Title: Active Face Emissions: An Opportunity for Reducing Methane Emissions in Global Waste Management

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Active Face Emissions: An Opportunity for Reducing Methane Emissions in Global Waste Management

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Abstract

This study used mobile surveys of ten Canadian landfills to assess how methane emissions varied across different landfill sources and operational conditions. The studied landfills included two closed landfills, four open landfills equipped with Gas Collection and Control Systems (GCCS), and four open landfills operating without GCCS. We employed the Gaussian dispersion model to estimate emissions fluxes using on site and off site transect data. We observed high spatial variability of methane emissions and identified the sources that contributed significantly to overall landfill emissions, sources such as the active face, closed cells, compost areas, leachate systems, and GCCS. Overall, we found that the active face of landfills is a major emitter of methane, contributing 76% of the methane emissions for landfills with GCCS and 38% for landfills without GCCS. The results underscore the importance of improved monitoring and management strategies at landfill active faces to more effectively mitigate methane emissions from landfills.

Keywords: landfill, methane, mobile survey, active/working face.

1 Introduction

The waste sector emits 20% of global methane into the atmosphere making the sector one of the highest contributors to global greenhouse gas emissions (United Nations Environment Programme & Climate and Clean Air Coalition, 2021). Canada's "Faster and Further: Methane Strategy" aims to reduce waste sector emissions by 45% by 2030 (Government of Canada, 2022) with Environment Climate Change Canada (ECCC) drafting regulations to achieve the reduction goal (Government of Canada, 2024). Similar international guidelines require waste operators to monitor and control landfill gas emissions in United States, Australia, the European Union, and the United Kingdom (European Union, 2024; EPA, 2023; GOV.UK, 2020; Victoria, E.P.A., 2018).

There is a high spatial variability in methane emissions from municipal solid waste landfills (Delgado et al., 2022; Huang et al., 2021; Gonzalez-Valencia et al., 2016; Abichou et al., 2011; Bogner et al., 1997; Czepiel et al., 1996). Czepiel et al. (1996) observed that 5% of a landfill's surface was responsible for more than half of its total methane emissions. Bergamaschi et al. (1998) estimated that up to 70% of emissions from two landfills escaped through leaks. The reported uneven distribution of emissions suggests that identifying the emissions sources is critical to mitigation strategies (Lando et al., 2017; Galle et al., 2001). According to Cusworth et al. (2024), persistent emissions from landfills occur from unexpected areas, and effective mitigation requires identifying the parts of a landfill operation that are potential emission sources.

The sealed areas of a landfill (closed cells) have been identified as a major emission source because methane escapes through the covers (Sirimangkhala et al., 2018; Zhang et al., 2012; Bogner et al., 2011). Related infrastructure, including pipes, wells, leachate ponds, and systems for gas collection and control (GCCS) emit methane (Allen et al., 2019; Emran et al., 2017; Scheutz et al., 2011; Bogner et al., 1995), and emissions have been reported from on site composting zones (Harrison et al., 2024; Scheutz et al., 2011; Andersen et al., 2010).

Increasingly studies recognize the operational area of a landfill where waste is currently being deposited (the active face) as a significant source of methane (Scarpelli et al., 2024; Kumar et al., 2023; Guha et al., 2020; Cusworth et al., 2020; Innocenti et al., 2017; Cambaliza et al., 2017; Goldsmith et al., 2012). At the active face, organic materials such as food waste decompose rapidly (Krause et al., 2023), and emissions from the active face might be underappreciated or even underestimated (Maasakkers et al., 2022) because of issues such as temporal fluctuations. Bogner et al. (2011) recognized that seasonal changes in soil moisture and temperature affect emission rates. Waste composition, landfill management practices, and microbial activity also cause temporal changes (Dimishkovska et al., 2019; Shen et al., 2018; Delkash et al., 2016; Rachor et al., 2013).

In this research, we assessed landfill methane emission sources at ten Canadian landfills using mobile surveys to define how much the active face and other landfill areas contributed to overall methane emissions. In the multi-day surveys, we measured on site, along fencelines, and off site, isolating sources we observed to have high levels of methane emissions. Our research provides insights into specific methane sources in different landfill environments and highlights mitigation opportunities for policy makers.

2 Materials and Methods

2.1 Measurements

For our mobile surveys, we used a sports utility vehicle with a Gill WindSonicM Ultrasonic Wind Sensor, compass, (Garmin 18x-5Hz GPS), and gas analyzers connected by tubing for sampling. The anemometer measured wind speed and direction with the accuracy of 3% and ±3°, respectively. We measured methane concentrations in ppmv using a Los Gatos Research Ultra-Portable Greenhouse Gas Analyzer or an LGR-ICOS Microportable Gas Analyzer (GLA131 Series), which has a precision of 1.4 ppb for methane. The anemometer, compass, and GPS collected wind data and recorded the vehicle's locations.

Before starting the daily mobile measurements, we benchmarked the gas analyzers against a standard gas cylinder to verify accuracy and to check for any instrument drift and we calibrated the compass towards the four cardinal directions. We also recorded the transit time from the inlet tube to the instrument to guarantee the accurate location of the concentration readings.

We surveyed each site (Table 1) for a total of 5 to 12 days during the summers and winters of 2023 and 2024. On field days, we drove through all accessible parts of each landfill, spending about seven hours per day transecting plumes on site, off site, and along the landfill fencelines. The extensive coverage, close to and far from the emission sources, allowed us to intercept methane plumes in diverse locations, and under different wind conditions. These observations gave us a picture of concentrations as a function of time and winds in all areas of the site, and off site. By measuring each source under various wind speeds and directions from multiple locations, with high repetition, we were able to triangulate and effectively map all emission sources and source locations at each landfill.

2.2 Source Identification

To localize emissions, we used two back-trajectory methods: a Lagrangian method and a triangulation method.

