Landfill methane: measurement and metrics

Research report

February 2026

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Contents

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Executive summary

Methane (CH_4) is an important Greenhouse Gas (GHG) which has a 100-year Global Warming Potential (GWP) 27 times that of carbon dioxide (CO_2).[1] Landfills are a major source of anthropogenic methane fugitive emissions, which are estimated to account for approximately 30% of the UK's methane emissions[2] and it is therefore important that release of this GHG from landfill sites is effectively managed to help support action to limit the impact of GHG's on the climate.

The UK government has already set into law legislation which ensures that effective management of landfills are in place to limit the impact of its contents on the wider environment, protecting human and environmental health. However, a combination of new requirements and general improvements to waste management have led to a reduction of biodegradable waste entering landfills. This is anticipated to lead to a reduction in methane generated within the landfill and further challenge the ability of existing methods to capture and treat the landfill gas.

This report details the findings from research undertaken with the overarching aim to evaluate potential regulatory approaches to support continued improvement of methane capture from landfills. To achieve this aim, this report first details findings from wider research to understand how methane emissions are likely to be influenced by site operations and meteorological conditions. The report then details two quantitative survey methods which have been evaluated for potential regulatory use in the future.

The two survey methods evaluated were the Tracer Dispersion Method (TDM) and Unmanned Aerial Vehicle (UAV) mass balance method. TDM surveys were carried out at four selected UK landfill sites and UAV mass balance surveys at three of the selected sites on multiple days between September 2024 and March 2025. The TDM surveys were completed by a team from The University of Southampton (UoS) and the UAV mass balance surveys were completed by a team from The University of Manchester (UoM).

Additionally, the operators of each landfill have provided records from their gas collection system and operational details which have been examined alongside the survey measurements to understand the performance of the gas collection system.

The key findings from the study are:

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[1] IPPC (2024), '*IPCC Global Warming Potential Values*', available from https://ghgprotocol.org/sites/default/files/2024-08/Global-Warming-Potential-Values%20%28August%202024%29.pdf

[2] Defra (2003), *'Methane emissions from landfill sites in the UK',* available from: [LQM methane emissions final report.PDF]()

- Generally, TDM and UAV mass balance surveys can effectively measure methane emissions from landfill sites, however the results from this study show a potential under-bias in the UAV mass balance measurements.

- The Methane Collection Efficiency (MCE) metric was identified as a suitable metric for evaluating landfill site performance.

- The MCE values measured at the four sites were in the following ranges:
    - Site X: 88%-99%
    - Site Y1: 74%-84%
    - Site Y2: 74%-94%
    - Site Z: 52%-82% (lower values were recorded when landfill gas collection systems were not operating correctly)

These results include MCEs calculated from UAV mass balance surveys which are associated with a potential (unquantified) systematic under bias.

- Methane Collection Efficiencies from the surveys were generally able to capture changes in gas management at the sites, demonstrating the suitability of the metric in a regulatory context.

A number of recommendations have been drawn from the findings of this study. These should be considered in the development of a regulatory framework for methane emissions from landfill sources.

A. Regulatory Use of Survey Techniques

- Adopt MCE as a regulatory performance metric, using it to benchmark site performance and trigger follow-up actions where necessary. This would require an assessment of the most appropriate benchmark for permitted sites.
- Allow flexibility in method selection (TDM, UAV mass balance or other method), provided the chosen method meets defined criteria for accuracy, uncertainty quantification, and site suitability.
- Require sites to conduct surveys under 'normal operating conditions' to ensure results are representative of typical site operation. These conditions should be verified by collection and analysis of long-term data on gas collection rates to demonstrate that the survey took place under normal operations.

B. Supporting Data Requirements

- Require submission of standardised operator data, including gas collection rates, methane content, flare and engine operation, and relevant site activities during the survey period as well as long-term data on gas collection. This data will support the interpretation of survey results and verification of operating conditions during surveys.

- Meteorological data should be collected or sourced to support surveying methods, interpretation of results and identify stable operating conditions.

C. Method Selection Guidance

- Develop a site suitability framework to guide the selection methods based on site layout, access, surrounding land use, and regulatory constraints (e.g. CAA restrictions).

D. Market Development and Oversight

- Encourage the development of a market for accredited survey providers, with clear standards for training, equipment, and reporting.

E. Future Enhancements

- Explore the integration of combustion efficiency and surface methane oxidation measurements into MCE calculations, where feasible.
- Continue to validate and refine models like GASSIM using empirical data from site surveys.

1 Introduction

Methane (CH_4) is an important Greenhouse Gas (GHG) which the Intergovernmental Panel on Climate Change estimates to have a 100-year Global Warming Potential (GWP), 27 times (without feedback) that of carbon dioxide (CO_2).[1] Landfills are a major source of anthropogenic methane fugitive emissions, which is estimated to account for approximately 30% of the UK's methane emissions[2] and are identified as a key source in the UK national inventory. Landfills are the largest emitter of methane in the waste sector. In modern permitted sites for biodegradable waste, landfill gas is collected and used, typically via gas engines, or flared. However, a proportion of the landfill gas escapes into the air through a variety of sources across a landfill. It is anticipated that many sites could improve their gas collection efficiency, and therefore reduce their fugitive emissions, however currently there is no formal mechanism to directly regulate fugitive emissions.

Effective control of landfill methane is an important part of landfill site management to reduce GHG impacts, manage safety risks and reduce the risk of localised odour problems. Furthermore, the quantities of methane generated at landfill sites are generally slowly declining in response to reductions in the amounts of biodegradable waste landfilled. Looking forward, Defra recently published the results of a consultation into ways of eliminating, as far as possible, the landfilling of biodegradable waste from 2028.[3] As the quantities of methane produced continue to decrease, ensuring effective ongoing control and utilisation of landfill methane might become progressively more challenging.

This report examines two different methods for measuring methane emissions from landfill sites: the Tracer Dispersion Method (TDM) and Unmanned Aerial Vehicles (UAV) mass balance approach. Evaluating their potential for deployment in a future approach for regulating the performance of methane collection at landfill sites.

The general principle of TDM is that a tracer gas released at the same location as the source of the target gas will be subject to the same atmospheric dispersion processes as the source gas when moving downwind. Using the known release rate of the tracer gas, measuring downwind above-background concentrations of both the target and tracer gases, and integrating measurement transects across the plume enables an estimation of the target gas emission rate to be made. The systematic uncertainties from these assumptions are minimised when the two gases are well-mixed and when measurement

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[3] https://www.gov.uk/government/consultations/near-elimination-of-biodegradable-waste-to-landfill

transects are far enough downwind to reduce errors associated with the location of the tracer gas release not fully replicating the spatial distribution of the emission source.

The TDM method requires the controlled release of a tracer gas located close to the primary emission source being measured. Simultaneous measurements of both gas concentrations are then made downwind of the site using a gas analyser, ideally linked to a global navigation satellite system (GNSS). Interpolation of the two gas measurements allows calculation of the source gas emission flux.

In the UAV mass balance method (Allen et al., 2015, 2018, 2019; Shaw et al., 2023), UAVs, or drones, equipped with high-precision methane sensors conduct spatial surveys downwind of emission sources, collecting gas concentration data alongside wind speed and direction. These measurements are used to calculate methane fluxes based on mass balance principles, calculating the total methane passing through a vertical plane perpendicular to the prevailing wind. The mass balance method is well-established in environmental research and provides a practical, cost-effective way to monitor emissions in real-world conditions. Drones can safely access areas that are difficult or unsafe to reach from the ground, and they can be quickly deployed and adapted to changing weather conditions.

Project objectives & scope

Quantification of landfill methane emissions can be challenging. Current measurement techniques to estimate whole site methane emissions vary in approach, frequency and accuracy which can result in inconsistencies in data collection. There is a need to produce standard quantification methodologies for measuring methane emissions that could be implemented on site (through continuous monitoring, seasonal or annual surveys), and accompanying standard data analysis processes to provide robust estimates of the amount of methane generated and emitted from the landfill and the effectiveness of site management of methane.

This study explores the use of whole-site methane surveys to assess landfill gas management performance and their potential for deployment in a regulatory context. Two established methods for measuring methane emissions, Tracer Dispersion and UAV mass balance, were utilised to provide whole-site methane emission fluxes which were used to investigate metrics for site performance at mitigating methane emissions.

Robust measurement procedures can be applied to regulatory settings to assist in understanding and reducing methane emissions at a site level. As well as evaluating the effectiveness of measurement techniques, this project examines landfills under a range of environmental conditions, and landfills which are in the process of operational change, such as changes in operation of gas collection systems, and one site which closed during the course of the project.

The aim of this project is to evaluate potential regulatory approaches to improving methane capture at operational sites. It seeks to establish the foundation for standard operating procedures that define effective methodologies for measuring fugitive methane emissions and calculating methane collection efficiency for regulatory purposes. By gathering evidence on emerging technologies and measurement techniques, the project supports the development of robust and informed regulatory frameworks for methane control.

This project has met its intended aims by:

- Testing how quantification techniques could be used in the regulatory monitoring of methane emissions from permitted operational landfill sites.
- Developing and testing metrics for the performance of landfill gas collection.
- Deploying survey technologies to deliver datasets to characterise methane fluxes and evaluate the effects of interventions on site methane emissions.
- Developing effective methodologies for measuring methane emissions that can be implemented on site and accompanying data analysis to provide emissions estimates.
- Supporting and validating modelled estimates of landfill methane emissions with empirical data to support site-specific evaluations.
- Development of potential regulatory approaches and assessment of and sites against a metric for the collection of landfill gas.
- Evaluating the impacts of operational and meteorological conditions and on-site interventions on methane capture performance.

To deliver this project, the EA appointed a project team led by Ricardo. Ricardo held responsibility for project management, design and analysis for the project with the support of two project partners, The UoM and the UoS.

UoM was responsible for conducting surveys of methane flux using an UAV mass balance method, whilst the UoS was responsible for carrying out methane surveys using the TDM method. Both partners were responsible for the organisation of surveys and providing an analysis of the survey data collected using each method.

In addition to project management and design, Ricardo installed meteorological stations at three of the four landfill sites used in this study and collated and reported on the measurements. Ricardo also collated key operational data from each of the landfill operators and completed and reported on a comparison of the results from each survey technique alongside existing methods used by landfill sites in the UK.

Ricardo designed a program of research in order to:

- Quantify the whole-site fugitive emissions of methane from four operational permitted landfill sites for non-hazardous biodegradable waste using TDM and UAV mass balance approach.
- Understand the uncertainties associated with the survey techniques.
- Investigate causes of variation in methane emissions and possible influences of site operations at the time of, and leading up to, the quantification exercises. Additional data collected included:
    - Detailed meteorological data
    - Gas collection data
    - On-site operations
    - Operational plans / site topography plans
- Develop and test appropriate calculation techniques to use measurements of fugitive emissions as a metric for efficiency of gas collection.

2 Current monitoring and reporting requirements

Landfill operators are required to comply with The Environmental Permitting (England and Wales) Regulations (2016) which encompasses regulations set by the EU in council directive 1999/31/EC. The regulations require operators to hold an environmental permit. Each permit states the conditions for landfill operation, including the design of the landfill, how the landfill is managed and the type of waste that can be accepted by the operator. Under the Environmental Permitting Regulations, landfill operators are required to undertake gas monitoring of each section of the landfill following the approaches recommended in the LFTGN07 guidance document. The EA recommends the following two staged approach to evaluating the performance of landfill caps:

1. A walk over survey of each capped area using a handheld gas detector. The purpose of this stage is to identify locations where the cap has a potential to require remediation.
2. Flux box surveys of all capped areas and temporary capped areas intended to be in place for a period of 12 months or more. The purpose of this stage is to estimate the average methane flux of each surveyed zone which can then be compared to emission standards and be used to estimate the sites gas collection efficiency and validate submissions to the EA pollution inventory.

As with other processes regulated by the EA, operators are required to submit an annual report to the EA Pollution Inventory[4], and the Pollution Release and Transfer Registry (PRTR).[5]

Currently The landfill directive (1999)[6] underlines regulatory requirements for the management of landfills. To achieve compliance with this legal obligation, landfill operators are required to meet operational standards detailed within *The Environment Permitting*

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[4] Environment Agency, ‘*PI reporting guidance notes*’, available from: https://www.gov.uk/government/publications/pollution-inventory-reporting-guidance-notes/landfill-operations-pollution-inventory-reporting

[5] https://www.gov.uk/guidance/uk-pollutant-release-and-transfer-register-prtr-data-sets

[6] UK GOV (1999), ‘*The Landfill Directive’,* available from https://www.legislation.gov.uk/eudr/1999/31

(England and Wales) 2016.[7] The Environment Agency published its *Guidance on monitoring landfill gas surface emissions (2010)*[8] (LFTGN07) document to support operates meet their obligations.

The EA landfill guidance document provides a recommended set of methods to monitor methane emissions from landfill sites which are then used to assess the performance of any onsite gas management system and to understand methane emissions through capped areas.

To support operators with reporting to the EA Pollutant Inventory, the EA has provided a guidance document[4] which covers releases to air of methane and other substances. The guidance divides releases into two categories (fugitive emissions from the landfill site and point source emissions). These categories correspond to landfill emissions through the filled area of the landfill site, and emissions from treatment or leakage of landfill gas captured through the collection system. The EA requires operators to calculate the total volume of landfill gas emitted from the landfill using the GASSIM v2.5 modelling tool[9] and to then report the volume of Carbon Dioxide that is released from the landfill during the corresponding year.

Landfill operators are also required to report to the PRTR if the site has received waste since 2001 and has a total capacity of 25,000 tonnes or more, or receives 10 tonnes per day or more if below this capacity. The PRTR only captures pollutant releases above stated thresholds, such as a 100,000,000 kg/year for release of Carbon Dioxide and a 100,000 kg/year for methane, when released to air. Operators can in principle submit either measured or estimated values, although measured values are not used for landfill sites.

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[7] UK GOV (2016), '*The environmental permitting (England and Wales Regulation)'*, available from https://www.legislation.gov.uk/uksi/2016/1154/contents

[8] EA (2010), *'Guidance on monitoring landfill gas surface emissions',* available from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/321614/LFTGN07.pdf

[9] http://www.GASSIM.co.uk/

3 Factors affecting methane emissions

This section provides an overview of current knowledge of the influence of landfill design and operation, and meteorological influences on CH_4 flux emissions.

3.1 Published literature on the influence of landfill design and meteorological conditions on methane emissions

A review of research was undertaken to identify the key components to effective management of methane generated from landfill sites. The review uncovered clear evidence that capping has an influential role on methane emissions. Zhang et al (2025)[10] analysed methane measurements collected by the TROPOMI instrument based on the Sentinel-5P satellite over three categories of landfills, (1) open dump landfills in India, (2) covered and capped landfills using a high-density polyethylene (HDPE) geomembrane with an average 80% collection efficiency gas management system in China, and (3) a covered and capped landfills using fine soil as a geomembrane with a landfill gas system with an average collection efficiency of 85%. Each group of sites accepted municipal waste of similar size.

The results from this study suggest that a HDPE geomembrane is the most effective means of reducing CH_4 flux from the landfill. This study is limited by the use of satellite measurements with associated geographical, timing and detection limit constraints, but the findings are consistent with the effectiveness of control that can be delivered by a HDPE membrane with a suitable gas collection and combustion system.

With regard to soil covers and capping, the review identified a number of studies that could be of interest when considering landfill design and operation. The European Commission[11] has published research showing effective management of methane gas that is produced in

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[10] Zhang, S. Menglin, L. Huang, X. Yuzhong, Z (2025), '*Evaluation of methane emissions from MSW landfills in China, India, and the U.S from space using a two-tier approach*'. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0301479725006814

[11] European Commission (2018), *'Innovative methods for residual landfill gas emission mitigation fin mediterranean regions'*, available from: https://webgate.ec.europa.eu/life/publicWebsite/project/LIFE14-CCM-IT-000464/innovative-methods-for-residual-landfill-gas-emissions-mitigation-in-mediterranean-regions

too small quantities to be effectively captured in a landfill gas management system installed with a goal for the gas to be combusted. This method is centred on the installation of bio-based materials at methane hotspot locations above the landfill cell. This method has been recommended in the EU strategy to reduce methane emissions which is designed to complement the new landfill target set for biodegradable waste composition entering the landfill of less than 10% by 2035[12] and should be considered if landfill gas systems in the UK show low methane content[13] as the biodegradable content of sites continues to reduce.

The review also identified a number of studies led by Feng[14,15] who has shown that soil types used as landfill covers have a significant impact on methane oxidation. The review also identified publications by Lui et al (2024)[16] who investigated the impacts of three types of soil covers on methane oxidation during periods of dry and wet conditions. The periods were designed to reflect potential future conditions where a landfill may experience a long dry period followed by a heavy rainfall.

A second key finding from the review was the influence of atmospheric conditions on methane flux emission rates.

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[12] European Commission (2020), *'EU strategy to reduce methane emissions'*, available from: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0663

[13] Environment Agency, 2017. *Landfill methane oxidation techniques*. [pdf] Bristol: Environment Agency. Available at: https://assets.publishing.service.gov.uk/media/5a82aea140f0b62305b93cb6/Landfill_methane_oxidation_techniques_-_report.pdf [Accessed 21 Jul. 2025].

[14] Feng, S. Leung, A.K. Liu, H.W. Ng, C.W.W. Zhan, L.T. Chen, R (2019), '*Effects of thermal boundary conditions on methane oxidation in landfill cover soil at different ambient temperatures'.* Available from: https://www.sciencedirect.com/science/article/abs/pii/S0048969719332218

[15] Feng et al (2019), *'Effects of thermal boundary conditions on methane oxidation in landfill cover soil at different ambient temperatures',* available from: https://www.sciencedirect.com/science/article/pii/S0048969719332218

[16] Lui et al (2024), '*Experimental study of methane oxidation efficiency in three configurations of earthen landfill cover through soil column tests'*, available from: https://www.sciencedirect.com/science/article/pii/S0956053X2400521X?ref=pdf_download&fr=RR-2&rr=958d94c2fee46430

Delkash et al (2023)[17] considered the impact of meteorological conditions at a landfill in southeast USA. The landfill site did not have an active gas collection system during the period of the study and had only an intermediate cover consisting of clay and sand up to 0.9m thick. The study showed that air temperature was a stronger influence on CH_4 flux emissions from the site, with it correlating strongly in stable atmospheric conditions (i.e Methane Flux was found to increase as temperature increased). A weaker correlation was observed in unstable conditions. The research also showed a negative correlation between atmospheric pressure and CH_4 flux during some, but not all, months of the year, with a weaker correlation during June.

The supplementary appendix to that study suggests that CH_4 flux movement through the landfill cell is significantly influenced by near surface wind speed, atmospheric pressure and soil saturation.

The Delkash et al study states that higher near surface wind speeds have been shown to increase CH_4 flux through the soil layer of the landfill with research published by Delkash et al (2016)[18] showing a positive correlation between near surface wind speed and methane flux. With regard to atmospheric pressure, the study states that change in barometric pressure is more influential than instantaneous pressure with CH_4 flux increasing as the pressure gradient becomes negative after a period where the landfill experiences a positive pressure gradient change. The authors attribute this to the creation of a vertical pressure gradient within the soil after atmospheric pressure has been released.

Soil saturation is also stated to be a key factor as modelling showed that higher moisture levels reduce molecular diffusion within the soil due to higher soil pore demand which increases the importance of gas advection. Increase in CH_4 flux were found to be higher during wetter periods during a negative pressure gradient. This was explained to be due to the limited opportunity for gas advection to occur during periods where soil saturation is higher, resulting in a higher CH_4 flux as the pressure gradient changes. This observation could further be explained by conclusions made by Feng et al[15] who state that methane oxidation within soils is reduced when landfill cell pressure is greater than atmospheric

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[17] Delkash, M. Chow, F K. Imhoff (2023). '*Diurnal landfill methane flux patterns across different seasons at a landfill in southeastern US'.* Available from: https://www.sciencedirect.com/science/article/abs/pii/S0956053X22001313

[18] Delkash, M. Zhou, B. Han, B. Chow, F.K., Rella, C.W. (2016), '*Short-term landfill methane emissions dependency on wind'.* Available from: https://www.sciencedirect.com/science/article/abs/pii/S0956053X16300575

pressure, forcing a vertical direction of gas movement and reducing the potential for oxygen diffusion into the soil which would be used to oxidise passing methane.

Some evidence to support this finding was also shown by Feng et al (2019)[14] and Agham et al (2017)[19] and Brille et al (2024).[20] The research (Agham, 2017) looked at the influence of meteorological conditions on methane measurements collected at a closed municipal landfill site with a HDPE membrane and gas collection system in Denmark. The study concludes that changes in barometric pressure are a significant factor in CH_4 flux and that regulation of the gas collection system is likely to reduce release of CH_4 from the landfill site to the wider environment. This study highlights the importance of considering meteorological and site operational conditions such as these when evaluating survey results.

Brille et al (2024) found that there was a large variation in CO_2 and CH_4 flux emissions due to meteorological factors at two landfill sites in Italy. The sites were similar in terms of the waste type collected (domestic municipal waste) and were both closed with a small difference in operational years (33 and 22 years). The sites differed in design, with one known to have a HDPE capping layer and a functional gas recovery system whilst the other was forcibly closed due to poor site management, with the gas recovery system never initiated and the status of capping not stated.

The study concluded that although the two sites showed variability in the level of influence on emissions, barometric pressure, solar radiation, air and ground temperature and participation were influential. The study also highlights that the level of grass cover on top of capped areas is influential on higher C-fixations during the growing season (spring). The study states that the presence of a gas management system was the largest influence on GHG flux release.

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[19] Aghdam, E.F. Scheutz, C & Kjeldsen, P. (2017), *'Impact of meteorological parameters on extracted landfill gas composition and flow*'. Available from https://www.sciencedirect.com/science/article/pii/S0956053X18300667

[20] Brilli, L. Toscano, P. Carotenuto, F. Di Lonardo, S. Di Tomassi, P. Magliulo, V. Manco, A. Vitale, L. Zaldei, A. Gioli, B. (2024), '*Long term investigation of methane and carbon dioxide emissions in two Italian landfills*'. Available from: https://www.sciencedirect.com/science/article/pii/S2405844024053878

The review found only a limited number of studies which shed light on what factors most influence methane emissions from landfills in the UK[21]. The EA has published a Chief Scientist's Group report which investigated the variability in landfill methane emissions using air quality monitoring data. Based on results at a single site, an analysis using a boosted regression tree (BST) approach was used to look at the strength in relationships between measured meteorological variables and emission rates captured across the landfill by flux box measurements.

With regards to the influence of meteorological conditions on methane emissions from the landfill, the study concluded that "*meteorological factors are not a dominant factor in the variability of methane emission rates. While wind speed and barometric pressure may have some effect on landfill methane emissions rate, that effect is relatively small".*[22] Changes in capping and gas extraction were found to be the main factors at that site.

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[21] Rees-White, T. and Beaven, R., 2019. *The variability of whole-site methane emissions from landfill (DEFRA Project WR1920)*. [pdf] University of Southampton. Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=20156 [Accessed 21 Jul. 2025].

22 Environment Agency (EA) / Chief Scientists Group (2024), *'Investigating variability in landfill emission using air quality monitoring'*. Available from: https://assets.publishing.service.gov.uk/media/66d582bec52d5fb4c82ddcc7/Investigating_variability_in_landfill_methane_emissions_using_air_quality_monitoring_data_-_report.pdf

4 Survey method and site selection

4.1 Survey methods

Two survey methods were used to estimate methane gas emissions from each site selected for this research project. Table 4-1 provides an overview of the survey methods used.

Table 4-1: Description of survey methods

Method	Description of method	Reasons for selection
TDM	The Tracer Dispersion Method (TDM) is a whole site emissions monitoring technique in which a tracer gas is released at a controlled rate from the facility being measured. The concentrations of the tracer gas and target gas are then measured simultaneously downwind using a mobile, high-resolution gas analyser. The site emission flux can be calculated by comparing the concentration measurements from the two gases.	Established technique for measuring landfill gas emissions. Relatively simple and inexpensive to perform. Viable at most landfill sites.
UAV	We use Unmanned Aerial Vehicles (UAVs, or drones) equipped with high-precision instruments to measure methane (CH_4) and carbon dioxide (CO_2) concentrations. An onboard anemometer records wind speed and direction. The drones are flown downwind of the landfill to track how greenhouse gases are carried through the air. Flights are planned daily based on wind conditions, and the drones fly at different heights to map the shape and spread of the emission plume.	It allows to measure emissions directly in the air downwind of the landfill, where greenhouse gases are most detectable. Drones can safely access areas that are difficult or unsafe to reach from the ground, and they can be quickly deployed and adapted to changing weather conditions. The combination of precise gas concentration and wind measurements enables to collect high-quality data over a wide area

Method	Description of method	Reasons for selection
		without interrupting landfill operations. The mass balance method is well-established in environmental research and provides a practical, cost-effective way to monitor emissions in real-world conditions.

4.2 Site selection process

The first phase of survey planning was to identify the sites at which the three aspects of practical work (TDM surveys, UAV mass balance surveys, and meteorological data collection) as well as the landfill data collection from site operators, would be carried out.

Co-operation of the site operators was a fundamental requirement. This was secured on a voluntary basis from three leading waste management industry companies. The next steps of the site selection process therefore involved liaising with operators to confirm willingness of cooperation and to secure agreement for using the selected sites for the investigation.

It was necessary that the chosen sites should meet the minimum requirements to be suitable for TDM and UAV mass balance method. Primarily, it is essential that the site emits a detectable level of methane, and that the surrounding road networks or accessible flight corridors were suitable for monitoring the methane downwind. To confirm suitability, each site underwent a desk-screening study and preliminary site visit with background methane concentration measurement survey. The preliminary site visit was designed to determine the extent and concentration of the methane plume, identify accessibility for on-site tracer release and off-site monitoring, and screen for any other nearby sources of methane that might affect the results. The determinants for the feasibility of TDM and UAV mass balance method was as follows:

TDM Requirements:

- Clear methane plume propagation downwind of the landfill
- Access routes downwind of the landfill
- No significant nearby source of methane

- Vehicle access around site

UAV mass balance Requirements:

- Clear methane plume propagation downwind of the landfill
- No significant nearby source of methane
- Clear line of sight for drone surveys
- No unacceptable drone flight restrictions
- Avoid potential terrain and man-made obstacles (e.g. trees, fences)

Although the selection criteria listed above were important in identifying suitable sites, in practice compromises had to be made. For example, there were other methane sources close to two of the test sites, and no access for UAVs at the remaining site Y2. Hence, a fourth site was added with limited surveys.

4.3 The selected sites

For this project, the operators requested anonymity as a condition for participating in the research. As a result, the sites have been anonymised. Under an anonymised nomenclature, the four selected sites were:

- Site X, operator X
- Site Y1, operator Y
- Site Y2, operator Y
- Site Z, operator Z

4.4 Description of sites

It has been particularly important to confirm the collection of associated data, including meteorological measurements that form part of the core method, as well as operational information from the landfill site that supports interpretation of the results. This information encompasses waste receipts, quantities of landfill gas collected and burnt in flares or engines, any maintenance activities, operational incidents, gas field balancing data, and up-to-date site plans. We have also sought to obtain and analyse operator GASSIM models used to model the production of landfill gas at landfill sites.

Figure 4-1 to Figure 4-4 provides an illustration of the layout of each landfill site. These images are based on information provided by each site operator. Some operational and temporary capped layers may not truly reflect the site operations at the time of each survey measurement due to natural changes in the site operational areas. Diagrams have been simplified to protect site anonymity. Additional site information is provided in Table 4-2.

Table 4-2: Summary of selected site details

	Site X	Site Y1	Site Y2	Site Z
Year opened	Mid 1990's	Early 2000's	1980's	Early 1990's
Current capped size (ha) – from site pan	38	30	38	29
Operational area - total site boundary (ha)	46	43	71	72
Site capped (yes / no)	Part	Part	Part	Part
Type of capping	Temporary clay cap, permanent clay cap, permanent clay geomembrane cap, permanent geomembrane cap	Temporary, clay, capped clay, capped lap lay m membrane, GCL	Temporary cap, capped clay, GCL	Clay cap
Current status (operational, closed)	Operational	Operational	Closed	Operational
Landfill gas collection systems in place	8 x 1 MW Jenbacher Gas Engines in total (Usually running 5/6) and 3 flares with total capacity of 4000m^3/hr on standby.	3 x Jenbacher Gas Engines giving a total of 1.9 MW generation and a 2000 m^3/hr flare on standby.	3 x 1 MW Jenbacher Gas Engines and a 3000 m^3/hr flare on standby.	2 x 1 MW Jenbacher Gas Engines and 2 flares with total flaring capacity of 2500m^3/h on standby.

	Site X	Site Y1	Site Y2	Site Z
Average quantity of waste landfilled (kt / year)	600	950	120	120

Figure 4-1: Indicative layout of Site X

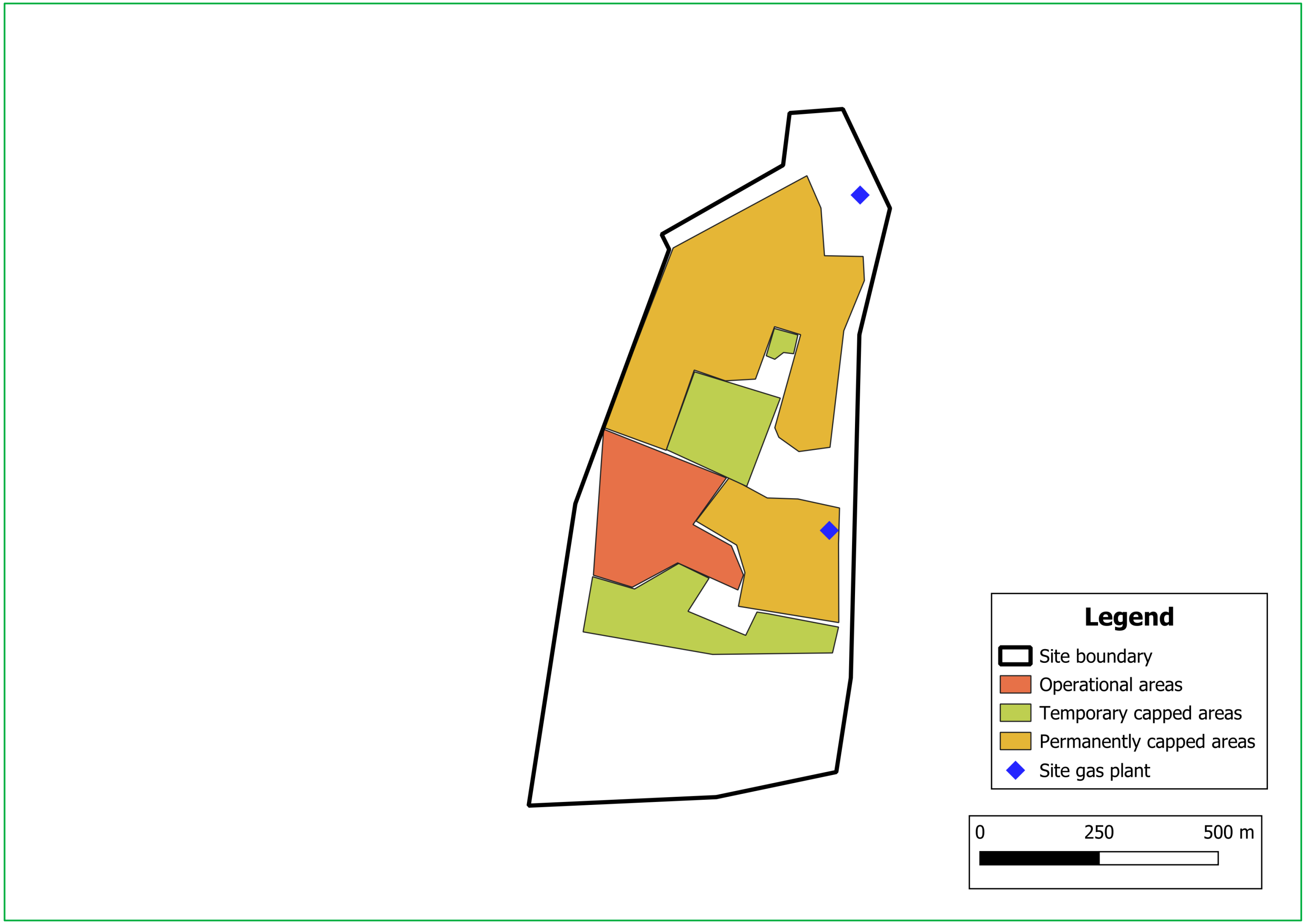


Figure 4-2: Indicative layout of Site Y1

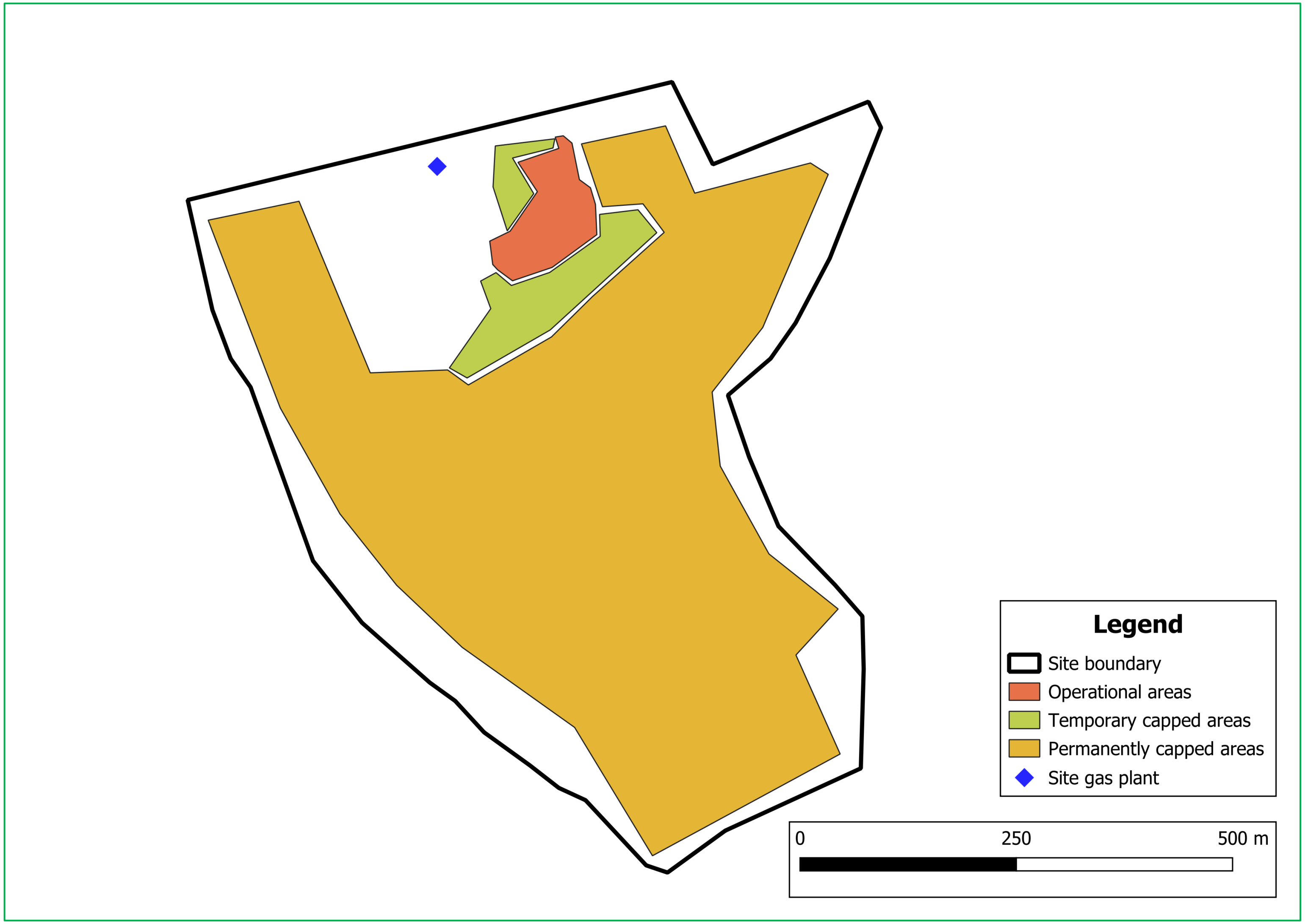


Figure 4-3 Indicative layout of Site Y2

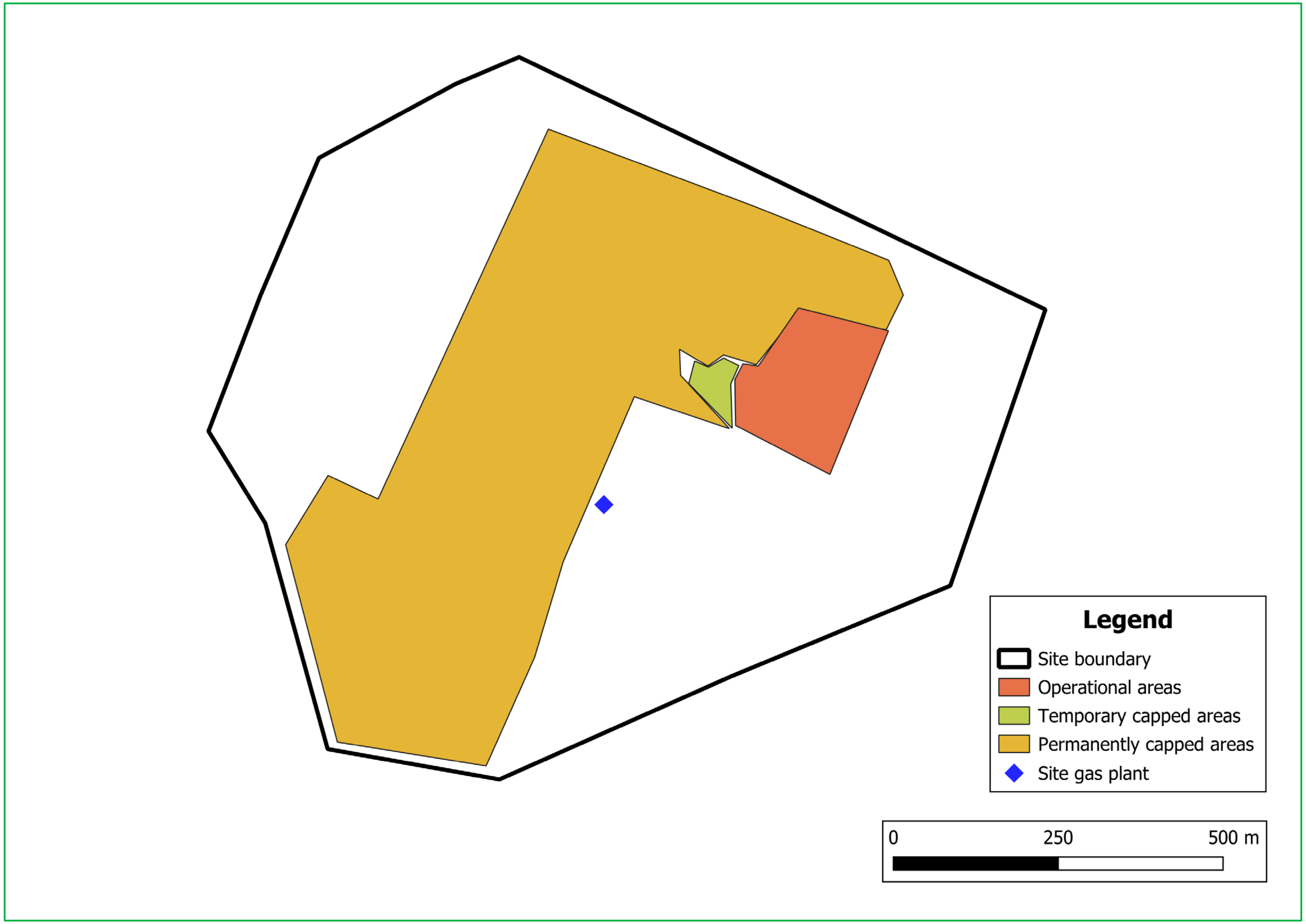
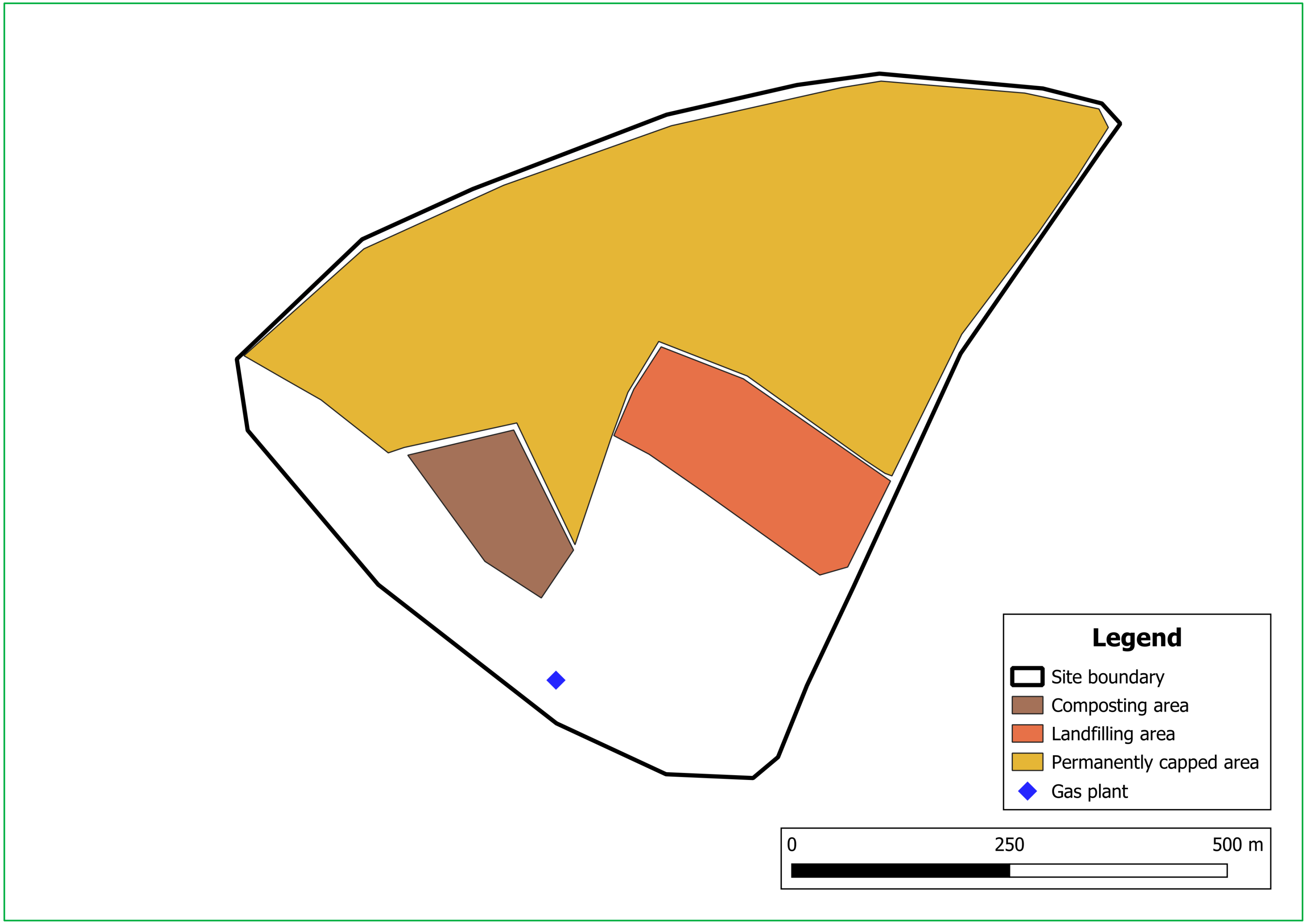


Figure 4-4: Indicative layout of Site Z



5 Surveys

This section provides an overview of the measurement techniques used for each component of the study. The results for each set of measurements are detailed within the Section 6 of this report.

