

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

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1 Active Face Emissions: An Opportunity for 2 Reducing Methane Emissions in Global 3 Waste Management

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9 Abstract

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

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

23 **1 Introduction**

24 The waste sector emits 20% of global methane into the atmosphere making the sector
25 one of the highest contributors to global greenhouse gas emissions (United Nations Environment
26 Programme & Climate and Clean Air Coalition, 2021). Canada's "Faster and Further: Methane
27 Strategy" aims to reduce waste sector emissions by 45% by 2030 (Government of Canada, 2022)
28 with Environment Climate Change Canada (ECCC) drafting regulations to achieve the reduction
29 goal (Government of Canada, 2024). Similar international guidelines require waste operators to
30 monitor and control landfill gas emissions in United States, Australia, the European Union, and
31 the United Kingdom (European Union, 2024; EPA, 2023; GOV.UK, 2020; Victoria, E.P.A.,
32 2018).

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

43 The sealed areas of a landfill (closed cells) have been identified as a major emission
44 source because methane escapes through the covers (Sirimangkhala et al., 2018; Zhang et al.,
45 2012; Bogner et al., 2011). Related infrastructure, including pipes, wells, leachate ponds, and
46 systems for gas collection and control (GCCS) emit methane (Allen et al., 2019; Emran et al.,
47 2017; Scheutz et al., 2011; Bogner et al., 1995), and emissions have been reported from on site
48 composting zones (Harrison et al., 2024; Scheutz et al., 2011; Andersen et al., 2010).

49 Increasingly studies recognize the operational area of a landfill where waste is currently
50 being deposited (the active face) as a significant source of methane (Scarpelli et al., 2024; Kumar
51 et al., 2023; Guha et al., 2020; Cusworth et al., 2020; Innocenti et al., 2017; Cambaliza et al.,
52 2017; Goldsmith et al., 2012). At the active face, organic materials such as food waste
53 decompose rapidly (Krause et al., 2023), and emissions from the active face might be
54 underappreciated or even underestimated (Maasakkers et al., 2022) because of issues such as
55 temporal fluctuations. Bogner et al. (2011) recognized that seasonal changes in soil moisture and
56 temperature affect emission rates. Waste composition, landfill management practices, and
57 microbial activity also cause temporal changes (Dimishkovska et al., 2019; Shen et al., 2018;
58 Delkash et al., 2016; Rachor et al., 2013).

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

65 **2 Materials and Methods**

66 **2.1 Measurements**

67 For our mobile surveys, we used a sports utility vehicle with a Gill WindSonicM
68 Ultrasonic Wind Sensor, compass, (Garmin 18x-5Hz GPS), and gas analyzers connected by
69 tubing for sampling. The anemometer measured wind speed and direction with the accuracy of
70 3% and $\pm 3^\circ$, respectively. We measured methane concentrations in ppmv using a Los Gatos
71 Research Ultra-Portable Greenhouse Gas Analyzer or an LGR-ICOS Microportable Gas
72 Analyzer (GLA131 Series), which has a precision of 1.4 ppb for methane. The anemometer,
73 compass, and GPS collected wind data and recorded the vehicle's locations.

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

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

87 2.2 Source Identification

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

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

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

$$101 \quad x_{source} = x_1 + d \cos \theta, y_{source} = y_1 + d \sin \theta \quad (1)$$

102 d represents the distance from coordinates (x_1, y_1) to the source, and θ is the wind direction
103 angle in radians. Each source point was weighted by multiplying the methane levels at the two
104 peaks, after subtracting the background methane level, to emphasize its severity and likelihood
105 as a source. This process was repeated for each pair of peaks, generating numerous triangulated,
106 weighted excess concentration points. Then, we applied Kernel Density Estimation (KDE) to
107 spatially smooth the distribution of these points and to create a hotspot map of excess
108 concentrations. A grid with 50-meter resolution was overlaid on this hotspot map. Within each
109 grid cell, we calculated the maximum weighted excess concentration. To prevent overestimation

110 in the subsequent quantification method, we ensured that no two maximum points were within
111 50 meters of each other by retaining only the point with the higher weight.

