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Reconciling a national methane emission inventory with in-situ measurements

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ABSTRACT

Reconciling top-down and bottom-up country-level greenhouse gas emission estimates remains a key challenge in the MRV (Monitoring, Reporting, Verification) paradigm. Here we propose to independently quantify cumulative emissions from a significant number of methane (CH_4) emitters at national level and derive robust constraints for the national inventory. Methane emissions in Cyprus, an insular country, stem primarily from waste and agricultural activities. We performed 24 intensive survey days of mobile measurements of CH_4 from October 2020 to September 2021 at emission 'hotspots' in Cyprus accounting together for about 28 % of national CH_4 emissions. The surveyed areas include a large active landfill (Koshi, 8 % of total emissions), a large closed landfill (Kotsiatis, 18 %), and a concentrated cattle farm area (Aradippou, 2 %). Emission rates for each site were estimated using repeated downwind transects and a Gaussian plume dispersion model. The calculated methane emissions from landfills of Koshi and Kotsiatis (25.9 ± 6.4 Gg yr^{-1}) and enteric fermentation of cattle (10.4 ± 4.4 Gg yr^{-1}) were about 129 % and 40 % larger, respectively than the bottom-up sectorial annual estimates used in the national UNFCCC inventory. The parametrization of the Gaussian plume model dominates the uncertainty in our method, with a typical 21 % uncertainty. Seasonal variations have little influence on the results. We show that using an ensemble of in situ measurements targeting representative methane emission hotspots with consistent temporal and spatial coverage can contribute to the monitoring and validation of national bottom-up emission inventories.

1. Introduction

Methane (CH_4) is a potent greenhouse gas with a nine-year atmospheric lifetime and 28 times the global warming potential of CO_2 on a 100-year horizon (Masson-Delmotte et al., 2018). The globally averaged surface mole fraction of CH_4 has already increased 2.6 times above pre-industrial levels, from 722 ppb to 1895.7 ppb (NOAA, 2022). The annual growth rate reached 17 ppb in 2021, the largest rate since the start of direct measurements in 1983. Methane's short lifetime compared to CO_2 and its strong radiative forcing make it a key target in the climate change mitigation action portfolio (Nisbet et al., 2020). However, CH_4 emissions and sinks are still poorly constrained at all scales due to the variety, heterogeneity and variability of anthropogenic and natural sources and sinks, with emissions often overlapping geographically (Saunois et al., 2020).

Anthropogenic CH_4 emission inventories are based on activity data and emission factors. Other bottom-up approaches for biogenic fluxes may rely on numerical simulations of emission processes at all relevant scales, typically for biogenic processes such as wetland models (e.g., Wania et al., 2013). Atmospheric measurements, either from space or in-situ from long term networks and mobile platforms (e.g., vehicles, ships and aircraft) can provide valuable insight on bottom-up emissions from local to global scales (e.g. Brantley et al., 2014; Lan et al., 2015; Turner et al., 2016; Johnson et al., 2017; Defratyka et al., 2021; Paris et al., 2021; de Foy et al., 2023). At large scales, inverse modeling uses atmospheric measurements to correct CH_4 emissions inventories. These top-down methods have been applied to optimize global, continental or national-scale emission estimates (e.g. Bergamaschi et al., 2015; Lu

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et al., 2022). Recent top-down inversion studies using TROPOMI data suggested that CH_4 bottom-up emissions were underestimated by 21 % in China (Chen et al., 2022), a result contrasting the synthesis of Saunois et al. (2020). Additionally, anthropogenic CH_4 national total emissions estimated using inverse modeling in Europe, the United States, Canada and Mexico are higher by about 20 %–40 %, 40 %, 30 % and 20 %, respectively, compared to bottom-up national emission inventories (Cheewaphongphan et al., 2019; Bergamaschi et al., 2015; Peng et al., 2016; Lu et al., 2022).