5.1 Measuring meteorological conditions

Meteorological conditions were measured for the duration of the project at Sites X, Y1 and Z for the duration of the project. For security reasons, it was not possible to install a met station at Site Y2. Instead, site operator data or locally publicly available data was used in the analysis.

The meteorological equipment selected for use in this project was the GMX-550 Weatherfile station (Gill Instruments). This equipment was selected for various reasons:

- Ability to transmit 1-minute data via the website interface for use whilst on site
- Ability to record and log 1-second data within the onboard SD card for retrieval at a later date.
- Easy to assemble equipment with provision of 3 m mast giving the ability to install without attaching to a larger structure.

The GMX-550 stations recorded the following meteorological variables (as 1-minute averages or at 1 Hz):

- Atmospheric pressure (hPa)
- Relative humidity (%)
- Precipitation total (mm)
- Air temperature (°C)
- Dew point temperature (°C)
- Average wind direction relative to North (°)
- Wind direction backed (°)
- Wind direction veered (°)
- Average wind speed (m/s)
- Wind speed high (m/s)

- Wind speed low (m/s)

The weather stations proved to be unreliable and frequently shut down for unknown reasons. The long-term data record is, therefore, somewhat intermittent. This was particularly apparent during colder periods, and may have been caused through rapid battery drainage and slow solar charging. The station installed at Site Z failed completely a few weeks after installation and was replaced with the station from Site X for the remainder of the project.

5.2 Methane emission survey methods

This section provides an overview of each survey method. Full technical details of each survey and emissions quantification method are detailed in Appendix 6.

Tracer Dispersion Method (TDM)

The UoS carried out whole-site methane emission quantification surveys around the four selected landfill sites using the Tracer Dispersion Method. TDM is a whole-site emission quantification technique based on the principle that a tracer gas released from the same location as the source of the target gas will be subject to the same atmospheric dispersion when moving downwind as the target gas. By knowing the release rate of the tracer gas and by measuring downwind above-background concentrations of both the target and tracer gases, then through the integration of concentration measurements across the plume (termed a plume transect), an estimation of the target gas emission rate can be made. The systematic uncertainties from these assumptions are minimised when the two gases are well-mixed and when measurement transects are far enough downwind to reduce errors associated with the location of the tracer gas release not fully replicating the spatial distribution of the emission source.

With suitable monitoring equipment and good control on tracer release, and under ideal atmospheric conditions, TDM is capable of resolving emission rates down to ~5 kg/hour.

Unmanned Aerial Vehicles (UAV) mass balance method

The UoM carried out surveys using a rotary UAV platform and in situ infrared spectrometer sensing technology. Pre-survey site recce visits were arranged to define on-site locations for UAV take-off and landing, and aerial operational and sampling constraints.

Surveys were carried out using a DJI M600 Pro hexacopter, equipped with an ABB GLA133-GPC OA-ICOS infrared spectrometer, a gas sampling inlet, and a TriSonica (2D) Mini anemometer. All flights were operated over a preset (programmed, but manually interruptible) flight path at a speed of 3-4 m/s.

Measurements were collected by defining a flight path downwind of GHG sources on the landfill site, within the site perimeter, or above land adjacent to the site (where permitted), avoiding people, buildings, animals and property. Flight plans were programmed each day based on the forecast and measured wind direction for that day. Flight plans typically consisted of a transit from the take-off/landing point to a working survey area where we flew a “ladder” (stacked horizontal lines at various heights) aligned perpendicular to the prevailing wind direction and downwind of the landfill plume.

Emission rates were estimated using a mass balance approach originally developed by Allen et al. (2015, 2018, 2019) and further refined by Shaw et al. (2023) and Yong et al. (2024). This method integrates measured CH_4 enhancements (relative to ambient background concentrations) combined with wind field data to calculate the total net flux of emissions through a characterizable volume of air as it advects across a source of interest (See Appendix 4 for further details).

6 Results of Methane Surveys

Details of survey-specific findings are detailed in Appendix 2. The following section provides a comparison of the results from each survey method.

6.1 TDM surveys

6.1.1 Site X

Table 6-1: Methane measurements collected at Site X per survey

Survey No.	Date	Time	Number of Plume Transects	Calculated CH_4 Flux (kg / hour)	Standard Deviation (kg / hour)
1	11/09/24	19:55-21:40	15	71	9
2	25/11/24	14:37-16:05	14	83	12
3	26/11/24	07:25-09:17	20	62	10
4	21/01/25	19:25-19:31	23	34	5
5	20/03/25	18:35-21:05	18	107	19

6.1.2 Site Y1

Table 6-2: Methane measurements collected at Site Y1 per survey

Survey No.	Date	Time	Number of Plume Transects	Calculated CH_4 Flux (kg / hour)	Standard Deviation (kg / hour)
1	19/10/24	15:25-17:45	19	100	17
2	19/10/24	21:30-23:06	17	94	12

Survey No.	Date	Time	Number of Plume Transects	Calculated CH_4 Flux (kg / hour)	Standard Deviation (kg / hour)
3	10/12/24	19:20-21:35	13	95	15
4	09/01/25	19:10-21:05	17	90	10
5	27/02/25	20:00-22:15	24	72	12

6.1.3 Site Y2

Table 6-3: Methane measurements collected at Site Y2 per survey

Survey No.	Date	Time	Number of Plume Transects	Calculated CH_4 Flux (kg / hour)	Standard Deviation (kg / hour)
1	05/12/24	07:10-09:45	18	126	21
2	17/12/24	12:40-14:45	15	42	8
3	14/01/25	13:27-15:32	19	34	3
4	04/02/25	05:57-8:10	17	34	2
5	18/03/25	17:14-19:20	17	53	13
6	21/03/25	10:30-12:36	15	130	21

6.1.4 Site Z

Table 6-4: Methane measurements collected at Site Z per survey

Survey No.	Date	Time	Number of Plume Transects	Calculated CH_4 Flux (kg / hour)	Standard Deviation (kg / hour)
1	20/01/25	12:51	18	287	42
2	20/01/25	19:25	23	260	43
3	19/03/2025	17:20	24	141	33
4	19/03/2025	22:25	18	94	15

6.2 UAV Mass Balance Surveys

6.2.1 Site X

Table 6-5: Methane and carbon dioxide measurements collected at Site X per survey

Survey No.	Date	Time	CH_4 Flux (kg/h)	CH_4 uncertainty (kg/h)	CO_2 Flux (kg/h)	CO2 uncertainty (kg/h)
1	26/11/2024	12:11-12:24 12:33-12:41	26.2	7.7	3833.7	1134.5
2	26/11/2024	14:37-14:49 14:57-15:04	22.0	5.7	976.5	252.8
3	26/11/2024	15:17-15:28 15:35-15:45	19.5	3.5	2136.0	392.6
4	26/11/2024	15:55-16:09	14.6	3.0	2608.3	549.9

Survey No.	Date	Time	CH_4 Flux (kg/h)	CH_4 uncertainty (kg/h)	CO_2 Flux (kg/h)	CO2 uncertainty (kg/h)
5	27/11/2024	13:15-13:29 13:35-13:49	40.9	6.2	574.9	86.1
6	27/11/2024	14:02-14:15 14:25-14:41	78.5	13.0	5707.1	944.6
7	27/11/2024	14:53-15:08 15:15-15:30	72.1	13.9	3885.7	746.2

6.2.2 Site Y1

Table 6-6: Methane and carbon dioxide measurements collected at Site Y1 per survey

Survey No.	Date	Time	CH_4 Flux (kg/h)	CH_4 uncertainty (kg/h)	CO2 Flux (kg/h)	CO2 uncertainty (kg/h)
1	29/10/2024	13:12-13:22 13:36-13:43	67.3	11.9	3421.8	552.9
2	29/10/2024	14:00-14:12	41.2	8.7	2326	478
3	29/10/2024	15:24-15:36	93.9	26.5	1403.6	390.9
4	29/10/2024	16:00-16:20	35.9	7.8	1395.3	293.6
5	30/10/2024	10:20-10:34	-	-	1584.3	528.7

Survey No.	Date	Time	CH_4 Flux (kg/h)	CH_4 uncertainty (kg/h)	CO2 Flux (kg/h)	CO2 uncertainty (kg/h)
6	30/10/2024	10:47-11:01 11:12-11:25	58.0	19.1	1356.6	439.6
7	30/10/2024	11:41-11:53 12:02-12:13	74.7	23.8	1042.2	326.0

6.2.3 Site Y2

No surveys were completed for this site using the UAV mass balance method.

6.2.4 Site Z

Table 6-7: Methane and carbon dioxide measurements collected at Site Z per survey

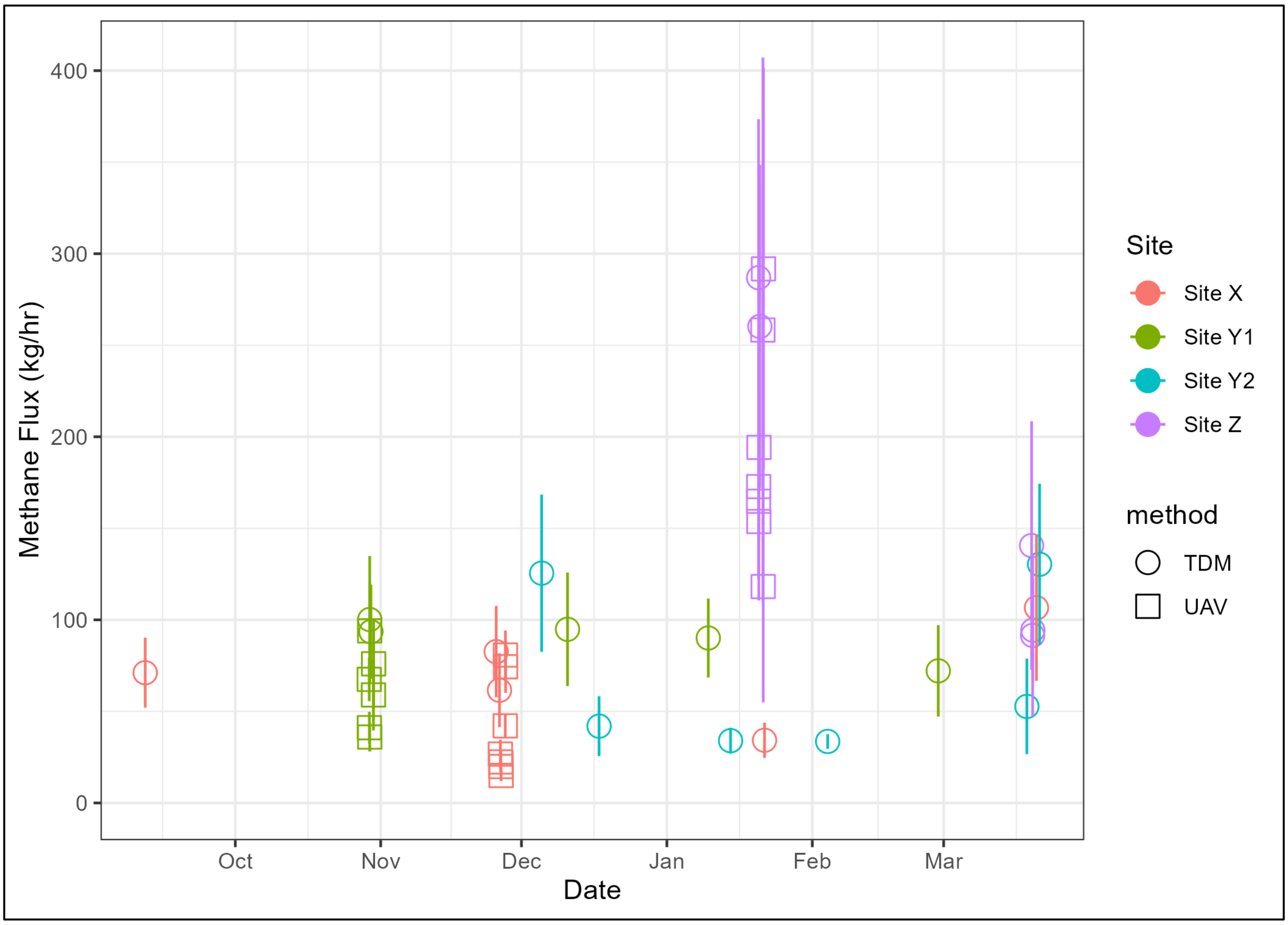
Survey No.	Date	Time	CH_4 Flux (kg/h)	CH_4 uncertainty (kg/h)	CO2 Flux (kg/h)	CO2 uncertainty (kg/h)
1	20/01/2025	13:10-13:21	160.9	41.6	748.7	190.0
2	20/01/2025	13:42-13:53	168.8	48.6	657.0	182.0
3	20/01/2025	14:26-14:39 14:45-14:48	150.1	42.1	1318.6	360.1
4	20/01/2025	15:09-15:21	189.6	49.5	1615.1	414.8
5	21/01/2025	11:17-11:29	252.4	145.4	1408.5	634.0

Survey No.	Date	Time	CH_4 Flux (kg/h)	CH_4 uncertainty (kg/h)	CO2 Flux (kg/h)	CO2 uncertainty (kg/h)
		11:36-11:48				
6	21/01/2025	12:45-12:56 13:13-13:18	115.7	62.0	2479.4	1163.0
7	21/01/2025	14:14-14:27 14:36-14:46	287.5	108.3	2069.4	519.7

6.3 Summary of Survey Results

The survey results are shown throughout the duration of the survey period (September 2024 to March 2025) in Figure 6-1. The sites are shown in different colours, with circle symbols used for TDM results and square symbols used for UAV mass balance results. The error bars in this figure show the quoted uncertainty ranges given in the tables in this chapter.

Figure 6-1: Summary of survey results



The results shown in Figure 6-1 indicate reasonably consistent methane flux results for sites X and Y1. At Site Y2 relatively high methane fluxes were measured during surveys 1 and 6 compared to surveys 2, 3, 4 and 5. At Site Z, significantly higher fluxes were measured in the surveys carried out in January than the surveys in March.

6.4 Estimation of Methane Slip using TDM

Methane slip is defined as uncombusted methane co-emitted with CO_2 from the engine stack(s) or flares at the landfill sites.

At Site X, one of the site's two gas utilisation plants (GUP) is located outside the boundary of the landfill. In surveys 1 and 5, owing to the wind direction, a separate methane plume, distinct from the methane plume from the landfill, was clearly discernible (Figures 61 and 62). In survey 1, tracer gas (acetylene) was released from close to the GUP. The alignment of the tracer and methane plumes, Figure 61, demonstrated that the smaller methane plume originated from the GUP.

The estimated methane flux from the GUP was between 7 and 14 kg/hour for survey 1 and 5 respectively (Table 6-8). This gas may be from leaks in the pipework and/or from unburnt methane in the exhaust of the engines/flare. It is not possible to differentiate between leaks and unburnt methane using TDM.

Warm, buoyant, unburnt methane from the engines will disperse in a different way to ground-based pipework leaks, and buoyant gas may be partly or entirely undetectable at ground level (where TDM measurements are typically made). The assumption of full mixing of the methane and tracer gases from the GUP may, therefore, not be accurate. Any flux calculation of gas from the GUP where a proportion of the gas is from slippage (i.e. unburnt methane) may, therefore, be an underestimate.

The emissions measured from the GUP in surveys 1 and 5, would typically form part of the whole-site emission calculation given in Table 6-1 to Table 6-4. It would not normally be possible to differentiate between GUP emissions and landfill emissions as they would form part of the same dispersion plume. For example, at Site X there is a second GUP located near the centre of the landfill. It was not possible to discern emissions from this using TDM as any measurable methane from slippage would mix with and form part of the plume from the landfill. For all the sites surveyed in the project, any leakage or slippage from the GUP that was measurable at ground level would be captured in the whole-site survey.

For leaks, it is assumed that any methane leaking from pipework in the GUP would come after the blower (positive pressure side) and before the engine. The location of the flow meter used for measuring the volumetric flow of gas going to the plant is, therefore, important. If the flow meter is before the blower (low pressure side), or indeed before any leaks, then any methane leaking from pipework after the flow meter would be double-counted, firstly by the gas utilisation flow meter and secondly as part of the TDM measurement. Likewise, any unburnt methane from the engines/flare that is measured in a TDM would be double counted. Routine monitoring in and around a GUP is therefore essential to locate, quantify and repair leaks.

Figure 6-2: Measurements collected at Site X during survey 1 showing excess (above background) concentrations of methane from the landfill and the GUP.

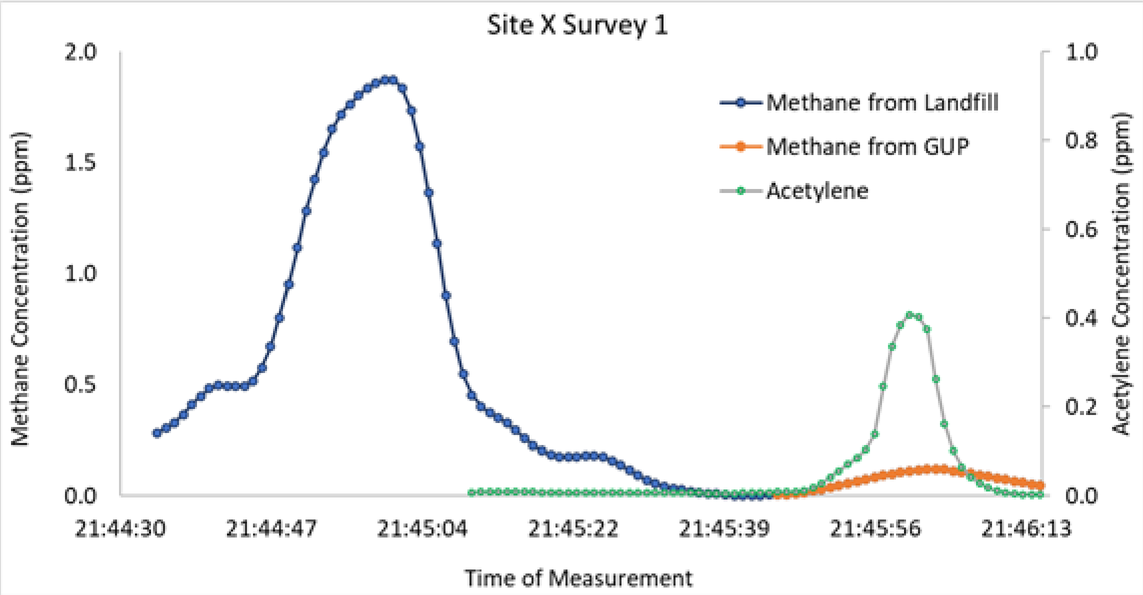


Figure 6-3: Measurements collected at Site X during survey 5 showing excess (above background) concentrations of methane from the landfill and GUP.

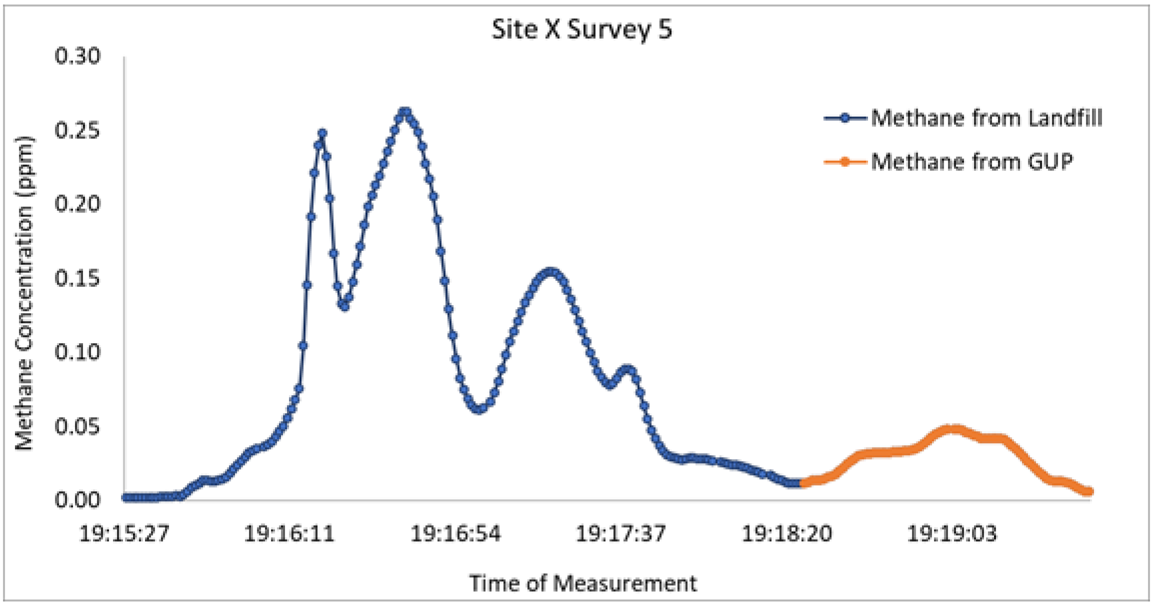


Table provides an estimate of the methane flux from the GUP during Surveys 1 and 5.

Table 6-8: GUP flux estimates from surveys 1 and 5 at Site X

Survey No.	Methane Flux from GUP kg/hr	Standard Deviation kg/hr	Whole Site Emission Flux kg/hr	GUP flux as % of Total	GUP flux as % of methane collected[1]
1	7.2	3.9	71	10	1.2%
5	13.8	2.0	107	13	1.9%

[1] Note, this is flux from only 1 of 2 GUPs but gas collection data was not provided separately each for each GUP.

6.5 Estimation of Methane Slip using UAV mass balance

The work presented in this section represents results additional to the project objectives and we present it as a novel demonstration of how combustion efficiency may be derived from UAV-based measurements. Table 6-9 presents the combustion efficiency and the ratio ΔCH4/ΔCO2 (based on two highly novel methods explained in Appendix 2). The latter is used as an indicator of anthropogenic emissions related to combustion and flaring (e.g., based on thresholds defined by Nara et al., (2014)). Values below 20 ppb/ppm typically indicate combustion-related emissions with minimal influence from fugitive or background methane sources. In contrast, ratios greater than 20 ppb/ppm suggest a significant contribution from uncombusted (fugitive) methane sources.

The Time column in Table 6-9 shows the UAV flight periods for each survey, which consisted of either a single continuous flight or a series of consecutive flights separated by brief intervals for battery replacement. In the table below, the methods for calculating efficiency (labelled “rectangle” or “points”) refer to novel approaches developed by the UoM team. Further explanation and an example of this calculation is provided in see Appendix 2.

Table 6-9 Estimated combustion of landfill gas efficiencies from UAV-based measurements

Site	Date	Time	Efficiency (rectangle method) (%)	Efficiency (points method) (%)	$\Delta CH_4/\Delta CO2$ Rectangle (ppb/ppm)	$\Delta CH_4/\Delta CO2$ Points (ppb/ppm)
Site Y1	**29/10/2024**	14:00-14:12	99.26%	99.36%	7.44	6.44

Site	Date	Time	Efficiency (rectangle method) (%)	Efficiency (points method) (%)	$\Delta CH_4/\Delta CO2$ Rectangle (ppb/ppm)	$\Delta CH_4/$ $\Delta CO2$ Points (ppb/ppm)
Site Y1	**29/10/2024**	15:24-15:36	98.40%	99.01%	16.24	9.95
Site Y1	**29/10/2024**	16:00-16:20	96.21%	97.28%	39.33	27.94
Site Y1	**30/10/2024**	10:20-10:34	-	-	-	-
Site Y1	**30/10/2024**	10:47-11:01 11:12-11:25	97.21%	97.25%	28.67	28.17
Site Y1	**30/10/2024**	11:41-11:53 12:02-12:13	97.88%	98.89%	21.62	11.13
Site X	**26/11/2024**	12:11-12:24 12:33-12:41	98.99%	98.86%	10.15	11.52
Site X	**26/11/2024**	14:37-14:49 14:57-15:04	98.30%	98.44%	17.25	15.82
Site X	**26/11/2024**	15:17-15:28 15:35-15:45	98.83%	98.79%	11.83	12.23
Site X	**26/11/2024**	15:55-16:09	98.41%	98.52%	16.15	14.96
Site X	**27/11/2024**	13:15-13:29	98.28%	98.26%	17.43	17.69

Site	Date	Time	Efficiency (rectangle method) (%)	Efficiency (points method) (%)	$\Delta CH_4/\Delta CO2$ Rectangle (ppb/ppm)	$\Delta CH_4/\Delta CO2$ Points (ppb/ppm)
		13:35-13:49				
Site X	**27/11/2024**	14:02-14:15 14:25-14:41	98.24%	98.61%	17.90	14.02
Site X	**27/11/2024**	14:53-15:08 15:15-15:30	98.49%	98.56%	15.24	14.55
Site Z	**20/01/2025**	13:10-13:21	63.66%	66.34%	570.77	507.23
Site Z	**20/01/2025**	13:42-13:53	65.24%	63.29%	532.61	569.96
Site Z	**20/01/2025**	14:26-14:39 14:45-14:48	78.02%	77.88%	281.68	283.98
Site Z	**20/01/2025**	15:09-15:21	73.66%	73.42%	357.44	361.97
Site Z	**21/01/2025**	11:17-11:29 11:36-11:48	66.48%	64.29%	503.98	555.39
Site Z	**21/01/2025**	12:45-12:56 13:13-13:18	86.36%	85.79%	157.81	165.51
Site Z	**21/01/2025**	14:14-14:27	74.51%	72.77%	341.92	374.10

Site	Date	Time	Efficiency (rectangle method) (%)	Efficiency (points method) (%)	$\Delta CH_4/\Delta CO2$ Rectangle (ppb/ppm)	$\Delta CH_4/\Delta CO2$ Points (ppb/ppm)
		14:36-14:46				

The table highlights all events where a combusted (or rather, partially combusted) plume was sampled by the UAV. For an event to be triggered as combusted for analysis, inspection of CO_2/CH_4 mixing lines is required. If two distinct mixing lines are observed (see Appendix 4 for examples), this indicates distinct airmasses, where the airmass with a greater CO_2/CH_4 ratio is assumed to be from the combusted source (in this case the engine stack). We see that calculated combustion efficiencies vary from ~63% (at site Z) to >97% in all cases at sites X and Y.

An important point is that it is not possible to robustly isolate the fluxes from combustion sources on site using the UAV mass balance method. UAV sampling is a highly efficient way to identify a partially combusted plume's existence, and we have demonstrated how such measurements can be used to define a combustion efficiency (residual methane %) in a world-first example. However, subtracting this from the wider landfill plume is non-trivial and could introduce compounding errors. Instead, the mass balance method is best suited to whole-site net emissions snapshots only, but with the added value of being able to detect and define combustion efficiency for stack-focussed sampling.

As the combustion efficiency approach described here is highly novel and beyond the objectives of this project, the project team will seek to publish these results in the peer-reviewed literature in due course.

6.6 Comparison of TDM and UAV mass balance methods

At three of the sites in this study, both TDM and UAV mass balance methods were used to estimate methane flux. An objective of this project was to compare the results of each method to better understand sources of bias and uncertainty and how precision may be impacted by the differences in assumptions inherent to each method and operational constraints (such as time of day, meteorology and atmospheric dynamics, and sampling constraints). As both methods are now in use by academic teams in the UK and internationally, and for commercial survey work, these comparative findings are highly relevant to informing effective UK monitoring regulation.

To enable direct comparison between the two approaches, surveys were scheduled to overlap in time where possible. At each site, at least one TDM and one UAV mass balance survey were conducted on the same day, and at two of the sites, there was a period of direct temporal overlap between the two methods.

Table 6-10 presents the results of this comparison for each site, together with the metered methane collected at the time of the survey and the calculated methane production for reference (explanation provided in section 7.1). Figure 6-4 to Figure 6-6 then illustrate this data in graphical format.

Table 6-10 Comparison of TDM and UAV mass balance

Site	Date	Survey Method	Start Time	End Time	Metered Methane Collected (kg/h)[1]	Survey Methane Flux (kg/h)[2]	Total Estimated Methane Generation (kg/h)[2,3]
Site X	26/11/25	TDM	07:33	09:17	875 ± 15	62 ± 20	925 ± 21
		UAV mass balance	12:11	12:41	874 ± 22	27 ± 8	885 ± 30
		UAV mass balance	14:37	15:04	873 ± 22	22 ± 6	880 ± 29
		UAV mass balance	15:17	15:45	870 ± 22	20 ± 4	874 ± 29
		UAV mass balance	15:55	16:09	865 ± 22	15 ± 3	864 ± 28
Site Y1	29/10/25	UAV mass balance	13:12	13:43	297 ± 8	68 ± 12	366 ± 16
		UAV mass balance	14:00	14:12	303 ± 8	41 ± 9	343 ± 13
		UAV mass balance	15:24	15:36	303 ± 8	94 ± 27	401 ± 29
		UAV mass balance	16:00	16:20	304 ± 8	36 ± 8	338 ± 13
		TDM	15:51	17:46	302 ± 6	100 ± 35	407 ± 36
		TDM	21:57	23:07	304 ± 5	93 ± 26	401 ± 29
Site Z	20/01/25	UAV mass balance	13:10	13:21	318 ± 8	165 ± 43	545 ± 45
		TDM	13:08	15:55	320 ± 1	286 ± 86	632 ± 96

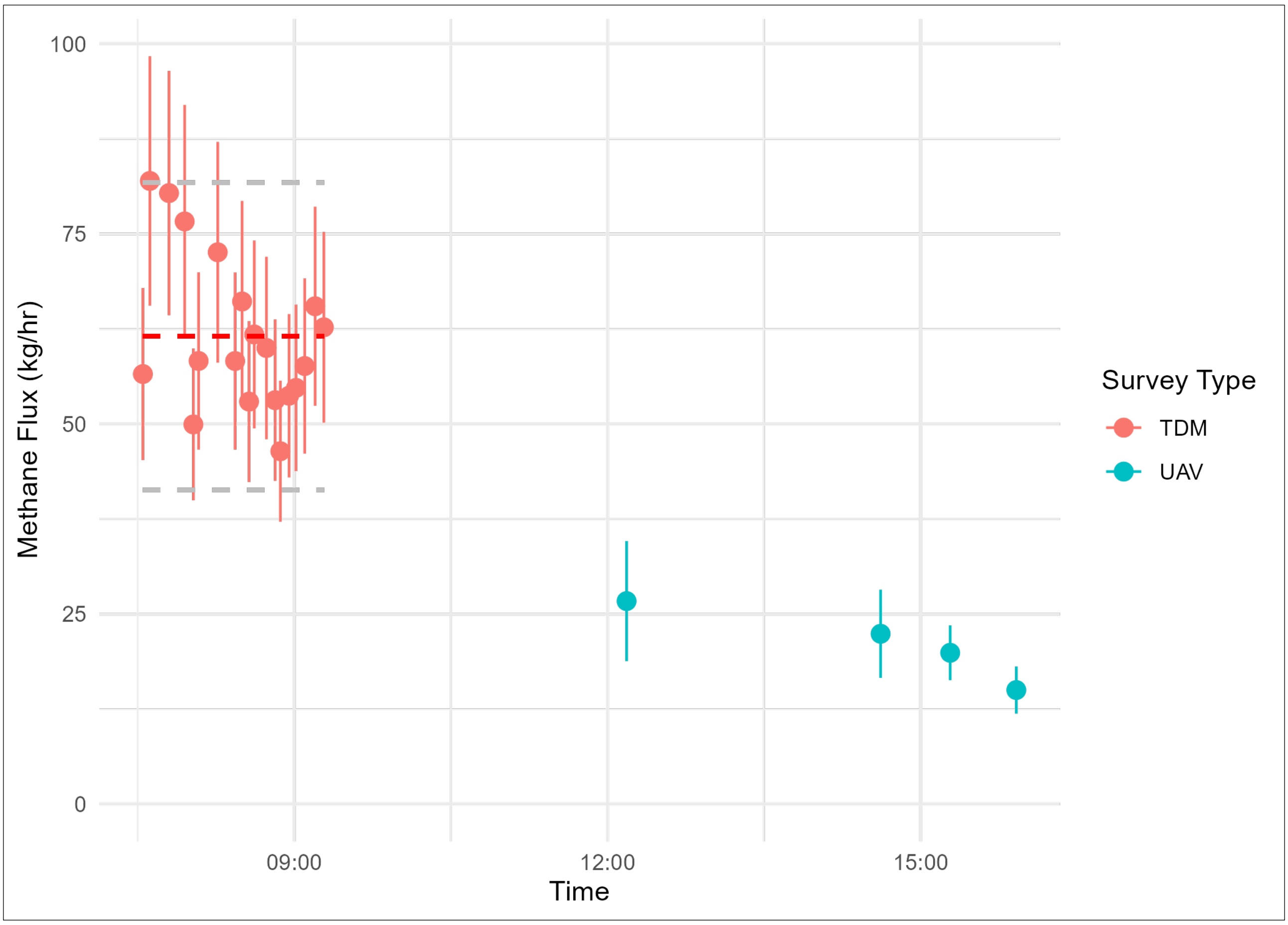
Site	Date	Survey Method	Start Time	End Time	Metered Methane Collected (kg/h)[1]	Survey Methane Flux (kg/h)[2]	Total Estimated Methane Generation (kg/h)[2,3]
		UAV mass balance	13:42	13:53	318 ± 8	173 ± 50	504 ± 52
		UAV mass balance	14:26	14:48	318 ± 8	154 ± 43	482 ± 45
		UAV mass balance	15:09	15:21	318 ± 8	194 ± 51	527 ± 53
		TDM	19:36	21:17	321 ± 1	260 ± 88	603 ± 98

[1]Uncertainty of the methane collected calculated as the measurement error on the gas flow meter and the gas analyser propagated using the quadrature method.

[2]For TDM uncertainties on the methane flux are calculated as 2 standard deviations of the individual measurements for each survey, equivalent to 95th percentile confidence interval for a normally distributed set of measurements. For UAV mass balance uncertainties, the relative uncertainty in the flux was calculated as the square root of the sum of the squared relative uncertainties of background concentration and wind speed component.

[3]Total Estimated Methane Generation includes assumptions for surface methane oxidation (estimated to be 10% of methane not collected) and methane slippage methane slippage (estimated to be 2% of methane collected). More detail on how this is calculated provided in section 7.3.

Figure 6-4: Comparison of individual TDM and UAV mass balance flux measurements at Site X on 26/11/24.

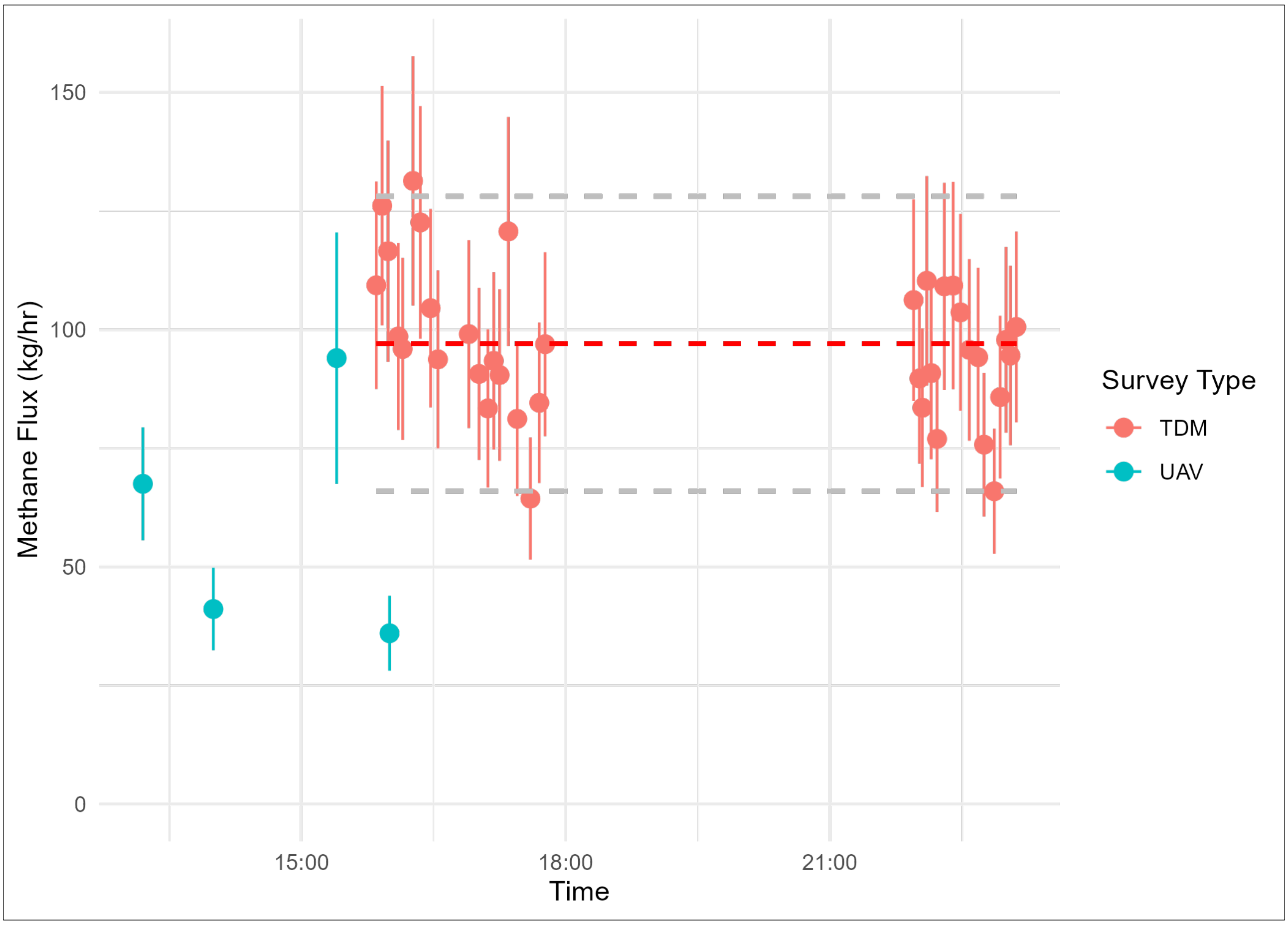


Note: Error bars represent the estimated measurement uncertainty. Red dashed line shows the average flux calculated from the TDM survey which is used as the basis for comparison with UAV methane balance estimates, grey dashed lines indicate upper and lower uncertainty bounds.

At Site X there was no direct temporal overlap between the TDM and UAV mass balance surveys conducted on the same day, so a definitive quantitative comparison cannot be made as it may be possible that the site emissions changed in the 3 hours between the TDM and UAV mass balance surveys - the TDM survey was carried out in the morning (07:33–09:17), while the UAV mass balance surveys took place in the afternoon (14:48–16:01). The pressure changed by 3.5 hPa over this time and the temperature by 4 K. However, it is not possible to conclude whether such environmental change is responsible for the different fluxes measured by the methods at different times. The flux measurements from the two techniques do not overlap within their respective uncertainties at Site X.

This could be due to systematic differences in the application of the TDM and UAV mass balance flux methods, and/or due to operational or meteorological differences associated with the time of day. It is simply not possible to say which of these effects was or was not responsible, or to what degree due to the lack of time overlap. However, the metered methane collected remained broadly stable throughout the day, suggesting that on-site emissions may be stable. We also note that, temporal offset notwithstanding, the UAV mass balance fluxes are biased systematically lower than TDM fluxes (which we discuss further below).

Figure 6-5: Comparison of individual TDM and UAV mass balance flux measurements at Site Y1 on 29/10/24.

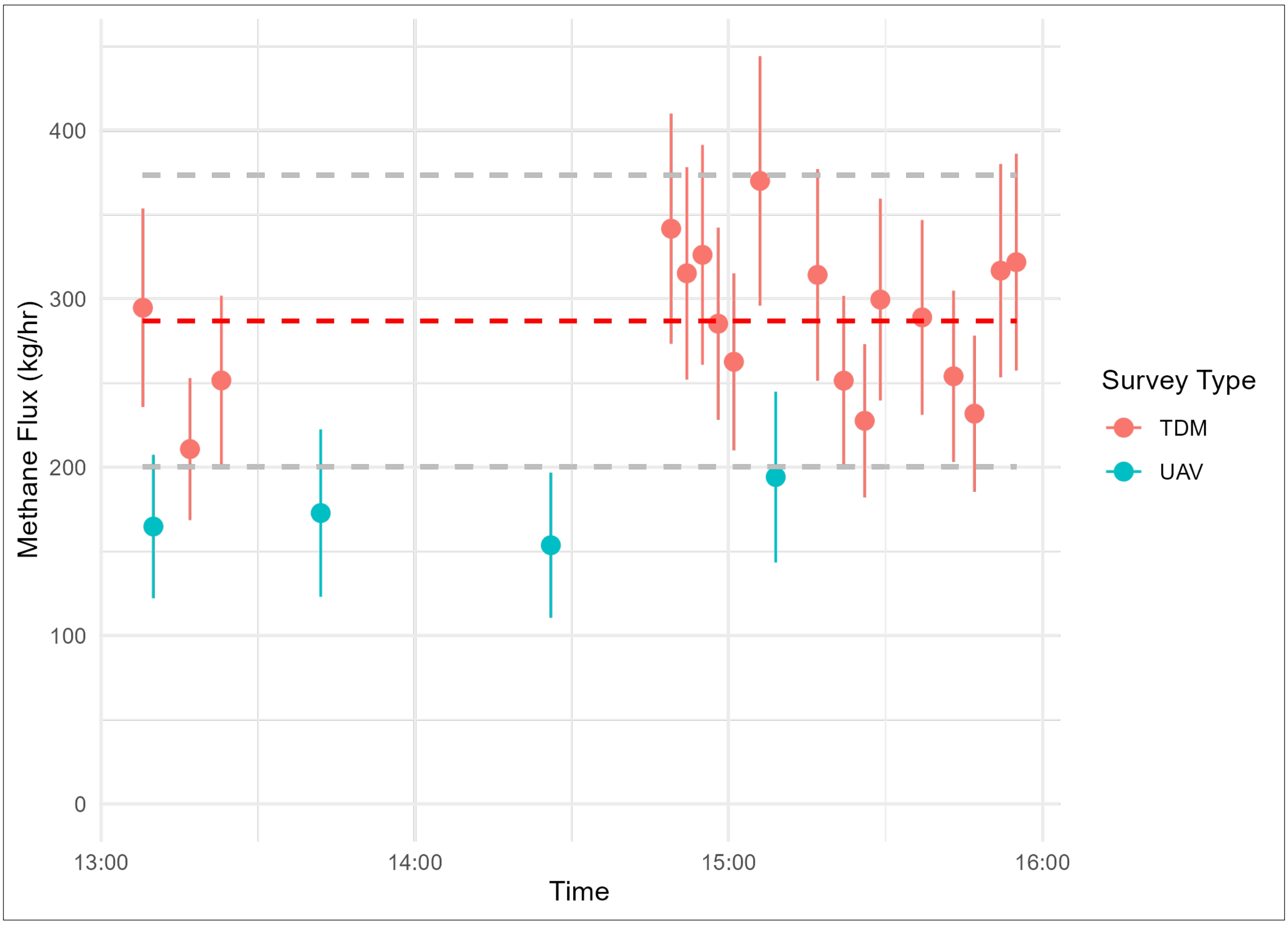


Note: Error bars represent the estimated measurement uncertainty. Red dashed line shows the average flux calculated from the TDM survey which is used as the basis for comparison with UAV methane balance estimates, grey dashed lines indicate upper and lower uncertainty bounds.