112 **2.3 Quantification**

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

$$114 \quad C(x, y, z) = \frac{Q}{2\pi \sigma_y \sigma_z U} \exp\left(\frac{-y^2}{2\sigma_y^2}\right) \left(\exp\left(\frac{-(z+H)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z-H)^2}{2\sigma_z^2}\right)\right) \quad (2)$$

115 where

116 Q = pollutant emission rate (g s^{-1});

117 σ_z = vertical standard deviation of the concentration distribution (m);

118 σ_y = crosswind standard deviation of the concentration distribution (m);

119 U = mean horizontal wind velocity at pollutant release height (m s^{-1});

120 $C(x, y, z)$ = concentration at source location (x, y, z) (g m^{-3});

121 and, H = pollutant release height (m).

122 We quantified the flux using two distinct approaches, each approach with different inputs.

123 The first approach used on site and fenceline transects to quantify directly upwind from

124 triangulated point sources. To tie the sources to landfill operational attributes, we used maps and

125 other information provided by the landfill operators, photographs taken during field work, and

126 satellite imagery to define polygons representing the functional areas of each landfill. We then

127 calculated the sum of emissions from the quantified triangulated point sources using on site and

128 fenceline surveys that fell within these specific polygons, for example, from the active face,

129 closed cells, and compost areas. We averaged these sums, representing emissions from each

130 source type, over all measurements (Table S1).