It has been debated whether atmospheric-based approaches at local scales could be more relevant to support the reported national inventories (Leip et al., 2017). However, large discrepancies do exist between top-down (TD) and bottom-up (BU) estimates at local/regional scales (Hsu et al., 2010; Lamb et al., 2016; Ren et al., 2018; Lu et al., 2022; Vechi et al., 2022). For example, airborne-based CH_4 calculated emissions in the San Francisco Bay Area was approximately twice as large as the respective values given on regional scale inventories (Guha et al., 2020). For point sources, Lavoie et al. (2015) reported that methane emission measurements from airborne mass balance approach were 3.2–5.8 times greater than the bottom-up estimates. Foulds et al. (2022) found that methane emissions fluxes from offshore oil and gas facilities were 42 % larger than the inventory data for the area. Upscaling nationally, several recent studies have suggested that in US methane emissions from oil and gas supply chains, animal husbandry and fossil fuel industries estimated by top-down approach is higher than the inventory estimate (Miller et al., 2013; Allen et al., 2013; Alvarez et al., 2018; Rutherford et al., 2021). Similarly, Vechi et al. (2022) reported that bottom-up inventories underestimated national CH_4 emissions in Denmark from cattle farms by 35 % in comparison with the top-down method. Therefore, it is necessary to better understand these discrepancies to improve confidence in methane emission estimates from both methods.

Reconciling top-down and bottom-up approaches at the national level is required to establish a reliable estimate of global methane emissions and to monitor the impact of mitigation strategies on emissions. However, comparing national emission inventories with atmospheric measurements is still hindered by several factors. First, atmospheric dynamics have to be characterized and simulated properly as the atmosphere is an integrator of any combination of emitters along air mass trajectory and a dispersion mechanism for individual sources. Second, the activity sectors identified in national inventories are not necessarily spatially separated on the ground and disentangling their contributions in individual measurements may be challenging. Finally, both top-down and bottom-up methods are associated with significant methodological uncertainties and there is no single ground truth (Yu et al., 2020). Therefore, discrepancies are difficult to interpret because approaches cannot be easily reproduced with complete, independent, temporally and spatially consistent data (Schwietzke et al., 2017).

Methane inventories in “small” countries and emerging hotspots of climate change, such as the Eastern Mediterranean and the Middle East (EMME) region, are still poorly developed (Giorgi, 2006). It remains challenging to characterize, validate and quantify spatial distributions and emission magnitudes in these regions. Such countries may present a relatively small number of large emitters and their national inventories cannot be easily compared to global or regional inversions. We therefore investigate a representative EMME country to assess whether independent, mobile, repeatable atmospheric measurements can be robustly used in the verification of reported national inventories.

We performed mobile CH_4 measurements (24 survey days within one full year) in Cyprus, an island country of 9251 km^2 in the eastern Mediterranean Sea with a population of 1.2 million. Cyprus provides a very relevant framework to work on the bottom-up versus top-down discrepancies: it is located in an emerging hotspot of GHG emissions (EMME region), it has only two main sectors emitting methane (agriculture and waste), and its reasonable surface area makes it possible to monitor a larger part of national emissions with mobile platforms. According to Cyprus's National Inventory Report (NIR) for 2022 submitted to the United Nations Framework Convention on Climate Change (UNFCCC), in Cyprus, 57 % of CH_4 is emitted from waste and 41 % from agricultural activities. The representative local CH_4 emission hotspots Koshi (active landfill), Kotsiatis (closed landfill) and Aradippou area (cattle farms), accounting for about 28 % of CH_4 national emissions (NIR, 2022), were selected to validate the national bottom-up inventory. We quantified the emission rates of these hotspots using a Gaussian plume model (Mallet et al., 2007). This comprehensive study aims at bridging the gap between top-down and bottom-up approaches and improving our understanding of CH_4 emissions on the national scale for Cyprus. After presenting this work's methodology (Section 2), we detail and discuss the results obtained (Section 3).