The Lagrangian method (Göckede et al., 2006) uses pre-calculated footprint source weight functions and environmental variables to simulate backward trajectories from sensors to potential sources. This approach aggregates all particle movements, regardless of direction, to generate maps that identify and characterize hotspots.

Generating probable source locations using triangulation involved several steps. We first computed ambient local background concentrations across the landfill by applying a running median filter to all concentration time series from which we identified local minima. We then identified peaks using a gradient descent algorithm, and we backtracked upwind from two peaks' detection coordinates (x_1, y_1) and (x_2, y_2). The point where the backward trajectories intersected with the detection coordinates (under different wind directions) allowed us to establish the probable origin (x_{source}, y_{source}) using equation (1).

$$x_{source} = x_1 + d\ \cos\theta, y_{source} = y_1 + d\ \sin\theta \tag{1}$$

d represents the distance from coordinates (x_1, y_1) to the source, and θ is the wind direction angle in radians. Each source point was weighted by multiplying the methane levels at the two peaks, after subtracting the background methane level, to emphasize its severity and likelihood as a source. This process was repeated for each pair of peaks, generating numerous triangulated, weighted excess concentration points. Then, we applied Kernel Density Estimation (KDE) to spatially smooth the distribution of these points and to create a hotspot map of excess concentrations. A grid with 50-meter resolution was overlaid on this hotspot map. Within each grid cell, we calculated the maximum weighted excess concentration. To prevent overestimation in the subsequent quantification method, we ensured that no two maximum points were within 50 meters of each other by retaining only the point with the higher weight.

2.3 Quantification

To estimate methane flux, we applied the Gaussian dispersion model (Turner, 2020):

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

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 source location (x,y,z) (g m^{-3});

and, H = pollutant release height (m).

We quantified the flux using two distinct approaches, each approach with different inputs. The first approach used on site and fenceline transects to quantify directly upwind from triangulated point sources. To tie the sources to landfill operational attributes, we used maps and other information provided by the landfill operators, photographs taken during field work, and satellite imagery to define polygons representing the functional areas of each landfill. We then calculated the sum of emissions from the quantified triangulated point sources using on site and fenceline surveys that fell within these specific polygons, for example, from the active face, closed cells, and compost areas. We averaged these sums, representing emissions from each source type, over all measurements (Table S1).

In parallel with the on site measurements and analysis, we used off site and fenceline transects with a Gaussian-based joint inversion to fit the observed concentration time series to multiple sources. This approach provided a single flux estimate for the entire site that we compared to the sum of the on site sources. Examples of on site and off site transects are represented in Figure S1.

2.4 Sites Description

The landfill sites were in three Canadian provinces: Nova Scotia, Quebec, and Alberta. We surveyed two closed landfills, four open landfills with Gas Collection and Control Systems (GCCS), and four open landfills without GCCS. The Alberta sites were in an IPCC Boreal-Temperate dry climate zone, while the others were in a Boreal-Temperate wet zone. Table 1 summarizes the characteristics of these landfills. We selected a diverse mix of landfills, each with different operational and environmental characteristics, ensuring a broad analysis of methane emissions across varied settings.

These ten sites did not fully represent all 3,000 municipal solid waste landfills in Canada, but eight of the sites were among the 270 larger landfills that handled and housed >90% of the country's waste, between 100,000 and 450,000 tonnes for closed and open sites, respectively.

LF ID	Status	Surface Area (~ha)	Cumulative Waste Disposal (Mt)	Province	2023 ECCC, IPCC Methane Generation Estimate (t yr^{-1})	Paired Estimates (t yr^{-1}) from ON-FL and OFF-FL
LF1	Closed	53	4.5	NS	1426	912, 1340
LF2	GCCS	60	2.5	QC	0	1070,990
LF3	Non GCCS	23	1.3	NS	2741	3474, 3438
LF4	Non GCCS	47	4.5	AB	2586	1340, 1139
LF5	Non GCCS	57	3.6	AB	2620	402,329

LF6	Closed	66	-	AB	5707	7278, 8068
LF7	Non GCCS	107	0.6	NS	791	714, 368
LF8	GCCS	42	1.3	NS	2305	4110, 4892
LF9	GCCS	27	0.9	QC	969	1169, 1252
LF10	GCCS	109	4.9	QC	2534	1986, 4266

Table 1. Site descriptions and total emissions estimates.

This table provides detailed descriptions of various landfill sites along with their total site emissions estimates from both on site-fenceline (ON-FL) and off site-fenceline (OFF-FL) transects. "ECCC" refers to Environment and Climate Change Canada, and "GCCS" refers to Gas Collection and Control System. The provinces were Quebec (QC), Alberta (AB), and Nova Scotia (NS), with QC and AB having provincial landfill gas (LFG) regulations that require gas collection systems for certain landfills to control emissions. QC is the only province that mandates surface emission monitoring three times annually for landfills equipped with GCCS. Note: Cumulative waste disposal data for site LF6 were unavailable.

3 Results and Discussion

To present results of our analysis, we categorized the sites into three operational types: open landfills with Gas Collection and Control Systems (GCCS), open landfills without GCCS, and closed landfills.

3.1 Evaluating Methane Emissions Identification and Quantification Techniques

Figure 1 shows that total aggregate methane emissions measured from on site/fenceline transects using one dispersion model agreed well in magnitude with emissions measured independently from off site/fenceline transects (slope = 0.77; R^2 = 0.60). Because the aggregated per-source estimates were produced from individual measurements which contained uncertainties (e.g., sensitivity to the 50-meter grid size), we were concerned that our results would over- or under-estimate emissions once aggregated to the site level. However, the good linear relationship between the two measurement approaches gave us confidence that our source-level estimates and aggregations were accurate. The median flux for the measurement period calculated by each approach for a given site is listed in Table 1 as the total estimated methane rate for that site. However, in some cases, we lacked measurements due to weather conditions or access restrictions; for instance, we did not have off site transects for all measurement periods at site LF7, and there was insufficient on site coverage at LF10.

