



Satellite Constraints on European Landfill Methane Emissions Reveal Underestimation in Reported Inventories

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Abstract. This study evaluates the consistency between landfill methane emissions reported in European Union bottom-up inventories—the European Pollutant Release and Transfer Register (E-PRTR) and the Industrial Emissions Directive (IED)—and independent satellite-derived estimates compiled by the United Nations Environment Programme’s International Methane Emissions Observatory (IMEO). Additional emission estimates from GHGSat observations are included to extend the satellite-based assessment. Our study reveals that satellite detections remain limited, with cloud cover representing a major observational constraint, and primarily capture a subset of the largest emitters, preventing comprehensive characterization of landfill methane emissions across Europe. Among the datasets considered, GHGSat provides comparatively better spatial coverage and improved capability for detecting moderate emitters. The comparison between European Union inventory data and satellite-derived observations reveals a systematic underestimation of landfill methane emissions in bottom-up inventories. Measurements from NASA’s high-resolution Earth Surface Mineral Dust Source Investigation (EMIT) instrument indicate methane emission rates that exceed reported inventory values by up to one order of magnitude. Additionally, satellite observations reveal pronounced seasonal variability in landfill emissions that is not captured by annual inventory reporting. Although the available observations cannot establish whether this bias is representative of the entire European landfill sector, if confirmed across a larger and representative sample of facilities, such systematic underestimation could indicate that the European anthropogenic methane budget is significantly underestimated. These findings highlight the need to integrate facility-level reporting with satellite observations to better constrain landfill methane emissions, improve emission verification, and support the assessment of progress toward EU methane-mitigation and climate-neutrality targets.

1 Introduction

Methane (CH₄) is the second-most important anthropogenic greenhouse gas, with a 100-year global-warming potential (GWP) more than 28 times that of CO₂ (IPCC, 2023). Although its atmospheric lifetime (~12 yr) is an order of magnitude shorter than that of CO₂, methane’s high radiative efficiency makes it responsible for roughly 30 % of the observed increase in global surface temperature since the pre-industrial era (IPCC, 2023). In addition to its climate impact, methane participates in tropospheric chemistry and contributes to the formation of ground-level ozone, a pollutant harmful to human health and ecosystems (Hayes et al., 2025).

Human activities account for about 65 % of the global methane budget (Saunio et al., 2025). Within the anthropogenic sector, waste-related processes—principally landfill decomposition—contribute ~19 % of global emissions (Saunio et al., 2025). In the European Union (EU) this share is even larger: the waste sector is estimated to generate ~27 % of the EU’s total methane emissions (European Environment Agency, 2025). The EU policy framework explicitly targets the waste sector. The Landfill Directive (1999/31/EC, amended 2022) caps the proportion of municipal waste sent to landfill at 10 % by 2035, a measure projected to halve landfill-derived methane emissions (European Commission, 2022). Under the permitting and after-care regime established by EU legislation, landfill operators are required to monitor and report landfill gas generation and emissions, including methane. In practice, total methane emissions are most estimated using a bottom-up approach based on a First-Order



Decay (FOD) model. This model assumes that degradable organic carbon in waste decomposes progressively over time. It requires operational input data such as the annual quantity of waste deposited, waste composition, degradable organic carbon content, methane generation potential, and gas recovery rates. Net methane emissions are calculated by estimating methane generation and subtracting recovered and oxidised fractions. Reported facility-level methane emissions are submitted under the EU industrial reporting framework, previously through the Regulation (EC) No 166/2006 (E-PRTR) and now under the Industrial Emissions Directive 2010/75/EU (IED) and its associated Industrial Emissions Portal. These reported data contribute to transparency at installation level and may inform national greenhouse gas inventories. Despite this structured bottom-up reporting system, significant uncertainties persist in landfill methane emission estimates, as acknowledged in the EU Methane Strategy. Key sources of uncertainty include assumptions on waste composition, decay constants, gas collection efficiencies, oxidation rates, and incomplete capture of diffuse emissions. Moreover, bottom-up inventories can overlook a large proportion of landfill methane emissions, since landfills are obliged to report emissions only when they exceed 0.01 t h^{-1} thresholds. To address these uncertainties, independent top-down (atmospheric) approaches have increasingly been used to infer methane surface fluxes from atmospheric CH_4 concentrations measured by ground stations, aircraft, or satellites, usually through inverse-modelling (Atherton et al., 2017; Baray et al., 2018; Chan et al., 2020; Conrad et al., 2023). Recent satellite-based monitoring systems and data platforms, such as the International Methane Emissions Observatory (IMEO) of the United Nations Environment Programme (UNEP) (last access: 24 February 2026) (<https://methanedata.unep.org/>), which integrates emission estimates from multiple satellite observations, and the high-resolution GHGSat constellation (Jervis et al., 2021), provide observation-driven methane emission estimates at spatial scales ranging from several kilometres to tens of metres. A persistent mismatch between methane emissions reported by bottom-up inventories and top-down observational estimates has been documented at the global, regional, and national scales (Saunois et al., 2025). For the EU waste sector, the magnitude of this discrepancy—and its implications for policy compliance—remains poorly quantified. This discrepancy is amplified by the fact that the inventories are compiled on an annual basis, whereas landfill emissions are highly dynamic and controlled by seasonal factors such as ambient temperature, soil-water content, and the composition of the waste stream. These drivers can induce substantial intra-annual fluctuations that a single annual figure cannot capture, creating large uncertainties about the true methane release from landfills. Moreover, bottom-up inventory emissions do not provide quantified uncertainties for the reported values.

This study investigates landfill-related methane emissions across Europe by integrating facility-level E-PRTR/IED inventories with satellite-based emission estimates from IMEO and GHGSat. The analysis aims to assess the capability of different satellite observing systems to detect and quantify landfill methane emissions, examine their spatial and seasonal variability, and determine the consistency of satellite-derived estimates across instruments and with reported emissions. Particular attention is given to landfills repeatedly observed by multiple satellite systems, allowing facility-level variability and discrepancies with bottom-up inventories to be evaluated. By identifying systematic discrepancies, observational limitations, and remaining data gaps, the study aims to support improvements in EU methane reporting and strengthen the monitoring of landfill methane mitigation under the Landfill Directive.

2 Data, Methods and Analysis

This study analyses landfill methane emissions across Europe by integrating facility-level reported emissions with satellite-based emission estimates. Three complementary datasets are considered: (i) E-PRTR/IED, which provides facility-level bottom-up methane emissions reported by landfill operators; (ii) the IMEO dataset, which compiles methane emission estimates produced by different institutions and derived from observations acquired by multiple satellite instruments, ranging from global methane mappers to high-resolution imaging spectrometers; and (iii) GHGSat emission estimates, which provide an additional independent, high-resolution dataset of quantified landfill methane emissions.



The analysis is structured in four main steps. First, E-PRTR/IED emissions are characterized using country-level descriptive statistics to establish the distribution and magnitude of reported landfill methane emissions. Second, the satellite datasets are evaluated in terms of spatial and temporal coverage, detection frequency, and emission-rate distributions, with particular attention to differences among satellite observing systems. Third, satellite-derived estimates are compared across countries and for a subset of landfills repeatedly observed by multiple satellite systems, including an assessment of seasonal variability and observational constraints. Finally, satellite-derived estimates are matched with E-PRTR/IED facility-level emissions to quantify their agreement through bias and correlation analyses.

2.1 E-PRTR/IED landfill inventory

This section analyses the geographic distribution of landfill sites across the European Union and the methane-emission figures reported under the EU Industrial Emissions Directive (IED) reporting framework, formerly published through the E-PRTR European Pollutant Release and Transfer Register and now integrated into the IED Industrial Emissions Portal, here in after called E-PRTR/IED database. The E-PRTR/IED database contains more than 3000 reported methane releases from landfills since 2007. Of these, approximately 60% are calculated, 30% are estimated, and 10% are directly measured. This highlights that only a minority of values are directly measured, underscoring the urgent need for improved monitoring and verification. It should be noted that not all landfill sites report methane emissions, as facilities are obliged to report only when emissions exceed 0.01 t h^{-1} . This results in gaps in both emission values and reporting years. The available data span the period 2007–2023, depending on the reporting history of each facility. Since this study aims to identify potentially unreported emissions, all landfill sites are considered, including those that do not report methane emissions. Figure 1 maps the locations of landfills reported in the E-PRTR/IED database and visualises their yearly emission intensities. Empty circles denote landfills for which zero emissions or no emissions are reported, while the colour of each circle corresponds to the estimated emission intensity, as indicated by the accompanying colour scale.

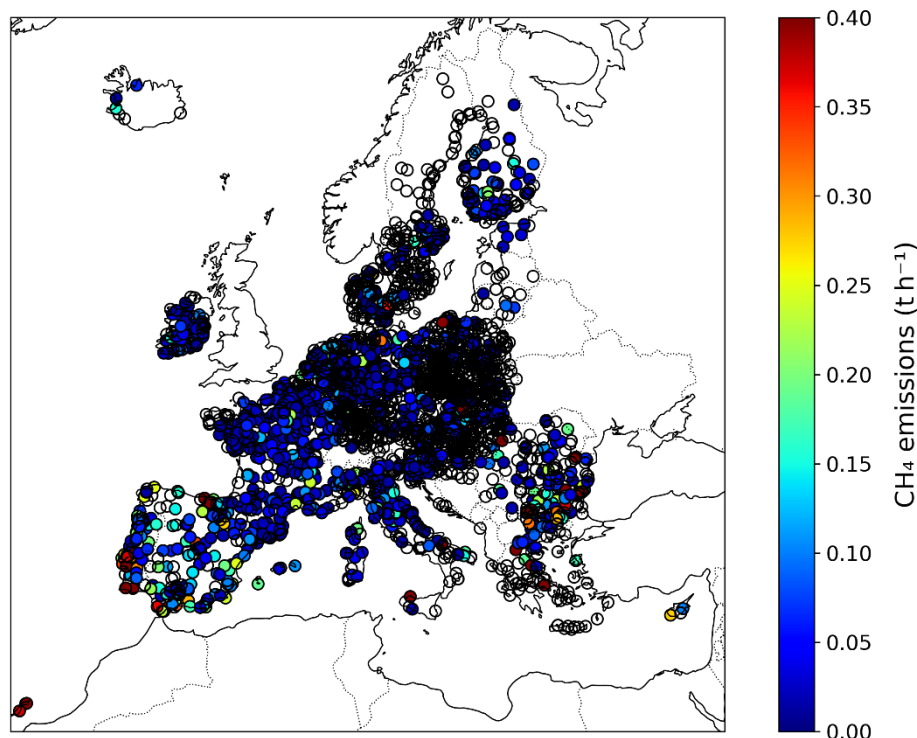


Figure 1. Spatial distribution of EU landfill sites and their reported methane-emission rates (combined E-PRTR + IED dataset). Filled circles represent landfills that provide a quantified methane emission; empty circles denote sites with no reported emission. Circle colour encodes the reported emission magnitude (t h^{-1}) according to the accompanying colour, ranging from low (blue) to high (red). The map highlights the overall density of landfill locations, the regions where reporting gaps are prevalent, and the clusters of higher-emitting facilities.

