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Abstract

Romania hosts one of the largest and oldest natural gas production sectors in Europe, yet direct measurements of methane emissions from its principal gas-producing region, the Transylvanian Basin, remain limited. Here, we present the first basin-scale, measurement-based assessment of methane emissions from natural gas production facilities in the Transylvanian Basin based on 160 methane emission quantifications performed at 127 facilities and complementary screening surveys covering 520 facilities. Methane emissions were quantified using multiple independent approaches, including the Tracer Release Method (TRM), Other Test Method 33A (OTM-33A), Gaussian Plume Method (GPM), High-Flow Sampling (HFS), and a novel Large-Scale Flow Chamber (LSFC). Site-level methane emissions exhibited strongly skewed, approximately log-normal distributions and pronounced temporal variability, with repeated measurements frequently differing by up to an order of magnitude. Combining all representative facility-scale measurements yielded a methane emission factor of $1.7 \text{ kg CH}_4 \text{ h}^{-1} \text{ site}^{-1}$ (95% confidence interval: $1.1\text{--}2.6 \text{ kg CH}_4 \text{ h}^{-1} \text{ site}^{-1}$). While emissions from natural gas production facilities were primarily associated with leaking infrastructure components, two previously undocumented water-degassing tanks were identified as methane super-emitters, with combined emissions exceeding those measured from all quantified production facilities. Upscaling the derived emission factor yielded methane emissions of approximately $42 \text{ kt CH}_4 \text{ yr}^{-1}$ (95% confidence interval: $27\text{--}64 \text{ kt CH}_4 \text{ yr}^{-1}$) from natural gas production well sites in the Transylvanian Basin. This estimate is comparable to currently available national-scale estimates for Romania's natural gas sector, highlighting the importance of measurement-based approaches for improving greenhouse-gas inventories and identifying methane mitigation opportunities.

1. Introduction

The release of natural gas associated with the production, transport, and use of oil and gas (O&G) contributes approximately 20% of total anthropogenic emissions of methane (CH₄), a potent greenhouse gas, to the atmosphere. In Europe, total CH₄ emissions from this sector amount to nearly 2 Mt yr⁻¹ (Saunois et al., 2025). Recent measurement-based studies have demonstrated that methane emissions from upstream O&G activities frequently exceed estimates derived from emission factors used in national greenhouse-gas inventories (Alvarez et al., 2018; Caulton et al., 2014; Howarth et al., 2011; Riddick et al., 2019; Zavala-Araiza et al., 2017; Zavala-Araiza et al., 2021; Mehrotra et al., 2017; Irakulis-Loitxate et al., 2022; Korbeň et al., 2022; Lauvaux et al., 2022; Stavropoulou et al., 2023; Maazallahi et al., 2024). Such discrepancies between direct observations and inventory-based estimates undermine efforts to accurately quantify emissions and prioritize mitigation actions. At the same time, previously unaccounted-for methane emissions represent an attractive mitigation opportunity, as a large fraction of these emissions can be reduced at little or no net cost while generating additional value through gas recovery (IEA, 2024). Indeed, several studies suggest that as much as 97% of emissions associated with equipment leaks can be mitigated cost-effectively (Holmes, 2016; Shindell et al., 2021; Höglund-Isaksson et al., 2020).

Methane can be released throughout the entire O&G supply chain as either vented or fugitive emissions (Cooper et al., 2021; Alvarez et al., 2018). Venting refers to the intentional release of methane during routine operation or maintenance activities, whereas fugitive emissions result from unintended leaks from infrastructure components such as valves, flanges, connectors, and other equipment. Effective mitigation of methane emissions therefore requires robust characterization and management of both emission categories. Although a variety of leak detection and repair (LDAR) technologies and methodologies are currently available, their implementation varies substantially among operators and regions.

Numerous studies examining CH₄ emissions from O&G facilities have consistently reported strongly skewed emission distributions, with a relatively small fraction of facilities accounting for a disproportionately large share of total emissions (Brandt et al., 2014; Alvarez et al., 2018; Stavropoulou et al., 2023; Irakulis-Loitxate et al., 2022; Zavala-Araiza et al., 2017). These facilities, commonly referred to as “super-emitters”, can dominate regional methane budgets. Such emission distributions are commonly described by log-normal functions, which provide an appropriate framework for estimating expected regional-scale emissions and associated confidence intervals. Consequently, log-normal statistical methods are widely applied when scaling site-level observations to basin-scale emission estimates. This approach is adopted in the present study.

Methane emissions from O&G facilities can be quantified using a variety of complementary methods. Component-level measurements are commonly performed using High-Flow Sampler (HFS) techniques, in which leaking equipment is enclosed and methane loss rates are directly measured (Howard et al., 2015; Zimmerle et al., 2022). Site-level methane emission rates can be derived from methane enhancements measured within downwind plumes using approaches such as Gaussian Plume Models (GPM) or the EPA OTM-33A method (Caulton et al., 2018; Lushi & Stockie, 2010; Edie et al., 2020). Alternative approaches employ controlled tracer releases near emission sources, enabling methane emission rates to be quantified from measured ratios between methane and tracer concentrations (Mønster et al., 2014; Ars et al., 2017; Delre et al., 2022). Each method provides distinct advantages in terms of spatial coverage, detection capability, operational constraints, and uncertainty

structure, making integrated measurement strategies particularly valuable for comprehensive emission assessments.

Romania is the second-largest producer of oil and natural gas in the European Union (Energy Institute, 2024) and one of the major methane emitters from the European energy sector (UNFCCC, data available at https://di.unfccc.int/flex_annex1). Consequently, reducing emissions from O&G activities is essential for achieving both national and European climate objectives. However, significant uncertainties remain regarding the magnitude of methane emissions from Romania's natural gas sector. Current national greenhouse-gas inventory estimates rely largely on generic emission factors within a Tier 1 reporting framework, while direct measurement-based assessments remain scarce and geographically limited (Delre et al., 2022; Korbeń et al., 2022). As a result, it remains unclear whether reported emissions accurately represent methane releases from Romania's extensive and ageing natural gas production infrastructure.

To address this knowledge gap, the Romanian Methane Emissions from Oil and Gas (ROMEО) project was established to characterize methane emissions from O&G production activities using state-of-the-art measurement techniques. The first phase of the project, conducted between September and October 2019, focused primarily on oil-production facilities in southern Romania while also investigating selected elements of the natural gas sector (Korbeń et al., 2022; Delre et al., 2022; Stavropoulou et al., 2023; Maazallahi et al., 2024). These efforts were complemented by urban methane measurement campaigns conducted in Bucharest and Ploieşti (Fernandez et al., 2022), providing additional insight into methane emissions from the Romanian energy sector.

In this study, we present results from the second phase of the project (ROMEО-B), conducted between 13 June and 4 July 2021 in the Transylvanian Basin, the principal natural-gas-producing region of Romania. The campaign focused exclusively on natural gas production infrastructure and employed multiple complementary methane quantification techniques to characterize emissions from natural gas production facilities and associated infrastructure. Integrating these measurements enabled the first regional-scale, measurement-based assessment of methane emissions from Romanian natural gas production. Unlike previous ROMEО studies that focused primarily on oil production activities and selected elements of the gas sector, the ROMEО-B campaign targeted the principal natural gas-producing region of Romania and combined multiple independent quantification approaches with repeated measurements and extensive screening observations. This design enabled both facility-scale characterization of methane emissions and the first measurement-based basin-scale assessment of methane emissions from Romanian natural gas production infrastructure.

Specifically, we sought to address four key questions. First, what are the representative methane emission factors for natural gas production facilities in the Transylvanian Basin? Second, which infrastructure elements contribute most strongly to regional methane emissions, and what role do super-emitters play in shaping the overall regional methane budget? Third, how consistent are methane emission estimates derived using different quantification approaches under operational field conditions? Finally, to what extent do measurement-based methane emissions agree with current national greenhouse-gas inventory estimates derived from generic emission factors?

Answering these questions provides the first independent assessment of methane emissions from Romanian natural gas production. More broadly, our results contribute to the growing body of evidence that measurement-based approaches can reveal substantial discrepancies between observed and reported emissions, with important implications for national greenhouse-gas inventories, methane mitigation strategies, and climate policy. As methane emissions from the energy

sector receive increasing regulatory attention in Europe, robust observational constraints are becoming essential for developing effective and transparent monitoring frameworks.

2. Materials and Methods

2.1 Study area

The Transylvanian Basin is a mature natural gas province located in central Romania and bounded by the Apuseni Mountains to the west and the Eastern and Southern Carpathians to the east and south, respectively (Fig. 1). The basin hosts one of the largest onshore natural gas accumulations in Europe and represents the principal gas-producing region of Romania. The dominant petroleum system is associated with Neogene (Badenian–Sarmatian) sedimentary deposits, which primarily contain microbially generated methane (Popescu, 1995; Krézsek et al., 2010; Krézsek and Bally, 2006). Thermogenic methane may occur at greater depths and in the eastern part of the basin due to the thermal influence of Neogene volcanic activity in the Eastern Carpathians (Baciu et al., 2018). Hydrocarbon accumulations are primarily trapped within structural and stratigraphic reservoirs sealed by shale formations, effectively limiting natural methane migration to the atmosphere (Krézsek et al., 2010). Natural gas composition varies across the basin. Gas produced from the western and central sectors typically contains more than 98% CH₄, providing a unique opportunity to study emissions from infrastructure associated with nearly pure methane reservoirs. In contrast, reservoirs in the eastern basin frequently contain elevated concentrations of CO₂ and N₂ (Etiope et al., 2011).

2.1.1 Natural gas production in Transylvanian Basin

Commercial exploitation of natural gas resources in the Transylvanian Basin began more than one century ago and has been dominated by the state-owned operator ROMGAZ. Cumulative gas production from the basin has been estimated at approximately 850 billion cubic metres (BCM), while remaining recoverable reserves are estimated at approximately 570 BCM (Pawlewicz, 2005; Krézsek, 2011). More than 100 gas fields are distributed across the basin, making it the most important natural gas-producing region in Central and South-Eastern Europe. Most major gas accumulations were discovered and developed before the 1980s, with production peaking in 1976. Since then, annual production has steadily declined, particularly after 1988, reflecting reservoir depletion and the limited likelihood of discovering additional large gas accumulations. As a result, the basin is now characterized by ageing production infrastructure, which may influence methane emission patterns and increase the importance of direct emission measurements.

2.2 The ROME0-B campaign

The ROME0-B campaign was conducted between 13 June and 4 July 2021 as the second phase of the Romanian Methane Emissions from Oil and Gas (ROME0) project. The campaign focused exclusively on methane emissions from natural gas production infrastructure located within the Transylvanian Basin.

The operator provided a detailed inventory containing geographical coordinates for 2,804 well sites and 416 auxiliary natural gas facilities. For the purposes of this study, each well site was treated as an individual potential methane emission source. Because comprehensive quantification of all facilities

was not feasible within the campaign period, a subset of sites was selected for detailed characterization.

2.2.1 Site selection

The site selection strategy was designed to maximize geographical coverage while capturing the diversity of infrastructure present within the basin. The selected facilities included isolated and clustered well sites, installations of different ages, and a range of auxiliary infrastructure associated with gas production and gathering systems.

A total of 160 well sites, corresponding to 5.7% of all active gas-production well sites in the basin, were quantitatively characterized during the campaign. Additional measurements were performed at auxiliary facilities, including gas processing and water-degassing installations. Screening surveys were conducted over a substantially larger number of facilities, allowing the representativeness of the quantified sites to be assessed relative to the broader infrastructure population.

Because international travel was still restricted during the COVID-19 pandemic, field activities were conducted primarily by Romanian and Polish researchers, with additional support from collaborating partners providing instrumentation and technical expertise.

Prior to the main campaign, pilot measurements were performed by the Babeş-Bolyai University (UBB) team between July and October 2020 using a portable PNI JL269 methane detector. These preliminary surveys consistently detected methane enhancements exceeding 50 ppm at facility boundaries and identified numerous individual leak sources associated with valves and other infrastructure components. The pilot campaign confirmed the suitability of the selected facilities for detailed methane quantification during ROMEO-B.