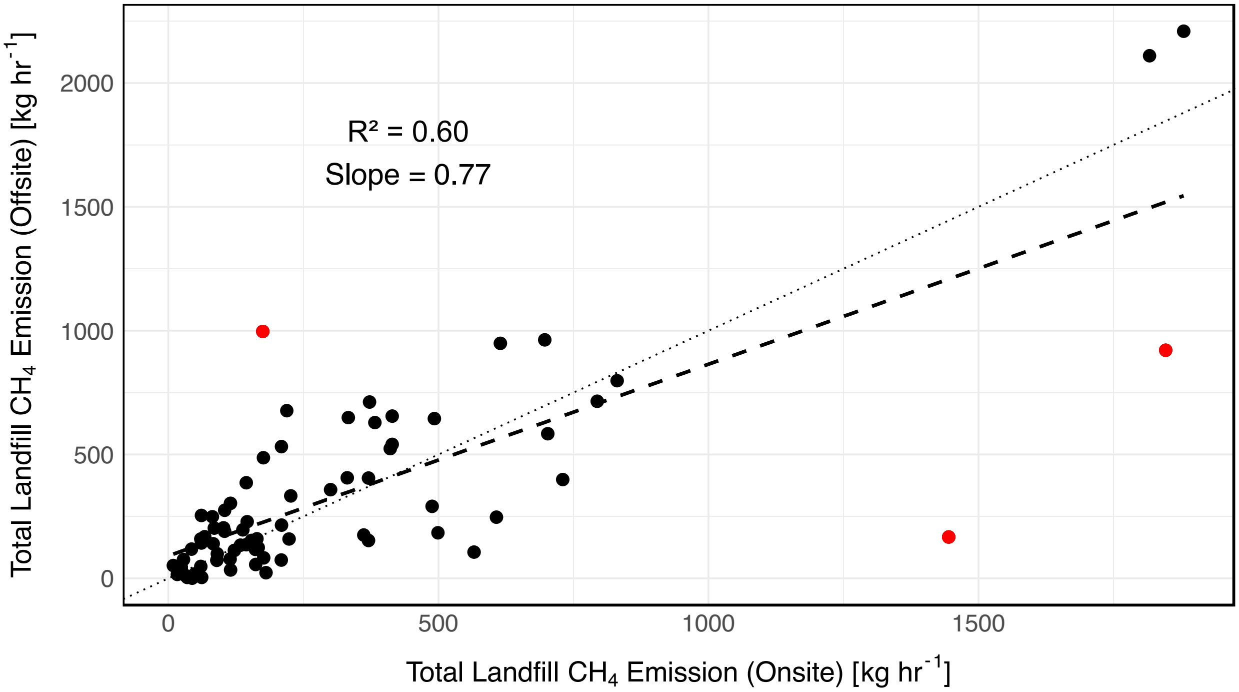

Figure 1: Comparison of landfill emissions from Gaussian dispersion models.

Scatter plot comparing total landfill emissions estimated using two Gaussian dispersion models from on site/fenceline and triangulation sources, and off site/fenceline surveys and optimized random sources. The dotted line indicates the 1:1 correspondence line, and the dashed line represents the linear regression. Outliers, colored in red, are from landfill LF6. The plot shows a linear regression with a slope of 0.77 and an R^2 value of 0.60. When the outliers were excluded, the R^2 value improves to 0.79.

Figure 2 illustrates the plumes identified using the Lagrangian and triangulation back-trajectory methods on the same measurement day. This comparison shows that the localization and identification methods were consistent with each other, and the figure displays different sources within each landfill (the active face, closed cells, compost zones, or leachate systems) as the emission hotspots for different landfills with specific features.