Figure 6-5 shows the comparison for Site Y1, noting that two UAV mass balance surveys coincided with TDM surveys in this case (between 15:00 and 16:30). The first of the UAV mass balance surveys which coincided with TDM (at 15:24) sampled 94 ± 27 kg/h, compared to an average flux of 100 ± 35 kg/h from the TDM survey, with both fluxes agreeing well within each method's uncertainty envelope. The next overlapping UAV flight

(16:10) sampled 36 ± 8 kg/h, which is significantly lower than the estimated flux from the TDM survey. However, the individual TDM transect measurements between 15:00 and 18:00 saw a consistent declining trend through the day. Nonetheless, UAV mass balance flux at 16:10 does not overlap within uncertainty with TDM emissions at that time. As at Site X, UAV mass balance fluxes are systematically lower than TDM results.

Figure 6-6: Comparison of individual TDM and UAV mass balance flux measurements at Site Z on 20/01/25. Error bars represent the estimated measurement uncertainty.



Note: Red dashed line shows the average flux calculated from the TDM survey which is used as the basis for comparison with UAV methane balance estimates, grey dashed lines indicate upper and lower uncertainty bounds.

Figure 6-6 shows the comparison for Site Z. At this site, all UAV mass balance surveys were conducted within an hour of a corresponding TDM survey, providing the best-case study for comparison. Two observations can be made: firstly, that UAV mass balance fluxes are systematically lower (individually and on average) than the TDM flux; and secondly, that UAV mass balance and TDM fluxes generally overlap within the bounds of their one standard deviation envelopes. Given that the underestimation of UAV mass balance vs TDM is a consistent feature at all 3 sites, there is reasonable confidence in the conclusion that there is a fundamental bias in the two methods, which needs consideration.

One possible reason for the UAV mass balance underestimation of emissions may be the UAVs incapability to sample the first few meters above the ground (for safety reasons). This is due to the presence of obstacles e.g. trees and fences on the site. Also, for security reasons the UAVs should fly 2 m above the ATEX zoning. In essence, the UAV mass balance may be expected to systematically sample a smaller flux compared to TDM. Also, because of the location of the flight, there may well be a part of the plume due to engines located at the borders of the landfill perimeter, from which it was not possible to sample by the UAV due to horizontal boundary limitations. It may be possible to extrapolate spatially sampled data (e.g. from the minimum sampling height to the ground), so long as any extrapolated flux is added to the flux uncertainty, however we would note that this is a poorly constrained/known uncertainty and would mix random and systematic errors in such a way that methodological uncertainty becomes less transparent than applying a forward-propagated statistical uncertainty via the mass balance flux equation based on sampled data alone.

In contrast, all site emissions can be sampled in principle by the TDM, so long as there are corresponding tracer measurements. A converse requirement exists for the TDM method - if any plumes from the site are lofted convectively or turbulently, and do not mix down to the surface, where they can be sampled on public roads, the TDM method may return a null result (i.e. not zero flux, but a failure to detect). A further source of systematic uncertainty exists for the TDM method in cases where there may be a plume from another methane source directly upwind of the target site, which would manifest as an over-bias in quantified flux. Conversely, this can be accounted from in the UAV mass balance method (in the subtracted background used in the mass balance equation). However, the presence of such a source can often be detected by screening surveys in the TDM method, meaning that the presence of such an error (or its absence) may be known, even if it cannot be precisely accounted for.

7 Data analysis and site performance

7.1 Methane balance

Methane balance is an important concept for understanding variability in emission rates at a landfill. It assumes that methane generation is balanced by removal from the landfill via a number of pathways, plus potentially changes in the amount of methane stored in the landfill:

Equation 1; assumed method of calculating methane generation, fundamental to the concept of methane balance.

$$\begin{aligned} &Methane\ generation\ = Methane\ collected \\ &+Methane\ flux\ emitted\ to\ the\ atmosphere \\ &+Change\ in\ storage\ within\ the\ landfill \\ &+Methane\ oxidation\ in\ cover\ layers \\ &+Lateral\ migration \end{aligned}$$

For well-established landfills not going through substantial change, methane generation rates can be expected to be relatively stable over periods of months. This means that variability in methane flux must be determined by the changes in the other parameters in the methane balance. Lateral migration should be minimal or zero from a landfill designed and operated to current standards, meaning that the key variables are the collection rate, methane oxidation and changes in storage within the landfill.

It seems unlikely that methane oxidation would change rapidly[23], and metering shows that methane collection rates are typically stable over a survey period of a few hours. The most

[23] Several studies have shown that methane oxidation rates in landfill cover soils are largely dependent on meteorological conditions such as soil moisture and temperature as well as cover soil properties, which are not expected to change rapidly under stable atmospheric conditions:

Spokas, K.A. & Bogner, J.E. (2010), *Limits and dynamics of methane oxidation in landfill cover soils*. *Waste Management*. Available from: https://doi.org/10.1016/j.wasman.2009.12.018

likely cause of short-term fluctuations in methane flux is therefore changes in methane storage in the landfill.

7.2 Metrics for Assessment of Landfill Performance

A range of metrics were considered which could be used to describe site performance in collection and combustion of methane, and residual methane flux to the environment. As outline below, after consideration, it was concluded that some of these metrics would not be appropriate for tracking site performance:

- **Measured methane flux (kg/hour).**
  The rate of methane production and release depends on a wide range of factors including the site age, amount and type of waste in place, as well as the effectiveness of landfill gas control systems. Smaller and longer-established sites with less biodegradable waste in place would tend to have lower methane fluxes than newer and larger sites. It would not be possible to distinguish the effects of site performance from these other factors. Because of this, the measured methane flux would not itself be a reliable metric of how well the site is performing in control of methane. This is illustrated by the reported fluxes in Figure 6-1 which cannot be directly linked to the estimated performance via Methane Collection Efficiency reported in section 7.4.

- **Measured methane flux per tonne of waste in place (kg/hour per tonne waste)**
  The rate of methane production and release is linked to the amount of waste in place, so this is in principle a more attractive metric for describing site performance than the methane flux itself. However, measured methane flux also depends on other factors including the site age and type of waste. It would not be possible to distinguish the effects of site performance on methane flux per tonne of waste in place from these other factors. Because of this, the measured methane flux per tonne of waste in place would also not be a reliable metric of site performance in control of methane. To demonstrate the uncertainty associated with this potential metric, methane flux by waste deposition have

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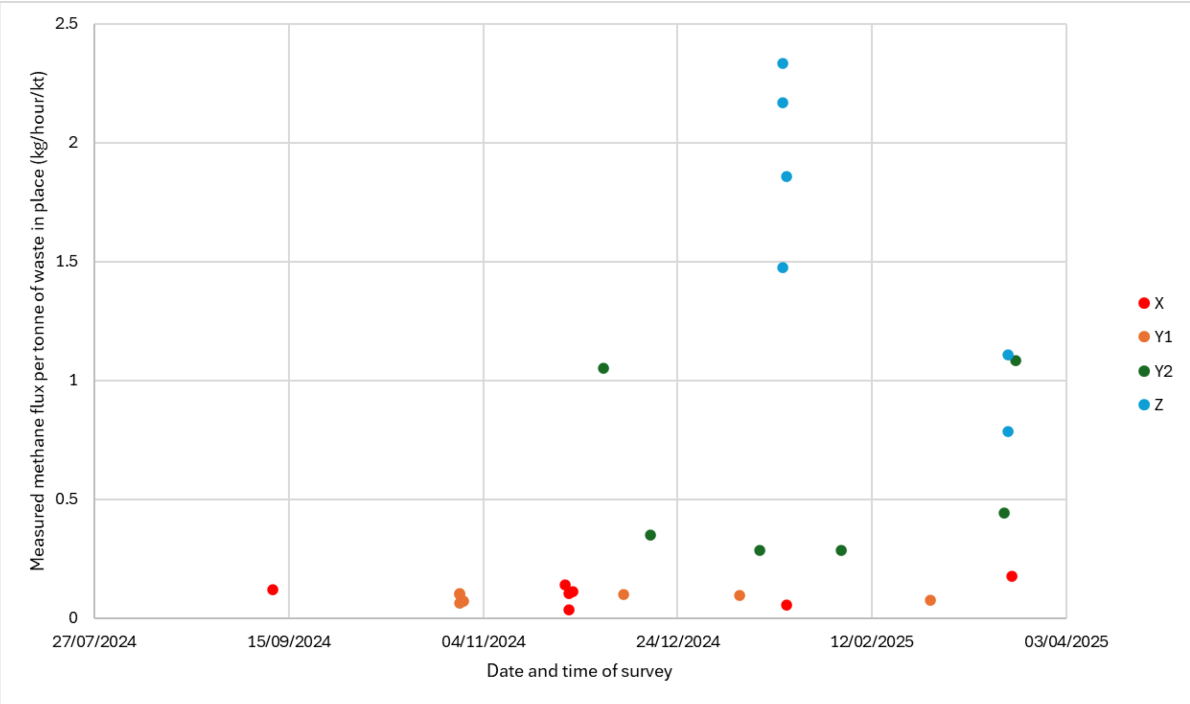
Abushammala, M.F.M., Ahmad Basri, N.E., Irwan, D., & Younes, M.K. (2014), *Methane Oxidation in Landfill Cover Soils: A Review*. Asian Journal of Atmospheric Environment, 8(1), pp. 1–14. Available from: http://dx.doi.org/10.5572/ajae.2014.8.1.001

been calculated and illustrated below (Figure 7.1Figure). This involved use of the average methane flux from each site in turn with average waste arisings per annum extracted from GasSim or other waste model equivalents (i.e the site Y1 model). Overall, Figure 7.1Figure shows the mapping results for this metric are scattered and inconsistent, making methane flux by amount of waste landfilled an unhelpful indicator.

Figure 7-1 Methane flux per tonne of waste in place, plotted against the date of survey



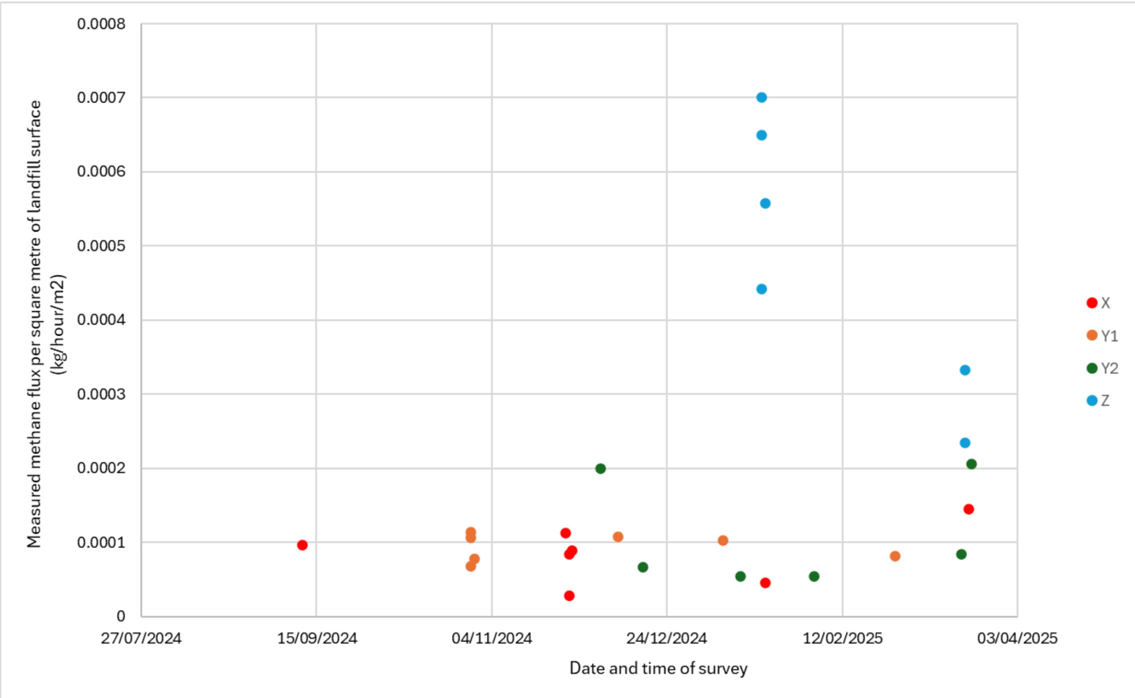
- **Measured methane flux per square metre of landfill surface (kg/hour per square metre)**
  The rate of methane production and release is linked to the area of the site to some extent. Methane can be released through the landfill surface, particularly through uncapped cells – principally the active tipping area, or inadequately capped areas of older sites. However, measured methane flux also depends on other factors including the site age, amount and type of waste in place. It would not be possible to distinguish the effects of site area on methane flux per tonne of waste in place from these other factors. At some sites, it may be difficult to effectively define the "site area" for the purpose of this calculation. For example, the measured methane flux may include older site areas which are not within the permitted area of the site.

  Furthermore, methane flux will vary greatly from one part of the site to another.

This variation would not be clearly reflected in an overall figure for methane flux per unit area of the site as a whole.

To demonstrate the uncertainty associated with this potential metric, methane flux by site area have been calculated and illustrated below (Figure 7-2)Figure .Figure This involved use of the average methane flux from each site in turn with permitted site area extracted from each site plan. Overall, Figure shows the mapping results for this metric are scattered and inconsistent, making methane flux by site area an unhelpful indicator.

Figure 7-2 Methane flux per square metre of landfill surface, plotted against the date of survey



- **Methane collection efficiency (dimensionless)**
  Methane collection efficiency is in principle the amount of methane collected by a landfill site divided by the total amount of methane produced at the site. This has been used in the past as a benchmark for site performance, but has always faced problems due to the difficulty of determining the total amount of methane produced and consequently the amount of methane emitted. This has in the past usually been calculated from a model such as GASSIM.

  The techniques deployed in this study now enable the total amount of methane produced at the site to be calculated as the sum of methane collected and measured methane flux. Some additional adjustments are needed to account for methane collected but not combusted ("methane slip") and to account for surface methane oxidation. However, this metric does enable site performance to be evaluated because it enables the variations between gas production at different sites to be accounted for when determining site performance.

7.3 Methane Collection Efficiency

Based on these considerations, a key metric for assessing performance of landfill sites is to determine the methane collection efficiency (MCE), which estimates the proportion of the total landfill methane that has been collected and burnt in engines or flares (Equation 2).

Equation 2 Methane Collection Efficiency (1)

$$MCE = \frac{Methane\ collected}{Methane\ collected\ +\ Site\ methane\ flux}$$

Comparing with Equation 1 highlights that this equation is based on the assumption that there is no significant change in storage of methane within the landfill during the survey period. We also assume that there is no significant lateral migration in a well-managed landfill site. As a result, methane formed in the landfill is either collected in the gas collection system, or released through the cover layers of the landfill site with oxidation of a proportion of the methane, and the remaining methane released to the atmosphere.

Calculations of whole-site methane flux from direct measurements are provided by the TDM and UAV mass balance surveys, while data on collected methane is provided by the operator (or gas sub-contractor) of the landfill, allowing MCE to be calculated for each survey conducted.

The portion of the methane produced by a landfill site which is oxidised in the landfills cover soil (where present) should also be considered when calculating the MCE. Surface methane oxidation is not routinely measured at landfill sites. A default factor of 10% methane oxidised in cover soils, provided in the IPCC Guidelines,[24] has been widely used and has been validated in the literature.[25] However, this value is highly uncertain (likely to

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[24] IPCC guidelines 2006 (Volume 5 Section 3.3)

[25] Innocenti, F et al (2012), '*Measurement Of Methane Emissions And Surface Methane Oxidation at Landfills: A Supplementary Survey*', available from https://www.environmental-expert.com/articles/measurements-of-methane-emissions-and-surface-methane-oxidation-at-landfills-wr1125-449702

vary by at least a factor of two) and depends on various factors, including the nature of the emission source, meteorological conditions, cell age, and capping material, and differs significantly between capped and operational areas. Methane oxidation is also highly seasonal and will fluctuate throughout the year in response to changes in soil moisture content and temperature[24]. In section 7.3.1 we discuss the impact of including a surface methane oxidation factor.

A portion of the methane collected may not be oxidised in the flare or engine. This is typically a small percentage of the methane combusted in landfill gas engines. Research carried out for the Environment Agency indicates that approximately 2% of methane passed through landfill gas engines may be released unburnt[26] – this is referred to as "methane slip." This is also not accounted for in the above MCE calculation, and the implication of this is considered in the subsequent sections.

It is important to note that methane slip refers specifically to non-combusted methane emitted from the engines and does not account for pipework leaks in the gas collection network. If gas escapes the network upstream of the metering point, these methane emissions will be captured in the methane flux and surface oxidation estimates. However, if gas escapes the system downstream of the metering point, this will be measured in both the metered methane and the methane flux if captured by the measurement method, leading to a potential double count in the collection efficiency.

7.3.1 Inclusion of surface methane oxidation

Including surface methane oxidation would result in a revision to the methane collection efficiency calculation as follows.

Equation 3 Methane Collection Efficiency (accounting for surface methane oxidation)

$$MCE = \frac{Methane\ collected}{Methane\ collected\ +\ Methane\ surface\ oxidation + Site\ methane\ flux}$$

This would reduce the calculated methane collection efficiency at all sites. For a site with a methane collection efficiency of around 75%, assuming that 10% of methane is oxidised in the landfill surface would reduce the calculated MCE by about 2 percentage points (e.g. from 75% to 73%).

[26] Ricardo for Environment Agency (2025), 'Methane slip report'

7.3.2 Inclusion of methane slip

Including methane slip would result in a revision to the methane collection efficiency calculation as follows (assuming that methane slip is captured in the measurement of site methane flux).

Methane collected is the sum of the methane combusted and the engine slippage.

Equation 4 Methane collected

$$Methane\ collected = \ Methane\ Combusted + Methane\ Slippage$$

The potential double count would then be accounted for in the methane collection efficiency calculation.

Equation 5 Methane Collection Efficiency (accounting for surface methane slippage)

$$MCE = \frac{Methane\ collected}{Methane\ collected + \ Site\ methane\ flux - Methane\ slippage}$$

Inclusion of this assumption would reduce the calculated methane collection efficiency at all sites. For a site with a methane collection efficiency of around 75%, assuming that 2% of methane collected is released without combustion would reduce the calculated MCE by about 0.5 percentage points (e.g. from 75% to 74.5%).

7.3.3 Inclusion of surface methane oxidation & methane slip

Combing the two effects presented previously the overall equation for calculating methane collection efficiency is given in Equation 6.

Equation 6 Methane Collection Efficiency (accounting for surface methane oxidation & methane slip)

$$MCE = \frac{Methane\ collected}{Methane\ collected\ + \ Methane\ surface\ oxidation - Methane\ slip + \ Site\ methane\ flux}$$

The methane collection efficiency results presented in the subsequent section include standard assumptions on the amount of methane slip and surface methane oxidation, following the methodology presented in Equation 6.

7.3.4 Uncertainty in the methane collection efficiency

Uncertainties in the calculation of methane collection efficiency arise from the following sources:

1. Uncertainties in metered landfill gas flow rate. This uncertainty is typically relatively small – for example, one typical supplier quotes an uncertainty of up to 2% reading, and up to 0.5% full scale.[27]
2. Uncertainty or variability in landfill methane content. This uncertainty is typically small for individual landfills, particularly where engines are being run to generate revenue. Variation between sites is likely to be greater, but data for a specific landfill site should be available to within a small uncertainty (c. 1% or better). The uncertainty in methane content data is likely to be larger where there is more flaring.
3. Uncertainties in the measured methane flux using TDM or UAV mass balance methods. These uncertainties are described in the results set out above and are typically in the range ±10% to ±40%. These uncertainties are the principal contribution to uncertainties in the calculation of MCE.

The overall uncertainty will be dependent on the balance between methane collection and methane released to the atmosphere. For a site with approximately 75% MCE, the uncertainty in this figure is likely to be of the order of a quarter of the percentage uncertainty in the measured methane flux. That is, if the measured methane flux has an uncertainty of ±40%, the calculated MCE would have an uncertainty of ±10% (i.e. 75% ± 7.5%).

The uncertainties presented are calculated as two standard deviations of the average methane collection efficiency (MCE) values for each survey. These values account for the variability in measurements derived from individual transects for the Tracer Dispersion Method (TDM) and from individual flights for the Unmanned Aerial Vehicle (UAV) method. This approach corresponds to a 95% confidence interval, assuming a normal distribution of the measurement data and assuming that uncertainties in the measurement process make a smaller contribution to overall uncertainty than the variability in individual survey results. The estimated uncertainty from this method was determined to be generally higher than uncertainty calculated via propagation using the quadrature method for each variable in the MCE calculation (Equation 6), and so was chosen as a more conservative estimate of the overall uncertainty.

[27] https://www.fluidcomponents.com/products/mass-flow-meters/st-series-flow-meters/st51-mass-flow-meter

The MCE calculation for each individual transect or flight is described in Equation 7. The average MCE is then calculated as the mean of these values. The uncertainty is the average MCE is therefore calculated as:

Equation 7 Uncertainty in average MCE

$$MCE\ Uncertainty = 2\sigma$$

Where,

Equation 8 Standard deviation in average MCE

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}$$

σ – population standard deviation
N – number of individual flights or transects in average MCE
x_i – Calculated MCE for each individual transect or flight
μ – Mean MCE

7.4 Measured methane collection efficiencies

This section presents calculated methane collection efficiencies (MCEs). The calculated MCE values include an allowance for surface methane oxidation (estimated to be 10% of methane not collected) and methane slippage methane slippage (estimated to be 2% of methane collected).

Table 7-1: Site X Methane Collection Efficiency

Survey Type	Survey No	Date	Start Time	End Time	Survey Methane Flux (kg/h)	Metered Methane Collected (kg/h)	Total Estimated Methane Production (kg/h)[1]	Methane Collection Efficiency (%)[2]
TDM	1	11/09/24	20:17	21:28	71	865	926	93 ± 2%
TDM	2	25/11/24	14:48	16:01	83	882	955	92 ± 3%
TDM	3	26/11/24	07:33	09:17	62	875	925	95 ± 2%

Survey Type	Survey No	Date	Start Time	End Time	Survey Methane Flux (kg/h)	Metered Methane Collected (kg/h)	Total Estimated Methane Production (kg/h)[1]	Methane Collection Efficiency (%)[2]
UAV mass balance	4	26/11/24	12:11	15:55	21	870	876	99 ± 1%
UAV mass balance	5	27/11/24	13:15	14:53	66	908	963	94 ± 5%
TDM	6	21/01/25	19:38	21:31	34	765	787	97 ± 4%
TDM	7	20/03/25	18:42	21:05	107	733	836	88 ± 5%

[1]Including surface oxidation and methane slippage assumptions.

[2] Uncertainty calculated as 2 standard deviations of the individual measurements for each survey, equivalent to 95th percentile confidence interval for a normally distributed set of measurements

The methane collection efficiency results from the 7 surveys at Site X shows effective operation of the gas management system, with calculated collection efficiencies ranging from 88-99%. Total estimated methane production ranged from 787 ± 12 to 963 ± 55 kg/h, indicating relatively consistent methane generation throughout the survey period. Notably, lower methane collection during Survey 6 corresponded with low methane flux, whereas similar collection levels in Survey 7 occurred alongside relatively high methane flux. Collection efficiencies were particularly high in Survey 4 (UAV mass balance, 99%) and Survey 6 (TDM, 97%), suggesting optimal capture during those periods. These values are significantly higher than expected and may reflect overestimation due to standard assumptions regarding methane slippage and oxidation. This may be in part due to underestimation of the methane flux from the UAV mass balance approach, which would lead to higher MCEs However, collection efficiency remains high for TDM. The lowest collection efficiency in Survey 7 (88%) still shows strong overall performance. Overall, both TDM and UAV mass balance methods demonstrated reliable performance with low variability, and contemporaneous results from 26th November showed good agreement, though not within the calculated uncertainty.

Table 7-2: Site Y1 Methane Collection Efficiency

Survey Type	Survey no	Date	Start Time	End Time	Survey Methane Flux (kg/h)	Metered Methane Collected (kg/h)	Total Estimated Methane Production (kg/h)[1]	Methane Collection Efficiency (%)[2]
UAV mass balance	1	29/10/24	13:12	16:00	60	302	362	84 ± 13%
TDM	2	29/10/24	15:51	17:46	100	302	407	74 ± 7%
TDM	3	29/10/24	21:57	23:07	94	304	402	76 ± 6%
UAV mass balance	4	30/10/24	10:47	11:41	68	304	372	82 ± 6%
TDM	5	10/12/24	19:44	21:11	95	314	413	76 ± 6%
TDM	6	09/01/25	19:44	21:13	90	290	384	76 ± 5%
TDM	7	27/02/25	20:22	22:25	72	252	327	77 ± 6%

[1]Including surface oxidation and methane slippage assumptions.

[2] Uncertainty calculated as 2 standard deviations of the individual measurements for each survey, equivalent to 95th percentile confidence interval for a normally distributed set of measurements

The methane collection efficiency results from the seven surveys at Site Y1 show more variable performance compared to Site X. However, all collection efficiencies agree within the estimated uncertainties, indicating consistent system performance over the dates surveyed across the survey period. Methane collection rates also appear relatively stable across the surveys, suggesting steady operational conditions, except during the survey 7 where methane collection is lower. The TDM and UAV mass balance surveys conducted on the 29th and 30th of October produced comparable results within their respective uncertainties, demonstrating that both techniques can yield consistent outcomes; despite potential under bias in the UAV mass balance approach. For the UAV mass balance surveys conducted on the 29th October there was greater variability between individual survey measurements on that day, possibly related to on-site activities, changes in meteorological conditions or measurement issues, leading to higher estimated uncertainty in the average MCE. Overall, the results suggest a reasonably effective gas collection system although performance is generally below sites X and Y2.

Table 7-3: Site Y2 Methane Collection Efficiency

Survey Type	Survey no	Date	Start Time	End Time	Survey Methane Flux (kg/h)	Metered Methane Collected (kg/h)	Total Estimated Methane Production (kg/h)[1]	Methane Collection Efficiency (%)[2]
TDM	1	05/12/24	07:18	08:40	126	447	577	78 ± 6%
TDM	2	17/12/24	13:05	14:48	42	169	212	80 ± 7%
TDM	3	14/01/25	13:53	15:37	34	212	246	86 ± 3%
TDM	4	04/02/25	06:28	08:22	34	449	477	94 ± 1%
TDM	5	18/03/25	17:35	19:25	53	394	444	89 ± 6%
TDM	6	21/03/25	10:38	12:36	130	396	533	74 ± 6%

[1]Including surface oxidation and methane slippage assumptions.

[2] Uncertainty calculated as 2 standard deviations of the individual measurements for each survey, equivalent to 95th percentile confidence interval for a normally distributed set of measurements

All surveys at Site Y2 were conducted using TDM, providing a consistent basis for comparison. The methane collection efficiency results from the 6 surveys at Site Y2 indicate a range of performance, from 74% to 94%.

Surveys 2 and 3 recorded lower gas collection and correspondingly low methane fluxes, suggesting that more methane may have been temporarily retained within the landfill site.

Further analysis of the site data shows that gas extraction appears to be low for the days preceding and during survey 2, with only one gas engine in operation. A second gas engine began extracting around 14:00 on the 18/12/25 with gas extraction returning to expected levels by 15:00. The reason for operating only one engine during this period is unclear, as the site operator did not report any issues. However, the data suggests that the gas field was being managed to match the extraction rate to the capacity of a single engine. It is also possible that the gas extraction system was being managed to respond to meteorological conditions. Atmospheric pressure data shows a sustained period of high pressure (1020-1040 hpa) from the 9th to 17th December. It has been suggested that periods of high or increasing atmospheric pressure reduce diffusion of gas out of a landfill[28], possibly resulting in landfill gas being compressed further into the landfill where extraction is more difficult. Gas extraction then increased on 18th December when a second engine became operational, suggesting that the level of extraction was managed based on engine capacity. As gas extraction at the site increased, atmospheric pressure decreased to below 1010 hpa.

During survey 3 the gas extraction level and methane flux also appear to be dependent on the operation of the gas extraction system. Gas extraction at the site drops significantly from 12:00 on 13th January, coinciding with the flare going offline. From that point, only one engine is used for extraction until 20:00 on 14th January when the flare resumes operation and extraction increases. The reasons behind these changes in the operation of the gas management system are unclear. No significant issues were reported by the operator, although the operator suggested there could have been issues with the flare, preventing it from operating. It is not possible to determine whether meteorological factors had an impact on the gas management system, but it is worth noting that there was a significant increase in atmospheric pressure leading up to the survey, from 970 hpa on 6th Jan to 1040 hpa on the 13th January, which could have had an effect.

Fluxes measured during surveys 1 and 6 were significantly higher than in the other four surveys. Analysis of the gas extraction data shows that abnormal operation of the gas extraction system was occurring during these surveys. During survey 1, both gas engines and a flare were in operation, while during survey 6 a single engine was in operation with the flare. The results seem to suggest that higher fluxes coincide with operation of the flare, although it is not clear whether operation of the flare directly caused higher fluxes at the site. Generally, a flare would be expected to have a higher combustion efficiency than

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[28] Xu, L. et al. (2014), 'Impact of Changes in Barometric Pressure on Landfill Methane Emission', *Global Biogeochemical Cycles*, 28(7), pp. 679–695. Available from https://doi.org/10.1002/2013GB004571

a gas engine as they are optimised for complete combustion rather than power production. It may therefore be the case that there are other factors causing operation of the flare to coincide with higher fluxes.

Surveys 4 and 5 were the only surveys conducted under normal operating conditions, and these surveys demonstrated the highest performance, achieving 89-94% MCE. This demonstrates the influence of operation of the gas extraction system on site performance and the site's ability to achieve high performance under normal operating conditions. The robustness of the methodology is further supported by its ability to capture the impact of gas extraction system operation on the results.

It is worth noting that surveys 5 and 6 took place after the cessation of waste receipts and the completion of a temporary cap on the operational area, however there was no obvious improvement in methane collection efficiency or fluxes. This suggests that operation of the gas extraction system has a greater impact on the methane collection efficiency than cessation of waste receipts.

As previously discussed, methane production estimates ranged from 212 to 577 kg/h, showing a broader range than observed at other sites. Despite this variability, the system appears to operate relatively consistently, with no extreme outliers in performance. It is unclear whether the gas extraction system can adapt to changing landfill gas release rates without a drop in performance, or if the snapshots provided by surveys simply missed periods of higher emissions that may be expected to follow low extraction.

Table 7-4: Site Z Methane Collection Efficiency

Survey Type	Survey no	Date	Start Time	End Time	Survey Methane Flux (kg/h)	Metered Methane Collected (kg/h)	Total Estimated Methane Production (kg/h)[1]	Methane Collection Efficiency (%)[2]
TDM	1	20/01/25	13:08	15:55	280	320	625	52 ± 10%
UAV mass balance	2	20/01/25	13:10	15:09	177	321	511	63 ± 5%
TDM	3	20/01/25	19:36	21:17	260	321	603	53 ± 8%

Survey Type	Survey no	Date	Start Time	End Time	Survey Methane Flux (kg/h)	Metered Methane Collected (kg/h)	Total Estimated Methane Production (kg/h)[1]	Methane Collection Efficiency (%)[2]
UAV mass balance	4	21/01/25	11:17	14:14	223	319	560	58 ± 24%
TDM	5	19/03/25	17:44	19:35	133	435	575	76 ± 11%
TDM	6	19/03/25	22:59	01:01	94	440	536	82 ± 5%

[1]Including surface oxidation and methane slippage assumptions.

[2] Uncertainty calculated as 2 standard deviations of the individual measurements for each survey, equivalent to 95th percentile confidence interval for a normally distributed set of measurements

At site Z fewer surveys were conducted compared to other sites and over a shorter period due to the logistical constraints within the project. The estimated methane collection efficiencies show a wide range of performance across the survey period, which can be divided into two distinct phases: 20th-21st January and 19th-20th March. In the first phase the methane collection efficiency was lower (53-63%), while the methane flux was higher (177-280 kg/hr), with the total methane production staying relatively stable across both periods. By the second phase, the gas collection system appears to have recovered, with methane collection efficiencies increasing to around 80% showing a significant improvement in performance.

These observations could be explained by the impact of cold weather on the gas management operations at the site. The operator reported that in January 2025, severe cold weather led to condensate separator failures and freezing of leachate discharge pipework, significantly disrupting gas collection operations. As a result, the extraction system was not fully operational and extraction was reduced which can be seen in the gas collection data provided by the operator. The results suggest that lower extraction rates led to an increase in methane flux escaping from the landfill, as total methane production remained comparable to levels observed in the March 2025 surveys.

By March 2025, the operator reported gas collection became more consistent with expected levels, and an improvement in the collection efficiency can be observed. The results clearly show the reduced effectiveness of the collection system which is backed up by testimony from the operator. This gives confidence in robustness of measurement techniques as they are able to reflect changes in gas extraction at the site.

The calculated collection efficiencies across 20th and 21st January from both TDM and UAV mass balance all agree within the calculated uncertainties, despite potential under bias in the UAV mass balance approach. The calculated uncertainties are relatively high.

Figure 7-3 Methane Collection Efficiency (MCE) values over time for the four landfill sites: Site X, Site Y1, Site Y2, and Site Z. Each method TDM (open circles) and UAV mass balance

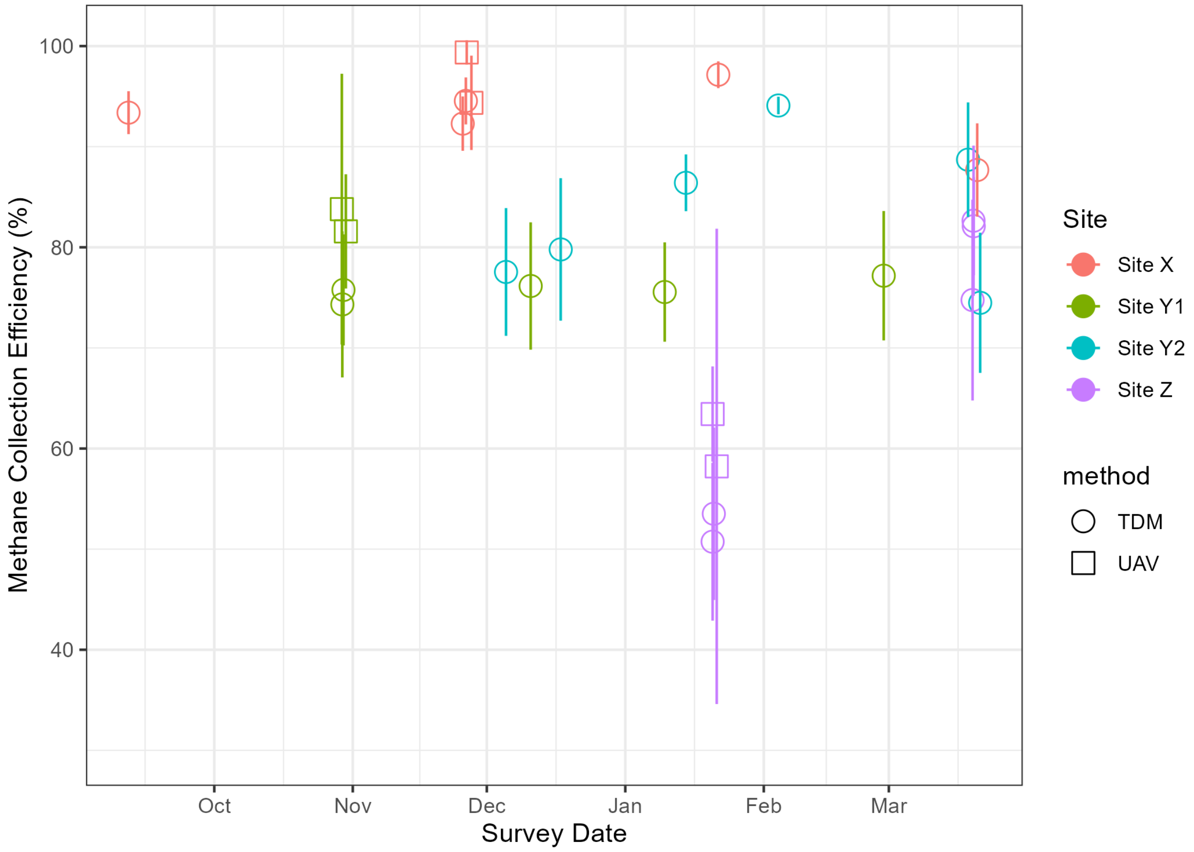

Figure 7-3 compares the calculated Methane Collection Efficiencies (MCEs) across the four landfill sites. Site X consistently demonstrated the highest MCEs, indicating effective gas collection performance. Both Site X and Site Y1 showed relatively consistent results across the survey period, suggesting minimal disruption to their gas extraction systems during the surveys.

In contrast, Sites Y2 and Z exhibited a greater range in MCEs across surveys. For Site Z, the differences can be attributed to the disruption of the gas extraction system during the

January surveys, coinciding with severe cold weather. At Site Y2, the observed differences in MCEs can also be directly linked to changes in the gas extraction system, which may also be influenced by meteorological conditions at the site.

Section 8 provides a more detailed discussion of the factors affecting methane emissions.

7.5 Methane storage

The sum of the measured methane collection rate and the contemporaneous methane flux measurement can be taken to be a measure of the methane generated plus or minus the change in storage. Averaging this sum from every survey across the entire survey period would give a figure that could be a reasonable estimate of the methane generation rate at that landfill (neglecting methane oxidation), provided site operation is consistent across that period. This appears to be the case for Site X, Site Y1 and Site Z.

Site Y2 exhibited significant differences in the sum of collection rate and flux between Surveys 1, 4, 5 and 6, and Surveys 2 and 3. These two periods were treated separately. Analysis of the influence of meteorological conditions on methane storage and flux at Site Y2 was limited to Surveys 1, 4, 5 and 6. Surveys 2 and 3 were not evaluated because there were relatively few measurements in these two surveys, resulting in greater uncertainty in this analysis. There are also greater uncertainties in the conceptual model for methane formation, storage and release during these periods as the model indicates an unexpectedly high flow of methane into storage. A summary of the methane collection rate plus methane flux is shown in Table 7-5.

Table 7-5: Methane balance

Site	Average methane collection rate plus methane flux across all surveys
Site X	888 ± 25 kg/hour
Site Y1	377 ± 19 kg/hour
Site Y2 Surveys 1, 4, 5 and 6	509 ± 23 kg/hour
Site Y2 Surveys 2 and 3	231 ± 10 kg/hour
Site Z	671 ± 44 kg/hour

Subtracting these average values from the measured values enables us to evaluate the change in storage of methane in the landfill over time for the duration of the project.

The correlation between methane storage and weather conditions during the survey periods was evaluated using a multivariate correlation approach. The weather conditions recorded during each survey were tabulated alongside the calculated difference in methane storage compared to the average value. The aim of this was to determine if weather conditions were significantly correlated with changes in methane storage. The significance of each weather condition in determining the calculated change in methane storage (assuming a causal relationship exists) was determined as follows:

(a) Obtain the correlation coefficient of each meteorological parameter with the calculated change in methane storage (value A in the tables below)
(b) Calculate the standard deviation of each meteorological parameter as an indication of the variation of each parameter (value B in the tables below)
(c) Multiply A by B to give an indication of how much changes in each meteorological parameter affect the calculated change in methane storage.

This approach was adopted to enable a focus on parameters which are important in determining calculated methane storage. For example, some meteorological values have a relatively high numerical value (e.g. atmospheric pressure) but vary to a much more limited extent around these higher values. Considering the product of correlation coefficient and standard deviation enables the influence of each parameter to be understood.

The findings of this multivariate analysis are summarised in the Table 7-6.

Table 7-6: Correlation between methane storage change and weather conditions

Site	Correlation coefficient	Temperature (ºC)	Temperature gradient (ºC/day)
		A × B	A × B
Site X	89%	18.1	-32.6

Site	Correlation coefficient	Temperature (ºC)	Temperature gradient (ºC/day)
		A × B	A × B
Site Y1	79%	18.0	15.8
Site Y2 (1,4,5,6)	88%	11.2	14.7
Site Z	25%	29.0	-30.8

Note: A: Coefficient B: Standard Deviation

Site	Air pressure (kPa)	24 hour air pressure gradient (kPa/hour)	Rainfall in past 24 hours (mm)
A	A	A	A x B
0.2	195.5	86.3	40.0

Site	Air pressure (kPa)	24 hour air pressure gradient (kPa/hour)	Rainfall in past 24 hours (mm)
3.6	242.1	-516.1	-50.1
-2.0	-106.2	n/a	n/a
-1.8	-758.5	-336.3	-12.5

Note: A: Coefficient B: Standard Deviation n/a: Not applicable (no rainfall occurred)

Higher temperature appears to be consistently associated with higher than average methane storage. The pattern is less consistent for other parameters. A positive air pressure gradient was found to be associated with higher than average methane storage at Sites X and Y1, but lower than average methane storage at Sites Y2 and Z (although the correlation at Site Z was low).

8 Assessment of factors affecting methane emissions

8.1 Approach to identifying key influences on methane emissions

The data collated from each of the surveys undertaken, alongside the operational data provided by each of the operators was used to identify whether there is any correlational relationship between data variables (e.g. atmospheric pressure, ground temperature, operational conditions) and the measured methane flux or the calculated methane efficiency.