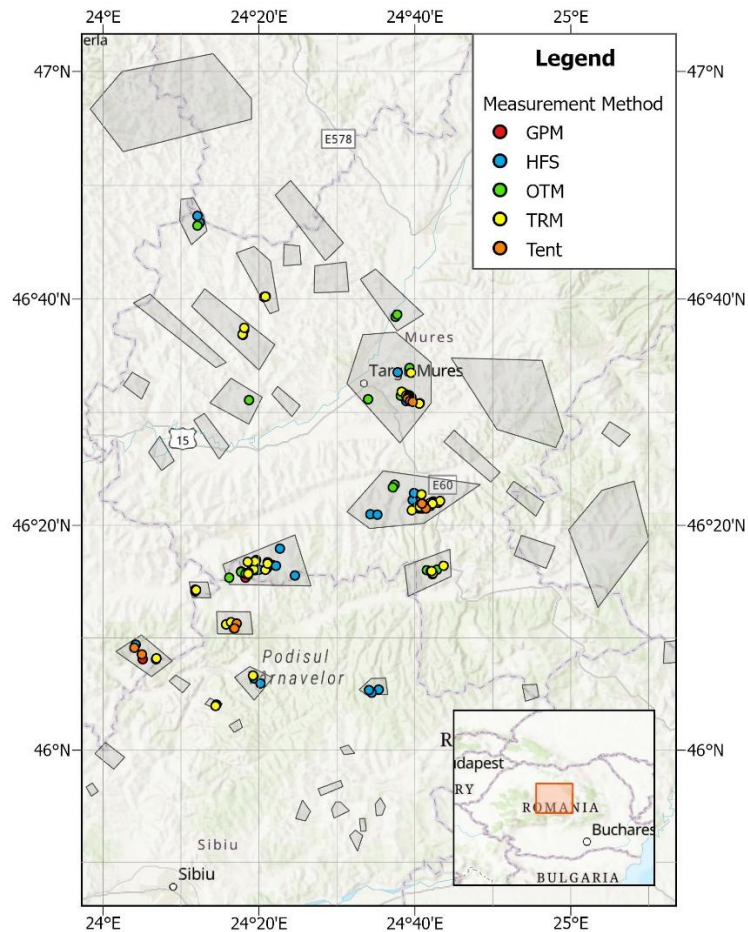


Figure 1. Distribution of natural gas production infrastructure within the Transylvanian Basin and location of the study area within Romania (inset). Well sites are aggregated in clusters above major subsurface gas reservoirs. Facilities were characterized using multiple measurement approaches, including the Gaussian Plume Method (GPM), High-Flow Sampling (HFS), Other Test Method 33A (OTM-33A), Tracer Release Method (TRM), and Large-Scale Flow Chamber (LSFC) measurements. The inset illustrates the location of the Transylvanian Basin within Romania.

2.3 Instrumentation and measurement vehicles

The ROMEO-B campaign employed five complementary measurement teams operating independently across the basin. Each team utilized dedicated instrumentation and quantification approaches to characterize methane emissions over a wide range of emission magnitudes and infrastructure types (Table 1).

The measurement strategy combined facility-scale quantification using plume-based approaches, component-level leak measurements, tracer-based emission estimates, and enclosure methods. Specifically, methane emissions were quantified using the Gaussian Plume Method (GPM), Other Test Method 33A (OTM-33A), Tracer Release Method (TRM), High-Flow Sampling (HFS), and a newly developed Large-Scale Flow Chamber (LSFC) approach. Screening surveys were additionally performed

using mobile methane analyzers and Optical Gas Imaging (OGI) systems to identify emission sources and prioritize facilities for detailed investigation.

Repeated measurements were intentionally conducted at many facilities using either identical or independent methods. This measurement redundancy enabled evaluation of methodological consistency, short-term temporal variability, and uncertainty associated with different quantification approaches.

Table 1. Overview of participating teams (acronyms refer to institute names), measurement equipment, measured species and measurement approaches employed during ROMEO-B.

Vehicle	1	2	3	4	5
Team	AGH, UBB	AGH, UBB	UBB	Sniffers	UBB
Equipment	LGR MGGA-918	Picarro G2203	Picarro G2301	HFS, OGI camera	GasScouterTM G4301
Species	CH ₄ , CO ₂ , H ₂ O	C ₂ H ₂ , CH ₄	CH ₄ , CO ₂ , H ₂ O	CH ₄	CH ₄ , CO ₂ , H ₂ O
Wind anemometer	2D Gill Windsonic 60	3D Young 81000	3D Young 05103	none	none
GPS logger	yes	yes	yes	no	yes
Measurement techniques	OTM-33A GPM Screening LSFC	TRM GPM Screening	OTM-33A Screening	HFS Camera	Sampling Screening

2.4 Measurement approaches

To characterize methane emissions from natural gas production facilities, the ROMEO-B campaign employed a suite of complementary measurement techniques covering multiple spatial scales, from individual leaking components to entire production sites. The use of multiple approaches allowed independent cross-validation of emission estimates while capturing sources with markedly different emission characteristics. The applied methods included the Gaussian Plume Method (GPM), Other Test Method 33A (OTM-33A), Tracer Release Method (TRM), High-Flow Sampling (HFS), a novel Large-Scale Flow Chamber (LSFC) approach, Optical Gas Imaging (OGI), and basin-wide screening surveys.

2.4.1 Gaussian Plume Method (GPM)

The Gaussian Plume Method (GPM) is one of the most widely applied approaches for quantifying methane emissions from localized sources (Ars et al., 2017; Caulton et al., 2018; Kumar et al., 2021; Korbeń et al., 2022; Thoma and Squier, 2014; Yacovitch et al., 2015). The method estimates methane emission rates from measured downwind concentration enhancements by combining atmospheric observations with a Gaussian representation of plume dispersion.

Methane mole fractions were measured while repeatedly traversing plumes downwind of emitting facilities. To improve characterization of plume geometry and temporal variability, each measurement

typically consisted of 10–15 transects performed over approximately 20 min at distances of approximately 20 m from the source. Emission rates were estimated using the standard Gaussian plume formulation (Turner, 2020):

$$C(x, y, z) = \frac{Q}{2 \cdot \pi \cdot u \cdot \sigma_y \cdot \sigma_z} \cdot \left\{ \exp\left(\frac{-(z - z_{\text{source}})^2}{2 \cdot \sigma_z^2}\right) + \exp\left(\frac{-(z + z_{\text{source}})^2}{2 \cdot \sigma_z^2}\right) \right\} \cdot \exp\left(\frac{-y^2}{2 \cdot \sigma_y^2}\right) \quad (1)$$

where x , y , and z describe the position of the receptor relative to the source, z_{source} denotes source height, u is wind speed, and σ_y and σ_z are the horizontal and vertical dispersion parameters. Dispersion parameters were derived from measured meteorological conditions and atmospheric stability classifications.

Following Kumar et al. (2021), the effective wind direction was determined using the coordinates of the maximum observed methane enhancement relative to the emitting facility. This approach improved the agreement between observed and modelled plume geometry and reduced uncertainty associated with local wind variability.

2.4.2 Other Test Method (OTM33A)

The Other Test Method 33A (OTM-33A) is a stationary plume characterization technique developed by the United States Environmental Protection Agency and extensively applied for methane quantification at oil and gas facilities (Brantley et al., 2014; Edie et al., 2020; Omara et al., 2018; Robertson et al., 2017; Robertson et al., 2020; Stavropoulou et al., 2023; Korbeń et al., 2022; Thoma and Squier, 2014).

The method combines high-frequency methane measurements with simultaneous wind observations. Temporal fluctuations in wind direction move the plume across the measurement location, allowing the relationship between plume concentration and atmospheric transport to be reconstructed directly from observations. During the ROMEO-B campaign, methane mole fractions were measured using fast-response analyzers coupled with two- or three-dimensional anemometers operating at matching temporal resolutions.

A total of 34 OTM-33A quantifications were performed at 30 natural gas production facilities. Two high-emitting water-degassing installations were additionally characterized using extended measurement periods. For 14 long-duration deployments, ranging up to approximately two hours, automated analysis was used to evaluate both median emission rates and short-term variability. These observations served as an important benchmark for comparison with other quantification techniques.

2.4.3 Tracer Release Method (TRM)

The Tracer Release Method (TRM), also referred to as the dynamic plume tracer dispersion method, estimates methane emissions by comparing methane enhancements with those of an intentionally released tracer gas (Allen et al., 2013; Ars et al., 2017; Daube et al., 2023; Defratyka et al., 2021; Delre et al., 2022; Lamb et al., 1995; Mønster et al., 2014; Roscioli et al., 2015; Yver Kwok et al., 2015).

The underlying principle is that methane and tracer plumes released in close proximity experience nearly identical atmospheric transport and dispersion. Consequently, the ratio of measured plume enhancements is proportional to the ratio of emission rates:

$$Q_{\text{CH}_4} = Q_{\text{tracer}} \left(\frac{C_{\text{CH}_4}}{C_{\text{tracer}}} \right) \quad (2)$$

where Q_{CH_4} and Q_{tracer} are the methane and a tracer emission rates, respectively, and C_{CH_4} and C_{tracer} are the plume enhancements.

Acetylene (C_2H_2) was used as the tracer gas throughout the campaign. Methane and tracer concentrations were measured simultaneously using a Picarro G2203 cavity ring-down spectrometer. Multiple plume transects were performed downwind of each facility to characterize both gases under comparable transport conditions.

A total of 76 TRM measurements were conducted at natural gas production facilities, with an additional eight measurements performed at auxiliary installations. To ensure reliable plume pairing, only measurements exhibiting strong methane-tracer correlations were retained. Quality control required a coefficient of determination $R^2 > 0.95$. Following this criterion, 62 measurements from 58 locations were retained for further analysis.

Because atmospheric transport effects largely cancel when concentration ratios are used, TRM is generally considered one of the most robust approaches for facility-scale methane quantification (Lamb et al., 1995).

2.4.4 High Flow Sampler (HFS)

High-Flow Sampling (HFS) is a component-level quantification technique designed to directly measure methane emissions from individual leaking elements such as valves, connectors, flanges, and pressure-control equipment. The method is commonly used in leak detection and repair (LDAR) programs and has been extensively applied within the oil and gas sector (Connolly et al., 2019).

Potential emission points were first identified using Optical Gas Imaging (OGI). Individual components exhibiting methane emissions were subsequently enclosed within a sampling bag connected to a Bacharach High Flow Sampler. The instrument actively extracts air from the enclosure and combines measured methane concentrations with air-flow data to derive methane emission rates.

The instrument calculates methane emissions according to:

$$Q_{CH_4} = V(C_s - C_{bckg}) \quad (3)$$

where Q_{CH_4} is the methane emission rate, V is the sampling flow rate, C_s is the methane mole fraction measured within the enclosure, and C_{bckg} is the ambient background concentration.

To evaluate measurement consistency, observations were performed using instrument flow rates of 120 and 170 L min⁻¹. Measurements exhibiting differences greater than 20% between flow settings were excluded from further analysis. In total, 229 individual methane plumes were identified at 164 facilities. Multiple leak sources were observed at 109 sites, whereas no detectable leaks were identified at 55 sites. The largest number of independent leaks observed at a single facility was nine. Emission rates were quantified for 118 individual leaks located at 57 facilities. Of these, 39 facilities were fully quantified and retained for detailed analysis. Seven facilities were revisited during the same day to evaluate short-term temporal variability.



Figure 2. The Sniffers team scanning a site with an infrared camera (right panel) and deploying the HiFlow sampler on a leak (left panel) (Fotos: The Sniffers 2022)

2.4.5 Large-Scale Flow Sampling (LSFC)

To complement established quantification approaches, a novel Large-Scale Flow Chamber (LSFC) was developed and deployed during ROMEO-B. Unlike conventional HFS measurements, which are restricted to individual components, the LSFC enables direct quantification of methane emissions from entire well-site installations.

The chamber consisted of a hemispherical enclosure constructed from transparent polyethylene foil supported by a collapsible PVC frame. The structure had a radius of approximately 3 m and an internal volume of roughly 55 m³. Owing to its lightweight design, the chamber could be assembled or removed in less than one minute, allowing deployment at operational facilities.

During measurements, air within the enclosure was mixed continuously using an internal fan while methane concentrations were monitored in real time. Methane emission rates were derived from the temporal rate of methane accumulation:

$$Q_{CH_4} = \frac{dC}{dt} V \quad (4)$$

where Q_{CH_4} is the emission rate of CH₄, $\frac{dC}{dt}$ is the rate of methane concentration increase inside the chamber, and V is the enclosure volume.

The primary limitation of the approach was a wind-induced “breathing” effect, whereby external pressure fluctuations periodically displaced methane-rich air from the enclosure and replaced it with background air. To minimize associated biases, only periods exhibiting stable and approximately linear concentration accumulation were used for emission-rate determination.

Controlled validation experiments were conducted in Kraków, Poland, using known methane release rates. Measured emissions showed good agreement with reference release rates over the tested range of approximately 24–220 g CH₄ h⁻¹, confirming the applicability of the method. Under field conditions, the LSFC achieved a detection limit of approximately 1.8 g CH₄ h⁻¹.

For safety reasons, the chamber was equipped with a ventilation system that prevented methane concentrations from approaching the lower explosive limit by introducing ambient air whenever methane concentrations exceeded predefined thresholds.

