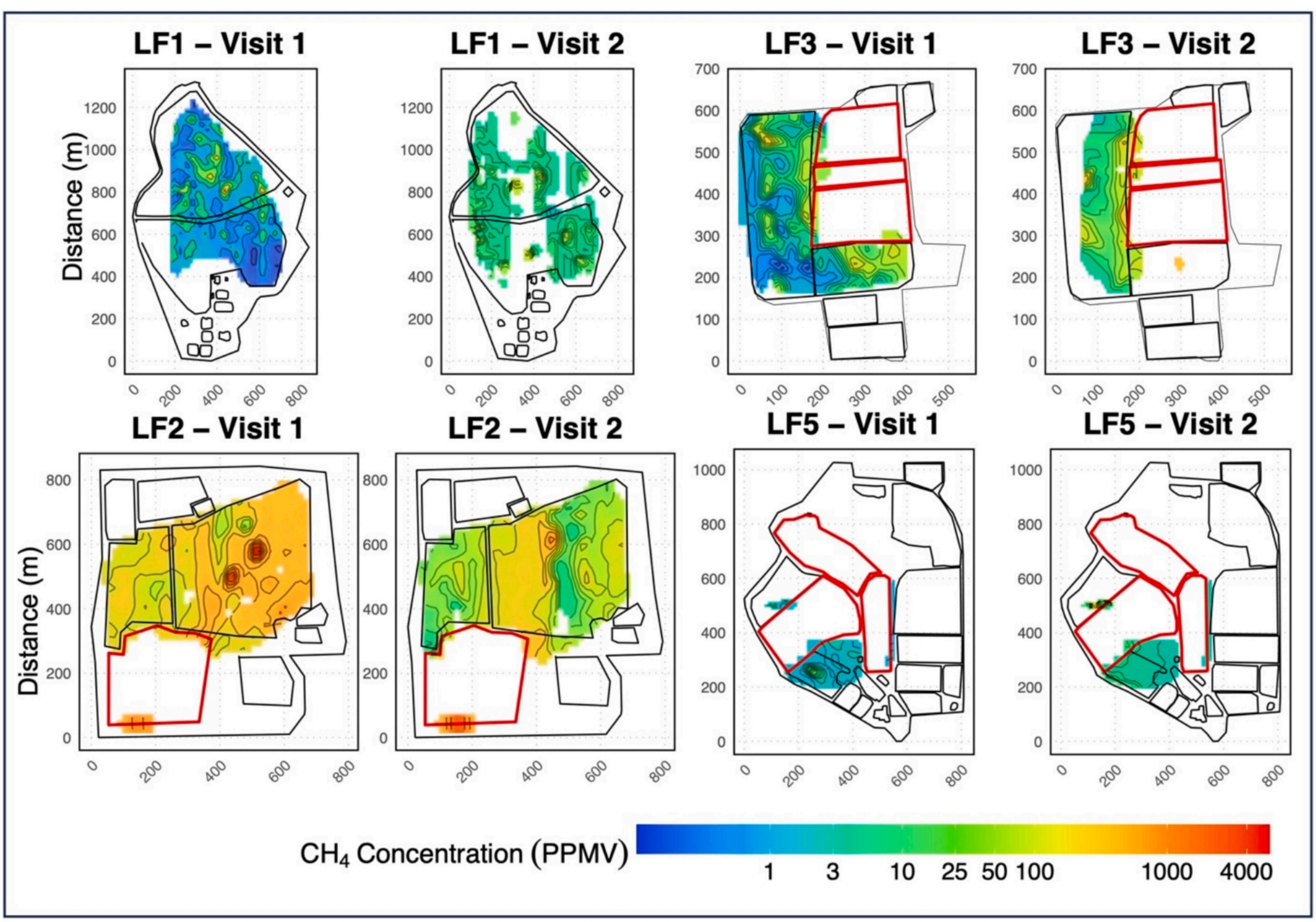

Fig. 3. SEM maps of surveyed landfills. LF1 (closed), LF2, LF3, and LF5 from Visit 1, conducted between August and September 2023, and Visit 2, conducted between October and November 2023. The colored areas represent the SEM CH_4 survey; the SEM concentrations were interpolated. The black borders outline the landfill perimeters and the component areas. Red borders highlight active face zones, identified as major contributors to emissions at most sites. These active areas are typically not covered by SEM measurements.

not covered by the SEM surveys. We excluded the limited number of SEM measurements from the active face from Fig. 3 and from the areal and rate coverage analysis in this section because draft Canadian government regulations do not require fresh waste gas monitoring (Government of Canada, 2024).