Methane flux was selected as a key component for the analysis as understanding how emission rates are likely to be influenced by other factors will provide greater understanding of how survey results can be interpretated. However, for the reasons set out in section 7, methane flux cannot readily be compared between sites because of differences resulting from factors including the quantity, type and age of waste, historical landfill practices, and the extent of installed controls. In contrast, methane collection efficiency (MCE) is designed to be readily compared between sites. We have therefore evaluated the influence of potentially relevant factors on methane flux at individual sites, and also the influence of these factors across all sites to identify any potentially observable correlations.

A multi linear correlation analysis was carried out in each case, to identify the extent to which each factor was correlated with methane flux and MCE. It was inherently assumed that if any correlation exists, it can be represented as a linear correlation within the range of values observed in each survey.

As with the evaluation of methane storage, the potential contribution of each observed factor (weather conditions and operational factors) to the calculated methane flux and MCE for each survey period was evaluated using a multivariate correlation approach. The weather conditions and site operational factors recorded during each survey were tabulated alongside the calculated methane flux and MCE. The aim of this was to determine if the observed factors were significantly correlated with changes in methane flux and MCE. The significance of each observed factor in determining the calculated change in methane flux or MCE (assuming a causal relationship exists) was determined as follows:

(a) Obtain the correlation coefficient of each observed factor with the calculated methane flux or MCE (value A in the tables below)

(b) Calculate the standard deviation of each observed factor as an indication of the variation of each parameter (value B in the tables below)
(c) Multiply A by B to give an indication of how much changes in each observed factor affect the calculated change in methane flux or MCE.

This approach was adopted to enable a focus on parameters which are important in determining methane flux and MCE. For example, some meteorological values have a relatively high numerical value (e.g. atmospheric pressure) but vary to a much more limited extent around these higher values. Considering the product of correlation coefficient and standard deviation enables the influence of each parameter to be understood.

The factors considered were divided into environmental factors (i.e. past and current weather conditions) which were common to all sites, and operational factors which were identified separately for all sites and depended on the relevance of different factors to each site and the availability of information. Operational factors were modelled using a binary system of applying a factor of 0 or 1. For example, for Site X, a factor of 0 was applied for surveys when a temporary cap was not present, and a factor of 1 was applied for surveys when a temporary cap was present. The contribution of other operational factors such as operation of flares and engines were also assessed where possible.

Environmental factors:

- Air temperature at the time of the survey(^{o}C)
- Air temperature gradient for the preceding five days (^{o}C/day)
- Air pressure at the time of the survey (kPa)
- Air pressure gradient for the preceding 24 hours (kPa/hr)
- Rainfall during the survey (mm)
- Rainfall during the preceding 24 hours (mm)

Operational factors:

- Site X: Existence of temporary cap
- Site Y1: Tipping taking place
- Site Y2: Flare operating; issue with engines; tipping taking place; open tipping face
- Site Z: Tipping taking place; flaring taking place

8.2 Key findings from the analysis

Key findings from the analysis are provided below. Full details of the findings from the analysis are provided in Appendix 6.

8.2.1 Factors correlating with methane flux at individual sites

The multi-linear regression analysis identified that the 24-hour air pressure variable was the biggest influence on methane flux at three of the four sites. All sites also showed that air temperature was an important factor. At site Y2, the 24 hour trend in air pressure was shown to be significant but not the biggest factor. At this site, the five-day temperature gradient, and the presence of an open tipping face during the survey had the most significant effect on methane flux.

The influence of the 24-hour pressure gradient variable is consistent with observations highlighted by the research detailed in section 33. The analysis did not identify the underlying causes for this observation with the further review of the data finding that the relationship between methane flux and the 24-hour pressure gradient were mixed. (For example, the data shows that methane flux increased as the pressure gradient decreased at site Y2 whilst the reverse was seen at site Z.) While it would be possible to speculate about causes for these observations, there is not sufficient information to be confident about the reasons for these different observations. This includes the possibility that associations may not be causal, with other factors being responsible for the observed variation in methane flux.

8.2.2 Factors correlating with methane collection efficiency

The multi linear analysis undertaken to examine the relationship between the MCE found similar observations to those reported for the methane flux analysis with the 24-hour pressure gradient being identified as being an important factor at all sites.

The analysis also found that site operations had a significant effect on MCE. At Site Y2, the engine issues and open face/site open variables were found to have the largest impacts, whilst the temporary capping variable was shown to be a significant variable at site X.

8.2.3 Conclusions from the factor analysis

The factor analysis has highlighted that the 24-hour pressure gradient and air temperature were significant factors on both methane flux emissions and methane collection efficiency at all sites during the time of each survey. The data has shown that site management variables are important factors with consideration to MCE.

These observations provide useful indications, but are drawn from a small sample of landfill sites on a relatively small number of occasions. These insights should be considered when undertaking methane surveys from landfill sites as the data suggests that methane flux is linked to the pressure gradients experienced by the landfill, an observation which is supported by wider research. Future validation of these observations alongside better understanding of their causes could help to inform how to interpret collected methane measurements and reported methane collection efficiencies.

9 Potential approach to regulation using Methane Survey Methods

9.1 Implications for use of TDM and UAV mass balance methods

This section covers the implications of the study findings for survey accuracy and choice of survey method depending on conditions, and provide views on what may need to be taken into account in a regulatory context.

Section 6.6 indicates that UAV mass balance and TDM methods broadly agree within the one-standard-deviation bounds of each method, but that UAV mass balance fluxes are systematically under-biased relative to TDM flux in all cases. There are known reasons for UAV mass balance under-estimation, due to sampling/flight constraints (i.e. the potential for not capturing the full landfill plume and that of all onsite emissions sources).

There are also known reasons for over-bias of TDM fluxes, but only where an additional source may be directly upwind or between the emission being measured and the monitoring point. On balance, it is our conclusion that the UAV mass balance method is likely to suffer more often from a flux under-bias than it is for the TDM method to suffer from an over-bias. However, it is possible to identify what areas of the site may have been missed in the UAV mass balance approach based on an analysis of the fetch from the extreme bounds of the sampling (i.e. 4 corners of a sampling plane in the survey type employed in this work). Additionally, the TDM method may not be able to sample all on-site sources if they have different dispersion profiles to the tracer release – for example, methane slip from engines or flares.

Neither method is ideal in all circumstances and for all on-site source types, but this study demonstrates that, when properly implemented, the methods can and do agree within maximal one-sigma error and can therefore meaningfully deliver flux quantification within the uncertainty envelope calculated for either method. However, the nature and conditions of the survey and on-site sources (especially buoyant plumes from combustion sources) must be acknowledged when interpreting results in future survey work, with the caveat that there may be some sources or areas of the site not accounted for. In this work, a careful examination of the mapped data in conjunction with ambient winds helped to confirm this for the UAV mass balance method. Similar investigations would be best practice in future work to help diagnose if any sources may not have been sampled by either method.

It is possible to overcome some of these limitations by combining the approaches. For example, if TDM cannot sample lofted combusted plumes, UAVs may be targeted to those sources alone. If sources exist nearby and upwind of the target site, UAVs could also help to establish a background for TDM methods. And, as has been reported in Yong et al., 2024, and trialled by Scheutz et al., 2025,[29] a suite of instruments installed on a UAV that can measure a tracer gas and methane simultaneously, would allow the TDM and mass balance methods to be applied simultaneously to the same dataset, so long as the UAV could be flown sufficiently far downwind that the assumption of co-mixing of tracer and landfill plume can be satisfied. For example, in this study, UAV sampling along the landfill fenceline for mass balancing would not be suitable for the TDM method as the plume and tracer cannot be expected to have mixed well. Furthermore, UAV flying further from the site perimeter can add logistical challenges in terms of access and permissions. In summary, while a combination of the methods with UAV sampling could yield higher accuracy and reduce missed sources, the practicalities of conducting such a survey are challenging and not always possible.

We conclude that either method could be suitable for whole-site emissions quantification, so long as there is a thorough appraisal of what source(s) may, or may not, have been missed. This is an objective judgment that can be made by examining mapped survey data in conjunction with wind direction to assess whether plumes from areas of the site may be expected to have not been sampled. It is less straightforward (i.e. requires numerical modelling) to do this for buoyant (e.g. combusted) plumes in the case of the TDM method. Repeating surveys, using either method, under a different wind direction, may also help demonstrate whether any other source of methane has an influence on the measurements and flux determination. Both methods deliver an emission snapshot, that can be repeated as many times as necessary. e.g. 10 times per day for one day or for several days at a time, or on return visits. The cost clearly scales proportionately with the number of days in the field and the instrumentation used, while analysis costs reduce as methods and software mature (and have matured for many commercial providers). It would be impractical to sample every landfill on every day to capture all instances of operational change with either of these methods. But a regulatory approach could be implemented to assess how a collection system performs under normal operating conditions.

The purpose of monitoring here is to provide a measure as to the effectiveness of the gas collection system, whilst minimising the costs (on operators and the taxpayer) of monitoring. The metrics and indicators required for regulation need to be as simple and

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[29] Scheutz, C., Knudsen, J. E., Vechi, N. T., & Knudsen, J. (2025). '*Validation and demonstration of a drone-based method for quantifying fugitive methane emissions*'. Journal of Environmental Management, 373, 123467.

transparent as possible, with a good understanding of methodological uncertainty, and honest appraisal of survey-specific conditions (e.g. potential missed sources). It is the case that a single operator may be operating with reduced efficiency on a single day compared to the industry-average over a year. However, it is not possible to monitor ad infinitum. Instead, for example. it may be reasonable to survey a site (e.g. for one day, or for consecutive days per year) within defined criteria under normal operating conditions to demonstrate what performance the gas collection system can achieve when operating normally. This is a compromise between practicality of costs and detection of poor performance which can be shifted in the direction of need. We offer some thoughts below on how a monitoring regime may be meaningful from a regulatory perspective.

9.2 Framework for potential regulatory approach:

The results set out in this study demonstrates that TDM and UAV mass balance methane surveys could be used to provide a snapshot of gas management performance at a landfill site. While various meteorological and operational factors have been shown to influence methane collection efficiency, the evidence from this study shows that the design and effective operation of the gas management system is the dominant factor in determining the MCE at a site.

Therefore, deploying these survey techniques in a regulatory context can be used to assess the performance of gas management systems and encourage better gas management practices to reduce emissions. An approach to regulating methane emissions from landfill in England has previously been discussed in the literature (Bourn et al., 2018)[30], and this has informed the potential regulatory application of these techniques outlined below.

To provide a meaningful assessment of the effectiveness of a gas collection system at a site, while balancing costs to both operators and the Environment Agency, it is feasible that an annual survey requirement could be introduced as part of a future regulatory framework[30]. For such a survey to reliably reflect overall site performance, it would need to be conducted under ‘normal operational conditions’, as defined by long-term gas collection data specific to the site. Clear criteria on what constitutes normal operating conditions would need be provided within the regulatory guidance. Since a single survey provides

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[30] Bourn, M., Robinson, R., Innocenti, F., & Scheutz, C. (2018). ‘*Regulating landfills using measured methane emissions: An English perspective*’. Waste Management, 87, 860–869, https://doi.org/10.1016/j.wasman.2018.06.032

only a snapshot of site performance, this approach would remove the short-term impact from operational factors that impact gas collection and provide a more representative view of site performance. This would encourage adoption of better landfill gas management practices at underperforming sites, including improvements to operation and design of the gas collection system. The efficacy of these interventions could then be monitored through subsequent annual surveys.

A regulatory process would need to consider both operational and atmospheric conditions when determining whether a survey was conducted under normal conditions. This data would need to be submitted by operators alongside survey results and would be used as the basis for assessing regulatory outcomes. This is discussed in more detail in section 9.4.

Step 1 – Conduct methane measurement survey

Operators could be required to conduct an annual methane survey at their sites to estimate methane flux using a regulatory-approved methodology. The chosen method may be determined by site-suitability.

Step 2 – Calculate methane collection efficiency as a metric of landfill performance

Operators could be required to submit gas collection data, both long-term and at the time of the surveys, both to estimate the Methane Collection Efficiency (MCE) and determine whether surveys are conducted under normal operating conditions.

Step 3 – Assess landfill site against benchmark for performance

Site performance could then be assessed against a benchmark for performance which would determine the regulatory outcome. This benchmark could be determined by collecting survey results under the regulation. An example of potential regulatory outcomes is given in Table 9-1 below.

Table 9-1: Potential regulatory outcomes (Step 3)

Assessment against performance benchmark	Regulatory Outcome
Above the regulatory benchmark (even when accounting for uncertainty)	No regulatory action required
Approaching benchmark (Benchmark falls within calculated uncertainty of MCE)	No regulatory action required.

Assessment against performance benchmark	Regulatory Outcome
Below regulatory benchmark (even when accounting for uncertainty)	Regulatory action required. Operator will need to demonstrate interventions to improve gas management at the site, which could be monitored through subsequent surveys.

It is important to consider the uncertainty associated with the MCE calculated from a survey when assessing performance in a regulatory context. Doing so ensures that any regulatory action taken is reasonable, fair and credible. To maintain consistency, any regulatory approach would need to standardise how uncertainty is estimated. This study reports an approach based on the 95% confidence interval, as it was found to be more conservative than alternative methods (see section 7.3.4 for further discussion).

Where an MCE plus its estimated uncertainty meets the regulatory benchmark, it should be considered compliant, as the result cannot be reliably determined to be below the benchmark. This approach is consistent with other regulatory practices for accounting for uncertainty in emissions monitoring. For example, Environment Agency guidance on assessing compliance of stack emissions with an emission limit value (ELV) uses the concept of 'approach to a limit', whereby a measured value is considered compliant if the value minus its associated uncertainty falls below the ELV[31]. For the context of MCEs at landfill sites, the process is slightly different because a MCE is a minimum standard which should be exceeded, whereas ELVs are specified as maximum limits which should not be exceeded. A comparable approach would be that a MCE is considered as 'approaching the benchmark' if the benchmark is within the calculated uncertainty range of the MCE.

Consequently, any regulatory framework would need to tightly constrain the estimation of uncertainty from a survey method. This could be achieved by specifying minimum uncertainty requirements within regulatory guidance and requiring surveys to be repeated if those standards are not met.

[31] 'Monitoring stack emissions: maximum uncertainty values for periodic monitoring', 2021, available from: https://www.gov.uk/guidance/monitoring-stack-emissions-maximum-uncertainty-values-for-periodic-monitoring#ELV-compliance

Operators should be required to submit supporting information, such as operation of engines/flares, changes to the gas management system and meteorological conditions happening during the survey, to ensure that results are representative of the site under normal operating conditions. Information on the gas management system in operation at a site could also form the basis of recommendations or regulatory requirements to the site.

9.3 Example regulatory process based on survey results

Table 9-2 to Table 9-5 give an example of how a potential regulatory process could have been applied for each survey result conducted in this study. This is provided to indicate the range of potential outcomes, and the representativeness of findings, if the surveys carried out had been for regulatory application. In this example we have used **85%** collection efficiency as an indicative regulatory benchmark for site performance (this aligns with the ESA Net Zero target, see section 10.1). Each survey result is treated as an individual annual survey and is considered as 'approaching the benchmark' if the 85% benchmark is within the calculated uncertainty range of the MCE.

Table 9-2: Example regulatory outcomes at Site X

Survey Type	Survey No	Date	MCE (%)	MCE upper range value (%)	MCE lower range value (%)	Assessment of site performance	Survey conducted under normal operation	Regulatory outcome	Comment on survey representativeness of site performance
TDM	1	11/09/24	93 ± 2%	95%	91%	Above 85 % benchmark	Yes	No regulatory action required	Survey appears to accurately represent site performance.
TDM	2	25/11/24	92 ± 3%	95%	89%	Above 85 % benchmark	Yes	No regulatory action required	Survey appears to accurately represent site performance.
TDM	3	26/11/24	95 ± 2%	97%	93%	Above 85 % benchmark	Yes	No regulatory action required	Survey appears to accurately represent site performance.
UAV mass balance	4	26/11/24	99 ± 2%	100%	97%	Above 85 % benchmark	Yes	No regulatory action required	Survey appears to accurately represent site performance. Possible under-bias in UAV fluxes and so over-bias in MCE should be considered.

Survey Type	Survey No	Date	MCE (%)	MCE upper range value (%)	MCE lower range value (%)	Assessment of site performance	Survey conducted under normal operation	Regulatory outcome	Comment on survey representativeness of site performance
UAV mass balance	5	27/11/24	94 ± 1%	95%	93%	Above 85 % benchmark	Yes	No regulatory action required	Survey appears to accurately represent site performance. Possible under-bias in UAV fluxes and so over-bias in MCE should be considered.
TDM	6	21/01/25	97 ± 4%	100%	93%	Above 85 % benchmark	Yes	No regulatory action required	Survey appears to accurately represent site performance.
TDM	7	20/03/25	88 ± 5%	93%	83%	Approaching benchmark	Yes	No regulatory action required.	Survey appears to accurately represent site performance.

Table 9-3: Example regulatory outcomes at Site Y1

Survey Type	**Survey No**	**Date**	**MCE (%)**	MCE upper limit (%)	MCE lower limit (%)	**Assessment of site performance**	**Survey conducted under normal operation**	**Regulatory outcome**	**Comment on survey representativeness of site performance**
UAV mass balance	1	29/10/24	84 ± 13%	97%	71%	Approaching benchmark	Yes	No regulatory action required. Uncertainty in MCE may be above regulatory standard. Efforts should be made to reduce uncertainty.	Of the three surveys conducted on 29th October, the UAV mass balance survey would provide a different regulatory outcome based on an 85% benchmark than either of the TDM surveys, despite agreeing within the estimated uncertainty. This could be related to possible systematic under bias of the UAV mass balance approach previously discussed. High uncertainty in the MCE also makes assessment of

Survey Type	Survey No	Date	MCE (%)	MCE upper limit (%)	MCE lower limit (%)	Assessment of site performance	Survey conducted under normal operation	Regulatory outcome	Comment on survey representativeness of site performance
									performance difficult.
TDM	2	29/10/24	74 ± 7%	81%	67%	Below regulatory benchmark	Yes	Regulatory action required. Operator will need to demonstrate interventions to improve gas management at the site, which would be monitored through subsequent surveys.	Of the three surveys conducted on 29th October, the UAV mass balance survey would provide a different regulatory outcome based on an 85% benchmark than either of the TDM surveys, despite agreeing within the estimated uncertainty. This could be related to possible systematic under bias of the UAV mass balance approach previously discussed.

Survey Type	Survey No	Date	MCE (%)	MCE upper limit (%)	MCE lower limit (%)	Assessment of site performance	Survey conducted under normal operation	Regulatory outcome	Comment on survey representativeness of site performance
TDM	3	29/10/24	76 ± 6%	82%	70%	Below regulatory benchmark	Yes	Regulatory action required. Operator will need to demonstrate interventions to improve gas management at the site, which will be monitored through subsequent surveys.	Of the three surveys conducted on 29th October, the UAV mass balance survey would provide a different regulatory outcome based on an 85% benchmark than either of the TDM surveys, despite agreeing within the estimated uncertainty. This could be related to possible systematic under bias of the UAV mass balance approach previously discussed.
UAV mass balance	4	30/10/24	82 ± 4%	86%	78%	Approach to a limit	Yes	No regulatory action required. Operator should be	Survey result in agreement with results from previous day,

Survey Type	Survey No	Date	MCE (%)	MCE upper limit (%)	MCE lower limit (%)	Assessment of site performance	Survey conducted under normal operation	Regulatory outcome	Comment on survey representativeness of site performance
								provided with best practice guidance on how to achieve higher performance.	however, a different regulatory outcome would be reached when comparing to the TDM surveys. This could be related to possible systematic under bias of the UAV mass balance approach previously discussed.
TDM	5	10/12/24	76 ± 6%	82%	70%	Below regulatory benchmark	Yes	Regulatory action required. Operator will need to demonstrate interventions to improve gas management at the site, which will be monitored through	Survey appears to accurately represent site performance.

Survey Type	**Survey No**	**Date**	**MCE (%)**	MCE upper limit (%)	MCE lower limit (%)	**Assessment of site performance**	**Survey conducted under normal operation**	**Regulatory outcome**	**Comment on survey representativeness of site performance**
								subsequent surveys.	
TDM	6	09/01/25	76 ± 5%	81%	71%	Below regulatory benchmark	Yes, gas data shows reduced extraction prior to survey but is stabilised by the time of the survey.	Regulatory action required. Operator will need to demonstrate interventions to improve gas management at the site, which will be monitored through subsequent surveys.	Survey appears to accurately represent site performance.
TDM	7	27/02/25	77 ± 6%	71%	83%	Below regulatory benchmark	Yes	Regulatory action required. Operator will need to demonstrate interventions to improve gas management at	Survey appears to accurately represent site performance.

Survey Type	Survey No	Date	MCE (%)	MCE upper limit (%)	MCE lower limit (%)	Assessment of site performance	Survey conducted under normal operation	Regulatory outcome	Comment on survey representativeness of site performance
								the site, which will be monitored through subsequent surveys.	

Table 9-4: Example regulatory outcomes at Site Y2

Survey Type	Survey No	Date	MCE (%)	MCE upper limit (%)	MCE lower limit (%)	Assessment of site performance	Survey conducted under normal operation	Regulatory outcome	Comment on survey representativeness of site performance
TDM	1	05/12/24	78 ± 6%	72%	84%	Below regulatory benchmark	Gas data from this site is more limited. Gas extraction looks reasonable at point of survey but drops off just after.	It is likely that survey would need repeating to ensure normal operation. If survey outcome was used,	Survey appears to accurately represent site performance during survey, with abnormal operation of gas extraction system reflected in lower performance.

Survey Type	Survey No	Date	MCE (%)	MCE upper limit (%)	MCE lower limit (%)	Assessment of site performance	Survey conducted under normal operation	Regulatory outcome	Comment on survey representativeness of site performance
							Site is operating two engines and a flare during the survey. Would likely not be considered under 'normal operation'.	regulatory action would be required. Operator will need to demonstrate interventions to improve gas management at the site, which will be monitored through subsequent surveys.	
TDM	2	17/12/24	80 ± 7%	87 %	73%	Approaching benchmark	No, only one engine was in operation during this survey. Low gas extraction suggests	Survey not considered for regulatory outcome as not under normal operation. Would require a	Analysis of site and survey data shows that both methane flux and collection are low during this survey. Suggesting storage of methane within the landfill. Abnormal

Survey Type	Survey No	Date	MCE (%)	MCE upper limit (%)	MCE lower limit (%)	Assessment of site performance	Survey conducted under normal operation	Regulatory outcome	Comment on survey representativeness of site performance
							the gas field was being managed to match the extraction rate to the capacity of a single engine during the survey.	repeat survey.	operations at site not captured in the survey result.
TDM	3	14/01/25	86 ± 3%	89%	83%	Approaching benchmark	No, only one engine was in operation during this survey. Low gas extraction suggests the gas field was being managed to match the extraction	Survey not considered for regulatory outcome as not under normal operation. Will need a repeat survey.	Analysis of site and survey data shows that both methane flux and collection are low during this survey. Suggesting storage of methane within the landfill. Abnormal operations at site not captured in the survey result.

Survey Type	Survey No	Date	MCE (%)	MCE upper limit (%)	MCE lower limit (%)	Assessment of site performance	Survey conducted under normal operation	Regulatory outcome	Comment on survey representativeness of site performance
							rate to the capacity of a single engine during the survey.		
TDM	4	04/02/25	94 ± 1%	95%	93%	Above 85 % benchmark	Yes	No regulatory action required	Survey appears to accurately represent site performance.
TDM	5	18/03/25	89 ± 6%	95%	83%	Approaching benchmark	Yes	No regulatory action required.	Survey appears to accurately represent site performance.
TDM	6	21/03/25	74 ± 6%			Below regulatory benchmark	No, only one engine and flare in operation during survey.	Survey not considered for regulatory outcome as not under normal operation. Will need a	Survey appears to accurately represent site performance during this survey. Abnormal operation of the gas extraction system at this time is reflected in lower MCE.

Survey Type	Survey No	Date	MCE (%)	MCE upper limit (%)	MCE lower limit (%)	Assessment of site performance	Survey conducted under normal operation	Regulatory outcome	Comment on survey representativeness of site performance
								repeat survey.	

Table 9-5: Example regulatory outcomes at Site Z

Survey Type	Survey No	Date	MCE (%)	MCE upper limit (%)	MCE lower limit (%)	Assessment of site performance	Survey conducted under normal operation	Regulatory outcome	Comment on survey representativeness of site performance
TDM	1	20/01/25	52 ± 10%	62%	42%	Below regulatory benchmark	No, operator reported issues with gas collection system and extraction is significantly reduced.	Survey not considered for regulatory outcome as not under normal operation. Would need a repeat survey.	Survey result captures reduced performance of the gas management system at this time.
UAV mass balance	2	20/01/25	63 ± 3%	66%	60%	Below regulatory benchmark	No, operator reported	Survey not considered for	Survey result captures reduced performance of the

Survey Type	Survey No	Date	MCE (%)	MCE upper limit (%)	MCE lower limit (%)	Assessment of site performance	Survey conducted under normal operation	Regulatory outcome	Comment on survey representativeness of site performance
							issues with gas collection system and extraction is significantly reduced.	regulatory outcome as not under normal operation. Will need a repeat survey.	gas management system at this time.
TDM	3	20/01/25	53 ± 8%	61%	45%	Below regulatory benchmark	No, operator reported issues with gas collection system and extraction is significantly reduced.	Survey not considered for regulatory outcome as not under normal operation. Will need a repeat survey.	Survey result captures reduced performance of the gas management system at this time.
UAV mass balance	4	21/01/25	58 ± 19%	77%	39%	Below regulatory benchmark	No, operator reported issues with gas	Survey not considered for regulatory outcome as	Survey result captures reduced performance of the gas management system at this time.

Survey Type	Survey No	Date	MCE (%)	MCE upper limit (%)	MCE lower limit (%)	Assessment of site performance	Survey conducted under normal operation	Regulatory outcome	Comment on survey representativeness of site performance
							collection system and extraction is significantly reduced.	not under normal operation. Will need a repeat survey. Uncertainty in MCE may be above regulatory standard. Efforts should be made to reduce uncertainty.	High uncertainty in the MCE also makes assessment of performance difficult.
TDM	5	19/03/25	76 ± 11%	87%	65%	Approaching benchmark	Yes	No regulatory action required. Uncertainty in MCE may be above	Survey result captures improved performance of the gas management system at this time. High uncertainty in the MCE also makes assessment

Survey Type	Survey No	Date	MCE (%)	MCE upper limit (%)	MCE lower limit (%)	Assessment of site performance	Survey conducted under normal operation	Regulatory outcome	Comment on survey representativeness of site performance
								regulatory standard. Efforts should be made to reduce uncertainty.	of performance difficult.
TDM	6	19/03/25	82 ± 5%	87%	77%	Approaching benchmark	Yes	No regulatory action required.	Survey result captures improved performance of the gas management system at this time

9.4 Data collection requirements for potential regulatory approach

Under a regulatory approach, essential data would need to be submitted by operators to the regulator. Gas collection data during the surveys would be needed to calculate the MCE from survey flux results, whilst longer-term data and details of operations would need to be provided to assess whether a survey is conducted under normal operating conditions.

Table summarises the essential data that would be required under the regulatory approach explored here.

Table 9-6: Data requirements for landfill methane surveys

Data	Description	Reason for collection
Gas collection data during survey	Total amount of gas collected during survey and transported to gas engines or flares (usually in m3/h). Minimum hourly resolution, higher resolution preferable. This should include the measurement method and associated uncertainty.	The gas collection data is used to estimate the methane collected on site and is essential for estimating the MCE.
Methane composition of gas collected during survey	Measured methane composition of the landfill gas that is collected during survey and transported to gas engines or flares (%). Minimum hourly resolution, higher resolution preferable. This should include the measurement method and associated uncertainty.	Methane composition is used to estimate the methane collected on site and is essential for estimating the MCE.
No. of engines or flares in operation at time of surveys	Sites usually operate multiple engines for combustion of landfill gas. Flares used to increase extraction often when an engine is undergoing maintenance.	Collecting information on the operation of the gas management system at a site may provide basis for recommendations for improving site performance and identify whether surveys occur under normal operating conditions.

Data	Description	Reason for collection
Long-term gas extraction data	Long-term data on gas collection, composition and number of engines/flares. Over a period of several months at a minimum. This should include the measurement method and associated uncertainty.	Long-term gas extraction data will be used to assess whether surveys occur under normal operation of the gas extraction system. This will determine whether a survey needs to be repeated.
Site Operational works e.g. gas well drilling, capping works	Any significant operational activities happening on site that may affect collection efficiency performance.	Operators would be required to submit supporting information to determine whether surveys are conducted under normal conditions.
Meteorological data	Atmospheric pressure (absolute and trend), temperature, rainfall, wind direction, windspeed. If no onsite meteorological data is available, publicly available data can be extracted from nearby weather stations.	Meteorological factors have been shown to influence emissions from landfills. Regulation will need to specify whether certain atmospheric conditions fall outside of the specified conditions for a survey.

If the regulatory approach is to specify the conditions under which surveys can be conducted, the data listed Table 9-6 would be essential for determining normal conditions. Operational data such as long-term gas collection rates, operation of the engines and flares, and any site works occurring can be used to provide an assessment of the operating conditions during the survey. Meteorological conditions will also need to be assessed as part of the approach, and regulation may include specified limits for certain factors. For example, in the Danish Biocover Initiative, landfill emission measurements are required to be performed within a period of a maximum change in the atmospheric pressure of ±3 mbar[32]. Alongside the provision of data, Bourn et al. have proposed

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[32] DEPA, 2017 – referenced in: Bourn, M., Robinson, R., Innocenti, F., & Scheutz, C. (2018). '*Regulating landfills using measured methane emissions: An English*

operators include a brief qualitative summary indicating whether the conditions at the time of measurement were likely to result in relatively high or low methane emissions. This would be used to inform regulatory actions and potential reduce the initial regulatory burden.

9.5 Method selection for regulatory approach

9.5.1 Meteorological Constraints

Both the TDM and UAV mass balance surveys are sensitive to meteorological conditions, which must be suitable for accurate and reliable data collection. Key atmospheric factors include:

- Wind speed and direction
- Precipitation
- Atmospheric stability

TDM surveys are particularly affected by unstable or convective conditions, such as those occurring on warm summer afternoons with rising thermally driven air currents. To mitigate this, survey planning should incorporate national and regional weather forecasts, with flexibility to confirm or cancel surveys at short notice based on real-time conditions.

UAV mass balance surveys are also influenced by wind variability during individual flight windows. Variations in wind speed and direction introduce quantifiable uncertainty into flux estimates derived from the mass balance method. This uncertainty is propagated through the calculation as a statistical component of the final emission estimate.

Both methods require favourable wind directions relative to site layout and surrounding features:

- TDM requires a clear road network downwind of the emission source and separation from confounding sources.
- UAV mass balance surveys must be conducted along unobstructed site boundaries, free from barriers such as treelines or buildings.

Table 9-7 summarises the meteorological limitations associated with each method.

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perspective'. Waste Management, 87, 860–869, https://doi.org/10.1016/j.wasman.2018.06.032

Table 9-7: Meteorological limitations

Meteorological variable	TDM	UAV mass balance
Wind Speed	Not suitable in slack winds.	Not suitable in slack or high winds.
Wind Direction	May only be applicable at certain wind directions due to road network and confounding sources.	May only be applicable at certain wind directions due to layout of site boundaries and potential obstructions.
Atmospheric stability	Not suitable in unstable or convective conditions.	Suitable in convective conditions.
Precipitation	Not suitable to conduct during light precipitation due to effects on plume dispersion which has been observed to force the plume to ground level.	Not suitable to conduct during precipitation.

9.5.2 Method selection

To support method selection for individual landfill sites, it is important to establish clear criteria indicating when TDM or UAV mass balance survey methods are suitable. Certain site-specific characteristics will determine which method can be effectively deployed. In some cases, both methods may be feasible, offering flexibility in approach. However, for other sites, neither method identified in this study may be suitable due to physical, operational, or logistical constraints. In such instances, alternative measurement techniques may need to be considered. Key criteria for the selection of UAV mass balance and TDM are outlined in Table 9-8.

Table 9-8: Survey technique selection criteria

Site Characteristic	TDM	UAV mass balance
Within CAA restrictions	✓ - TDM surveys can operate under CAA restrictions.	UAV mass balance surveys cannot operate under CAA (e.g close to airports) or may require

Site Characteristic	TDM	UAV mass balance
		specific permission to operate.
No suitable road network	✗ - TDM requires accessible road network.	✓ - UAV mass balance surveys do not require road network.
No suitable boundary clear of obstructions	✓ - TDM surveys conducted at a distance from the site, not sensitive to boundary obstructions.	✗ - UAV mass balance surveys require suitable boundary free of obstructions to conduct surveys (e.g trees, buildings)
Adjacent confounding sources	✗ - TDM cannot isolate adjacent confounding sources if with the measured plume.	✓ - UAV mass balance surveys may be able to isolate landfill emissions from adjacent sources by flying along the boundary.
No clear line of site surrounding landfill	✓ - TDM surveys do not require clear line of site.	✗ - UAV mass balance surveys require clear line of site.

10 Comparison of sites

10.1 Site performance

The information presented in Table 7-5 shows the range of measured methane formation at the four case study sites:

- Site X 888 ± 25 kg/hour
- Site Y1 377 ± 19 kg/hour
- Site Y2 Surveys 1, 4, 5 and 6 509 ± 23 kg/hour
- Site Y2 Surveys 2 and 3 231 ± 10 kg/hour
- Site Z 671 ± 44 kg/hour

The range of values reflects differences between the sites, in terms of the site history, capacity, rate of waste deposition, type of waste received and management of the site, particularly older parts of well-established sites.

The range of methane formation rates at Site Y2 was more unexpected. Using the model of gas flows set out in Chapter 7, the most likely explanation for the low methane formation rate during Surveys 2 and 3 is that much of the methane being generated during these surveys was being stored within the landfill rather than collected by the gas collection system or released through the landfill surface. The site operator noted that “Data shows only 1 (of 2) engines online during survey, no flaring happening” during both Surveys 2 and 3. Additionally, during Survey 2, it was noted that there was a “low flow of gas collection.”

We conclude that the limited operation of the gas collection system did not result in an increase in methane emissions from the site because there was capacity within the landfill to temporarily store methane as it was generated. At a later point, if there was an ongoing delay in full operation of the landfill gas collection system, this would be expected to result in increased methane emissions as the site reached the point where methane could no longer be stored in the body of waste.

Table 7-1 to Table 7-4 present the range of calculated Methane Collection Efficiency across the four case study sites. It is important to note that these ranges incorporate both TDM and UAV mass balance methods, and the results indicate a consistent under bias in the UAV mass balance method when compared to TDM.

- Site X 88% to 99%
- Site Y1 74% to 84%
- Site Y2 74% to 94%
- Site Z 52% to 82%

Sites Y2 and Z showed significant changes in MCE across different surveys. The evidence indicates that these reflect operational challenges which took place at those sites. Engine issues at Site Y2 and flare operation at Site Z were both found to be associated with lower levels of MCE, as would be expected in principle.

The Environmental Services Association (ESA) in its Net Zero Strategy has committed the UK waste and recycling sector to increase methane capture from landfill sites to 85% by 2030 *("We committed to the following targets relating to landfill and the control of methane emissions: … to increase capture of methane emissions from landfill to 85% by 2030")*[33]. Earlier Environment Agency guidance also encouraged sites to aim for capturing 85% of methane formed at the site. [34] The metrics to be used for these targets was not definitely specified.

Under optimal conditions, all four sites were found to achieve or nearly achieve this objective. Site X consistently achieved this during all seven surveys, and Site Y2 achieved this target during three of the six surveys.

10.2 Comparison with site-specific models

To assess consistency of modelled methane estimates with direct measurements, monthly methane generation (in m^3/h) was modelled and compared with values derived from survey flux and gas collection data. As discussed previously in the Introduction, the field measurements do not directly measure total methane generation. Instead, methane flux is measured in the survey, metered gas collection is taken from operator data, and surface oxidation is estimated based on standard approaches. The determination of methane generation rate is shown in Equation 1.

10.2.1 GASSIM

GASSIM is a system for modelling the formation of methane in a landfill site. GASSIM and similar models can be very valuable – for example, in projecting future trends in methane production to assist in site planning and management.

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[33] ESA Net Zero Strategy (written evidence to UK Parliament, 2021), reaffirmed in ESA Annual Report 2022 and Policy Scorecard 2023.

GASSIM input files (.gss) were provided by the operators for sites X, Y1, and Z. These were updated and run using site-specific waste input data for the waste deposition, waste composition, and the flare and engine specifications. For the remaining parameters, defaults were used. These parameters were:

- Cap Infiltration
- Cap and Liner Hydraulic Conductivity
- Gas Collection Efficiency
- Methane Oxidation Factor
- Waste Moisture Content
- Degradation Rate Constants
- Methane to CO_2 Ratio
- Hydrogen Production
- Bulk Gas Destruction Efficiency
- Flare Air-to-Fuel Ratio
- Stack Height, Temperature, and Orifice Diameter
- Trace Gas Destruction Efficiencies
- Exhaust Concentrations
- Flare and Engine Downtime
- Meteorological Data

This allowed for a comparison of modelled data with that measured from the TDM and UAV mass balance surveys and other data sources as outlined above. To ensure fair comparison as outlined in the equation above, the modelled methane generated was compared with the measured methane flux, in concert with metered gas collection and surface oxidation. The survey data provided field data of measured methane flux at a specific point in time, whereas the GASSIM system provides monthly average model outputs based on certain assumptions. The outputs of site surveys and GASSIM models were compared. The focus for comparison was the calculated or estimated quantity of methane generated during the survey periods.

At site Y2, GASSIM is not used for emission estimation. Instead, a custom Excel spreadsheet calculator is used by the operator to generate this data. In the same way, modelled estimates for the methane generated, and collection efficiency were compared with those measured through UAV mass balance and TDM surveys.

10.2.2 Comparison between model and survey methane production estimates

The monthly average methane production rates presented here represent the combined results of all individual measurements conducted within each month, incorporating data from both TDM and UAV mass balance survey methods.

Table 10-1: Comparison of modelled methane generation at monthly average from survey results (kg/hr) – Site X

Month	Total CH_4 Production from GASSIM model (kg/hr)	Total CH4 Production from Surveys (kg/hr)
September 2024	899	926 ± 23
November 2024	879	934 ± 55
January 2025	871	787 ± 12
March 2025	880	836 ± 58

Table 10-2: Comparison of modelled methane generation at monthly average from survey results (kg/hr) – Site Y1

Month	Total CH4 Production from GASSIM model (kg/hr)	Total CH4 Production from Surveys (kg/hr)
October 2024	363	399 ± 44
December 2024	359	413 ± 34
January 2025	346	384 ± 21
February 2025	355	327 ± 27

Table 10-3: Comparison of modelled methane generation at monthly average from survey results (kg/hr) – Site Y2

Month	Total CH4 Production from Excel model (kg/hr)	Total CH4 Production from Surveys (kg/hr)
December 2024 Survey 1	430	577 ± 23
December 2024 Survey 2		212 ± 9
January 2025	428	246 ± 7
February 2025	417	477 ± 6
March 2025	421	486 ± 98

Table 10-4: Comparison of modelled methane generation at monthly average from survey results (kg/hr) – Site Z

Month	Total CH4 Production from GASSIM model (kg/hr)	Total CH4 Production from Surveys (kg/hr)
January 2025	355	603 ± 123
March 2025	354	563 ± 77

This analysis shows that the GASSIM and spreadsheet models provided a good performance in calculating methane generation rates which align well with the measured values, except for the two site Z results, and one site Y2 result in January 2025.

For site X and Y1, the modelled estimates were respectively within 9.70% and 14.10% of the measured estimates.

For site Y2, a single result in January 2025 skewed the difference between the modelled and measured estimates to approximately 42.60%. During January 2025 abnormal operation of the gas extraction system led to reduced methane collection and correspondingly low methane flux at the site, suggesting increased storage with the landfill site itself (see section 7.4). All other measurements are consistent not only with each other, but also with the modelled estimates. There are several environmental factors and site characteristics which can influence methane emissions, resulting in anomalies. These determinants have been discussed and reviewed in section 3 Factors affecting methane emissions, and summarised and outlined in section 8 Assessment of factors affecting methane emissions.

At Site Z, the modelled values were significantly lower than the measured values, differing by up to 70% despite methane generation remaining relatively stable. This is likely due to modelled estimates not capturing the full scope of methane generation at Site Z. Table 4-2 shows that the site was operational since the early 1990's, whereas the Gassim input file only exhibits waste arisings from 1997 onwards. This suggests that not all the waste inputs of the site are accounted for. This would tend to reduce modelled methane estimates. After liaison with the operator and investigation of the historical site plan, it was found that several restored areas could be responsible for the underprediction of the modelled methane. Whilst these sites are not included as cells with waste inputs within the Gassim model, they presumably are continuing to release methane. The site is adjacent to four restored areas, with remediation dates as follows:

- 4.09 hectares, restored in 1990/91
- 3.59 hectares, restored in 1984/85
- 2.59 hectares, restored in 1981
- 1.01 hectares, restored in 1981

This is likely to be at least part of the reason for the higher measured methane production at Site Z compared with the modelled estimate.

11 Conclusions and recommendations

11.1 Survey techniques

This project has demonstrated that empirical data collected using either TDM or UAV-mass balance methods can be used alongside gas collection and meteorological data to establish a site's gas collection efficiency as a measure of site performance.

The results show methane flux calculated from TDM and UAV mass balance surveys are generally comparable within uncertainty bounds. However, an under bias of UAV mass balance fluxes relative to TDM was observed at all three sites where both methods were deployed. Each method offers distinct advantages and limitations, but both were successfully deployed across multiple sites. Their complementary strengths and limitations of each method suggest that a technology flexible approach would be most effective for regulatory applications, enabling the selection of the most appropriate technique for each specific landfill site. This would need be supported by robust collection of site operational data and meteorological data to effectively interpret results.

There may be some landfill sites that would not be suitable for either the TDM or UAV mass balance methods discussed in this report, in these instances other established survey methods will need be deployed, for example the DIAL method[35] or inverse modelling[36].

These methods provide valuable insights into site-specific methane fluxes and collection efficiencies, offering a more accurate and transparent basis for assessing landfill gas management performance than model-based estimates alone. Landfill gas models were found to give consistent results with the survey data for most of the surveys, but exceptions were observed. At Site Y2, measured methane production was much lower than modelled levels for two of the six surveys, probably representing short-term issues with the landfill gas collection systems. At Site Z, modelled methane production was significantly lower than the measured values, with an incomplete landfill gas model likely to be part of the reason for this.

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[35] Innocenti, F., Robinson, R., Gardiner, T., Finlayson, J., Connor, A., 2017. Differential absorption lidar (DIAL) measurements of landfill methane emissions. Rem. Sens. 9 (9), 953. https://doi.org/10.3390/rs9090953.

[36] Quantifying methane emissions using inverse dispersion modelling - GOV.UK

11.2 Performance Metric

Methane Collection Efficiency (MCE) has been identified as a robust and meaningful metric for assessing landfill gas management performance. It accounts for site-specific differences in scale and waste type between landfill sites and enables fair comparison across sites.