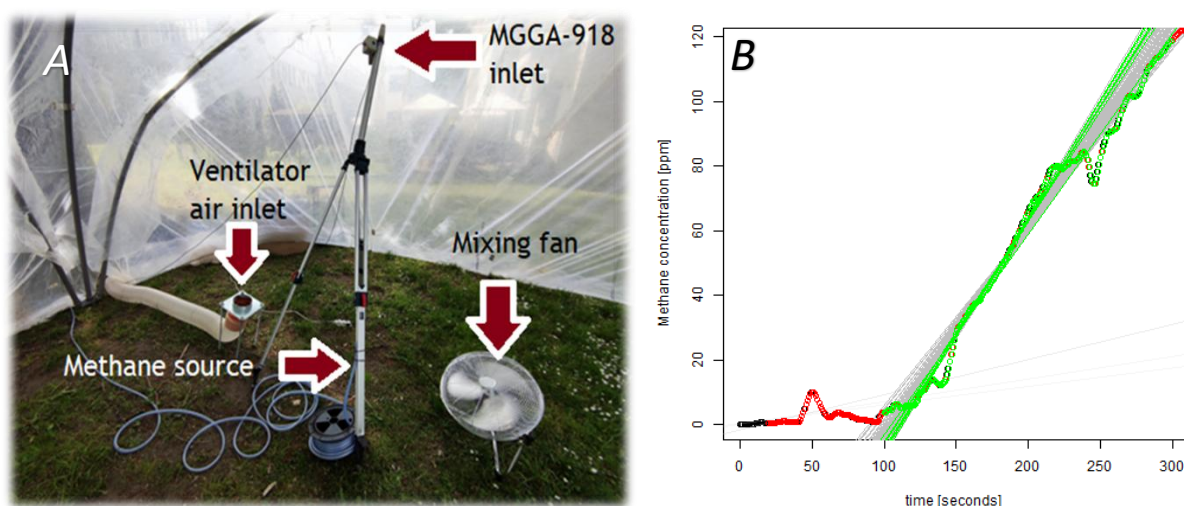


Figure 3. A: Test setup of the LSFC approach with a high flow ventilator air inlet, a controlled CH_4 source and a mixing fan within the chamber enclosure. B: Example of concentration increase inside the chamber. Multiple linear regression lines are fitted (see text). Green lines highlight the 10% of the fits with highest R^2 values. The median value of the slope parameter $\frac{dc}{dt}$ is used to calculate the emission rate according to equation (4).

Validation of the Large-Scale Flux Chamber

Performance of our novel Large-Scale Flux Chamber approach with the LSFC was validated in a controlled experimental settings in Kraków, Poland. Briefly, known amounts of pure CH_4 were steadily released into the chamber to increase the CH_4 concentration in the enclosure volume and estimate the emission rate according to equation (4). The estimated CH_4 emission rates were in agreement with the experimental release rate controlled with a mass flow meter (Fig. 4).

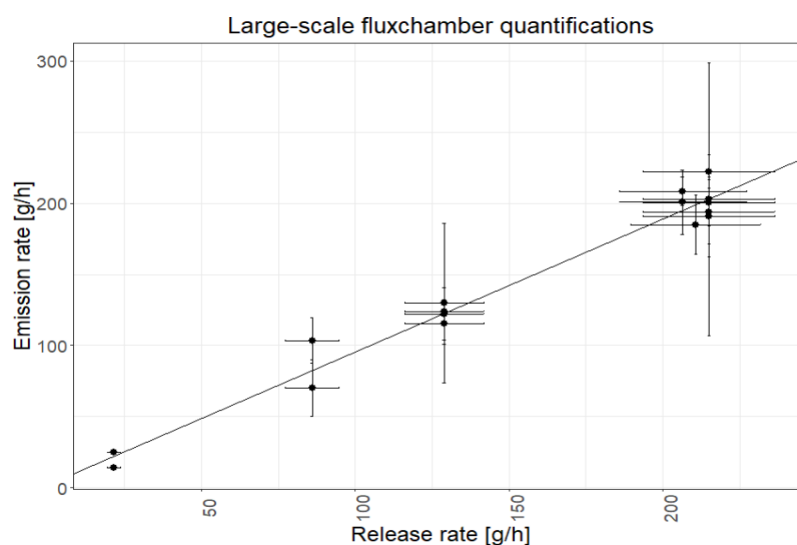


Figure 4: Results of release tests using the large-scale flux chamber. The chamber was tested for low release rates between 24 g/h and 220 g/h.

The chamber itself was equipped with safety ventilator that delivered the external air to the chamber and excluded the possibility of methane concentration rising above the lower explosion limit. This

decreases the chamber sensitivity somewhat but is an necessary safety precaution. This ventilator can be switched on (>100 ppm) and off (<100 ppm) depending on the instantaneous methane levels inside the “tent” and if the concentration inside the chamber is rising very slowly, not reaching values above 100 ppm its usage is not necessary.

2.4.6 Optical Gas Imaging (OGI)

Optical Gas Imaging was used as a rapid screening tool for locating methane emission sources and characterizing emission activity at production facilities (Lyman et al., 2019). The method was not used for direct quantification of methane emissions but provided essential information regarding the occurrence and spatial distribution of leaks.

A total of 171 well sites were inspected using OGI. Approximately 32% of surveyed facilities exhibited no detectable methane emissions. Across all surveyed sites, 208 individual leak sources were identified, corresponding to an average of 1.2 emitting components per facility. Of these, 124 leaks were subsequently quantified using one or more quantitative measurement techniques.

These observations provided an independent estimate of leak prevalence and supported basin-scale extrapolation of quantified emissions.

2.4.7 Screening surveys

In addition to the dedicated quantification approaches described in sections above, we have taken snapshots of emissions from a larger fraction facilities hereafter referred as “screening”. This effort involved single instantaneous measurements for each facility from a mobile vehicle equipped with the methane sensor but without precise characterization of associated meteorological conditions needed for robust plume quantification.

The screening was used to identify leaks requiring immediate maintenance but also for selecting wellheads and other parts of the gas production and transportation system which release relatively large quantities of. when a large number of installations are included in a mobile survey, the resulting distribution, despite method limitation, still likely represents a realistic emission distribution across sites/facilities (see Chen et al., 2025).

Several assumptions were used to convert the highest recorded CH₄ mole fraction (in ppm) found near the wellheads into the emission (g/h). Firstly, we assumed a wind speed of 2.5 m/s as averaged value during the survey. Secondly, we assumed a constant atmospheric stability that is Pasquill’s class B (Pasquill, 1975), as most appropriate given the prevailing meteorological condition during the campaign and we used neighboring stability classes to potentially range of emission values representing uncertainty.

The CH₄ enhancement attribution to a particular well or other gas infrastructure was based on the distance between the site and the route of the vehicle with methane sensor. Whenever the analyzer recorded an enhanced CH₄ mole fraction while passing by gas installation at a distance < 50 m, a Gaussian peak was fit to the spatial distribution of the observed CH₄ mole fraction. This was done using a new peak search algorithm described in Stavropoulou et al. (2023). Each identified peak was assigned to the most likely source from the inventory provided by the operator..

The instantaneous plume encountered during a single pass-by is generally sharper, and thus higher, than an average Gaussian plume as used in the Gaussian plume model, for which the dispersion parameters are assumed to be 60-minute averages. To account for that effect we scaled the maximum

amplitude of a Gaussian fit to the observed CH₄ mole fraction using the square root of the observation time scale relative to the GPM time scale ($t_{peak} = 60$ s for a single peak transect relative to $t_{GPM} = 3600$ s in the GPM approach):

$$C_{mod} = C_{max} \left(\frac{t_{peak}}{t_{GPM}} \right)^{-\frac{1}{2}} = C_{max} \left(\frac{60s}{3600s} \right)^{-\frac{1}{2}} = C_{max} \cdot 0.13 \quad (5)$$

The modified C_{mod} was then used in a simplified Gaussian plume equation to derive a rough estimate of the emission rate Q_{est} according to

$$Q_{est} = 2k \pi u \sigma_y(x_0) \sigma_z(x_0) C_{mod}(x_0, 0, 0) \quad (6)$$

Where, k is a constant to convert units, u represents the assumed wind speed (2.5 m/s), $\sigma_y(x_0)$ and $\sigma_z(x_0)$ are the dispersion coefficients of the Gaussian plume for atmospheric conditions met during the measurements as estimated using equation (6) according to (Hanna et al., 1982):

$$\sigma_i(x) = e^{(A_i + B_i \ln(x_0) + C_i (\ln(x_0))^2)} \quad (7)$$

Where A_i , B_i and C_i are quantized coefficients related to Pasquill classes of atmospheric stability and indexed as y or z coordinate. The x_0 refers to the distance between the plume center and the wellhead. All routes of four active measurement vehicles during the campaign passed within a distance closer than 50 m to 852 wellheads and other potential known sources of CH₄. The Gaussian fits were quality checked (using the Shapiro-Wilk test) and 443 out of 852 fits from the screening were accepted with, the mean value used for site where more than one snapshot measurement was taken.

2.5 Data quality and inter-method comparison

Given the diversity of measurement approaches employed during the ROMEO-B campaign, a comprehensive quality assurance and quality control (QA/QC) framework was implemented to ensure consistency, comparability, and robustness of methane emission estimates. Method-specific acceptance criteria were applied prior to further analysis, and measurements failing predefined quality standards were excluded from the final dataset.

For the Tracer Release Method (TRM), only observations exhibiting a strong linear relationship between methane and tracer-gas enhancements were retained. A coefficient of determination of $R^2 > 0.95$ was required to ensure that methane and tracer plumes experienced comparable atmospheric transport and dispersion. Measurements failing to meet this criterion were discarded. As a result, 62 of the 76 well-site TRM measurements passed quality control and were retained for further analysis.

For High-Flow Sampling (HFS), measurement repeatability was assessed by quantifying emissions at two different instrument flow settings (120 and 170 L min⁻¹). Measurements exhibiting discrepancies greater than 20% between the two flow rates were considered unreliable and excluded from further analysis. In addition, only facilities for which all identified leaks could be quantified were classified as fully characterized and used in site-level assessments.

For OTM-33A measurements, raw concentration and meteorological data were screened for periods exhibiting stable instrument operation and sufficient variability in wind direction required for plume reconstruction. Long-duration measurements were processed automatically to derive median

emission rates and associated short-term variability. Where multiple OTM estimates were available for a single facility, median values were used in subsequent analyses.

470 For Gaussian Plume Method (GPM) measurements, quality control focused on plume identification and model performance. Measurements affected by rapidly changing wind directions, insufficient plume contrast relative to background concentrations, or poorly constrained source locations were excluded. Multiple downwind transects were performed whenever possible to improve the robustness of fitted plume parameters.

475 The Large-Scale Flow Chamber (LSFC) approach required additional screening because concentrations within the enclosure could be affected by wind-induced pressure fluctuations. Only periods characterized by approximately linear methane accumulation were retained for emission-rate calculations. To minimize the influence of the chamber "breathing effect", emission rates were derived from multiple regression windows and only the highest-quality fits were retained. Validation
480 experiments conducted under controlled-release conditions confirmed the accuracy of the approach across the tested range of methane emission rates.

Quality control for screening measurements focused on the statistical validity of identified methane plumes. Gaussian functions were fitted to observed concentration enhancements and evaluated using standard goodness-of-fit criteria. Fits failing the Shapiro-Wilk test or exhibiting unrealistic plume
485 characteristics were rejected. Of the 852 potential methane sources surveyed during screening campaigns, 443 observations satisfied all quality-control requirements and were retained for analysis.

To evaluate methodological consistency, a subset of facilities was measured repeatedly using either the same technique or multiple independent techniques. These repeated observations provided insight into both methodological uncertainty and short-term temporal variability of methane
490 emissions. Where multiple valid quantifications were available for a facility, emissions were compared across methods and used to identify systematic biases or differences in detection capability.

The resulting quality-controlled dataset forms the basis for all subsequent analyses, including the derivation of representative methane emission factors, characterization of emission distributions, and basin-scale upscaling of methane emissions from natural gas production infrastructure in the
495 Transylvanian Basin.

No single measurement technique is capable of fully characterizing methane emissions across the broad range of source types and emission magnitudes encountered within natural gas production systems. Consequently, the ROMEO-B campaign combined multiple complementary approaches operating at different spatial scales and with different detection capabilities. Table 2 summarizes the
500 principal characteristics of the applied methods, including their measurement objectives, spatial scales, observational coverage, strengths, and limitations. The integration of these approaches allowed both detailed source-level characterization and the development of representative basin-scale emission estimates.

Table 2: Comparison of the basic characteristics of the applied methods.

Method	Spatial scale	Primary objective	No. of measurements	Relative sensitivity	Main strengths	Principal limitations
Tracer Release Method (TRM)	Facility	Direct emission quantification	62 accepted measurements at 58 locations	High	Minimizes atmospheric transport uncertainties; robust facility-scale emission estimates	Requires tracer gas deployment, additional instrumentation, and favorable meteorological conditions
Other Test Method 33A (OTM-33A)	Facility	Direct emission quantification	34 measurements at 30 facilities	Moderate	Widely accepted methodology; accounts for local wind variability	Requires long measurement periods and reliable wind characterization
Gaussian Plume Method (GPM)	Facility	Direct emission quantification	Multiple plume transects at selected facilities	Moderate	Rapid deployment; suitable for mobile surveys	Strong dependence on atmospheric transport assumptions and plume structure
High-Flow Sampling (HFS)	Component	Leak quantification	118 quantified leaks at 57 facilities	High	Direct measurement of individual leak rates; well-established method	Applicable only to accessible components that can be enclosed
Large-Scale Flow Chamber (LSFC)	Entire well site	Whole-site emission quantification	Site-specific deployments	Very high	Direct measurement of total site emissions; exceptionally low detection limit ($\sim 1.8 \text{ g CH}_4 \text{ h}^{-1}$)	Labor intensive; sensitive to wind-induced chamber disturbances
Optical Gas Imaging (OGI)	Component	Leak detection and source identification	171 surveyed well sites	Moderate	Rapid identification of emission sources;	Does not provide quantitative emission rates

<i>Method</i>	<i>Spatial scale</i>	<i>Primary objective</i>	<i>No. of measurements</i>	<i>Relative sensitivity</i>	<i>Main strengths</i>	<i>Principal limitations</i>
					supports HFS deployment	
Screening surveys	Basin-wide	Source screening and emission distribution characterization	443 accepted observations from 852 surveyed facilities	Low to moderate	Fast characterization of large infrastructure populations; supports upscaling analyses	High uncertainty; simplified meteorological assumptions

The applied methods were intentionally selected to provide complementary information across multiple spatial scales. While HFS and OGI focused on individual emission sources, TRM, OTM-33A, GPM and LSFC enabled facility-scale quantification. Screening measurements extended the spatial coverage of the campaign and supported basin-scale interpretation of measurement results. The integration of these methods allowed both detailed source characterization and the derivation of representative emission factors for subsequent regional upscaling.