The E-PRTR/IED dataset comprises 3068 landfills across 29 European countries, including EU Member States and selected non-EU European countries. The database has been compiling data since 2007, the year E-PRTR reporting began. A key limitation is the scarcity of quantitative methane data: roughly two-thirds ($\approx 67\%$, 2047 landfill) of the sites has never reported emissions estimates because their outputs fall below the reporting threshold of 0.01 t h^{-1} . Consequently, only roughly one-third of the landfills – about 1 017 sites ($\approx 33\%$) – have reported emission values at least once, providing data suitable for analysis. For the subset of facilities that do report methane emissions, the values are modest. The smallest reported emission is 0.01 t h^{-1} , the mean is 0.10 t h^{-1} , and the largest reaches 2.7 t h^{-1} . Table 1 summarises these statistics for each country giving the total number of landfills, the number and percentage of sites with no reported methane emission, the minimum, mean and maximum reported emission rates (t h^{-1}), the aggregate national emissions, and the country's share of the EU-wide total. The countries included in the analysis are Austria (AT), Belgium (BE), Bulgaria (BG), Switzerland (CH), Cyprus (CY), Czechia (CZ), Germany (DE), Denmark (DK), Estonia (EE), Spain (ES), Finland (FI), France (FR), Greece (GR), Croatia (HR), Hungary (HU), Ireland (IE), Iceland (IS), Italy (IT), Lithuania (LT), Luxembourg (LU), Latvia (LV), Montenegro (ME), the Netherlands (NL), Poland (PL), Portugal (PT), Romania (RO), Serbia (RS), Sweden (SE), Slovenia (SI), and Slovakia (SK).



Country	Number of landfills	Landfills not reporting	Mean emission (t h ⁻¹)	Max emission (t h ⁻¹)	Not reporting (%)
AT	141	134	0.05	0.08	95
BE	25	18	0.02	0.05	72
BG	90	44	0.24	2.69	48.9
CH	1	0	0.01	0.01	0
CY	3	1	0.19	0.28	33.3
CZ	40	27	0.03	0.11	67.5
DE	535	406	0.04	0.37	75.9
DK	136	118	0.07	0.35	86.8
EE	6	1	0.03	0.04	16.7
ES	215	79	0.14	1	36.7
FI	89	54	0.05	0.21	60.7
FR	299	82	0.05	0.93	27.4
GR	63	50	0.3	1.24	79.4
HR	26	26	nan	nan	100
HU	114	111	0.05	0.1	97.4
IE	72	29	0.05	0.33	40.3
IS	6	3	0.08	0.16	50
IT	222	121	0.07	1.08	54.5
LT	12	9	0.06	0.09	75
LU	2	0	0.07	0.1	0
LV	6	6	nan	nan	100
ME	1	1	nan	nan	100
NL	49	30	0.08	0.19	61.2
PL	470	426	0.05	0.4	90.6
PT	55	7	0.17	0.76	12.7
RO	75	46	0.12	1.28	61.3
RS	9	4	0.07	0.18	44.4
SE	179	158	0.04	0.17	88.3
SI	44	7	0.03	0.27	15.9
SK	83	55	0.06	0.5	66.3
TOTAL	3068	2053	0.08	2.69	66.9

Table 1 Summary of landfill methane emissions reported in the E-PRTR/IED dataset for the 29 European countries included in the analysis. For each country, the table reports the total number of landfills, the number and percentage of sites without reported methane emissions, and the mean and maximum reported emission rates (t h⁻¹). Country codes: AT, Austria; BE, Belgium; BG, Bulgaria; CH, Switzerland; CY, Cyprus; CZ, Czechia; DE, Germany; DK, Denmark; EE, Estonia; ES, Spain; FI, Finland; FR, France; GR, Greece; HR, Croatia; HU, Hungary; IE, Ireland; IS, Iceland; IT, Italy; LT, Lithuania; LU, Luxembourg; LV, Latvia; ME, Montenegro; NL, the Netherlands; PL, Poland; PT, Portugal; RO, Romania; RS, Serbia; SE, Sweden; SI, Slovenia; and SK, Slovakia.



2.2 Satellite-Based Retrievals of European Landfill Methane emissions

135 This section evaluates satellite-based methane emission estimations of European landfills using data reported through the IMEO, complemented by independent measurements from the commercial GHGSat constellation, which are not included in the IMEO dataset. GHGSat provides high-spatial-resolution observations specifically designed to detect and quantify CH₄ point-source emissions at the facility scale.

The analysis first examines the spatial and temporal coverage of landfill detections reported by IMEO, distinguishing between the global methane mapper and high-resolution hotspot imagers. For each observational approach, we assess the geographic distribution and frequency of detections, national emission statistics, and seasonal variability. Country-level emission estimates derived from the different satellite instruments and products represented in IMEO are subsequently compared to evaluate the influence of observational coverage, instrument characteristics, and data aggregation on the resulting emission estimates.

140 GHGSat emission values are then examined independently to characterize the spatial distribution, frequency, and seasonal patterns of landfill detections. Unlike the publicly available IMEO dataset, the GHGSat dataset is not publicly accessible and was provided directly by GHGSat. The dataset contains the locations of detected European landfills and the acquisition time of all available detection events, allowing us to investigate their spatial distribution, detection frequency, and seasonal patterns. However, quantified methane emission rates were available for only 12 observations across the entire dataset. Therefore, the analysis of emission magnitude is restricted to these 12 observations.

145 Finally, a facility-level intercomparison is conducted for six selected landfills characterized by multiple detection events across different satellite instruments and products. These sites were selected because their relatively high number of observations enables a more robust comparison of methane emission estimates from IMEO and GHGSat with reported inventory data. Differences between satellite-derived and bottom-up estimates are assessed together with the temporal and seasonal variability captured by the satellite observations. This comparison provides insight into the agreement among independent datasets and highlights their complementary capabilities and limitations for quantifying methane emissions at the individual landfill scale.

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2.2.1 UNEP IMEO dataset

In contrast to bottom-up inventories, which rely on activity data and emission factors, top-down approaches use satellite observations of the column-averaged dry-air mole fraction of methane (XCH₄) to identify atmospheric methane enhancements and infer the emissions responsible for them. This section provides an assessment of European methane landfill emissions based on satellite observations reported to IMEO. The database provides a public platform that integrates methane emission estimates derived from multiple satellite observations to support the identification and mitigation of major methane sources.

160 All these emission-data sources rely on observations from multiple satellite instruments, ranging from global flux mapper, such as TROPOspheric Monitoring Instrument (TROPOMI) instrument (Veefkind et al., 2012) aboard ESA's Copernicus Sentinel-5P satellite; to high-resolution hotspot detectors, including Hyperspectral Precursor of the Application Mission (PRISMA) operated by the Italian Space Agency – ASI (Cogliati et al., 2021), Environmental Mapping and Analysis Program (EnMAP) (operated by the German Aerospace Center – DLR) (Guanter et al., 2015) and Earth Surface Mineral Dust Source Investigation (EMIT) (operated by NASA – USA National Aeronautics and Space Administration) (Connelly et al., 2021; Thorpe et al., 2023).

165 Within IMEO, the Methane Alert and Response System (MARS) integrates observations from multiple satellite instruments and data providers to detect, quantify, and attribute large methane emission events worldwide. Among these contributors, Kayrros provides satellite-based methane emission estimates to support the identification and characterization of major emission sources. Kayrros adopts a source-agnostic approach, combining satellite imagery, artificial intelligence, and geo-

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analytics to detect, quantify, and attribute methane emission events. The Kayrros Methane Watch system integrates observations from a range of satellite instruments with complementary capabilities, ranging from global flux mapper to high resolution point source imagers. Global mapping instruments, such as TROPOMI, are used to routinely identify large methane plumes over broad geographic areas and, for selected events, derive emission rates with associated uncertainties. The reported observations include the sensing date, approximate source location, presumptive source category and, when available, methane emission rate and associated uncertainty. Although Kayrros Methane Watch incorporates observations from several additional satellite instruments, such as Sentinel-2, these are not discussed further here because no landfill methane detections from these sensors are present in the European dataset analysed in this study.

Among the satellite-based products incorporated into IMEO is the Copernicus Atmosphere Monitoring Service Methane Hotspot Explorer (CAMS MHE), an interactive platform for detecting and quantifying large methane emission events from TROPOMI XCH₄ observations. The underlying system, developed for CAMS by SRON – Netherlands Institute for Space Research, applies an automated machine-learning algorithm trained on validated high-emission scenes to identify anomalous methane enhancements and plume-like structures associated with potential point sources. Following plume detection, methane emission rates are quantified using the Integrated Mass Enhancement (IME) approach (Varon et al., 2018). TROPOMI-derived methane enhancements are combined with the European Centre for Medium-Range Weather Forecasts (ECMWF) wind fields to relate the observed excess methane mass within the plume to an estimated source emission rate. Source attribution is subsequently performed by evaluating the detected plume location and its surrounding emission context using bottom-up inventories and information on nearby emitting activities. Detected events are assigned to broad source sectors, including coal, oil and gas, agriculture, and solid waste. In this study, only CAMS MHE detections attributed to the solid-waste sector and associated with landfills within the European domain are considered.

2.2.1.1 TROPOMI-Based Methane Emission Estimates in IMEO

Approximately half of the European landfill methane observations available in IMEO, corresponding to 94 detected emission events, are based on TROPOMI measurements. The CAMS MHE serves as the principal monitoring system, accounting for about 77 % of the TROPOMI-derived emissions recorded in the IMEO, while Kayrros provides the remaining share. TROPOMI provides daily XCH₄ observations at a nominal spatial resolution of approximately 7×5.5 km², with a local overpass time of about 13:30. As a global mapping instrument, TROPOMI is particularly well suited to identifying large and persistent methane enhancements over broad spatial scales. However, it was not specifically designed for facility-scale source characterization, and the attribution and quantification of individual point-source emissions are therefore more uncertain than for high-resolution imaging spectrometers specifically designed to detect localized methane plumes.

The kilometre-scale TROPOMI footprint is substantially larger than the spatial extent of individual methane point sources. Following Duren et al., (2019), a methane point source can be operationally defined as a single facility emitting more than 10 kg CH₄ h⁻¹ over an area smaller than 30 × 30 m². Consequently, a facility-scale methane enhancement is sampled within a much larger TROPOMI footprint, where the signal can be spatially diluted or mixed with emissions from nearby sources. Atmospheric transport may further displace the observed enhancement from its actual source location, introducing additional uncertainty in source attribution and emission quantification.

TROPOMI data availability is also spatially and temporally heterogeneous. Cloud cover, large solar zenith angles, and high aerosol loads can substantially reduce the number of valid retrievals (Gao et al., 2023). These limitations should therefore be considered when interpreting TROPOMI-derived landfill emissions and are particularly important when comparing them with facility-level E-PRTR/IED data, as satellite observations and reported inventories characterize methane emissions at markedly different spatial and temporal scales.

Figure 2 depicts the spatial distribution of landfill hotspots detected up to the end of 2025, with blue markers representing detections reported by CAMS MHE and in orange the hotspot detected from Kayrros system. Each point represents the estimated centre of a detected plume, while the point size is proportional to the inferred emission rate, providing a visual indication of



both the spatial distribution and relative magnitude of the emissions. Because of the intrinsic spatial-resolution limits of TROPOMI and the influence of atmospheric transport, the mapped locations should be interpreted as approximate source areas rather than precise facility coordinates. This positional uncertainty is explicitly considered in all subsequent quantitative analyses of landfill methane emissions.