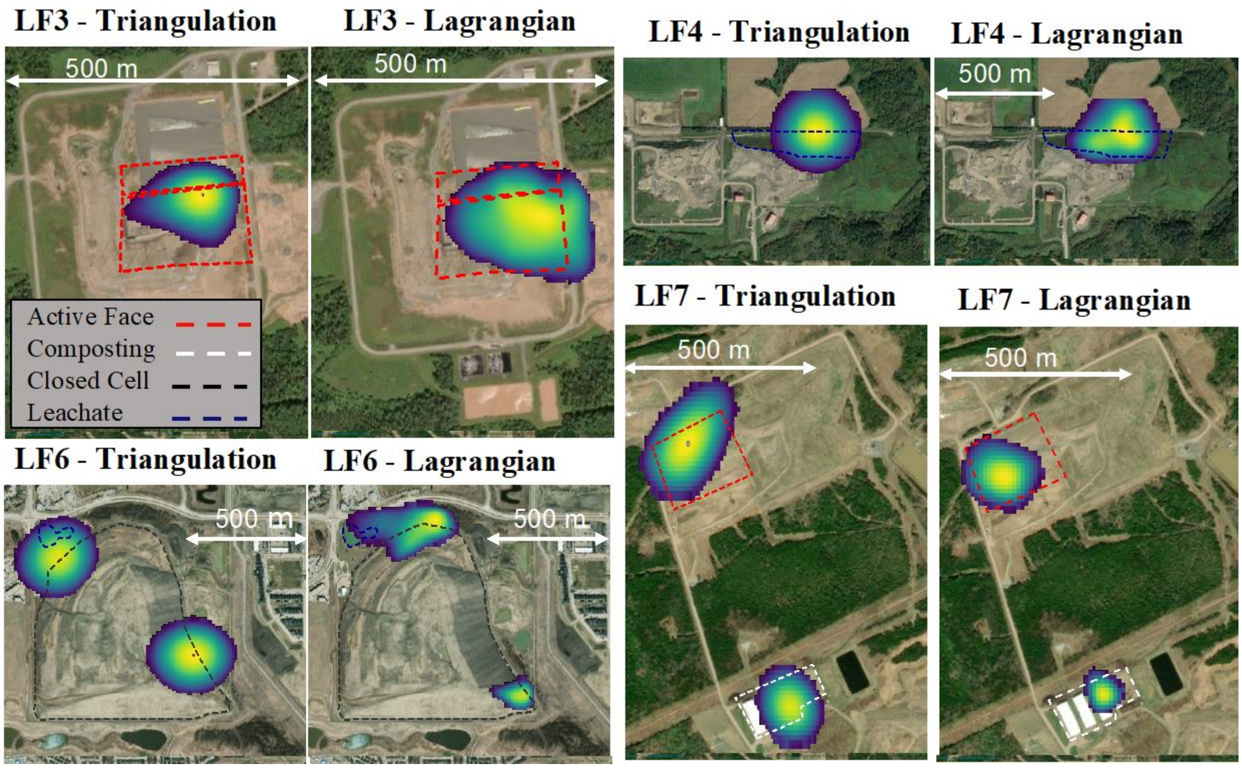

Figure 2: Hotspot detection using triangulation and Lagrangian methods.

This figure illustrates hotspot results derived from daily measured data using both triangulation and Lagrangian methods. Active face areas are outlined by dashed red lines, composting zones by dashed white lines, and leachate systems by dark blue lines. LF6 is a closed site with emissions from a leachate system and closed cell. LF3 shows dominant active face emissions.

LF7 combines active face and composting emissions, and LF4 displays noticeable leachate emissions from a biocover landfill. Additional hotspot maps for other landfills are available in Figure S2.

3.2 Emissions at Open Landfills with/without Gas Collection and Controlling System

Our results show that the active faces in landfills were critical areas where methane emissions were substantial and exhibited high variability. On average, these areas contributed approximately 18 kg hr^{-1} ha^{-1} (Table S1). At the open landfills, emission rates from these areas typically exceeded 100 kg hr^{-1} (Figure 3). This high modal value (>100 kg hr^{-1}) indicated that the active faces were significant in the overall landfill methane emissions profile.

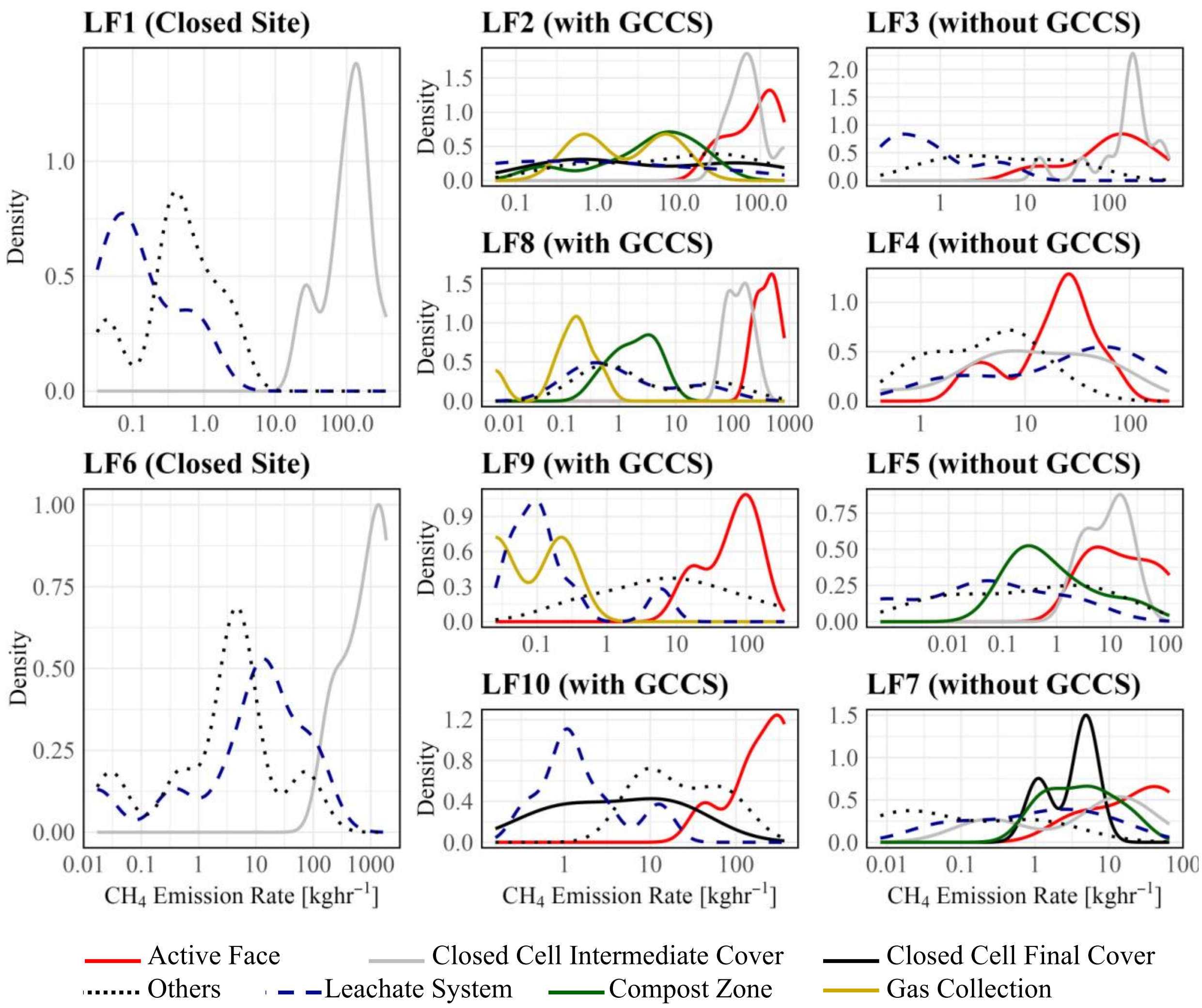

Figure 3. Visualization of methane emission rates from various landfill sources.