2. Materials and methods

2.1. Mobile system

We conducted 24 mobile surveys (24 days) between October 2020 and September 2021. A cavity ring-down spectrometer (CRDS) model G2401 manufactured by Picarro Inc. (USA) was employed to measure CH_4 with 1 Hz time resolution (Crosson, 2008). The analyzer was calibrated every month using the WMO X2004 scale (Yver Kwok et al., 2015). All the data reported in this study were quality controlled with the Integrated Carbon Observation System-Atmosphere Thematic Center (ICOS-ATC). The precision in measured CH_4 is 0.7 ppb (Yver Kwok et al., 2015). The instrument was installed into a thermal-engine vehicle also equipped with a GPS device (NEO-M8N-0-10 U-Blox) and a sonic anemometer (150WX RS232 Weather Station Instrument) on the roof. In addition, the air inlet was added to the roof of the car, close to the anemometer (about 190 cm above the ground), as shown in Fig. 1. A real-time charging system was setup in the vehicle, allowing the battery to get charged while driving. The latter allowed for prolonged observations. All the data recorded were visible in real-time and used for decision-making during each mobile measurement survey. Data logs accounted for the time delay of air traveling from the inlet to the analyzer for each survey day.

2.2. Survey area

We conducted mobile GHG measurements throughout Cyprus. Most people live in the following four cities Nicosia, Larnaca, Limassol, and Paphos. The national methane inventory indicate that agriculture (mostly ruminants) and waste management (mostly solid waste) are the highest emitting sectors. Energy only represents 2 % of methane emissions (NIR, 2022). The active landfill Koshi was selected as a major CH_4 emission hotspot. Kotsiatis, the largest closed landfill still emitting CH_4, was selected as another major survey hotspot. Aradippou, with relatively concentrated cattle farms and about 5.2 % of the total national cattle population (82,904 cows in total) (NIR, 2022), was selected as the last survey area. In summary, surveyed areas account for about 28 % of the total CH_4 emissions in Cyprus (NIR, 2022), as shown in Fig. 2.

2.3. Measurement protocol and data collection

Every month, two consecutive days of mobile survey were carried out around midday, when the air was well mixed in the planetary boundary layer. This allowed us to collect data in all seasons and under different wind conditions for each emitter. Each fieldwork day surveyed the three selected sites. Whenever CH_4 emission plumes were visible on the monitoring screen, 3–5 repeated transects, used to investigate gradual changes in CH_4 concentrations, were followed at a driving speed of 20–30 km h^{-1}, if the traffic condition permitted. This speed range has been identified optimal (Lowry et al., 2020) during Gaussian plume peak shape characterization. Generally, the duration of each survey was 6–7 h. A pre-survey was performed at Aradippou to confirm this area is only

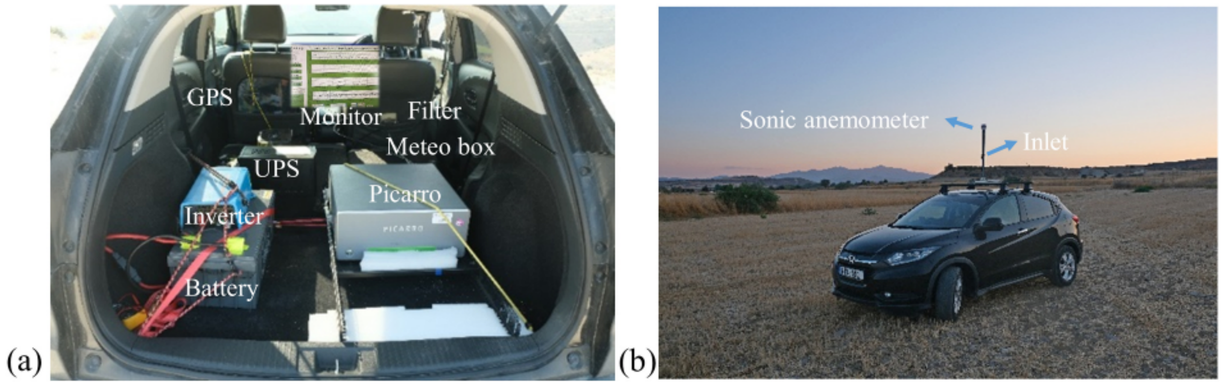

Fig. 1. Components of the mobile measurement system, (a) is the setup inside the car and (b) is outward of the car.