The spatial distribution of the detected plumes shows a strong concentration over the Mediterranean region, where relatively low cloud cover favours satellite observations (see Supplementary Material Figs). This distribution highlights the regions where the satellite-based system achieves higher detection frequencies, as well as areas affected by observational gaps caused by persistent cloud cover, unfavourable solar-zenith angles, or elevated aerosol concentrations.

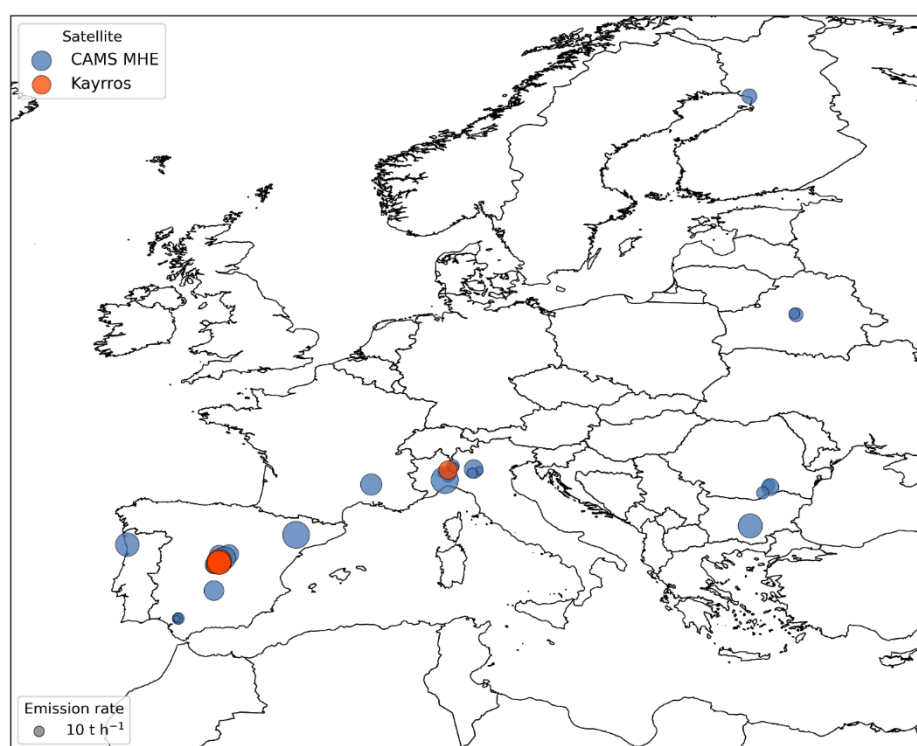


Figure 2. Spatial distribution of landfill-related methane emissions detected by CAMS MHE (blue) and Kayrros (orange) between July 2024 and December 2025. Marker size is proportional to the estimated methane emission rate.

Based on the IMEO data, the CAMS MHE system detected 72 landfill-related methane plumes over Europe, while the Kayrros system identified 22 plumes. Across all detections the mean emission rate was 18.5 t h^{-1} (Table 2), with a maximum of 68 t h^{-1} (CAMS MHE) and a minimum of 3 t h^{-1} (CAMS MHE). The lower end of the CAMS MHE range is consistent with previously reported detection limits for TROPOMI-derived methane retrievals: Dubey et al., (2023) found limits of $0.5\text{--}8.8 \text{ t h}^{-1}$ per pixel, Jacob et al., (2016) estimated a threshold of roughly 5 t h^{-1} , Schuit et al., (2023) reported a 5th-percentile limit of about 8 t h^{-1} . These estimates are substantially lower than the detection threshold of approximately $25 \text{ t CH}_4 \text{ h}^{-1}$ reported by Lauvaux et al., (2021).

Based on the inventory values reported in Table 1, none of the European landfills would be expected to be detectable by TROPOMI, as the maximum reported emissions remain below the instrument's detection threshold. The fact that TROPOMI nevertheless identifies methane plumes over several landfill sites provides independent evidence that reported emissions may be systematically underestimated.



Table 2 summarises, for each country, the number of detections, the corresponding mean emission rates, and the average total emissions reorted in the IMEO database during the study period.

Detection counts vary markedly across countries, with 47 detections recorded in Spain and 9 in Italy, together accounting for approximately 90% of all observations, indicating a strongly uneven geographical distribution of detections.

NAME	CAMS_MHE	Kayrros	Total	Mean (t h ⁻¹)
Spain	54	21	75	17
Italy	9	1	10	21
Romania	3	0	3	18
Belarus	2	0	2	14.5
France	1	0	1	42
Finland	1	0	1	21
Bulgaria	1	0	1	54
Portugal	1	0	1	51
TOTAL	72	22	94	18.5

Table 2 — Number of landfills-related methane plume detections per European country (only countries with at least one detection) for the two monitoring systems (CAMS MHE, Kayrros) and the combined total, together with the mean emission rate (t h⁻¹) calculated over all detections.

We analysed the annual and seasonal detection frequencies to assess the systems’ capability to monitor landfill emissions throughout the year and to identify seasonal variations in detection performance, which may partly reflect differences in cloud-cover conditions. Table 3 reports the number of detected landfills-related methane emission events across Europe, aggregated on seasonal basis for the two systems. The CAMS MHE analysis is restricted to 2025 because the 2024 dataset begins in mid-July and therefore does not provide complete seasonal coverage. By contrast, Kayrros observations are available from January 2024, allowing the full observation period to be considered. Seasonal detection frequencies are expressed as percentages and evaluated separately for each year; however, the limited number of Kayrros detections prevents a robust seasonal pattern from being established. Approximately half of all landfill-related methane detections occur during the summer months, with lower detection frequencies in spring, autumn, and winter. Although the available observations do not allow the influence of individual environmental factors to be isolated, this distribution indicates a marked seasonality in TROPOMI-based detections, with greater detection frequency during summer. This pattern is consistent with more favourable observational conditions, including reduced cloud cover, as suggested by the seasonal cloud-cover analysis presented in the Supplementary Material.



Season	CAMS MHE*	Kayrros	Total	Percentage
Winter	7	2	9	18.4
Spring	4	0	4	8.2
Summer	21	5	26	53.1
Autumn	10	0	10	20.4

Table 3 — Seasonal counts and percentage of landfill-related methane emission events detected across Europe by the two monitoring systems. The CAMS MHE figures refer only to 2025 (the 2024 dataset starts in mid-July, missing spring observations and providing incomplete summer and winter coverage), whereas the Kayrros figures cover the full 2024 – 2025 period, allowing a complete seasonal breakdown.

2.2.1.2 Hotspot-Imager-Based Methane Emission Estimates in IMEO

In the following section, we analyse landfill methane emission estimates reported in IMEO and derived within the MARS framework from high-resolution observations acquired by EMIT, EnMAP, and PRISMA, following the same analytical approach applied to the TROPOMI-based detections.

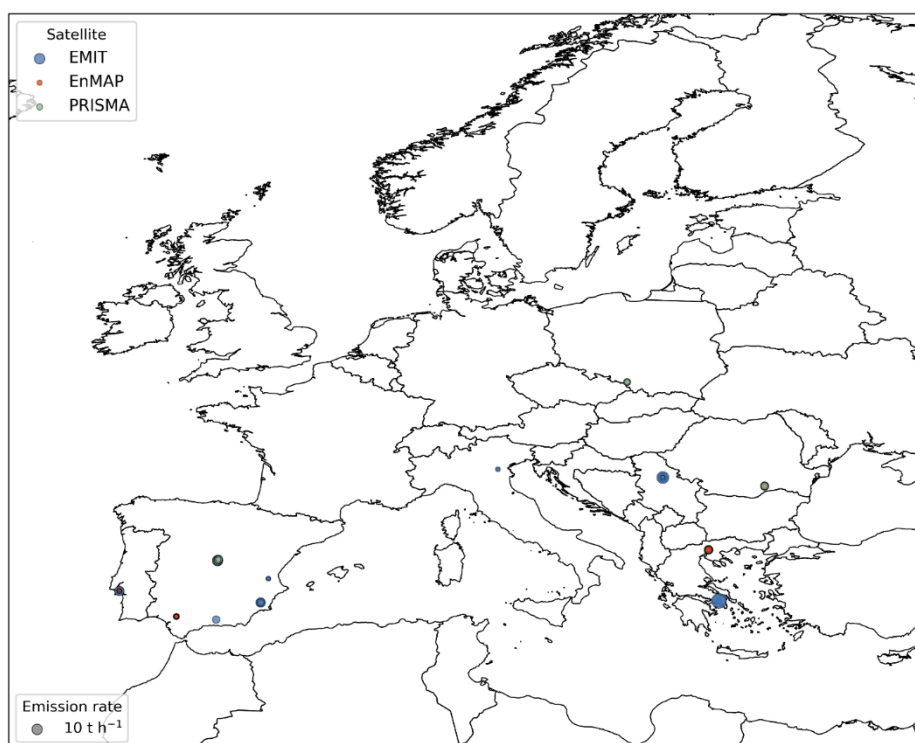
The satellite that provides the second-largest share of landfill detections in Europe, as reported in IMEO, is NASA’s EMIT instrument, which identified 69 plumes ($\approx 37\%$).

EMIT, originally designed to characterize the mineral composition of arid surfaces and their potential contribution to atmospheric dust, has operated aboard the International Space Station since 2022 in a 51.6° inclined orbit with variable local overpass times. The instrument provides observations at a spatial resolution of approximately $60 \times 60 \text{ m}^2$, with an estimated methane point-source detection sensitivity of approximately $100\text{--}1000 \text{ kg CH}_4 \text{ h}^{-1}$ and a nominal revisit time of about three days (Cusworth et al., 2019).

The remaining detections are supplied by DLR’s EnMAP (15 plumes, $\approx 8\%$) and ASI’s PRISMA (8 plumes, $\approx 4\%$). PRISMA, operated by the Italian Space Agency (ASI) since 2019, and EnMAP, operated by the German Aerospace Center (DLR) since 2022, are hyperspectral imaging missions capable of detecting and characterizing localized methane enhancements. Both instruments provide observations at a spatial resolution of approximately $30 \times 30 \text{ m}^2$ over scenes of about $30 \times 30 \text{ km}^2$ and include spectral coverage around the $2.3 \mu\text{m}$ methane absorption region, with a spectral resolution of approximately 10 nm . Their sensitivity to methane point sources is typically in the range of $100\text{--}1000 \text{ kg CH}_4 \text{ h}^{-1}$, depending on surface and atmospheric conditions. Unlike systematic global mapping instruments, PRISMA and EnMAP primarily operate through targeted acquisitions requested by the scientific community and other users, with a nominal revisit time of approximately four days. Level-1 data are made freely available upon request, although methane retrieval and plume quantification require dedicated processing by the user (Cusworth et al., 2019; Guanter et al., 2021).

This satellite-derived dataset provides a comprehensive assessment of spatial distribution, magnitude, and temporal evolution of methane emissions detection capability of European landfills as observed by the three high resolution satellites. As for the landfill emissions spotted by TROPOMI, the majority of the detections are inside the Mediterranean area characterized by infrequent cloud cover, special during the summer season (see Supplementary Material).