To evaluate surface CH_4 concentrations, we analyzed the SEM data across all landfills. Fig. 4(a) shows the surface CH_4 concentrations. In the figure, the red vertical line depicts the regulatory threshold of 500 ppmv. Fig. 4(b) compares the areal coverage (C_{areal}) and rate coverage (C_{rate}) of SEM across measured landfills.

Generally, closed landfills showed higher averaged SEM coverage. LF1 had C_{areal} of 36 % and a C_{rate} of 47 %, while LF6 showed even more coverage, with a C_{areal} of 66 % and a C_{rate} of 88.43 %. There was a noticeable variation in the SEM coverage of LF1 across two visits with a standard deviation of 36 % which highlights the challenge of consistently capturing emissions, especially during colder seasons, even in closed landfills.

The overall spatial coverage for the open landfills remained low due to SEM's limited ability in covering active landfill components (i.e., active face, leachate, compost, and gas collection system). On average, the surveyed open landfills exhibited a C_{areal} of 21 % and a C_{rate} of 17 %. The highest recorded C_{rate} was 36 % at LF4, and LF9 showed the maximum C_{areal} at 36 % (Fig. 4(b)). Additionally, large error bars at some sites highlighted discrepancies in the monitoring of accessible landfill sections.

Table 2 lists the average contributions from each landfill feature across the open landfills, with and without landfill GCCS. We see that the active face is, on average, the biggest source contributor: 69 % and 42 % for landfills with and without GCCS, respectively. Since SEM does not cover the active face, the maximum effectiveness is bounded to 31 % and 58 % of emissions at these site types. SEM also does not typically cover other components like leachate systems or compost. These areas are large contributors to total emissions, so failing to capture these emission sources resulted in a reduced overall emission coverage as shown in Fig. 4(b) where SEM captured maximally 36 % of emissions at open sites.

Fig. 4(b) shows that closed landfills had much better emission rate coverage from SEM coverage, and the open landfills had much lower coverage. It appears that comprehensive SEM coverage is possible at closed sites where intermediate or final cover dominates, in addition to GCCS infrastructure. There are however still gaps, and we note that although SEM at LF6 achieved > 80 % rate coverage, its leachate management source—including all wastewater-related infrastructure—was emitting approximately 50 kg hr^{-1} CH_4 (Table S.2), yet this source was not covered by SEM at this closed site.

4. Conclusion

This study assessed how well SEM surveys captured emissions from different sources at landfills. We evaluated how much different landfill components contributed to total emissions and compared the results with the areal coverage of SEM at ten Canadian landfills.

Our findings showed that SEM effectively captured sources of emissions from closed sites, with an average rate coverage of 68 %. While this level of coverage may not represent full quantification, it may be adequate if SEM is used in combination with other measurement strategies and if the expected emission reductions from such sites do not exceed this coverage level.

At open landfill sites, the story is different. SEM coverage misses most of the sources and thus it is not recommended to be used alone in a regulatory framework trying to mitigate emissions. It is important to