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

136 2.4 Sites Description

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

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

147

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

148 **Table 1. Site descriptions and total emissions estimates.**

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

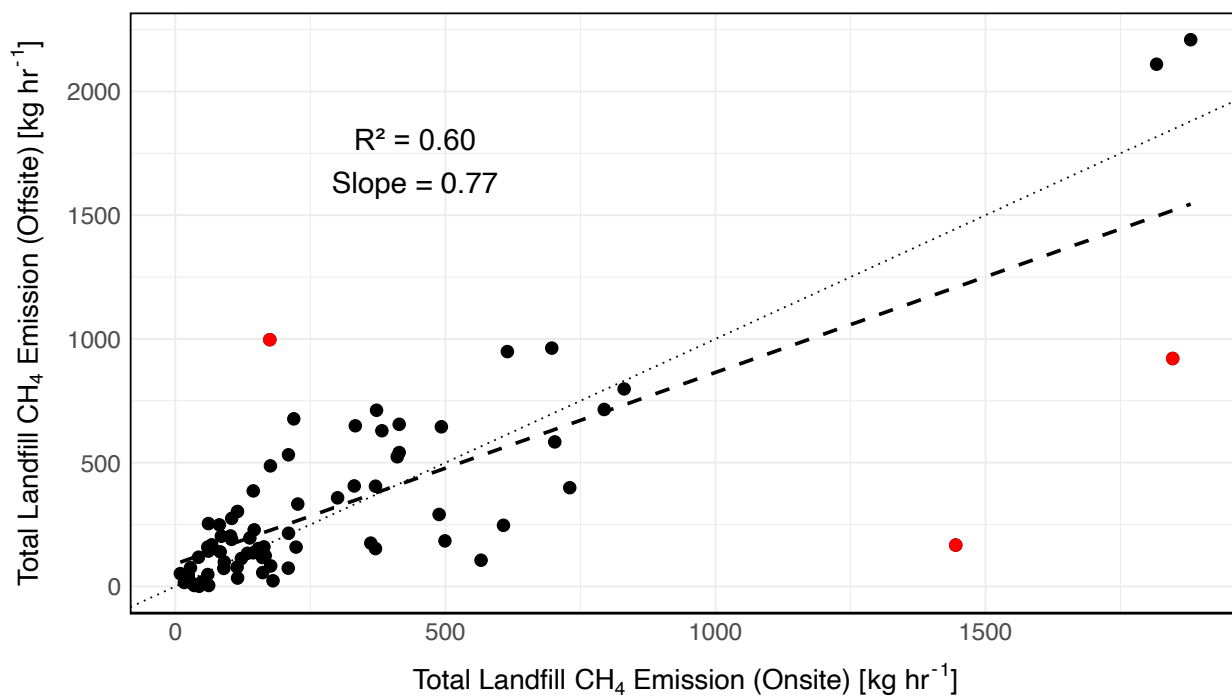
157 **3 Results and Discussion**

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

161 **3.1 Evaluating Methane Emissions Identification and Quantification Techniques**

162 Figure 1 shows that total aggregate methane emissions measured from on site/fenceline
163 transects using one dispersion model agreed well in magnitude with emissions measured
164 independently from off site/fenceline transects (slope = 0.77; $R^2 = 0.60$). Because the aggregated
165 per-source estimates were produced from individual measurements which contained

166 uncertainties (e.g., sensitivity to the 50-meter grid size), we were concerned that our results
167 would over- or under-estimate emissions once aggregated to the site level. However, the good
168 linear relationship between the two measurement approaches gave us confidence that our source-
169 level estimates and aggregations were accurate. The median flux for the measurement period
170 calculated by each approach for a given site is listed in Table 1 as the total estimated methane
171 rate for that site. However, in some cases, we lacked measurements due to weather conditions or
172 access restrictions; for instance, we did not have off site transects for all measurement periods at
173 site LF7, and there was insufficient on site coverage at LF10.