This figure visualizes the distribution of methane emission rates from various sources at landfills, distinguished by different colors. Each density curve represents aggregated data from multiple measurements for each source type at a given site. These plots were created using kernel density estimation to provide a smooth representation of the data distribution on a logarithmic scale to showcase the range and variability of emissions. The number of measurements per site varies and is listed in Table S1.

For the sites with GCCS, the active faces were the primary emissions sources, accounting for 76% of total emissions (Figure 4). The estimates consistently showed a left-skewed distribution, indicating that all sites had relatively high active face emissions (Figure 3). These observations are consistent with reports of high emissions from similar areas in various countries, including India, Pakistan, and the United States (Siddiqui et al., 2024; Rafiq et al., 2018; Scarpelli et al., 2024). However, our results contrast with findings by Yeşiller et al. (2022), who reported that intermediate cover contributed the most to the total emissions, accounting for 62% to 97%, and Scheutz et al. (2011) who reported that old cells emitted three times more than the active face. At sites with GCCS, the predominance of active area emissions was largely due to the management contrast between the active and covered areas, where gas was collected from the covered areas but not the active face.

We saw clear temporal variability in the active face emissions, but each site behaved uniquely. For instance, the standard deviation of active face emissions at LF4 was 19.5 kg hr^{-1}, whereas at LF8, the standard deviation was 208 kg hr^{-1} (Table S1).

For landfills lacking GCCS, the spatial patterns were different. The closed cell intermediate cover areas were the highest emitters with, on average, 47% of total emissions, followed by the active faces with 38% (Figure 4). We expect this pattern for the none-GCCS landfills because emissions from older waste are mostly unabated, leading to a higher proportion of emissions from closed cells and intermediate cover (Grégoire et al., 2023). In our results, we observed similar levels of variability for the closed cell intermediate cover and active face, with emission estimates ranging from 0.3 to 464 kg hr^{-1} and 2.7 to 530 kg hr^{-1}, respectively (Figure 3 and Table S1).

Other sources of methane emissions that we identified included leachate systems, compost areas, and GCCS. Leachate systems, while not the most intense emitters, were commonly identified as sources of emissions for all landfill types (Figure 3) with estimated emission rates maxing at 13.2 kg hr^{-1} ha^{-1} (Table S1). Additionally, areas designated as composting zones contributed to the overall emissions profile (Figure 4). Emission rates from composting zones varied, with median estimated rates over the measurement period ranging from 0.3 kg hr^{-1} ha^{-1} to 2.8 kg hr^{-1} ha^{-1} across all sites (Table S1). GCCS components, including flare systems and gas collection areas, also influenced the total emissions, with varied measurements across all sites (Table S1).

We did not observe consistent seasonal variability in the emissions. However, the analysis of temporal, daily measurement variability in emissions had distinct patterns across different landfill management systems. Landfills lacking GCCS had greater temporal variability in emissions as represented through the wider density plots of source emissions in Figure 3 (closed cells and active faces, especially). In contrast, landfills equipped with GCCS had less variability and more stable emission rates over time.

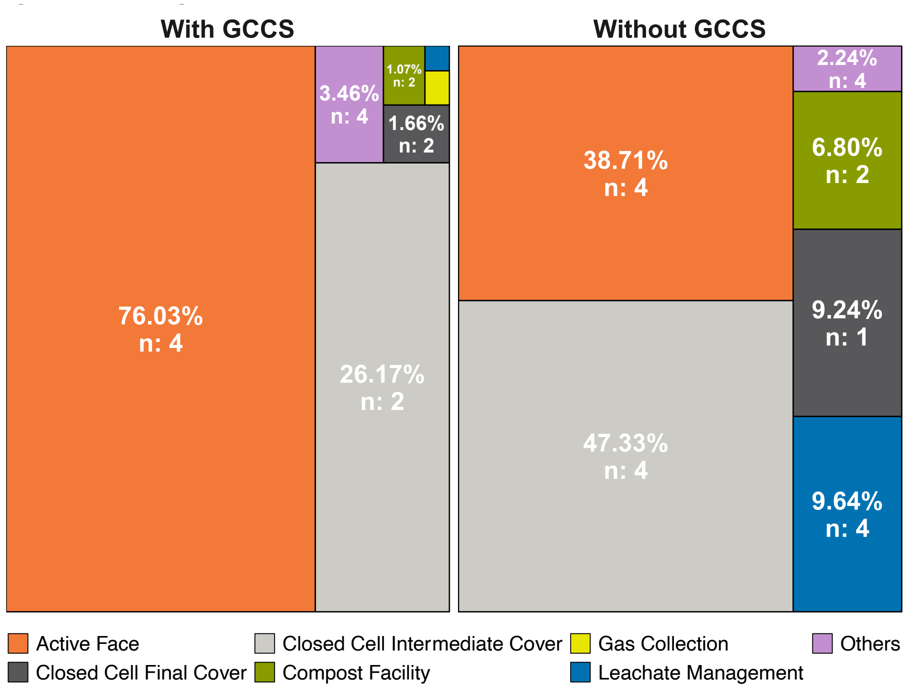

Figure 4. Treemaps of methane source contributions in landfills with and without GCCS. This figure presents treemaps that illustrate the weighted average contributions of various sources to the overall methane emissions from open landfills, differentiated by landfills equipped with Gas Collection and Control Systems (GCCS) and those without. The weights were based on each landfill's total emissions, with more emphasis on the sources in landfills with higher emission volumes. The symbol 'n' represents the number of landfills that contain each specific source because not all landfills contained the same sources.

It is important to note that mobile surveys might not capture all emissions. For instance, measurements from smaller landfill components, like leachate management areas and GCCS systems, might not be fully captured if obstacles to airflow are present, or downwind road accessibility is poor. This does not suggest an absence of emissions but points to the technical difficulties in acquiring comprehensive emission data when relying on a single measurement strategy. We found that larger sources were easier to measure with good repetition. We also acknowledge that the mobile Gaussian model we used might underestimate actual emission rates, a concern pointed out by Hossain et al. (2024). If our Gaussian model underestimated emissions, we would however expect the problem to be systematic, which would not affect our proportional source estimates.

