

Methane Emission Quantification Using UAV-based Measurements

- Comparing Existing Landfill Methane Monitoring Methods

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Methane Emission Quantification Using UAV-based Measurement Techniques

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Bachelor thesis, 15 credits, in Physical Geography and Ecosystem Analysis

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Abstract

According to the Intergovernmental Panel on Climate Change (IPCC), atmospheric methane (CH₄) concentrations are considered a crucial factor in global warming, particularly in the near term, due to its high warming potential (~ 80 times more potent than carbon dioxide, or CO₂) and shorter atmospheric lifetime compared to CO₂. CH₄ emissions have more than doubled since the industrial revolution and CH₄ has increased exponentially from the 1850's to the current level of 1943 ppb. A substantial contribution stems from landfills and waste constituting 68 Mt per year, or 17% of total anthropogenic CH₄ emissions. Furthermore, in Sweden, approximately 13% of all anthropogenic CH₄ emissions are generated from landfills. There is therefore a need to mitigate fugitive CH₄ emissions from landfills in the waste sector: both in Sweden and the rest of the world, necessitating accurate and scalable quantification techniques. By utilizing strategies like UAV-based methane measurement techniques, Swedish methane emissions, and particularly the effectiveness of implemented mitigation measures, can be efficiently monitored. Monitoring greenhouse gas emissions is an important contribution to achieving Sweden's emissions reduction goals.

This study evaluates the performance and applicability of the UAV-based GASTRAQ method by comparing its results from field campaigns at Filborna and Rönneholm landfill with those from a recently validated Drone Flux Method (DFM), applied to data from a wastewater sludge landfill in Linköping Sweden. Both methods rely on mass balance theory yet differ in the sense that GASTRAQ utilises ground-based wind profiles while DFM incorporates real-time onboard wind sensing. Flux estimates were analysed alongside uncertainty tests, highlighting that the DFM is more scalable and adaptable due to its wind assumptions, while GASTRAQ is susceptible to inaccuracies under variable wind conditions. Relative errors varied considerably across campaigns, indicating that wind field characterization is a primary uncertainty source. Despite these limitations, GASTRAQ remains practical for routine monitoring in stable atmospheric conditions. The study concludes that UAV-based methods can yield adequate CH₄ flux estimates, provided that site-specific constraints such as wind turbulence and spatial coverage are adequately quantified and that the footprint of the flights are representative for the landfill. Future developments including onboard wind sensors and autonomous flight paths may improve flux accuracy and enable broader regulatory application of UAV-based CH₄ monitoring in the waste sector.

Keywords: Methane, CH₄, UAV, Mass Balance Theory, GASTRAQ, DFM, Drone Flux Method, Landfill, Rönneholm, Filborna, Linköping

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1 Introduction

In 2019, a European Green Deal was proposed to tackle climate and environmental challenges that are defining for this generation. The European Green Deal aims are as the following:

“The European Green Deal is a response to these [climate and environmental] challenges. It is a new growth strategy that aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use.” (European Commission, 2019).

In 2024, the European Commission introduced an intermediate 2040 climate target for the European Union after the global stocktake under the Paris Agreement, which proposes to reduce net greenhouse gas (GHG) emissions by 90% by 2040 compared to GHG emissions in 1990, to ensure that the European Union can deliver on its commitment to be climate neutral by 2050. Furthermore, during the 28th meeting of the Conference of the Parties (COP28), agreed that deep and rapid reductions in global GHG emissions are required to limit global warming to 1.5°C (European Commission, 2024).

Since methane’s characteristics include a lifetime of 9.1 years, the GHG may be seen as short-lived (Staniaszek *et al.*, 2022). Due to its intense warming potential, ~ 80 times more potent than CO₂ in the first two decades of staying in the atmosphere, and due to its short atmospheric lifetime, CH₄ is a particularly potent GHG with short-term impact (Forster *et al.*, 2021).

CH₄ is emitted from several sources that are directly and indirectly related to human (anthropogenic) activities (Bracmort *et al.*, 2014). In the *Global Methane Budget 2000–2020* CH₄ emissions summed from known sources on the ground (bottom-up measurements) between 2000 and 2019 were calculated to be 669 Mt CH₄ per year according to the estimates of Sauniois *et al.*’s (2025) model. Out of 669 Mt of CH₄ per year, 211 Mt or approximately 31 % was directly derived from agriculture and waste (Sauniois *et al.*, 2025), visualized in Figure 1.

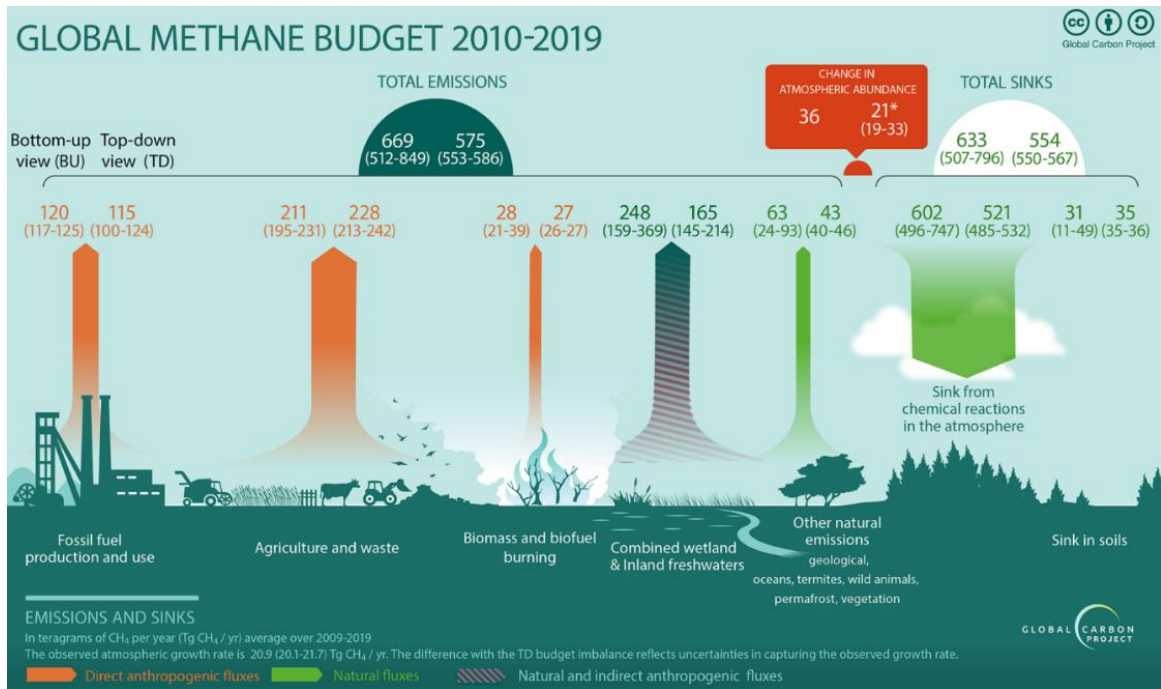


Figure 1: CH₄ emissions summed from known sources on the ground (bottom-up, left) and emission estimations using atmospheric measurements of CH₄ concentrations (top-down, right) provided for each sector with its emission or sinks (in Tg CH₄ yr⁻¹), as well as total emissions and total sinks. Anthropogenic CH₄ sources (orange arrows) and natural CH₄ sources (green and blue arrows) are distinguished by colour and text underneath.

Source: Saunio *et al.* (2025).

To distinguish between the agriculture and waste sectors, the global waste sector is responsible for almost 20% of all anthropogenic emissions (Clean Air Task Force, 2025). Despite the high emission levels from agriculture, in Sweden and globally (Shaefer, 2019; Ministry of Environment, 2020), decisions must balance emission reductions with the requirements of food and energy supplies. It is important to cut CH₄ emissions where easily possible, such as in the waste management sector. Out of all Swedish CH₄ emissions, and to put the emissions into a Swedish perspective, approximately 13% was directly derived from landfills (Ministry of Environment, 2020). Actively lowering CH₄ emissions from landfills may therefore generate large differences in total Swedish CH₄ emission mitigation and thus contribute to Sweden's net zero greenhouse gas emissions by 2050.

Landfills remain a large source of anthropogenic CH₄ emissions globally and in Sweden, accounting for a major share of waste-sector greenhouse gas outputs, and accurately quantifying these emissions is important for climate change mitigation. Data collection of CH₄ concentrations using Unmanned Aerial Vehicles, UAVs, show promising developments in recent years (Allen *et al.*, 2019; Knudsen & De Rossi, 2022; Fosco *et al.*, 2025), where the UAV-based measurements allow CH₄ emission quantification with high spatial resolutions if the CH₄ plume heterogeneity is considered (Tassielli *et al.*, 2025; Abichou *et al.*, 2023). The company ReSource Sverige AB utilizes a specific approach (GASTRAQ, or GAS TRacing And Quantification), to quantify CH₄ emissions on landfills, which is based on mass balance box modeling (Scheutz *et al.*, 2020; ReSource Sverige AB, 2025). Furthermore, other mass balance box approaches have been developed to quantify CH₄ emission fluxes for landfills, where

revised methods like the Drone Flux Method (DFM) (Knudsen & DeRossi, 2022) have been thoroughly validated (Scheutz *et al.*, 2025). Some key operational differences between GASTRAQ and the DFM include how the wind measurement is handled, where previous research has indicated that UAV-based CH₄ quantification is highly sensitive to wind conditions and the accuracy of wind field representation (Scheutz *et al.*, 2025; Knudsen & De Rossi, 2022).

1.1 Aim

In this bachelor's thesis, the aim is to review the two UAV-based methods for CH₄ monitoring, GASTRAQ and Drone Flux Method, and to assess how GASTRAQ aligns with or differs from the latest academic findings to assess the method's strengths and weaknesses. Two landfills in Rönneholm and Filborna, Sweden, where ReSource Sverige AB in collaboration with the Technical University of Denmark has performed CH₄ flux calculations with GASTRAQ, were used as examples and were raised as two case studies in this thesis. CH₄ flux calculations, using the Drone Flux Method, were performed on a wastewater sludge landfill in Linköping, Sweden. The yielded results from the wastewater sludge landfill were qualitatively compared to the case studies, to assess the advantages and disadvantages of GASTRAQ and the Drone Flux Method. Additionally, uncertainties of all measured fluxes and hence the uncertainties of the two methods were used to contrast between the methods. To achieve the aim, the following questions were to be answered through a literature review, the case studies of Rönneholm and Filborna landfill, and calculations of measurement data on Linköping landfill:

- 1 What are the strengths and limitations of UAV-based CH₄ emission quantification methods, and how does the GASTRAQ method approach compare to the Drone Flux methodology?
- 2 What are the key challenges in applying UAV-based CH₄ measurement techniques to landfill emissions, and how do these challenges affect model accuracy?

1.2 Hypothesis

H₀₁ GASTRAQ and the Drone Flux Method will produce comparable landfill CH₄ flux estimates under steady wind conditions, but DFM will yield more accurate results under higher wind speeds.

H₀₂ Assumptions of wind will affect model accuracy for GASTRAQ.

H₀₃ The uncertainty of the CH₄ flux estimations will increase with the size of the landfill for both GASTRAQ and the Drone Flux Method.

These hypotheses relate to the research questions above in *1.1 Aim*, where falsifying or confirming **H₀₁** will answer question 1, and where falsifying or confirming **H₀₂** and **H₀₃** will answer question 2. **H₀₁** addresses the expected difference in performance between GASTRAQ, which relies on ground-based anemometers and assumes a steady wind profile, and DFM, which integrates real-time wind measurements directly on the UAV. **H₀₂** builds on this by

basing that GASTRAQ's reliance on assumed wind fields introduces model uncertainty. **H03** suggests that spatial heterogeneity and incomplete plume coverage in larger landfills can result in greater uncertainty, and that the area will directly affect the uncertainty.

1.3 Delineations

The project will focus on methane emissions originating from landfills, and no other substances found in gases emitted from landfills. The reason for this decision is because the data used for achieving the project's aims are only representative for methane. What is worth pointing out with this delineation is that the results do not describe the total GHG emissions from the landfills examined, but one of the gases with the largest impact on climate, methane (Mar *et al.*, 2022; NASA, ND).

Additionally, this project will focus on UAV-based measurement methods for methane quantification, whereas other traditional methods like static flux chambers and eddy covariance towers will only be described in this project to contrast to UAV-based measurement methods.

2 Background and Literature Review

2.1 Literature review

The purpose of this literature review was to describe two UAV-based methods for CH₄ monitoring, GASTRAQ and DFM, and to assess how GASTRAQ aligns with or differs from the latest academic findings. Additionally, strengths and weaknesses of the two methods were presented.

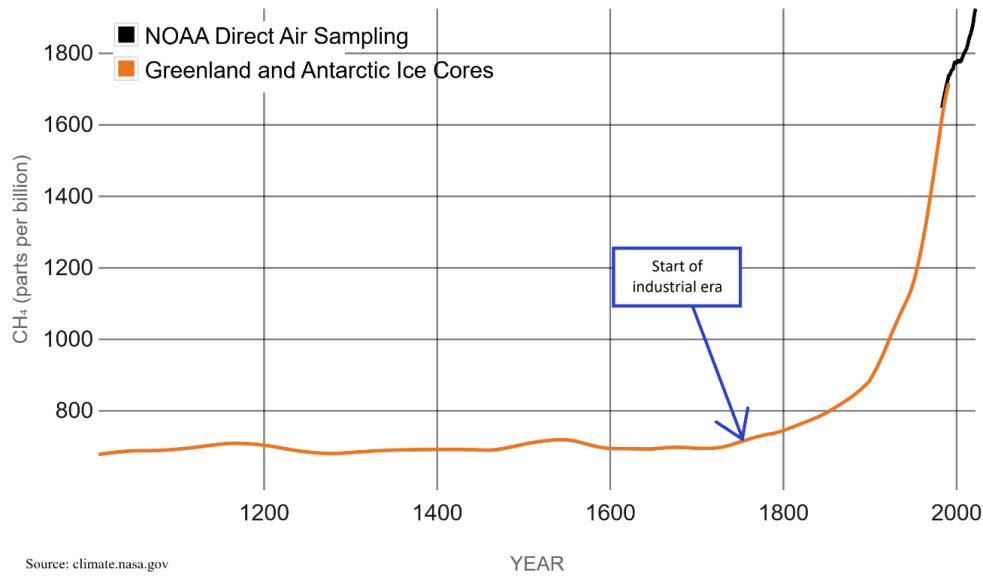
The search was limited to research published from 2014 to 2025 as to include relevant research as the progress within this research area is rapid and comprehensive. Allen *et al.* (2014) first presented the UAV-based mass balance modelling in 2014, which is the only relevant modelling approach for this bachelor thesis. Since 2019, GASTRAQ has been an early adopter of Allen *et al.* (2019)'s method, where GASTRAQ still has not yet been validated thoroughly. In contrast, the DFM is a newer method (Knudsen & DeRossi, 2022) where the extensive validation from Scheutz *et al.* (2025) concluded that the DFM agreed closely with the reference Tracer Dispersion Method (TDM) which is seen as a reliable UAV-based quantification method (Delre *et al.*, 2018),

The review was concentrated on prior works that were representative of the aims, where the studies were screened to assess scientific quality. To assess the quality of the literature, simple inclusion and exclusion criteria method presented by Mengist *et al.* (2020) was used to choose literary references, with some adaptations. For example, Swedish studies were used, and not only literature published in the English language. The searches were concentrated in the database Web of Science, where key terms like UAV AND mass balance AND methane were used. In total, 16 articles and projects were chosen for this review.

2.2 CH₄'s Impact on the Atmosphere

Between 1850 and late 1970, CH₄ has increased exponentially from 830 ppb to 1500 ppb (Kirschke *et al.*, 2013). This exponential increase of atmospheric CH₄ is visualized in Figure 2, where a trend can be seen since the industrial era where currently in 2025 CH₄ concentrations

in the atmosphere is at approximately 1930 ppb (Etheridge *et al.*, 1998; NOAA Global Monitoring Laboratory, N.D.)



*Figure 2: CH₄ concentrations (orange and later black line due to changes in the measurement source) in ppb in the atmosphere since year 1010. Atmospheric CH₄ has more than doubled since pre-industrial times and has increased exponentially after 1850. This exponential increase can be seen after the start of the industrial era (marked in blue). Source: Etheridge *et al.* (1998) and NOAA Global Monitoring Laboratory.*

CH₄'s global warming potential (GWP), which measures the relative warming impact of a greenhouse gas compared to carbon dioxide (CO₂), is significantly higher compared to CO₂ (Champecharoensuk *et al.*, 2023), seen in Table 1. CH₄ in the atmosphere has specific lifetime, 9.1 ± 0.9 years, and is eventually converted to CO₂ due to the oxidative capacity of the atmosphere. The resulting CO₂ is a stable molecule and is not further transformed in the atmosphere. CH₄ is therefore not only a direct radiative force but also indirect in the sense that oxidation of CH₄ leads to the production of other greenhouse gases (Mar *et al.*, 2022).