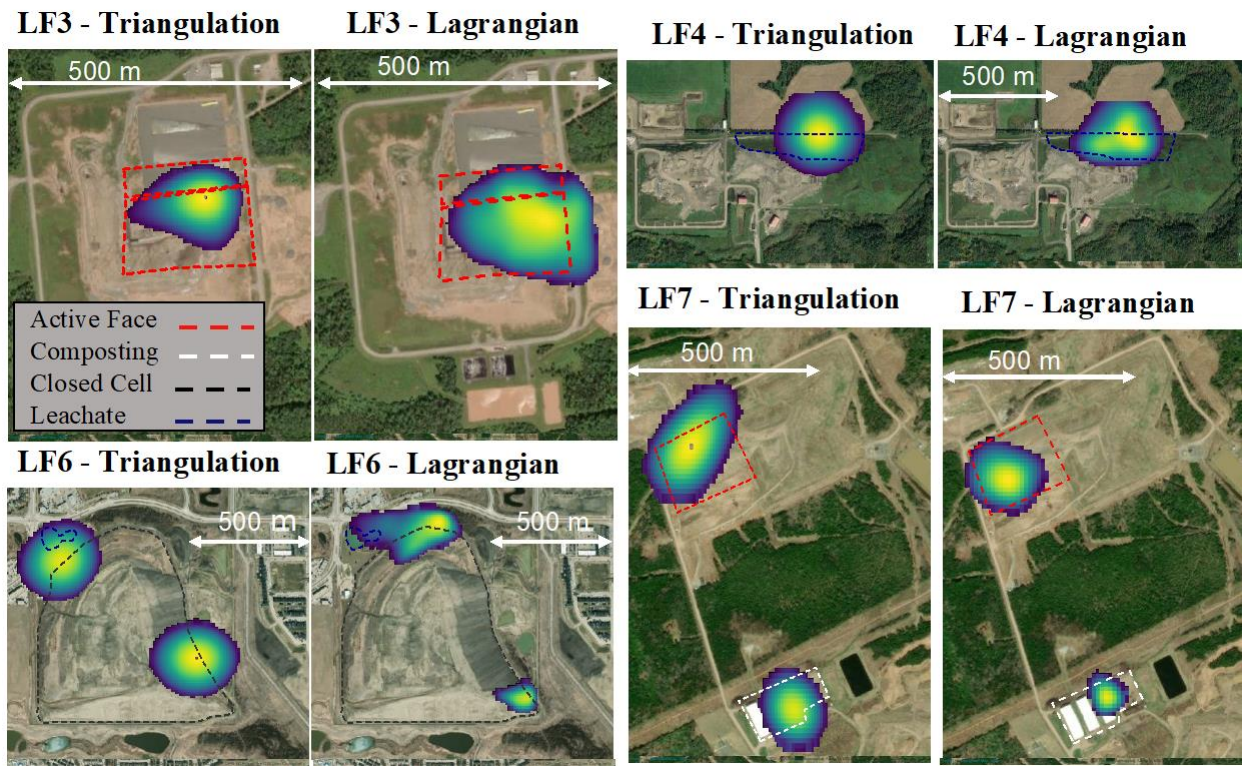


174
175 **Figure 1: Comparison of landfill emissions from Gaussian dispersion models.**

176 Scatter plot comparing total landfill emissions estimated using two Gaussian dispersion models
177 from on site/fenceline and triangulation sources, and off site/fenceline surveys and optimized
178 random sources. The dotted line indicates the 1:1 correspondence line, and the dashed line
179 represents the linear regression. Outliers, colored in red, are from landfill LF6. The plot shows a

180 linear regression with a slope of 0.77 and an R^2 value of 0.60. When the outliers were excluded,
181 the R^2 value improves to 0.79.

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



187

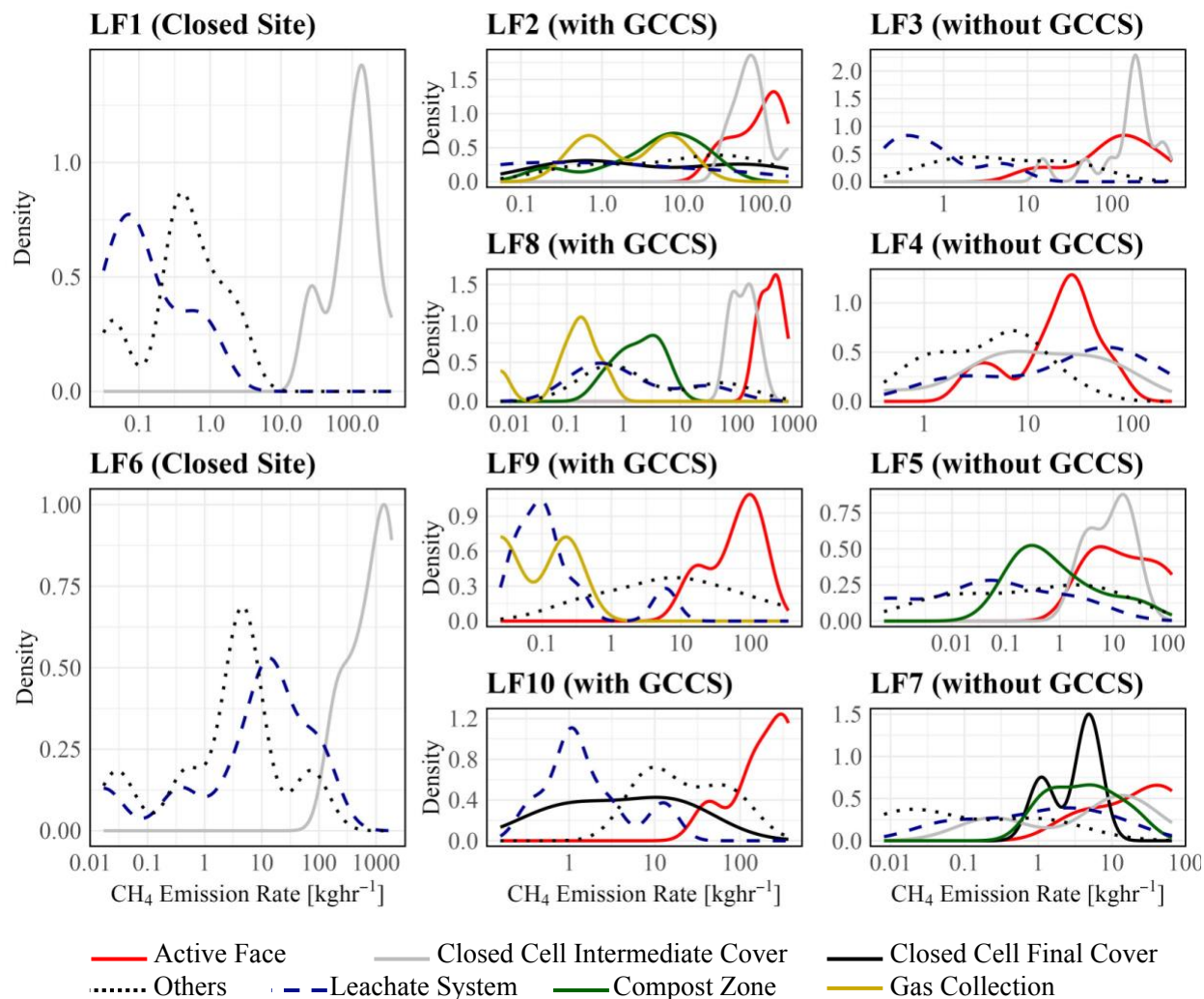
188 **Figure 2: Hotspot detection using triangulation and Lagrangian methods.**