Figure 3 maps the locations of the landfill plumes detected across Europe, with each satellite colour-coded for easy reference: blue = EMIT (NASA), orange = EnMAP (DLR), green = PRISMA (ASI).



310 **Figure 3. Spatial distribution of landfill-related methane emissions detected by EMIT, EnMPA, PRISMA satellites. Blue , orange**
and green points indicate the estimated locations of the detected plumes from EMIT, EnMPA, PRISMA , respectively, while marker
size is proportional to the inferred emission intensity.

The table 4 reports the number of detections from each high-resolution satellites for country with at least one emission value,
 315 the total number of country detections, and the mean values per each country and total in Europe.

The NASA's EMIT satellites monitored the 75 % of the total high-resolution detection points, followed by EnMAP with
 roughly 16 % and PRISMA contributing the remaining 10 %. In a comparable pattern to the TROPOMI observations, Spain is
 the most-monitored country, representing 38 % of the detections.

Large discrepancies are observed between the average emissions measured by the global-flux mapper TROPOMI and those
 320 derived from high-resolution satellites, the latter amounting on average to only one-fifth of the TROPOMI estimates. Table 4
 summarises, for each country, the number of detections and the mean landfill emission, with an overall average emission of
 4.2 t h⁻¹.

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NAME	EMIT	EnMAP	PRISMA	Total	Mean (t h ⁻¹)
Spain	25	5	5	35	3.8
Greece	14	3	0	17	5.6
Romania	7	3	1	11	4
Portugal	8	2	0	10	4.1
Serbia	10	0	0	10	5.3
Poland	3	2	2	7	2.4
Italy	2	0	0	2	1.6
TOTAL	69	15	8	92	4.2

Table 4 — Number of landfills-related methane plume detections per European country for each hyperspectral imaging system (EMIT, EnMAP and PRISMA) and the combined total, together with the mean emission (t h⁻¹) calculated for each country based on the aggregate emissions reported.

Similarly to the TROPOMI analysis, Table 5 presents the annual and seasonal detection frequencies to assess the capability of these systems to monitor landfill methane emissions throughout the year, with seasonal variations in detection frequency suggesting a potential influence of cloud cover, solar illumination, and solar viewing geometry on detection performance.

Table 5 presents the number of landfills-related methane emission events detected across Europe, aggregated on a seasonal basis for the two satellite systems. The EnMAP detections shown are restricted to 2025 because the 2024 data set begins only at the end of May, leaving the year incomplete and jeopardising seasonal representativeness. By contrast, EMIT and PRISMA provide data from the first 30 and 32 days of each year, respectively, enabling inclusion of the entire observation period. However, PRISMA recorded only a limited number of detections, which precludes a reliable seasonal analysis.

As for the TROPOMI detections, roughly half of all landfills-related methane events are observed in summer, while detection rates are markedly lower in the other seasons. This analysis highlights the pronounced seasonality of high-resolution retrieval systems and confirms that variability in cloud cover is a key factor governing plume detectability (see Chapter 2).

Season	EMIT	EnMAP*	PRISMA	Total	Percentage
Winter	5	1	0	6	9.7
Spring	7	5	3	15	24.2
Summer	29	4	0	33	53.2
Autumn	2	5	1	8	12.9

Table 5 presents the seasonal counts and percentages of landfill-related methane emission events detected across Europe by the EMIT, EnMAP and PRISMA satellites. EnMAP observations are limited to 2025 because the 2024 dataset begins only at the end of May, omitting the earlier months. In contrast, EMIT and PRISMA data start from the 30th and 32nd days of 2024, respectively, and cover the full 2024 – 2025 period, enabling a complete seasonal breakdown.



2.2.2 Comparison of Country-Level Methane Emissions from different satellites

In this section we compare the country-level distributions of landfill methane emission rates estimated from observations acquired by the different satellite instruments and products, with coloured dots indicating the corresponding mean values. The comparison is used to assess whether the magnitude and distribution of detected emissions are consistent across European countries and whether different satellite instruments preferentially detect plumes associated with different emission ranges. Such differences may reflect the specific observational characteristics and detection capabilities of each instrument. TROPOMI-based emission estimates reported by CAMS MHE and Kayrros show close agreement and are therefore combined into a single TROPOMI category for the subsequent analysis.

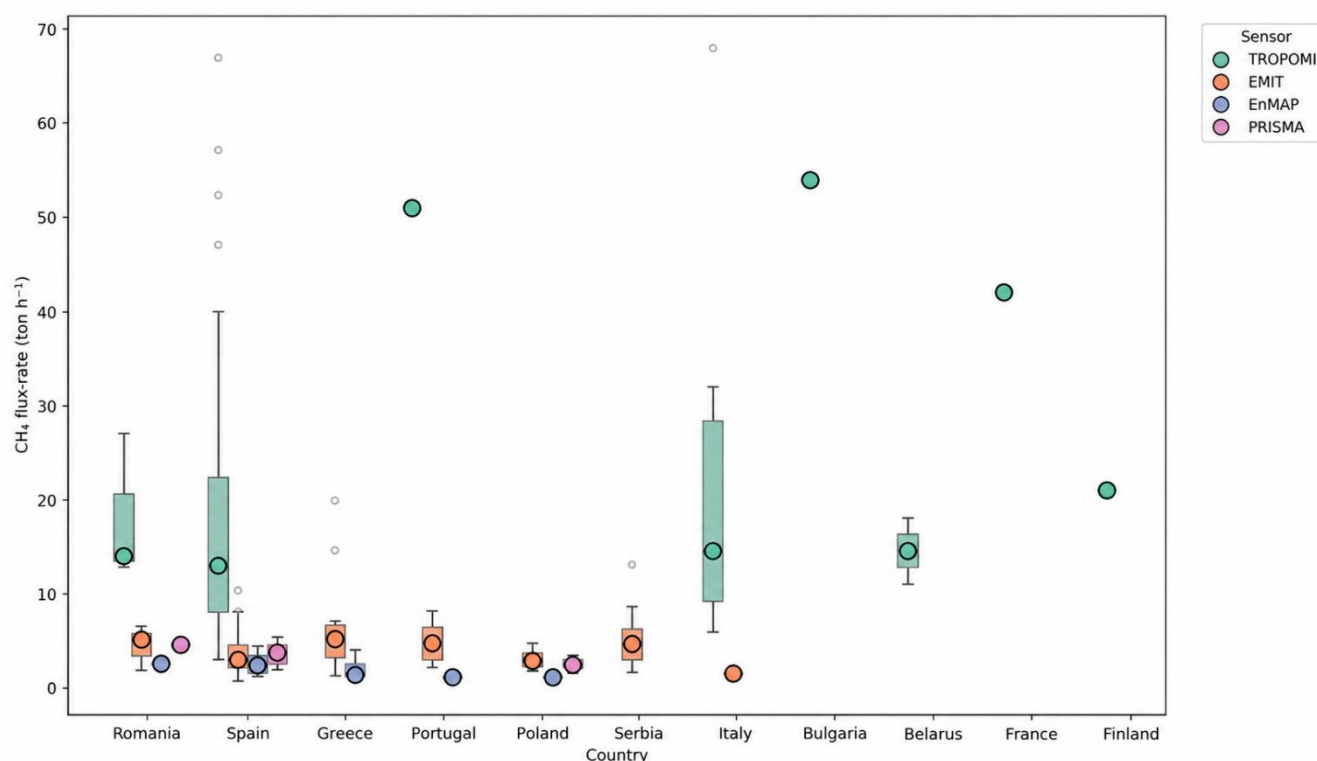


Figure 4. Country-level distribution of landfill methane emission rates ($\text{t CH}_4 \text{ h}^{-1}$) estimated from observations acquired by different satellite instruments. For each country and satellite, boxplots show the interquartile range, with coloured dots indicating the median emission rate, whiskers extending to the most extreme non-outlier values, and open circles representing outliers. Green boxes represent emission estimates derived from TROPOMI observations, orange boxes those derived from EMIT observations, blue boxes those derived from EnMAP observations, and violet boxes those derived from PRISMA observations.

Figure 4 displays the country-level methane emissions retrieved based on images from TROPOMI (green), EnMAP (blue), EMIT (orange) and PRISMA (violet). The analysis shows that the median emission values estimates from TROPOMI images are systematically higher than the the median country emissions obtained from the high-resolution hotspot-satellite. Because TROPOMI observes at a coarse (kilometre-scale) resolution and has a relatively high detection threshold, it records mainly the stronger plumes and misses many of the weak emissions that tens-of-metres hotspot sensors are able to capture.



However, the country emission distributions derived from TROPOMI is characterised by a pronounced high-emission tail, whereas the high-resolution satellite data show a narrow spread that includes numerous low-level plumes.

This discrepancy can be explained by TROPOMI's large footprint, which integrates emissions over a wider area. As a result, emissions from several nearby point sources may be aggregated into a single, higher-value detection, whereas high-resolution hotspot detectors can resolve individual sources and therefore report lower, source-specific fluxes. Similar discrepancies have also been reported for oil and gas facilities in Jervis et al., (2025).

This underscores the complementary nature of the two observational approaches: global flux mappers enable the routine detection and monitoring of large methane emitters worldwide, whereas high-resolution hotspot imagers provide more spatially resolved observations, allowing individual emission sources and their associated plumes to be more accurately characterized and quantified.

2.3 High-resolution Methane Retrievals from GHGSat : coverage, seasonal detection frequency

This section evaluates the capability of the GHGSat constellation to detect and quantify methane emissions from European landfills and investigates whether the spatial distribution of detected hotspots is associated with regions characterized by comparatively low cloud cover.

GHGSat is a commercial satellite constellation specifically designed for the detection and quantification of methane point-source emissions at the facility scale (Jervis et al., 2021). Operating since 2016, GHGSat instruments acquire targeted observations over selected areas of approximately $12 \times 12 \text{ km}^2$, with a spatial resolution of about $25 \times 25 \text{ m}^2$, with the detection threshold of GHGSat-D of $1\text{--}3 \text{ t h}^{-1}$ (Jervis et al., 2021), and GHGSat-C1,C2 $0.1\text{--}0.2 \text{ t h}^{-1}$ (Gauthier, 2021).

Unlike global methane mappers, GHGSat employs targeted observations and instrument pointing to achieve high spatial and spectral resolution while enhancing the signal-to-noise ratio. The constellation architecture enables frequent revisits of selected sites, supporting repeated monitoring of individual emission sources and their temporal variability. Following plume detection, GHGSat estimates methane emission rates using the Integrated Mass Enhancement (IME) approach. This method relates the total excess methane mass contained within the observed plume to the source emission rate by accounting for wind speed and the characteristic dimensions and morphology of the plume. Accurate wind information is therefore an important component of the quantification, as atmospheric transport controls the dispersion of methane downwind of the source. By combining high-resolution methane observations with wind information, GHGSat can derive facility-scale methane emission rates from individual detected plumes. This targeted, high-resolution observing strategy makes GHGSat particularly suitable for locating and quantifying methane emissions from individual facilities, including landfills.

Here we analyze the distribution of landfill emissions detected by GHGSat and examine the seasonality of detection counts to assess how the instrument's capability varies with season.