Table 1: Comparative global warming potentials (GWPs) of greenhouse gases in IPCC's 6th Assessment Reports. The atmospheric lifetimes, radiative efficiency, and global warming potential over 20-year and 100-year time horizons is shown for the greenhouse gases. Under the GWPs it can be seen that CH₄, both from fossil sources and non-fossil sources, is approximately 80 times more potent than CO₂. Source: Forster *et al.* (2021)

Species	Lifetime (Years)	Radiative Efficiency (W m ⁻² ppb ⁻¹)	GWP-20	GWP-100
CO ₂	Multiple	1.33 ± 0.16 × 10 ⁻⁵	1.	1.000
CH ₄ -fossil	11.8 ± 1.8	5.7 ± 1.4 × 10 ⁻⁴	82.5 ± 25.8	29.8 ± 11
CH ₄ -non fossil	11.8 ± 1.8	5.7 ± 1.4 × 10 ⁻⁴	79.7 ± 25.8	27.0 ± 11
N ₂ O	109 ± 10	2.8 ± 1.1 × 10 ⁻³	273 ± 118	273 ± 130
HFC-32	5.4 ± 1.1	1.1 ± 0.2 × 10 ⁻¹	2693 ± 842	771 ± 292
HFC-134a	14.0 ± 2.8	1.67 ± 0.32 × 10 ⁻¹	4144 ± 1160	1526 ± 577
CFC-11	52.0 ± 10.4	2.91 ± 0.65 × 10 ⁻¹	8321 ± 2419	6226 ± 2297
PFC-14	50,000	9.89 ± 0.19 × 10 ⁻²	5301 ± 1395	7380 ± 2430

Furthermore, CH₄ is responsible for ozone production via reactions of nitrogen oxides (NO_x) (Ocko & Hamburg, 2022). This means that an increase in atmospheric CH₄ chemical lead directly to higher concentrations of tropospheric ozone (National Oceanic and Atmospheric Administration, 2022; Mar *et al.*, 2022), a strong GHG that absorbs radiation (United Nations Environment Programme, 2022). Tropospheric ozone not only affect the atmospheric climate, but has impacts on evaporation rates, cloud formation, precipitation levels, and atmospheric circulation (United Nations Environment Programme, 2023; Collins *et al.*, 2014).

This issue is relevant due to the scale of tropospheric ozone being produced by CH₄. Over 50% of tropospheric ozone is attributable reactions involving CH₄ (National Oceanic and Atmospheric Administration, 2022). A recent study (Staniaszek *et al.*, 2022) simulated what impact lowering CH₄ would do to tropospheric ozone concentrations in the atmosphere, where a 26% reduction in CH₄ could decrease surface ozone by about 9.7% by 2050 (Staniaszek *et al.*, 2022).

2.3 Sweden's CH₄ Emissions and Landfills

Swedish landfill regulations play a central role in shaping national waste management practises and their impact on CH₄ emissions, to help achieve Sweden's net zero greenhouse gas emissions by 2050. According to 4§ in Swedish waste regulation law (SFS 2011:927)

“... a landfill refers to a storage site for waste that is on or in the ground.”. Since 2011, this regulation has continuously changed and adapted to today's time, where its accompanying regulations (SFS 2020:614; SFS 2001:512) have been adapted to account for both active and inactive phases of landfills. Today, the Swedish waste management is made up of hierarchical levels, to prevent the creation of waste. The prioritisation of waste management is as followed:

1. waste prevention
2. reuse
3. material recycling and biological treatment
4. other recycling, e.g. energy recovery
5. disposal, e.g. to landfills.

With these hierarchical levels of waste management, it is then up to municipalities to separately be responsible for ensuring that waste is transported and recycled in the best possible way, or disposed of when that is suitable (Avfall Sverige, 2024).

In 2020, CH₄ emissions in Sweden corresponded to approximately 9% of Sweden’s total GHG emissions, where CH₄ emissions from waste have decreased by approximately 80% since 1990 (Ministry of the Climate and Enterprise, 2022). One explanation for this decline may be explained through the regulation 8 § 7 p. in (SFS 2001:512) set in 2001, which states that organic waste is no longer legal to landfill. CH₄ emissions from landfills in Sweden still correspond to approximately 13% of total CH₄ emissions recorded in 2020, which can be visualized in Figure 4.

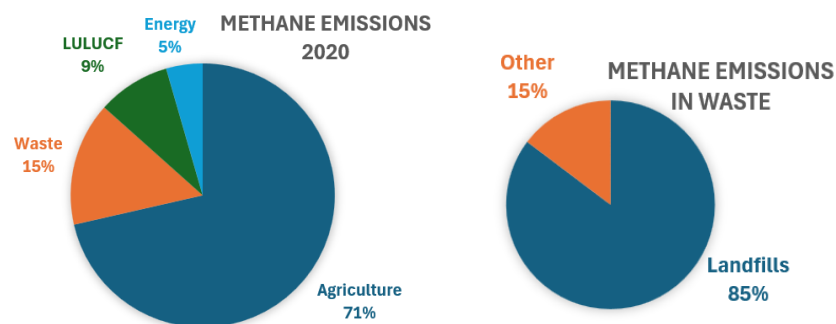


Figure 3: CH₄ emissions in Sweden in 2020. The waste sector (orange on the left) emitted 15% of total emissions in Sweden, where 85% derived from Landfills (blue on the right) and the remainder from “other”. CH₄ emissions derived directly from landfills are therefore approximately 13% summed up. Data source: Ministry of the Climate and Enterprise, Government Offices of Sweden (2022).

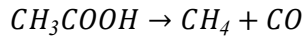
2.4 The Production of CH₄ in Landfills

Today, landfills are still affecting the environment in several ways. Since the waste is extremely heterogeneous, no pollution can be neglected (Naturvårdsverket, 2011). Leachate extracts soluble or suspended solids from landfills to waterways during precipitation events, leading to pollution in the waterways (Naturvårdsverket, 2008). Regulated landfills containing organic material undergo anaerobically decomposition, producing CH₄ and CO₂ with two biochemical processes: acetogenesis and methanogenesis (Themelis & Ulloa, 2007).

Acetogenesis



Methanogenesis



2.5 UAV-Based Measurement Approaches

Due to CH₄'s impacts on a global scale, Tassielli *et al.* (2025) and Allen *et al.* (2014) suggest it is important to monitor all sectors. It is especially important to monitor waste management practices such as landfills, as they are anthropogenic sources of CH₄ emissions that can be effectively mitigated. An alternative to time-consuming methods like the static chamber flux method, which are commonly used to quantify CH₄ emissions (Yilmaz *et al.*, 2021; Wang *et al.*, 2019; Levy *et al.*, 2011), is using Unmanned Aerial Vehicles, or UAVs, to map larger areas.

Eddy covariance towers is one of the main conventional tools used for smaller local and larger local scales, typically suitable for areas smaller than 100 hectares (Allen *et al.*, 2014), but can yield large uncertainties (Yong *et al.*, 2024; Bolek, 2024). Moreover, eddy covariance towers are fixed installations that require accessible terrain and long-term setup, making them impractical for remote or spatially complex landfill sites (Mønster *et al.*, 2019). The fixed setup of eddy covariance towers leads to a limited surface coverage, hence that the quantification does most likely not provide representative emissions for the whole landfill site (Mønster *et al.*, 2019).

In contrast, UAV-based CH₄ quantification methods are easy to deploy and can be operated over otherwise inaccessible or hazardous areas with minimal setup time (Allen *et al.*, 2014). UAV-based CH₄ quantification methods can also be used for a number of purposes over smaller scales (Allen *et al.*, 2014), while delivering high-resolution spatial data over extensive areas, while simultaneously offering time reductions during data collection (Tassielli *et al.*, 2025).

UAVs with a CH₄ sensor attached measure CH₄ concentrations, and how the measured concentrations are transformed into fluxes varies depending on flux calculation methodology and assumptions made for modelling flux estimations. Despite the increasing interest in UAV-based monitoring methods, a clear knowledge gap remains in developing standardized, validated methods that can reliably quantify landfill emissions across different spatial and temporal scales, with reduced uncertainty and operational feasibility for routine use. Advancements in the latest years have offered enhancements of UAV-based methods to access comprehensive flux estimation results that are representative for real-life situations (Liang *et al.*, 2024; Abichou *et al.*, 2023).

2.5.1 Classic Mass balance flux approach

A mass balance flux approach combined with UAVs have been identified as a “promising approach” by Allen *et al.* (2019). Allen *et al.* (2014) identified a feasible mass balance method, which follows equation 3:

$$Flux = \int_0^z \int_A^B (S_{ij} - S_0) n_{ij} U_{\perp ij} dx dz \quad (3)$$

In this method, CH₄ flux is calculated by measuring how much CH₄ passes through an imaginary vertical wall (called plane AB) that is placed downwind of the source and perpendicular to the wind direction (Allen *et al.*, 2014) seen in Figure 4. At each point on this wall, the amount of CH₄ ($S_{ij} - S_0$) is measured in concentrations as molar densities, and the background level (S_0) is determined from measurements taken upwind of the landfill (Figure 4), where only natural atmospheric emissions are expected and not emissions from the landfill.

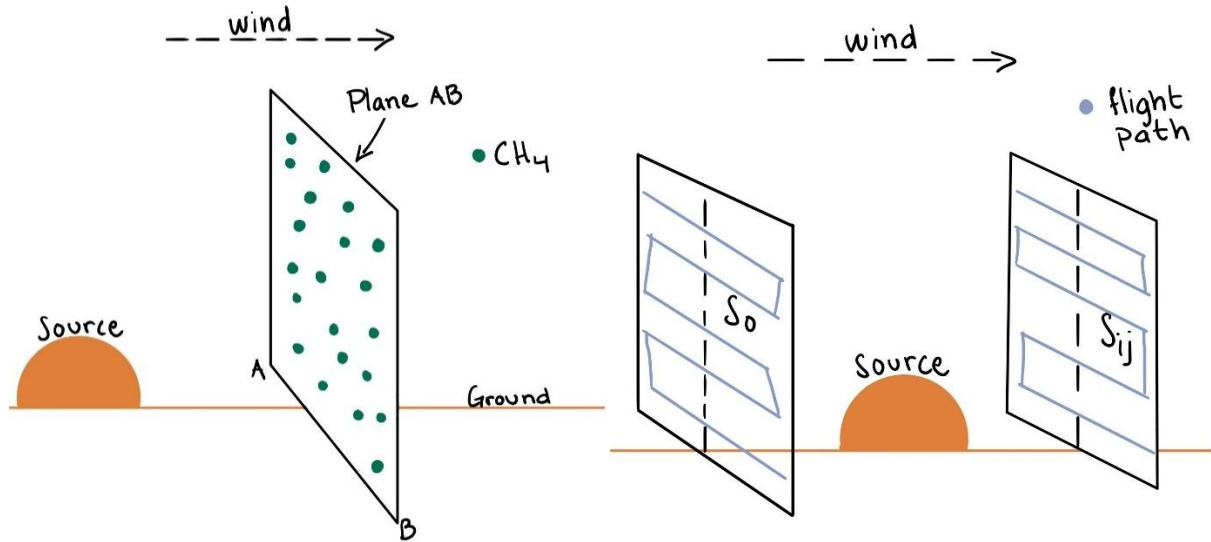


Figure 4: Conceptual sketches on how UAV-based measurements are taken. On the left, the wall “Plane AB” is shown, which is measured downwind at the source, perpendicular to the wind. On the right, flightpaths for S_{ij} (same as Plane AB) and background CH₄ S_0 (upwind to the source) are shown.

The mole density of air (n_{ij}) is calculated using the ideal gas law, based on the air temperature and air pressure at the time. Wind speed that moves air through the wall ($U_{\perp ij}$) is also measured at each point in m/s. By multiplying these values together (n_{ij} , $U_{\perp ij}$, and $(S_{ij} - S_0)$) and integrating them both vertically and horizontally across the wall, as in equation 3, the total CH₄ flux through the wall is found in kg h^{-1} .

To find the average emission per unit of surface, the total flux is divided by the area of the landfill. The flight paths and sampling strategy need to be carefully planned to cover the plume effectively and get the most accurate results possible (Allen *et al.*, 2019).

This method of calculating fluxes, along with minor differences in flight paths with the UAVs and assumptions, has been used as a basis of mass balance theory within UAV CH₄ monitoring in several projects (Gålfalk *et al.*, 2021; Fosco *et al.*, 2025; Scheutz *et al.*, 2020). ReSource Sverige AB, a company that delivers consultant services as well as operational solutions, have been quantifying CH₄ emissions through GASTRAQ, a method based on the mass balance flux approach (Scheutz *et al.*, 2020; Allen *et al.*, 2014).

Recent advancements within UAV-based flux calculation methods include the Tracer Dispersion Method (TDM), which has been used for multiple CH₄ emission campaigns, or surveys (Delre *et al.*, 2017; Mitchell *et al.*, 2015; Reinelt *et al.*, 2017), and is promoted by the United States Environmental Protection Agency for source emission measurements (Foster-Wittig *et al.*, 2015). The United States Environmental Protection Agency considers TDM to be reliable, and hence it is an often-used technique for fugitive CH₄ quantification. A tracer gas, often acetylene, is released at a known rate and compared with CH₄ concentrations downwind. The CH₄ flux is then inferred from the ratio of CH₄ to tracer in the plume (Foster-Wittig *et al.*, 2015). While TDM is seen as reliable, it requires handling of gases on site and is thus less convenient operationally; UAV performing direct CH₄ measurements are therefore logistically simpler for routine monitoring.

2.5.2 The Drone Flux Method

The Drone Flux method, DFM, is often described as a mass balance vertical flux plane approach, which directly computes CH₄ emission rates by integrating the CH₄ passing through a cross-sectional area downwind of the landfill (Shaw *et al.*, 2021). In practice, a UAV has an attached CH₄ sensor, together with an anemometer, and flies through the plume. The UAV makes horizontal transects at multiple altitudes and maps the concentration distribution. The flux is then calculated by integrating the plume's CH₄ enhancement above background CH₄ times the perpendicular wind speed over the plume's cross-sectional area (Knudsen & De Rossi, 2022). The reported uncertainties (~50%) were dominated by variability in background CH₄ and wind measurements but were comparable to uncertainties of ground-based methods where the anemometer is mounted on masts on the ground.

Another study, Gålfalk *et al.* (2021), deployed a custom UAV with the onboard CH₄ analyser MIRA Pico (Aeris Technologies, USA) and the 3D anemometer TriSonica Mini LI-550 (LI-COR, United States), eliminating the need for ground-based wind masts. The sludge landfill from a wastewater treatment was the focus of their project, where the quantified emissions from January 2020 were compared to a prior study at the same wastewater plant lasting a year using an Ultraportable Greenhouse Gas Analyzer (UGGA) (Los Gatos, Switzerland) (Gålfalk *et al.*, 2021). Furthermore, the results were compared using ground-based hyperspectral remote sensing measurements on the same wastewater plant (Gålfalk *et al.*, 2015). These three results agreed with each other, leading to the assumption of a correct quantification of CH₄ emissions from the landfill (Gålfalk *et al.*, 2021).

Similarly, Fosco *et al.* (2025) developed a UAV mass balance approach and tested it on an Italian municipal landfill. The results yielded values 2 to 4 times higher than those found from flux chambers and stressed the ability of UAV based measurements. A significant development for this approach was made by the validation study by Scheutz *et al.* (2025), who utilized the Drone Flux Method for the updated mass balance approach. Scheutz *et al.* (2025) tested the DFM on multiple scenarios, like single versus multiple leaking sources of CH₄, and leaking CH₄ close to the ground versus CH₄ plumes from the landfill that have risen to higher elevations. To simulate these conditions, a controlled release of CH₄ at a constant flow rate was simulated, where both the Tracer Dispersion Method (TDM) and the DFM were tested. The UAV-derived fluxes were within +33% to -35% of the true values from a controlled release of CH₄ when the DFM was tested, whereas a strong agreement was found between DFM and the TDM (Scheutz

et al., 2025): often known as a gold-standard technique (Delre *et al.*, 2018). The study showed that a well-executed DFM can match TDM results within a few percent (Scheutz *et al.*, 2025).

2.5.3 GASTRAQ

Similar to DFM, GASTRAQ utilizes UAVs to measure various atmospheric variables. The UAV, is equipped with GLA131-GGA (ABB-Los Gatos, Switzerland), a CH₄ gas sensor, and flown downwind of the area of interest at increasing heights. To know the optimal flight paths, a screening flight is done to assess where the plume is located on the area of interest (ReSource Solutions Sverige, 2025).

In order to incorporate the wind component, ReSource Sverige AB uses one mast, with the anemometer TriSonica Mini LI-550 (LI-COR, United States) mounted at 2 and 10 meters above ground level. Their method, therefore, bases its wind assumptions on ground-based measurements and assumes uniform wind behaviour at ground-level, applicable in the inertial surface layer, as they are using a modelled wind profile based on the fixed mast readings (ReSource Solutions Sverige, 2025). This is the main difference between the GASTRAQ method and DFM. Hence, compared to DFM and due to reliance on ground-based wind measurements, GASTRAQ is particularly vulnerable to inaccuracies arising from variable wind profiles according to Scheutz *et al.* (2025)'s recommendations. Choosing the right wind conditions is also part of the methodology, to reduce uncertainties coming wind speed variations. When high winds are present, the velocity gradient is pronounced along the vertical profile, which increases the measurement uncertainty, especially near the surface (Fosco *et al.*, 2025). Consequently, when wind speeds exceed 6-7 m/s, the uncertainty in the estimate is increased (Fosco *et al.*, 2025). Additionally, variations in wind direction increase the uncertainty of the flux estimates (Allen *et al.*, 2019; Yong *et al.*, 2024). The UAV is therefore needed to be deployed during the most favourable environmental conditions (wind speeds lower than 6-7 m/s, with low but still with fully developed turbulent conditions) to apply the ground-based wind measurements and its logarithmic profile as proxy for the different conditions up at the altitude of the UAV. A logarithmic profile still requires steady state and fully developed turbulent conditions, flat and horizontal homogeneous areas, and being in the inertial surface layer (ReSource Sverige AB, 2025).