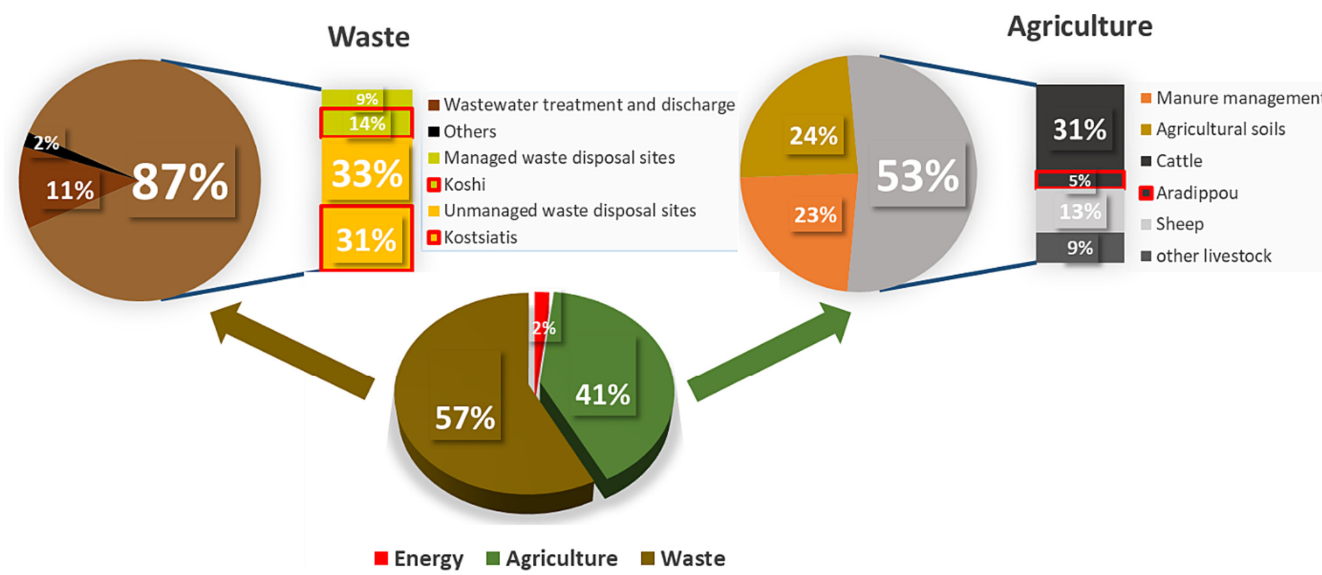

Fig. 2. The source categories of methane emissions in Cyprus (NIR, 2022).

for cattle farms and find proper driving paths to catch plumes for later mobile measurements.

The second percentile of measured methane mole fractions in each survey was selected as the daily background for emission rate calculations of all transects. Fig. 3 shows the geographical locations of these three hotspots and an example of a one-day survey path at each site (about 15 km between sites).

2.4. Emission rate estimates from in-situ measurements

The emission rates were estimated using the Gaussian plume model by comparing the model output to the observations for each measured transect. We obtained 65, 81 and 108 transects for Koshi, Kotsiatis and Aradippou, respectively. However, in some cases, the model cannot reasonably reproduce the observations and obtain similar plume structure due to excessive atmospheric variability (e.g. wind direction and wind speed), long source-receptor distance, the presence of obvious turbulent structures or unfavorable transport conditions in the model (e.g. low wind condition) (Ars et al., 2017; Caulton et al., 2018). In such situations, the confidence in about 40 % of the transects was deemed too low and disregarded from the analysis. Finally, only 41, 50 and 53 transects were considered for analysis at Koshi, Kotsiatis and Aradippou, respectively (Figs. S1 and S2 provided simulation results including selected, flagged out transect examples and source plume examples at each site).