Interestingly, our source maps show multiple smaller emission sources in the landfills without GCCS, indicating a broader dispersal of emission sources across the sites as natural seepage through the cap. These findings differ from the findings of Czepiel et al. (1996) who reported that landfill surface emissions were highly concentrated in a small fraction of the total area, although landfills in Canada are often capped with clay rather than highly impermeable geotextiles that are more common elsewhere. We observed a more highly skewed profile with active face dominance and relatively low emissions elsewhere from sites with GCCS.

In general, the active face is an area with huge potential for emissions mitigation, and more measurements are needed to understand the evolution of methanogenesis, the impact of different daily cover regimes, and limits on active face size. But the dynamic nature of the operational active face poses extra challenges for measuring emissions accurately, as mentioned by Cusworth et al., (2020), including continual changes in shape, form, and location of filling area. Continuous sensors, or mobile monitoring systems on operations equipment, could scan emissions levels across different parts of the active face to support management decisions.

3.3 Emissions at Closed Landfills

Two of the landfills we studied were closed: LF1 and LF6 active from 1975 to 1996 and 1986 to 2013, respectively. The older site, LF1, had emissions ranging from 23.8 kg hr^{-1} to 361.7 kg hr^{-1}, and LF6, the more recent of the two, had a broader range of emissions from 167 kg hr^{-1} to

2209 kg hr^{-1}. Both sites had emissions from closed cells and leachate systems. Moreover, each landfill had passive venting from unfinished GCCS infrastructure, with methane gas escaping through these vents at both sites.

3.4 Implications for Policy and Regulation

Although numerous sites collect gases at the active face using available technology, the reason for implementing such systems is normally site-specific and related to odour complaints, nearby commercial development pressures, or both. Active face monitoring systems are often used as a "good neighbour" technology. Existing landfill gas regulations do not typically mandate monitoring of landfill gas emissions from fresh waste in active areas (EPA, 2016; Victoria, E.P.A., 2018; European Union, 2024; GOV.UK, 2020; Government of Canada, 2024) although waste-to-energy incentives in some countries may increase the popularity of such systems outside regulation. But even in jurisdictions where active face collection is common, neither policies nor regulations point toward monitoring as a method to drive longer term improvement in active face gas collection. And, without any active face collection or monitoring requirements, the effectiveness of mitigation regulations resulting from policy could be severely limited. For example, Canada's proposed landfill methane regulation (Government of Canada, 2024) is expected to trigger the installation of traditional covered-area GCCS systems at another approximately 100 medium to large landfills, which, if 100% effective, might reduce overall emissions at these 100 sites by ~47%, which equals the proportion of emissions attributable to the covered area at non-GCCS sites we found in this study. The proposed regulation would not, however, significantly affect gas collection requirements or outcomes at smaller sites, or at larger sites already collecting but still emitting significant quantities from the active face. The proposed regulation would create better monitoring and reporting requirements, and more specific daily cover requirements, but without some focus on active face collection supported by monitoring requirements, it seems likely that Canada will fall short of the proposed overall sector reduction target of 50% by 2032 because reductions of that magnitude would only be achieved at a fraction of landfills.

It is perhaps not surprising that policies and regulations do not emphasize active face collection. Although there have been numerous studies that defined high levels of active face emissions at individual sites, the pervasiveness of such emissions is now much more clearly emphasized in large scale studies from Cusworth et al. (2024) and Scarpelli et al. (2024). Timing is also important, since methane reductions are the biggest issue of the past 5 years in waste management. We note that the aircraft measurement methodology used in those two studies was less sensitive than our measurement technology and could have underestimated some types of dispersed emissions. Our more sensitive on site approach paints a more nuanced and consistent image of active face emissions. Overall, scientific understanding of active face emissions has evolved quickly in the recent years, whereas writing and adopting regulations takes years and begins with available data. Developing the current regulations relied on historic data from up to a decade ago when we did not appreciate the active face as an emissions source nor its mitigation potential.

4 Conclusion

In this study, we investigated the complexity and dynamics of methane emissions from ten Canadian landfills. We confirmed that the active faces in open landfills are significant emissions hotspots. In addition to the active face, we found that closed cells, composting zones, leachate systems, and GCCS are other potential common sources of emissions.

To effectively manage waste emissions, we recommend a shift in the regulatory approach and the technological approaches used to monitor and reduce landfill methane emissions. Enhanced monitoring techniques that accurately detect and quantify emissions from all landfill sources, including active faces, closed cells, compost zones, and leachate systems, are crucial and need to be adopted by regulators as management tools. A combined approach that employs ground-based surveys and remote sensing technologies could provide a more accurate and detailed emissions profile. Even before new regulation, stakeholders must mandate more data collection. New and comprehensive datasets would enhance strategic planning and help steer mitigation efforts.

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6 Contributions

- Contributed to conception and design: A. Omidi, and D. Risk.
- Contributed to acquisition of data: D. Risk, G. Perrine, N. Tarakki, R. Martino, J. Stuart
- Contributed to analysis and interpretation of data: A. Omidi, E. Bourlon, A. Khaleghi.
- Drafted and/or revised the article: A, Omidi, E. Bourlon, A. Khaleghi, and D. Risk.
- Approved the submitted version for publication: A. Omidi, E. Bourlon, A. Khaleghi, G. Perrine, N. Tarakki, R. Martino, and D. Risk.

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10 AI disclosure statement

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11 Supplemental material

The supplemental material submitted with the article consists of a single DOC file named "Risk et al. 2025_Supplemental Infromation.docx".