2.5.4 The Wind Components

The mass balance formula divides concentrations by wind speed, so any error in wind measurement translates directly to flux error. As GASTRAQ and DFM handle wind differently, differences in wind component errors will be found. Both Scheutz *et al.* (2025) and Knudsen & De Rossi (2022) utilized CH₄ sensors and anemometers that are both attached to the UAVs, which eliminates the need for ground masts. As GASTRAQ calculates an average wind profile over the flight duration (ReSource Sverige AB, 2025), which is explained more in depth in 3.2.3 *The GASTRAQ method*, the assumptions somewhat compensate for issues like time variations and differences in the wind profile.

2.5.5 Diode Laser Absorption Spectroscopy

To measure CH₄ concentrations directly from the UAV, Diode Laser absorption Spectroscopy (TDLAS) has been utilized for multiple studies in the latest years (Knudsen & De Rossi, 2022;

Gålfalk *et al.*, 2021). The GASTRAQ method uses a more robust TDLAS cavity ring spectroscopy GLA131-GGA (ABB-Los Gatos, Switzerland) (Scheutz *et al.*, 2020), while Gålfalk *et al.* (2021) utilized the MIRA Pico (Aeris Technologies, USA). Diode Lasers are good light sources when used for absorption spectroscopy as they have smooth wavelength tunability, easy manoeuvring, and high accuracy (Wang *et al.*, 2024). Details on TDLAS, and TDLAS cavity ring spectroscopy, can be found in *Appendix D*.

3 Methods

3.1 Case Study Sites and GASTRAQ Method Application

Two landfills were used as examples of the usage of GASTRAQ. With these case studies, on Rönneholm and Filborna landfill, the accuracy of the GASTRAQ method was assessed. To assess the accuracy of GASTRAQ, results (a clarifying flowchart and source of the procedure can be seen in *Appendix A*) from previous projects conducted by ReSource Sverige AB were examined and compared to a practical analysis with the DFM. Results from four campaigns using GASTRAQ were assessed and qualitatively compared to Drone Flux Method outputs, focusing on relative error and uncertainty. The campaigns include 2 from Filborna and 2 from Rönneholm, where both sites are landfills and located in Sweden.

What is missing from the information of the landfills are the exact nature of the research sites, like landfill composition. It is therefore important to note that only indirect comparison could be done to assess the accuracy of GASTRAQ when comparing with the method DFM. What was comparable were the yielded relative errors calculated using the same formula seen in *3.3 Uncertainty testing*, and the rest of the comparisons were realized through discussion.

3.1.1 Filborna Landfill: Site Characteristics and GASTRAQ Campaign

In October 2023 and November 2024, two campaigns were executed by ReSource Sverige AB to quantify CH₄ on Filborna landfill in Helsingborg, Sweden. Filborna landfill (Figure 5) is operated by Nordvästra Skånes Renhållnings AB, which has been in operation since 1951 (Nilsson, 2008). The landfill is estimated to be around 35 hectares (Möller, 2022; ReSource Sverige, 2025). The waste that is found along this site is for example industrial and commercial waste, household waste, and waste sludge. Additionally, Filborna has one biogas collection facility site of 1 hectare within its area (ReSource Sverige AB, 2025) which has been in operation since 1985 (Scheutz *et al.*, 2020).



Figure 5: An overviewing aerial photo of Filborna landfill (marked in blue) situated in Helsingborg, Sweden. Modified image from ©Google Earth 2025.

3.1.2 Rönneholm Landfill: Site Characteristics and GASTRAQ Campaign

In March 2024 and May 2024, ReSource Sverige AB surveyed the Rönneholm landfill for fugitive CH₄. Rönneholm Landfill (Figure 6), situated in Eslöv, Sweden, collects waste from sources such as construction and demolition waste from households, asbestos, concrete and brick, and garden waste (Höör's Kommun *et al.*, 2024). The responsible operator over this landfill is Merab, who has 6 landfill areas for waste management where Rönneholm landfill is the largest site with an area of approximately 28 hectares (Eslövs Kommun *et al.*, 2024; ReSource Sverige AB, 2025).



Figure 6: An overviewing aerial photo of Rönneholm landfill (marked in blue), situated in Eslöv, Sweden. Modified image from ©Google Earth 2025.

3.1.3 GASTRAQ Methodology: Data Collection, Wind Modeling, and Flux Calculation

GASTRAQ utilizes the ground-based anemometer TriSonica Mini LI-550 (LI-COR, United States) to measure various atmospheric variables, including: temperature, air pressure, and relative humidity. The UAV Matrice 600 Pro (DJI, United States) is equipped with the CH₄ gas sensor GLA131-GGA (ABB-Los Gatos, Switzerland), and flown downwind of the area of interest at increasing heights (ReSource Sverige AB, 2025).

Each data point will have a measured concentration after the source that is estimated with TDLAS cavity ring spectroscopy, measured in ppm. Atmospheric (background) CH₄ is later measured with the UAV by flying upwind before the sampling of the plume. Background CH₄ (S₀) is then subtracted from the total CH₄ (S_{ij}). The concentration is later converted into an absolute mass concentration C_m with equation 4 (Scheutz *et al.*, 2020).

$$C_m = ppmv \cdot \frac{v_{air}}{M_{methane}} \cdot \frac{T_s}{T_m} \cdot \frac{P_m}{P_s} \quad (4)$$

Where:

- C_m = absolute mass concentration of CH₄ (kg/m³)
- ppmv = parts per million of gas (ppm)
- V_{air} = molar volume of air at standard conditions (~22.4 liters)
- M_{CH₄} = molecular weight of CH₄ (~16.0425g/mol)
- T_s = standard temperature (273.15K)
- T_m = median measured temperature (K)
- P_m = median measured pressure (mB)
- P_s = standard pressure (1013mB)

The absolute mass concentrations of CH₄ for each measurement point needs to be incorporated together with wind speed to convert the data into fluxes. As the wind profile varies with its

vertical and horizontal axes, ground-based measurements are used to estimate the average logarithmic wind profile to somewhat compensate for vertical variations and variations in time of the wind field. The velocity at the height z above ground v_z is then calculated with equation 5 (ReSource Sverige AB, 2025).

$$v_z \approx v_{ref} \cdot \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)} \quad (5)$$

Where:

- v_2 = wind speed at the bottom anemometer (m/s)
- v_1 = wind speed at the top anemometer in (m/s)
- z_1 = height above ground of the top anemometer (10 meters)
- z_2 = height above ground of the bottom anemometer (2 meters)
- z_0 = surface roughness length (m)
- d = zero plane displacement
- v_{ref} = wind speed measured at the top ground-based anemometer (m/s)
- v_z = velocity at the height z above ground (m/s)

The absolute mass concentration was then divided by the estimated wind speed, to acquire the CH_4 flux in kilograms CH_4 per m^2 and hour ($\text{kg m}^{-2} \text{h}^{-1}$). Lastly, the CH_4 fluxes were interpolated using Ordinary Kriging to generate a cross-section of the gas plumes, in 2D, where an example can be seen in Figure 7. An integration of the kriged result found the total flux volume of the area, in kg h^{-1} (Scheutz *et al.*, 2020). As another visualization, to quantify if the size of the landfill affects the model accuracy, the total CH_4 flux for every campaign was divided by the size of the landfill, in the unit hectare to get the flux in the unit $\text{kg ha}^{-1} \text{h}^{-1}$.

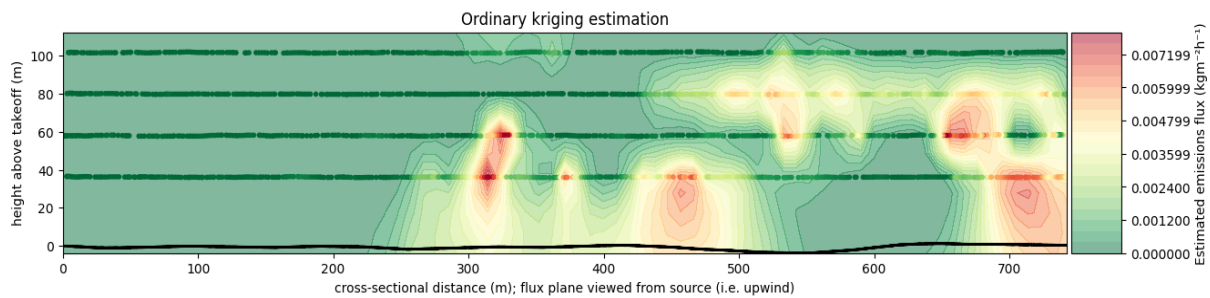


Figure 7: This is a cross-sectional heatmap plot of CH_4 flux estimates, where CH_4 plumes (red “clouds”) can be seen. The UAV measured CH_4 concentration on the transects (dark green points), and were later interpolated with Ordinary Kriging, where the black line represents the ground. This example was generated on the Filborna campaign. Source: ReSource Solutions Sweden (2025).

Kriging is a local statistical interpolation method, meaning that the surface may be modelled as a random probability distribution surface. It uses a group of different local interpolation

methods, where Ordinary Kriging has the mean value as unknown and the mean is instead determined during the interpolation (Stadler *et al.*, 2023). Ordinary Kriging has been widely used in atmospheric science (Tadic *et al.*, 2017; Morales *et al.*, 2022; Bolek *et al.*, 2024) and is suitable when there is a large number of data points as a random function (Lister *et al.*, 2000). Yong *et al.* (2024) highlights the need for geospatial interpolation of sparse sample data by using Kriging to fill in unsampled regions of the plane to avoid bias if sampling misses peak concentrations: and was therefore used for this data set.

3.2 Analysis of Measurement Data Using DFM

3.2.1 Data and instrumentation

To compare GASTRAQ with the Drone Flux Method by Knudsen & De Rossi (2022), UAV based measurement data was accessed from Gålfalk *et al.* (2021). The data was divided into 3 flights, hence 3 parts: and was collected on the 24th of January 2020. The study area was on a sludge landfill on a wastewater treatment plant in Linköping, Sweden, with a size of 35x35 m (or 1225 m²). The flight paths consisted of vertical plane flights and the data collected included the following: log time, coordinates (long/lat), altitude, wind speed and wind direction from the anemometer TriSonica Mini LI-550 (LI-COR, United States), air pressure, air temperature, relative humidity, and CH₄ concentrations in ppm by using the MIRA Pico (Aeris Technologies, USA). At each point, the CH₄ concentration was measured, and the background level (S_0) was determined from measurements taken upwind of the landfill. The UAV Matrice 210 (DJI, United States) was flown manually at a set speed of 1 m/s to avoid obstacles and to keep accuracy high.

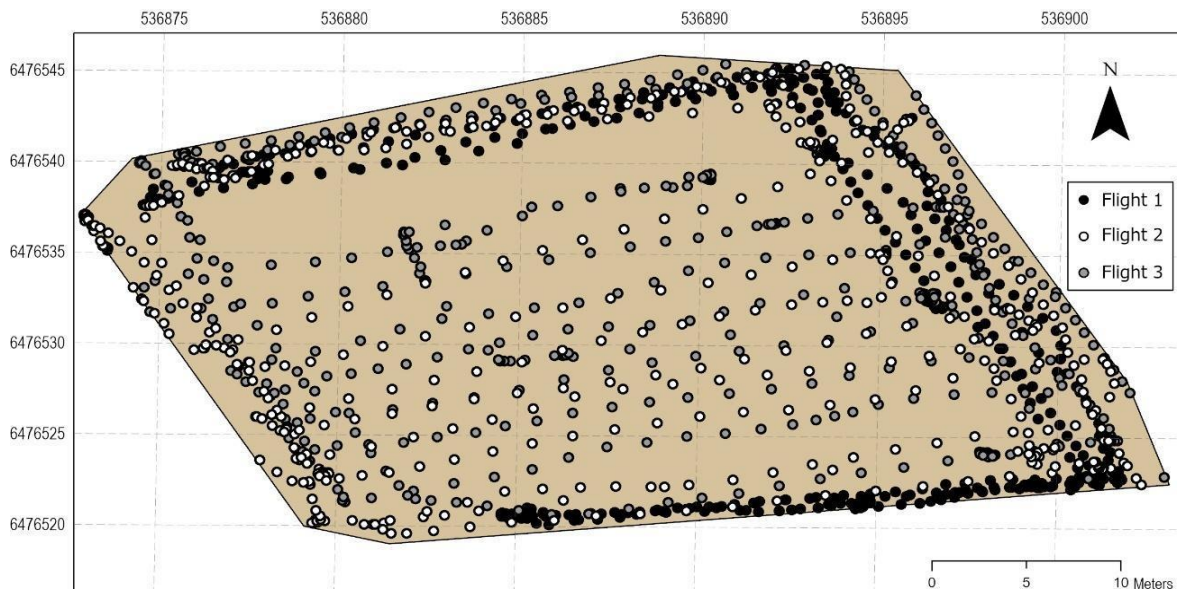


Figure 8: Measurement points from flight 1 (black), 2 (white), and 3 (grey) are shown in the study area as points. The flight tracks used for this project are vertical planes, along with the horizontal surface. Source: Gålfalk *et al.* (2021). Projection: SWEREF 99

3.2.2 Drone Flux Measurement Method

The recent Drone Flux Measurement Method (DFM) was used to compare with the GASTRAQ method, where the DFM uses the same foundation as GASTRAQ as they both are mass balance methods, but they differ in how to obtain and apply the values required for the flux calculation. Knudsen & De Rossi (2022) measure wind and CH₄ at the same place and time, minimizing mismatch. Wind fluctuations (gusts, veers, lulls) are captured as they occur in the plume.

In this thesis, I performed all flux calculations based on the methodology by Knudsen & De Rossi's (2022) and Scheutz *et al.*'s (2025) validations. A clarifying flowchart and source of the procedure can be seen in in *Appendix A*.

The data set from Gålfalk *et al.* (2021) obtained by the UAV has the required CH₄ concentrations, as background S₀ and total CH₄ concentrations S_{ij}, where the background was subtracted to get CH_{4ppm}. CH_{4ppm} were converted into an absolute mass concentration C_{methane}, which was done through equation 6, derived from the ideal gas law.

$$C_{methane} = \frac{CH_{4ppm} \cdot M_{ch4} \cdot P}{R \cdot T} \quad (6)$$

where:

- C_{methane} = absolute mass concentration (mg/m³)
- CH_{4ppm} = CH₄ concentration (S_{ij} - S₀) (ppm)
- M_{ch4} = molecular weight of CH₄ (≈16.04 g/mol)
- P = atmospheric pressure (Pa)
- T = temperature (K)
- R = the universal gas constant (8.314 J/(molK))

Wind speed was subsequently accounted for to acquire the flux, as errors in wind speed can cause significant flux errors (Scheutz *et al.*, 2025). The measured wind components were used to calculate the difference between the wind's direction and the wall-normal direction to get the component of wind velocity that is perpendicular to the wall (normal wind speed).

I then calculated flux density by dividing this component with the corresponding CH₄ absolute mass concentration to yield a local mass flow rate. These calculations were lastly interpolated using ordinary kriging, and zonal statistics were applied over the interpolated fluxes to compute the total CH₄ flux in kg h⁻¹. As another visualization, to quantify if the size of the landfill affects the model accuracy, the total CH₄ flux for Linköping campaign was divided by the size of the landfill, in the unit hectare, to get the flux in kg ha⁻¹ h⁻¹.