2.6 Statistical analysis and emission-factor derivation

Methane emissions from natural gas production facilities are often characterized by highly skewed distributions, with a relatively small number of facilities contributing disproportionately to total emissions (Brandt et al., 2014; Alvarez et al., 2018; Zavala-Araiza et al., 2017; Stavropoulou et al., 2023). Consistent with previous studies, site-level methane emission rates obtained during the ROMEO-B campaign were therefore analysed in logarithmic space and described using log-normal distributions (Alvarez et al., 2018; Robertson et al., 2020; Zavala-Araiza et al., 2015; Zavala-Araiza et al., 2018; Stavropoulou et al., 2023).

For each measurement approach, a normal distribution was fitted to the logarithm of the observed emission rates. The resulting parameters μ and σ represent the mean and standard deviation of the log-transformed data, respectively. These parameters were subsequently used to derive representative methane emission factors according to the statistical estimator approach commonly applied in methane-emission studies:

$$EF = \exp(\mu + 0.5\sigma^2) \quad (8)$$

where EF denotes the expected value of the corresponding log-normal distribution. Emission factors were derived separately for each quantification approach and for the combined dataset. The combined analysis included all site-level methane emission estimates obtained using the Tracer Release Method (TRM), High-Flow Sampling (HFS), Other Test Method 33A (OTM-33A), and Gaussian Plume Method (GPM). Measurements obtained with the Large-Scale Flow Chamber (LSFC)

were not included in the combined analysis because the deployment strategy intentionally targeted low-emitting facilities and therefore did not provide a representative sample of the overall well-site population.

Where repeated measurements were available, all valid emission estimates were retained in the statistical analysis to account for temporal variability observed at the facility level. The suitability of the log-normal representation was evaluated using both graphical inspection and formal statistical tests, where applicable.

Uncertainties associated with the derived emission factors are reported as 95% confidence intervals. These emission factors were subsequently used to estimate methane emissions from natural gas production facilities across the Transylvanian Basin.

3. Results

3.1 Pre-campaign

A pilot survey was conducted prior to the ROMEO-B campaign to evaluate methane occurrence across the Transylvanian Basin and to support the design of the main measurement activities. Five natural gas production clusters comprising approximately 50 well sites were visited during this preliminary phase.

Methane enhancements were detected at all surveyed production areas. Measured methane mole fractions at facility boundaries typically ranged from background levels to 300–400 ppm above ambient concentrations, while several sites exhibited enhancements reaching 1,000–2,000 ppm. Measurements performed directly at leaking components, such as valves and fittings, revealed methane concentrations of up to 30,000 ppm.

These observations confirmed the widespread occurrence of methane emissions throughout the surveyed infrastructure network and demonstrated the suitability of the selected facilities for detailed quantitative investigations. The pre-campaign survey was further used to optimize measurement protocols, select appropriate quantification techniques, and refine field deployment strategies for the main ROMEO-B campaign.

3.2. Method-specific emission quantifications

During the ROMEO-B campaign, 520 of the 2,804 natural gas production facilities listed in the operator inventory were visited, corresponding to approximately 18% of the infrastructure population within the Transylvanian Basin. A total of 160 methane emission quantifications were performed at 127 individual facilities using five complementary quantification approaches (Fig. 1). Together, these measurements provide the first basin-scale, measurement-based characterization of methane emissions from Romanian natural gas production infrastructure.

Summary statistics of the methane emission quantifications are presented in Table 3, whereas Figure 5 illustrates the corresponding emission distributions and fitted log-normal functions. Panels A–E show results obtained using individual measurement approaches, while panel F compares all datasets and presents the combined emission distribution used in subsequent analyses. Because methane emissions span several orders of magnitude, all distributions are shown on a logarithmic scale.

TRM quantifications ($n = 62$; Fig. 5D) exhibited a log-normal emission distribution with site-level methane emission rates ranging from 0.03 to 26 kg CH₄ h⁻¹. The arithmetic mean and median emission

rates were 1.3 and 0.5 kg CH₄ h⁻¹, respectively (Table 3). Most facilities exhibited relatively low emissions, while a limited number of high-emitting sites formed the upper tail of the distribution.

HFS quantifications were available for 39 fully characterized facilities following source identification using OGI surveys (Fig. 5B). A total of 118 individual leaks were quantified, with component-level methane emission rates ranging from 0.01 to 7.7 kg CH₄ h⁻¹ (Fig. A2). When aggregated to the facility level, methane emissions ranged from 0.04 to 7.9 kg CH₄ h⁻¹, with a mean and median of 1.4 and 0.5 kg CH₄ h⁻¹, respectively (Table 3). Although the resulting distribution visually resembles a log-normal function, the Shapiro–Wilk test rejected strict log-normality at the 5% significance level, indicating deviations from a simple statistical form.

OTM-33A quantifications comprised 34 measurements at 30 facilities (Fig. 5C). Estimated methane emission rates ranged from 0.02 to 78 kg CH₄ h⁻¹, with a mean of 3.3 kg CH₄ h⁻¹ and a median of 0.3 kg CH₄ h⁻¹ (Table 3). The resulting distribution broadly followed a log-normal pattern but exhibited indications of bimodality, potentially reflecting differences in facility type or operating conditions.

GPM quantifications (n = 13) yielded methane emission rates between 0.007 and 45 kg CH₄ h⁻¹ (Fig. 5D). The corresponding mean and median emission rates were 5.7 and 1.4 kg CH₄ h⁻¹, respectively (Table 3). Although based on the smallest dataset, the observed distribution was broadly consistent with those derived from the other facility-scale quantification approaches. However, GPM was generally applied to facilities exhibiting clearly detectable methane plumes and therefore preferentially sampled the upper portion of the emission distribution.

LSFC quantifications were successfully performed at 12 facilities (Fig. 5E), yielding methane emission rates ranging from 0.0018 to 1.5 kg CH₄ h⁻¹. The mean and median emission rates were 0.3 and 0.1 kg CH₄ h⁻¹, respectively (Table 3). Notably, the lowest-emitting facility identified during the campaign was detected exclusively by the LSFC approach and remained below the practical detection limits of all other deployed techniques. The corresponding methane emission rate of 0.0018 kg CH₄ h⁻¹ is equivalent to approximately 16 kg CH₄ yr⁻¹. Once enclosed within the chamber, methane mole fractions increased by only approximately 5 ppm above ambient levels, illustrating the exceptional sensitivity of the LSFC approach for quantifying very small methane emissions.

Because LSFC deployments intentionally targeted facilities expected to exhibit relatively low methane emissions in order to ensure safe chamber operation, the resulting dataset is affected by a deliberate low-emission sampling bias. Consequently, LSFC quantifications were not included in the derivation of representative basin-scale emission factors. Nevertheless, the successful deployment of the LSFC demonstrates its potential for quantifying emissions substantially below the practical detection limits of conventional facility-scale methods.

Overall, all quantification approaches revealed strongly skewed emission distributions characterized by a predominance of low-emitting facilities and a small number of substantially larger emitters. Despite differences in sampling strategy, spatial scale, and detection capability, the individual datasets exhibited broadly comparable distributional characteristics, supporting their combined use in the subsequent derivation of representative emission factors for the Transylvanian Basin.

Table 3: Summary statistics of methane emission quantifications obtained using different measurement approaches during the ROMEO-B campaign..

Method	# Measurements	Emission rate range [kg/h]	Mean [kg/h]	Median [kg/h]
TRM	62	0.03 – 26	1.3	0.5
OTM-33A	34	0.02 – 78	3.3	0.3
HFS	39	0.04 – 7.9	1.4	0.5
GPM	13	0.007 – 45	5.7	1.4
LSFC	12	0.002 – 1.5	0.3	0.1

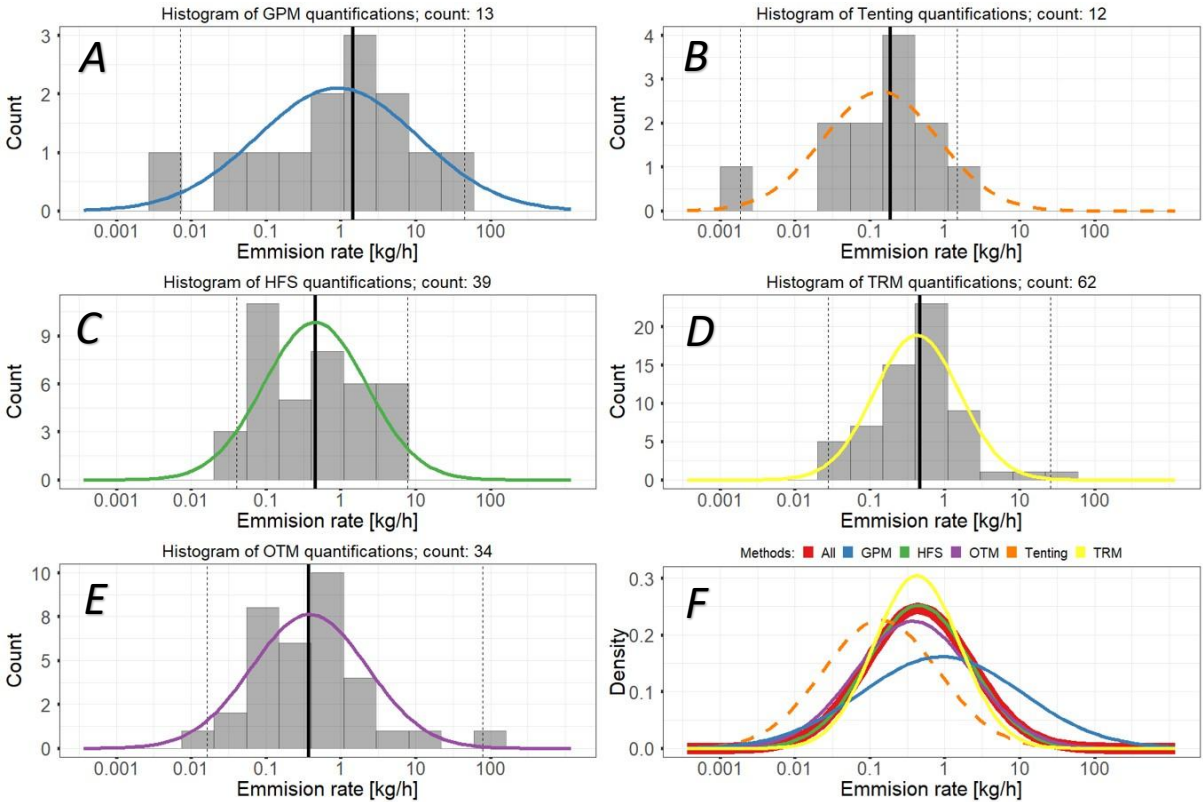


Figure 5. Site-level methane emission distributions derived using the different quantification approaches applied during the ROMEO-B campaign: (A) Gaussian Plume Method (GPM), (B) High-Flow Sampling (HFS), (C) Other Test Method 33A (OTM-33A), (D) Tracer Release Method (TRM), (E) Large-Scale Flow Chamber (LSFC), and (F) comparison of all quantification methods. Histograms show measured methane emission rates, whereas solid curves represent fitted log-normal distributions. The vertical dashed lines indicate the minimum, mean, and maximum emission rates observed within each dataset. Note the logarithmic x-axis, reflecting the highly skewed nature of methane emissions across natural gas production facilities.

3.3 Repeatability and temporal variability of emissions

Repeated methane emission quantifications were available for 33 facilities, providing an opportunity to evaluate both methodological consistency and short-term temporal variability in emissions. Repeated measurements were performed either using the same quantification approach or by applying multiple independent methods to the same facility. The results are summarized in Figure 6.