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

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

196 **3.2 Emissions at Open Landfills with/without Gas Collection and Controlling** 197 **System**

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



203

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

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

211 For the sites with GCCS, the active faces were the primary emissions sources, accounting
212 for 76% of total emissions (Figure 4). The estimates consistently showed a left-skewed
213 distribution, indicating that all sites had relatively high active face emissions (Figure 3). These
214 observations are consistent with reports of high emissions from similar areas in various
215 countries, including India, Pakistan, and the United States (Siddiqui et al., 2024; Rafiq et al.,
216 2018; Scarpelli et al., 2024). However, our results contrast with findings by Yeşiller et al. (2022),
217 who reported that intermediate cover contributed the most to the total emissions, accounting for
218 62% to 97%, and Scheutz et al. (2011) who reported that old cells emitted three times more than
219 the active face. At sites with GCCS, the predominance of active area emissions was largely due
220 to the management contrast between the active and covered areas, where gas was collected from
221 the covered areas but not the active face.

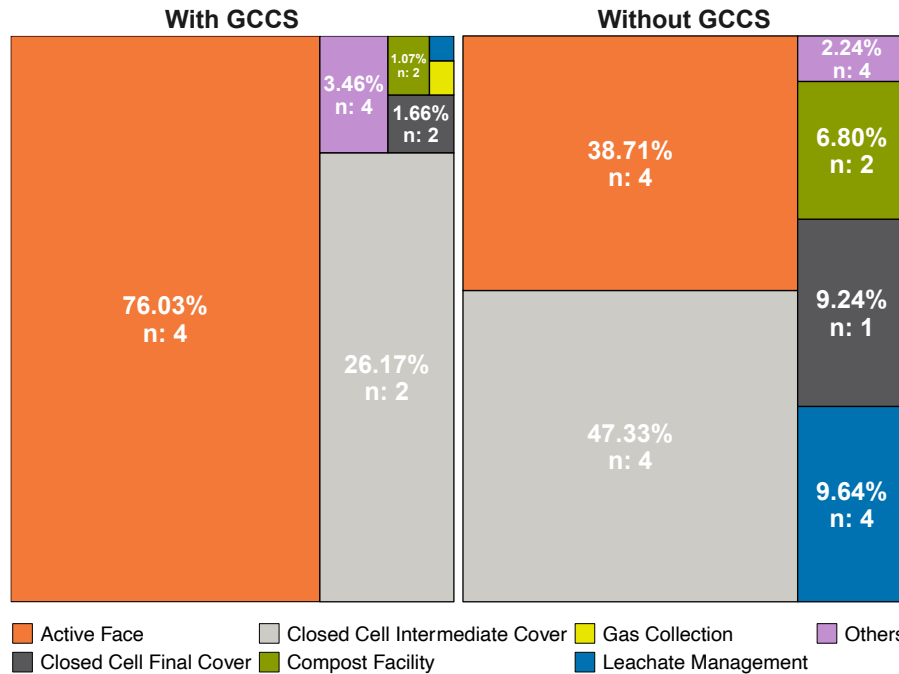
222 We saw clear temporal variability in the active face emissions, but each site behaved
223 uniquely. For instance, the standard deviation of active face emissions at LF4 was 19.5 kg hr⁻¹,
224 whereas at LF8, the standard deviation was 208 kg hr⁻¹ (Table S1).