3.3 Uncertainty testing

To assess accuracy for the DFM and GASTRAQ, an uncertainty test was conducted based on the approach developed by Allen *et al.* (2018). The test has been performed using data from ReSource Sverige AB's measurement campaigns (ReSource Sverige AB, 2025) and the flux estimates obtained from the Linköping landfill. ReSource Sverige AB performed the uncertainty testing for the campaigns where GASTRAQ was used, while I performed the

uncertainty testing for the campaign where the DFM was used. Equation 7 was utilized for all uncertainty quantifications.

$$\sigma_T = F \sum_i^N \sqrt{\frac{\sigma_f^2}{\bar{f}} + \frac{\sigma_\varepsilon^2}{\bar{X}} + \frac{\sigma_{ws}^2}{\bar{ws}} + \sigma_{wd}^2 + \frac{\sigma_B^2}{\bar{B}}} \quad (7)$$

Where:

- σ_T = total flux uncertainty (1σ) summed over N grid cells for the entire flux plane (kg h^{-1})
- F = total flux (kg h^{-1})
- σ_f = standard deviation of measured mass concentrations in each cell (kg m^{-3})
- σ_ε = instrumental measurement precision (ppm)
- \bar{f} = mean point flux ($\text{kg m}^{-2} \text{ h}^{-1}$)
- \bar{X} = mean measured concentration in each cell (ppm)
- σ_{ws} = standard deviation of measured wind speed across measurement period (m/s)
- \bar{ws} = mean wind speed (m/s)
- σ_{wd}^2 = standard deviation of background emissions (unitless)
- σ_B^2 = standard deviation of background emissions (ppm)
- \bar{B} = mean measured concentration in each grid cell of the background plane (ppm)

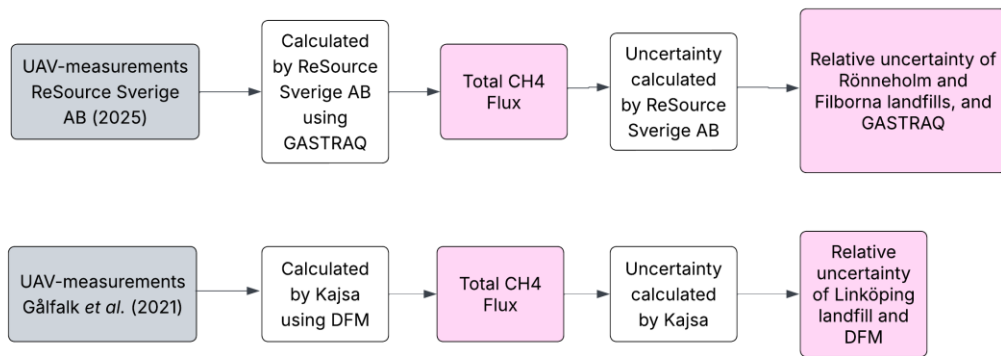


Figure 9: A simplified flowchart on where data was derived from and what procedures were done to get a relative error for each landfill campaign. The data sources (grey), responsible for the procedure (white), and the produced results (pink) are shown within the flowchart.

4 Results

4.1 CH₄ Flux Quantification from GASTRAQ Campaigns

The two campaigns done on the landfill site Filborna on yielded measured fluxes of 111.1 kg h^{-1} on October 2023 and on November 2024, the same area rose to a flux of 129.8 kg h^{-1} , seen in Table 2. The relative errors corresponding to the calculated CH₄ emissions fluxes are seen in Table 2.

Table 2: The results yielded from the GASTRAQ method, measured and modelled by ReSource Sverige AB. Calculated CH₄ flux, averaged over number of flights are shown. The relative errors from uncertainty testing are shown per campaign, in kgh⁻¹. The relative errors describe how much the CH₄ fluxes from Table 2 can deviate, calculated by ReSource Sverige AB as in equation 7. To distinguish between campaigns, see Date.

Campaign	n of flights	Date	Area (ha)	Total CH ₄ emissions flux (kgh ⁻¹)	Relative error (kgh ⁻¹)
Filborna	7	October 2023	36	111.1 kgh ⁻¹	± 33.2
Rönneholm	6	March 2024	28	9.0 kgh ⁻¹	+8.7/-7.5
Rönneholm	9	May 2024	28	13.0 kgh ⁻¹	+11.1/-8.7
Filborna	9	November 2024	36	129.8 kgh ⁻¹	+119.3/-51.4

The errors for the measurements done range asymmetrically in all campaigns except Filborna in October 2023 seen in Table 2, meaning that the other campaigns had an asymmetrical distribution of data points around the central value. It is seen that the only symmetrical error reflects a well-behaved dataset with minimal bias, stable wind conditions, and consistent plume capture during all flights. The estimate is just as likely to be overestimated as underestimated. One thing to note is that all campaigns have at least 3 flights, which correspond well to recommendations given by Scheutz *et al.* (2025), as increased flights decrease uncertainties.

Rönneholm landfill has varying ranges of error within its site, although on different days. In March 2024, the relative error range was +8.7/-7.5 kgh⁻¹, while the same site yielded a relative error of +11.1/-8.7 kgh⁻¹ in May 2024. That is an increase of 2 percentage points in the positive error range, and a decrease of 1.2 percentage points in the negative range

To contrast, the two surveys done on Filborna landfill produced errors that are hugely different. In October 2023, the differences are ± 33.15 kgh⁻¹ (Table 2), while the errors in November 2024 were +119.3/-51.4 kgh⁻¹ (Table 2). That is an increase of 86 percentage points in the positive error range, and a decrease of 18 percentage points in the negative range.

4.2 CH₄ Flux Quantification Using DFM

CH₄ concentrations measured during flights 2 and 3 are visualised in Figure 10 through interpolation made by the author or this thesis, where flight 2 and 3 have visual differences in CH₄ concentration hotspots. The largest difference seen visually is the hotspot on the north wall seen through flight 2. This is not as visible in flight 3. They do however have multiple closer similarities where the eastern wall seems to be high in CH₄ concentrations in both, suggesting that the highest emissions will be seen is on the eastern wall and southeast corners.

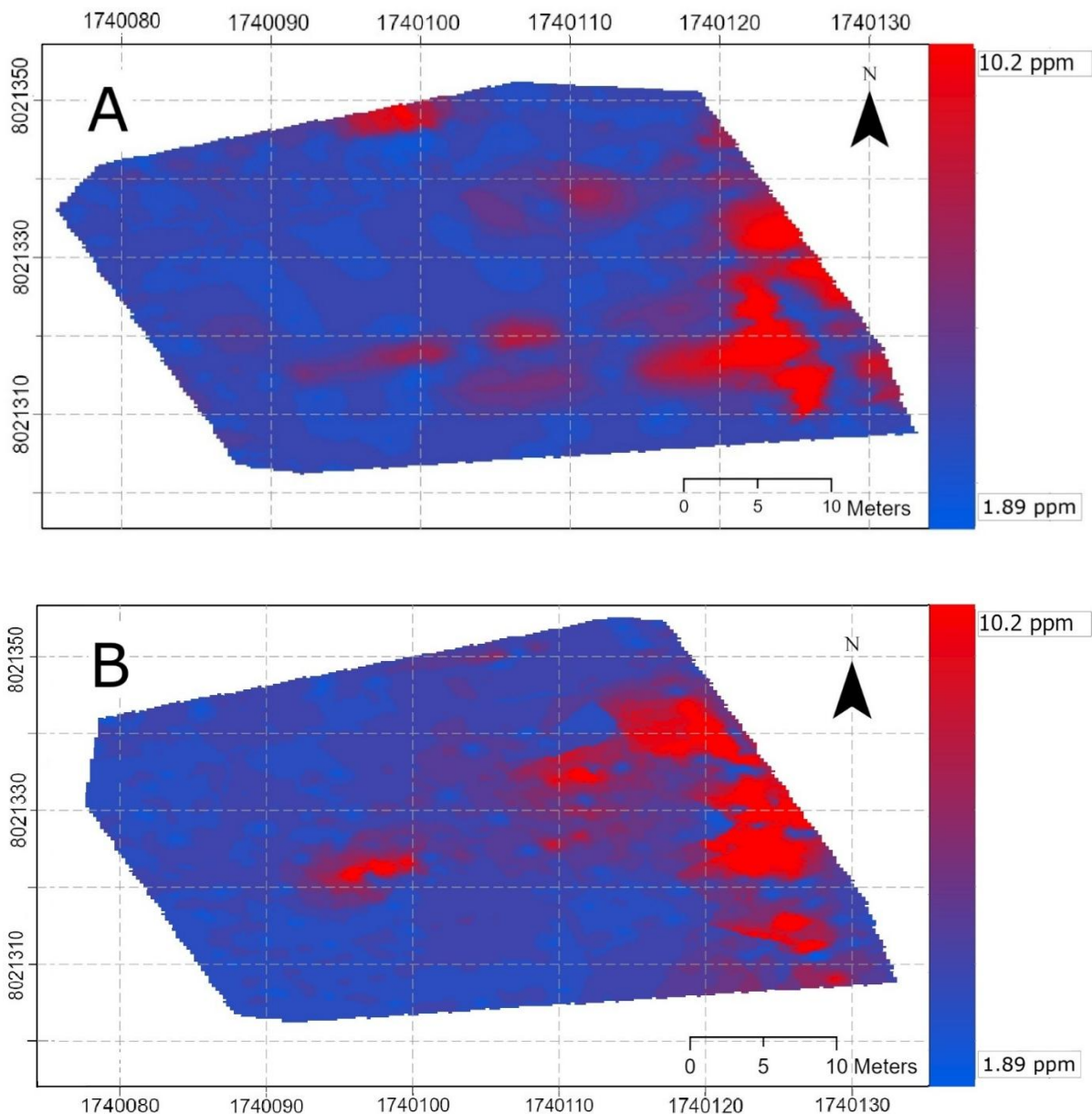


Figure 10: Horizontal maps of Linköping landfill and its CH₄ concentrations in ppm, using UAV measurement data from Gålfalk et al. (2021). The concentrations have been interpolated to show distribution over the sludge landfill with the size 35x35 m. Flight 2 (A) and flight 3 (B) is shown respectively. See Figure A1 in Appendix A for details on the interpolation procedure. Projection: SWEREF 99 TM

The third and second flight have some different flight paths (seen in Figure 12). As the first flight mostly only measures the edges of the landfill (see Figure 12), not taking the west side into account, the hotspot map for flight 1 was chosen not to be included, as it generated an extremely heterogeneous hotspot map not suitable for hotspot mapping on its own. It was, however, used to generate a more fully mapped area with all flights combined, seen in Figure 11, which was interpolated with Kriging. Here, with the combination of three flights, the hotspots still seem to be seen on the eastern wall, along with two more hotspots closer towards

the centre of the landfill. This combined interpolated surface also suggests that the concentration of CH₄ is higher along the eastern border, along with two more hotspots that can be seen in both Figure 10 and Figure 11.

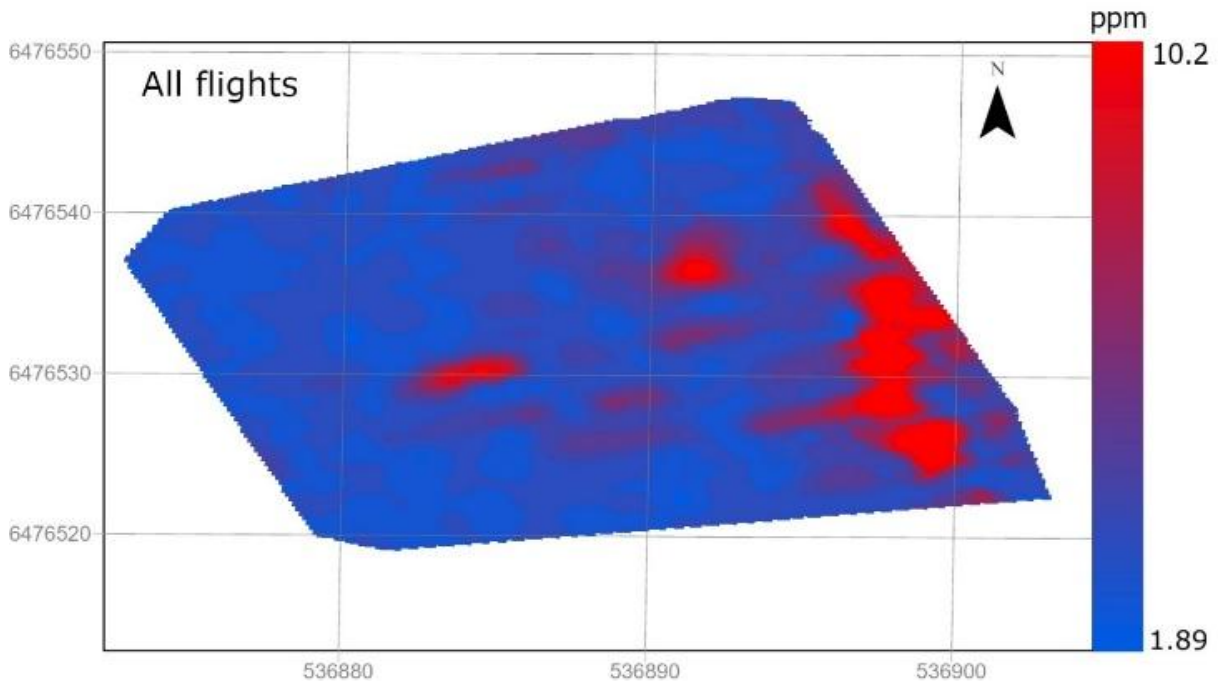


Figure 11: Horizontal map of Linköping landfill and its CH₄ concentrations in ppm for all flights, using UAV measurement data from Gålfalk et al. (2021). The concentrations have been interpolated to show distribution over the sludge landfill with the size 35x35 m².

Concentrations are based on absolute CH₄ concentrations, background CH₄ included including the background level. See Figure A1 in Appendix A for details on the interpolation procedure. Projection: SWEREF 99 TM

The measurements taken during the three flight paths can be seen in Figure 12. The second flight was done between 12.44 pm and 12.54 pm on January 2020 (see *Appendix B*), and the third flight was done between 12.59 and 13.08 pm on January 2020 (see *Appendix B*). These two flights are seen to be more spread out and cover a larger surface compared to flight 1. Flight 1 was measured between 12.32 pm and 12.40 pm on January 2020 (see *Appendix B*). The purpose of flight 1 path was to look at specific walls (Gålfalk et al., 2021), whereas the purpose of this project is to focus on the flux of the entire area. Therefore, even though the path was not covering the entire area, it was still chosen to generate the total flux as it would only increase the accuracy of the later interpolated result.



Figure 12: Measurement points from flight 1 (black), 2 (white), and 3 (grey) are shown in the study area as points. Data source: Gålfalk et al (2021). Projection: SWEREF 99 TM

The CH₄ flux for Linköping landfill on January 2020, through using the DFM method, yielded a total flux of 8.21 kg h⁻¹. The results are yielded from the DFM method, where the calculated CH₄ emissions flux was averaged over number of flights. There were three number of flights used for the calculation, and the relative error derived from uncertainty testing for the total CH₄ flux is ±1.36 kg h⁻¹, or ±16.6%. The uncertainty seen in Linköping waste landfill in January 2020 is symmetrical, where the symmetry suggests a symmetrical distribution of data points around the central value. This flux is based on absolute CH₄ concentrations, including background CH₄, on the sludge landfill with an area of 1225 m².

4.3 Qualitative Comparison Between Landfill Sites

To compare CH₄ fluxes between Rönneholm, Filborna, and Linköping Landfill, total CH₄ flux can be divided with area, which has been visualized in Table 3. Rönneholm then produced 0.3 kg ha⁻¹ h⁻¹ of and 0.5 kg ha⁻¹ h⁻¹ of CH₄ in March 2024 and May 2024 (respectively). Filborna produced 3.1 kg ha⁻¹ h⁻¹ and 3.6 kg ha⁻¹ h⁻¹ of CH₄ in October 2023 and November 2024 (respectively). A large leap to Linköping wastewater sludge landfill can be seen, with 67.0 kilograms of CH₄ per hour per hectare.

Table 3: CH₄ Flux per hectare for all landfill surveys. The CH₄ flux of Linköping campaign was calculated by using the Drone Flux Method, while the CH₄ fluxes on Filborna and Rönneholm landfills were calculated by ReSource Sverige AB using GASTRAQ.

Campaign	Date	CH ₄ Flux per hectare (kg ha ⁻¹ h ⁻¹)
Linköping	Jan 2020	67.0
Filborna	Oct 2023	3.1
Rönneholm	Mar 2024	0.3
Rönneholm	May 2024	0.5
Filborna	Nov 2024	3.6

5 Discussion

5.1 Comparison of GASTRAQ and DFM Flux Estimates

Extremely varying calculated CH₄ fluxes can be seen in Table 2, estimated with the GASTRAQ model. These variations likely reflect a combination of real-world differences in emission rates between sites, and methodological limitations inherent to the measurement systems. In campaigns with highly asymmetric error margins, like Filborna November 2024, the wind model may have not accurately represented plume dynamics, resulting in over- or underestimation.

Furthermore, a large difference in total CH₄ emissions may be seen when comparing the total flux of Linköping landfill (Table) with the total fluxes of Rönneholm and Filborna landfills (Table). These large values suggest that Filborna is not comparable to the landfill site Rönneholm, just as the total flux for Linköping landfill cannot be compared to Rönneholm and Filborna: as the sites are too different. Filborna landfill has a biogas plant within its area to actively collect CH₄ gas, making it different from Rönneholm and landfill, and Linköping landfill is much smaller compared to Rönneholm and Filborna landfill, which is another difference between the three. Linköping landfill is also the home of wastewater sludge, causing the landfill to emit large amounts of CH₄. Typically, 40-45% of the volatile matter in the feed sludge is converted to CH₄ and CO₂, where leakage of CH₄ is unavoidable and forms one of the major sources of CH₄ released during sewage treatment (Hobson, J., 2000).

The differences discussed above suggest that these three landfills, Filborna, Rönneholm, and Linköping, are fundamentally different with different characteristics, and it is therefore more suitable to compare these methods qualitatively: looking at the two methods general strengths, weaknesses and practical behaviour, rather than trying to determine which method is “better” through these direct flux estimates derived through different methods alone.