2.5. The Gaussian plume model

The Gaussian plume model used in this study is embedded in the Polyphemus air quality modeling system (http://cerea.enpc.fr/polyphemus/introduction.html) (Mallet et al., 2007). This model is described in the study by Korsakissok and Mallet (2009), and has been proved to be adequate for gas emission estimates at a local scale. Some assumptions are generally made in analyzing the Gaussian plume model, including constant wind speed and direction with time and elevation and the terrain is relatively flat and open country. Gaussian plume models are based on a simple formula, which provides the concentration of methane emitted from a point source during ambient stationary weather conditions:

$$\mathrm{C}(\mathrm{x},\mathrm{y},\mathrm{z}) = \frac{q}{2\pi\overline{u}\sigma_y\sigma_z}exp\left(-\frac{(y-y_s)^2}{2{\sigma_y}^2}\right) \times \left[exp\left(-\frac{(z-z_s)^2}{2{\sigma_z}^2}\right)+exp\left(-\frac{(z+z_s)^2}{2{\sigma_z}^2}\right)\right] \quad (1)$$

Here, C is the methane concentration at coordinates (x,y,z); the x-axis is in the wind direction, the y-axis refers to the horizontal crosswind direction, and the z-axis is the vertical coordinate. Further, y_s is the source ordinate, z_s refers to the release height above the ground (e.g. for stack emissions), and σ_y and σ_z are the Gaussian plume standard deviations in the horizontal and vertical directions, respectively. The