The calculated MCEs in this study reveal differences in the performance of gas management systems across the four case study sites. Site X showed consistently high MCE across the surveys (88-99%). Site Y1 also showed relatively consistent performance across the surveys although at a lower level then site X (74-84%), suggesting consistent operation of the gas management systems at these sites.

In contrast, the results from Y2 show different levels of performance across the surveys, which appear to correlate with changes in the gas management system (number of engines/flares operational). During surveys 2 and 3 at this site, estimated methane production was significantly lower than in other surveys. This was not directly reflected in the performance metric as methane flux was also low, most likely due to increasing methane storage within the landfill during this time.

At site Z very distinct levels of MCE were observed between the surveys occurring in January versus those in March. Significantly lower MCE was observed in January when there were known issues with the gas collection system caused by severe cold weather. By March, the system had stabilised, and MCEs improved markedly. This demonstrates the robustness of both the survey methods and performance metric which successfully captured the operational impacts on gas collection efficiency.

Whilst the results show that effective gas management can consistently deliver a good standard of performance, it remains unclear whether the highest levels of methane collection efficiency observed at Site X are primarily due to better gas management practices, or site characteristics such as waste composition, age, or the extent of permanently capped areas at the site. Older sites with larger closed areas that have permanent capping and established gas extraction infrastructure such as Site X, may be able to achieve higher methane collection performance. This distinction is important for interpreting performance benchmarks and informing future regulatory expectations.

Table 9-5 in section 9 outlines a potential approach for applying these techniques within a regulatory context. Under this approach, annual surveys conducted by operators using approved survey techniques would be required to take place under the normal operating conditions of the gas management system. These conditions would be verified through the provision of long-term gas collection data from operators which ensures that the surveys are more representative of typical site performance.

An example of potential regulatory outcomes under this approach, based on a benchmark Methane Collection Efficiency (MCE) of 85%, is presented in Table 9-2 to Table 9-5. These examples illustrate which surveys may be considered representative of normal operating conditions and demonstrate the possible outcomes of applying this regulatory framework.

11.3 Meteorological factors affecting methane flux and MCE

The analysis also highlights that meteorological factors, particularly air pressure trends and temperature, can influence methane flux and gas storage within landfills. Although operational factors such as active flaring, tipping activity, and abnormal operation were more strongly correlated with changes in MCE, meteorological conditions must also be considered when deploying these survey techniques in a regulatory context.

Air pressure gradient was found to make a significant contribution to overall variability in methane flux, if the observed correlation is causal, at three of the four sites. However, at two of the sites, an increase in air pressure gradient was associated with higher methane flux, whereas at one of the sites, an increase in air pressure gradient was associated with lower methane flux. Higher temperatures were associated with higher methane flux at two of the four sites. Recent rainfall did not seem to be significantly correlated with methane flux. While it would be possible to speculate about the causes of these observations, we do not have sufficient information to reach a definitive view on the causes of this observation. It is worth noting that the operation of gas extraction systems is not static and can be adapted in response to meteorological conditions. For example, the results from Surveys 2 and 3 at Site Y2 suggest a potential link between the operation of the gas extraction system and trends in atmospheric pressure. This indicates that meteorological and operational factors may be interdependent, making it challenging to assess their individual impacts in isolation.

Wider research indicates that higher levels of MCE are typically associated with periods of increasing air pressure. This pattern was only observed at one of the four sites in this study (Site Z).

The survey window for this project was limited to the period between October and March providing a relatively narrow dataset relative to the full range of meteorological conditions that a landfill site may experience throughout a year. Expanding measurements to cover a broader portion of the annual cycle would provide a more comprehensive dataset of the influence of meteorological factors on landfill emissions and site performance.

11.4 Recommendations

In this report, we outlined a potential regulatory framework that could be applied to landfill sites using TDM and UAV mass balance methods. For effective deployment in a regulatory setting, standardisation of survey methodologies, data collection protocols, and the assessment of an appropriate regulatory benchmark would be required. To support the development of a framework for landfill methane control, the following recommendations are made:

A. Regulatory Use of Survey Techniques

- Adopt MCE as a regulatory performance metric, using it to benchmark site performance and trigger follow-up actions where necessary. This will require an assessment of the most appropriate benchmark for permitted sites.
- Allow flexibility in method selection (TDM, UAV mass balance or other method), provided the chosen method meets defined criteria for accuracy, uncertainty quantification, and site suitability.
- Require sites to conduct surveys under 'normal operating conditions' to ensure results are representative of typical site operation. These conditions should be verified by collection and analysis of supporting operational data.

B. Supporting Data Requirements

- Require submission of standardised operator data, including gas collection rates, methane content, flare and engine operation, and relevant site activities during the survey period and over a longer-term timeframe. This data will support the interpretation of survey results and verification of operating conditions during surveys.
- Meteorological data should be collected or sourced to support surveying methods, interpretation of results and identify stable operating conditions.

C. Method Selection Guidance

- Develop a site suitability framework to guide the selection methods based on site layout, access, surrounding land use, and regulatory constraints (e.g. CAA restrictions).

D. Market Development and Oversight

- Encourage the development of a market for accredited survey providers, with clear standards for training, equipment, and reporting.

E. Future Enhancements

- Explore the integration of combustion efficiency/methane slip and surface methane oxidation measurements into MCE calculations, where feasible.
- Continue to validate and refine models like GASSIM using empirical data from site surveys.

11.5 Further Work

The evidence base developed in the project could be expanded to provide guidance for the selection of the methane survey techniques based on site-specific characteristics, including operational status, surrounding land use, accessibility, and meteorological conditions. This could include standardised reporting of operational data by landfill sites that can feed into a framework for assessing site performance. Further field work to refine and test this guidance is likely to be needed.

Applying these survey techniques in the regulatory context would be expected to encourage the development of a market for specialist survey providers. This will need to be carefully management to avoid any market distortions and provide confidence for service providers to invest in staff training and development, and purchase of equipment and consumables.

Further research could focus on the following:

- **Expanding the evidence based through additional surveys** - Conducting surveys across a wider range of atmospheric and operational conditions provide more evidence for understanding how these factors influence methane emissions Additionally, including a broader selection of landfill sites would support a more comprehensive assessment of performance variability across the sector. This would not only help to identify the most effective gas management practices but also contribute to a more robust evidence base for determining an appropriate regulatory benchmark for methane collection efficiency.

- **Include combustion efficiency measurements in site performance analysis** - Develop a standard approach for estimating combustion efficiency and identify slippage for assessment of site performance.

- **Include surface methane oxidation measurements in site performance analysis** – Incorporation of direct measurements of surface methane oxidation would provide a direct evidence base for inclusion in MCE calculations. This could use carbon isotope measurement techniques which have been deployed in the UK for research into landfill methane emissions. This may be important in refining calculated MCE at sites which are close to regulatory thresholds, rather than relying on default assumptions.

- **Source separation:** Investigate further the ability of TDM and UAV mass balance methods to separate out contributions from landfill fugitive emissions, landfill point source emissions (i.e. methane slip) and other local sources of emission.

- **Wider applicability techniques:** Identify techniques that can be applied in situations where neither TDM or UAV mass balance methods are practicable and incorporate into standard guidance for landfill sites.

- **Integrate into other research:** Integrate this research into ongoing Defra-supported research[37] into measurement of landfill methane emissions which is focused principally on improving the national greenhouse gas inventory.

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[37] Defra research into landfill methane emissions includes 'WR1928: Direct Measurement of Landfill Methane Emissions' and 'Direct Measurement of Landfill Methane Emissions 2' (available at https://www.find-tender.service.gov.uk/Notice/015543-2024?origin=SearchResults)

A.1. Survey details

TDM

Site X

A.1. 1 Site X survey temporal details

Survey No.	Date of survey	Start time	End Time	Duration (mins)
1	11/09/24	19:55	21:40	105
2	25/11/24	14:37	16:05	88
3	26/11/24	07:25	19:10	105
4	21/01/25	19:25	21:30	125
5	20/03/25	18:35	21:00	145

A.1. 2 Meteorological conditions recorded at Site X per survey

Survey No.	Temperature (ºC)	Barometric Pressure (mbar)	Wind Speed (m/s)	Wind Direction (Degrees)	Cloud Cover (%)
1	8.1	1005	3.5	217	100
2	9.0	990	3.5	239	75
3	4.1	1001	2.6	217	75
4	4.6	1002	2.6	194	0
5	9.1	1013	3.8	115	0

Site Y1

A.1. 3 Site Y1 survey temporal details

Survey No.	Date of survey	Start time	End Time	Duration (mins)
1	19/10/24	15:25	17:45	140
2	19/10/24	21:30	23:06	96
3	10/12/24	19:20	21:35	135
4	09/01/25	19:10	21:05	115
5	27/02/25	20:00	22:15	135

A.1. 4 Meteorological conditions recorded at Site Y1 per survey

Survey No.	Temperature (ºC)	Barometric Pressure (mbar)	Wind Speed (m/s)	Wind Direction (Degrees)	Cloud Cover (%)
1	13.9	1013	1.7	314	100
2	10.4	1015	1.5	323	100
3	5.6	1025	2.8	41	100
4	0.4	1003	2.3	281	100
5	4.3	1014	2.0	323	0

Site Y2

A.1. 5 Site Y2 survey temporal details

Survey No.	Date of survey	Start time	End Time	Duration (mins)
1	05/12/24	07:10	09:45	155
2	17/12/24	12:40	14:45	125
3	14/01/25	13:27	15:32	125
4	04/02/25	05:57	08:10	133
5	18/03/25	17:14	19:20	126
6	21/03/25	10:30	12:31	121

A.1. 6 Site Y2 survey temporal details

Survey No.	Temperature (ºC)	Barometric Pressure (mbar)	Wind Speed (m/s)	Wind Direction (Degrees)	Cloud Cover (%)
1	12.0	1007	2.7	220	75
2	10.0	1021	3.4	197	100
3	9.8	1033	1.8	230	100
4	6.6	1020	2.7	202	100
5	5.7	1023	12.2	69	0
6	17.4	1008	1.8	130	0

Site Z

A.1. 7 Site Y2 survey temporal details

Survey No.	Date of survey	Start time	End Time	Duration (mins)
1	20/01/25	12:51	15:40	145
2	20/01/25	19:25	21:15	110
3	19/03/2025	17:20	19:20	120
4	19/03/2025	22:25	00:50	145

A.1. 8 Site Y2 survey temporal details

Survey No.	Temperature (ºC)	Barometric Pressure (mbar)	Wind Speed (m/s)	Wind Direction (Degrees)	Cloud Cover (%)
1	6.8	1008	3.4	234	70
2	5.6	1007	2.7	237	100
3	6.1	1014	3.1	147	40
4	0.8	1015	2,1	216	10

UAV mass balance

Note that UAV mass balance surveys are typically completed in one or two efficient flights, depending on the survey area and power availability.

Site X

A.1. 9 Site X survey temporal details

Survey No.	Date of survey	Flight 1	Flight 2	Total duration (mins)
1	26/11/24	12:11 – 12:24	12:33 – 12:41	21
2	26/11/24	14:37 -14:49	14:57 – 15:04	19
3	26/11/24	15:17 – 15:28	15:35 - 15:45	21
4	26/11/24	15:55 – 16:09	-	
5	27/11/24	13:15 – 13:29	13:35 – 13:49	33
6	27/11/24	14:02 – 14:15	14:25 – 14:41	29
7	27/11/24	14:53 – 15:08	15:15 – 15:30	30

A.1. 10 Meteorological conditions recorded at Site X per survey

Survey No.	Temperature (ºC)	Barometric Pressure (mbar)	Wind Speed (m/s)	Wind Direction (Degrees)	Cloud Cover (%)
1	7.5	1006.5	3.9	229	Not measured
2	7.8	1007.9	4.0	255	
3	7.3	1008.0	4.3	249	
4	6.2	1008.4	2.9	231	
5	4.9	1006.4	3.8	318	
6	5.5	1006.8	4.7	323	
7	4.7	1007.3	4.6	307	

Site Y1

A.1. 11 Site Y1 survey temporal details

Survey No.	Date of survey	Flight 1	Flight 2	Duration (mins)
1	29/10/24	13:12 – 13:22	13:36 – 13:43	17
2	29/10/24	14:00 – 14:12		12
3	29/10/24	15:24 – 15:36		12
4	29/10/24	16:00 – 16:20		20
5	30/10/25	10:20 – 10:34		14
6	30/10/25	10:47 – 11:01	11:12 – 11:25	27
7	30/10/25	11:41 – 11:53	12:02 -12:13	23

A.1. 12 Meteorological conditions recorded at Site Y1 per survey

Survey No.	Temperature (ºC)	Barometric Pressure (mbar)	Wind Speed (m/s)	Wind Direction (Degrees)	Cloud Cover (%)
1	14.3	1012.8	2.0	309	Not recorded
2	14.9	1012.8	1.6	298	
3	14.5	1012.9	0.8	334	
4	14.2	1012.9	2.1	305	
5	11.1	1018.1	2.4	286	
6	11.2	1018.1	1.5	346	
7	11.5	1018.0	0.9	303	

Site Z

A.1. 13 - Site Z survey temporal details

Survey No.	Date of survey	Flight 1	Flight 2	Duration (mins)
1	20/01/25	13:10 – 13:21		11
2	20/01/25	13:42 – 13:53		11
3	20/01/25	14:26 – 14:39	14:45 – 14:48	16
4	20/01/25	15:09 – 15:21		12
5	21/01/25	11:17 – 11:29	11:36 – 11:48	24
6	21/01/25	12:45 – 12:56	13:13 – 13:18	17
7	21/01/25	14:14 – 14:27	14:36 – 14:46	26

A.1. 14 Meteorological conditions recorded at Site Z per survey

Survey No.	Temperature (ºC)	Barometric Pressure (mbar)	Wind Speed (m/s)	Wind Direction (Degrees)	Cloud Cover (%)
1	4.4	10093	1.8	209	Not recorded
2	4.4	10090	2.9	226	
3	4.6	10085	1.3	216	
4	4.8	10083	2.0	220	
5	5.1	10055	3.7	197	
6	5.2	10045	3.2	217	
7	5.4	10093	2.9	207	

A.2. Key findings from TDM and UAV methane balance surveys

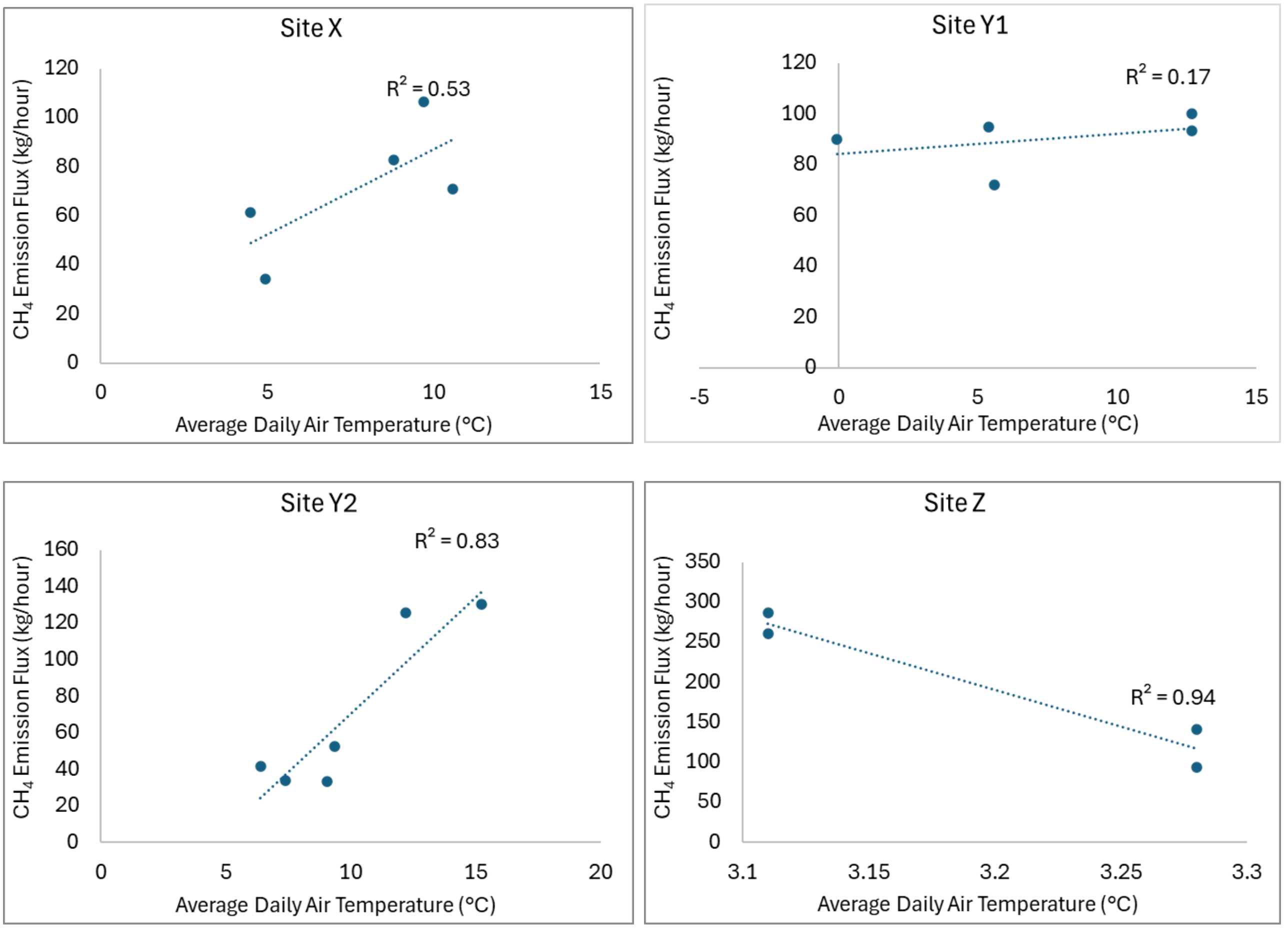
Key findings from TDM surveys

Comparison with meteorological data

Only two survey periods were carried out at Site Z. Statistical analysis is, therefore, not possible. Data is included for comparison only.

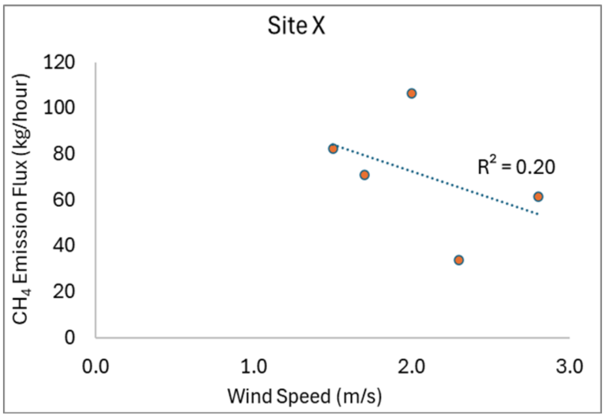
Air Temperature

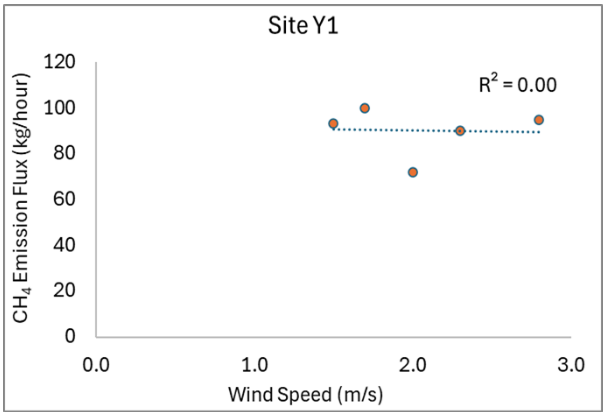
TDM data is compared to the average air temperature measured at the time of each survey. There is a weak positive corelation with air temperature at Site X and at Site Y2.

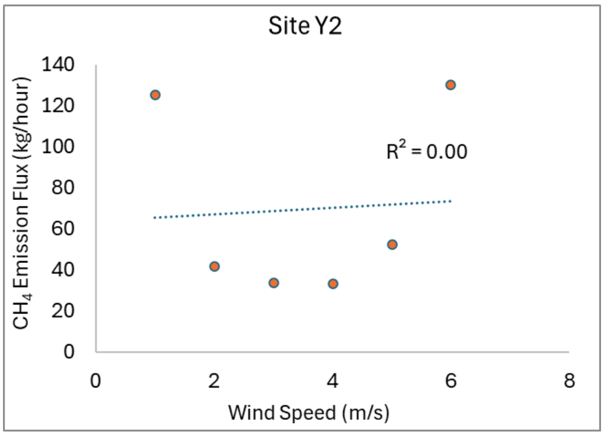


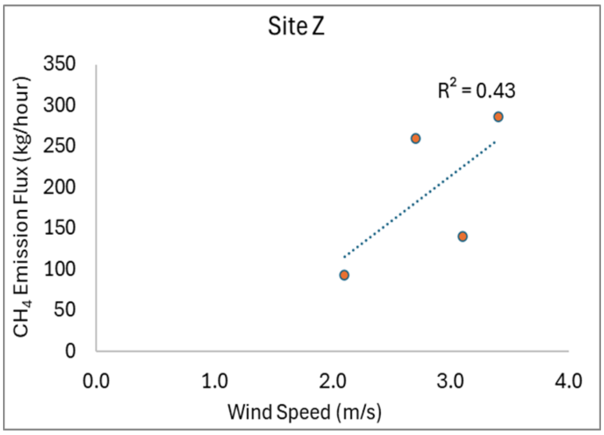
Wind Speed

TDM data is compared to the average wind speed measured at the time of each survey. There is no corelation with wind speed at any of the landfills.



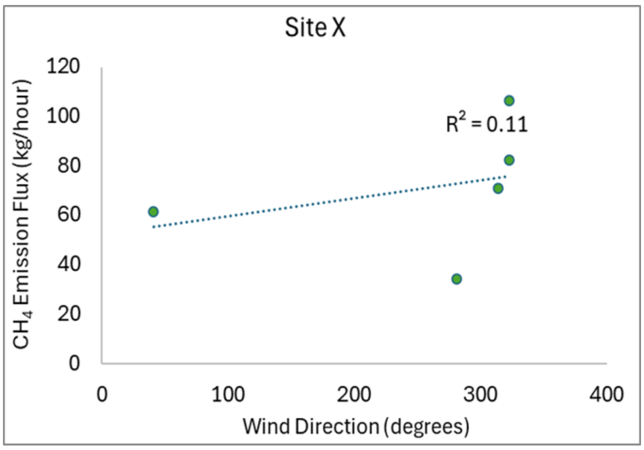


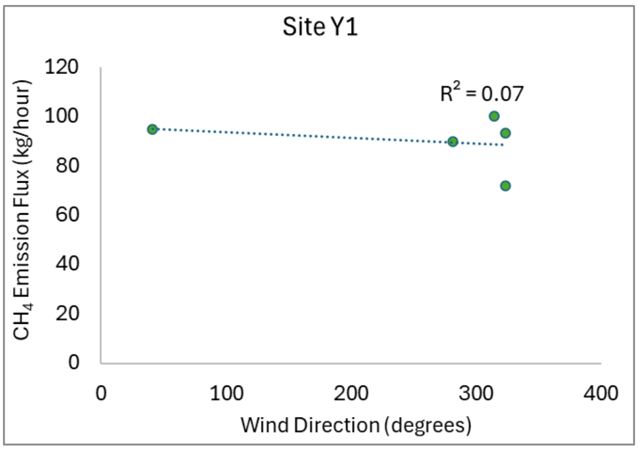


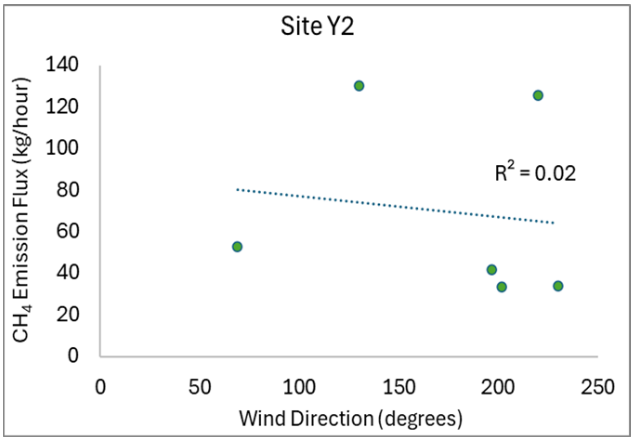


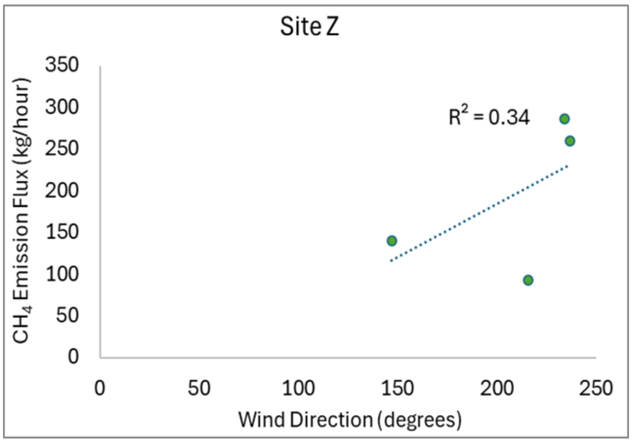
Wind Direction

TDM data is compared to the average wind direction measured at the time of each survey. There is no corelation with wind direction at any of the landfills.



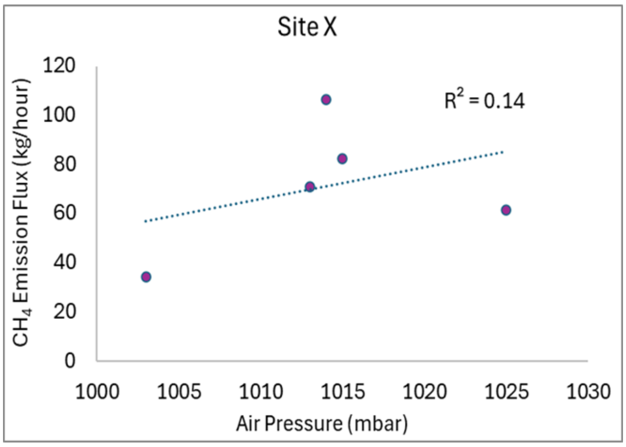


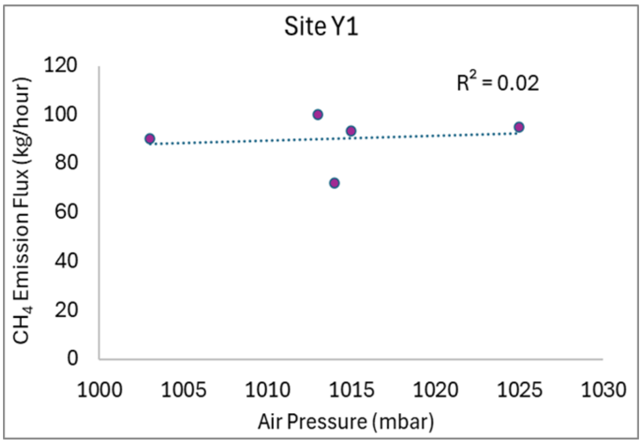


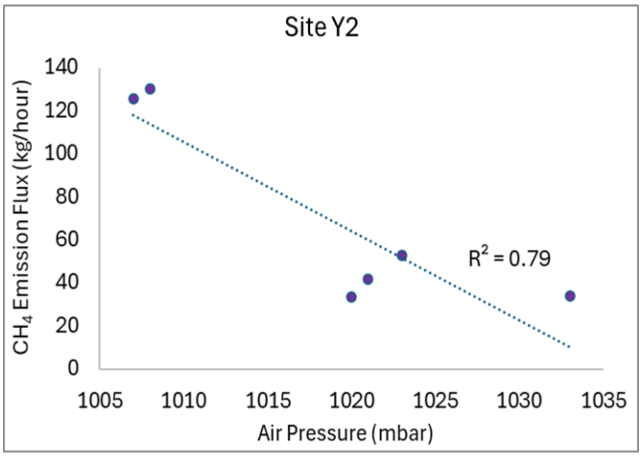


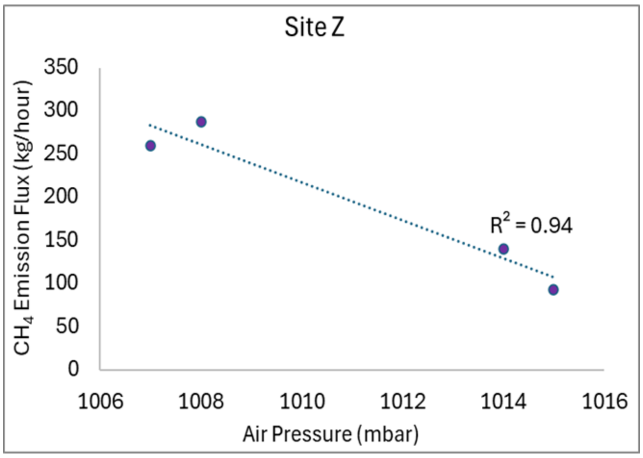
Air Pressure

TDM data is compared to the average air pressure measured at the time of each survey. There is a strong inverse correlation at Site Y2, with the highest absolute pressure measurements occurring with the lowest measured emissions.

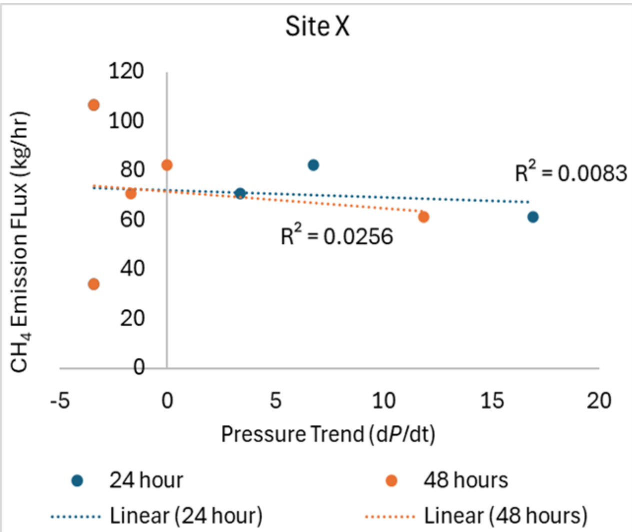


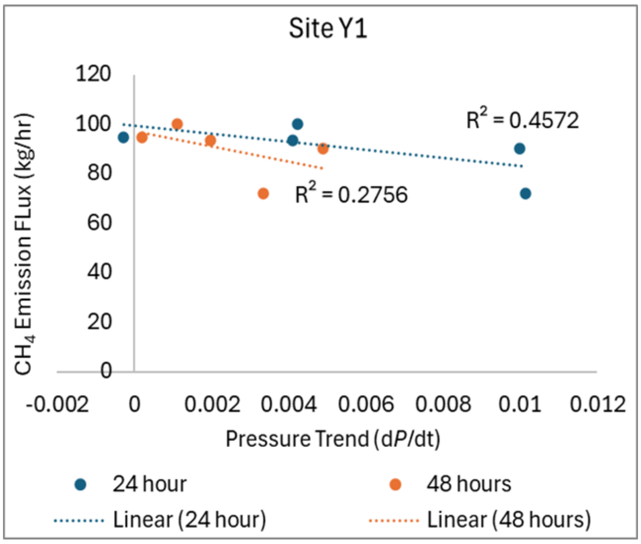


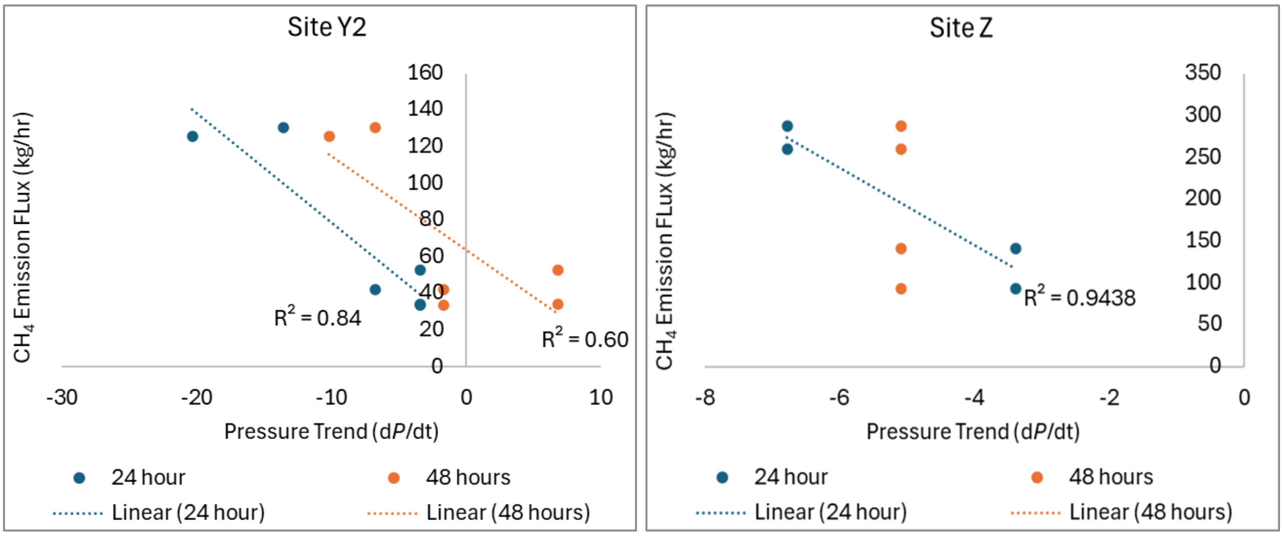




The relationship between air pressure and methane emissions from landfill is well documented (e.g. Kissas et al, 2022). Typically, it is the trend and rate of pressure rise and fall that has the most influence. TDM data is compared to the pressure trend ($\Delta p/\Delta t$) where Δp is the change in pressure p in time period, t. Data is plotted for t = 24 hours and t = 48 hours. There is a clear inverse relationship bewtween pressure trend and measured emissions at Site Y2, most noted when measured over 24 hours.





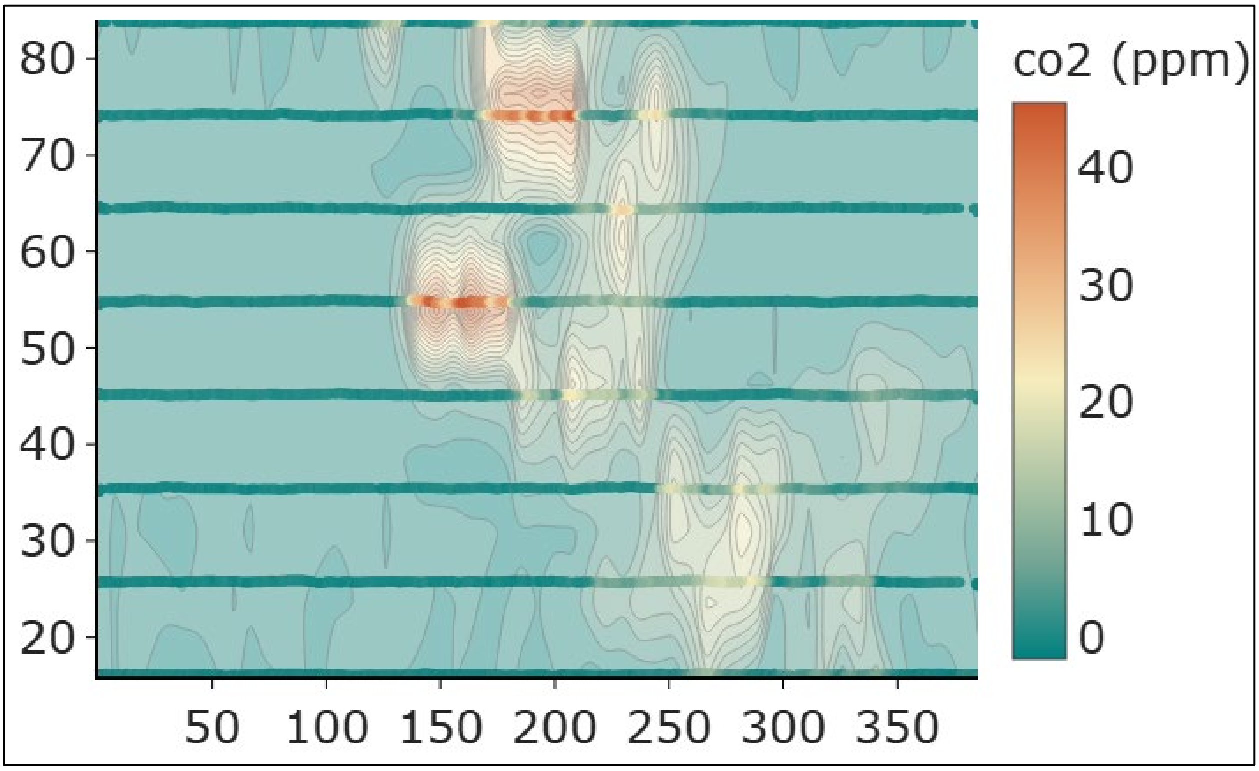


Key findings from the UAV mass balance survey

Figure A.2. 1 to Figure A.2. 4 illustrate two examples of surveys conducted at different sites, showing distinct patterns in the CO_2 and CH_4 plumes. In Figure A.2. 1 and Figure A.2. 2 ,the CO_2 and CH_4 plumes are spatially separated (indicating separate sources such as combusted plumes from on-site engines), while in Figure A.2. 3 and Figure A.2. 4, the plumes are collocated (and highly enriched in CO_2, indicating engine slippage), highlighting the variability in gas distribution across different sites. These differences in plume patterns reflect the dynamic nature of gas emissions and on-site sources in landfill environments.

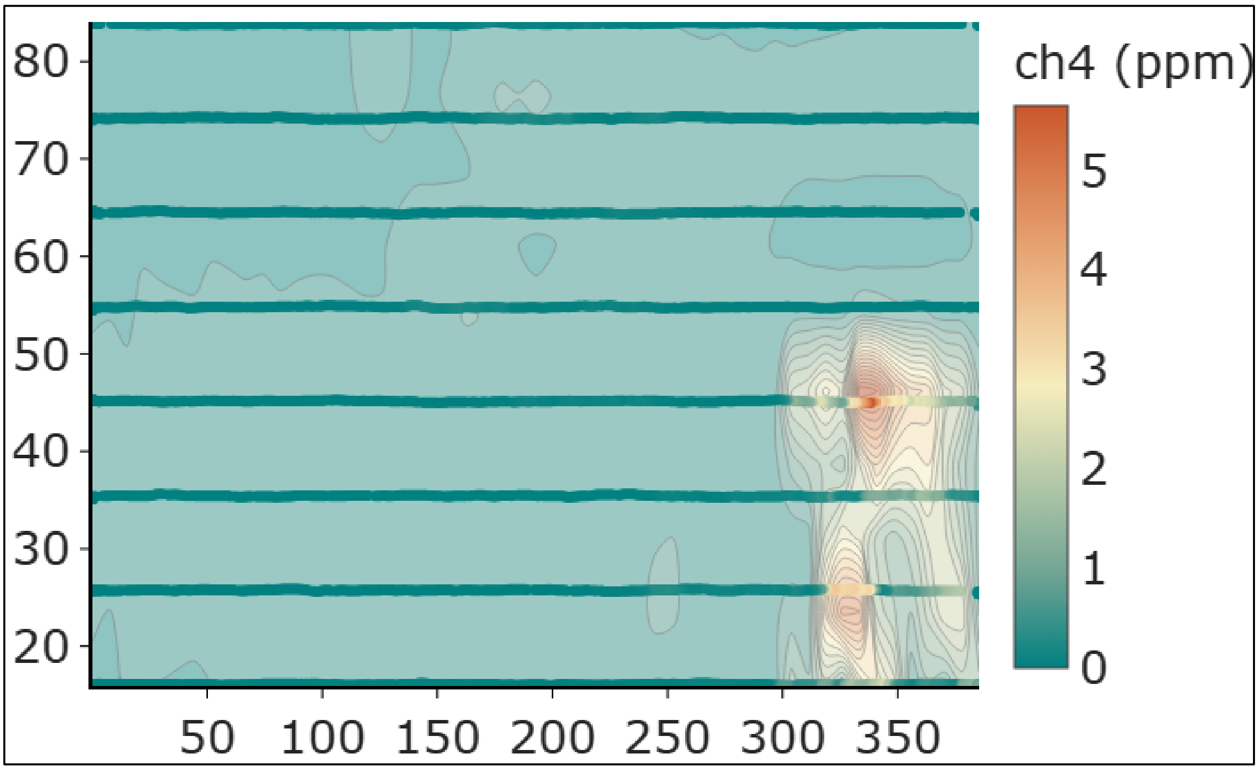
Figure A.2. 5 and Figure A.2. 6 show the results of all the surveys, including the CO_2 and CH_4 fluxes (kg/h) and their associated uncertainties. The fluxes were calculated using a mass balance method with two different wind inputs: the UAV-based wind and the logarithmic wind profile. Each survey was conducted during either a single continuous flight or a combination of consecutive flights, with short time gaps between them due to battery changes.

A.2. 1 CO_2 concentration enhancements (above background concentrations) in Site Y, 29/10/2024, Flight 2, with kriged contours.