5.2 Spatial Coverage and Measurement Density

The differences in number of flights in Table 2 is explained through the fact that mapping the areas needed several measurement rounds, as the size of the landfill sites varied. Filborna landfill is 36 hectares in total, while Rönneholm landfill is 28 hectares, meaning that the likely

difference in number of flights may be explained through the difference in area. All campaigns at the Filborna and Rönneholm landfills included at least six flights, reflecting the fact that these sites are larger than the Linköping landfill and therefore required more flights to cover the entire area. In contrast, the survey of Linköping landfill only had 3 flights performed. This can be explained by the fact that the sludge landfill is 1 225 m², or ~ 0.12 hectares, meaning that to map this smaller area, 6 to 9 flight paths may not make sense due to the area size being approximately 300 times smaller than Filborna landfill and 230 times smaller than Rönneholm landfill.

Each campaign has its own challenges which could explain why there will be differences in the number of flights. Wind fluctuations are seen for Filborna and Rönneholm landfills, but also for Linköping sludge landfill, in *Appendix B*. In May 2024, winds above 6.6 m/s were recorded on Rönneholm landfill (Table A4), while winds above 7 m/s were recorded in October 2023 (Table A2) and November (Table A5) 2024 on Filborna landfill. To contrast with lower wind speeds, Rönneholm landfill in March 2024, had recorded wind speeds of 0.8-2.1 m/s (Table A3). Consequently, Rönneholm landfill in March 2024 is the landfill with the lowest negative and positive error, which means that higher error may indicate higher wind speeds.

Linköping sludge landfill in January 2020 had recorded wind speeds over 3.8 m/s (Table A1) at the time of the surveying, but as the wind speeds were recorded differently between GASTRAQ and DFM (ground-based and UAV-based), the wind assumptions will directly affect the scale of uncertainty. Since GASTRAQ used stationary anemometers, and since the wind speeds exceeded 6-7 m/s, the uncertainty in the estimate is increased (Fosco *et al.*, 2025).

Taken together, the differences in spatial coverage, area size, and meteorological conditions affect how effective UAV-based measurement campaigns can be, and that the flight path decisions and the spatial coverage need to be tailored to individual sites as every landfill is fundamentally different. Larger sites will naturally require more extensive coverage and more flight paths, but smaller sites demand multiple flights as well if atmospheric conditions introduce significant variability.

5.3 Suitability of Methods for Routine Monitoring

A study (Scheutz *et al.*, 2020) commissioned by The Technical University of Denmark (DTU), Lund University, Sweco Environment, FORCE Technology, and ReSource Sverige AB, used multiple methods (DFM and GASTRAQ included) to assess if UAV-based technology held up against traditional methods like ground-based plume measurement and surface flux chambers (Scheutz *et al.*, 2020). The study was executed on real landfill settings, and the resulting flux estimates from the UAV-based methods agreed closely with the results when the TDM was utilized as a reference method. This study provided the first clear evidence that UAV-derived emissions can “give similar results to the currently accepted tracer dispersion method” in real landfill settings (Scheutz *et al.*, 2020).

Routine operational monitoring at landfills needs methods that are practical to deploy, reliable under varying field conditions, and capable of delivering data with minimal delay. By comparing GASTRAQ and DFM, considerations regarding setup complexity, assumptions, and real-time data availability are needed to see how suitable the methods are in certain conditions.

GASTRAQ surveys involve more field setup due to their reliance on ground-based wind measurements, where the wind model assumptions may directly translate to error in the flux

calculation. In practice, short-term gusts and wind direction shifts during a flight may not be captured by the masts, making the GASTRAQ flux estimates sensitive to wind mischaracterization. Therefore, its uncertainty may be higher if wind conditions are more turbulent (Wilson *et al.*, 2022) which makes GASTRAQ mostly suitable for weather conditions with lower wind speed (Simon *et al.*, 2022).

In contrast, DFM integrates wind onboard the UAV: eliminating the need for separate wind measurement infrastructure on the ground. Therefore, deployment of the UAV will be simpler, as the only requirement is to have the anemometer some distance from the propellers (Knudsen & De Rossi, 2022). Furthermore, as the wind component is measured on board the UAV, flux calculations should be more accurate during less steady wind conditions (Cossel *et al.*, 2023).

5.4 Influence of Wind Modeling on Flux Accuracy

A strength of the DFM method is the integrated wind measurement, which captures the complex wind variations during each flight and thus improves flux estimation when winds are unsteady (Knudsen & De Rossi, 2022). Scheutz *et al.* (2025) specifically highlight that measuring wind on the UAV (rather than relying on a single point measurement) yields better results, as it accounts for temporal and/or spatial variability in the plume transport. The study even noted that by using a fixed wind averaged over a flight, significant errors in fluxes may occur (up to the largest errors in their tests) (Scheutz *et al.*, 2025). Both Scheutz *et al.* (2025) and Gålfalk *et al.* (2021) utilized CH₄ sensors and anemometers that are both attached to the UAVs, which eliminates the need for ground masts. However, due to the wind speed and direction being measured directly on the UAV in the DFM method, a consistent error can be found in the wind direction component (Scheutz *et al.* 2025), as the direction of the wind should be perpendicular to the wall to see how much CH₄ passes through the wall (Allen *et al.*, 2014).

ReSource Sverige AB uses ground-based sensors in masts for GASTRAQ, meaning that any short-term gust that occurs while the UAV is sampling would not have the same variation seen by ground-based sensors, where ground-based wind measurements differ from UAV-based wind measurements in studies like Gålfalk *et al.* (2021), especially when altitude increases (Han *et al.*, 2024). Therefore, GASTRAQ is more suitable for conditions with lower turbulence (Simon *et al.*, 2023; Yong *et al.*, 2024) and wind speeds lower than 6-7 m/s (Fosco *et al.*, 2025).

Some of these sources of uncertainty are considered when ReSource Sverige AB are quantifying CH₄ fluxes. These include averages of wind speeds over the course of each flight, where large uncertainties are associated (ReSource Sverige AB, 2025). Wind direction measurements are also a source of uncertainty that they explore. As the plane is plotted at a rough 90 degrees to the wind, asymmetrical errors may occur when the angle changes (Scheutz *et al.*, 2020). ReSource Sverige AB (2025) state that this error is typically less than 5%. To compare this statement, Scheutz *et al.* (2025) performed wind direction accuracy tests of anemometers for ground-based and UAV-based wind measurements, where the errors of wind direction varied approximately $\pm 10\%$ from the reference angles both around the vertical and horizontal axes. This is an error estimation larger than ReSource Sverige AB (2025), where Scheutz *et al.* (2025) tested multiple scenarios of anemometers being attached to the UAV, as well as where anemometers were ground-based.

5.5 Limitations and Sources of Uncertainty

Based on the relative errors seen visualized in *Appendix C* the relative errors in CH₄ flux estimates across different GASTRAQ campaigns vary widely, where campaigns like Filborna (November 2024) had high asymmetric uncertainty. The study by Fosco *et al.* (2025) explains that when a plume is measured, it is associated with peaks and asymmetry in the distribution of data. This has been reported by several other authors like Allen *et al.* (2019) and Yong *et al.* (2024). Fosco *et al.* (2025) goes on to state that “numerous field tests have corroborated these findings. For instance, when analysing measurements taken from areas influenced by a plume, it is often seen that concentrations are significantly higher in some points, leading to a right-skewed distribution.” (Fosco *et al.*, 2025). This variability and asymmetry seen in using GASTRAQ likely then stems from a combination of site-specific conditions as well as plume capture.

5.5.1 Instrument and Methodological Uncertainties

Instrumentation can also be an uncertainty affecting flux estimations. Details on the precision of CH₄ sensor can be found in *Appendix D*, but as the differences are seen to be small and the TDLAS instruments are seen to be a reliable tool (Wang *et al.*, 2024) with smaller errors influencing the results, they will not be discussed in detail here.

Wind variations also affect the UAVs stability and thus the wind measurement accuracy. Strong winds may cause the UAV to pitch or yaw as it tries to maintain a stable flight, which in turn can disturb the anemometer readings. Furthermore, propeller-induced wind turbulence can skew the true wind speed and wind direction if the sensor is too close to the rotors. The UAV’s propellers generate turbulence (downwash and vortex effects) that may bias the anemometer’s readings, so careful sensor deployment is critical. Studies (Knudsen & De Rossi, 2022; Scheutz *et al.*, 2020) emphasize mounting the anemometer at a sufficient distance above or below the rotor plane to minimize propeller interference. This is further highlighted by Ding *et al.* (2022) who recommended that wind disturbances will be significantly reduced if the anemometer was placed at least 30-50 cm above the rotor plane (Ding *et al.*, 2022).

The precision and response of the anemometer itself also influence data quality, as any measurement bias or slow response will propagate into flux calculations. The anemometer TriSonica Mini LI-550 (LI-COR, United States) has an uncertainty of 0.1 m/s for wind speed and 1° for its wind direction and was used both for the data collection for the GASTRAQ’s case studies (ReSource Sverige AB, 2025) and during the data collection done by Gålfalk *et al.* (2021). Consequently, the errors, although small, will in theory be the same for all the campaigns and therefore not an issue that might affect the comparison between GASTRAQ and the DFM.

The variation in uncertainty across GASTRAQ campaigns appears to stem primarily from differences in wind conditions. For example, the campaigns exhibiting highly skewed uncertainty (Filborna, November 2024; Rönneholm, May 2024) likely due to high wind speeds that were not fully captured by the fixed ground-based anemometers used in GASTRAQ, especially on large sites like Filborna and Rönneholm, where full plume capture is more difficult (Morales *et al.*, 2022). By contrast, campaigns such as Linköping (2020), using the Drone Flux Method, showed relatively low and symmetrical error bounds. Smaller sized landfills seem to be more effectively mapped, as their limited size allows for more complete

spatial coverage with a smaller number of flights. This improves the method's ability to account for both temporal and spatial wind variability during data collection. These findings seem to describe that if the size of the landfill is larger, the reliability of UAV-based flux estimates may be compromised under rapid changes in atmospheric conditions or limited spatial coverage, where studies like Wilson *et al.* (2022) and Simon *et al.* (2023) further support this claim.

Differences in methodology, whether that be the speed of the UAV or the UAV being manually steered, will have an impact on the accuracy of the CH₄ flux estimations (Gålfalk *et al.*, 2021; Yong *et al.*, 2024): both for the DFM and the GASTRAQ model. The speed of the UAV will influence the initial resolution before interpolating, which means that the UAVs speed will control how dense the measurement data will be. ReSource Sverige AB uses a set speed for a transect but the speed varies depending on the area of interest (ReSource Sverige AB, 2025). To contrast with the case studies, and in turn to contrast with the GASTRAQ method, the data from Linköping landfill which was used to test the DFM method Gålfalk *et al.* (2021) used a set speed of 1 m/s when steering the UAV. The differences in UAV speed could have a large impact on the data sampling, as a higher speed may underestimate true releases of CH₄ (Nathan *et al.*, 2015) as it is attributed towards incomplete sampling of CH₄ plumes: especially during highly variable weather conditions (Morales *et al.*, 2022). Controlled release experiments (Morales, *et al.*, 2022) have demonstrated that during unstable wind conditions, faster or sparser UAV transects can underestimate true CH₄ emissions by around 11% (Morales, *et al.*, 2022), as a coarse spatial resolution, which can arise from flying too quickly, will underestimate the size of the plume compared to a finer spatial resolution which can be generated through lower wind speeds (Mohammadloo *et al.*, 2025).

5.5.2 Validation

By using the Drone Flux Method to quantify whole site CH₄ emissions on Linköping landfill, a result of $8.21 \pm 1.36 \text{ kg h}^{-1}$ was yielded. When Gålfalk *et al.* (2021) calculated whole site CH₄ emissions on the same landfill with the same dataset, the yielded result was 178.4 kilograms of CH₄ per day, or 7.4 kilograms of CH₄ per hour when using their mass balance theory approach on the same data. To enable a valid comparison the results from Linköping landfill, which was calculated using the DFM for this project, were derived using the same dataset with the same mass balance theory foundation as Gålfalk *et al.* (2021). A difference between Gålfalk *et al.* (2021) and my calculations yielded a difference of $\sim 0.78 \text{ kg h}^{-1}$, which is a difference of 9.49%. When viewed in the context of the uncertainty ranges discussed in this paper, where relative errors using UAV-methods can range between $\pm 30\%$ to over $\pm 100\%$ depending on site conditions and wind modelling; this 9.49% deviation falls well within expected and acceptable bounds. The similarity not only reinforces the validity of DFM, but also suggests that under optimized conditions, different UAV-based mass balance approaches can yield comparable flux estimates. The difference of 9.49% may therefore be seen as a good agreement between the two results, as the difference may be explained through interpolation differences or differences in methodology, as both results exhibit similar patterns in flux density.

The DFM was thoroughly validated by Scheutz *et al.* (2025) through both controlled release experiments and comparisons with the standard reference method TDM. These validations included practical field trials. In the controlled release tests, the DFM produced results within +33% and -35% of the true values. During field trials, the DFM estimated a CH₄ flux of 25.3

± 6.2 kg/h, which closely matched the TDM reference method's estimate of 25.7 ± 4.4 kg/h. This validation demonstrated that Knudsen & De Rossi (2022) successfully applied the mass balance theory in their UAV-based approach, achieving similarly strong agreement with established methods without the need for tracer gas, which presents a significant operational advantage. Furthermore, Scheutz et al. (2025) reported that the expanded uncertainty for a single DFM flight was approximately $\pm 46\%$ (95% confidence), which decreased with additional flights: two flights reduced uncertainty by $\sim 33\%$, and three flights brought a further $\sim 27\%$ reduction.

ReSource Sverige AB addresses systematic uncertainties and assumptions in their methodology, although some are not quantifiable (ReSource Sverige AB, 2025). For example, the uncertainty of height above ground seemingly has no size of error. Model parameter estimates from González-Rocha *et al.* (2020) found that the difference between wind measurements on the ground and wind measurements on board the UAV fluctuate significantly at higher elevations, meaning that the error of wind speed may grow larger with height above ground (González-Rocha *et al.*, 2020).

Secondly, ReSource Sverige AB addresses background CH₄ emissions. The background inbound emissions, of each flight, are measured upwind by fitting a Weibull curve to the distribution. The left-hand range of this curve was then used as the estimation of background CH₄ uncertainty (ReSource Sverige AB, 2025). Weibull distribution is a skewed distribution (Pérez *et al.*, 2022), where the outliers can be used for background CH₄ estimation.

5.6 Implications for Future Landfill Monitoring

The Plane Project (Knudsen & De Rossi, 2022) emphasizes mounting both wind and gas sensors on the UAV platform to reduce uncertainties from misaligned wind profiles. They state that "... any type of UAV can be used if the wind and gas sensors can be installed in a configuration that prevents the impact of the UAVs air displacement on the collected data." (Knudsen & De Rossi, 2022). As it is necessary to not have the UAVs blades interfering with the wind measurements, the anemometer and CH₄ sensor need to be placed in similar areas on the UAV. One way to achieve this, which can generate smaller uncertainties for future landfill monitoring projects, is to have a longer mast between the rotary plane and the anemometer, proposed and tested by Yong *et al.* (2024) seen in Figure 13. This was done similarly by Gålfalk *et al.* (2021), which may be seen in Figure 14.

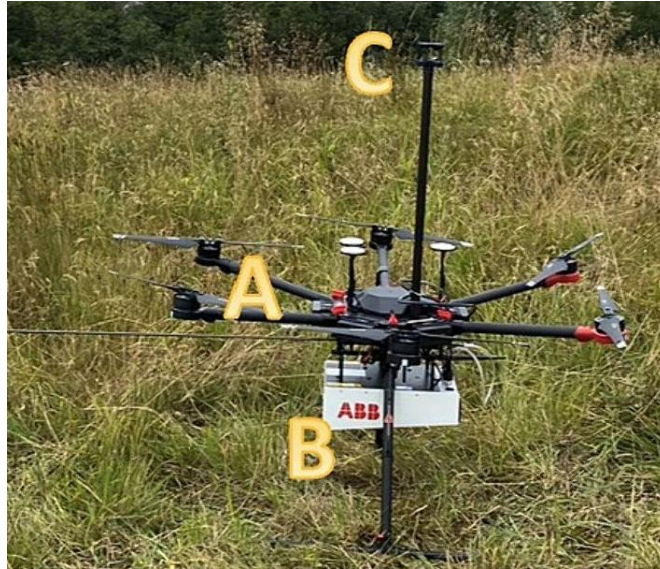


Figure 13: UAV system setup by Yong et al. (2024). The anemometer (C) is placed on a 60 cm long mast supplied with the sensor (B), pointed vertically above the plane of the rotors (A) to reduce the influence of the propeller-induced flow.



Figure 14: The setup of the UAV system by Gålfalk et al. (2021). The anemometer and air inlet marked with arrows are located 40 cm above the propellers.