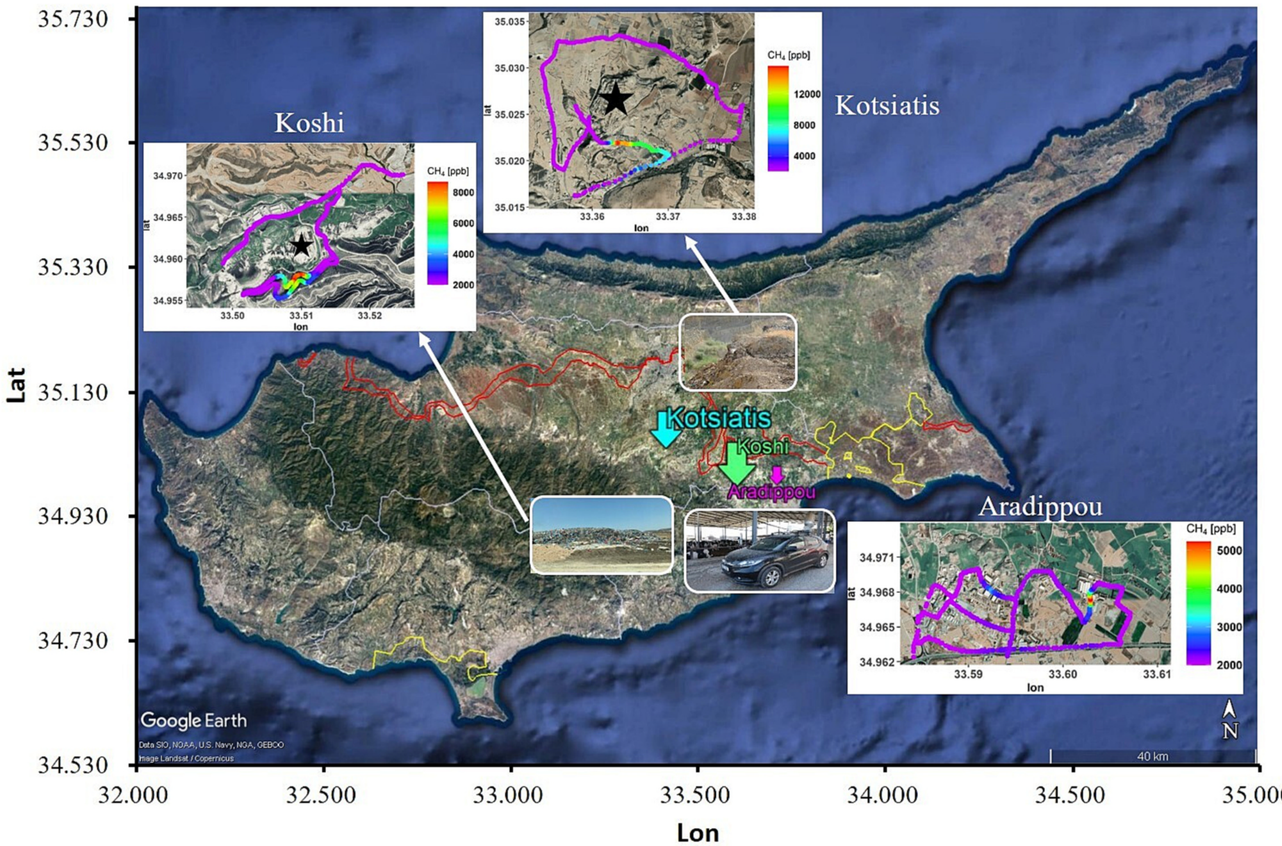

Fig. 3. Locations and pictures of surveyed areas (Koshi, Kotsiatis and Aradippou) and an example of one-day survey paths at each site. Base map © Google Earth 2022.

outcome concentration is strongly dependent on these parameters. There are several ways to determine them in the Polyphemus platform by using the Doury formulations (Doury, 1976), Briggs parametrization (Briggs, 1971) or a parametrization on similarity theory (Ars et al., 2017). The Briggs parametrization, the most flexible one, has been selected for this study. Because it considers the atmosphere's stability via six classes of the Pasquill classification from extremely unstable (class A) to extremely stable (class F) based on wind speed and solar irradiance (as shown in Table S1), and it considers the type of urban environment for emission sources surrounded by buildings and rural environment for isolated sites (Ars et al., 2017).

The study of Korsakissok and Mallet (2009) has validated that the Briggs parametrization has a good representation of measurements by comparing it with different parametrizations at different distances from emitting sources. The following equation gives the associated standard deviations:

$$\sigma_y = \frac{\alpha x}{\sqrt{1+\beta x}} \text{ and } \sigma_z = \alpha x(1+\beta x)^{\gamma} \tag{2}$$

where α, β, γ are coefficients depending on the Pasquill-Turner stability class (Pasquill, 1961).

In addition to meteorological data (temperature, wind direction and speed, stability class), source identification is required as input, including source position, and source input strength. The measurements and modeled concentrations are integrated along y, and the concentration is linear with the emission rate, as shown in the Eq. (1). Therefore, the emission rate can be estimated by the following formula:

$$Q = \frac{\sum C_{Observation} - C_{Background}}{\sum C_{Model}} \times Q_{input} \tag{3}$$

where Σ means summation over y (Caulton et al., 2018). Different factors could impact the calculated emission rate, as discussed in Section 3. The mass loss of dry/wet deposition was neglected since CH_4's solubility is small (Ars et al., 2017). Methane chemistry is neglected for the temporal and spatial scales of the study.

2.6. UNFCCC inventory calculations

Methane emissions are estimated and reported in GHG national inventory reports (NIR) under UNFCCC for countries participating in the Kyoto protocol, following the revised 2006 International Panel of Climate Change (IPCC) guidelines (IPCC, 2006). The emission factors used for Cyprus' NIR were derived from the 2006 IPCC Guidelines and special attention was paid in selecting the emission factors and parameters that are most representative of practices and conditions in Cyprus.