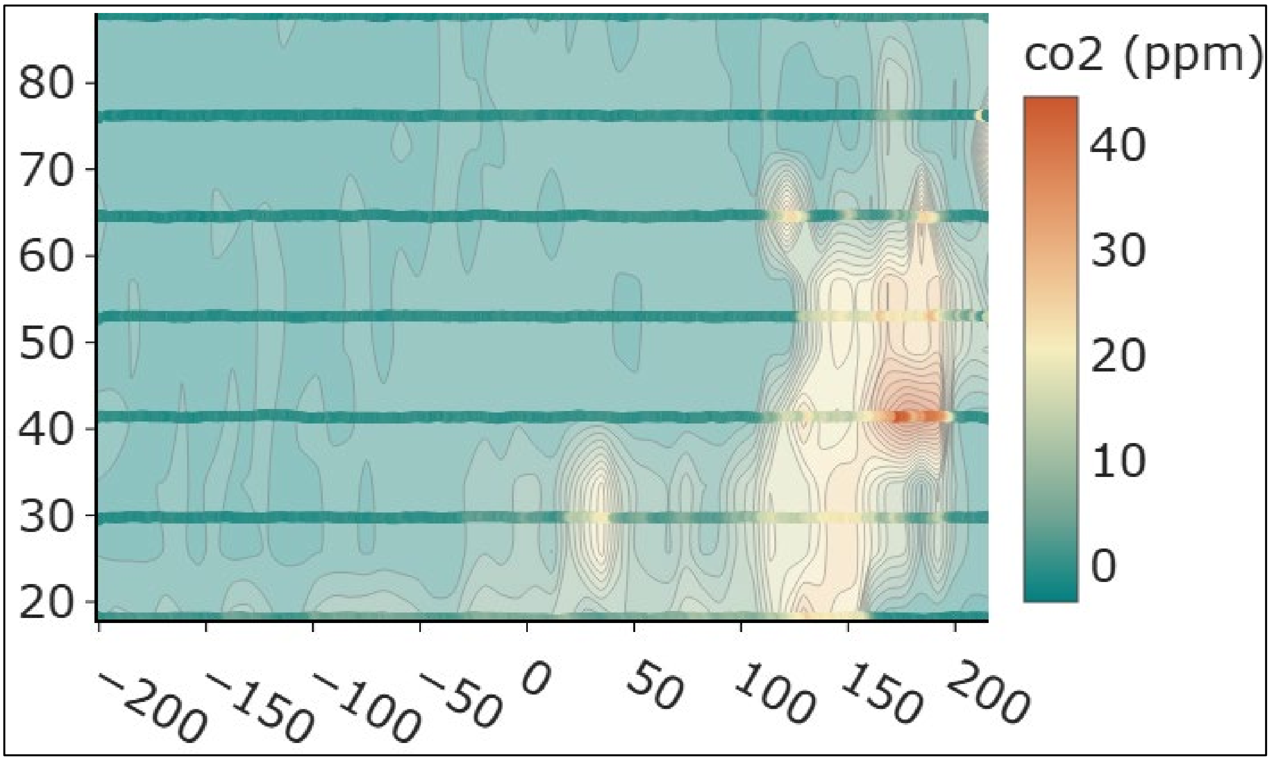
Note: The x-axis represents horizontal distance from the plane, and the y-axis represents altitude.

A.2. 2 CH_4 concentration enhancements (above background concentrations) in Site Y, 29/10/2024, Flight 2, with krigged contours



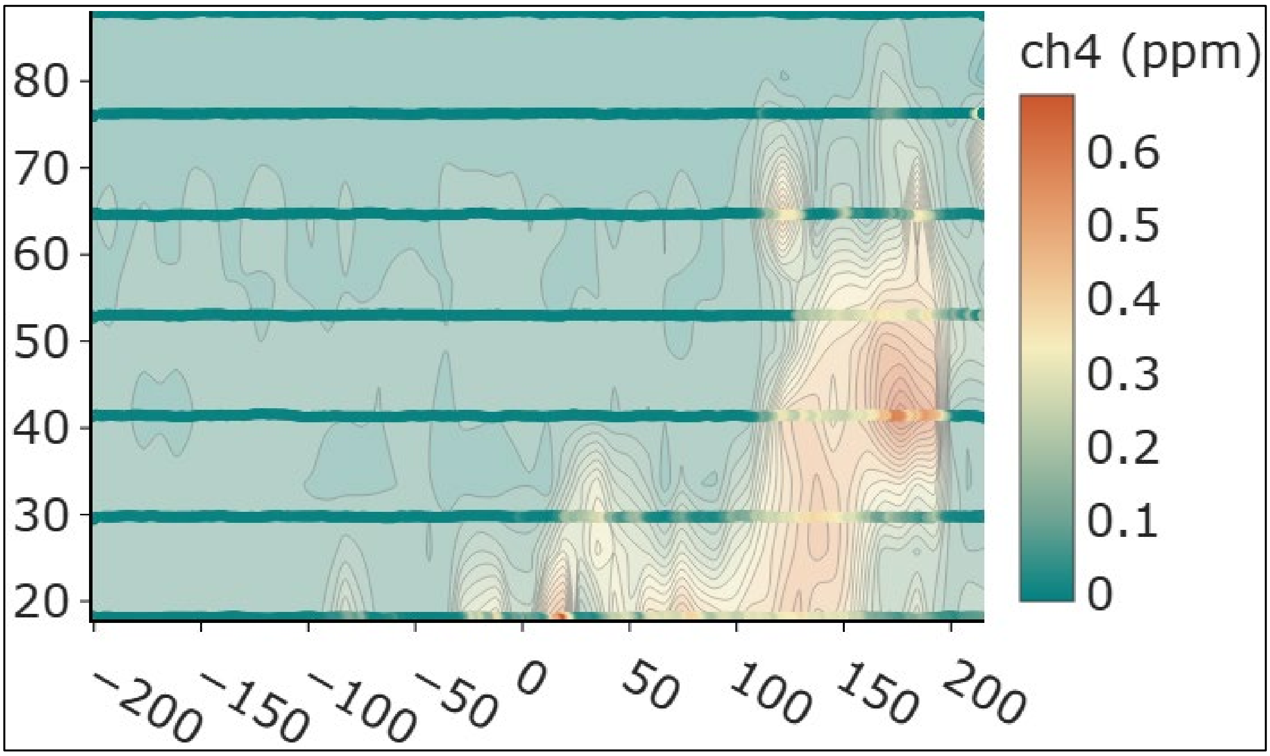
Note: The x-axis represents horizontal distance from the plane, and the y-axis represents altitude.

A.2. 3 CO_2 concentration enhancements (above background concentrations) in Site X, 26/11/2024, Flight 4, with kriged contours.



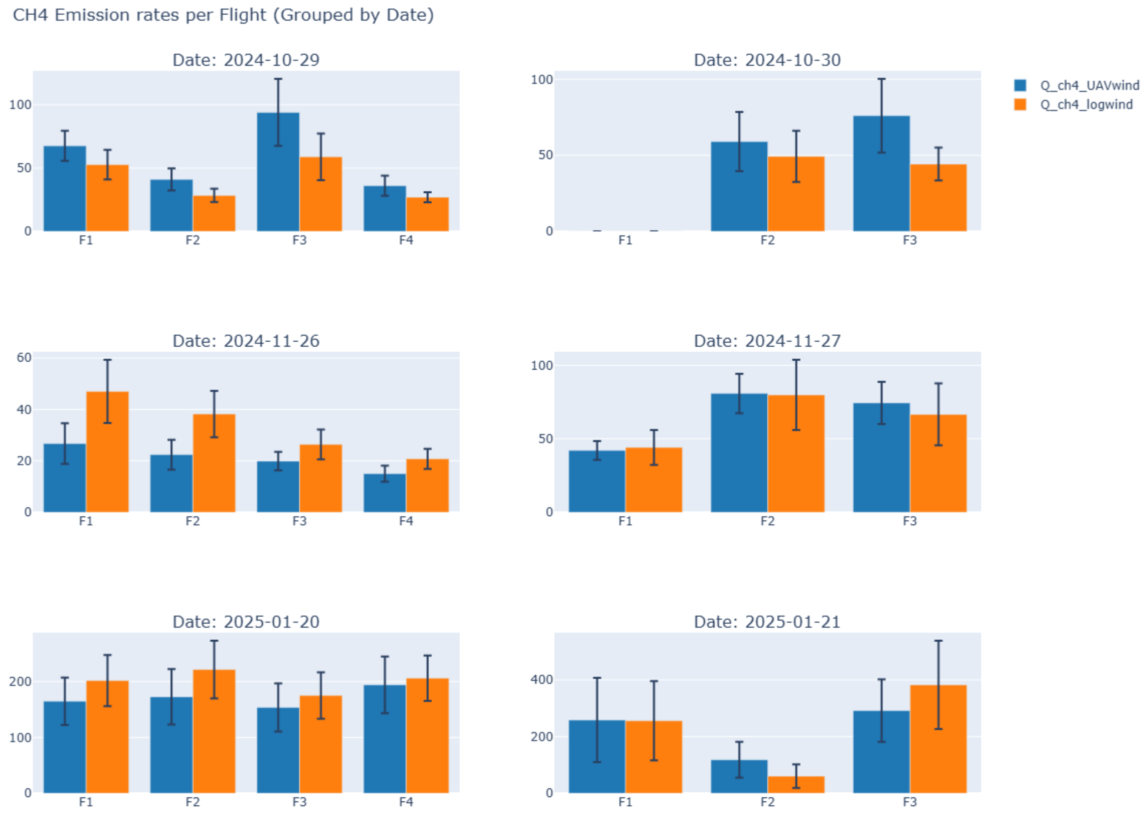
Note: The x-axis represents horizontal distance from the plane, and the y-axis represents altitude.

A.2. 4 CH_4 concentration enhancements (above background concentrations) in Site X, 26/11/2024, Flight 4, with kriged contours



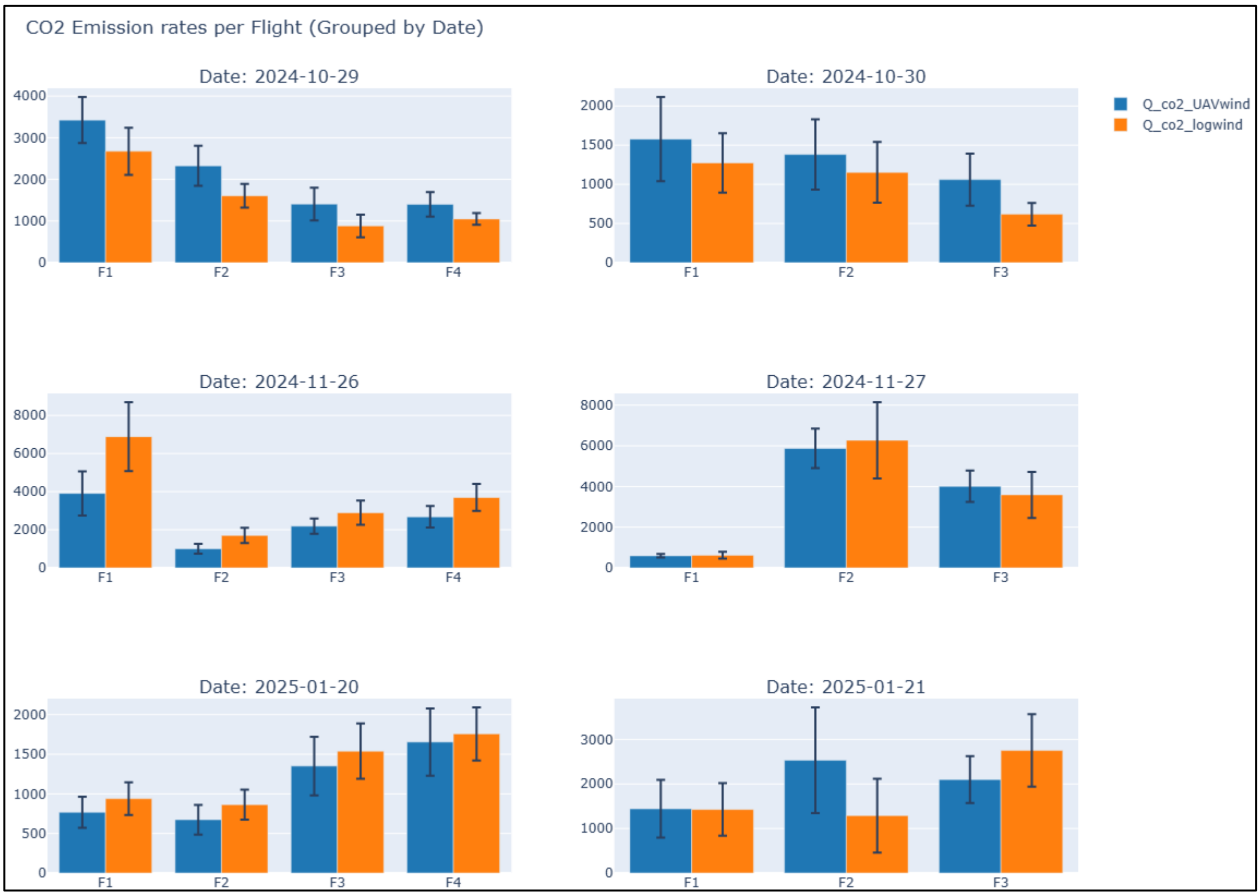
Note: The x-axis represents horizontal distance from the plane, and the y-axis represents altitude.

A.2. 5 CH_4 fluxes (in kg/h) for Sites Y (29–30/10/2024), X (26–27/11/2024), and Z (20–21/01/2025)



Note: Each bar represents the flux measurement for the corresponding site and flight, with the bar range indicating the uncertainty in the flux estimate. Blue bars represent fluxes based on UAV-based wind measurements, while orange bars represent fluxes based on Log10 wind data

A.2. 6 CH_4 fluxes (in kg/h) for Sites Y (29–30/10/2024), X (26–27/11/2024), and Z (20–21/01/2025)



Note: Each bar represents the flux measurement for the corresponding site and flight, with the bar range indicating the uncertainty in the flux estimate. Blue bars represent fluxes based on UAV-based wind measurements, while orange bars represent fluxes based on Log10 wind data

Plume structure and emission characteristics

Table 24 presents the combustion efficiency and the ratio $\Delta CH_4/\Delta CO_2$. Column Time shows the flight times for each survey. The latter is used as an indicator of anthropogenic emissions related to flaring (e.g., Nara et al., (2014)[48] references therein). Values below 20 ppb/ppm typically indicate combustion-related emissions with minimal influence from fugitive or background CH_4. In contrast, ratios greater than 20 ppb/ppm suggest a significant contribution from uncombusted (fugitive) methane sources.

A.2. 7 Estimated combustion of landfill gas efficiencies from UAV measurementsmass balance surveys.

Site	Date	Time	Efficiency rectangle (%)	Efficiency Points (%)	$\Delta CH_4/\Delta CO2$ Rectangle (ppb/ppm)	$\Delta CH_4/\Delta CO2$ Points (ppb/ppm)
Site Y1	**29/10/2024**	14:00-14:12	99.26	99.36	7.44	6.44
Site Y1	**29/10/2024**	15:24-15:36	98.40	99.01	16.24	9.95
Site Y1	**29/10/2024**	16:00-16:20	96.21	97.28	39.33	27.94
Site Y1	**30/10/2024**	10:20-10:34	-	-	-	-
Site Y1	**30/10/2024**	10:47-11:01 11:12-11:25	97.21	97.25	28.67	28.17
Site Y1	**30/10/2024**	11:41-11:53 12:02-12:13	97.88	98.89	21.62	11.13
Site X	**26/11/2024**	12:11-12:24 12:33-12:41	98.99	98.86	10.15	11.52
Site X	**26/11/2024**	14:37-14:49 14:57-15:04	98.30	98.44	17.25	15.82
Site X	**26/11/2024**	15:17-15:28 15:35-15:45	98.83	98.79	11.83	12.23
Site X	**26/11/2024**	15:55-16:09	98.41	98.52	16.15	14.96
Site X	**27/11/2024**	13:15-13:29 13:35-13:49	98.28	98.26	17.43	17.69
Site X	**27/11/2024**	14:02-14:15 14:25-14:41	98.24	98.61	17.90	14.02
Site X	**27/11/2024**	14:53-15:08 15:15-15:30	98.49	98.56	15.24	14.55
Site Z	**20/01/2025**	13:10-13:21	63.66	66.34	570.77	507.23
Site Z	**20/01/2025**	13:42-13:53	65.24	63.29	532.61	569.96
Site Z	**20/01/2025**	14:26-14:39	78.02	77.88	281.68	283.98

Site	Date	Time	Efficiency rectangle (%)	Efficiency Points (%)	$\Delta CH_4/\Delta CO2$ Rectangle (ppb/ppm)	$\Delta CH_4/\Delta CO2$ Points (ppb/ppm)
		14:45-14:48				
Site Z	**20/01/2025**	15:09-15:21	73.66	73.42	357.44	361.97
Site Z	**21/01/2025**	11:17-11:29 11:36-11:48	66.48	64.29	503.98	555.39
Site Z	**21/01/2025**	12:45-12:56 13:13-13:18	86.36	85.79	157.81	165.51
Site Z	**21/01/2025**	14:14-14:27 14:36-14:46	74.51	72.77	341.92	374.10

Site Y1 (29-30 October 2024)

Site Y1 exhibited intermediate values of carbon dioxide and methane fluxes, with significant variability in the former (Figure. 13 and Figure 14). Methane fluxes remained relatively stable over the two days, ranging from 36 to 76 kg/h, with a peak of 94 kg/h on the first day. Carbon dioxide fluxes showed a decreasing trend throughout the survey. The first flight of the first day recorded a flux of 3424 kg/h, which dropped to 1059 kg/h by the end of the survey on the second day. Across all analysed flights, wind variability was the primary contributor to total uncertainty, with values ranging from 83.02% to 97.06%, and a mean contribution of approximately 93.42%. Background concentration contributed between 2.94% and 16.98%, averaging 6.58%, indicating a consistently minor influence on the total uncertainty.

On 29 October 2024, four UAV flights were conducted under relatively stable meteorological conditions, with northwesterly winds ranging from 3 to 4.5 m/s on average. In all flights, two distinct air masses were observed, with CO_2 and CH_4 plumes exhibiting different vertical distributions.

CO_2 plumes had a large spatial extent and high variability, with enhancements up to 40 ppm and mean ΔCO_2 values within the analysis rectangles around 9.3 ppm. These plumes were generally located between 15 and 80 m altitude, although a secondary CO_2 plume was detected at 120 m in Flight 1, potentially indicating an external source.

Across all flights, the main CO_2 plume was collocated with a weaker secondary CH_4 maximum (e.g. Figure 9 and Figure 10). This CH_4 signal was particularly weak in Flights 1 and 2. In contrast, the strongest CH_4 plumes were consistently found close to the surface for all flights, up to 25–30 m (in Flights 1 and 4) or slightly higher (up to 50–60 m in Flights 2 and 3) depending on the wind conditions. This indicates that the main source of CH_4 in Site Y is fugitive emissions of landfill gas from the active landfill area.

$\Delta CH_4/\Delta CO_2$ ratios computed within the CO_2 plume regions indicated predominantly anthropogenic combustion-related CH_4 emissions in Flights 2 and 3, while a high ratio in Flight 4 suggested a mixed signature including fugitive emissions (Table 24). Flight 1 did not yield a conclusive interpretation based on the ratio. Combustion efficiencies derived from the same CO_2-rich regions ranged between 97.51–99.36% for Flights 1–3, consistent with well-oxidized emissions, and slightly lower in Flight 4 (96.21–97.28%), supporting the presence of less efficient combustion and/or fugitive CH_4 sources.

On 30 October 2024, the plumes at Site Y exhibited a different pattern compared to the previous day. Plumes were less distinct overall, particularly for CO_2, which showed higher variability and weaker spatial definition across both flights. Winds remained northwesterly but slightly weaker (2–3.5 m/s), potentially contributing to greater mixing and less stratified plume structures.

In both flights, two vertically separated air masses were again observed. In Flight 1, the main CO_2 plume was detected between 40–60 m, while the primary CH_4 enhancement occurred below 40 m, consistent with near-surface landfill gas. A secondary CO_2 maximum at 100–120 m was not associated with CH_4 enhancements, suggesting a separate source. The $\Delta CH_4/\Delta CO_2$ ratio was elevated, pointing to a mixture of anthropogenic and fugitive CH_4 emissions, supported by a slightly lower combustion efficiency (97.21–97.25%, Table 1).

Flight 2 showed increased variability in CO_2 concentrations across the plume and a less defined structure. The main CO_2 enhancement occurred at higher altitudes (70–100 m), while CH_4 concentrations were more broadly distributed below 70 m but of lower amplitude compared to the previous day. Combustion efficiency ranges from 97.88–98.89%, indicating predominantly well-oxidized emissions.

Overall, the first day there was a consistent spatial and vertical separation of plume types at the site, with CH_4 likely dominated by landfill gas near the surface and CO_2 associated with combustion sources at higher altitudes. On the second day, lower wind resulted in more diffuse and intermixed plumes, with indications of both combustion and fugitive sources.

Site X (26-27 November 2024)

Methane fluxes showed low variability on the first day, ranging from 15 to 26 kg/h, with stable and low emissions (Figure 13 and Figure 14). Methane fluxes recorded on the first day were the lowest among the three sites. On the second day, there was an increase, ranging from 42 to 80 kg/h; however, these values remained the lowest compared to the other sites. A similar pattern was observed for CO_2 fluxes. Emissions were lower on the first day and peaked on the second day, showing greater variability than methane. CO_2

fluxes ranged from 997 to 3905 kg/h on the first day and increased from 591 to 5873 kg/h on the second day. Overall, Site X exhibited the highest CO_2 fluxes compared to Sites Y and Z. Wind variability also dominated the flux uncertainty at this site, with contributions ranging from 97.2% to 99.87% and a mean of about 98.74%. Background concentrations accounted for only 0.13% to 2.8%, with a mean of 1.26%.

On 26 November 2024 at Site X, four UAV flights were conducted under stronger southwesterly winds (6.2–9.8 m/s). Across most flights, two distinct air masses were observed, except in Flight 4, which showed a more homogeneous structure.

Flight 1 showed elevated background CO_2 across the plane, but with moderate plume amplitude compared to other flights and to Site Y. The main CH_4 plume in both flights were confined below 40m, consistent with fugitive emissions from landfill gas. However, the amplitude of the plumes is significantly lower compared to Site Y (1 and 6 ppm respectively) in all flights. $\Delta CH_4/\Delta CO_2$ ratios within the CO_2 plumes pointed to predominantly anthropogenic (combustion-related) sources, supported by high combustion efficiencies (>98.86 and >98.3 in Flights 1 and 2, respectively; Table 24). In Flights 1 and 2, the CO_2 plumes were laterally displaced toward the right edge of the plane, potentially leading to underestimated fluxes.

Flight 3 captured a well-defined CO_2 plume centrally located in the plane at 60–100 m, with the highest amplitude of the day. This was collocated with a secondary CH_4 maximum. The ratio analysis again indicated combustion-related CH_4 emissions, with combustion efficiency from 98.79-98.83. In contrast, Flight 4 exhibited a single, vertically extended plume from the surface to 70 m, with full colocation of CH_4 and CO_2 and the lowest CH_4 amplitude observed (Figure 5). This suggests effective gas control, with no strong evidence of near-surface fugitive CH_4 emissions and high combustion efficiency (98.41-98.52).

On 27 November 2024, flights were conducted under northwesterly winds of 8.2–9.2 m/s, leading to a change in flight location compared to the previous day. Across all three flights, CO_2 and CH_4 plumes were consistently well-captured and colocated, with CO_2 enhancements showing the highest amplitudes observed at this site, while CH_4 plumes exhibited the lowest amplitudes across all surveyed sites. Each flight also detected a secondary CH_4 plume close to the surface (up to 40–50 m), likely associated with landfill gas, although its amplitude remained below 1 ppm. In Flight 1, this surface CH_4 plume was more spatially coherent, suggesting a more stable fugitive source. Despite the presence of these surface signals, $\Delta CH_4/\Delta CO_2$ ratios across all flights indicated predominantly anthropogenic combustion-related emissions, with negligible influence from fugitive CH_4 sources. Combustion efficiency remained consistently high throughout the day, ranging from 98.24 to 98.61.

Overall, emissions at Site X were well managed and dominated by controlled, combustion-driven sources, as evidenced by the clear co-location of CO_2 and CH_4 plumes, high CO_2

amplitudes and low CH_4 enhancements- indicating efficient combustion (combustion efficiency > 98.26) and minimal fugitive leakage (low $\Delta CH_4/\Delta CO_2$ ratios).

Site Z (20-21 January 2025)

Methane fluxes at Site Z exhibited relatively small variability between flights over the two survey days (Figure 13 and Figure 14). On the first day, fluxes ranged from 153 to 194 kg/h, while on the second day, values increased from 118 to 291 kg/h. Among all sites, Site Z had the highest methane fluxes. Carbon dioxide fluxes showed significant variability. On the first day, emissions were relatively low, starting at 673 kg/h and increasing to 1654 kg/h by the last flight of the day. The upward trend continued the second day, with fluxes increasing from 1441 to 2532 kg/h. Wind variability remained the primary source of uncertainty in most flights, contributing between 44.37% and 96.39%, with a mean of approximately 80.55%. However, background concentration played a more significant role compared to the other sites, ranging from 3.61% to 55.63%, and averaging 19.45%. Notably, in two instances, background concentration exceeded 20%, and in one case, it became the dominant contributor—highlighting increased variability in the uncertainty partitioning at this site.

At this site on 20 January 2025, all four flights revealed well-collocated CO_2 and CH_4 plumes extending up to 50 m, except in Flight 3, where plumes were confined below 30 m. Both gases showed elevated concentrations, with CH_4 amplitudes being the highest among all surveyed sites, and wind conditions primarily from the SW (5.5-7 m/s).

Flight 1 featured broad, well-captured plumes with CH_4 slightly more extended near the surface, suggesting combined anthropogenic and fugitive sources. The impact of fugitive emission is also supported by a high $\Delta CH_4/\Delta CO_2$ ratio and low combustion efficiency (63.7–66.3) in the CO2-plume area (Table 24). Flight 2 showed a similar vertical structure but with more concentrated plumes and a distinct secondary CH_4 enhancement near the surface, again consistent with mixed emissions and low combustion efficiency (63.3–65.2).

Flight 3 differed slightly, with shallower but horizontally broader plumes, likely due to air mass accumulation near the surface under lighter wind, and improved combustion performance (77.9–78.0). Flight 4 resembled Flights 1 and 2, but with the highest CO_2 amplitude and CH_4 levels comparable to Flight 2, along with moderate combustion efficiency (73.4–73.7). In all cases, $\Delta CH_4/\Delta CO_2$ ratios indicated both anthropogenic and fugitive CH_4 contributions.

On 21 January 2025, this site exhibited well-collocated CO_2 and CH_4 plumes, with particularly wide vertical and horizontal extents during Flights 1 and 2, reaching up to 100 m for CO_2. Flight 3 showed plumes up to 40 m. All flights were characterized by slack and variable winds (1–6 m/s) with shifting directions (W–WNW to S to WSW–W), influencing plume distribution and signal strength.

In Flight 1, plumes extended from the surface to the top of the measurement plane, especially for CO_2, which may be underestimated as concentrations remained high at the upper edge. This flight recorded the highest amplitudes for both gases among all sites, with CH_4 peaks mostly below 50 m. Slack winds (~2 m/s) likely contributed to vertical accumulation. $\Delta CH_4/\Delta CO_2$ ratios indicated both anthropogenic and fugitive CH_4 sources, with low combustion efficiency (64.3–66.5).

Flight 2 displayed a similar pattern, though the plume shifted laterally toward the left side. It also showed evidence of mixed emission sources, but with a notable improvement in combustion efficiency (85.8–86.4), despite the lowest wind speeds observed (1 m/s).

In Flight 3, plume characteristics resembled those of Flight 1 but were confined below 40 m. CH_4 concentrations were higher than in Flight 2, likely due to a wind shift to WSW and an increase in wind speed (6 m/s), which may have enhanced the signal from the active area. Again, $\Delta CH_4/\Delta CO_2$ ratios pointed to combined sources, with combustion efficiency ranging from 72.8 to 74.5.

Overall, emissions at this site were dominated by mixed anthropogenic and fugitive CH_4 sources, with consistently high CH_4 amplitudes and well-collocated CO_2–CH_4 plumes. Despite some improvement, overall combustion performance was variable, suggesting less effective gas control compared to Sites X and Y.

Synthesis

Overall, across all sites, we consistently observed two air mass types: i) CO_2-rich, CH_4-poor plumes at mid to high altitudes—indicative of combustion products and ii) CH_4-rich, CO_2-weak plumes near the surface—consistent with fugitive emissions from raw landfill gas.

Site Y showed the most complex vertical structure and source separation, whereas Site X demonstrated consistent and efficient combustion with minimal CH_4 leakage. Site Z had the highest CH_4 emissions overall, likely reflecting both intense combustion activity and substantial fugitive emissions, particularly under low wind and variable flow conditions.

Differences and Comparison of UAV-Based and Log10 Wind

The differences between UAV-based wind and Log10 wind methods are evident for both CH_4 and CO_2 flux estimates (Figure 13 and Figure 14). For CH_4 flux, UAV-based wind generally produces lower flux estimates compared to Log10 wind at most sites. For instance, at Site Z on 20/01/2025, CH_4 flux using UAV-based wind is 164.8 ± 42.6 kg/h, whereas CH_4 flux using Log10 wind estimates 201.9 ± 45.7 kg/h. However, there are instances where UAV-based estimates are higher, such as at Site Y on 29-30/10/2024.

For CO_2 flux, the differences are even more pronounced, with Log10 wind consistently yielding higher flux estimates (except at Site Y). At Site Z on 20/01/2025, CO_2 flux using UAV-based wind is 767.2 ± 194.7 kg/h, while CO_2 flux using Log10 wind estimates 939.5 ± 207.7 kg/h. These discrepancies emphasize the sensitivity of mass balance calculations to the choice of wind data input method.

While the variability patterns observed using both methods are generally consistent, Log10 wind consistently yields higher flux estimates. This suggests that the Log10 wind method may not adequately capture localized variations in wind flow, potentially overestimating wind speed or failing to fully account for dynamic wind changes. UAV-based measurements, being more responsive to real-time atmospheric conditions, can more accurately reflect these variations. The discrepancies between the methods highlight the importance of carefully selecting the wind data input method, as it can significantly influence both flux estimates and the associated uncertainties. To summarize, we recommend onboard wind measurement where possible, recognising that log10 profile assumptions can introduce a significant unknown emissions bias (up to ±25% for methane in this study).

A.3. Methane collection efficiencies

Figure A.3. 1 Methane collection efficiency at Site X

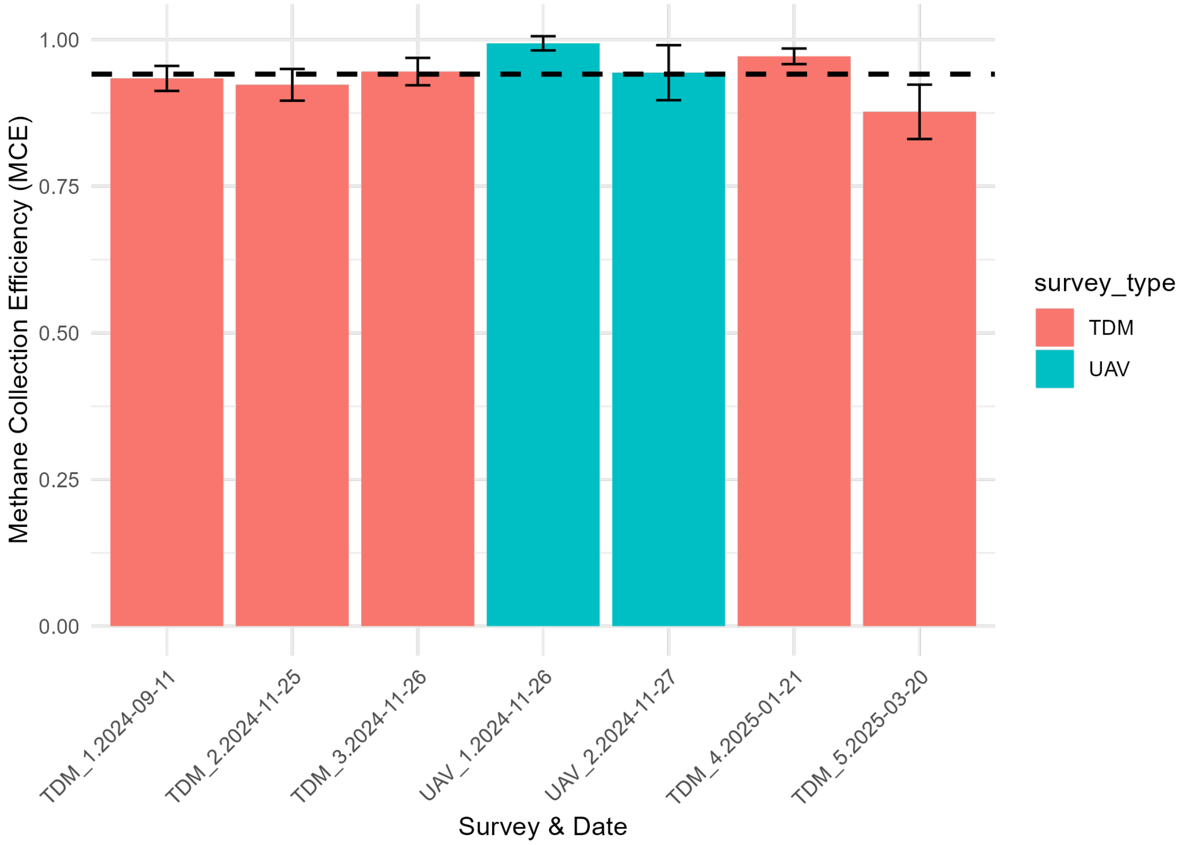


Figure A.3. 2 Methane collection efficiency at Site Y1

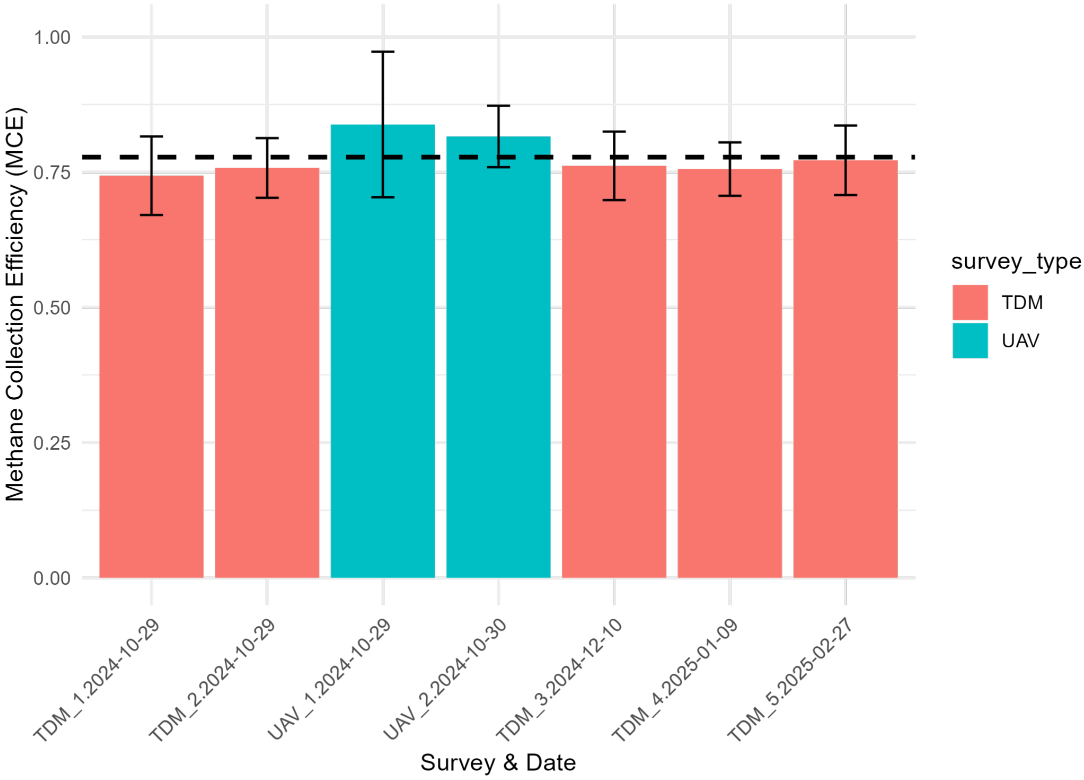


Figure A.3. 3 Methane collection efficiency at Site Y2

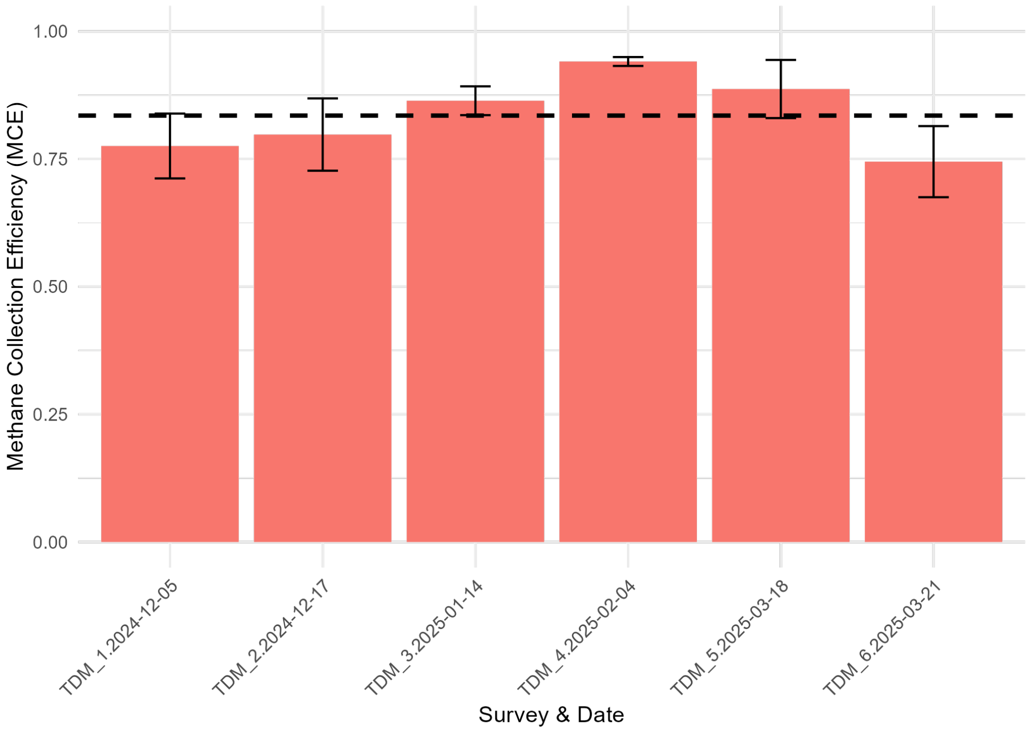


Figure A.3. 4 Methane collection efficiency at Site Z

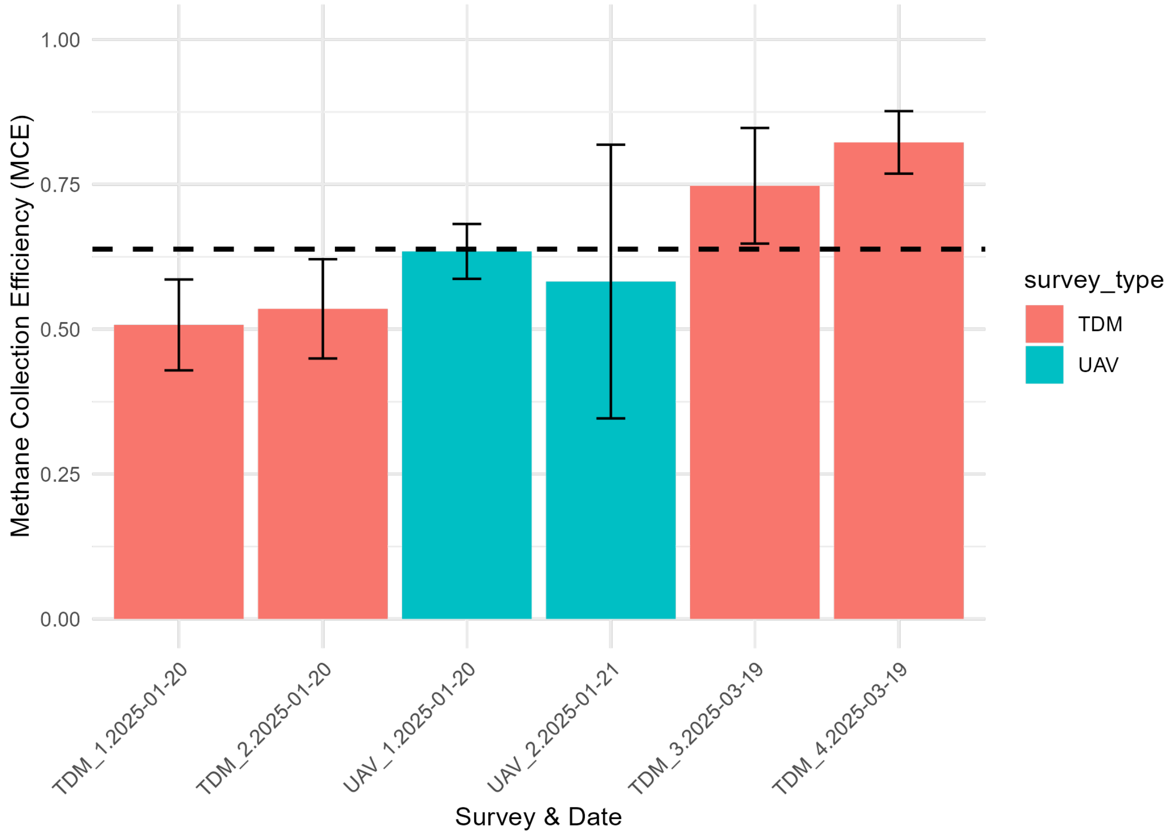
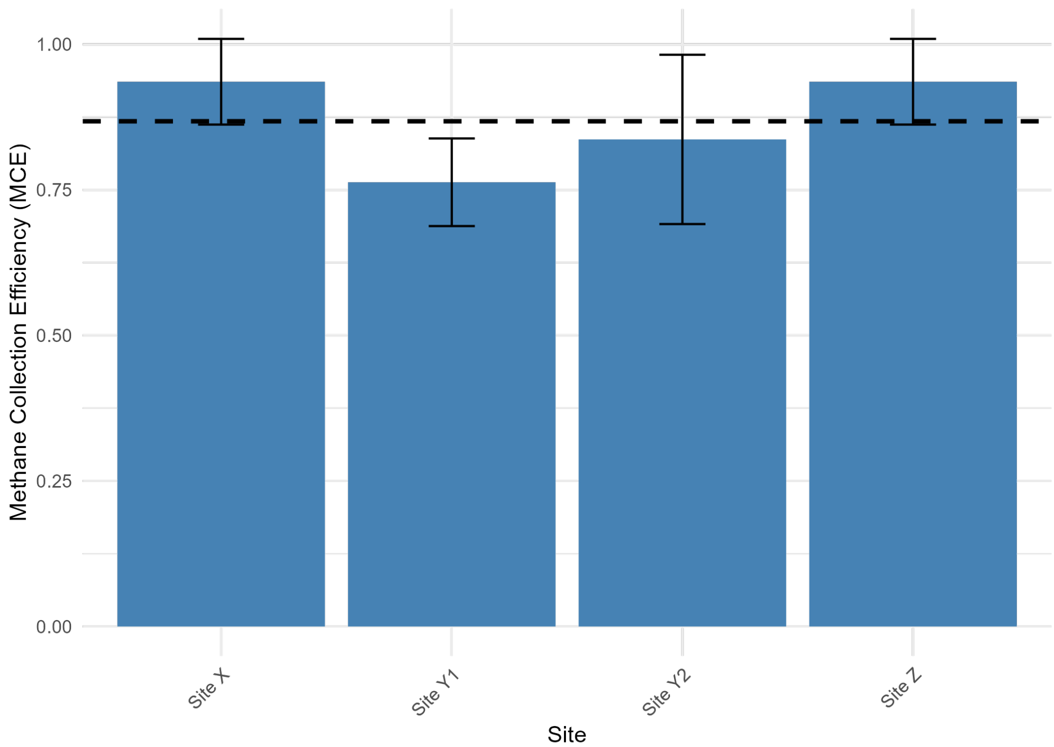