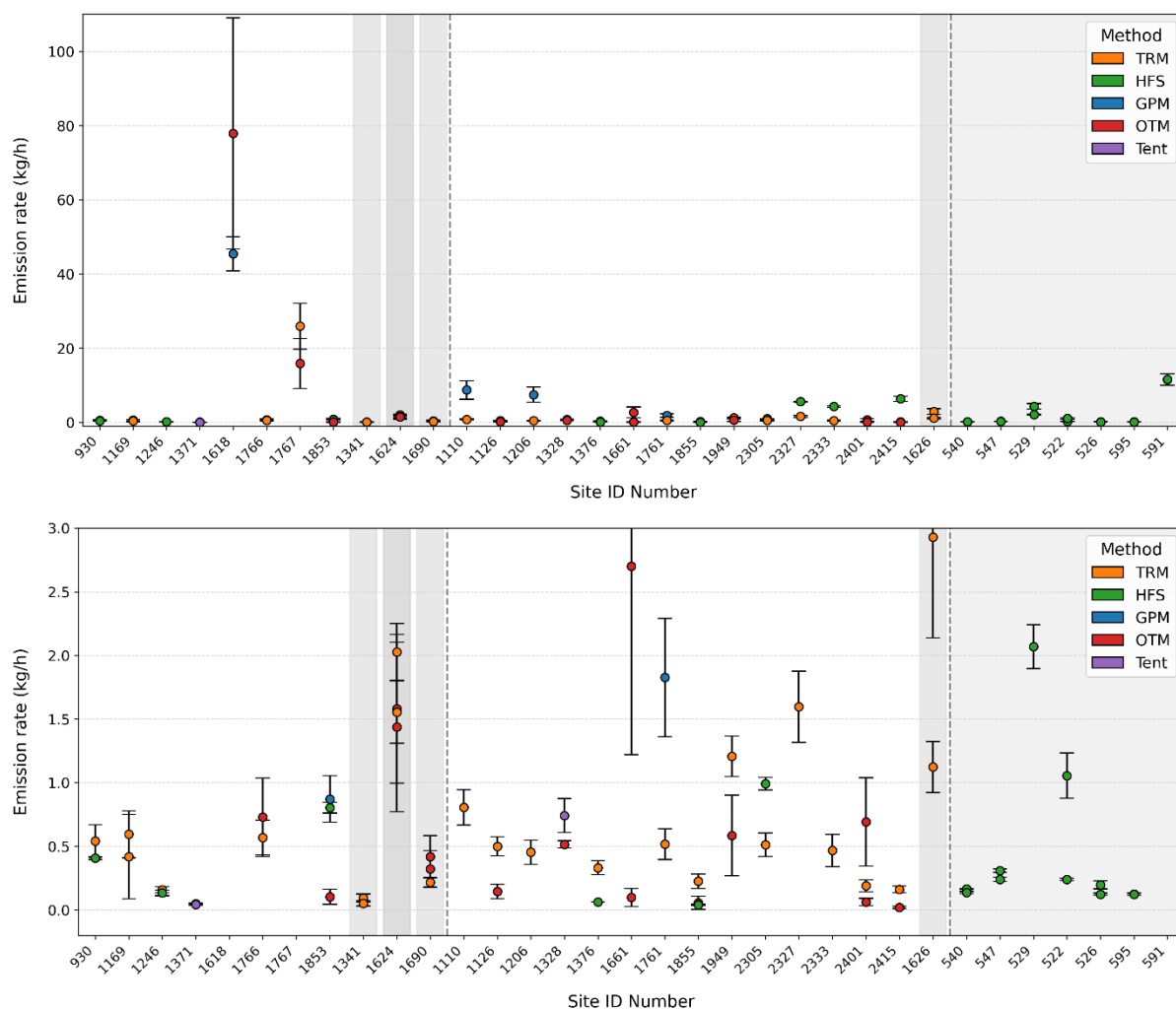


Figure 6. Comparison of repeated methane emission quantifications at 33 natural gas production facilities. Colours indicate the quantification approach used, as listed in the legend. The upper panel shows the complete emission range, whereas the lower panel expands the range between 0 and 3 kg CH₄ h⁻¹. Facilities to the left of the first dashed line include at least two emission estimates that agree within their combined uncertainties. Facilities located between the dashed lines exhibit mutually inconsistent repeated estimates. Grey shading highlights facilities for which repeated measurements were performed on the same day, including repeated HFS quantifications and same-day applications of other methods.

To facilitate interpretation, facilities were grouped into three categories: (i) sites for which at least two repeated emission estimates agreed within their combined uncertainties, (ii) sites for which all repeated estimates were mutually inconsistent, and (iii) facilities measured repeatedly on the same

day using the HFS approach. Despite the short time intervals involved, only four of the seven facilities quantified twice on the same day using HFS yielded consistent results within uncertainty bounds, suggesting that both method sensitivity and short-term emission variability contribute to differences between repeated observations.

Variations in production rates and operational conditions can influence methane emissions from natural gas facilities. However, large changes in production are unlikely over the relatively short time intervals separating most repeated measurements in this study. In the absence of documented maintenance activities, equipment replacements, or accidental failures, we consider a factor-of-three change in emission rate to represent a reasonable estimate of short-term variability at the facility scale.

Under this assumption, a number of repeated quantifications can be considered consistent. For example, repeated TRM measurements at facilities #1169, #1341, and #1624, as well as repeated OTM-33A measurements at facilities #1624 and #1690, agree within the combined effects of measurement uncertainty and expected temporal variability. These observations support the robustness of the applied quantification methods under relatively stable operating conditions.

However, many facilities exhibited substantially larger differences. For instance, repeated TRM measurements at facility #1626 indicate an approximate doubling of the methane emission rate between visits, while estimates obtained at facility #2401 differ by more than one order of magnitude. Similarly, measurements performed eight days apart at facility #1661 yielded strongly divergent emission rates, suggesting the occurrence of intermittent high-emission events or rapidly changing leak conditions.

Overall, only 13 of the 33 repeatedly quantified facilities exhibited agreement among repeated measurements, while differences exceeding one order of magnitude were observed at numerous sites. These discrepancies cannot be fully explained by methodological uncertainty alone and instead indicate that methane emissions from natural gas production facilities are highly dynamic. Significant variability is observed across a broad range of emission magnitudes and appears to occur on timescales ranging from hours to days.

The observed temporal variability has important implications for methane-emission characterization. Single measurements may not always provide representative estimates of long-term facility emissions, particularly for sites experiencing intermittent releases. Consequently, repeated measurements and sufficiently large sample sizes are essential for developing representative regional emission factors and reducing uncertainties associated with basin-scale emission estimates.

3.4 Screening observations

Mobile screening surveys identified methane enhancements associated with 520 natural gas production facilities across the Transylvanian Basin. In total, 852 methane enhancements were detected using the automated plume-identification algorithm, with some facilities characterized repeatedly and up to 35 observations available for individual sites. Following quality-control procedures described in Section 2.5, 443 screening observations were retained for further analysis (Fig. A5). Methane emission rates inferred from the screening observations follow a broadly log-normal distribution (Fig. 7A), consistent with the distributions obtained using dedicated quantification methods. The mean emission rate derived from the screening dataset is comparable to the mean emission rate obtained from direct facility-scale quantifications. However, the screening-derived distribution spans a substantially wider range of emission rates and exhibits a more pronounced upper tail than the distributions obtained from the dedicated quantification approaches.

This behavior is expected given the intrinsic characteristics of the screening approach. Mobile screening preferentially detects moderate and large methane plumes while exhibiting reduced sensitivity toward low-emitting facilities. Consequently, the resulting distribution is shifted toward higher emission rates and does not represent the true facility population without additional corrections.

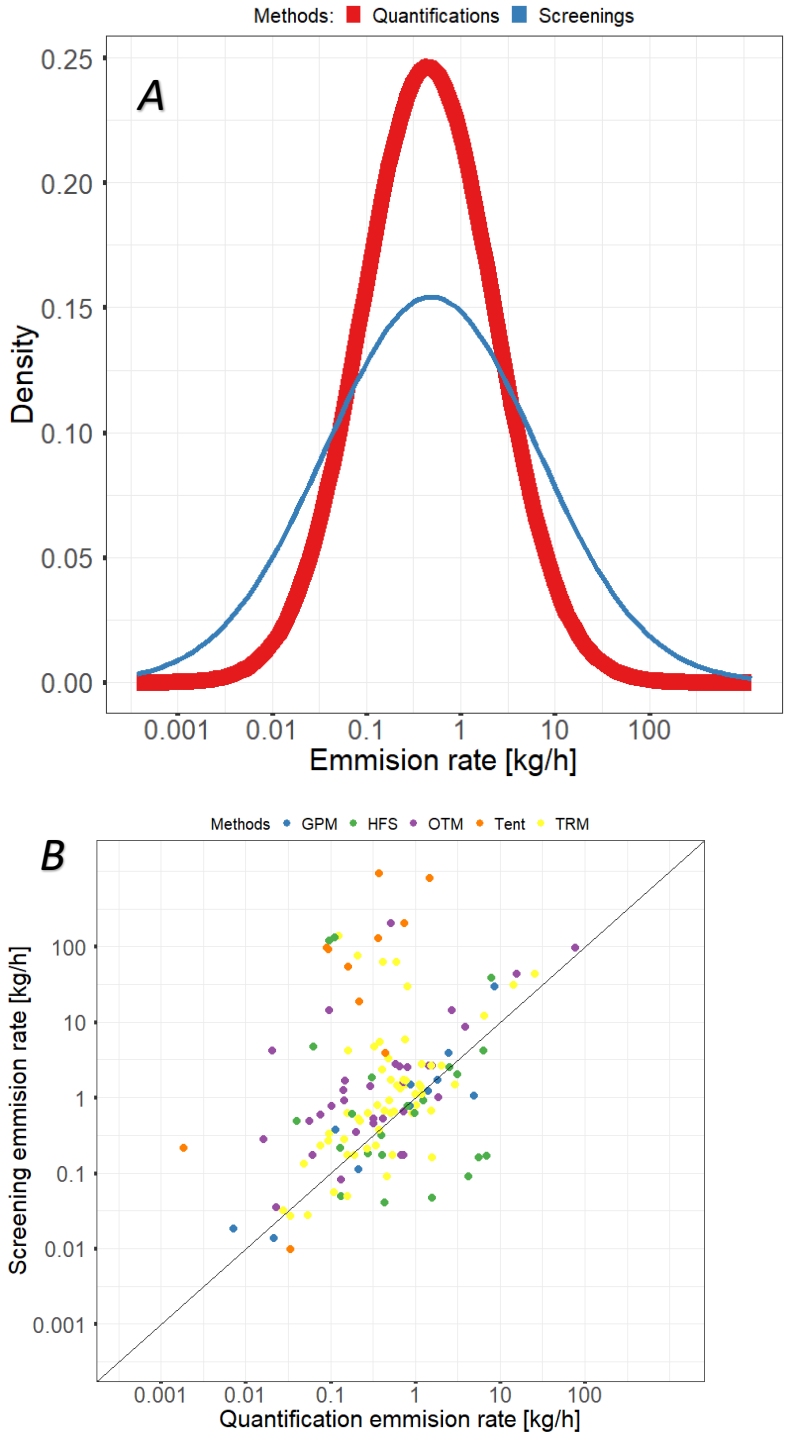


Figure 7. (A) Methane emission-rate distributions derived from mobile screening observations (blue dashed line) and direct quantification methods (red line). (B) Comparison between emission-rate

estimates obtained from screening observations and dedicated quantification approaches. The black line indicates the 1:1 relationship. Both axes are logarithmic.

710 Comparison of emission rates obtained from screening observations and direct quantification methods shows a broadly positive relationship (Fig. 7B). In general, screening-derived emission estimates follow the 1:1 relationship reasonably well, despite substantial scatter. Because both axes are shown on logarithmic scales, apparent proximity to the 1:1 line can still correspond to differences approaching an order of magnitude.

715 Several pronounced outliers are evident in the comparison. In these cases, screening-derived emission rates exceed corresponding direct quantifications by more than two orders of magnitude and frequently surpass 100 kg CH₄ h⁻¹. Such discrepancies likely result from plume interference, overlapping emissions from nearby infrastructure, or incorrect source attribution during mobile surveys. This interpretation is supported by several LSFC-targeted facilities that appear among the
720 most extreme outliers. Because LSFC deployments intentionally targeted low-emitting facilities, the large screening-derived emission estimates observed at these locations are unlikely to originate from the enclosed installations themselves and instead probably reflect emissions from nearby sources.

Additional uncertainty arises from methodological assumptions used in the screening analysis. Wind variability was not explicitly resolved for individual observations, although plume transport and
725 dispersion depend strongly on wind speed and atmospheric stability. Furthermore, the quality-control procedure preferentially rejected observations associated with the lowest inferred emission rates, which may further contribute to an overrepresentation of higher-emitting facilities within the accepted dataset.

Despite these limitations, screening surveys provide valuable information on methane emissions at
730 the basin scale. Their principal strength lies in the ability to rapidly characterize large numbers of facilities and capture the upper tail of the emission distribution, which often contributes disproportionately to total methane emissions. Consequently, screening observations are particularly useful for identifying potential super-emitters, evaluating the representativeness of quantified facilities, and supporting regional upscaling efforts when interpreted together with direct
735 quantification measurements.

3.5 Super emitters (emission > 100 kg/h)

The highest methane emissions observed during the ROMEO-B campaign did not originate from natural gas production wellheads but from two water-degassing tanks associated with gas-processing
740 infrastructure. These facilities were not included in the operator's well-site inventory and were identified through elevated methane enhancements detected during mobile surveys, followed by direct on-site inspection (Fig. 8A).

Both facilities generated methane plumes substantially larger than those associated with individual well sites. Subsequent quantification using the Tracer Release Method (TRM) confirmed that the tanks
745 represent super-emitters, with methane emission rates of 146 ± 58 kg CH₄ h⁻¹ and 310 ± 120 kg CH₄ h⁻¹, respectively. These emission rates exceed those measured at any individual natural gas production

facility during the campaign and are more than one order of magnitude larger than the highest emissions observed at well sites.

One of the super-emitters was additionally characterized using OTM-33A. Measurements conducted approximately 79 m downwind of the source recorded methane enhancements exceeding 500 ppm above background concentrations (Fig. 8B), resulting in an independent emission estimate consistent with the TRM quantification. Such methane enhancements were among the largest observed during the entire campaign.