12 Figures

13 Tables

Active Face Emissions: An Opportunity for Reducing Methane Emissions in Global Waste Management

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Figures

Tables

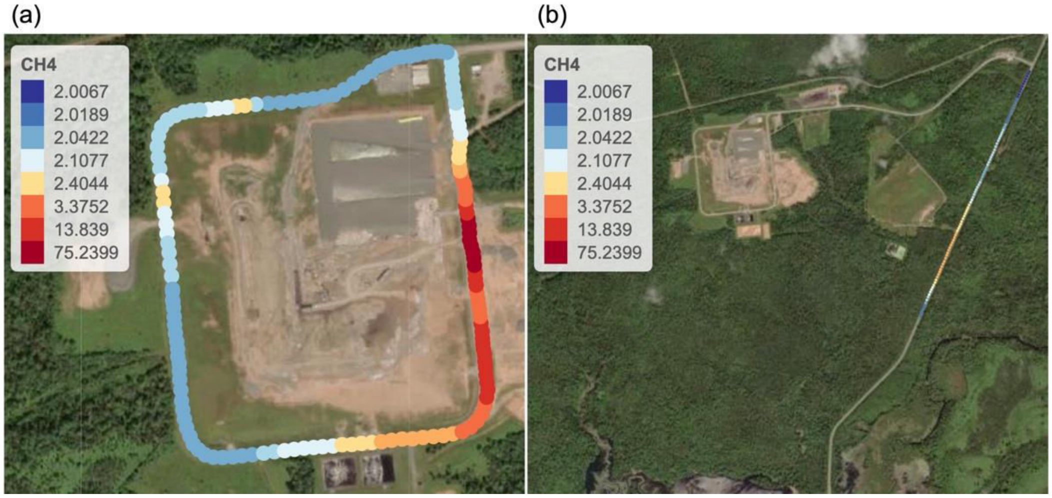

Figure S 1 On-site and off-site transect measurements at a landfill.

This figure illustrates examples of on-site (a) and off-site (b) transect measurements of a landfill. The colors on the map represent different concentrations with red representing the highest values and dark blue the lowest or ambient background.

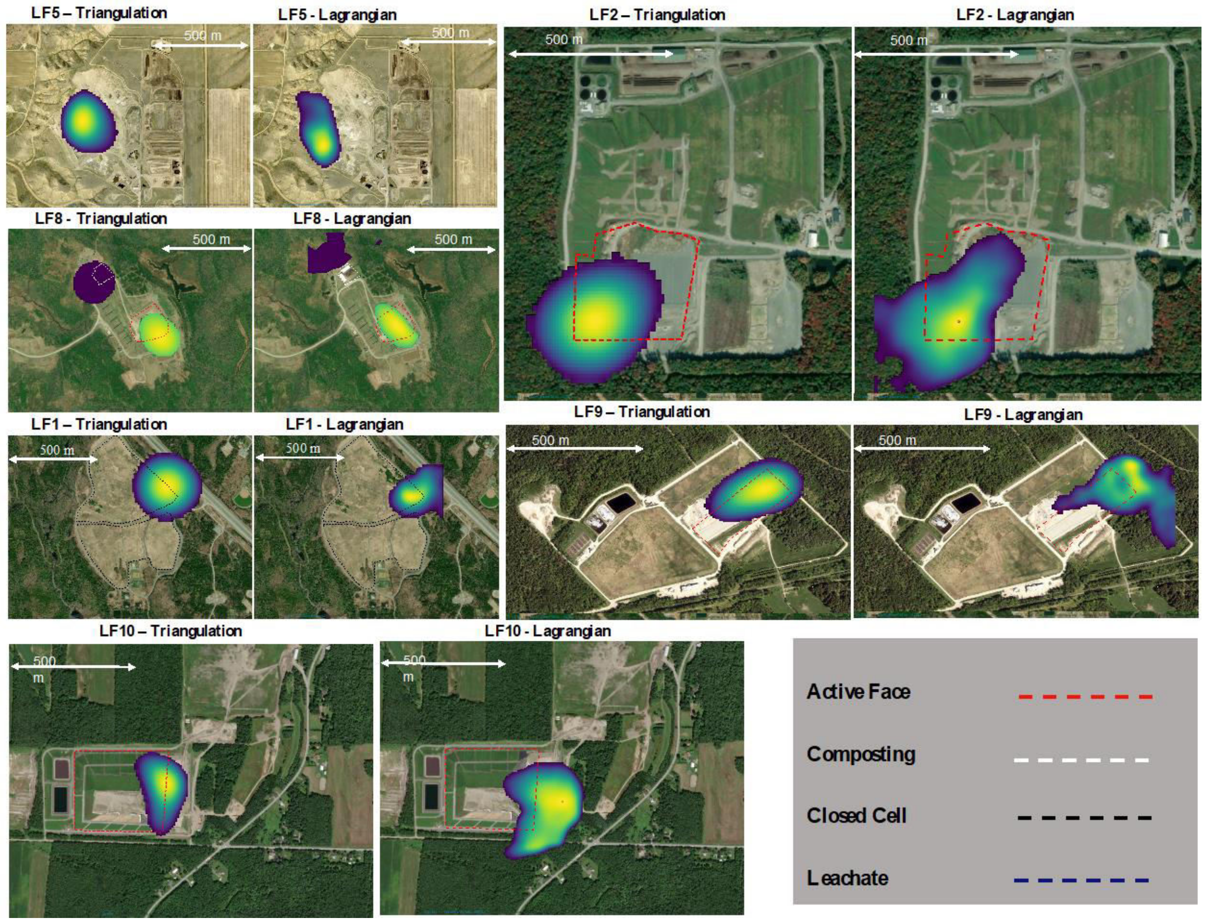

Figure S 2. Hotspot detection using triangulation and Lagrangian methods.

This supplementary figure displays hotspot results derived from daily measured data using triangulation and Lagrangian methods. Active face areas are outlined in dashed red lines, composting zones in dashed white lines, and leachate systems in dashed dark blue lines.