Another future improvement proposed by Larsson (2019) is that the sensor technology could be further enhanced for UAV-based CH₄ quantification. One development is the use of tuneable diode absorption spectroscopy that operates at longer wavelengths. Larsson (2019) goes on to explain that the challenge with implementing this type of sensor may be somewhat difficult to address, as it requires a camera that must be cool off with the thermal noise from the background and the electronics. However, if managed correctly, this sensor would significantly improve the sensitivity of CH₄ detection in environments such as in some industrial processes or landfills (Wang, 2017). By integrating this sensor into UAV-based CH₄ quantification methods, measurement uncertainty could be reduced, whilst improving the resolution of emission mapping in complex landfill environments. This would increase accuracy under difficult measurement conditions such as high dust or aerosol load in the air (Wojtas, 2024).

Autonomous sampling is also something which can improve efficiency of collection of data, as well as being able to distribute the measurement points more evenly. Pre-programmed patterns may be implemented if the campaign area is surveyed before actual measurements are taken, which can be done with handheld CH₄ monitoring, or test runs with a UAV (Yong *et al.*, 2024). This may be more time consuming when surveying a landfill but may yield higher accuracy due to the mitigated error of human interaction.

These suggested improvements can pave the way towards increased precision and adaptability in UAV-based landfill monitoring. As both sensor technology and UAV integration methods advance, complete mapping of CH₄ emissions can be improved in variable environments like landfills, to fully capture CH₄ plumes and in turn to increase the accuracy of CH₄ flux estimates. Furthermore, by incorporating autonomous sampling, it can be possible to do larger scale operations of UAV-based monitoring with optimized spatial coverage. Future landfill monitoring will not only support regulations for CH₄ mitigation, but also climate accountability. These methods of monitoring CH₄, if developed in the future, can be capable of responding dynamically to changing landfill conditions and mitigate CH₄ emissions when necessary.

As another future improvement, endorsed by namely Mønster *et al.* (2019), is to use static eddy covariance systems simultaneously over longer periods as UAV-based methods are responsible for the frequent short-term measurements. This can make continuous measurements possible, and thereby capture the temporal emission variations, making it possible to know when UAV-based methods are the most representative for landfill CH₄ monitoring (Mønster *et al.*, 2019). In longer term, this hybrid approach can validate UAV-based methods in the sense that it will be possible to know when UAV-based methods are most efficient to use.

6 Conclusion

This study aimed at evaluating the GASTRAQ method for calculating CH₄ fluxes from UAV-based concentration measurements and to investigate how well the method holds up to recent developments of UAV-based CH₄ quantification methods. Two case studies, Filborna and Rönneholm landfill, were assessed using GASTRAQ and qualitatively compared to a DFM-based analysis at Linköping landfill. It was found that GASTRAQ is dependent on its assumption of an average wind profile through ground-based wind measurements, where rapid fluctuations may cause GASTRAQ to become less accurate. This confirms the hypothesis that DFM will yield more accurate results under turbulent wind due to onboard wind measurements (H_{01}). While both GASTRAQ and DFM are based on mass balance theory, DFM's ability to respond to real time wind fluctuations provided an advantage in certain environmental conditions. However, GASTRAQ is still a practical alternative in more stable wind conditions where ground-based wind measurements can be available.

Somewhat supporting H_{03} , CH₄ flux estimates and its associated uncertainties varied considerably between landfills, which can be reflected in differences in sizes of area where the spatial coverage will be increasingly difficult to complete with larger areas. However, based on the results, it was not possible to reject or support H_{03} whether landfill size was directly affecting the accuracy of CH₄ flux estimations. The accuracy of CH₄ flux estimates were also considered to be dependent on atmospheric conditions when the results were realized through discussion.

Supporting H₂O, the study showed that wind field characterization is the largest source of uncertainty.

Both GASTRAQ and DFM show promising results for routine landfill monitoring. However, the DFM's setup with an anemometer on top of the UAV makes it more scalable and adaptable to different conditions (area size, wind fluctuations, and plume locations). Autonomous flight paths may improve complete mapping of landfills for both methods, to fully capture plumes. By taking wind measurements on top of the UAV, and to introduce autonomous flight paths, these developments could reduce uncertainty for any UAV-based method. These innovations can then support broader regulatory goals in multiple sectors where CH₄ emissions are an issue and can moreover help achieve climate mitigation goals in the waste sector.

New questions emerged during this work: How can UAV-based methods be integrated with satellite or ground-based systems to develop hybrid CH₄ monitoring strategies? What level of error is acceptable for regulatory compliance, and how should these uncertainties be communicated in reports? If this work was to continue, it would be of value to carry out coordinated DFM and GASTRAQ campaigns on the same site under controlled conditions, to better quantify differences and biases. Additionally, the Trace Dispersion Method can be incorporated as a reference method. The measurements performed by ReSource Sverige AB on Filborna and Rönneholm were performed in conjunction with the Technical University of Denmark, where the data yet have to be published. This could bring better understanding on the GASTRAQ method's differences and biases. Additional attention can also be set on understanding how weather variability impacts flux interpolation and plume capture, and how these variables impact emissions themselves: how temperature and precipitation can lead to fluctuations in CH₄ emissions.

If the study was to be repeated, access to more data would be essential to assess the methods quantitatively. It was difficult to assess the methods based solely on the data collected during this project, as there was limited access to all data: in particular to alternative methods for the same landfill and ground-truth data. More emphasis should be placed on validating wind profiles with higher resolution meteorological data to ensure complete mapping of CH₄ plumes, and to standardize data processing methods between campaigns.

7 References

- Abdel-Shafy, H.I., Ibrahim, A.M., Al-Sulaiman, A.M., Okasha, R.A. (2024). Landfill leachate: Sources, nature, organic composition, and treatment: An environmental overview. *Ain Shams Engineering Journal*, 15(1), 102293. <https://doi.org/10.1016/j.asej.2023.102293>.
- Abichou, T., Del'Angel, J.M., Koloushani, M., Stamatiou, K., Belhadj Ali, N., Green, R. (2023). Estimation of total landfill surface CH₄ emissions using geospatial approach combined with measured surface ambient air CH₄ concentrations. *Journal of Air Waste Management Association*, 73(12), 902–913. <https://doi.org/10.1080/10962247.2023.2271431>.
- Achebak, H., Garatachea, R., Pay, M.T., Jorba, O., Guevara, M., García-Pando, C.P., Ballester, J. (2024). Geographic Sources of Ozone Air Pollution and Mortality Burden in Europe. *Nature Medicine*, 30(6), 1732–1738. <https://doi.org/10.1038/s41591-024-02976-x>.
- Allen, G., Hollingsworth, P., Kabbabe, K., Pitt, J.R., Mead, M.I., Illingworth, S., Roberts, G., Bourn, M., E. Shallcross, D.E., Percival, C.J. (2019). The development and trial of an unmanned aerial system for the measurement of CH₄ flux from landfill and greenhouse gas emission hotspots. *Waste Management*, 87(1), 883-892. <https://doi.org/10.1016/j.wasman.2017.12.024>.
- Allen, G., Martin Gallagher, M., Hollingsworth, P., Illingworth, S., Kabbabe, K., Percival, C. (2014). Feasibility of aerial measurements of CH₄ emissions from landfills. (SC130034). Environment Agency, Horizon House, Deanery Road, Bristol: Environment Agency. Retrieved 30 March, 2025, from https://assets.publishing.service.gov.uk/media/5a7f0195ed915d74e6227db6/SC130034_Report.pdf.
- Allen, G., Williams, P., Ricketts, H., Shah, A., Hollingsworth, P., Kabbabe P.K., Helmore, J., Finlayson, A., Robinson, R., Rees-White, T., Beaven, R., Scheutz, C., Fredenslund, A. (2018). Validation of landfill CH₄ measurements from an unmanned aerial system: Project SC160006. Retrieved 4 April, 2025, from https://backend.orbit.dtu.dk/ws/portalfiles/portal/146793011/Validation_of_landfill_CH_4_measurements_from_an_unmanned_aerial_system_report.pdf.
- Avfall Sverige. (2013). *Handbok för deponigas Rapport 2013:02*. Malmö: Avfall Sverige. Retrieved 9 April, 2025, from <https://www.avfallsverige.se/rappporter-utveckling/rappporter/2013-d02-handbok-for-deponigas/>.
- Avfall Sverige. (2023). Swedish Waste Management. Malmö: Avfall Sverige. Retrieved 9 April, 2025, from <https://www.avfallsverige.se/aktuellt/nyheter/har-ar-svensk-avfallshantering-2023/>.
- Bel Hadj Ali, N., Tarek Abichou, T., Green, R. (2020). Comparing estimates of fugitive landfill CH₄ emissions using inverse plume modeling obtained with Surface Emission Monitoring (SEM), Drone Emission Monitoring (DEM), and Downwind Plume Emission Monitoring (DWPEM). *Journal of the Air & Waste Management Association*, 70(4), 410–424. <https://doi.org/10.1080/10962247.2020.1728423>.
- Bolek, A., Heimann, M., Göckede, M. (2024). UAV-based in situ measurements of CO₂ and CH₄ fluxes over complex natural ecosystems. *Atmospheric Measurement Techniques*, 17(18), 5619–5636. <https://doi.org/10.5194/amt-17-5619-2024>.
- Bracmort, K., Folger, P., Marples, D.J., McCarthy, J.E., Ramseur, J.L. (2011). CH₄ Capture: Options for Greenhouse Gas Emission Reduction. Congressional Research Service. Retrieved 2 April, 2025, from <https://www.congress.gov/crs-product/R40813>.

- Champeechoensuk, A., Shobhakar, D, Nuwong, C. (2023). Climate Change Mitigation in Thailand's Domestic Aviation: Mitigation Options Analysis Towards 2050. *Energies*, 16(20), 7199. <https://doi.org/10.3390/en16207199>.
- Clean Air Task Force. (2025). The Waste CH₄ Toolbox: Policy Solutions for a Low CH₄ Future. Retrieved 9 June, 2025, from <https://www.catf.us/resource/waste-CH4-toolbox-policy-solutions-low-CH4-future/>.
- Collins, W. J., O'Connor, F. M., Barker, C. R., Byrom, R. E., Eastham, S. D., Hodnebrog, Ø., Jöckel, P., Marais, E. A., Mertens, M., Myhre, G., Nützel, M., Olivie, D., Bieltvedt Skeie, R., Stecher, L., Horowitz, L. W., Naik, V., Faluvegi, G., Im, U., Murray, L. T., Shindell, D., Tsigaridis, K., Abraham, N. L., Keeble, J. (2024). Climate Forcing due to Future Ozone Changes: An intercomparison of metrics and methods. *EGUsphere*, [preprint]. <https://doi.org/10.5194/egusphere-2024-3698>.
- Cossel, K.C., Waxman, E.M., Hoenig, E., Hesselius, D., Chaote, C., Coddington, I., Newbury, N.R. (2023). Ground-to-UAV, laser-based emissions quantification of CH₄ and acetylene at long standoff distances. *Atmospheric Measurement Techniques*, 16(22), 5697–5707. <https://doi.org/10.5194/amt-16-5697-2023>.
- Delre, A., Mønster, J., Samuelsson, J., Fredenslund, A.M., Scheutz, C. (2018). Emission quantification using the gas dispersion method: The influence of instrument, tracer gas species and source simulation. *Science of The Total Environment*, 634, 59-66. <https://doi.org/10.1016/j.scitotenv.2018.03.289>.
- Delre, A., Mønster, J., Scheutz, C. (2017). Greenhouse gas emission quantification from wastewater treatment plants, using a tracer gas dispersion method. *Science of the Total Environment*, 605-606, 258-268. <https://doi.org/10.1016/j.scitotenv.2017.06.177>.
- Dhakal, S., Minx, J.C., Toth, F.L., Abdel-Aziz, A., Figueroa Meza, M.J., Hubacek, K., Jonckheere, I.G.C., Yong-Gun Kim, J., Nemet, G.F., Pachauri, S., Tan, X.C., Wiedmann, T. (2022). Emissions Trends and Drivers. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.004.
- Ding, W., Chen, H., Chang, H., Wang, Y., Zhou, D., & Feng, W. (2022). Near-surface wind profile test based on accuracy verification of UAV anemometer lifting height in an urban fringe built-up area. *Environmental science and pollution research international*, 29(54), 81468–81480. <https://doi.org/10.1007/s11356-022-21486-2>.
- Eslöv Kommun, Höörs Kommun, Hörby Kommun, Mellanskånes Renhållningsaktiebolag. (2024). Avfallsplan för Eslöv, Höör & Hörby - Med handlingsplan för resurshushållning och cirkulära materialflöden 2023–2026. Retrieved 3 May, 2025, from <https://eslov.se/app/uploads/avfallsplan-for-eslovs-kommun.pdf>.
- European Commission: Directorate-General for Climate Action, COWI, Eunomia, Technopolis Group, Stede, J., Garber, H., Steinert, M., Stanilovaityte, I., Edander Arvefjord, L., Blauert, M., Coatanroch, G., Jones, H., Zhechov, R., Lo Piparo, L., Karlsson, N., Geilhardt, G. F., Hansen-Duncan, B., Munk Sørensen, M., Franca, G., Somlai, C. (2024). In-depth report on the results of the public consultation on the EU climate target for 2040: final report, Publications Office of the European Union. <https://data.europa.eu/doi/10.2834/48495>.
- European Commission. (2019). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS The European Green Deal: final report, Publications Office of the

- European Union. Retrieved 13 May, 2025, from <https://op.europa.eu/en/publication-detail/-/publication/b828d165-1c22-11ea-8c1f-01aa75ed71a1/language-en>.
- Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., Lunt, D.J., Mauritsen, T., Palmer, M.D., Watanabe, M., Wild, M., Zhang, H. "2021: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity." *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (2021)*: 923–1054. Retrieved 4 April, 2025, from https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter07.pdf
- Foster-Wittig, T.A., Thoma, E.D., Green, R.B., Hater, G.R., Swan, N.D., Chanton, J.P. (2015). Development of a mobile tracer correlation method for assessment of air emissions from landfills and other area sources. *Atmospheric Environment*, 102, 323-330. <https://doi.org/10.1016/j.atmosenv.2014.12.008>.
- Gustafsson, U. (2000). Diode laser spectroscopy in extended wavelength ranges. [Doctoral Thesis (compilation), Atomic Physics]. Department of Physics, Lund University. <https://portal.research.lu.se/en/publications/diode-laser-spectroscopy-in-extended-wavelength-ranges>.
- González-Rocha, J., De Wekker, S. F. J., Ross, S. D., Woolsey, C. A. (2020). Wind Profiling in the Lower Atmosphere from Wind-Induced Perturbations to Multirotor UAS. *Sensors*, 20(5), 1341. <https://doi.org/10.3390/s20051341>.
- Gålfalk, M., Nilsson Paledal, S., Bastviken, D. (2021). Sensitive Drone Mapping of CH₄ Emissions without the Need for Supplementary Ground-Based Measurements. *ACS earth & space chemistry*, 5(10), 2668–2676. <https://doi.org/10.1021/acsearthspacechem.1c00106>.
- Gålfalk, M., Olofsson, G., Crill, P., Bastviken, D. (2015). Making CH₄ visible. *Nature Climate Change*, 6(4), 426–430. <https://doi.org/10.1038/nclimate2877>.
- Han, T., Xie, C., Liu, Y., Yang, Y., Zhang, Y., Huang, Y., Gao, X., Zhang, X., Bao, F., Li, S.-M. (2024). Development of a continuous UAV-mounted air sampler and application to the quantification of CO₂ and CH₄ emissions from a major coking plant. *Atmospheric Measurement Techniques*, 17(2), 677–691. <https://doi.org/10.5194/amt-17-677-2024>.
- Hobson, J. (2000). CH₄ and N₂O Emissions From Wastewater Handling. In: Background Papers, IPCC Expert Meetings on Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, 441-454. Retrieved 13 May, 2025, from https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/5_2_CH4_N2O_Waste_Water.pdf.
- Houweling, Sander, Thomas Kaminski, Frank Dentener, Jos Lelieveld, and Martin Heimann. (1999). Inverse Modeling of CH₄ Sources and Sinks Using the Adjoint of a Global Transport Model. *Journal of Geophysical Research: Atmospheres*, 104(21), 26137-26160. <https://doi.org/10.1029/1999JD900428>.
- Höör Kommun, Eslöv Kommun, Hörby Kommun, Mellanskånes Renhållningsaktiebolag. (2024). Föreskrifter om avfallshantering Höör, Hörby & Eslöv Kommun. Retrieved 3 May, 2025, from <https://www.hoor.se/app/uploads/avfallsforeskrifter-for-eslov-hoor-och-horby-kommuner-ink-bilagor-2.pdf>.
- Kirschke, S., Bousquet, P., Ciais, P., Saunoy, M., Canadell, J.G., Dlugokencky, E.J., Bergamaschi, P., Bergmann, D., Blake, D.R., Bruhwiler, L., Cameron-Smith, P., Castaldi, S., Chevallier, F., Feng, L., Fraser, A., Heimann, M., Hodson, E.L., Houweling, S., Josse, B., Fraser, P.J., Krummel, P.B., Lamarque, J.F., Langenfelds, R.L., Quéré, C., Naik, V., O'Doherty, S., Palmer, P.I., Pison, I., Plummer, D., Poulter, B., Prinn, R.G., Rigby, M., Ringeval, B., Santini, M., Schmidt, M., Shindell, D.T., Simpson, I.J., Spahni, R., Steele, L.P., Strode, S.A., Sudo, K., Szopa, S., van der Werf, G.R., Voulgarakis, A., van