For Cyprus, the landfill CH_4 emissions in 2020 were calculated at 21.66 ± 9.19 Gg (NIR, 2022) by applying Tier 2 approach referring to IPCC (2006), which is based on the first-order degradation (FOD) model. The active landfill Koshi and the closed landfill Kotsiatis are reported to emit 3.34 Gg and 6.74 Gg CH_4 in 2020 respectively, accounting for about 47 % of solid waste CH_4 emissions in Cyprus (NIR, 2022). The activity data used in this approach for Cyprus include disposed waste amounts, compositions and population (urban and rural) (NIR, 2022). The disposed waste amount in Koshi is estimated at 227.63 Gg in 2020. The suggested default values for degradable organic carbon (DOC) cover the whole southern Europe region, and the methane generation rate constant is the default one for dry temperatures. Landfill CH_4 emissions are calculated by reducing the fraction of collected CH_4 and the fraction of oxidized CH_4 in the landfill cover soil from CH_4 generation. Thus, the uncertainty is related to CH_4 production/generation, variances in time collection efficiency and the part being oxidized (Scheutz et al., 2022). The uncertainty given for reported landfill CH_4 emissions is 42 % (NIR, 2022).

For the category of agriculture, 53 % of methane emissions is from livestock, among which 31 % from cattle (NIR, 2022). IPCC Tier 2 method (IPCC, 2006) is used to estimate gross energy intake and determine the country-specific emission factor of activity data, such as pregnancy rate, digestibility, and nutrient content of the feed. Errors in feed intake estimation mainly determine the uncertainty of this method (Bannink et al., 2011; Million et al., 2022). In 2020, the partition between dairy (39.5 in 1000s) and non-dairy cattle (43.4 in 1000s) was 48 % and 52 % respectively (NIR, 2022). Only dairy cattle emissions were calculated using the Tier 2 method. Tier 1 approach (IPCC, 2006), with a default emission factor, was used for non-dairy cattle. Country-specific animal weight was used. Finally, in 2020, the enteric methane emission from dairy and non-dairy cattle was 4.82 Gg and 2.47 Gg, respectively. The uncertainty given for this sector is 50 % (NIR, 2022).

3. Results and discussion

Table 1 summarizes the mobile in-situ measurements for individual sites at different seasons, measurement days and transect numbers, as well as estimated emission rates. Regarding solid waste disposal, emission rates were estimated at 10.1 Gg yr^{-1} (5 % to 95 % confidence range: 7.3 to 12.9 Gg yr^{-1}) and 15.8 Gg yr^{-1} (5 % to 95 % confidence range: 12.2 to 19.4 Gg yr^{-1}), for the active landfill (Koshi) and the closed landfill (Kotsiatis) respectively. Those findings indicate that the methane emission estimated from the closed landfill is about 50 % larger than that from the active landfill.

Regarding livestock, in the Aradippou area, the initial surveys revealed ten emitters (livestock farms). Due to their geographic clustering, the ten-point sources were surveyed and analyzed as three distinct groups, as shown in Fig. 4. Then, summing up the emission rates estimated from these three parts yielded the total CH_4 emission rate for this area. That sum is calculated at 0.54 Gg yr^{-1} (5 % to 95 % confidence range: 0.31 to 0.77 Gg yr^{-1}).

Fig. 5 shows the seasonal variability of the estimated emission rates from the three studied hotspots. There are only small seasonal variabilities (2.3 Gg yr^{-1} for Koshi active landfill, 3.3 Gg yr^{-1} for Kotsiatis closed landfill and 0.02 Gg yr^{-1} for Aradippou cattle farms). We estimate that this limited seasonality is due to the stable subtropical stable climate with an annual average temperature of 25 °C in Cyprus (Giannakopoulos et al., 2010). Several factors may potentially influence the seasonal variation of methane emissions of landfills. Emissions can be impacted by meteorological conditions, soil/cover conditions and waste and landfill conditions (Kjeldsen, 1996). Besides, landfills are generally managed to mitigate CH_4 emissions using gas collection and recovery systems, and CH_4 oxidation installations (Mønster et al., 2019), although we did not have access to management information for these landfills. Regarding livestock, manure management situation and animal number changes in time are probably the potential drivers. Therefore, strengthening cooperation with operators and managers would help better understanding seasonal fluctuations of these significant methane emitters.