Figure 5 shows the geographic distribution of landfill methane hotspots identified by GHGSat during 2025, the most recent year in which the constellation was fully operational. The map is divided into the four meteorological seasons: winter (DJF; December–January–February), spring (MAM; March–April–May), summer (JJA; June–July–August), and autumn (SON; September–October–November), enabling a direct visual comparison of the satellite's seasonal footprint. The illustration shows that GHGSat is capable of acquiring measurements across a broad latitudinal span, including high-latitude regions that host occasional hotspots.

The observed spatial pattern is primarily driven by customer-initiated observation requests rather than by any intrinsic orbital or instrumental limitation of the constellation. Nonetheless, seasonal clustering is evident: the highest density of detections occurs during summer (JJA), when the probability of clear-sky conditions—and consequently the likelihood of successful observations—is greatest. This seasonal bias reflects the combined effects of user demand for monitoring of specific landfill and reduced cloud interference during the warm months.



year 2025

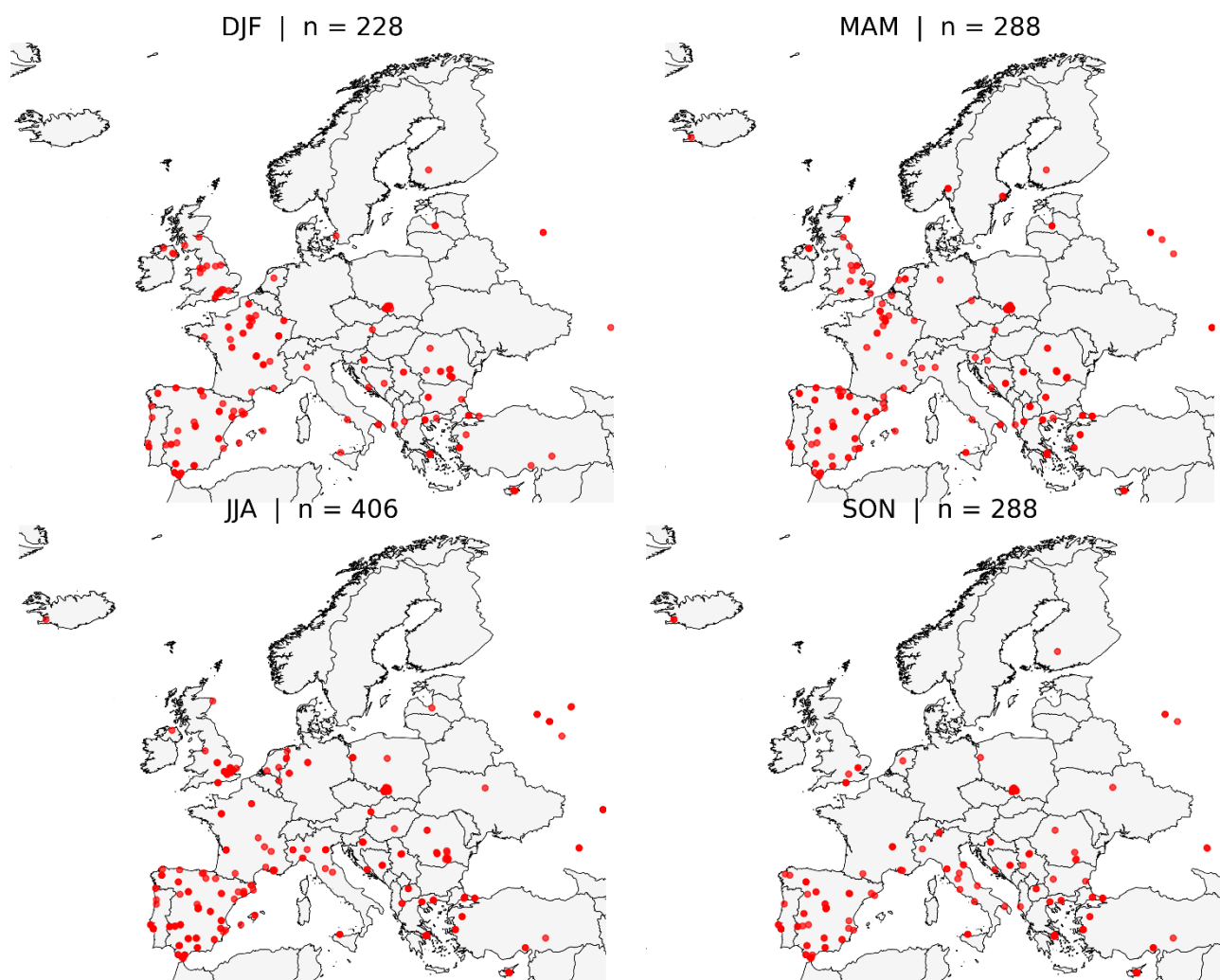


Figure 5. Seasonal footprint of GHGSat-detected landfill hotspots (2025). Locations of landfills observed by the GHGSat constellation are plotted for each meteorological season (DJF, MAM, JJA, SON). Panels distinguish the four seasons, allowing a direct visual comparison of the spatial coverage throughout the year.

Figure 6 aggregates the number of landfill observations for each season across the full 2021 – 2025 record. The bar chart shows a clear seasonal bias: the summer months (June–August) consistently yield the highest number of detections, which can be attributed to the reduced probability of cloud obstruction during this period. In contrast, the winter, spring and autumn seasons generally produce fewer than two hundred observations per year. Despite this seasonal modulation, the annual total of observations exhibits a steady upward trend, reflecting the growing interest of users in locating and quantifying methane hotspots.



Taken together, the results indicate that GHGSat is able to monitor landfill emissions across a broad latitudinal range, but the likelihood of a successful detection is enhanced in cloud-free conditions, especially during the summer season. The observed increase in the volume of data over time underscores the expanding demand for high-resolution, satellite-based methane monitoring of landfill sites. The average yearly count of landfill-hotspot detections in the two most complete years (2024 – 2025) is 1 158 observations, highlighting both the rapidly expanding data volume driven by user demand and GHGSat’s ability to monitor a much larger number of European emissions sites than those reported in CAMS MHE and IMEO. GHGSat’s global, point-based monitoring provides a more flexible coverage than the swath-based TROPOMI instrument, and the upward trend in total observations from year to year reflects increasing user demand.

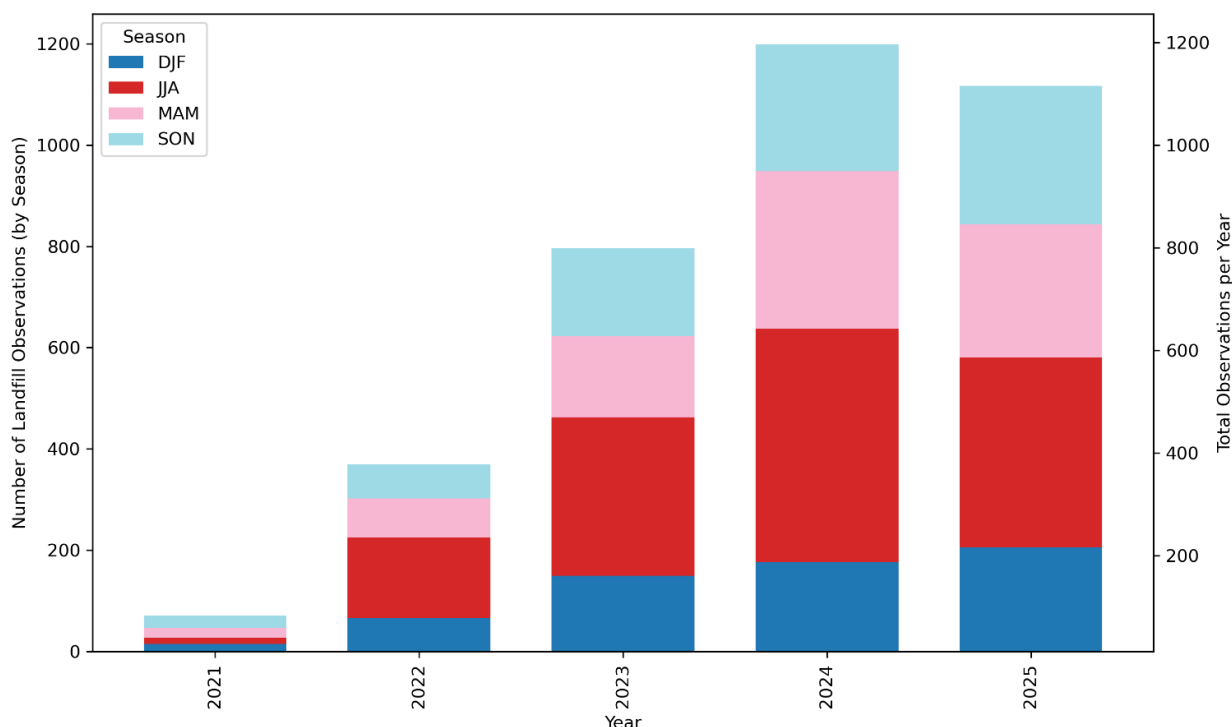


Figure 6. Seasonal and annual counts of landfill hotspots detected by GHGSat (2021 – 2026). The bar chart shows the total number of valid observations for each season (DJF, MAM, JJA, SON) and year. Summer (JJA) consistently yields the highest number of detections, reflecting the more favorable, less-cloudy conditions during that period, whereas the other seasons typically produce fewer than 200 observations per year. The upward trend in the total number of observations from year to year indicates growing demand for hotspot identification.



2.4 Facility-Level Comparison of Methane Emissions from IMEO, GHGSat, E-PRTR, and IED

In this section, we move from national aggregates to the facility scale by examining methane emission estimates for a set of individually identified landfills. For each landfill, satellite detections within $\pm 0.05^\circ$ in both latitude and longitude of the reported facility coordinates are considered, defining a $0.1^\circ \times 0.1^\circ$ coordinate-based matching window. This co-location criterion was selected to account for the relatively coarse spatial resolution of TROPOMI (approximately $5 \times 7 \text{ km}^2$) and the associated uncertainty in source localization. Only landfills for which methane plumes were detected by at least two different satellite instruments are retained. All TROPOMI-based observations—whether reported by CAMS MHE or Kayros—are pooled under the label TROPOMI, as the two products show broadly consistent emission estimates across the analysed landfill detections (Section 2.2.1.1). The Fig. 7 displays box-plots for each data source together with the individual emission points, colour-coded by season of detection, allowing a visual assessment of both the magnitude and the seasonal variability of the reported fluxes. By comparing the satellite-derived estimates with the bottom-up values from the E-PRTR/IED, we evaluate the consistency across observation-based and inventory-based approaches, identify systematic biases, highlight the added value of integrating multi-resolution satellite data with established emission inventories for robust landfill-level methane monitoring. Figure 7a shows the landfill-related emissions in Portugal obtained from 10 satellite observations (EMIT and EnMAP) together with the value reported in the E-PRTR/IED for a specific corresponding area. The EMIT measurements yield a median emission of roughly 5 t h^{-1} , but the individual observations span a wide range, from about 2 t h^{-1} to 8 t h^{-1} , with the largest fluxes detected mainly in summer. In contrast, EnMAP detected two distinct plumes during the spring season, for which the median emission is approximately 1 t h^{-1} . The E-PRTR/IED inventory lists an emission of 0.3 t h^{-1} (insert the actual figure), a value that is considerably lower than any of the satellite-derived estimates. This discrepancy highlights a clear inconsistency between the bottom-up inventory (E-PRTR/IED) and the top-down measurements obtained from space-borne sensors, underscoring the need for further investigation of the factors that cause the under-estimation in the reported inventory. The Pinto landfill is located close to Madrid area, and its emissions are reported in Fig 7b. Emission estimates based on TROPOMI observations range from approximately 3 to $52 \text{ t CH}_4 \text{ h}^{-1}$, with the highest values occurring during the summer period and a median emission rate of approximately $5 \text{ t CH}_4 \text{ h}^{-1}$. Similar median values is obtain trough the EMIT detections, ranging between more than 10 t h^{-1} to more than 3 t h^{-1} . Emission estimates based on PRISMA and EnMAP observations, together with those reported by GHGSat, show comparable median values of approximately $4 \text{ t CH}_4 \text{ h}^{-1}$. The Pinto methane emission reported in the official data base is around 0.7 t h^{-1} , around one order of magnitude of the average median emission reported by all satellites.