- Weele, M., Weiss, R.F., Williams, J.E., Zeng, G. (2013). Three decades of global CH₄ sources and sinks. *Nature Geoscience*, 6, 813–823. <https://doi.org/10.1038/ngeo1955>.
- Knudsen, J., De Rossi, L. (2022). Mapping and quantification of GHGs from diffuse emission sources using drone technology and vertical measuring walls. In: Knudsen, B., Scheutz, C., Fredenslund, A. (Eds.), MUDP Report, April 2022. The Danish Environmental Protection Agency. Retrieved 14 April, 2025, from <https://www2.mst.dk/Udgiv/publications/>.
- Krier, A., Huang, X.L., Sherstnev, V. (1970). Mid-infrared Electroluminescence in LEDs Based on InAs and Related Alloys. *Springer Series in Optical Sciences*, 118, 359-394. DOI:10.1007/1-84628-209-8_11.
- Larsson, J. (2019). Diode-laser absorption spectroscopy - applications in medicine and environmental monitoring. [Doctoral Thesis (compilation), Atomic Physics]. Department of Physics, Lund University. <https://portal.research.lu.se/en/publications/diode-laser-absorption-spectroscopy-applications-in-medicine-and->
- Liang, C.W., Zheng, Z.C., Chen, T.N. (2024). Monitoring landfill volatile organic compounds emissions by an uncrewed aerial vehicle platform with infrared and visible-light cameras, remote monitoring, and sampling systems. *Journal of Environmental Management*, 365, 121575. <https://doi.org/10.1016/j.jenvman.2024.121575>.
- Lister, A.J., Riemann, R., Hoppus, M. (2001). A Nonparametric Geostatistical Method for Estimating Species Importance. In: Reams, Gregory A.; McRoberts, Ronald E.; Van Deusen, Paul C., eds. 2001. Proceedings of the second annual Forest Inventory and Analysis symposium; 2000 October 17-18; Salt Lake City, UT. Gen. Tech. Rep. SRS-47. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. pp. 52-59. <https://research.fs.usda.gov/treearch/4526>.
- Mar, K.A., Unger, C., Walderdorff, L., Butler, T. (2022). Beyond Co₂ Equivalence: The Impacts of CH₄ on Climate, Ecosystems, and Health. *Environmental Science & Policy*, 134(9), 127-136. <https://doi.org/10.1016/j.envsci.2022.03.027>.
- Mengist, W., Soromessa, T., Legese, G. (2020). Method for conducting systematic literature review and meta-analysis for environmental science research. *MethodsX*, 7, 100777. <https://doi.org/10.1016/j.mex.2019.100777>.
- Ministry of Climate and Enterprise. (2022). *Sweden's CH₄ Action Plan. Mapping of Sweden's CH₄ emissions, projections, policies and measures*. [M2022/02106]. Ministry of the Environment. Retrieved 5 April, 2025, from <https://www.government.se/contentassets/303c37911a6c4a9a895c3b4049b8ee9b/swedens-CH4-action-plan---mapping-of-swedens-CH4-emissions-projections-policies-and-measures.pdf>.
- Ministry of the Environment. (2020). *Sweden's long-term strategy for reducing greenhouse gas emissions*. Retrieved 5 April, 2025, from <https://faolex.fao.org/docs/pdf/swe204610.pdf>.
- Mitchell, A.L., Daniel S., Tkacik, D.S., Roscioli, J.R., Herndon, S.C., Yacovitch, T.I., Martinez, D.M., Vaughn, T.L., Williams, L.L., Sullivan, M.R., Floerchinger, C., Omara, M., Subramanian, R., Zimmerle, D., Marchese, A.J., Robinson, A.L. (2015). Measurements of CH₄ Emissions from Natural Gas Gathering Facilities and Processing Plants: Measurement Results. *Environmental Science & Technology*, 49(5), 3219-3227. <https://doi.org/10.1021/es5052809>.
- Mohammadloo, T.H., Jones, M., van de Kerkhof, B., Dawson, K., Smith, B.J., Conley, S., Corbett, A., IJzermans, R. (2025). Quantitative estimate of several sources of uncertainty in drone-

- based CH₄ emission measurements. *Atmospheric Measurement Techniques*, 18(5), 1301–1324. <https://doi.org/10.5194/amt-18-1301-2025>.
- Morales, R., Ravelid, J., Vinkovic, K., Korbeň, P., Tuzson, B., Emmenegger, L., Chen, H., Schmidt, M., Humbel, S., Brunner, D. (2022). Controlled-release experiment to investigate uncertainties in UAV-based emission quantification for CH₄ point sources. *Atmospheric Measurement Techniques*, 15(7), 2177–2198. <https://doi.org/10.5194/amt-15-2177-2022>.
- Möller, L. (2022). Mätmetoder för ytemissioner av deponigas - En fallstudie på Filbornadeponin i Helsingborg. [Master thesis, Environmental Science]. Studies in Environmental Science, Lund University. <https://lup.lub.lu.se/studentpapers/search/publication/9086724>.
- Mønster, J., Kjeldsen, P., Scheutz, C. (2017). Methodologies for measuring fugitive CH₄ emissions from landfills – A review. *Waste Management*, 87, 835-859. <https://doi.org/10.1016/j.wasman.2018.12.047>.
- National Aeronautics and Space Administration (NASA). (N.D.). Atmospheric CH₄ Concentrations since the year 1010. Data sources: Etheridge et al., 1998 and NOAA Global Monitoring Laboratory. Retrieved 23 May, 2025, from <https://climate.nasa.gov/vital-signs/CH4/?intent=121>.
- Nathan, B.J., Golston, L.M., O'Brien, A.S., Ross, K., Harrison, W.A., Tao, L., Lary, D.J., Johnson, D.R., Covington, A.N., Clark, N.N., Zondlo, M.A. (2015). Near-field characterization of CH₄ emission variability from a compressor station using a model aircraft. *Environmental Science & Technology*, 49(13), 7896–7903. <https://doi.org/10.1021/acs.est.5b00705>.
- Naturvårdsverket. (2008). *FAKTA: Lakvatten från deponier, Rapport 8306*. Stockholm: Naturvårdsverket. Retrieved 5 April, 2025, from <https://www.naturvardsverket.se/globalassets/media/publikationer-pdf/8300/978-91-620-8306-9.pdf>.
- Naturvårdsverket. (2011). *Underlag för vägledning beträffande inventering, undersökning och riskklassning av gamla deponier. Lakvatten och deponigas Rapport 13 897*. Stockholm: Naturvårdsverket. Retrieved 5 April, 2025, from <https://www.naturvardsverket.se/4ac311/contentassets/a6d19b240af0402ba97ffb7651ee25fa/deponi-rapport-sgi-lakvatten-o-deponigas.pdf>.
- Nilsson, F. (2008). Föroreningsspridning och geologi vid Filborna i Helsingborg. [Magisterexamen, Geology]. The Geological Institute, Lund University. <https://www.lu.se/lup/publication/2301891>.
- Pérez, I. A., García, M. Á., Sánchez, M. L., & Pardo, N. (2022). Trend analysis and outlier distribution of CO₂ and CH₄: A case study at a rural site in northern Spain. *The Science of the total environment*, 819, 153129. <https://doi.org/10.1016/j.scitotenv.2022.153129>.
- Reinelt, T., Delre, A., Westerkamp, T., Holmgren, M.A., Liebetrau, J., Scheutz, C. (2017). Comparative use of different emission measurement approaches to determine CH₄ emissions from a biogas plant. *Waste Management*, 68, 173-185. <https://doi.org/10.1016/j.wasman.2017.05.053>.
- ReSource Sverige AB. (2025). Method Description. Internal report [ReSource Sverige AB]. Unpublished, from personel communication.
- Saunois, M., Martinez, A., Poulter, B., Zhang, Z., Raymond, P. A., Regnier, P., Canadell, J. G., Jackson, R. B., Patra, P. K., Bousquet, P., Ciais, P., Dlugokencky, E. J., Lan, X., Allen, G. H., Bastviken, D., Beerling, D. J., Belikov, D. A., Blake, D. R., Castaldi, S., Crippa, M., Deemer, B.R., Dennison, F., Etiope, G., Gedney, N., Höglund-Isaksson, L.,

- Holgerson, M.A., Hopcroft, P.O., Hugelius, G., Ito, A., Jain, A.K., Janardanan, R., Johnson, M.S., Kleinen, T., Krummel, P.B., Lauerwald, R., Li, T., Liu, X., McDonald, K.C., Melton, J.R., Muhle, J., Muller, J., Murguia-Flores, F., Niwa, Y., Noce, S., Pan, S., Parker, R.J., Peng, C., Ramonet, M., Riley, W.J., Rocher-Ros, G., Rosentreter, J.A., Sasakawa, M., Segers, A., Smith, S.J., Stanley, E.H., Thanwerdas, J., Tian, H., Tsuruta, A., Tubiello, F.N., Weber, T.S., van der Werf, G.R., Worthy, D.E.J., Xi, Y., Yoshida, Y., Zhang, W., Zheng, B., Zhu, Q., Zhu, Q., Zhuang, Q. (2025). Global CH₄ Budget 2000–2020. *Earth System Science Data*, 17(5), 1873–1958. <https://doi.org/10.5194/essd-17-1873-2025>.
- Schaefer, H. (2019). On the Causes and Consequences of Recent Trends in Atmospheric CH₄. *Current Climate Change Reports*, 5, 259–274. <https://doi.org/10.1007/s40641-019-00140-z>.
- Scheutz, C., Kissas, K., Mønster, J., Kolmert Strickland, Å., Kivistö, J., Arvidsson, I., Björling, I., Łakomiec, P., McQuilkin, J., Sarno, A. (2020). Quantification of landfill CH₄ emissions – a method comparison study. Technical University of Denmark, FORCE Technology, Sweco Environment, Lund University, ReSource International, Region Gotland. Retrieved 9 May, 2025, from [https://h2020-memo2.eu/wp-content/uploads/sites/198/2020/06/Quantification-of-landfill-CH₄-emissions-%E2%80%93-a-method-comparison-study_Final-4_june.pdf](https://h2020-memo2.eu/wp-content/uploads/sites/198/2020/06/Quantification-of-landfill-CH4-emissions-%E2%80%93-a-method-comparison-study_Final-4_june.pdf).
- Scheutz, C., Knudsen, J.E., Vechi, N.T., Knudsen, J. (2025). Validation and demonstration of a drone-based method for quantifying fugitive CH₄ emissions. *Journal of Environmental Management*, 373, 123467. <https://doi.org/10.1016/j.jenvman.2024.123467>.
- Schiermeier, Q. (2020). Global CH₄ Levels Soar to Record High." *Nature*. doi:10.1038/D41586-020-02116-8.
- SFS 2001:512. Förordning om deponering av avfall. Miljödepartementet. Retrieved 14 April, 2025, from https://www.riksdagen.se/sv/dokument-lagar/dokument/svenskforfattningssamling/forordning-2001512-om-deponering-av-avfall_sfs-2001-512.
- SFS 2011:927. Avfallsförordning (2011:927). Miljödepartementet. Retrieved 14 April, 2025, from https://www.riksdagen.se/sv/dokument-och-lagar/dokument/svensk-forfattningssamling/avfallsforordning-2011927_sfs-2011-927/.
- SFS 2020:614. Avfallsförordning (2020:614). Miljödepartementet. Retrieved 14 April, 2025, from https://www.riksdagen.se/sv/dokument-och-lagar/dokument/svensk-forfattningssamling/avfallsforordning-2020614_sfs-2020-614/.
- Shah, A., Allen, G., Pitt, J. R., Ricketts, H., Williams, P. I., Helmore, J., Finlayson, A., Robinson, R., Kabbabe, K., Hollingsworth, P., Rees-White, T. C., Beaven, R., Scheutz, C., & Bourn, M. (2019). A Near-Field Gaussian Plume Inversion Flux Quantification Method, Applied to Unmanned Aerial Vehicle Sampling. *Atmosphere*, 10(7), 396. <https://doi.org/10.3390/atmos10070396>.
- Shah, A., Pitt, J.R., Ricketts, H., Leen, J.B., Williams, P.I., Kabbabe, K., Gallagher, M.W., Allen, G. (2020). Testing the near-field Gaussian plume inversion flux quantification technique using unmanned aerial vehicle sampling. *Atmospheric Measuring Techniques*, 13(3), 1467–1484. <https://doi.org/10.5194/amt-13-1467-2020>.
- Shaw, J. T., Shah, A., Yong, H., Allen, G. (2021). Methods for quantifying CH₄ emissions using unmanned aerial vehicles: a review. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, 379(2210), 20200450. <https://doi.org/10.1098/rsta.2020.0450>.

- Simon, N., Piqué, A., Snyder, D., Ikuma, K., Majumdar, A., Hultmark, M. (2023). Fast-response hot-wire flow sensors for wind and gust estimation on UAVs. *Measurement Science and Technology*, 34(2), 025109. [DOI:10.1088/1361-6501/ac9f5c](https://doi.org/10.1088/1361-6501/ac9f5c).
- Stadler, C., Fusé, V.S., Linares, S., Juliarena, P. (2023). Evaluation of interpolation methods for the prediction of urban CH₄ concentrations. *Urban Climate*, 49, 101556. <https://doi.org/10.1016/j.uclim.2023.101556>.
- Staniaszek, Z., Griffiths, P.T., Folberth, G.A., O'Connor, F.M., Abraham, N.L., Archibald, T. (2022). The role of future anthropogenic CH₄ emissions in air quality and climate. *npj Climate and Atmospheric Sciences*, 5, 21. <https://doi.org/10.1038/s41612-022-00247-5>.
- Szopa, S., V. Naik, B. Adhikary, P. Artaxo, T. Berntsen, W.D. Collins, S. Fuzzi, L. Gallardo, A. Kiendler-Scharr, Z. Klimont, H. Liao, N. Unger, and P. Zanis, 2021: Short-Lived Climate Forcers. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate*, 817–922. [Doi:10.1017/9781009157896.008](https://doi.org/10.1017/9781009157896.008).
- Tassielli, G., Cananà, L., Spalatro, M. (2025). Detection of CH₄ Leaks via Drone in Release Trials: Set-Up of the Measurement System for Flux Quantification. *Sustainability*, 17, 2467. <https://doi.org/10.3390/su17062467>.
- Themelis, N.J., Ulloa, P.A. (2007). CH₄ generation in landfills. *Renewable Energy*, 32(7), 1243-1257. <https://doi.org/10.1016/j.renene.2006.04.020>.
- Thoma, E.D., Shores, R.C., Thompson, E.L., Harris, D.B. (2005). Open-Path Tunable Diode Laser Absorption Spectroscopy for Acquisition of Fugitive Emission Flux Data. *Journal of the Air & Waste Management Association*, 55(5), 658-68. [doi:10.1080/10473289.2005.10464654](https://doi.org/10.1080/10473289.2005.10464654).
- Tittel, F., Richter, D., Fried, A. (2008). Mid-Infrared Laser Applications in Spectroscopy. *Topics in Applied Physics*, 89, 458-529. https://doi.org/10.1007/3-540-36491-9_11.
- United Nations Environment Programme (2022). *Integrated Assessment of Air Pollution and Climate Change for Sustainable Development in Africa: Summary for Decision Makers*. Retrieved 12 June, 2025, from <https://www.ccacoalition.org/resources/full-report-integrated-assessment-air-pollution-and-climate-change-sustainable-development-africa>.
- United Nations Environment Programme (2023). *Integrated Assessment of Air Pollution and Climate Change for Sustainable Development in Africa, Nairobi*. Retrieved 12 June, 2025, from <https://www.ccacoalition.org/resources/full-report-integrated-assessment-air-pollution-and-climate-change-sustainable-development-africa>.
- Wang Q., Xinru, Z., Xia, M., Xie, H. (2019). Field investigation of temporal variation of volatile organic compounds at a landfill in Hangzhou, China. *Environmental Science and Pollution Research*, 26(11), 18162–18180. <https://doi.org/10.1007/s11356-019-04917-5>.
- Wang, Y., Wei, Y., Chang, J., Zhang, T., Liu, T., Sun, T. & Grattan, K. T. V. (2017). Tunable diode laser absorption spectroscopy-based detection of propane for explosion early warning by using a vertical cavity surface enhanced laser source and principal component analysis approach. *IEEE Sensors Journal*, 17(15), 4975-4982. [Doi:10.1109/jsen.2017.2713769](https://doi.org/10.1109/jsen.2017.2713769).
- Wang, Z., Liu, S., Weng, W., He, Y., Aldén, M., Li, Z. (2024). Alkali metal release in thermochemical conversion of biomass and coal: Optical measurements and modeling. *Progress in Energy and Combustion Science*, 100, 101131. <https://doi.org/10.1016/j.pecs.2023.101131>.

- Wojtas, J. (2024). Towards the highest sensitivity and selectivity of the Earth's and Space's laser-based CH₄ sensors. *Measurement*, 225, 114064. <https://doi.org/10.1016/j.measurement.2023.114064>.
- Yilmaz, M., James M. Tinjum, J.M., Connor Acker, C., Marten, B. (2021). Transport mechanisms and emission of landfill gas through various cover soil configurations in an MSW landfill using a static flux chamber technique. *Journal of Environmental Management*, 280, 111677. <https://doi.org/10.1016/j.jenvman.2020.111677>.
- Yong, H., Allen, G., Mcquilkin, J., Ricketts, H., Shaw, J.T. (2024). Lessons learned from a UAV survey and CH₄ emissions calculation at a UK landfill. *Waste Management*, 180(1), 47-54. <https://doi.org/10.1016/j.wasman.2024.03.025>.