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

233 Other sources of methane emissions that we identified included leachate systems, compost
234 areas, and GCCS. Leachate systems, while not the most intense emitters, were commonly
235 identified as sources of emissions for all landfill types (Figure 3) with estimated emission rates
236 maxing at $13.2 \text{ kg hr}^{-1} \text{ ha}^{-1}$ (Table S1). Additionally, areas designated as composting zones
237 contributed to the overall emissions profile (Figure 4). Emission rates from composting zones
238 varied, with median estimated rates over the measurement period ranging from $0.3 \text{ kg hr}^{-1} \text{ ha}^{-1}$ to
239 $2.8 \text{ kg hr}^{-1} \text{ ha}^{-1}$ across all sites (Table S1). GCCS components, including flare systems and gas
240 collection areas, also influenced the total emissions, with varied measurements across all sites
241 (Table S1).

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

248



249
250 **Figure 4. Treemaps of methane source contributions in landfills with and without GCCS.**

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

257 It is important to note that mobile surveys might not capture all emissions. For instance,
258 measurements from smaller landfill components, like leachate management areas and GCCS
259 systems, might not be fully captured if obstacles to airflow are present, or downwind road
260 accessibility is poor. This does not suggest an absence of emissions but points to the technical
261 difficulties in acquiring comprehensive emission data when relying on a single measurement
262 strategy. We found that larger sources were easier to measure with good repetition. We also

263 acknowledge that the mobile Gaussian model we used might underestimate actual emission rates,
264 a concern pointed out by Hossain et al. (2024). If our Gaussian model underestimated emissions,
265 we would however expect the problem to be systematic, which would not affect our proportional
266 source estimates.

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

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

281 **3.3 Emissions at Closed Landfills**

282 Two of the landfills we studied were closed: LF1 and LF6 active from 1975 to 1996 and
283 1986 to 2013, respectively. The older site, LF1, had emissions ranging from 23.8 kg hr⁻¹ to 361.7
284 kg hr⁻¹, and LF6, the more recent of the two, had a broader range of emissions from 167 kg hr⁻¹ to

285 2209 kg hr⁻¹. Both sites had emissions from closed cells and leachate systems. Moreover, each
286 landfill had passive venting from unfinished GCCS infrastructure, with methane gas escaping
287 through these vents at both sites.