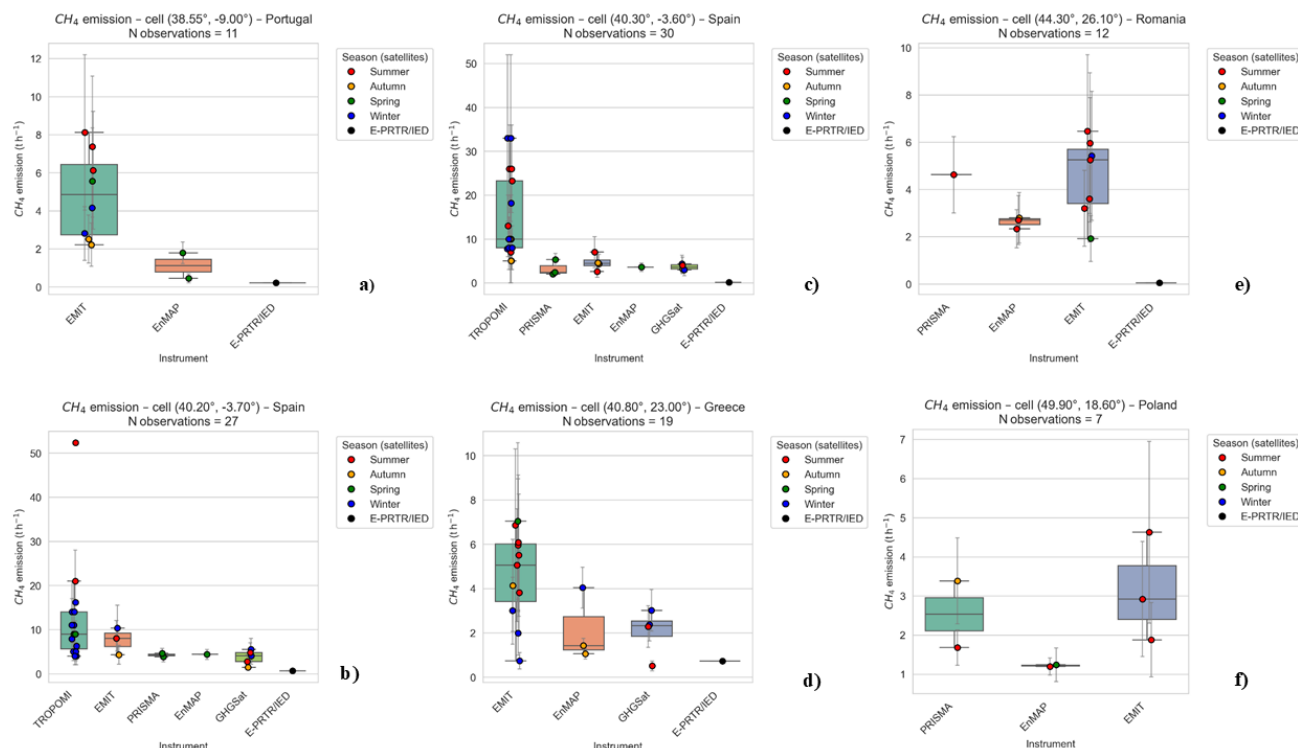


Figure 7. Seasonal box-plots of landfill CH₄ emissions. The box-plots (showing median, inter-quartile range and outliers) are constructed from the four satellite-based datasets used in this study—TROPOMI, EMIT, EnMAP and PRISMA—and are displayed alongside the values reported in the E-PRTR and IED inventories (when available). All fluxes are expressed in t h⁻¹. Seasonal observations are colour-coded: summer = red, autumn = orange, spring = green, winter = blue; inventory values are shown in black because they represent a single annual figure. The plots visualises how methane emissions from the sampled landfills vary across the four seasons.

The second spanish landfill, located on the outskirts of Madrid, is detected by all satellite sensors used in this study, and its emissions are displayed in Fig. 7c. TROPOMI records the highest fluxes and the greatest variability, with emissions ranging from almost 5 t h⁻¹ up to roughly 33 t h⁻¹; the largest values are observed during both winter and summer. The median emission derived from EMIT observations agree with those based on TROPOMI observations, in contrast, the median emissions estimated based on PRISMA (two detections), EnMAP (one detection) and GHGSat (five detections) observations are roughly half of those based on TROPOMI images, but inside the error bars of the multiple detections reported, and the figure listed in the E-PRTR/IED database is only about 0.1 t h⁻¹. The discrepancy between emissions from TROPOMI and those obtained from the hotspot-detector observations can be partially explained by their differing spatial resolutions: TROPOMI's broader footprint integrates the signal from multiple, possibly overlapping plumes in the densely populated Madrid region, whereas the hotspot detectors, with finer spatial detail, are able to isolate individual plumes. Consequently, the emission value reported in the E-PRTR/IED inventory appears unrealistically low when compared with the satellite-derived measurements. Nonetheless, a more detailed analysis—such as high-resolution plume modelling, ground-based verification, and an assessment of temporal coverage—is required to confirm the origin of these differences. The emissions reported in the Madrid inventory are highly variable, and on average they are roughly an order of magnitude lower than the values retrieved from satellite observations, indicating that the inventory figures are unrealistically low.



The Greek landfill emissions at Poligiros was observed eleven times by EMIT, three times by EnMAP, and on four passes by the GHGSat constellation, and the corresponding emissions are presented in Fig. 7d. EMIT based estimations recorded the greatest variability and the highest emissions, most of which occurred during the summer months. The median emission derived from EMIT is about 5.3 t h^{-1} , which is substantially larger than the medians obtained from EnMAP images ($\approx 1.8 \text{ t h}^{-1}$) and GHGSat observations ($\approx 2.2 \text{ t h}^{-1}$). In contrast, the E-PRTR/IED inventory reports only 0.7 t h^{-1} for this site. While the lowest satellite-derived value approaches the inventory figure, the satellite observations expose a pronounced temporal variability that the inventory does not capture. This order-of-magnitude gap between the bottom-up inventory and the top-down satellite estimates suggests that the reported inventory value warrants further investigation.

Methane plumes from the Romanian landfill were detected by PRISMA, EMIT, and EnMAP, while emissions from the same facility are also reported in the E-PRTR/IED inventory, enabling a direct comparison between satellite-derived and inventory-based estimates (Fig. 7e).

EMIT-based emission estimates show the highest flux rates, ranging from approximately 2 to $6.3 \text{ t CH}_4 \text{ h}^{-1}$, with the largest values observed during the summer months. The median emission estimates derived from all three satellite instruments are approximately one order of magnitude higher than the emission rate reported in the E-PRTR/IED inventory.

This substantial discrepancy, together with the pronounced seasonal variability captured by the satellites, suggests that the inventory substantially underestimates the true emissions from the site and warrants further investigation.

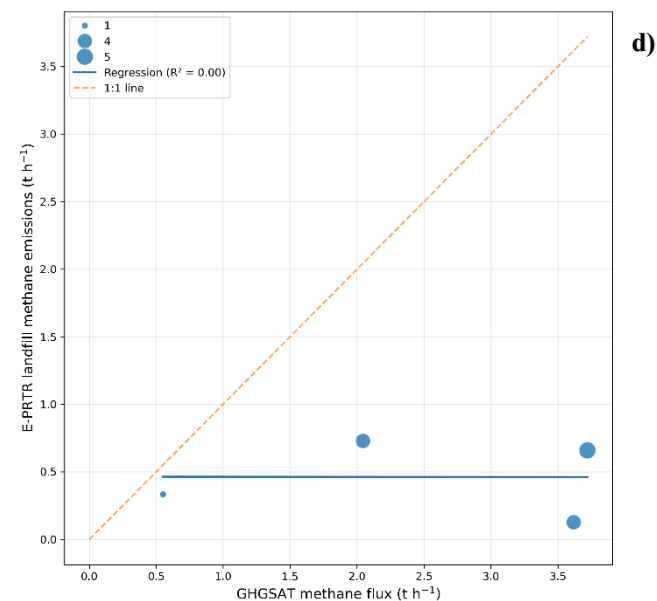
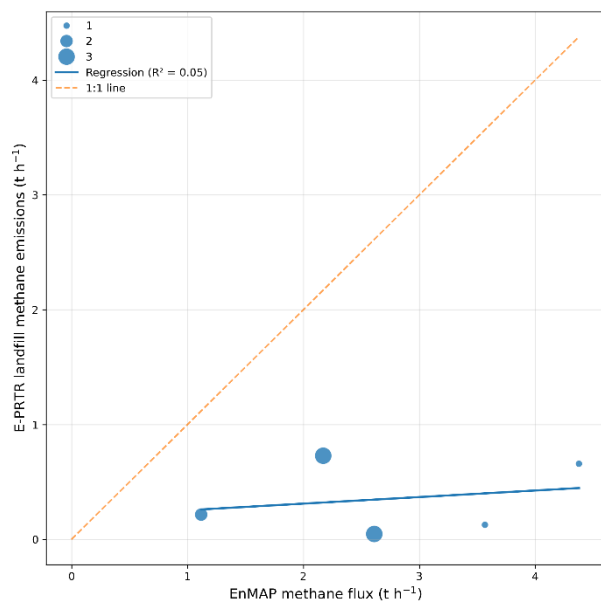
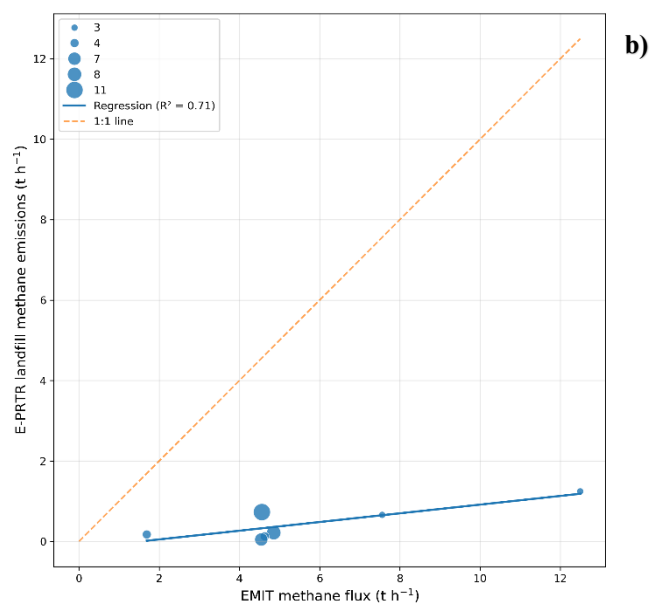
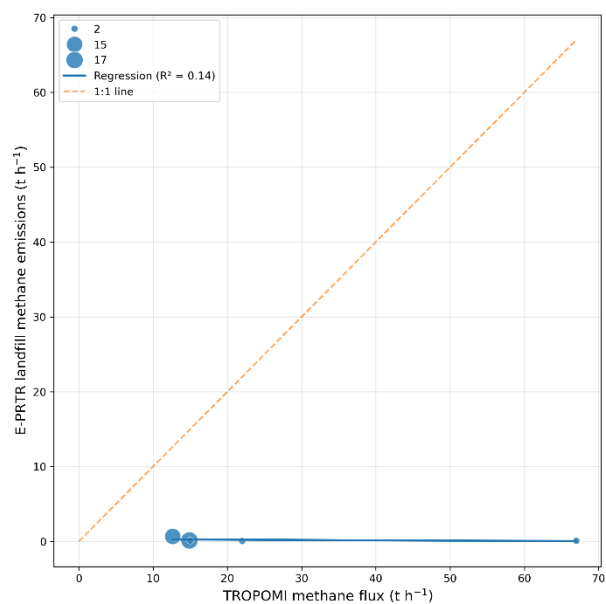
The Polish landfill emissions were detected by PRISMA, EMIT and EnMAP, with emissions ranging from 1.2 t h^{-1} to 4.7 t h^{-1} , as reported in Fig. 7f. The highest satellite-derived fluxes occurred during the summer months, while the E-PRTR/IED inventory contains no reported methane emissions for this facility. This mismatch highlights a clear inconsistency between the bottom-up inventory and the top-down satellite observations and suggests that the inventory may be substantially under-estimating—or completely missing—the landfill's contribution.