Appendix A

Table A1: Clarification on which data and method was used for calculating CH₄ fluxes on the respective landfill campaigns, the performer behind the calculations, the source, and date of the data collection.

Campaign	Dataset	Source	Performer of flux calculations and uncertainty testing	Method used for flux estimation
Linköping	2020-01-24	Gålfalk <i>et al.</i> (2021)	Kajsa-Lisa Powis	Drone Flux Method
Filborna	2023-10-17	ReSource Sverige AB (2025)	ReSource Sverige AB	GASTRAQ
Rönneholm	2024-03-07	ReSource Sverige AB (2025)	ReSource Sverige AB	GASTRAQ
Rönneholm	2024-05-31	ReSource Sverige AB (2025)	ReSource Sverige AB	GASTRAQ
Filborna	2024-11-15	ReSource Sverige AB (2025)	ReSource Sverige AB	GASTRAQ

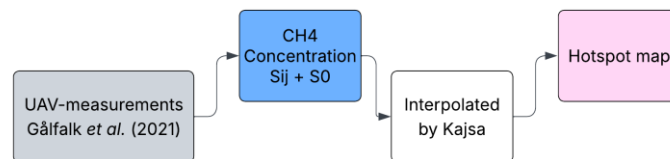


Figure A1: A flowchart showing the data source and performer of calculations (white) when the resulting hotspot maps (pink) were generated. The data source (grey) and atmospheric variable (blue) is also shown within the flowchart. The data source used for the calculations is Gålfalk *et al.* (2021) and performer of the calculations (Kajsa) is the author of this thesis.

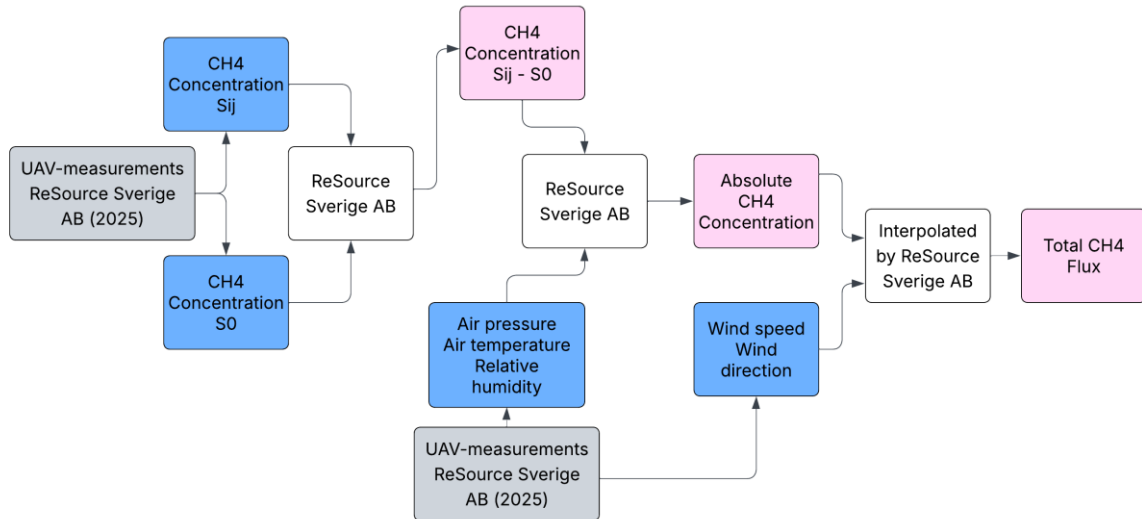


Figure A2: A simplified flowchart showing the data source and performer of calculations (white) when the resulting hotspot maps (pink) were generated. The data source (grey) and atmospheric variable (blue) is also shown within the flowchart. The data source and performer of the calculations is ReSource Sverige AB.

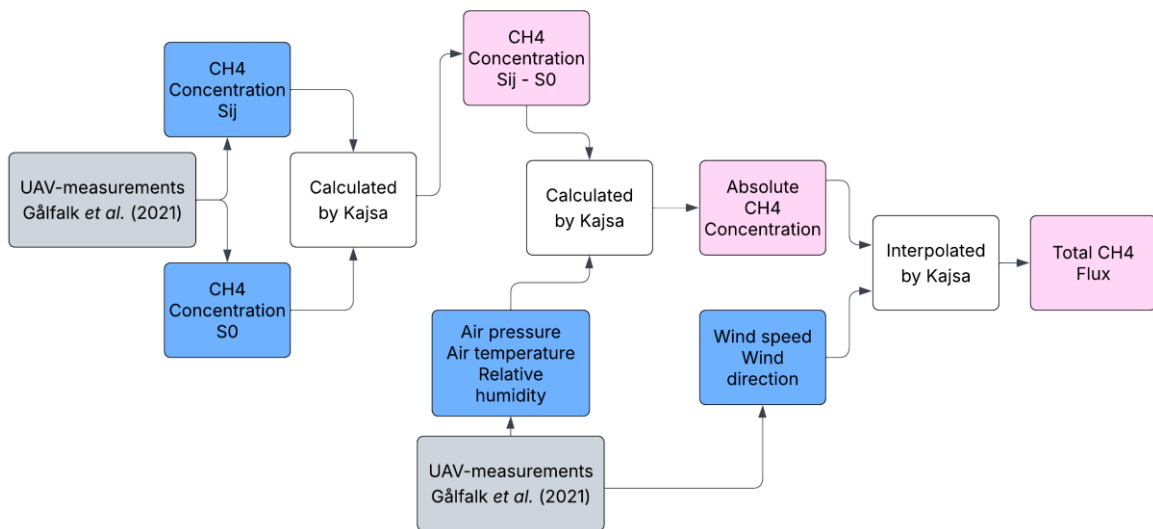


Figure A3: A simplified flowchart showing the data source and performer of calculations (white) when the resulting hotspot maps (pink) were generated. The data source (grey) and atmospheric variable (blue) is also shown within the flowchart. The data source used for the calculations is Gålfalk et al. (2021) and performer of the calculations (Kajsa) is the author of this thesis.

Appendix B

Table B1: Average wind speed per flight during the measurement period on Linköping landfill in January 2020.

Linköping	Date	Time	Wind speed m/s (averaged by flight)
Flight 1	2020-01-24	12:30 – 12:39	3.4
Flight 2	2020-01-24	12:44 – 12:55	3.4
Flight 3	2020-01-24	12:49 – 13:09	3.8
Average	2020-01-24	12.30 – 13:09	3.5

Table B2: Average wind speed per flight during the measurement period on Filborna landfill in October 2023.

Filborna	Date	Time	Wind speed m/s (averaged by flight)
Flight 1	2023-10-17	14:21 - 14:29	7.5
Flight 2	2023-10-17	14:38 - 14:45	7.3
Flight 3	2023-10-17	15:00 - 15:08	7.9
Flight 4	2023-10-17	17:02 - 17:09	7.0
Flight 5	2023-10-17	17:18 - 17:26	6.3
Flight 6	2023-10-17	17:32 - 17:40	6.3
Flight 7	2023-10-17	17:46 - 17:52	6.1
Average	2023-10-17	14:21 -17:52	6.9

Table B3: Average wind speed per flight during the measurement period on Rönneholm landfill in March 2024.

Rönneholm	Date	Time	Wind speed m/s (averaged by flight)
Flight 1	2024-03-07	11:24 - 11:31	1.0
Flight 2	2024-03-07	11:39 - 11:48	1.3
Flight 3	2024-03-07	14:10 -14:12	2.1
Flight 4	2024-03-07	14:31 - 14:38	1.8
Flight 5	2024-03-07	14:49 -14:55	1.9
Flight 6	2024-03-07	15:09 -15:16	1.4
Flight 7	2024-03-07	15:23 - 15:29	0.8
Flight 8	2024-03-07	16:15 - 16:21	1.1
Average	2024-03-07	11:24 - 16:21	1.4

Table B4: Average wind speed per flight during the measurement period on Rönneholm landfill in May 2024.

Rönneholm	Date	Time	Wind speed m/s (averaged by flight)
Flight 1	2024-05-31	13:34 - 13:39	6.6
Flight 2	2024-05-31	14:11 - 14:20	4.4
Flight 3	2024-05-31	14:25 - 14:32	4.8
Flight 4	2024-05-31	15:32 - 15:39	5.4
Flight 5	2024-05-31	15:49 - 15:56	4.7
Flight 6	2024-05-31	16:04 - 16:10	5.4
Flight 7	2024-05-31	16:24 - 16:30	5.6
Flight 8	2024-05-31	16:38 - 16:45	5.9
Flight 9	2024-05-31	17:37 - 17:44	5.0
Average	2024-05-31	13.34 - 17-44	5.3

Table B5: Average wind speed per flight during the measurement period on *Filborna* landfill in November 2024.

Filborna	Date	Time	Wind speed m/s (averaged by flight)
Flight 1	2024-11-15	11:04 - 11:10	7.8
Flight 2	2024-11-15	11:22 - 11:27	7.4
Flight 3	2024-11-15	11:35 - 11:40	7.0
Flight 4	2024-11-15	11:47 - 11:51	6.8
Flight 5	2024-11-15	14:56 - 15:02	7.1
Flight 6	2024-11-15	15:11 - 15:17	7.0
Flight 7	2024-11-15	15:26 - 15:32	7.1
Flight 8	2024-11-15	15:39 - 15:45	7.0
Average	2024-11-15	11:04 - 15:58	7.2

Appendix C

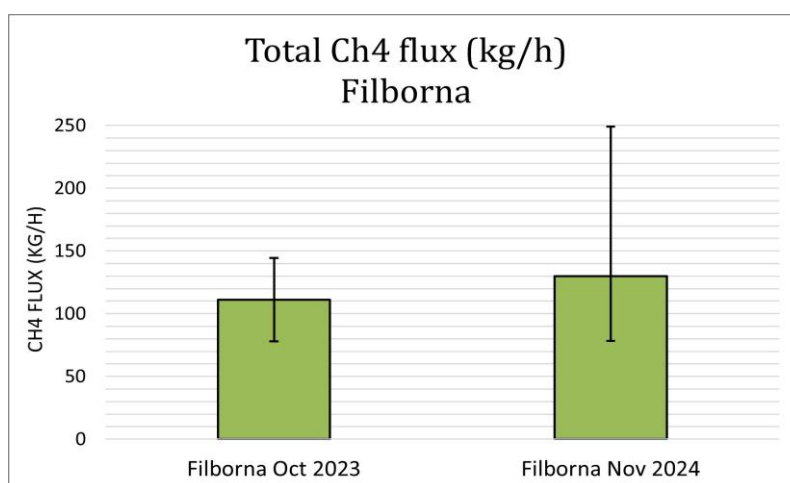


Figure C1: Total CH₄ flux in kg h^{-1} on Filborna landfill in October 2023 and November 2024 (green bars), which was calculated using the GASTRAQ methodology by ReSource Sverige AB. The error for the measurements done in November 2024 (black whiskers) range asymmetrically, meaning that the data had an asymmetrical distribution of data points around the central value.

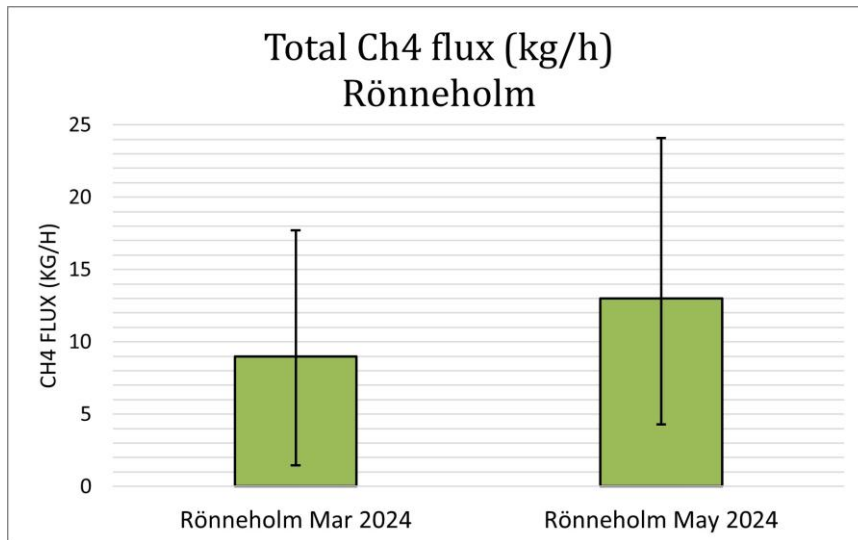


Figure C2: Total CH₄ flux in kg h^{-1} on Rönneholm landfill in March 2024 and May 2024 (green bars), which was calculated using the GASTRAQ methodology by ReSource Sverige AB. The errors (black whiskers) range asymmetrically, meaning that the data had asymmetrical distribution of data points around the central value.

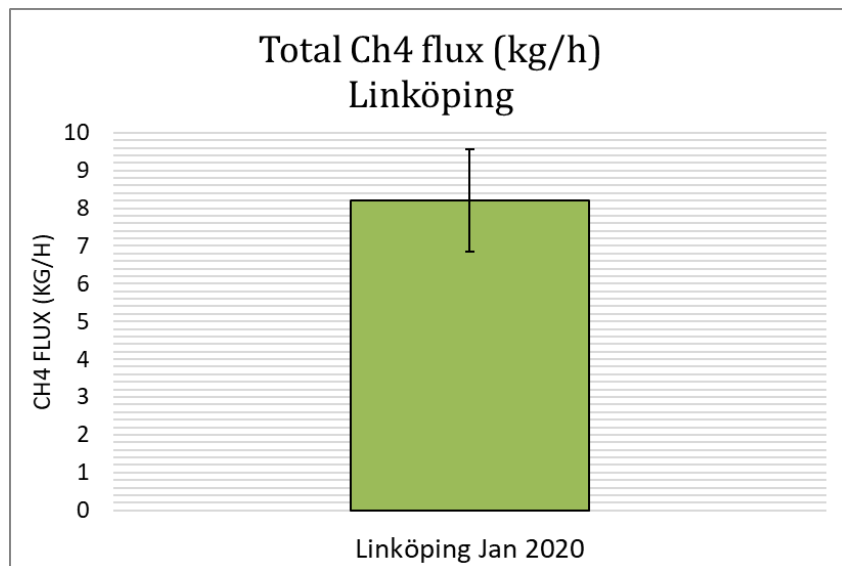


Figure C3: Total CH₄ flux in kg h^{-1} on Linköping sludge waste landfill in January 2020 (green bar), which was calculated using the Drone Flux methodology. The error (black whisker) ranges between $\pm 1.36 \text{ kg h}^{-1}$, or $\pm 16.57\%$.

Appendix D

Instrumental Uncertainties

TDLAS utilizes a narrow wave laser that is continuous as the light source to identify specific molecules like CH₄. As CH₄ gas has a known energy level, and varying levels of absorption or emission of electro-magnetic radiation, CH₄ has explicit spectroscopic features like vibrations and states (Tittel *et al.*, 2008). With these specific spectroscopic features of CH₄, the desired molecule may be identified whereas a concentration then can be quantified in ppb or ppm (Tittel *et al.*, 2008). Diode Laser absorption Spectroscopy produces higher accuracy within traces gases (Wang *et al.*, 2024) compared to its counterpart, Fourier-Transform Infrared (FTIR) Spectroscopy. FTIR, although with more versatile applications, has a lower precision than Diode Laser absorption Spectroscopy. For compounds like CH₄, Diode Laser absorption Spectroscopy possesses some significant advantages over FTIR when applying the instrument on fugitive emission measurements (Thoma *et al.*, 2005).

For CH₄ concentration estimation, GASTRAQ uses the GLA131-GGA (ABB-Los Gatos, Switzerland). It utilizes TDLAS cavity ring spectroscopy, called OA-ICOS technology. The main difference is that inside the instrument there is a chamber with mirrors that let the molecule of the gas make more passes. This results in a signal which is less subject to external disturbances. The GLA131-GGA (ABB-Los Gatos, Switzerland), used in GASTRAQ, has an uncertainty of <0.9 ppb for 1 Hz measurement: a low uncertainty (ReSource Sverige AB, 2025). What may be interfering with the CH₄ sensor however can be the turbulence of the propellers, which was solved somewhat by putting the inlet source 60 cm from the rotor plane (Scheutz *et al.*, 2020).

To contrast, the CH₄ sensor used by Gålfalk *et al.* (2021), the MIRA Pico (Aeris Technologies, United States), has a precision of ~ 2 ppb for 1 Hz measurement (Gålfalk *et al.*, 2021) which is a lower precision than the sensor used by ReSource Sverige AB (2025). This is a precision that indicates lower sensitivity precision than the CH₄ sensor used by ReSource Sverige AB, which causes higher uncertainty when using the same instrumentation as Gålfalk *et al.* (2021).