288 **3.4 Implications for Policy and Regulation**

289 Although numerous sites collect gases at the active face using available technology, the
290 reason for implementing such systems is normally site-specific and related to odour complaints,
291 nearby commercial development pressures, or both. Active face monitoring systems are often
292 used as a “good neighbour” technology. Existing landfill gas regulations do not typically
293 mandate monitoring of landfill gas emissions from fresh waste in active areas (EPA, 2016;
294 Victoria, E.P.A., 2018; European Union, 2024; GOV.UK, 2020; Government of Canada, 2024)
295 although waste-to-energy incentives in some countries may increase the popularity of such
296 systems outside regulation. But even in jurisdictions where active face collection is common,
297 neither policies nor regulations point toward monitoring as a method to drive longer term
298 improvement in active face gas collection. And, without any active face collection or monitoring
299 requirements, the effectiveness of mitigation regulations resulting from policy could be severely
300 limited. For example, Canada’s proposed landfill methane regulation (Government of Canada,
301 2024) is expected to trigger the installation of traditional covered-area GCCS systems at another
302 approximately 100 medium to large landfills, which, if 100% effective, might reduce overall
303 emissions at these 100 sites by ~47%, which equals the proportion of emissions attributable to
304 the covered area at non-GCCS sites we found in this study. The proposed regulation would not,
305 however, significantly affect gas collection requirements or outcomes at smaller sites, or at larger
306 sites already collecting but still emitting significant quantities from the active face. The proposed

307 regulation would create better monitoring and reporting requirements, and more specific daily
308 cover requirements, but without some focus on active face collection supported by monitoring
309 requirements, it seems likely that Canada will fall short of the proposed overall sector reduction
310 target of 50% by 2032 because reductions of that magnitude would only be achieved at a fraction
311 of landfills.

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

325 **4 Conclusion**

326 In this study, we investigated the complexity and dynamics of methane emissions from ten
327 Canadian landfills. We confirmed that the active faces in open landfills are significant emissions

328 hotspots. In addition to the active face, we found that closed cells, composting zones, leachate
329 systems, and GCCS are other potential common sources of emissions.

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

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492 **6 Contributions**

- 493 • Contributed to conception and design: A. Omid, and D. Risk.
- 494 • Contributed to acquisition of data: D. Risk, G. Perrine, N. Tarakki, R. Martino, J. Stuart
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- 496 • Drafted and/or revised the article: A, Omid, E. Bourlon, A. Khaleghi, and D. Risk.
- 497 • Approved the submitted version for publication: A. Omid, E. Bourlon, A. Khaleghi, G.
- 498 Perrine, N. Tarakki, R. Martino, and D. Risk.

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507 The authors have declared that no competing interests exist.

508 **10 AI disclosure statement**

509 During the preparation of this work the authors used ChatGPT in order to improve
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511 and take full responsibility for the content of the publication.

512 **11 Supplemental material**

513 The supplemental material submitted with the article consists of a single DOC file named
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Active Face Emissions: An Opportunity for Reducing Methane Emissions in Global Waste Management

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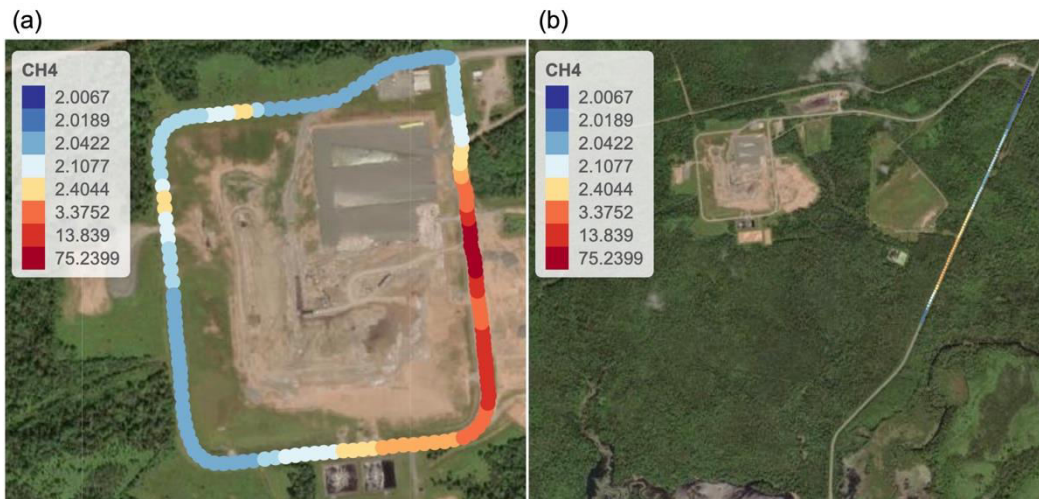


Figure S 1 On-site and off-site transect measurements at a landfill.