2.5 Relationship Between Satellite-Derived Methane Fluxes and Reported Landfill Emissions

In this section, we assess the relationship between satellite-derived emission estimates and reported facility-level emissions. As in the previous analyses, satellite detections are matched to reported landfill locations using a spatial co-location criterion of $\pm 0.05^\circ$ in latitude and longitude. This threshold was selected to account for the relatively coarse spatial resolution of TROPOMI (approximately $5 \times 7 \text{ km}^2$), which can introduce uncertainty in the attribution of detected methane enhancements to individual facilities. Several landfills included in the satellite datasets do not have corresponding reported emission estimates; these sites are therefore excluded from the correlation analysis.

Figure 8 compares reported facility-level methane emissions with emission estimates derived from satellite observations acquired by TROPOMI (including CAMS MHE and Kayros products), EMIT, EnMAP, and PRISMA, as compiled in the IMEO dataset, together with the 12 GHGSat observations for which quantified emission estimates are available.

Overall, no statistically significant correlation is found for emissions obtained from TROPOMI, EnMAP, PRISMA, or GHGSat observations. This lack of agreement is likely attributable to differences in spatial resolution, detection sensitivity, and source attribution capability, as well as to the limited number of matched landfills available for statistical analysis. In particular, the coarse spatial resolution of TROPOMI limits its ability to resolve individual landfill sources, thereby reducing its suitability for robust facility-scale comparisons.



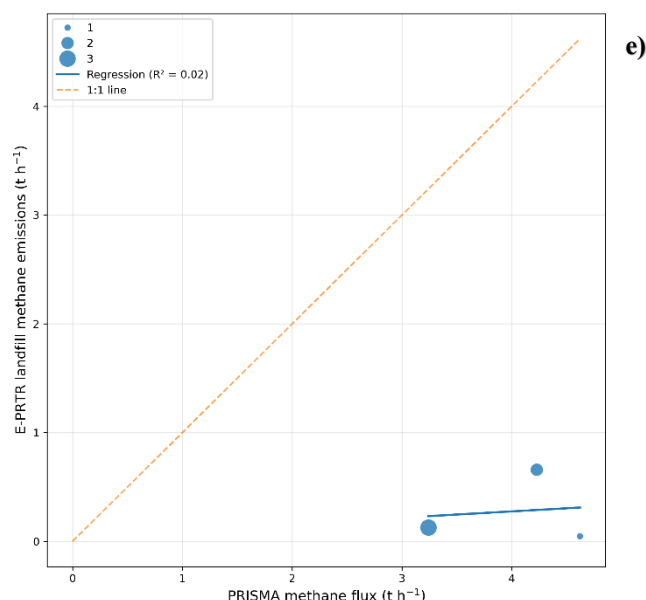


Figure 8. Comparison between landfill methane emissions reported in the E-PRTR inventory and satellite-derived methane emission estimates from (a) TROPOMI, (b) EMIT, (c) EnMAP, and (d) PRISMA. Each point represents a landfill facility (or a co-located satellite observation) matched using a spatial co-location criterion of $\pm 0.05^\circ$ latitude–longitude. Satellite-derived emissions are plotted against corresponding inventory-reported methane emissions. Solid lines indicate ordinary least-squares linear regression fits, while dashed lines represent the 1:1 correspondence line. Marker size is proportional to the number of individual observations used to compute each aggregated emission value. The coefficient of determination (R^2) is reported for each dataset to quantify the strength of the relationship. The comparison highlights differences in consistency between bottom-up inventory estimates and top-down satellite observations across the different observing systems.

Emission estimates based on PRISMA observations provide only a limited number of matched detections ($n = 3$), which is insufficient for a meaningful correlation analysis. Similarly, the small sample sizes available for EnMAP ($n = 5$) and GHGSat ($n = 4$) preclude robust statistical inference.

By contrast, emission estimates based on EMIT observations—characterised by higher spatial resolution and improved source-localisation capability—could be matched with reported emissions for seven landfill sites and show a statistically significant correlation ($R = 0.7$).

However, a systematic positive bias is observed, with satellite-derived emissions exceeding reported values by a mean of 5.31 t h^{-1} . This corresponds to a normalized mean bias of 11.6 and an average EMIT-to-EPRTR ratio of 12.6, indicating that EMIT-derived fluxes are approximately one order of magnitude higher than inventory-based estimates at co-located grid cells. This discrepancy likely reflects a combination of temporal representativeness differences (instantaneous satellite plume observations versus annual reported emissions), incomplete reporting in bottom-up inventories, and the episodic nature of methane emissions from landfills.

The results further suggest that current reporting frameworks may substantially underestimate landfill methane emissions, particularly when moderate and intermittent emitters are not fully captured. Such underestimation has important implications for regional and global methane budgets, potentially leading to a systematic bias in the attribution of methane sources and affecting the assessment of mitigation progress under climate and methane-reduction policies.



3 Discussion

3.1 Bottom-up inventories

The low reporting completeness implies that the bottom-up inventory is highly incomplete, making the EU landfill-sector methane budget highly uncertain and hampering efforts to improve our understanding of this emission sector.

575 Moreover, 67 % of landfills exhibit methane emissions below the reporting threshold of approximately 0.01 t h^{-1} and therefore do not report emissions. Even among facilities that do report emissions, the average value ($\approx 0.10 \text{ t h}^{-1}$) remains well below the detection limits of satellite sensors providing area-averaged (“global-mapper”) fluxes. For example, the single-overpass detection threshold of TROPOMI is approximately 0.5 t h^{-1} per pixel.

580 Consequently, most landfill sources would be invisible in the global-scale methane maps produced by such instruments. Using higher-resolution satellite sensors that operate as targeted hotspot detectors—e.g. the GHGSat constellation—methane fluxes as low as 100 kg h^{-1} ($\approx 0.10 \text{ t h}^{-1}$) can be retrieved.

This detection limit is comparable to the mean landfill-emission intensity reported in EU bottom-up inventories ($\approx 0.10 \text{ t h}^{-1}$). However, it remains insufficient to monitor most landfill emissions, particularly because many facilities report emissions below the regulatory threshold of 0.01 t h^{-1} . If inventory values are taken at face value, only about 7 % of the total European
 585 landfill-methane budget would exceed the detection threshold of hotspot-detection instruments such as GHGSat. This proportion corresponds to roughly 223 landfills, or about 20 % of all sites that have reported emissions.

In practice, however, GHGSat observations across Europe have already identified more than 3 441 individual landfill hotspots. The number of satellite-detected sources therefore far exceeds the 223 sites that inventories would suggest are observable based on declared emissions and instrument detection limits. This discrepancy provides a clear quantitative illustration of the
 590 systematic under-reporting of landfill methane emissions in the E-PRTR/IED dataset and highlights the added value of satellite observations for identifying previously unreported sources. It also underscores the importance of space-borne hotspot detection (Duren et al., 2019), the maximum emission reported in the E-PRTR/IED inventories (2.7 t h^{-1}) is almost one and a half orders of magnitude lower than the largest methane flux identified by the CAMS-MHE and IMEO products ($\approx 69 \text{ t h}^{-1}$) - see chapter 3. It should be noted that emission detections and reported emissions do not always refer to the same year. Moreover, inventory
 595 emissions are reported on an annual basis, whereas landfill emission detections represent instantaneous measurements.

Taken together, the prevalence of unreported emissions, the generally low magnitude of the reported values, and the stark contrast between the reported maximum and the satellite-observed maximum highlight a substantial under-representation of landfill methane in the official inventories. Closing this gap requires more comprehensive and consistent ground-based reporting, as well as targeted field campaigns in regions with low cloud cover. Integrating such observations with
 600 cloud-penetrating satellite sensors will improve the completeness and reliability of both bottom-up and top-down assessments of landfill methane emissions, thereby supporting the EU’s climate-neutrality and methane-reduction objectives.

3.2 Insights from Global and Hot-Spot Satellite Measurements

In our study we analysed emissions derived from a daily, globally-covering sensor (TROPOMI) together with high-resolution hotspot detectors such as PRISMA, EMIT and EnMAP. TROPOMI provides near-daily, worldwide observations with a pixel
 605 size of roughly $5 \text{ km} \times 7 \text{ km}$, so each measurement integrates the methane column over a large area that often contains several sources in addition to the landfill itself. This coarse spatial sampling tends to yield higher flux estimates; the elevated values are likely because the measured signal represents the combined contribution of multiple landfill plumes and may also include surrounding anthropogenic emissions, especially in densely populated regions.



The strength of TROPOMI lies in its ability to flag anomalous plume behaviour across broad spatial extents, making it well-suited for identifying where and when emission spikes occur. In contrast, hotspot detectors operate at much finer spatial scales (tens to a few hundred metres) and can isolate individual plumes, providing a more accurate quantification of the intensity of a single source. Consequently, while TROPOMI excels at detecting anomalies on a global scale, the hotspot instruments deliver the precise, source-specific emission rates required for detailed budgeting and mitigation planning.