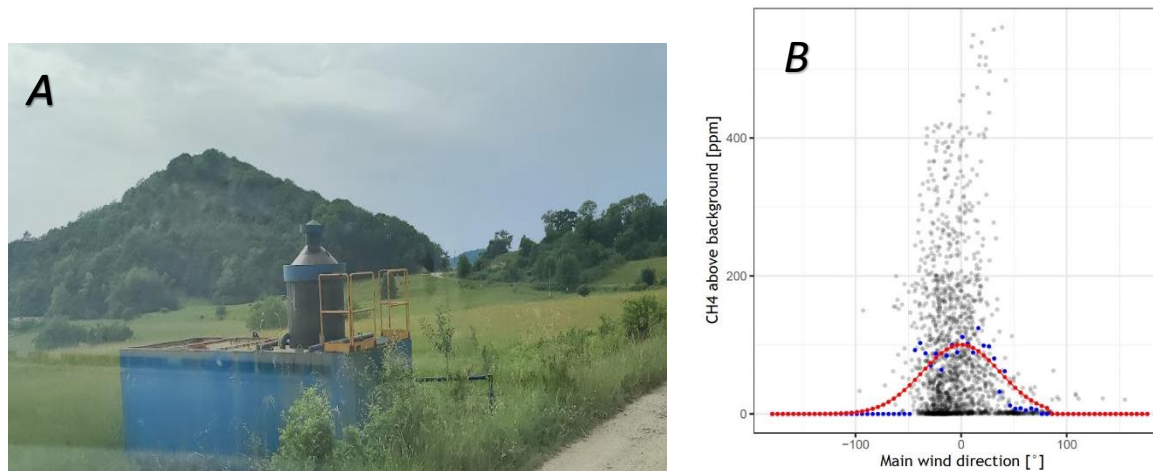


Figure 8. Super-emitting water-degassing facility identified during the ROMEO-B campaign. (A) One of the two degassing tanks responsible for the highest methane emissions observed in the study area. (B) Example of OTM-33A measurements performed approximately 79 m downwind from the source. Black points represent raw methane observations, blue points show 5° wind-direction bins, and the red line indicates the fitted model. Methane enhancements exceeding 500 ppm above background resulted in an estimated emission rate of $310 \pm 120 \text{ kg CH}_4 \text{ h}^{-1}$.

Remarkably, the combined methane emissions from the two identified super-emitters exceeded the sum of emissions measured from all 127 quantified natural gas production facilities. This finding highlights the disproportionate influence that a small number of high-emitting facilities can exert on regional methane budgets. Although these sources are not representative of the broader facility population, their contribution to total methane emissions is large enough to significantly affect basin-scale emission estimates if they are omitted from inventories or measurement campaigns.

The identification of these facilities further demonstrates the value of combining mobile screening surveys with targeted quantification approaches. While dedicated site-level measurements provide representative emission factors for the general facility population, mobile surveys are particularly effective at detecting rare, high-emitting sources that dominate total emissions. Consequently, comprehensive methane monitoring strategies should incorporate both approaches to accurately characterize regional methane emissions.

3.6 Derivation of representative site-level emission factors

To derive a representative methane emission factor for natural gas production facilities in the Transylvanian Basin, site-level methane emission estimates obtained using the different quantification

approaches were combined and analysed using the statistical framework described in Section 2.6. The resulting distribution of all accepted facility-scale measurements is shown in Figure 5F.

The combined dataset exhibits a strongly skewed distribution that is well approximated by a log-normal function. Consistent with previous studies of methane emissions from oil and gas production systems (Alvarez et al., 2018; Robertson et al., 2020; Stavropoulou et al., 2023; Zavala-Araiza et al., 2015; Zavala-Araiza et al., 2018), a Gaussian distribution was fitted to the logarithm of the measured emission rates. The fitted parameters were subsequently used to derive a representative site-level methane emission factor according to the statistical estimator approach described in Section 2.6.

Using the combined dataset, a representative methane emission factor of $1.7 \text{ kg CH}_4 \text{ h}^{-1} \text{ site}^{-1}$ was obtained, with a 95% confidence interval of $1.1\text{--}2.6 \text{ kg CH}_4 \text{ h}^{-1} \text{ site}^{-1}$. This value represents the expected methane emission rate of a natural gas production facility within the Transylvanian Basin and forms the basis for the regional upscaling analysis presented below.

Measurements obtained with the LSFC approach were excluded from the derivation of the representative emission factor because site selection for LSFC deployments intentionally targeted facilities expected to exhibit low methane emissions. Including these measurements would therefore introduce a systematic low-emission bias and distort the resulting population-level emission distribution.

Inspection of the individual datasets (Fig. 5A–F) indicates that emission estimates derived using GPM are generally higher than those obtained using the other facility-scale quantification approaches. This behavior is expected because GPM was primarily applied to facilities exhibiting clearly detectable methane plumes and therefore preferentially sampled the upper tail of the emission distribution. To evaluate the potential influence of this sampling bias, the statistical estimator was recalculated after excluding all GPM quantifications from the combined dataset.

Under this alternative scenario, the resulting emission factor decreased from 1.7 to $1.4 \text{ kg CH}_4 \text{ h}^{-1} \text{ site}^{-1}$, with a corresponding 95% confidence interval of $0.9\text{--}2.0 \text{ kg CH}_4 \text{ h}^{-1} \text{ site}^{-1}$. The relatively small change in the derived emission factor indicates that the overall estimate is robust and not strongly controlled by the comparatively small number of high-emission GPM observations.

Table 4 summarizes the fitted log-normal parameters, detection limits, and representative emission factors obtained for each quantification approach. Considerable differences are observed among methods, reflecting differences in sampling strategy, detection capability, and sensitivity to different parts of the emission distribution. Nevertheless, the method-specific emission factors generally fall within overlapping uncertainty ranges and collectively support the combined estimate.

Table 4. Parameters of the fitted log-normal distributions and corresponding methane emission factors derived for each quantification approach. EF denotes the expected value of the fitted log-normal distribution. The “Total” row represents the combined dataset used for regional upscaling.

Method	DL [kg/h]	μ	σ	EF (kg h^{-1} per site)	95% CI
TRM	0.07	-0.86	1.32	1.0	0.6 – 1.6
HFS	0.06	-0.83	1.64	1.7	0.8 – 4.0
OTM-33A	0.11	-1.11	1.87	1.9	0.6 – 6.9
GPM	0.11	0.07	2.10	9.7	1.5 – 122
Total	-	-0.82	1.63	1.7	1.1 – 2.6

Overall, the similarity of the fitted emission distributions and the limited sensitivity of the combined estimate to the exclusion of individual methods suggest that the derived emission factor provides a robust representation of methane emissions from natural gas production facilities in the Transylvanian Basin.

3.7 Basin scale methane emissions

The representative methane emission factor derived in Section 3.6 was used to estimate methane emissions from natural gas production facilities across the Transylvanian Basin. By multiplying the site-level emission factor of $1.7 \text{ kg CH}_4 \text{ h}^{-1} \text{ site}^{-1}$ by the total number of gas-production facilities listed in the operator inventory (2,804 facilities in 2021), methane emissions from well sites within the basin were estimated at approximately $42 \text{ kt CH}_4 \text{ yr}^{-1}$, with a 95% confidence interval of 27–64 $\text{kt CH}_4 \text{ yr}^{-1}$ (Fig. 9).

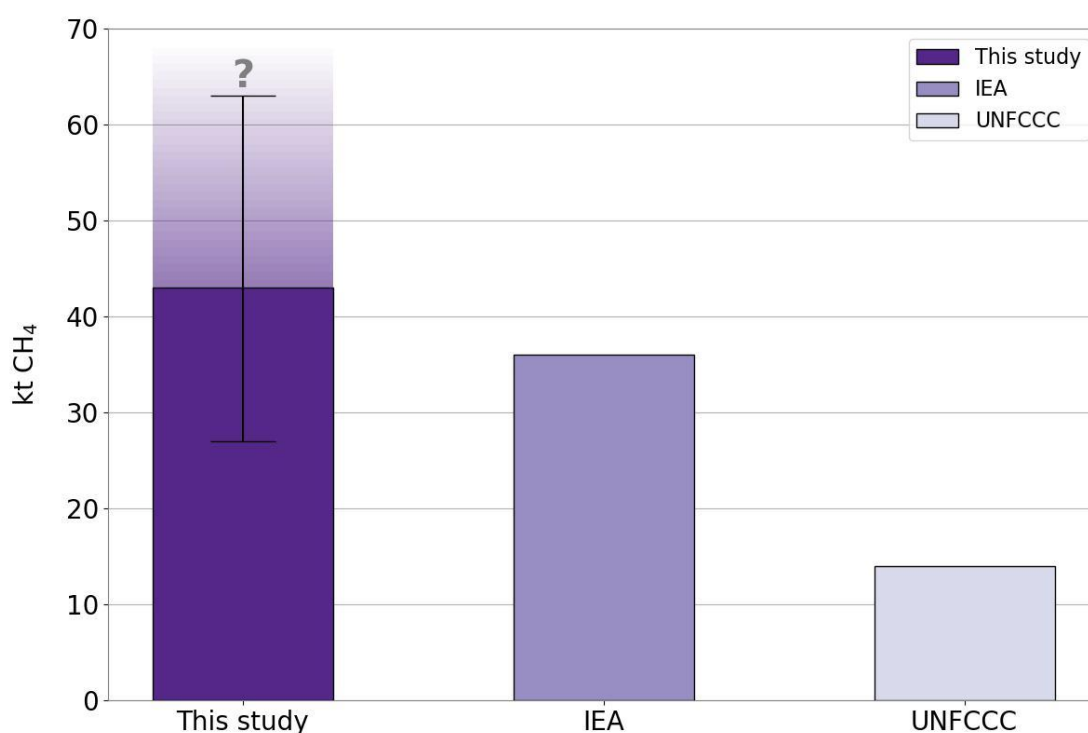


Figure 9. Basin-scale methane emissions derived from measurement-based emission factors obtained during the ROMEO-B campaign. The central estimate ($42 \text{ kt CH}_4 \text{ yr}^{-1}$) represents methane emissions from natural gas production well sites only and excludes emissions from compressor stations, gas-processing facilities, water-degassing installations, and other upstream infrastructure. The shaded envelope indicates the 95% confidence interval. Reported methane emissions from the Romanian natural gas sector based on IEA and UNFCCC inventories are shown for comparison.

This estimate includes emissions associated with natural gas production well sites only. Methane emissions from other elements of the upstream infrastructure, including compressor stations, gas-treatment facilities, gathering systems, and water-degassing installations, are not represented by the

applied upscaling procedure. In particular, the two super-emitting water-degassing tanks identified during the campaign (Section 3.5) were excluded from the basin-wide estimate because they were not part of the well-site inventory used for upscaling. Consequently, the derived value of 42 kt CH₄ yr⁻¹ should be regarded as a conservative estimate of methane emissions from natural gas production activities in the Transylvanian Basin.

For comparison, the International Energy Agency (IEA) estimates methane emissions from Romania's entire onshore natural gas production sector at 36 kt CH₄ in 2021. The corresponding estimate increases to 88 kt CH₄ in 2022, illustrating substantial year-to-year differences in reported emissions or methodological assumptions used for their derivation.

Romania's national greenhouse-gas inventory submitted to the United Nations Framework Convention on Climate Change (UNFCCC) reports combined methane emissions of approximately 14 kt CH₄ in 2021 for natural gas production, venting, and flaring categories. Although these inventory categories encompass production activities outside the Transylvanian Basin, they do not include all segments of the natural gas value chain. When all reported natural gas subsectors are considered together, total methane emissions from Romania's natural gas sector amount to approximately 52 kt CH₄ yr⁻¹.

The measurement-based estimate derived in this study is therefore comparable to existing national-scale estimates despite representing emissions from well sites in a single production basin. Moreover, because additional emissions from compressor stations, gas-processing facilities, degassing installations, and other elements of the production infrastructure were not included in the upscaling analysis, the total methane emissions associated with natural gas production activities in the Transylvanian Basin are likely higher than the estimate presented here.

These findings indicate that methane emissions from Romania's natural gas production sector may be substantially underestimated by inventory approaches relying primarily on generic emission factors. More broadly, the results illustrate the importance of direct observations for constraining regional methane budgets and identifying emission sources that may be insufficiently represented in conventional reporting frameworks.

4. Discussion

4.1 Emission distributions and temporal variability

Methane emissions from the 127 natural gas production facilities investigated in the Transylvanian Basin exhibited a strongly skewed distribution that was well described by a log-normal function. This observation is consistent with measurements from numerous oil and gas production regions worldwide, where a relatively small proportion of facilities contributes disproportionately to total methane emissions (Lyon et al., 2021). The present study extends these findings to one of Europe's oldest gas-producing regions and provides the first basin-scale, measurement-based characterization of methane emissions from Romanian natural gas production infrastructure.

A particular strength of this study is the combination of multiple independent quantification approaches, repeated measurements at individual facilities, extended measurement periods, and deployment of a novel Large-Scale Flow Chamber (LSFC). Together, these observations reveal substantial temporal variability in methane emission rates, with changes of up to an order of magnitude observed over timescales ranging from hours to days. In many cases, discrepancies

between repeated quantifications exceeded methodological uncertainty alone, indicating the presence of an additional source of uncertainty associated with temporal variability.