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.

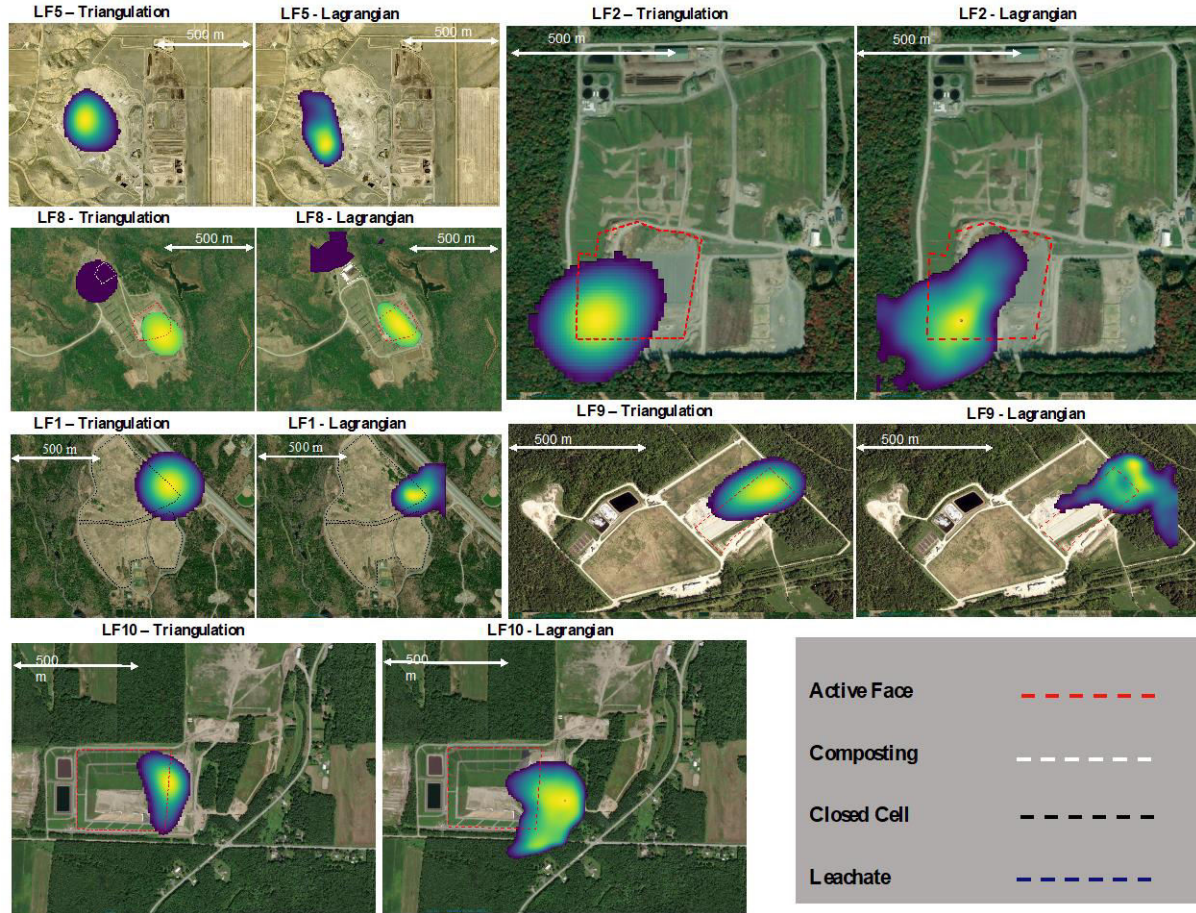


Figure S 2. Hotspot detection using triangulation and Lagrangian methods.

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.