Figure A.3. 5 Methane collection efficiency across all sites



A.4. Detailed survey results

Table A.4. 1 Site X Survey Results

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 1	1.01	11/09/2024	20:17	1.8	59	11.9
Survey 1	1.02	11/09/2024	20:24	1.7	90	17.9
Survey 1	1.03	11/09/2024	20:31	3.8	71	14.3
Survey 1	1.04	11/09/2024	20:36	3.9	78	15.6
Survey 1	1.05	11/09/2024	20:40	3.8	78	15.7
Survey 1	1.06	11/09/2024	20:44	2.7	87	17.4
Survey 1	1.07	11/09/2024	20:56	3.7	71	14.2
Survey 1	1.08	11/09/2024	21:00	3.6	72	14.4
Survey 1	1.09	11/09/2024	21:05	3.7	70	14.1
Survey 1	1.1	11/09/2024	21:10	5.3	70	14.0
Survey 1	1.11	11/09/2024	21:14	5.2	65	13.0
Survey 1	1.12	11/09/2024	21:21	5.2	64	12.7
Survey 1	1.13	11/09/2024	21:25	3.6	61	12.2
Survey 1	1.14	11/09/2024	21:28	3.6	59	11.7

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 2	2.01	25/11/2024	14:48	1.0	93	18.6
Survey 2	2.02	25/11/2024	14:56	2.5	89	17.8
Survey 2	2.03	25/11/2024	15:03	2.7	78	15.5
Survey 2	2.04	25/11/2024	15:07	2.8	77	15.4
Survey 2	2.05	25/11/2024	15:14	4.0	92	18.4
Survey 2	2.06	25/11/2024	15:20	4.1	95	19.0
Survey 2	2.07	25/11/2024	15:24	2.9	93	18.6
Survey 2	2.08	25/11/2024	15:32	4.2	93	18.6
Survey 2	2.09	25/11/2024	15:35	4.3	82	16.5
Survey 2	2.1	25/11/2024	15:40	4.3	63	12.5
Survey 2	2.11	25/11/2024	15:43	4.6	92	18.4
Survey 2	2.12	25/11/2024	15:48	3.3	76	15.1
Survey 2	2.13	25/11/2024	15:55	2.6	80	16.1
Survey 2	2.14	25/11/2024	16:01	1.2	54	10.8
Survey 3	3.01	26/11/2024	07:33	1.0	57	11.3
Survey 3	3.02	26/11/2024	07:37	1.1	82	16.4

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 3	3.04	26/11/2024	07:48	1.2	80	16.1
Survey 3	3.05	26/11/2024	07:57	3.6	77	15.3
Survey 3	3.06	26/11/2024	08:02	3.7	50	10.0
Survey 3	3.07	26/11/2024	08:05	4.1	58	11.7
Survey 3	3.08	26/11/2024	08:16	4.0	73	14.5
Survey 3	3.09	26/11/2024	08:26	4.0	58	11.7
Survey 3	3.1	26/11/2024	08:30	3.7	66	13.2
Survey 3	3.11	26/11/2024	08:34	3.6	53	10.6
Survey 3	3.12	26/11/2024	08:37	3.3	62	12.4
Survey 3	3.13	26/11/2024	08:44	4.8	60	12.0
Survey 3	3.14	26/11/2024	08:49	4.8	53	10.6
Survey 3	3.15	26/11/2024	08:52	4.0	46	9.3
Survey 3	3.16	26/11/2024	08:57	4.0	54	10.7
Survey 3	3.17	26/11/2024	09:01	4.0	55	11.0
Survey 3	3.18	26/11/2024	09:06	3.1	58	11.5
Survey 3	3.19	26/11/2024	09:12	2.8	65	13.1

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 3	3.2	26/11/2024	09:17	2.7	63	12.5
UAV mass balance		26/11/2024	12:11		27	7.9
UAV mass balance		26/11/2024	14:37		22	5.8
UAV mass balance		26/11/2024	15:17		20	3.6
UAV mass balance		26/11/2024	15:55		15	3.1
UAV mass balance		27/11/2024	13:15		42	6.4
UAV mass balance		27/11/2024	14:02		81	13.4
UAV mass balance		27/11/2024	14:53		74	14.3
Survey 4	4.01	21/01/2025	19:38	1.3	36	7.2
Survey 4	4.02	21/01/2025	19:45	1.2	35	6.9
Survey 4	4.03	21/01/2025	19:49	1.2	36	7.2

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 4	4.04	21/01/2025	19:53	1.2	36	7.3
Survey 4	4.05	21/01/2025	19:59	1.2	37	7.4
Survey 4	4.06	21/01/2025	20:04	1.2	33	6.5
Survey 4	4.07	21/01/2025	20:08	1.2	37	7.4
Survey 4	4.08	21/01/2025	20:12	1.2	40	7.9
Survey 4	4.09	21/01/2025	20:16	1.2	41	8.3
Survey 4	4.1	21/01/2025	20:21	1.2	41	8.2
Survey 4	4.11	21/01/2025	20:26	1.3	31	6.2
Survey 4	4.12	21/01/2025	20:43	1.2	31	6.2
Survey 4	4.13	21/01/2025	20:49	1.3	33	6.6
Survey 4	4.14	21/01/2025	20:54	1.3	25	5.0
Survey 4	4.15	21/01/2025	20:57	1.3	31	6.2
Survey 4	4.16	21/01/2025	21:01	1.2	26	0.9
Survey 4	4.17	21/01/2025	21:05	1.2	36	7.2
Survey 4	4.18	21/01/2025	21:11	1.2	28	5.6
Survey 4	4.19	21/01/2025	21:15	1.2	30	6.0

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 4	4.2	21/01/2025	21:18	1.2	41	8.3
Survey 4	4.21	21/01/2025	21:21	1.3	37	7.4
Survey 4	4.22	21/01/2025	21:26	1.2	28	5.6
Survey 4	4.23	21/01/2025	21:31	1.2	38	7.6
Survey 5	5.01	20/03/2025	18:42	1.7	101	20.3
Survey 5	5.02	20/03/2025	18:59	1.8	91	18.1
Survey 5	5.03	20/03/2025	19:05	1.8	94	18.9
Survey 5	5.04	20/03/2025	19:09	1.8	124	24.7
Survey 5	5.05	20/03/2025	19:14	1.8	108	21.7
Survey 5	5.06	20/03/2025	19:20	1.8	119	23.9
Survey 5	5.07	20/03/2025	19:27	1.9	123	24.6
Survey 5	5.08	20/03/2025	19:34	1.9	126	25.2
Survey 5	5.09	20/03/2025	19:40	2.0	112	22.5
Survey 5	5.1	20/03/2025	19:45	3.7	89	17.7
Survey 5	5.11	20/03/2025	19:54	3.7	66	13.2
Survey 5	5.12	20/03/2025	20:07	4.0	87	17.3

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 5	5.13	20/03/2025	20:16	4.0	74	14.8
Survey 5	5.14	20/03/2025	20:26	4.0	102	20.3
Survey 5	5.15	20/03/2025	20:33	4.0	137	27.4
Survey 5	5.16	20/03/2025	20:44	1.8	115	22.9
Survey 5	5.17	20/03/2025	20:56	2.7	126	25.1
Survey 5	5.18	20/03/2025	21:05	2.2	126	25.1

Table A.4. 2 Site Y1 Results

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
UAV mass balance		29/10/2024	13:12		67.5	11.9
UAV mass balance		29/10/2024	14:00		41.1	8.7
UAV mass balance		29/10/2024	15:24		94.0	26.5
UAV mass balance		29/10/2024	16:00		36.0	7.9

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 1	1.01	29/10/2024	15:51	2.2	109	21.9
Survey 1	1.02	29/10/2024	15:55	2.2	126	25.2
Survey 1	1.03	29/10/2024	15:59	2.2	117	23.3
Survey 1	1.04	29/10/2024	16:06	2.2	99	19.7
Survey 1	1.05	29/10/2024	16:09	2.3	96	19.2
Survey 1	1.06	29/10/2024	16:16	4.5	131	26.3
Survey 1	1.07	29/10/2024	16:21	3.8	123	24.5
Survey 1	1.08	29/10/2024	16:28	2.4	105	20.9
Survey 1	1.09	29/10/2024	16:33	2.4	94	18.7
Survey 1	1.1	29/10/2024	16:54	3.9	99	19.8
Survey 1	1.11	29/10/2024	17:01	2.2	91	18.1
Survey 1	1.12	29/10/2024	17:07	2.2	83	16.7
Survey 1	1.13	29/10/2024	17:11	2.2	93	18.7
Survey 1	1.14	29/10/2024	17:15	2.2	90	18.1
Survey 1	1.15	29/10/2024	17:21	4.0	121	24.1
Survey 1	1.16	29/10/2024	17:27	3.9	81	16.2

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 1	1.17	29/10/2024	17:36	2.1	64	12.9
Survey 1	1.18	29/10/2024	17:42	2.2	85	16.9
Survey 1	1.19	29/10/2024	17:46	2.2	97	19.4
Survey 2	2.01	29/10/2024	21:57	1.9	106	21.2
Survey 2	2.02	29/10/2024	22:01	1.9	90	17.9
Survey 2	2.03	29/10/2024	22:03	1.9	84	16.7
Survey 2	2.04	29/10/2024	22:06	1.9	110	22.1
Survey 2	2.05	29/10/2024	22:09	1.9	91	18.2
Survey 2	2.06	29/10/2024	22:13	1.9	77	15.4
Survey 2	2.07	29/10/2024	22:18	4.2	109	21.8
Survey 2	2.08	29/10/2024	22:24	4.3	109	21.9
Survey 2	2.09	29/10/2024	22:29	4.3	104	20.7
Survey 2	2.1	29/10/2024	22:35	4.3	96	19.1
Survey 2	2.11	29/10/2024	22:41	4.3	94	18.8
Survey 2	2.12	29/10/2024	22:45	1.9	76	15.2
Survey 2	2.13	29/10/2024	22:52	2.0	66	13.2

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 2	2.14	29/10/2024	22:56	2.2	86	17.2
Survey 2	2.15	29/10/2024	23:00	1.9	98	19.6
Survey 2	2.16	29/10/2024	23:03	1.9	95	18.9
Survey 2	2.17	29/10/2024	23:07	2.3	101	20.1
UAV mass balance		30/10/2024	10:47		59	19.4
UAV mass balance		30/10/2024	11:41		76	24.2
Survey 3	3.01	10/12/2024	19:44	4.2	78	15.6
Survey 3	3.02	10/12/2024	19:52	4.2	91	18.2
Survey 3	3.03	10/12/2024	19:59	4.2	74	14.7
Survey 3	3.04	10/12/2024	20:07	4.2	81	16.1
Survey 3	3.05	10/12/2024	20:11	3.5	103	20.5
Survey 3	3.06	10/12/2024	20:17	3.6	103	20.7
Survey 3	3.07	10/12/2024	20:24	3.7	93	18.6
Survey 3	3.08	10/12/2024	20:30	3.8	125	25.0
Survey 3	3.09	10/12/2024	20:37	4.0	80	16.1

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 3	3.1	10/12/2024	20:46	3.9	98	19.5
Survey 3	3.11	10/12/2024	20:55	4.0	117	23.5
Survey 3	3.12	10/12/2024	21:03	4.2	104	20.8
Survey 3	3.13	10/12/2024	21:11	4.1	87	17.4
Survey 4	4.01	09/01/2025	19:44	3.7	93	18.6
Survey 4	4.02	09/01/2025	19:51	3.6	85	17.1
Survey 4	4.03	09/01/2025	19:55	3.6	86	17.2
Survey 4	4.04	09/01/2025	19:59	3.6	90	17.9
Survey 4	4.05	09/01/2025	20:03	3.5	94	18.9
Survey 4	4.06	09/01/2025	20:08	3.5	98	19.7
Survey 4	4.07	09/01/2025	20:13	3.5	100	20.0
Survey 4	4.08	09/01/2025	20:37	3.7	98	19.6
Survey 4	4.09	09/01/2025	20:42	3.6	75	15.0
Survey 4	4.1	09/01/2025	20:47	3.5	82	16.4
Survey 4	4.11	09/01/2025	20:51	3.4	85	16.9
Survey 4	4.12	09/01/2025	20:56	3.1	74	14.7

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 4	4.13	09/01/2025	20:59	3.4	77	15.3
Survey 4	4.14	09/01/2025	21:03	3.4	111	22.2
Survey 4	4.15	09/01/2025	21:06	3.4	106	21.3
Survey 4	4.16	09/01/2025	21:10	3.3	95	18.9
Survey 4	4.17	09/01/2025	21:13	3.3	83	16.6
Survey 5	5.01	27/02/2025	20:22	2.0	79	15.8
Survey 5	5.02	27/02/2025	20:26	2.0	67	13.4
Survey 5	5.03	27/02/2025	20:31	2.0	76	15.2
Survey 5	5.04	27/02/2025	20:37	2.0	92	18.3
Survey 5	5.05	27/02/2025	20:42	2.0	61	12.2
Survey 5	5.06	27/02/2025	20:47	4.1	75	15.1
Survey 5	5.07	27/02/2025	20:56	4.0	80	16.0
Survey 5	5.08	27/02/2025	21:02	4.0	67	13.3
Survey 5	5.09	27/02/2025	21:08	4.0	91	18.2
Survey 5	5.1	27/02/2025	21:16	4.0	84	16.8
Survey 5	5.11	27/02/2025	21:25	4.1	106	21.3

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 5	5.12	27/02/2025	21:33	1.9	54	10.9
Survey 5	5.13	27/02/2025	21:41	1.8	71	14.1
Survey 5	5.14	27/02/2025	21:47	1.7	64	12.8
Survey 5	5.15	27/02/2025	21:51	1.6	72	14.4
Survey 5	5.16	27/02/2025	21:55	1.7	72	14.4
Survey 5	5.17	27/02/2025	22:00	1.6	63	12.6
Survey 5	5.18	27/02/2025	22:04	1.6	59	11.8
Survey 5	5.19	27/02/2025	22:07	1.6	53	10.7
Survey 5	5.2	27/02/2025	22:11	1.6	62	12.4
Survey 5	5.21	27/02/2025	22:16	1.6	66	13.3
Survey 5	5.22	27/02/2025	22:20	1.6	66	13.1
Survey 5	5.23	27/02/2025	22:23	1.6	80	15.9
Survey 5	5.24	27/02/2025	22:25	1.6	72	14.4

Table A.4. 3 Site Y2 Results

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 1	1.01	05/12/2024	07:18	2.1	143	28.7
Survey 1	1.02	05/12/2024	07:26	2.6	151	30.1
Survey 1	1.03	05/12/2024	07:30	2.4	114	22.9
Survey 1	1.04	05/12/2024	07:34	2.4	137	27.4
Survey 1	1.05	05/12/2024	07:38	2.5	127	25.4
Survey 1	1.06	05/12/2024	07:44	2.6	116	23.3
Survey 1	1.07	05/12/2024	07:49	2.5	116	23.1
Survey 1	1.08	05/12/2024	07:52	2.6	120	24.0
Survey 1	1.09	05/12/2024	07:56	2.6	156	31.3
Survey 1	1.1	05/12/2024	08:00	2.6	109	21.8
Survey 1	1.11	05/12/2024	08:05	2.6	169	33.7
Survey 1	1.12	05/12/2024	08:09	2.5	108	21.5
Survey 1	1.13	05/12/2024	08:11	2.5	98	19.6
Survey 1	1.14	05/12/2024	08:14	2.6	138	27.7
Survey 1	1.15	05/12/2024	08:19	2.2	111	22.1

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 1	1.16	05/12/2024	08:26	3.7	120	24.1
Survey 1	1.17	05/12/2024	08:31	2.0	85	17.1
Survey 1	1.18	05/12/2024	08:40	3.6	140	28.0
Survey 2	2.01	17/12/2024	13:05	2.0	49	9.8
Survey 2	2.03	17/12/2024	13:17	3.3	42	8.5
Survey 2	2.04	17/12/2024	13:24	3.3	40	8.1
Survey 2	2.05	17/12/2024	13:29	3.2	44	8.8
Survey 2	2.06	17/12/2024	13:36	3.2	39	7.8
Survey 2	2.07	17/12/2024	13:42	3.3	36	7.3
Survey 2	2.08	17/12/2024	13:48	3.3	50	10.0
Survey 2	2.09	17/12/2024	13:54	3.4	59	11.9
Survey 2	2.1	17/12/2024	14:26	3.3	31	6.2
Survey 2	2.11	17/12/2024	14:33	3.4	31	6.2
Survey 2	2.12	17/12/2024	14:37	3.4	42	8.3
Survey 2	2.13	17/12/2024	14:41	3.4	37	7.4
Survey 2	2.14	17/12/2024	14:44	3.4	51	10.2

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 2	2.15	17/12/2024	14:48	3.4	34	6.8
Survey 3	3.01	14/01/2025	13:53	1.4	28	5.6
Survey 3	3.02	14/01/2025	14:00	3.5	31	6.3
Survey 3	3.03	14/01/2025	14:06	3.4	35	7.0
Survey 3	3.04	14/01/2025	14:09	3.5	32	6.3
Survey 3	3.05	14/01/2025	14:13	3.3	32	6.4
Survey 3	3.06	14/01/2025	14:16	3.3	34	6.8
Survey 3	3.07	14/01/2025	14:22	1.1	36	7.2
Survey 3	3.08	14/01/2025	14:35	1.3	34	6.7
Survey 3	3.09	14/01/2025	14:39	1.5	32	6.4
Survey 3	3.1	14/01/2025	14:47	3.3	29	5.8
Survey 3	3.11	14/01/2025	14:54	3.3	32	6.5
Survey 3	3.12	14/01/2025	14:57	3.5	33	6.6
Survey 3	3.13	14/01/2025	15:00	3.7	40	8.1
Survey 3	3.14	14/01/2025	15:04	3.2	37	7.4
Survey 3	3.15	14/01/2025	15:09	3.9	38	7.6

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 3	3.16	14/01/2025	15:16	4.0	32	6.4
Survey 3	3.18	14/01/2025	15:32	3.4	36	7.2
Survey 3	3.19	14/01/2025	15:37	1.8	41	8.1
Survey 4	4.01	04/02/2025	06:28	3.3	31	6.1
Survey 4	4.02	04/02/2025	06:36	3.4	37	7.5
Survey 4	4.03	04/02/2025	06:42	3.4	31	6.1
Survey 4	4.04	04/02/2025	06:47	3.4	35	6.9
Survey 4	4.05	04/02/2025	06:52	3.4	33	6.6
Survey 4	4.06	04/02/2025	06:56	3.4	35	7.0
Survey 4	4.07	04/02/2025	07:08	3.2	32	6.5
Survey 4	4.08	04/02/2025	07:13	3.3	33	6.7
Survey 4	4.09	04/02/2025	07:19	3.2	34	6.8
Survey 4	4.1	04/02/2025	07:24	3.1	37	7.3
Survey 4	4.11	04/02/2025	07:35	3.4	35	7.1
Survey 4	4.12	04/02/2025	07:41	3.4	33	6.7
Survey 4	4.13	04/02/2025	07:47	3.4	34	6.8

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 4	4.14	04/02/2025	07:54	3.4	31	6.2
Survey 4	4.15	04/02/2025	08:13	3.3	34	6.7
Survey 4	4.17	04/02/2025	08:22	3.3	32	6.4
Survey 5	5.01	18/03/2025	17:35	2.6	86	17.2
Survey 5	5.02	18/03/2025	17:46	2.7	51	10.3
Survey 5	5.03	18/03/2025	17:56	2.4	65	13.0
Survey 5	5.04	18/03/2025	18:01	2.6	47	9.3
Survey 5	5.05	18/03/2025	18:05	2.4	63	12.6
Survey 5	5.06	18/03/2025	18:09	2.5	47	9.4
Survey 5	5.07	18/03/2025	18:16	2.4	33	6.5
Survey 5	5.08	18/03/2025	18:20	4.4	66	13.2
Survey 5	5.09	18/03/2025	18:27	4.3	47	9.5
Survey 5	5.1	18/03/2025	18:34	5.0	51	10.3
Survey 5	5.11	18/03/2025	18:40	5.5	46	9.1
Survey 5	5.12	18/03/2025	18:48	5.5	37	7.3
Survey 5	5.13	18/03/2025	18:58	2.6	47	9.4

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 5	5.14	18/03/2025	19:08	2.5	68	13.6
Survey 5	5.15	18/03/2025	19:13	2.6	44	8.8
Survey 5	5.16	18/03/2025	19:19	2.4	47	9.3
Survey 5	5.17	18/03/2025	19:25	2.4	53	10.5
Survey 6	6.01	21/03/2025	10:38	1.6	108	21.6
Survey 6	6.02	21/03/2025	10:46	2.7	110	22.1
Survey 6	6.03	21/03/2025	10:55	2.7	139	27.8
Survey 6	6.04	21/03/2025	11:09	2.5	114	22.9
Survey 6	6.05	21/03/2025	11:17	2.6	149	29.7
Survey 6	6.06	21/03/2025	11:24	2.6	93	18.7
Survey 6	6.07	21/03/2025	11:32	2.6	127	25.4
Survey 6	6.08	21/03/2025	11:40	2.6	127	25.3
Survey 6	6.09	21/03/2025	11:48	4.5	158	31.6
Survey 6	6.1	21/03/2025	11:59	5.0	113	22.7
Survey 6	6.11	21/03/2025	12:08	4.8	145	29.0
Survey 6	6.12	21/03/2025	12:19	4.9	106	21.2

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 6	6.13	21/03/2025	12:24	4.8	154	30.8
Survey 6	6.14	21/03/2025	12:29	5.3	151	30.3
Survey 6	6.15	21/03/2025	12:36	4.6	161	32.2

Table A.4. 4 Site Z results

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 1	1.01	20/01/2025	13:08	3.8	295	58.9
UAV mass balance		20/01/2025	13:10		165	42.6
Survey 1	1.02	20/01/2025	13:17	4.2	211	42.2
Survey 1	1.03	20/01/2025	13:23	1.7	252	50.3
UAV mass balance		20/01/2025	13:42		173	49.7
UAV mass balance		20/01/2025	14:26		154	43.1
Survey 1	1.04	20/01/2025	14:49	1.7	342	68.3

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 1	1.05	20/01/2025	14:52	1.7	315	63.0
Survey 1	1.06	20/01/2025	14:55	1.7	326	65.2
Survey 1	1.07	20/01/2025	14:58	1.7	285	57.1
Survey 1	1.08	20/01/2025	15:01	1.7	263	52.5
Survey 1	1.09	20/01/2025	15:06	3.5	370	74.0
UAV mass balance		20/01/2025	15:09		194	50.7
Survey 1	1.1	20/01/2025	15:17	3.6	314	62.9
Survey 1	1.11	20/01/2025	15:22	4.5	251	50.3
Survey 1	1.12	20/01/2025	15:26	4.2	228	45.5
Survey 1	1.13	20/01/2025	15:29	3.6	300	59.9
Survey 1	1.14	20/01/2025	15:37	3.5	289	57.8
Survey 1	1.15	20/01/2025	15:43	3.4	254	50.8
Survey 1	1.16	20/01/2025	15:47	3.4	232	46.4
Survey 1	1.17	20/01/2025	15:52	4.4	317	63.4
Survey 1	1.18	20/01/2025	15:55	4.2	322	64.4

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 2	2.01	20/01/2025	19:36	0.4	259	51.7
Survey 2	2.02	20/01/2025	19:40	0.9	237	47.4
Survey 2	2.04	20/01/2025	19:46	1.7	287	57.5
Survey 2	2.05	20/01/2025	19:48	1.7	285	57.0
Survey 2	2.06	20/01/2025	19:51	1.7	283	56.6
Survey 2	2.07	20/01/2025	19:54	1.8	334	66.7
Survey 2	2.08	20/01/2025	19:57	3.5	273	54.7
Survey 2	2.10	20/01/2025	20:06	3.6	360	72.0
Survey 2	2.11	20/01/2025	20:12	3.4	186	37.2
Survey 2	2.12	20/01/2025	20:17	3.4	201	40.2
Survey 2	2.13	20/01/2025	20:24	3.6	271	54.2
Survey 2	2.14	20/01/2025	20:28	4.3	232	46.4
Survey 2	2.15	20/01/2025	20:32	4.4	213	42.6
Survey 2	2.16	20/01/2025	20:36	4.4	274	54.9
Survey 2	2.17	20/01/2025	20:40	4.5	312	62.5
Survey 2	2.18	20/01/2025	20:44	3.2	205	40.9

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 2	2.19	20/01/2025	20:53	3.2	285	57.0
Survey 2	2.2	20/01/2025	21:00	3.1	232	46.5
Survey 2	2.21	20/01/2025	21:05	3.2	229	45.8
Survey 2	2.22	20/01/2025	21:12	4.4	240	48.0
Survey 2	2.23	20/01/2025	21:17	4.4	266	53.2
UAV mass balance		21/01/2025	11:17		258	148.8
UAV mass balance		21/01/2025	12:45		118	63.3
UAV mass balance		21/01/2025	14:14		292	109.9
Survey 3	3.01	19/03/2025	17:44	1.4	166	33.1
Survey 3	3.02	19/03/2025	17:48	1.4	129	25.9
Survey 3	3.03	19/03/2025	17:53	1.4	99	19.8
Survey 3	3.04	19/03/2025	17:56	1.4	198	39.5
Survey 3	3.05	19/03/2025	17:59	1.4	160	32.1
Survey 3	3.07	19/03/2025	18:05	1.4	201	40.2

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 3	3.08	19/03/2025	18:09	1.4	113	22.7
Survey 3	3.09	19/03/2025	18:12	1.4	167	33.5
Survey 3	3.1	19/03/2025	18:14	1.4	185	37.1
Survey 3	3.11	19/03/2025	18:18	4.1	145	29.0
Survey 3	3.12	19/03/2025	18:25	4.1	162	32.4
Survey 3	3.13	19/03/2025	18:28	4.1	143	28.6
Survey 3	3.14	19/03/2025	18:34	4.0	148	29.6
Survey 3	3.15	19/03/2025	18:42	4.6	122	24.4
Survey 3	3.16	19/03/2025	18:51	4.2	103	20.5
Survey 3	3.17	19/03/2025	18:55	4.2	106	21.2
Survey 3	3.18	19/03/2025	19:01	4.2	167	33.5
Survey 3	3.19	19/03/2025	19:06	4.2	103	20.6
Survey 3	3.2	19/03/2025	19:12	5.2	117	23.4
Survey 3	3.21	19/03/2025	19:18	5.1	144	28.8
Survey 3	3.22	19/03/2025	19:24	5.1	134	26.8
Survey 3	3.23	19/03/2025	19:30	5.1	66	13.1

Survey	Transect No.	Date	Time	Transect distance (km)	Survey flux (kg/hr)	Uncertainty (kg/hr)
Survey 3	3.24	19/03/2025	19:35	1.8	155	31.0
Survey 4	4.01	19/03/2025	22:59	1.6	123	24.6
Survey 4	4.02	19/03/2025	23:05	1.6	90	18.0
Survey 4	4.03	19/03/2025	23:09	1.6	79	15.9
Survey 4	4.04	19/03/2025	23:14	1.6	74	14.7
Survey 4	4.08	20/03/2025	00:07	3.0	65	13.1
Survey 4	4.09	20/03/2025	00:11	3.0	79	15.8
Survey 4	4.1	20/03/2025	00:15	3.0	90	18.0
Survey 4	4.11	20/03/2025	00:21	3.2	101	20.3
Survey 4	4.12	20/03/2025	00:26	3.2	112	22.5
Survey 4	4.13	20/03/2025	00:35	3.2	110	21.9
Survey 4	4.14	20/03/2025	00:39	5.0	89	17.8
Survey 4	4.15	20/03/2025	00:47	5.0	95	19.0
Survey 4	4.16	20/03/2025	00:51	4.7	106	0.1
Survey 4	4.17	20/03/2025	00:57	4.7	102	20.4
Survey 4	4.18	20/03/2025	01:01	4.7	88	17.7

A.5. Appendix 5: Assessment of factors affecting methane emissions

Methane flux and methane collection efficiency was evaluated at all four case study sites on multiple occasions. This enables an evaluation to be carried out of the factors that are correlated with changes in methane flux and methane collection efficiency. This in turn may provide pointers to the cause of differences in flux and methane collection efficiency.

For the reasons set out in section 7.2, methane flux cannot readily be compared between sites because of differences resulting from factors including the quantity, type and age of waste, historical landfill practices, and the extent of installed controls. In contrast, methane collection efficiency (MCE) is designed to be readily compared between sites. We have therefore evaluated the influence of potentially relevant factors on methane flux at individual sites, and the influence of these factors on MCE at individual sites and at all sites.

A multifactor correlation analysis was carried out in each case, to identify the extent to which each factor was correlated with methane flux and MCE. It was inherently assumed that if any correlation exists, it can be represented as a linear correlation within the range of values observed in each survey.

The potential contribution of each observed factor (weather conditions and operational factors) to the calculated methane flux and MCE for each survey period was evaluated using a multivariate correlation approach. The weather conditions and site operational factors recorded during each survey were tabulated alongside the calculated methane flux and MCE. The aim of this was to determine if the observed factors were significantly correlated with changes in methane flux and MCE. The significance of each observed factor in determining the calculated change in methane flux or MCE (assuming a causal relationship exists) was determined as follows:

(a) Obtain the correlation coefficient of each observed factor with the calculated methane flux or MCE (value A in the tables below)
(b) Calculate the standard deviation of each observed factor as an indication of the variation of each parameter (value B in the tables below)
(c) Multiply A by B to give an indication of how much changes in each observed factor affect the calculated change in methane flux or MCE.

This approach was adopted to enable a focus on parameters which are important in determining methane flux and MCE. For example, some meteorological values have a relatively high numerical value (e.g. atmospheric pressure) but vary to a much more limited extent around these higher values. Considering the product of correlation coefficient and standard deviation enables the influence of each parameter to be understood.

The factors considered were divided into environmental factors which were common to all sites, and operational factors which were identified separately for all sites and depended on the relevance of different factors to each site and the availability of information. Operational factors were modelled using a binary system of applying a factor of 0 or 1. For example, for Site X, a factor of 0 was applied for surveys when a temporary cap was not present, and a factor of 1 was applied for surveys when a temporary cap was present.

Environmental factors:

- Air temperature at the time of the survey(°C)
- Air temperature gradient for the preceding five days (°C/day)
- Air pressure at the time of the survey (kPa)
- Air pressure gradient for the preceding 24 hours (kPa/hr)
- Rainfall during the survey (mm)
- Rainfall during the preceding 24 hours (mm)

Operational factors:

- Site X: Existence of temporary cap
- Site Y1: Tipping taking place
- Site Y2: Flare operating; issue with engines; tipping taking place; open tipping face
- Site Z: Tipping taking place; flaring taking place

The total quantity of methane collected and emitted at Site Y2 was found to be significantly different during Surveys 2 and 3 compared to the total quantity of methane identified during Surveys 1, 4, 5 and 6. The overall quantity during Surveys 2 and 3 was less than half that identified during the other surveys. As a result, these two surveys were treated separately in the correlation analysis. At other sites, there was no evidence for systematic differences in the quantity of methane collected and emitted.

The analysis results are based on the follow equation and should be interpretated as:

$$mf = intercept - c[V1] * V1 + c[V2] * V \ldots . V[\quad] * V[]$$

- mf is the predicted methane flux (the dependent variable).
- intercept is the adjusted starting position for the prediction from 0.
- c[] is the coefficient of each respective independent variable (e.g c[V1] is the calculated coefficient of the first variable. This can be viewed as how much the mf (dependent variable) is changed by a unit change in V [independent variable], for example a temperature coefficient of 2 would mean that the predicted methane flux would double for each temperature increase should all other variables remain the same.
- V (number) is a variable

Each table in this section of analysis presents the coefficients for each variable and its corresponding level of variance (the standard deviation). The potential contribution is coefficient multiplied by the variance. The potential contribution provides a value that reflects the maximum influence a factor is predicted to have on methane flux or the methane collection efficiency.

Factors correlated with methane flux at individual sites

Table A.5. 1 Factors correlated with methane flux: Site X

Observation	Coefficient (A)	Standard Deviation (B)	Potential contribution (A × B)
Intercept	-4070.6		
Temp (°C)	-0.7	2.2	-1.5
5 day T gradient (oC/day)	38.3	1.5	**56.4**
Air pressure (kPa)	4.2	8.1	33.9
24hr air pressure gradient (kPa/hr)	-214.1	0.4	**-81.9**
Rainfall during survey (mm)	0.0	0.0	0.0
Rainfall previous 24 hours (mm)	-50.0	0.5	-23.3
Temporary cap	-138.9	0.5	-69.2
Correlation coefficient: 66% based on 95 observations			

Table A.5. 2 Factors correlated with methane flux, Site Y1

Observation	Coefficient (A)	Standard Deviation (B)	Potential contribution (A × B)
Intercept	-488.4		

Observation	Coefficient (A)	Standard Deviation (B)	Potential contribution (A × B)
Temp (ºC)	6.5	4.9	**32.3**
5 day T gradient (oC/day)	40.5	0.5	21.0
Air pressure (kPa)	0.4	9.0	3.8
24hr air pressure gradient (kPa/hr)	275.1	0.2	**55.0**
Rainfall during survey (mm)	0.0	0.0	0.0
Rainfall previous 24 hours (mm)	-214.8	0.1	-21.0
Temporary cap	-16.8	0.4	-7.4
Correlation coefficient: 25% based on 96 observations			

Table A.5. 3 Factors correlated with methane flux, Site Y2 Surveys 1, 4, 5 and 6

Observation	Coefficient (A)	Standard Deviation (B)	Potential contribution (A × B)
Intercept	22994.18		
Temp (ºC)	-1.56	4.16	-6.5
5 day T gradient (oC/day)	-82.61	1.23	**-102.0**
Air pressure (kPa)	-22.28	7.23	**-161.2**
24hr air pressure gradient (kPa/hr)	276.73	0.28	78.8
Rainfall during survey (mm)	0	0	0

Observation	Coefficient (A)	Standard Deviation (B)	Potential contribution (A × B)
Rainfall previous 24 hours (mm)	0	0	0
Flare operating/engine issue	-123.91	0.50	-62.4
Tipping occurring	1.35	0.50	0.7
Open face/site open	-173.74	0.50	-87.5
Correlation coefficient: 89% based on 66 observations			

Table A.5. 4 Factors correlated with methane flux, Site Y2 Surveys 2 and 3

Observation	Coefficient (A)	Standard Deviation (B)	Potential contribution (A × B)
Intercept	1109.58		
Temp (°C)	19.59	0.51	**9.9**
5 day T gradient (oC/day)	31.59	0.35	**10.9**
Air pressure (kPa)	-1.24	6.32	-7.8
24hr air pressure gradient (kPa/hr)	47.35	0.06	2.9
Rainfall during survey (mm)	0	0	0
Rainfall previous 24 hours (mm)	0	0	0
Flare operating	0	0	0
Engine issue	0	0	0

Observation	Coefficient (A)	Standard Deviation (B)	Potential contribution (A × B)
Tipping occurring	0	0	0
Open face/site open	0	0	0
Correlation coefficient: 80% based on 32 observations			

Site Y2 stopped accepting waste part-way through the measurement programme. This is reflected in the “Open tipping face” variable, which also corresponds to the site being open for acceptance of waste. This change was correlated with a reduction in methane emissions, although the effect was less significant than the correlation between methane emissions and both increasing ambient temperature, and operation of the flare.

Table A.5. 5 Factors correlated with methane flux, Site Z

Observation	Coefficient (A)	Standard Deviation (B)	Potential contribution (A × B)
Intercept	30659.6		
Temp (°C)	20.4	1.5	30.2
5 day T gradient (oC/day)	-637.3	0.3	-199.3
Air pressure (kPa)	-31.1	6.9	**-215.4**
24hr air pressure gradient (kPa/hr)	-3585.8	0.1	**-234.7**
Rainfall during survey (mm)	0.0	0.0	0.0
Rainfall previous 24 hours (mm)	-718.3	0.0	-26.8
Flaring taking place	260.7	0.5	130.5
Tipping taking place	16.4	0.5	7.5
Correlation coefficient: 76% based on 84 observations			

Factors correlated with MCE at individual sites

Table A.5. 6 Factors correlated with MCE, Site X

Observation	Coefficient (A)	Standard Deviation (B)	Potential contribution (A × B)
Intercept	6.350		
Temp (°C)	0.001	2.159	0.002
5 day T gradient (oC/day)	-0.049	1.470	-0.072

Observation	Coefficient (A)	Standard Deviation (B)	Potential contribution (A × B)
Air pressure (kPa)	-0.005	8.066	-0.044
24hr air pressure gradient (kPa/hr)	0.269	0.382	**0.103**
Rainfall during survey (mm)	0.000	0.000	0.000
Rainfall previous 24 hours (mm)	0.065	0.466	0.030
Temporary cap	0.165	0.498	**0.082**
Correlation coefficient: 70% based on 95 observations			

Table A.5. 7 Factors correlated with MCE, Site Y1

Observation	Coefficient (A)	Standard Deviation (B)	Potential contribution (A × B)
Intercept	-0.307		
Temp (ºC)	-0.013	4.943	**-0.063**
5 day T gradient (oC/day)	-0.114	0.519	-0.059
Air pressure (kPa)	0.001	8.995	0.012
24hr air pressure gradient (kPa/hr)	-0.600	0.200	**-0.120**
Rainfall during survey (mm)	0.000	0.000	0.000
Rainfall previous 24 hours (mm)	0.221	0.098	0.022
Temporary cap	0.034	0.441	0.015
Correlation coefficient: 7% based on 96 observations			

Table A.5. 8 Factors correlated with MCE, Site Y2 Surveys 1, 4, 5 and 6

Observation	Coefficient (A)	Standard Deviation (B)	Potential contribution (A × B)
Intercept	-35.700		
Temp (ºC)	0.001	4.163	0.003
5 day T gradient (oC/day)	0.136	1.235	**0.168**
Air pressure (kPa)	0.036	7.234	**0.257**
24hr air pressure gradient (kPa/hr)	-0.448	0.285	-0.128

Observation	Coefficient (A)	Standard Deviation (B)	Potential contribution (A × B)
Rainfall during survey (mm)	0	0	0
Rainfall previous 24 hours (mm)	0	0	0
Flare operating/engine issue	0.193	0.504	0.097
Tipping occurring	-0.002	0.498	-0.001
Open face/site open	0.305	0.504	**0.154**
Correlation coefficient: 92% based on 66 observations			

Table A.5. 9 Factors correlated with MCE, Site Y2 Surveys 2 and 3

Observation	Coefficient (A)	Standard Deviation (B)	Potential contribution (A × B)
Intercept	-13.460		
Temp (°C)	-0.039	0.506	-0.020
5 day T gradient (oC/day)	-0.098	0.345	**-0.034**
Air pressure (kPa)	0.014	6.323	**0.090**
24hr air pressure gradient (kPa/hr)	-0.729	0.061	**-0.045**
Rainfall during survey (mm)	0	0	0
Rainfall previous 24 hours (mm)	0	0	0
Flare operating	0	0	0

Observation	Coefficient (A)	Standard Deviation (B)	Potential contribution (A × B)
Engine issue	0	0	0
Tipping taking place	0	0	0
Open face/site open	0	0	0
Correlation coefficient: 91% based on 32 observations			

Site Y2 stopped accepting waste part-way through the measurement programme. This is reflected in the “Open tipping face” variable, which also corresponds to the site being open for acceptance of waste. This change was correlated with an increase in MCE, of similar significance to the correlations between increasing MCE and increasing temperature gradient, decreasing pressure gradient, and no operational issues at the site.

Table A.5. 10 Factors correlated with MCE, Site Z

Observation	Coefficient (A)	Standard Deviation (B)	Potential contribution (A × B)
Intercept	-36.2		
Temp (ºC)	-0.030	1.477	-0.045
5 day T gradient (oC/day)	0.787	0.313	**0.246**
Air pressure (kPa)	0.038	6.925	**0.261**
24hr air pressure gradient (kPa/hr)	4.453	0.065	**0.291**
Rainfall during survey (mm)	0.000	0.000	0.000
Rainfall previous 24 hours (mm)	0.890	0.037	0.033

Flaring taking place	-0.244	0.501	-0.122
Tipping taking place	-0.016	0.454	-0.007
Correlation coefficient: 88% based on 84 observations			

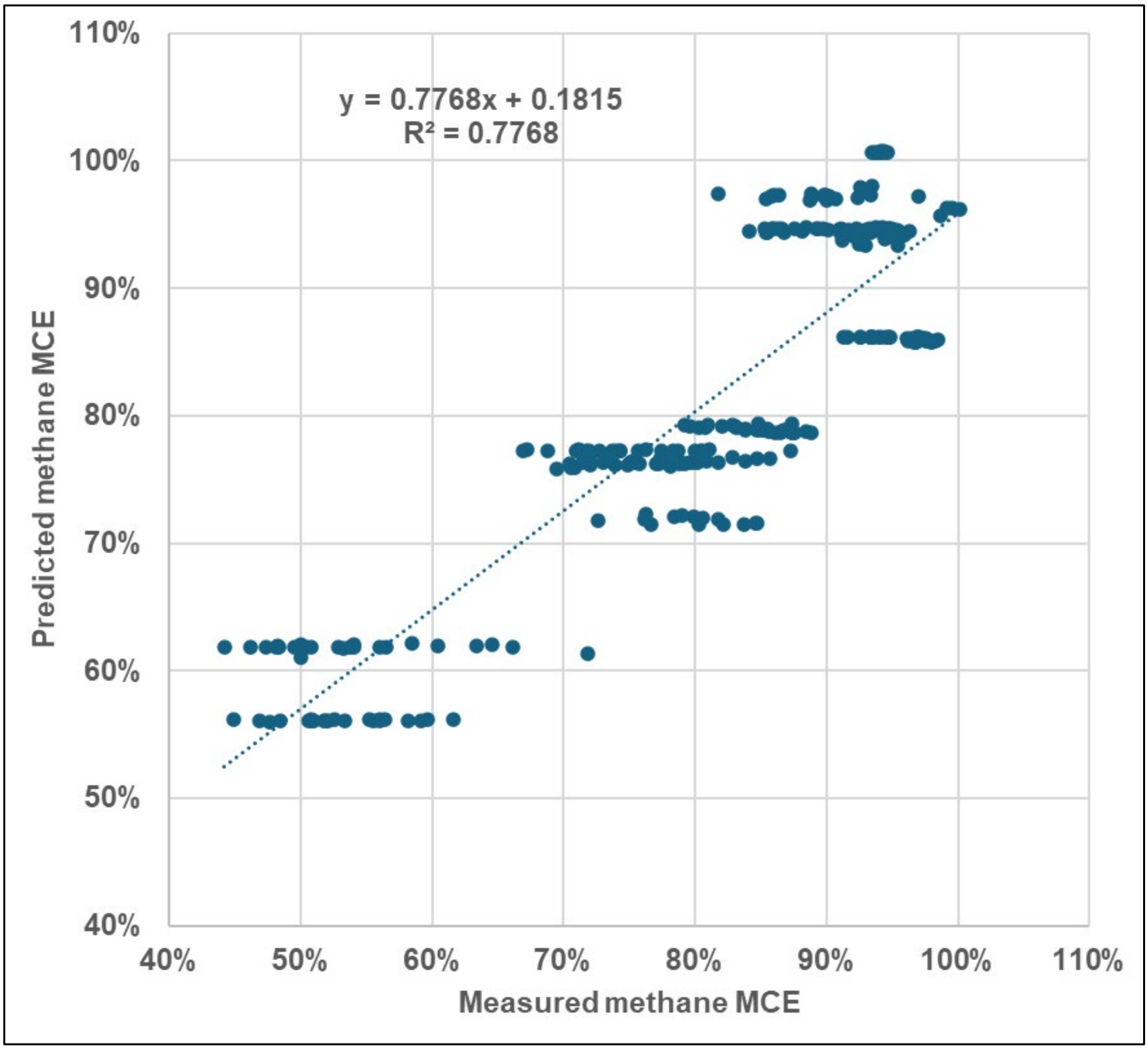
Factors correlated with MCE at all sites

Table A.5. 11 Factors correlated with MCE, all sites

Observation	Coefficient (A)	Standard Deviation (B)	Potential contribution (A × B)
Intercept	-4.1		
Temp (ºC)	0.002	1.477	0.003
5 day T gradient (oC/day)	0.017	0.313	0.005
Air pressure (kPa)	0.005	6.925	**0.034**
24hr air pressure gradient (kPa/hr)	-0.010	0.065	-0.001
Rainfall during survey (mm)	0.000	0.000	0.000
Rainfall previous 24 hours (mm)	0.025	0.037	0.001
Flaring taking place	0.144	0.501	**0.072**
Tipping taking place	0.060	0.454	**0.027**
Abnormal operations	-0.314	0.454	**-0.143**
Correlation coefficient: 78% based on 277 observations			

Figure A.5. 1 shows the observed MCE values compared with the values predicted using the correlation coefficients shown in Table A.5. 11.