These observations challenge the assumption that methane emissions from natural gas production facilities remain approximately constant under steady operating conditions. Instead, emissions appear highly dynamic, even in the absence of documented maintenance activities or operational interventions, consistent with recent observations from other natural gas production regions (Lyon et al., 2021). The observed temporal variability has important implications for methane monitoring because single facility visits may not always provide representative estimates of long-term emissions. Consequently, robust regional emission estimates require sufficiently large sample sizes and repeated observations capable of capturing both spatial and temporal variability.

4.2 Complementarity of methane quantification approaches

The ROMEO-B campaign highlights the value of combining multiple measurement approaches that operate at different spatial scales and detection limits. No individual quantification approach was capable of characterizing the full range of methane emissions encountered during the campaign. Instead, the combination of component-level, facility-level, and basin-scale observations proved essential for capturing both low-emitting facilities and rare but highly consequential super-emitters. Particularly noteworthy is the performance of the LSFC approach. Although its application is restricted to facilities that can be physically enclosed and to relatively calm meteorological conditions, LSFC enables direct quantification of methane emission rates substantially below the practical detection limits of conventional plume-based methods. Consequently, the method provides unique information on the lower tail of the facility emission distribution.

Conversely, plume-based approaches such as TRM, OTM-33A, and GPM are particularly effective for quantifying larger methane emissions under real operating conditions. Screening surveys further complement these methods by enabling rapid characterization of a large number of facilities and facilitating detection of anomalously large emitters.

The overall agreement observed among independent quantification approaches increases confidence in the resulting emission distributions and derived emission factors. More broadly, the results suggest that integrated observational frameworks provide a more complete characterization of methane emissions than any individual method applied in isolation.

4.3 Representative methane emission factors

The representative site-level methane emission factor derived from the combined dataset was 1.7 kg CH₄ h⁻¹ site⁻¹. Although the various quantification approaches sampled different portions of the emission distribution and operated at different spatial scales, the resulting emission-factor estimates were generally consistent within their respective uncertainty ranges.

Among the applied approaches, GPM yielded the highest average methane emission rates. This result is likely attributable to sampling strategy rather than methodological bias. Because GPM was primarily applied to facilities exhibiting clearly detectable methane plumes, it preferentially sampled the upper tail of the regional emission distribution. The limited effect of excluding GPM-derived quantifications from the combined statistical estimator further supports the robustness of the resulting representative emission factor.

The derived emission factor falls within the range reported for natural gas production infrastructure in other regions despite differences in facility age, reservoir characteristics, operating conditions, and

925 measurement methodologies. This agreement suggests that the processes governing methane leakage may be broadly comparable across mature natural gas provinces and supports the use of measurement-based statistical approaches for regional emission assessment.

4.4 Source attribution and mitigation opportunities

930 Screening surveys and subsequent source-level investigations indicate that methane emissions from natural gas production facilities are primarily associated with leaking infrastructure components, including valves, flanges, connectors, and other movable elements. Elevated methane concentrations were detected at a large fraction of surveyed facilities, demonstrating that fugitive emissions are widespread throughout the basin.

935 These findings have important implications for methane mitigation. Many identified emission sources appear to result from equipment degradation or infrastructure maintenance issues rather than from unavoidable characteristics of natural gas production itself. Consequently, a substantial fraction of measured emissions could likely be reduced through targeted leak detection and repair (LDAR) programmes, replacement of ageing infrastructure, and improved operational practices.

940 Such mitigation opportunities are particularly attractive because methane reductions in the natural gas sector can often be achieved at low or even negative net cost when the value of conserved gas is taken into account. The widespread occurrence of infrastructure-related leaks observed during the ROMEO-B campaign therefore suggests considerable potential for rapid and cost-effective methane mitigation within the Transylvanian Basin.

4.5 Super-emitters and inventory completeness

945 One of the most significant findings of this study was the identification of two water-degassing tanks as major methane super-emitters. These facilities were not included in the operator's inventory of natural gas production well sites and would therefore have remained undetected in surveys focusing exclusively on known production facilities.

950 The measured methane emission rates of approximately 146 and 310 kg CH₄ h⁻¹ greatly exceeded emissions observed at individual natural gas production facilities. Remarkably, the combined emissions from these two facilities exceeded the aggregate emissions measured from all 127 quantified production facilities. This observation illustrates the disproportionate influence that a very small number of sources can exert on regional methane budgets.

955 The discovery of these super-emitters demonstrates that comprehensive methane assessments cannot rely solely on predefined infrastructure inventories. Measurement-based surveys are essential not only for quantifying known emission sources but also for identifying previously undocumented emitters that may dominate regional methane emissions. From a mitigation perspective, these facilities represent particularly attractive targets because addressing a small number of sources could yield disproportionately large reductions in total methane emissions.

960 4.6 Basin-scale methane emissions and inventory reconciliation

Application of the representative methane emission factor to the operator inventory yielded an estimated methane emission of 42 kt CH₄ yr⁻¹ (95% CI: 27–64 kt CH₄ yr⁻¹) from natural gas production well sites in the Transylvanian Basin. Because this estimate excludes emissions from compressor stations, gas-treatment facilities, gathering systems, water-degassing installations, and identified

965 super-emitters, total methane emissions associated with natural gas production activities in the basin are likely higher.

Perhaps the most consequential finding of this study is that methane emissions estimated for natural gas production well sites in the Transylvanian Basin alone are comparable to currently available national-scale estimates for Romania's natural gas sector. This observation is particularly noteworthy 970 because the basin-scale estimate presented here represents emissions from production well sites only and excludes several infrastructure categories known to emit methane.

The observed discrepancies likely arise from methodological differences between measurement-based and inventory-based approaches. Measurement-based methods explicitly capture highly skewed emission distributions, intermittent emission events, and previously unidentified methane 975 sources. By contrast, inventory estimates derived from generic emission factors may not adequately represent the influence of temporal variability, exceptional emitters, or infrastructure-specific characteristics.

Consequently, the results suggest that methane emissions from Romania's natural gas production infrastructure may be substantially underestimated in existing national greenhouse-gas inventories 980 and related European assessments. At the same time, recent evidence indicating reductions in methane emissions following infrastructure upgrades demonstrates that targeted mitigation can deliver rapid and measurable improvements. Together, these findings highlight both the challenge and the opportunity associated with improving methane accounting across the sector.

4.7 Implications for methane monitoring and mitigation

985 Overall, this study highlights the value of integrated, multi-method observational strategies for characterizing methane emissions from natural gas production systems. The combination of temporally variable emissions, infrastructure-related leaks, and previously undocumented super-emitters illustrates the complexity of methane emission processes and highlights the limitations of relying solely on inventory-based approaches.

990 At the same time, the results reveal substantial opportunities for methane mitigation. Targeted maintenance, infrastructure upgrades, super-emitter detection, and comprehensive measurement-based monitoring represent cost-effective and immediately actionable pathways for reducing methane emissions from the natural gas sector.

As methane-monitoring requirements continue to expand across Europe, integrated observational 995 approaches such as those demonstrated here can provide the empirical foundation needed for accurate greenhouse-gas inventories, effective methane mitigation strategies, and transparent assessment of progress toward climate objectives.

5. Conclusions

1000 This study provides the first basin-scale, measurement-based assessment of methane emissions from natural gas production facilities in the Transylvanian Basin, Romania. By combining multiple complementary quantification approaches, repeated facility-level measurements, and statistical upscaling, we characterized methane emissions from one of Europe's oldest and most important natural gas production regions.

1005 Methane emissions were found to be highly heterogeneous and temporally variable, with emission rates spanning several orders of magnitude and exhibiting strongly skewed, approximately log-normal

distributions. Repeated measurements revealed substantial short-term variability, indicating that methane emissions from natural gas production facilities are often dynamic rather than constant. These findings highlight the importance of repeated observations and sufficiently large sample sizes when deriving representative emission factors.

The representative site-level methane emission factor derived from the combined dataset was $1.7 \text{ kg CH}_4 \text{ h}^{-1} \text{ site}^{-1}$ (95% CI: $1.1\text{--}2.6 \text{ kg CH}_4 \text{ h}^{-1} \text{ site}^{-1}$). Upscaling of this emission factor yielded estimated methane emissions of $42 \text{ kt CH}_4 \text{ yr}^{-1}$ (95% CI: $27\text{--}64 \text{ kt CH}_4 \text{ yr}^{-1}$) from natural gas production well sites in the Transylvanian Basin. Because this estimate excludes emissions from several additional infrastructure categories and identified super-emitters, total methane emissions associated with natural gas production activities in the basin are likely higher.

A substantial fraction of observed methane emissions originated from leaking infrastructure components, indicating considerable potential for emission reductions through targeted leak detection and repair programmes, improved maintenance practices, and infrastructure upgrades. In addition, the identification of two previously undocumented water-degassing tanks as methane super-emitters demonstrates that measurement-based surveys are essential both for quantifying known emission sources and for identifying unexpected facilities that can disproportionately influence regional methane budgets.

The results further demonstrate the value of integrating multiple quantification approaches across different spatial scales. In particular, the Large-Scale Flow Chamber (LSFC) complemented established plume-based methods by enabling direct quantification of methane emission rates below the practical detection limits of conventional facility-scale techniques.

Perhaps the most consequential finding of this study is that methane emissions estimated for natural gas production well sites in the Transylvanian Basin are comparable to currently available national-scale estimates for Romania's natural gas sector. This observation highlights the importance of direct measurements for constraining methane emissions and evaluating the robustness of inventory-based estimates.

More broadly, the results demonstrate that integrated, multi-scale observational approaches can improve understanding of methane emissions from natural gas production systems and identify substantial mitigation opportunities. As methane-monitoring requirements continue to expand across Europe, such measurement-based frameworks can provide the empirical foundation needed for accurate greenhouse-gas inventories, effective methane mitigation strategies, and transparent assessment of progress toward climate objectives.

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1225

Supplementary materials

A1: Consistency between emission rates calculated with the HFS sampler approach results for two different gas flow rates.

1230 The HFS can operate in two modes with two different gas flow rates, 120 l/min and 170 l/min, and the results derived from these two modes can be compared as a consistency check. Figure A1 shows the difference between two modes as a function of the derived mean emission rate. The relative differences between the emission rate estimates derived in both modes appear relatively equally distributed over the full range of emission rates. Thus, there is no clear dependence of the difference on the mean emission rate. Furthermore, there is a roughly similar amount of red points (results from the high flow mode is larger than the one from the low flow mode) than blue points. Discrepancies of > 20% occurred only for the red points. These measurements were excluded from further analysis.

HFS relative variance due to flow rate in relation to mean emission

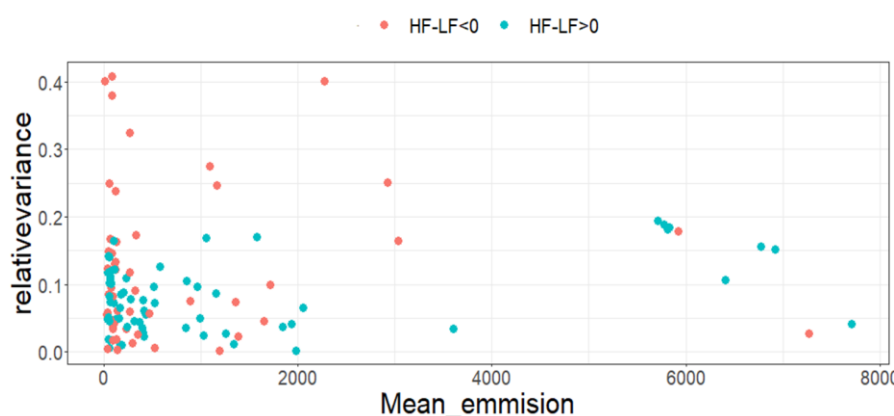


Figure A1. Relative differences between two operational modes of the HFS as a function of the mean derived emission rate. Red points indicate that the estimate from the low flow rate mode was higher, blue points that the estimate from the high flow mode was higher.

A2: Distribution of emission rate estimates of all 118 leaks identified across 57 gas wells with the HFS method.