LF ID	Source	Mean Q kg hr^{-1}	Median Q kg hr^{-1}	SD Q kg hr^{-1}	Area ha	n	Q kg hr^{-1} ha^{-1}	Status	Total LF Q kg hr^{-1}	Contribution (%)
LF1	Others	0.8	0.44	0.89	0.11	12	4	Closed	119.99	0.37
LF1	Closed Cell	130.29	119.46	91.08	52.05	12	2.3	Closed	119.99	99.56
LF1	Leachate Management	0.26	0.09	0.33	0.37	12	0.24	Closed	119.99	0.07
LF2	Others	26	13.85	31.84	0.77	12	18.04	With GCCS	216.18	6.4
LF2	Flare System	3.83	3.83	4.45	0.23	12	16.93	With GCCS	216.18	1.77
LF2	Active Face	97.14	122.83	52.95	8.42	12	14.58	With GCCS	216.18	56.82

LF2	Closed Cell Intermediate Cover	79.6	66.22	51.87	17.27	12	3.83	With GCCS	216.18	30.63
LF2	Compost Facility	7.9	6.69	7.62	2.42	12	2.77	With GCCS	216.18	3.1
LF2	Leachate Management	11	1.1	23.01	1.66	12	0.66	With GCCS	216.18	0.51
LF2	Closed Cell Final Cover	33.49	1.66	54.42	6.56	12	0.25	With GCCS	216.18	0.77
LF3	Active Face	168.37	120.5	155.39	5.64	12	21.38	Without GCCS	321.4	37.49
LF3	Closed Cell Intermediate Cover	199.14	195.96	125.44	9.82	12	19.96	Without GCCS	321.4	60.97
LF3	Others	14.59	4.37	18.79	1.03	12	4.24	Without GCCS	321.4	1.36
LF3	Leachate Management	1.55	0.57	2.21	0.83	12	0.69	Without GCCS	321.4	0.18
LF4	Leachate Management	57.14	44.46	70.57	9.46	10	4.7	Without GCCS	85.83	51.8
LF4	Active Face	25.52	24.78	19.48	14.79	10	1.68	Without GCCS	85.83	28.87
LF4	Closed Cell Intermediate Cover	24.4	10.51	26.7	9.55	10	1.1	Without GCCS	85.83	12.25
LF4	Others	6.69	6.08	7.16	9.72	10	0.63	Without GCCS	85.83	7.09
LF5	Closed Cell Intermediate Cover	11.13	11.57	7.99	3.03	8	3.82	Without GCCS	27.14	42.62
LF5	Active Face	35.21	14.56	43.93	12.95	8	1.12	Without GCCS	27.14	53.64
LF5	Compost Facility	4.66	0.54	9.78	1.61	8	0.33	Without GCCS	27.14	1.98
LF5	Leachate Management	0.51	0.06	0.94	0.31	8	0.19	Without GCCS	27.14	0.21
LF5	Others	2.38	0.42	3.3	3.78	8	0.11	Without GCCS	27.14	1.55
LF6	Closed Cell	1027.37	971.47	667.57		10		Closed	986.79	98.45
LF6	Leachate Management	27.73	11.43	38.29	0.86	10	13.24	Closed	986.79	1.16
LF6	Others	13.23	3.9	26.47	1.77	10	2.2	Closed	986.79	0.39
LF7	Active Face	31.41	28.14	26.38	3.16	11	8.89	Without GCCS	51.27	54.89
LF7	Compost Facility	6.71	4.8	6.86	2.51	11	1.91	Without GCCS	51.27	9.35
LF7	Leachate Management	3.49	1.74	4.87	0.99	11	1.77	Without GCCS	51.27	3.39
LF7	Closed Cell Intermediate Cover	9.38	11.82	8.19	7.35	11	1.61	Without GCCS	51.27	23.06

LF7	Closed Cell Final Cover	3.62	4.74	2.18	8.36	11	0.57	Without GCCS	51.27	9.24
LF7	Others	0.55	0.03	0.93	1.93	11	0.02	Without GCCS	51.27	0.06
LF8	Active Face	448.77	462.33	208.07	6.65	7	69.5	With GCCS	618.42	74.76
LF8	Closed Cell Intermediate Cover	145.6	152.16	69.45	15.34	7	9.92	With GCCS	618.42	24.61
LF8	Compost Facility	2.48	2.2	1.84	1.25	7	1.76	With GCCS	618.42	0.36
LF8	Flare System	0.19	0.17	0.16	0.38	7	0.44	With GCCS	618.42	0.03
LF8	Leachate Management	8.12	0.78	15.05	2.41	7	0.32	With GCCS	618.42	0.13
LF8	Others	19.05	0.78	31.93	9.35	7	0.08	With GCCS	618.42	0.13
LF9	Active Face	76.55	81.78	50.06	4.17	11	19.63	With GCCS	88.73	92.17
LF9	Others	47.61	6.71	104.33	4.83	11	1.39	With GCCS	88.73	7.57
LF9	Gas Collection	0.12	0.12	0.14	0.11	11	1.1	With GCCS	88.73	0.14
LF9	Leachate Management	0.85	0.11	2.07	1.52	11	0.07	With GCCS	88.73	0.12
LF10	Active Face	225.13	231.97	130.62	21.48	6	10.8	With GCCS	259.04	89.55
LF10	Others	35.73	19.55	35.39	26.45	6	0.74	With GCCS	259.04	7.55
LF10	Closed Cell Final Cover	9.31	6.23	10.9	26.06	6	0.24	With GCCS	259.04	2.4
LF10	Leachate Management	3.18	1.14	4.7	4.74	6	0.24	With GCCS	259.04	0.44
LF10	Flare System	0.16	0.16		1.96	6	0.08	With GCCS	259.04	0.06

Table S 1. Details of methane emission sources.

Q refers to methane emission rate. Averaged Q is the average rate (kg hr^{-1}) of the total source emission over the duration measurements, which varied from landfill to landfill, ranging from 5 to 12 days and represented as n. The "Other" 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.