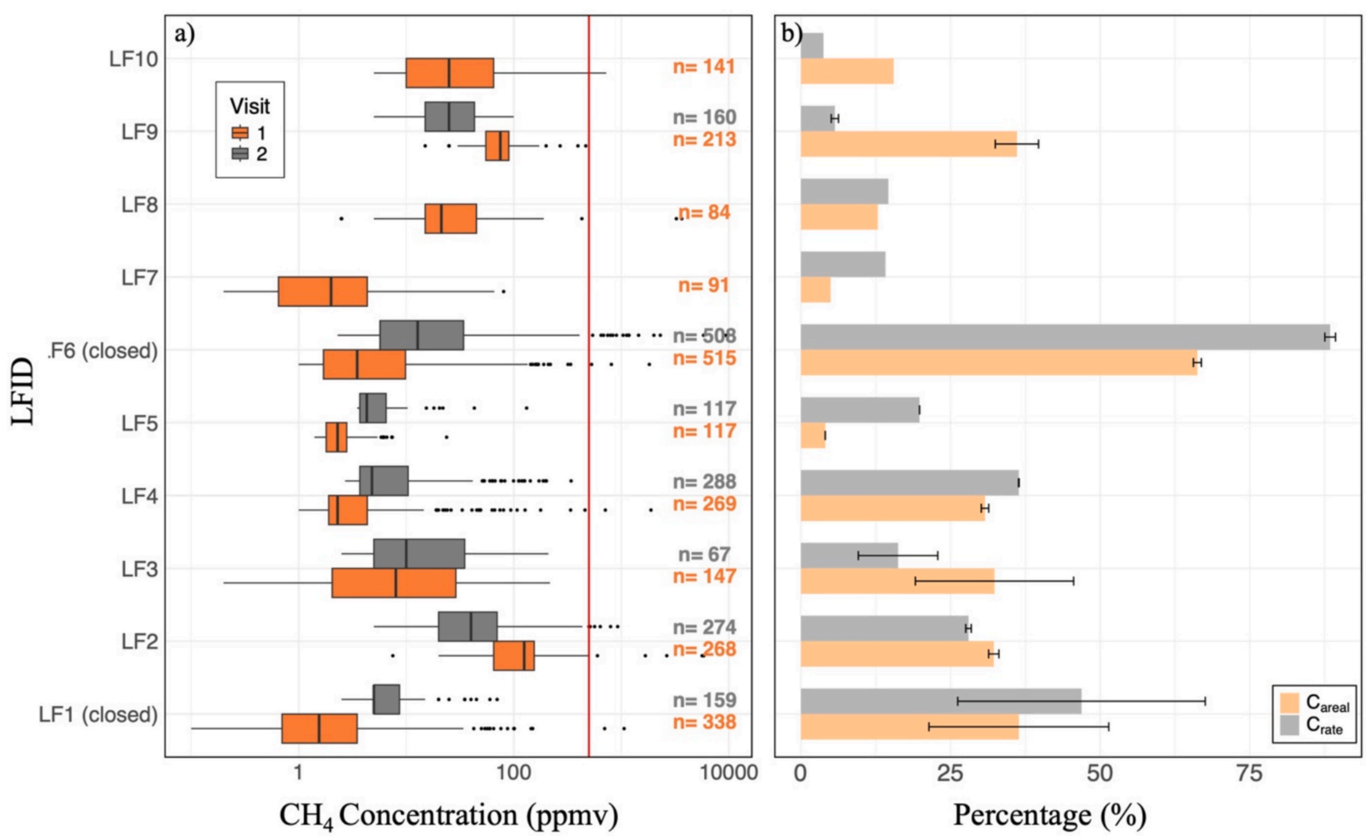

Fig. 4. (a) Box plots showing CH_4 concentrations (ppmv) across landfills over multiple visits. The boundaries of each box represent the interquartile range (25th to 75th percentiles), and the lines within the boxes represent the median values for each landfill's SEM measurements. The red vertical line indicates the regulatory proposed threshold for a single location, set at 500 ppmv, while n indicates the number of SEM measurements. (b) Bar chart showing the average total areal and rate coverage (C_{areal} and C_{rate}) across visits for each landfill, with error bars representing the standard deviation.

note that the total emissions were assumed to be those derived from mobile survey CH_4 measurements using Gaussian plume modeling. If we use SEM as the default approach to manage emissions, we are expending significant effort and cost to influence a small percentage of total site emissions. For open landfill sites we would suggest that regulators specify the use of alternative measurement methodologies capable of assessing emissions from all landfill components to cover all under some form of measurement-informed management. Applicable methodologies are available to replace SEM (Hossian et al., 2024; Mønster et al., 2019) and potentially at a lower cost. These may include mobile surveys, eddy covariance, drone- or aircraft-based measurements (Hossian et al., 2024). Regulators need to send clear signals on what performance requirements are needed. For example, it would be reasonable to specify minimum detection thresholds at 90 % probability of detection (Government of Canada, 2023; U.S. EPA, 2023). SEM could be used as a supplementary method to measure GCCS infrastructure and identify points of emissions but should not be the default or sole strategy. We also recommend that measurement and emissions management requirements for the active face be mandated in new regulations, given the importance of this source. Lastly, measurement requirements should be flexible and adaptable based on individual landfill operations since not all measurement approaches are available or useful everywhere. By combining SEM with other technologies, operators and regulators will build a more complete picture of landfill emissions and will be able to reduce methane emissions much further than is possible under the status quo.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication

CRediT authorship contribution statement

Athar Omidi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Evelise Bourlon:** Visualization, Methodology, Investigation. **Afshan Khaleghi:** Validation, Investigation, Data curation. **Nadia Tarakki:** Validation, Resources, Data curation. **Rebecca Martino:** Validation, Resources, Data curation. **Jordan Stuart:** Resources, Data curation. **David Risk:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [David Risk reports financial support was provided by Natural Resources Canada. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.].

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2025.115104.

Data availability

Data will be made available on request.

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