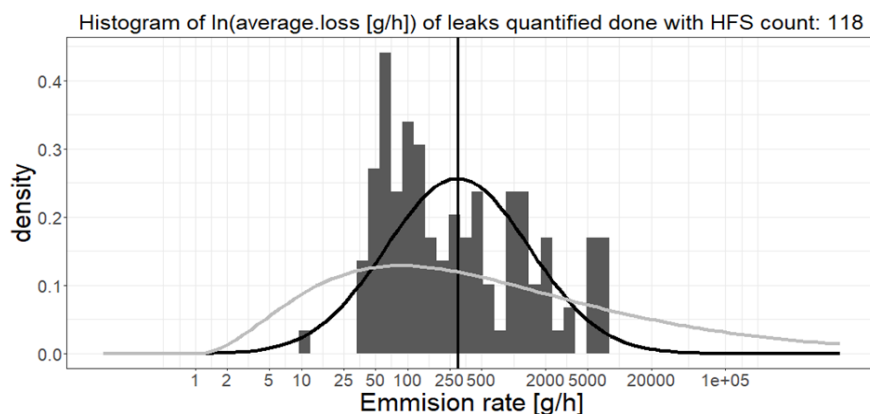
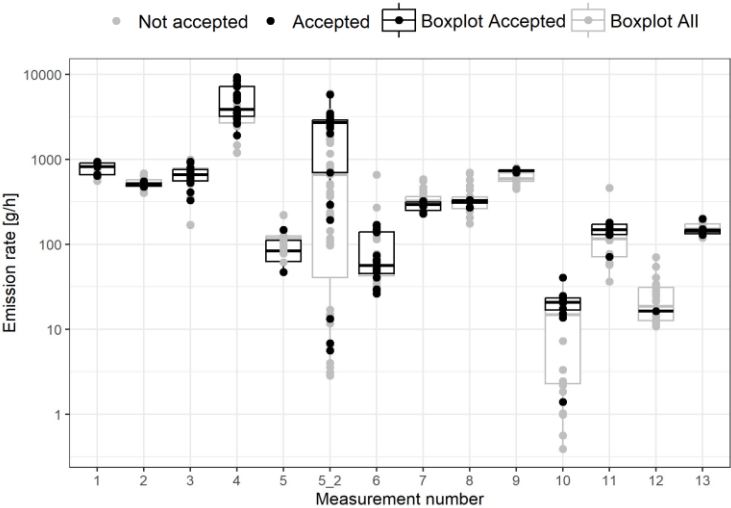


Figure A2: Histogram of emission rate estimates performed with the HFS approach (bars) and Gaussian fit to the histogram (line).

1250 **A3: Long-time OTM-33A measurements**



1255 *Figure A3. Emission rate estimates from long-term OTM-33A deployments where 2-minute windows were randomly selected from the longer time series to determine the variation of emission estimates over time, see methods for detailed description. Black symbols indicate estimates that pass data quality checks, and grey symbols points that did not pass the quality checks. The boxplots show the 25th and 75th percentile of measurements that pass (black box) or did not pass (grey box) the quality check.*

1260 **A4: results from the LSFC approach for low emitters**

Median value for normal distribution of those measurements equals 371 g/h.

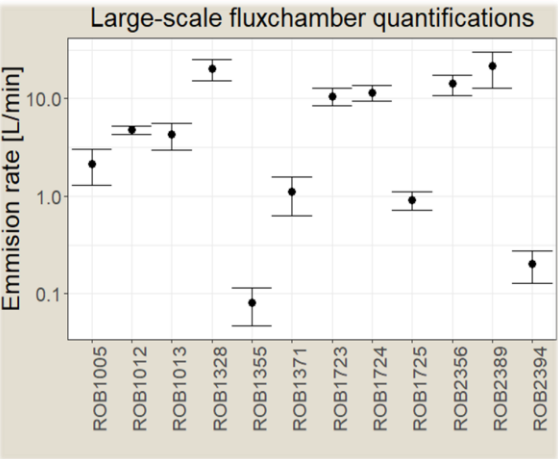


Figure A4: Emission rate estimates of whole installations in the Transylvanian basin obtained with the LSFC approach.

1265 **A5: results from screening measurements**

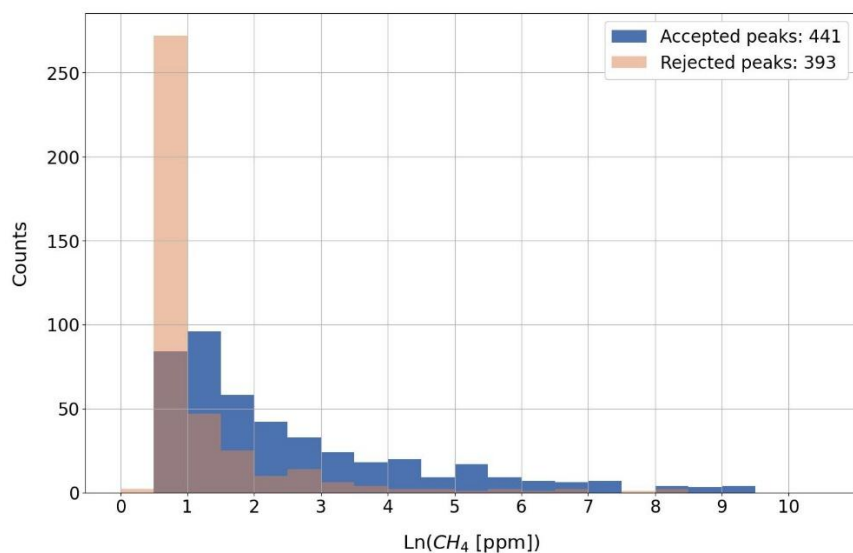


Figure A5: Distribution of accepted (blue) and rejected (pink) emission rate estimates from single-pass screening signals. Peaks are identified as a positive gradient of 2ppb for at least three measurement points.

1270

Tables

Table A1: Results of all emission rate quantifications

1275

ID	Date	Emission rate [kg/h]	Uncertainty [kg/h]	Method
32	19/06/2021	0,143	0,024	OTM
157	24/06/2021	0,028	0,021	TRM
236	24/06/2021	0,160	0,049	TRM
247	24/06/2021	1,560	0,458	TRM
257	24/06/2021	0,355	0,078	TRM
436	24/06/2021	0,614	0,166	TRM
437	24/06/2021	0,276	0,047	TRM
438	24/06/2021	0,771	0,146	TRM
522	25/06/2021	0,647	0,024	HFS
524	24/06/2021	0,023	0,012	OTM
526	25/06/2021	0,096	0,007	HFS
595	25/06/2021	0,123	0,013	HFS
930	15/06/2021	0,542	0,128	TRM
930	15/06/2021	0,407	0,011	HFS
938	15/06/2021	7,852	0,274	HFS
939	15/06/2021	3,179	0,508	HFS
942	15/06/2021	0,527	0,003	HFS
975	17/06/2021	6,468	0,323	TRM
994	17/06/2021	0,668	0,114	TRM
1005	17/06/2021	0,094	0,004	LSFC
1012	17/06/2021	0,160	0,003	LSFC
1013	17/06/2021	0,217	0,009	LSFC
1047	17/06/2021	0,386	0,063	TRM
1061	17/06/2021	0,923	1,202	TRM
1072	17/06/2021	0,345	0,087	TRM
1077	17/06/2021	0,146	0,033	TRM
1105	18/06/2021	1,237	0,008	HFS
1110	18/06/2021	8,719	2,499	GPM
1110	19/06/2021	0,805	0,139	TRM
1114	19/06/2021	0,396	0,014	HFS
1125	18/06/2021	0,076	0,031	TRM
1126	18/06/2021	0,500	0,075	TRM
1126	18/06/2021	0,145	0,056	OTM
1127	18/06/2021	0,209	0,039	TRM
1139	18/06/2021	2,558	0,250	HFS
1150	18/06/2021	6,969	1,060	HFS
1158	18/06/2021	1,003	0,185	TRM
1166	19/06/2021	1,429	NA	GPM

1169	19/06/2021	0,595	0,185	TRM
1169	20/06/2021	0,418	0,332	TRM
1172	19/06/2021	0,077	0,031	OTM
1175	19/06/2021	0,274	0,021	HFS
1176	18/06/2021	0,736	0,348	OTM
1177	18/06/2021	0,815	0,132	OTM
1178	18/06/2021	0,881	0,394	GPM
1204	18/06/2021	0,199	0,075	OTM
1206	18/06/2021	7,472	2,021	GPM
1206	19/06/2021	0,454	0,095	TRM
1208	19/06/2021	0,126	0,022	TRM
1221	19/06/2021	0,412	0,075	TRM
1226	19/06/2021	0,480	0,145	TRM
1227	19/06/2021	0,131	0,002	HFS
1228	18/06/2021	0,212	0,033	GPM
1246	18/06/2021	0,158	0,025	TRM
1246	19/06/2021	0,135	0,022	HFS
1253	18/06/2021	0,110	0,036	TRM
1263	19/06/2021	1,592	0,125	HFS
1267	18/06/2021	0,687	0,041	HFS
1284	18/06/2021	0,077	0,008	HFS
1292	19/06/2021	0,182	0,016	HFS
1318	18/06/2021	4,928	1,160	GPM
1328	16/06/2021	0,741	0,133	LSFC
1328	16/06/2021	0,516	0,028	OTM
1341	16/06/2021	0,093	0,033	TRM
1341	16/06/2021	0,051	0,021	TRM
1355	16/06/2021	0,002	0,000	LSFC
1371	16/06/2021	0,049	0,007	HFS
1371	16/06/2021	0,042	0,004	LSFC
1374	22/06/2021	0,231	0,131	OTM
1376	16/06/2021	0,332	0,055	TRM
1376	16/06/2021	0,062	0,000	HFS
1377	16/06/2021	2,458	1,076	GPM
1390	16/06/2021	1,083	0,043	HFS
1475	15/06/2021	0,758	0,105	TRM
1477	15/06/2021	0,432	0,061	TRM
1546	24/06/2021	0,656	0,156	OTM
1551	24/06/2021	3,859	2,185	OTM
1618	25/06/2021	77,893	31,163	OTM
1618	25/06/2021	45,442	4,627	GPM
1620	25/06/2021	0,722	0,245	TRM
1624	25/06/2021	2,027	0,224	TRM

1624	25/06/2021	1,581	0,585	OTM
1624	25/06/2021	1,554	0,244	TRM
1624	25/06/2021	1,437	0,665	OTM
1626	25/06/2021	2,930	0,792	TRM
1626	25/06/2021	1,123	0,201	TRM
1628	25/06/2021	1,020	0,327	TRM
1661	25/06/2021	2,701	1,482	OTM
1661	17/06/2021	0,097	0,071	OTM
1690	25/06/2021	0,418	0,165	OTM
1690	25/06/2021	0,322	0,144	OTM
1690	25/06/2021	0,216	0,038	TRM
1703	25/06/2021	1,881	0,809	OTM
1723	22/06/2021	0,367	0,008	LSFC
1724	23/06/2021	0,377	0,006	LSFC
1725	22/06/2021	0,034	0,001	LSFC
1728	22/06/2021	0,049	0,021	TRM
1733	21/06/2021	0,084	0,012	HFS
1740	22/06/2021	0,772	0,215	TRM
1761	23/06/2021	1,827	0,465	GPM
1761	23/06/2021	0,518	0,121	TRM
1764	23/06/2021	0,096	0,048	TRM
1766	23/06/2021	0,729	0,307	OTM
1766	23/06/2021	0,569	0,137	TRM
1767	23/06/2021	25,908	6,151	TRM
1767	23/06/2021	15,855	6,708	OTM
1808	21/06/2021	2,060	0,135	HFS
1843	22/06/2021	0,034	0,023	TRM
1846	21/06/2021	0,312	0,014	HFS
1850	22/06/2021	14,503	2,654	TRM
1852	22/06/2021	0,094	0,030	TRM
1853	22/06/2021	0,872	0,182	GPM
1853	21/06/2021	0,804	0,042	HFS
1853	22/06/2021	0,104	0,058	OTM
1855	22/06/2021	0,225	0,057	TRM
1855	21/06/2021	0,056	0,051	OTM
1855	21/06/2021	0,040	0,005	HFS
1867	22/06/2021	0,272	0,029	TRM
1885	22/06/2021	0,294	0,040	OTM
1896	22/06/2021	0,324	0,030	OTM
1926	23/06/2021	0,022	NA	GPM
1931	23/06/2021	0,007	NA	GPM
1948	23/06/2021	1,174	0,191	TRM
1949	23/06/2021	1,207	0,159	TRM

1949	23/06/2021	0,585	0,317	OTM
2014	22/06/2021	0,048	0,001	HFS
2050	22/06/2021	1,582	0,268	HFS
2305	24/06/2021	0,992	0,050	HFS
2305	21/06/2021	0,513	0,092	TRM
2306	21/06/2021	0,372	0,081	TRM
2316	21/06/2021	1,194	0,333	TRM
2317	24/06/2021	0,440	0,018	HFS
2327	24/06/2021	5,587	0,127	HFS
2327	26/06/2021	1,596	0,280	TRM
2330	24/06/2021	0,064	0,007	HFS
2333	24/06/2021	4,284	0,185	HFS
2333	26/06/2021	0,467	0,127	TRM
2336	21/06/2021	0,134	0,069	OTM
2345	21/06/2021	0,160	0,059	TRM
2353	24/06/2021	0,113	0,014	HFS
2356	24/06/2021	0,448	0,004	LSFC
2364	21/06/2021	0,538	0,184	TRM
2380	21/06/2021	0,126	0,067	OTM
2388	21/06/2021	0,184	0,072	OTM
2389	24/06/2021	1,470	0,040	LSFC
2394	21/06/2021	0,091	0,004	LSFC
2400	21/06/2021	0,114	0,040	GPM
2401	18/06/2021	0,691	0,347	OTM
2401	21/06/2021	0,191	0,047	TRM
2401	21/06/2021	0,062	0,030	OTM
2404	21/06/2021	0,054	0,020	TRM
2415	23/06/2021	6,402	0,685	HFS
2415	26/06/2021	0,162	0,025	TRM
2415	23/06/2021	0,021	0,009	OTM
2419	23/06/2021	0,149	0,040	OTM
2445	23/06/2021	0,099	0,003	HFS
2473	24/06/2021	0,016	0,009	OTM
2729	17/06/2021	1,657	0,077	HFS
2763	17/06/2021	0,121	0,006	HFS
2770	17/06/2021	0,328	0,030	HFS