3.3 Seasonal variability of landfill methane emissions

Landfill-derived methane shows seasonal variability when the different observation periods are examined. In our analysis we grouped the satellite-derived fluxes by season to highlight the influence of the main physical drivers. This approach is deliberately simple; a full quantification of the factors controlling landfill emissions would require site-specific modelling. Nevertheless, the main processes that modulate methane release can be summarised as follows. Waste composition matters: food-waste, yard-waste, textiles and other fractions each have a distinct biogeochemical response. Temperature and soil moisture also play a role—warm, dry conditions accelerate methanogenesis, whereas wet soils can either enhance or suppress emissions depending on oxygen availability. Runoff and leachate dynamics affect the movement of liquid through the waste mass, transporting methane-producing substrates or diluting them. Finally, biological time lags introduce characteristic delays between waste deposition and peak methane release. Food-waste typically peaks 150–200 days after placement, producing the highest fluxes in late summer or early autumn; yard-waste reaches its maximum earlier (spring to early autumn) because fresh plant material decomposes rapidly; textile-related waste shows a delayed response, with elevated emissions persisting into the cooler months.

This pattern—reflecting the combined effects of waste composition, temperature, moisture, runoff, and the intrinsic biological lag of different waste streams—appears to be supported by satellite observations, which show higher emission values during the summer months. However, nearly half of all detections also occur in summer, when reduced cloud cover and more favourable solar illumination increase the likelihood of detecting landfill emissions.

Given the limitations associated with satellite detection thresholds, cloud cover, and solar angle, further analyses are required to better constrain the quantitative assessment of seasonal variability in landfill methane emissions throughout the year.

Our results demonstrate that individual landfills can experience strong intra-annual fluctuations, a dynamic that is not captured by the single-year, bottom-up values reported in the E-PRTR/IED. This mismatch underscores the need for temporally resolved reporting in official emission inventories to better reflect the true seasonal behaviour of landfill methane emissions.

3.4 Evidence for Potential Underestimation of Reported Landfill Methane Emissions

The comparison between satellite-derived methane emissions and inventory-reported landfill emissions reveals substantial variability among the satellite datasets considered. While the overall correlations are generally weak, reflecting differences in temporal representativeness and the episodic nature of landfill methane emissions, the EMIT observations indicate emissions that are, on average, approximately one order of magnitude higher than the corresponding reported values. This finding suggests the potential for significant underestimation of landfill methane emissions in current reporting frameworks. However, similar discrepancies are not consistently observed in the other satellite datasets. This likely reflects differences in observational coverage, detection thresholds, revisit frequency, and retrieval sensitivity rather than evidence against inventory underestimation. In particular, the limited number of detections available from several satellite products reduces the statistical robustness of the comparison and may prevent the identification of moderate emitters. Consequently, although emission estimates based on EMIT observations suggest that reported landfill emissions may be substantially underestimated at some facilities, additional observations from current and future high-resolution methane-monitoring missions are needed to assess



whether these discrepancies are representative of the broader European landfill sector. If confirmed, such underestimation could have important implications for European methane budgets and the evaluation of methane mitigation policies.

4 Conclusions

This study aimed to assess the capability of current satellite observations to detect and quantify methane emissions from European landfills and to evaluate their consistency with facility-level emissions reported in the E-PRTR/IED inventories. By combining emission estimates reported in IMEO and derived from observations acquired by TROPOMI, EMIT, EnMAP, and PRISMA with independent GHGSat emission estimates, the analysis examined the spatial and temporal coverage of landfill methane detections, differences in emission estimates derived from different satellite observing systems, and discrepancies between satellite-derived and inventory-reported emissions.

The IMEO database provides a useful, although still limited, framework for identifying large landfill-related methane emissions across Europe. TROPOMI-based detections account for approximately half of the European landfill observations recorded in IMEO, with CAMS MHE contributing about 77% of the detections derived from TROPOMI observations. This highlights the value of global mapping instruments for identifying large methane emitters over broad spatial scales, while also reflecting their limitations for facility-scale source attribution and quantification.

TROPOMI-based products represent the largest fraction of landfill methane detections reported in IMEO. However, owing to TROPOMI's relatively coarse spatial resolution for facility-scale emission monitoring, detection threshold, and sensitivity to cloud cover, these products primarily identify large emission events. Detections are concentrated during the summer months and in Mediterranean regions, where observational conditions are generally more favourable.

Consequently, smaller or intermittent landfill emissions may remain undetected. These observational constraints indicate that the absence of a satellite detection should not be interpreted as evidence of negligible methane emissions and limit the fraction of the European landfill sector that can currently be monitored using TROPOMI alone.

Landfill methane detections retrieved from high-resolution satellite imagery and reported in IMEO complement the TROPOMI-based observations. In particular, EMIT, EnMAP, and PRISMA provide substantially finer spatial resolution and lower detection limits, enabling smaller methane plumes and their associated sources to be more accurately identified and characterized at the facility scale. Among the high-resolution satellite sensors, EMIT provides the largest share of detections, accounting for 37% of the total European landfill observations reported in IMEO. However, the limited number of available retrievals prevents a robust characterization of landfill methane emissions at the country level.

The majority of detected emissions considered are confined in Mediterranean basin—especially in the southern parts of Spain, Italy and Greece—where relatively low cloud cover improves the likelihood of successful satellite retrievals.

The sensitivity of satellite monitoring to cloud fraction and solar-zenith angle limits the ability to pinpoint individual facilities, a problem that becomes more acute at higher latitudes where persistent clouds and low sun angles are common.

I would add that result explicitly, while keeping the distinction between detections and quantified emissions:

In addition, the larger GHGSat dataset of landfill detection locations and acquisition times was analysed to characterize their spatial and seasonal distribution. In contrast to the IMEO detections, which are more concentrated in Mediterranean regions, GHGSat detections show a broader geographical distribution across Europe, indicating that landfill methane plumes are also detected extensively outside the Mediterranean area. However, quantified emission rates were available for only 12 observations, which were used to assess point-source emission magnitudes and enable comparison with IMEO-based and inventory-reported emission estimates.

Despite these constraints, TROPOMI provides a valuable first-order map that can be used to select candidate landfills for more detailed investigation. High-resolution methane hotspot detectors, including GHGSat, EMIT, EnMAP, and PRISMA, operate at spatial resolutions of tens of metres and can achieve detection limits on the order of $0.1 \text{ t CH}_4 \text{ h}^{-1}$, although sensitivity varies



among instruments and observing conditions. Their finer spatial resolution enables more accurate plume localization and source attribution at the facility scale, allowing the detection and quantification of smaller emission sources that may remain below the detection capability of TROPOMI.

695 Although the available satellite observations do not allow the entire European landfill sector to be comprehensively characterized, landfills detected from space show a clear tendency toward underestimation in reported emissions, with satellite-derived estimates approximately one order of magnitude higher than the corresponding inventory values. The largest discrepancies are observed during the summer months, potentially reflecting both seasonal increases in methane production associated with warmer conditions and more favourable satellite observing conditions, which increase the likelihood of plume detection.

700 Top-down landfill emission estimates reveal pronounced intra-annual variability that cannot be captured by annual bottom-up inventory figures. This variability likely reflects the combined effects of waste composition, temperature, soil moisture, and leachate dynamics. However, accurately quantifying the annual landfill emission budget requires consistent, year-round monitoring. Without monthly observations, satellite measurements may preferentially detect larger emissions during warmer periods—when higher temperatures, increased moisture, enhanced microbial activity, and more favorable cloud conditions promote stronger emissions and improved detectability—potentially leading to an overestimation of total annual emissions. Taken together, these results highlight three key messages:

1. Screening capability: Global flux mapper such as TROPOMI-derived estimates efficiently narrow the search space to the most active landfill emitters, but the satellite's kilometre-scale spatial resolution can blend the emissions of several nearby sources into a single plume. This mixing reduces the accuracy of the retrieved fluxes and masks the true variability of individual landfill emissions.

2. Value of high-resolution observations: EMIT, EnMAP, PRISMA and GHGSat provide the spatial detail needed to quantify individual landfill fluxes and to resolve the temporal variability that coarse-resolution products smooth out.

3. Bottom-up inventories: comparing the bottom-up figures with our top-down satellite estimates shows a pronounced under-reporting of landfill methane emissions. In most cases the inventory values are more than an order of magnitude lower than the fluxes derived from space, indicating that European landfill emissions are likely severely underestimated. However, constraining the annual emission budget requires year-round monitoring of emissions, which is not currently achievable using available satellite observations. A substantial proportion of landfills declare methane emissions below the reporting threshold of 0.01 t h^{-1} and therefore do not report emissions at all. In addition, inventories typically provide only annual totals, thereby omitting the strong seasonal variability revealed by satellite observations. This lack of temporal resolution can bias the assessment of both the magnitude and the timing of emissions. Consequently, future emission registries should adopt monthly or seasonal reporting windows to capture the intra-annual dynamics and to produce more realistic, policy-relevant inventories.

4. Systematic Emission Bias. TROPOMI-based methane emission estimates show limited correlation with inventory-reported values; however, its relatively coarse spatial resolution prevents robust facility-level source attribution and therefore precludes firm conclusions regarding the consistency between the two emission estimates at this scale. The high-resolution datasets from PRISMA, EnMAP, and GHGSat do not show statistically significant correlations with reported emissions; however, the number of available landfill detections is too limited to support robust statistical conclusions. For GHGSat, the absence of a significant correlation is consistent with the findings of Dogniaux et al., (2025) who also reported weak agreement between reported and satellite-derived landfill methane emissions. In contrast, the high-resolution EMIT dataset shows a substantially stronger relationship with reported emissions. EMIT, which accounts for approximately 75% of all high-resolution landfill detections considered in this study, exhibits a relatively strong correlation with inventory-reported values while simultaneously revealing a pronounced positive bias. For a subset of landfills, satellite-derived emissions exceed reported values by up to one order of magnitude, suggesting that current inventory frameworks may not fully capture the magnitude of methane emissions from some facilities. These findings highlight both the value of high-resolution satellite observations for independent emission verification and the potential limitations of existing reporting approaches. This discrepancy suggests that current inventories

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may not fully capture the magnitude and temporal variability of landfill methane emissions. These findings demonstrate that satellite observations provide critical and independent constraints on landfill methane emissions that are not captured by existing inventory frameworks.

740 Furthermore, the magnitude of the bias observed in the EMIT-based estimates suggests that methane emissions from some European landfills may be substantially underestimated. If this underestimation were confirmed across a larger and representative sample of facilities, it could indicate that the contribution of the landfill sector to the European methane budget is currently underestimated, with important implications for emission inventories, verification systems, and the assessment of progress towards EU methane mitigation targets.

745 Future work should focus on coupling satellite observations with ground-based flux measurements to quantify retrieval uncertainties, on expanding the temporal coverage of high-resolution sensors, and on developing data-fusion frameworks that can translate the rich, seasonally resolved satellite information into more accurate, policy-relevant inventory estimates.

Code and data availability

Meteorological data used in this study were obtained from the ERA5 reanalysis produced by ECMWF and are publicly available through the Copernicus Climate Data Store. Methane emission information was obtained from the International
750 Methane Emissions Observatory (IMEO) database through its respective data-access services.

GHGSat methane observations were provided through an ESA-funded project and are subject to commercial licensing restrictions. Consequently, the original GHGSat data cannot be redistributed by the author. Access to these data may be requested directly from GHGSat, subject to applicable licensing agreements.

755 The scripts used for data processing, analysis, and figure generation, together with the derived datasets necessary to reproduce the results presented in this paper, are available from the author upon reasonable request.

Author contributions

The author performed all aspects of the study and prepared the manuscript.

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Competing interests

The contact author has declared that none of the authors has any competing interests.

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780 Review statement

The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees according to their status anonymous or identified.

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