Figure A.5. 1 Measured versus predicted MCE based on measurements at all sites



A.6. Appendix 6: Standard Operating Procedures

Tracer Dispersion Method (TDM)

The following outlines the standard procedures that should be followed for the whole-site quantification of emission rates of a target gas using the Tracer Dispersion Method (TDM) (AKA Tracer Gas Dispersion Method, Tracer Correlation Method), specifically when using acetylene as the tracer.

The general principle of TDM assumes that a tracer gas released at the same location as the source of the target gas will be subject to the same atmospheric dispersion when moving downwind as the source gas. By knowing the release rate of the tracer gas and by measuring downwind above-background concentrations of both the target and tracer gases, then through the integration of measurement transects across the plume an estimation of the target gas emission rate can be made. The systematic uncertainties from these assumptions are minimised when the two gases are well-mixed and when measurement transects are far enough downwind to reduce errors associated with the location of the tracer gas release not fully replicating the spatial distribution of the emission source.

The TDM method requires the controlled release of a tracer gas located close to the primary emission source being measured. Simultaneous measurements of both gas concentrations are then made downwind of the site using a gas analyser, ideally linked to a global navigation satellite system (GNSS). Interpolation of the two gas measurements allows an accurate measurement of the source gas emission flux.

With suitable monitoring equipment and good control on tracer release, and under ideal atmospheric conditions, TDM can resolve emission rates from landfills down to ~5 kg/hour.

Equipment and Setup

<u>Gas Analyser</u>

The TDM requires a gas analyser capable of measuring two gases simultaneously (tracer and source) or a separate analyser for each gas. Where two analysers are used, although the data collection rate can differ, it is essential that the time stamp for each is synchronised prior to the test commencing.

The minimum detection limit of the target gas emission rate determined by the TDM technique is dependent on the resolution of the gas analyser(s) to detect the target and tracer gases, together with the tracer gas release rate. The gas analyser(s) must be able to detect low concentrations of the target and tracer gases, with good repeatability and at a high frequency (monitoring rate). Ideally readings should be taken at a minimum frequency of 1 hertz.

The gas analyser should be regularly calibrated using certified gas standards, as per the manufacturer's instructions.

Monitoring vehicle

The gas analyser(s) should be securely installed in the monitoring vehicle (e.g. a van or car) with an inlet hose to draw ambient air into the analyser connected to atmosphere. A filter should be attached to the inlet line to prevent dust entering the analyser. An external pump may be used to increase the airflow to the analyser. If an external pump is to be used, first check with the manufacturer of the analyser that it is compatible and suitable for use.

The monitoring vehicle should also contain a power supply for the analyser and any associated pump. This may be 12v DC or an AC supply through a power inverter.

A GNNS positioning device may be used to geolocate the measurements made by the analyser(s). Although not required for the analysis of TDM survey data, positioning data is useful for locating the gas plumes and other nearby sources of gas during postprocessing. If a GNNS is to be used, the output must be time stamped and synchronised with the analyser output.

Positioning of Tracer Gas Release

The principle of locating the tracer release point with respect to the landfill footprint and wind direction is that the release point should ideally be centred on the areas of the landfill emitting the most methane. On operational sites this is likely to be close to operational areas or parts of the site recently filled but with limited gas control measures installed. For closed sites this is likely to be near the centre of the site although site specific factors, such as age of waste and location/ efficiency of gas control systems, will also influence positioning.

In practice the final positioning of the tracer release point will usually be constrained by logistical factors such as the need for (vehicular) access and the requirement for there to be relatively level and stable ground to situate acetylene cylinders (where used as the tracer).

Where it is not possible to co-locate the tracer release point with the centre of the highest emitting areas, then a location should be chosen where the downwind dispersion characteristics (e.g. distance and type of topography covered) to the monitoring routes are similar. This may change depending on wind direction. Generally, it is preferable to locate the tracer release point along the centre line of the highest emitting areas perpendicular to the wind direction rather than moving the release point upwind or downwind.

Further details on potential errors associated with different locations of tracer release points are provided in Matacchiera et al (2019) Ref [38].

Tracer Gas Release Setup

The following procedures are specifically for the use of acetylene (C_2H_2) as the tracer gas. Most of the procedures described are applicable to other tracer gas species (e.g. ethane or N_2O).

Guidance on the safe transportation, storage or use of acetylene is beyond the scope of this document. The use of acetylene is covered by The Acetylene Safety (England and Wales and Scotland) Regulations 2014 with additional guidance provided by the 2014 Health and Safety Executive publication “Working safely with Acetylene”. Users should always follow guidance given by the British Compressed Gases Association (BCGA) and complete Risk Assessment for each survey being carried out.

Acetylene will typically be supplied in J-size (2.74 kg acetylene) or L-sized (9.0 kg acetylene) pressurised gas cylinders. The acetylene is dissolved in acetone within a porous agamassan filling, making it safe to transport and handle.

Acetylene is non-toxic and a license to release the gas to atmosphere is not required. The gas is, however, an asphyxiant and must only be used in the open and away from anywhere the gas could collect. Acetylene has a lower density than air (relative density = 0.9) so will disperse into the atmosphere and will not collect in pits or sink into drains. However, it could collect under overhead structures such as roofs, shelters and dense vegetation. The gas must, therefore, not be released underneath trees or immediately upwind of any outdoor shelters, barns or buildings.

Acetylene is a fire hazard and explosive hazard. The lower explosive limit (LEL) is 2.5 % (25,000 ppm). This is within the same range of methane. Where used on a survey site, cylinders and flow control equipment must be surrounded by a hazard barrier and given designated zonation signage in accordance with DSEAR Regulations.

When setting up acetylene cylinders, at least one member of the team supervising the gas cylinders should wear a personal gas monitor calibrated for fuel gases set at 10% of the LEL (2.5 % in air) or acetylene (alarm set at 20% of the LEL). No other members of the monitoring team should work in a closer proximity to the gas cylinders than the supervising member wearing the personal gas meter without also wearing a gas meter.

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[38] Matacchiera et al 2019. AERMOD as a Gaussian dispersion model for planning tracer gas dispersion tests for landfill methane emission quantification DOI: 10.1016/j.wasman.2018.02.007

When in use, each cylinder must be fitted with an acetylene specific regulator (supplied by BOC or other accredited manufacturer) and be fitted with a safe-guard flame arrester. It is recommended multi-stage regulators are used in preference to single-stage regulators as these provide better control of the stepped down pressure delivered to the flow rate controller. All cylinders should be located on level ground and the risks associated with the cylinders toppling over during use assessed and controlled.

A controlled flow device(s) should be used to regulate the tracer gas release and should be able to accommodate the mass flow rates as needed. Flow control may be automated (and logged) or controlled manually. The controlled flow device must have been calibrated to ensure correct output flow for the tracer gas being released. A typical manual flow control meter is rotameter or variable area flow meter, which has been calibrated for acetylene gas. This type of flow meter must be adjusted so that when in use the float cylinder is vertical, so that accurate readings are provided.

It is advisable to use an extension hose to locate the gas release point downwind and away from the flow meter. The recommended length of hose is 5 m (to help prevent tangling and kinking). The hose must be suitable for use with acetylene and must conform to BS EN ISO1256. It is permissible to extend the length of hose by coupling pipes together with brass threaded adaptors. A flame arrester should be fitted to the end of the hose, which should be located at least 1 m above ground level to aid dispersion. A hazard barrier should be used around the hose to reduce risks of tripping.

Gas cylinders and flow meters and all monitoring should be located upwind of the gas release point. No person should stand directly downwind of the gas release point during any release.

Whilst acetylene is being released from the cylinders, measures should be taken to ensure that there is no unauthorised entry into the DSEAR zones. In the event that DSEAR Zone is, or appears likely to be, breached the acetylene release from all cylinders must immediately be switched off.

At the end of each tracer release, the pressure regulators and associated flow equipment must be removed from all cylinders before handling and transport.

Tracer Release Rate

The flow rate (i.e. amount of tracer gas released during the survey) is determined by the ability to detect the tracer above background at the downwind monitoring points. The lower detection limit will be specific to the gas analyser being used.

The downwind concentration of tracer will be dependent on the dispersion of the gas, a function of distance downwind of the tracer release point, topography, wind speed and atmospheric stability.

Acetylene gas cylinders have a maximum advisable continuous withdrawal rate (i.e. maximum continuous release rate), and this will vary by the size and contents' pressure of the cylinder, and with temperature. Releasing gas at a rate higher than the advisable withdrawal rate will increase the risk of the liquid acetone in which the acetylene is dissolved, being carried in the flow of gas. Acetone is a solvent and may damage the seals found inside flow meters.

Recommended maximum continuous withdrawal rates are given in Table 11. In practice, different gas cylinders of the same design and supplier may behave differently in use, and the release rate can be variable. The release rate from cylinders and any associated drop in cylinder pressure should be carefully monitored for at least the first 15 minutes of operation to establish whether there are any cylinders that are not performing as expected.

Table A.6. 1 Maximum recommended acetylene withdrawal rates (adapted from British Compressed Gas Association Code of Practice 5)

Ambient Temperature (°C)	Maximum Continuous Withdrawal Rate per Cylinder (l/min)	Cylinder Pressure (bar)
-10	2.3	7.6
0	4.7	10.3
10	7.2	13.1
20	9.5	15.9

The flow rate chosen will determine the number of acetylene cylinders to use based on the above withdrawal rates. The maximum flow rate at which acetylene can be removed from a cylinder without acetone carry-over will reduce over the duration of a test as the cylinder pressure drops. Consequently, a tracer test should be planned based on conservative application of the flow rates in Table 1.

From experience, a volumetric flow rate of between 20 and 50 litre/minute is recommended for monitoring up to 5 km downwind, with between 4 and 8 J-size cylinders being used at the same time.

Tracer Gas Supply

A sufficient quantity of tracer gas cylinders should be available for the survey. This should include enough gas for the intended release rate and test duration, and spare cylinders in the event that the release rate from a cylinder(s) is lower than expected or the test duration is extended. In the case of acetylene, it is never possible to fully utilise all the gas in a cylinder as it is generally not possible to maintain desired gas flow-rates as the cylinders empty. For J-size cylinders, only ~70% of the gas in a cylinder can typically be used.

It is sometimes possible and more economical to utilise a mixture of new and partially used acetylene cylinders in a test, in which case starting target flow rates from the new cylinders are likely to be set higher than the used.

Tracer Release Flow Monitoring

The manufacturer's serial number of each gas cylinder being used should be recorded.

Gas cylinders should be weighed without any attached regulator before and after use to determine the mass of tracer used across the survey. Weighing scales need to be specified correctly to allow for the total weight of the cylinder (~35kg for J-size and ~90kg for L-size acetylene cylinders) and provide a resolution of approximately +- 10 gramme. It is recommended that cylinders are weighed at least two times before and two times after use to demonstrate repeatability in the measurement and to reduce the risk of an incorrect measurement being made or written down. A calibrated reference weight is also useful for demonstrating the correct performance of the scales during each weighing session.

Each gas cylinder used in a survey must be fitted with a multi-stage pressure regulator (specifically designed for the gas being used) a flame arrester and flow metering device in conjunction with flow control as detailed above.

Gas cylinders, flow meters and all monitoring must be located / undertaken upwind of the gas release point. No person should stand directly downwind of the gas release point. A personal gas monitor calibrated for fuel gases (alarm set at 20% of the LEL) should be located close to the work area, upwind of the release point. If the wind direction changes, flow from the cylinders must be stopped by closing the valves on each of the gas cylinders and the release point relocated downwind. When a new release point has been safely setup, and all other equipment moved upwind of the new release point the tracer release can resume.

Prior to any tracer gas release the pressure of gas in each cylinder should be recorded with the regulator screw valve closed and the cylinder valve open. Full cylinders obtained directly from the supplier are likely to register a pressure reading between 10 and 15 bar.

If variable area (float) flow meters are being used, then the regulator screw valve should be opened to create an operation pressure of between 0.5 and 1 bar. The needle valve on the flow meter should be adjusted to create the desired flow rate (probably between 4 and 10 L/min). The regulator screw valve can then be closed whilst other cylinders being used in the release can be setup in the same way with the desired flow rate.

On commencement of the tracer release test, the regulator screw on all cylinders being used can be quickly opened to create the desired operation pressure, meaning that only minor adjustments to the flow meter needle valves will then be needed to achieve the overall release rate.

The date / time of the start and finish of tracer release should be noted.

Throughout the tracer release experiment a record should be kept over time of each cylinder's pressure and the flow rate, which should be kept constant by minor changes to either the operation pressure if this has drifted from the set point or by adjusting the needle control valve.

The rate of pressure drop of a cylinder provides an indication of performance and can be used during the whole test to plan how the overall target release rate can be maintained. In particular, the pressure-drop in the initial 10 to 20 minutes of release will help identify poorly performing cylinders, The flow rate of poorly performing cylinders can be reduced if at the same time the flow rate of others are increased or additional spare cylinders are brought into service. The overall flow rate being released should stay the same.

Throughout the test a visual inspection should be maintained for the potential carry-over of acetone with the released acetylene gas. Where acetone is detected, the flow rate of the relevant cylinder should be significantly reduced, or preferably the cylinder taken out of service.

Downwind transect monitoring

The gas analyser(s), pump and GNSS should be switched on and allowed to warm up prior to use as per the manufacturer's guidelines. This also allows time for the tracer gas to propagate downwind, which will be dependent on the wind speed and topography. The monitoring vehicle should then be driven downwind to determine the location and size of the gas plumes (tracer and target gas). The location of the plumes can be estimated based on the wind speed and direction and it is recommended that the monitoring routes are travelled prior to monitoring to allow familiarisation with the road layout.

Once the location of the gas plumes is confirmed, monitoring can begin. It is important that the full width of the gas plumes is measured. This is termed a measurement or plume transect. A plume transect should include background gas concentration measurements either side of the plume. Once a full plume transect has been made, the monitoring vehicle should be turned around and the measurement repeated from the opposite direction. Monitoring will continue in this way until sufficient plume transects have been made. To reduce uncertainty, it is recommended that a minimum of 10 to 15 full plume transects are made per survey. If the road layout permits it, plume measurements should be made on routes at increasing distances downwind of the source.

It is important that, during off-site monitoring, only the methane from the target landfill is included within the plume transect. Interfering or confounding methane sources may include other landfill sites, wastewater treatment plants, agricultural facilities or leaking natural gas mains. It may not always be possible to separate out the plumes from different sources and, where plumes overlap, those transects should not be used to calculate a methane flux. A pre-survey desk study and background emissions check on roads around the target landfill is recommended to help identify other potential sources of methane. To avoid a confounding source, the TDM survey may only be possible within a specific wind direction(s). In some instances, where the target landfill plume cannot be separated from another source, a TDM survey will not be possible.

Data Processing

To aid test analysis, it is recommended that test data is be split into individual plume transects, with target and tracer gas concentrations tabulated and plotted for each complete drive through the gas plumes.

Where used, GNSS data must be synchronised with the gas analyser concentration data, taking into account any off-set caused as a result of the flow-through time (the time it takes the gas to travel from the inlet through the pipework to detection).

Emission rate calculation

The TDM is based on the assumption that a tracer gas released at an emission source will disperse in the atmosphere in the same way as methane emitted from the landfill. Assuming a defined wind direction, well mixed air above the landfill (causing the emitted methane and released tracer gas to be fully mixed), and a constant tracer gas release, the methane emission rate can be calculated as a function of the ratio of the integrated cross-plume concentration of the emitted methane and the integrated cross-plume concentration of the released tracer gas, as follows:

$$E_{gas} = Q_{tracer} \cdot \frac{\int_{Plumeend\,1}^{Plumeend\,2} C_{gas}\,dx}{\int_{Plumeend\,1}^{Plumeend\,2} C_{tracer}\,dx} \cdot \frac{MW_{gas}}{MW_{tracer}}$$

Where E_{gas} is the methane emission rate (kg/hour), Q_{tracer} is the release rate of the tracer gas (kg/hour), C_{gas} and C_{tracer} denote cross-plume concentrations above the background concentration, *MW* denotes molecular weights and *x* corresponds to distance or time across the plume. The background gas concentration for should be calculated for individual transects during the survey.

The above calculation should be made for all plume transects. The emission flux is the average calculation of all the transects.

Background Gas Concentration

Background gas concentration for the target and tracer gases must be determined for each plume transect. The background concentration will be the average concentration of the gas measured on either side of the plume. The average upwind concentration can also be used.

Uncertainty

By following best practice when carrying out surveys, the overall error of a tracer gas dispersion measurement, is very likely to be less than 20% Ref[39]

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[39] Fredenslund, Rees-White, Beaven, Delre, Finlayson, Helmore, Allen, Scheutz, 2019, Validation and error assessment of the mobile tracer gas dispersion method for measurement of fugitive emissions from area sources, Waste Management 83 68-78

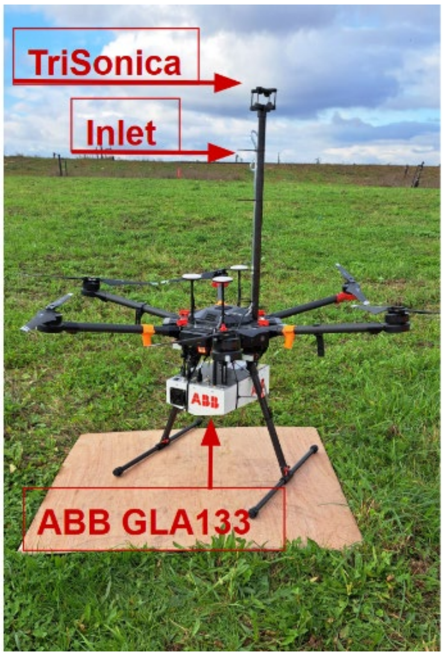
Unmanned Aerial Vehicles (UAV) mass balance method

After landfill sites have been identified and confirmed, pre-survey site recce visits were arranged to survey on-site locations for UAV take-off and landing and aerial sampling. The UAV team consisted of three members of University of Manchester staff.

Equipment details

The survey UAV in use was the University of Manchester DJI M600 Pro, carrying a scientific instrument payload (with a take-off-weight < 25 kg). The scientific instrument payload consisted of an a high-precision LGR Inc GLA-133 Greenhouse Gas infrared spectroscopic analyser, a 2.5 D sonic anemometer, and an onboard camera (see photographs of the UAV and payload below).

Figure A.6. 1 UAV platform and onboard instrumentation.



The DJI M600 Pro hexacopter is equipped with an ABB GLA133-GPC OA-ICOS infrared spectrometer, a gas sampling inlet, and a TriSonica Mini anemometer. Arrows indicate the positions of each component used for atmospheric measurements.

To ensure consistent data collection, we used UgCS (SPH Engineering) software to plan the drone's flight path in advance. One of the key advantages of this automated flight planning system was its ability to provide repeatable flight paths, allowing for consistent measurements under similar conditions. The drone's flight speed was set to a constant 3-4 m/s (depending on the flight and conditions of each survey).

Site consideration and survey details

The team consisted of trained UAV pilots with Civil Aviation Authority Flyer IDs, operating University of Manchester equipment at all times. Recce visits required a briefing by the site manager (or other site representative) to review site maps and any off-limits or hazardous areas, followed by an escorted walkover (or drive around) the site to locate and agree suitable working areas, selected for a range of prevailing wind conditions, as UAV sampling took place downwind of the landfill plume in each case. The UAV team also presented and discussed plans for each site with the site manager.

General airspace requirements and other off-site environments relevant to UAV flight regulation and safety were reviewed in advance. The recce visits also included any health and safety, and site-specific training and induction needed by the operator, followed by a site-specific risk assessment and method statement for UAV operations on site. PPE consisted of hard had, high visibility jacket/vest, gloves, steel toe-capped boots, safety gloves, and access to a personal gas alarm for hazardous areas.

All survey flights were conducted in the CAA "open" category, which require line-of-sight flight and an operational ceiling of 120 m (400 ft) above local ground level. The small unmanned aerial systems (UAS) carried the CAA-registered University of Manchester operator ID.

To collect this data, the UAV was flown downwind of GHG sources on the landfill site, within the site perimeter, or above land adjacent to the site where permitted, avoiding people, buildings, animals and property. Flight plans were programmed each day based on the forecast and measured wind direction for each day. Flight plans typically consisted of a transit from the take-off/landing point to a working survey area where we flew a "ladder" (stacked horizontal lines at various heights) aligned perpendicular to the prevailing wind direction and downwind of the landfill plume (see Figure below taken from our work reported by Yong et al., 2024[40], which shows example survey patterns from previous landfill work).

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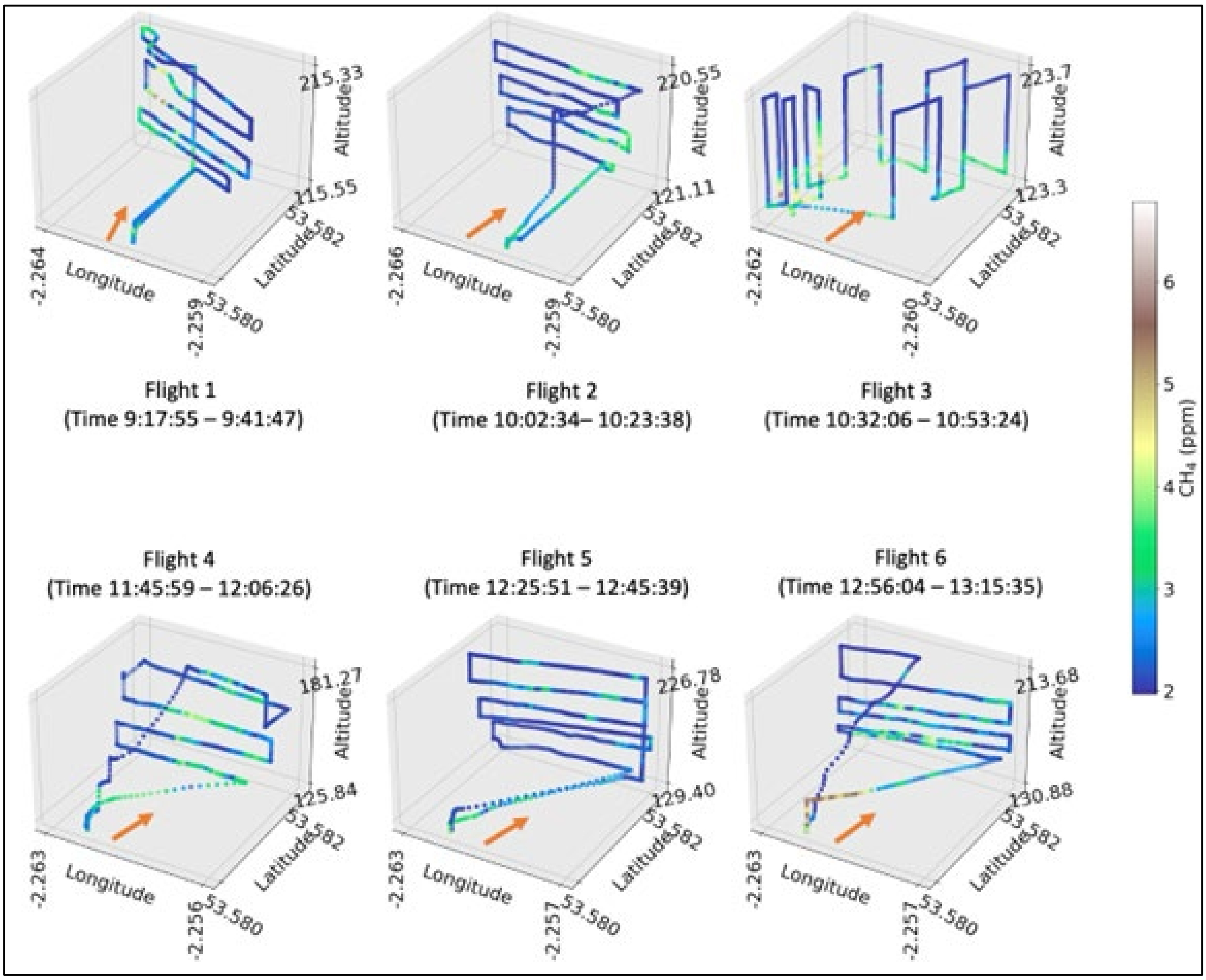
[40]Yong, H., Allen, G., Mcquilkin, J., Ricketts, H., & Shaw, J. T. (2024). Lessons learned from a UAV survey and methane emissions calculation at a UK landfill. *Waste Management*, *180*, 47-54. Available from: https://doi.org/10.1016/j.wasman.2024.03.025

Figure A.6. 2 Example UAV Flightpath, Yong et al. 2024



A total of three days' operational survey work using UAVs was conducted (one day for each site), with additional time allocated for pre-survey setup work, data analysis and contingency. UAV mass balance surveys were coordinated with the University of Southampton tracer dispersion method experiments/surveys and times to coincide where possible (e.g. due to weather constraints) to allow for the most direct comparison possible.

UAV flights were only conducted in conditions free of precipitation and windspeeds below 10 m/s during daylight hours. A minimum of 6 UAV flight surveys (and corresponding GHG net flux results) were completed for each day/site. Each flight took between 15-20 minutes, with 15 minutes between flights for battery changeover and staff welfare breaks during the working day. For each site, whole site fluxes were calculated using the mass balance method with data sampled by UAV for the following:

- CH_4 molar mass concentrations (at 5 Hz)
- CO_2 molar mass concentration (at 5 Hz)
- GPS UAV data (to geolocate gas concentration measurements)

Additionally, for GHG flux calculation, wind and meteorological data will be required covering the time of the UAV mass balance surveys, and provided by monitoring conducted at each site by Ricardo, consisting of:

- Wind speed – 1Hz frequency
- Wind direction – 1Hz frequency
- Temperature
- Pressure
- Relative Humidity
- Precipitation

No UAV instrumentation or other equipment related to UAV work was left at the site unattended or overnight. As operations are self-contained, the UAV team arrived and left site together after signing in and out with the site manager.

Data processing

Approach to calculating of CH_4 emissions

We estimated CH_4 emissions from landfill sites using a mass balance approach developed by Allen et al. (2014, 2015, 2018)[41][42][43] and further discussed by Shaw et al. (2019).[44] This

[41] Allen, G., Martin Gallagher, P., Hollingsworth, P., Illingworth, S., Kabbabe, K., Carl Percival, P., (2014). '*Feasibility of aerial measurements of methane emissions from landfills'.* Available from https://assets.publishing.service.gov.uk/media/5a7f0195ed915d74e6227db6/SC130034_Report.pdf#:~:text=This%20study%20delivers%20expert%20advice%20in%20the%20context,emissions%20from%20regulated%20landfill%20sites%20in%20the%20UK.

[42] Allen, G., Hollingsworth, J., Mead, P., Kabbabe, I., Roberts, K., Percival, G., (2015). 'Measuring landfill methane emissions using unmanned aerial systems: field trial and operational guidance Citation for published version (APA).' Available from https://pure.manchester.ac.uk/ws/portalfiles/portal/32553612/FULL_TEXT.PDF

[43] Allen, G., Williams, P., Ricketts, H., Shah, A., Hollingsworth, P., (2018). *'Validation of landfill methane measurements from an unmanned aerial system'.* Available from https://www.gov.uk/government/publications/validation-of-landfill-methane-measurements-from-an-unmanned-aerial-system

[44] Shaw, J.T., Allen, G., Pitt, J., Mead, M.I., Purvis, R.M., Dunmore, R., Wilde, S., Shah, A., Barker, P., Bateson, P., Bacak, A., Lewis, A.C., Lowry, D., Fisher, R., Lanoisellé, M.,

method calculates CH_4 flux by measuring concentration differences between inside and outside a defined source area downwind of the emission source.

The approach involves sampling CH_4 concentrations along a downwind plane perpendicular to the prevailing wind. Background concentration is measured outside the plume, and the difference between plume and background CH_4 concentrations is used to estimate the emission flux, F, according to the equation:

$$F = \int_{x_1}^{x_2} \int_{z_1}^{z_2} \left([CH_4] - [CH_4]_{background}\right) U \perp \ dxdz$$

where F is the CH_4 emission rate (g s^{-1}), U⊥ is the wind speed component normal to the measurement plane (m s^{-1}), and $[CH_4]$ and $[CH_4]_{background}$ are the CH_4 concentrations (g m^{-3}) within the plume and in the ambient background, respectively. The integral accounts for the horizontal (x_1 to x_2) and vertical (z_1 to z_2) extents of the measurement plane. A similar approach is used for CO_2 flux estimation by substituting CH_4 concentrations with CO_2 concentrations.

To account for unsampled locations within the survey area, kriging—a geostatistical interpolation technique—is applied to estimate values at unmeasured points based on spatial correlations in the data (Myers, 1991[45]). This method assumes that nearby observations are more similar than those farther apart, enabling a more continuous representation of CH_4 (or CO_2) concentrations and wind velocities across the survey area. By using kriging, the study minimizes underestimation of flux and improves the spatial resolution of mass balance calculations (Allen et al., 2015[42]; Mays et al., 2009[46]).

Estimating background CH_4 and CO_2 concentrations

The background CH_4 concentration was determined by analysing the distribution of CH_4 measurements from each flight using a histogram. The mode of the distribution, representing the most frequent value, was identified as the background concentration.

Ward, R.S., (2019). '*A baseline of atmospheric greenhouse gases for prospective UK shale gas sites*'. Sci. Total Environ. 684, 1–13. Available from: https://doi.org/10.1016/j.scitotenv.2019.05.266

[45] Myers, D.E., (1991). '*Interpolation and estimation with spatially located data*'. Chemom. Intell. Lab. Syst. 11, 209–228. Available from: https://doi.org/10.1016/0169-7439(91)85001-6

[46] Mays, K.L., Shepson, P.B., Stirm, B.H., Karion, A., Sweeney, C., Gurney, K.R., (2009). '*Aircraft-Based Measurements of the Carbon Footprint of Indianapolis*'. Environ. Sci. Technol. 43, 7816–7823. Available from: https://doi.org/10.1021/es901326b

Background measurements were obtained from the edges of the gas plume, as the flight path was extended toward the plume's outer limits.

Estimating the influence of wind

Two-dimensional winds are an input to the mass balance equation as described earlier. Natural variability, and measurement uncertainty in this wind vector is typically the largest source of flux uncertainty reported in studies that have used mass balancing. To examine this, we used two independent estimates of wind, derived from a nearby mast, and winds measured onboard the DJI-M600. Both winds were used to calculate flux reported later in this report, to examine sensitivity.

a) Drone-based

The anemometer mounted on the drone measures wind speed and direction relative to the drone's North orientation. To align the wind data with true North and account for the drone's motion, we applied trigonometric equations, the details of which are outside the scope of this report. After applying these corrections, the alignment between the drone-based wind data and the ground-mast measurements, especially the wind direction, improved across all sites relative to the agreement reported in Yong et al., 2024.[40]

b) Wind log profiles

In this study, wind speed was estimated using the logarithmic wind profile, as given by the following equation:

$$u(z) = u_{ref} * \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)}$$

Where u(z) and u_{ref} are the wind speeds at the measurement height z (the UAV flight heights) and the reference height z_{ref} (from the ground-mast anemometer, 3m), and z0 is the surface roughness length. For the local terrain, which is predominantly covered by tall grasses with some trees, fences and few buildings, we used z0 of 0.25 m (Anjum, 2014).[47]

As the wind direction input, we assumed a constant direction equal to that measured at 3 m by the ground-mast anemometer. This assumption simplifies the analysis but introduces

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[47] Anjum, L., (2014), '*Wind resource estimation techniques – An Overview', International journal of wind and renewable energy'*, vol 3, issue 2 (pp 26 -38), available from: https://www.researchgate.net/publication/305806761_Wind_Resource_Estimation_Techniques-An_Overview

a potential limitation, as it implies that the wind direction remains unchanged from 3 m up to the maximum UAV flight altitude of 120 m. In reality, wind direction can vary with height due to atmospheric conditions and local turbulence, which is not captured in this approach.

Estimation of flux uncertainties

To estimate the uncertainty in the flux calculations, we propagated the uncertainties of the background concentration and wind speed, as discussed by Allen et al (2018).[43] The relative uncertainty in the flux was calculated as the square root of the sum of the squared relative uncertainties of background concentration and wind speed component (perpendicular to the plane), following the equation:

$$uncertainty\ F = \sqrt{\left(\frac{\sigma_{background}}{\mu_{background}}\right)^2 + \left(\frac{\sigma_{wind}}{\mu_{wind}}\right)^2}$$

where σ represents the standard deviation and μ the mean value of each component. This approach accounts for variability in both key input parameters, ensuring a more robust estimate of flux uncertainty.

Combustion efficiency

To estimate combustion efficiency, we applied the method from Nara et al. (2014)[48] and Shaw et al. (2023[49]), where efficiency is defined as:

$$\eta[\%] = \frac{\Delta CO_2}{\Delta CO_2 + \Delta CH_4} \times 100$$

This approach assumes that all CH_4 in the fuel gas is either fully combusted to CO_2 or emitted unburned, and that the observed CO_2 originates solely from CH_4 combustion. In practice, however, landfill gas contains a substantial fraction of CO_2 (typically 40–60%) prior to combustion, and no direct measurements of CO or other hydrocarbons (e.g., ethane) were available in this study to independently confirm the combustion origin of the

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[48] Nara, H., Tanimoto, H., Tohjima, Y., Mukai, H., Nojiri, Y., and Machida, T (2024), '*Emissions of methane from offshore oil and gas platforms in Southeast Asia*', Sci. Rep.-UK, 4, 6503, available from https://doi.org/10.1038/srep06503

[49] Shaw, J. T., Foulds, A., Wilde, S., Barker, P., Squires, F. A., Lee, J., Purvis, R., Burton, R., Colfescu, I., Mobbs, S., Cliff, S., Bauguitte, S. J.-B., Young, S., Schwietzke, S., and Allen, (2023),' *Flaring efficiencies and NOx emission ratios measured for offshore oil and gas facilities in the North Sea'*, Atmos. Chem. Phys., 23, 1491–1509, Available from: https://doi.org/10.5194/acp-23-1491-2023

CO_2 signal. As a result, the calculated combustion efficiencies may be slightly overestimated.

To minimize this potential uncertainty, we adopted a plume isolation strategy based on the linear relationship between ΔCO_2 and ΔCH_4 enhancements, following the approach of Allen et al. (2019).[44] For each flight, scatter plots of ΔCH_4 versus ΔCO_2 were used to identify distinct air masses. When two clusters were apparent, the cluster characterized by elevated ΔCO_2 and lower ΔCH_4 was attributed to combustion plumes from landfill engines or flares. This attribution assumes that the CO_2 excess arises primarily from CH_4 oxidation, with negligible contributions from other hydrocarbons or CO (e.g., Shaw et al., 2019)[44]. When only a single, diffuse cluster was observed, a single mixed air mass was assumed.

A ΔCO_2 threshold was determined for each flight based either on a breakpoint in the ΔCH_4–ΔCO_2 relationship or, in the case of a single cluster, from the distribution of ΔCO_2 values in the enhancement plot. A rectangular sampling area was defined along the flight track to encompass the suspected combustion plume (Figure A.6. 3 b and Figure A.6. 4 b). Within this area, data points were classified as belonging to the combustion plume if they exceeded the ΔCO_2 threshold and formed a cluster of at least 2 to 5 adjacent values at similar altitudes—depending on the plume's spatial extent and continuity.

To account for uncertainty in plume isolation, combustion efficiency was calculated in two ways:

I. using only the threshold-exceeding, spatially coherent points; and
II. using all points within the rectangle.

These two estimates provide a first-order range of combustion efficiency.

Figure A.6. 3 and Figure A.6. 4 illustrate two example flights. In Figure A.6. 3a, two clusters appear in the ΔCH_4–ΔCO_2 space: one dominated by landfill gas (high CH_4, low CO_2), and one by combustion emissions (high CO_2, lower CH_4). The krigged maps of ΔCH_4 and ΔCO_2 (Figure A.6. 3b and Figure A.6. 3c) reveal that the CH_4 plume lies closer to the surface, while the CO_2 excess coincides with a secondary CH_4 maximum. In contrast, Figure A.6. 4 shows a well-mixed plume, with CH_4 and CO_2 enhancements spatially aligned. These examples demonstrate the plume identification methodology.

Figure A.6. 3 a) Scatter plot of ΔCH_4 vs. ΔCO_2 enhancements above background from Flight 2 at Site Y (29/10/2024), used to distinguish combustion plumes from raw landfill gas. b) Kriged ΔCO_2 map and c) ΔCH_4 map for the same flight. The red box marks the combustion plume identified in (a), with × symbols indicating locations where ΔCO_2 > 10 ppm (threshold from a).

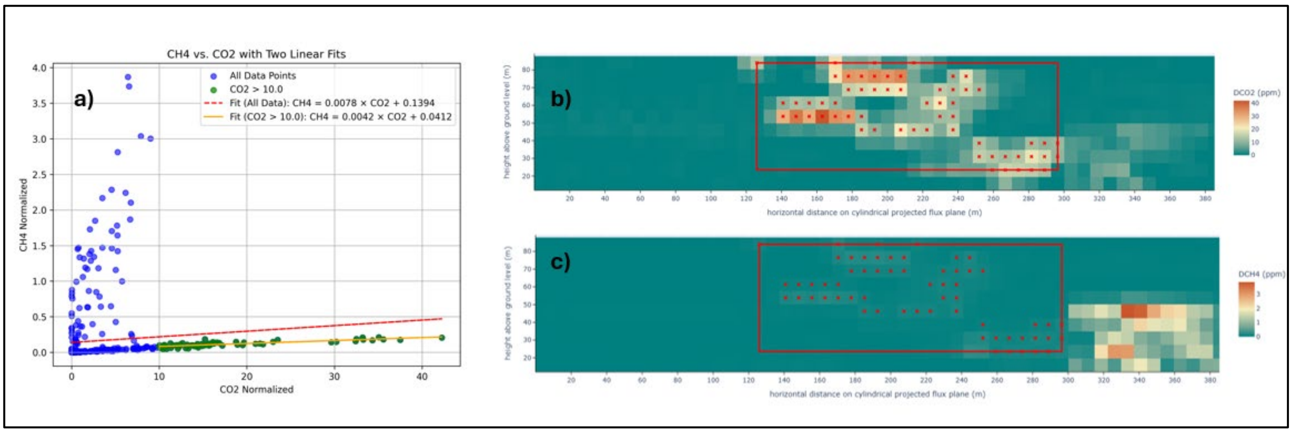
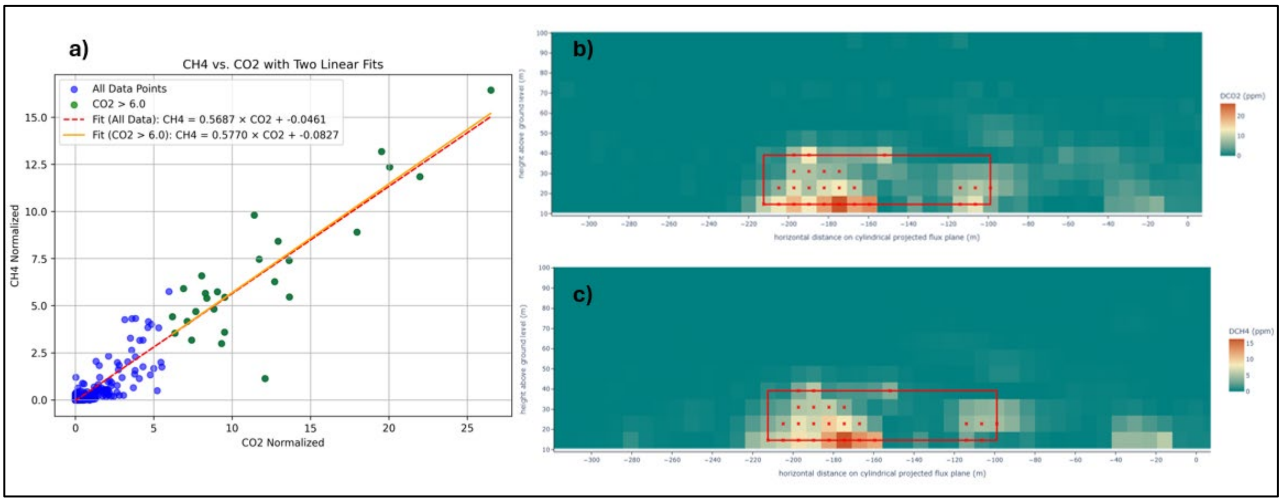


Figure A.6. 4 a) Scatter plot of ΔCH_4 vs. ΔCO_2 enhancements above background from Flight 2 at Site Z (20/01/2025), used to distinguish combustion plumes from raw landfill gas. b) Kriged ΔCO_2 map and c) ΔCH_4 map for the same flight. The red box marks the combustion pl



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