Table 1
A summary of mobile in-situ measurements at individual site.

Site	Season	Measurement days (transect number)	Stability class	Estimated mean emission rates (Gg yr^{-1})
Koshi	Spring	5(5)	B/C	13.18
	Sumer	6(15)	B/C	8.87
	Autumn	5(6)	B/C	13.66
	Winter	8(15)	B/C	8.84
Kotsiatis	Spring	5(10)	B/C	18.38
	Summer	6(20)	B/C	15.59
	Autumn	5(5)	B/C	8.04
	Winter	8(15)	B/C	16.98
Aradippou	Spring	5(13)	B/C	0.23
	Summer	6(5)	B/C	0.21
	Autumn	5(5)	B/C	0.19
	Winter	8(30)	B/C	0.15

3.1. Uncertainty of atmospheric estimations

Different input factors can result in under- or over-estimating emission rates. The main one would be the temporal variability, although we found limited seasonality in the emissions. Uncertainty can also be induced by poor representation of the dispersion downwind of the sites. To assess it within a single Gaussian plume estimate, we propagate the uncertainties linked to variability of wind speed and wind direction, and the choice of stability class. During this calculation, wind speed and wind direction were weighted by the statistical distribution according to the observed wind data during a single transect. The propagated uncertainty estimates for the active landfill (Koshi), the closed landfill (Kotsiatis) and the pasture area (Aradippou) are 18 %, 22 % and 23 %, respectively. The stability class contributes 38 % of the uncertainty due to one stability class discrepancy. On average, wind speed and direction changes contribute to 23 % and 39 % of the overall uncertainty, respectively. The detailed uncertainty budget for each site is shown in Table S2.

3.2. Reconciling top-down and bottom-up estimates

In our survey, the three measured hotspots account for about 28 % of the total CH_4 emission in Cyprus according to the bottom-up inventory. In Cyprus, waste management has changed much over the last decade. Waste minimization and recycling/reuse policies have been introduced to reduce the amount of waste generated, and increasingly, alternative waste management practices to solid waste disposal on land have been implemented to reduce the environmental impacts of waste management (NIR, 2022). Under managed waste disposal sites, Koshi accounted for 60 % of the total solid waste production. Besides, Kotsiatis accounted for 48 % of the total methane emissions from the unmanaged waste disposal sites. Therefore, after upscaling to the national level, in total, methane emissions from landfills are 49.7 Gg yr^{-1} through atmospheric measurement estimates. The Aradippou area includes 5.2 % of cattle emissions in Cyprus. It is assumed that the dairy and non-dairy cattle population distribution of the Aradippou area follows the national dairy and non-dairy cattle population distribution (48 % dairy cattle and 52 % non-dairy cattle in Cyprus, NIR, 2022). This assumption was used to obtain the amount of enteric CH_4 emission from cattle in Cyprus. Additionally, different emission factors for dairy cattle (120.5 kg CH_4 $head^{-1}$ yr^{-1}) and non-dairy cattle (57 kg CH_4 $head^{-1}$ yr^{-1}) are used to calculate the total emission from cattle. Based on the above, Cyprus CH_4 emission rate from cattle, under the sub-category livestock is estimated at 10.4 Gg yr^{-1} (5 % to 95 % confidence range: 6.0 to 14.8 Gg yr^{-1}).

Fig. 6 and Table 2 summarizes the results, combined with the bottom-up values from the Cyprus national inventory. Our estimation, based on mobile in-situ measurements for the sub-category of solid waste disposal, was 129 % larger than that reported in the bottom-up inventory. The significant difference may result from i) obsolete inventory data, possibly due to empirical/regional/default input values based on limited and outdated research; ii) incorrect attribution of emissions from the closed landfill, which is unmanaged and did not meet the standards for landfills of European Union directives, iii) uncertainties in the top-down estimates, including country-scale extrapolation. By considering top-down uncertainties, our results strongly suggest that the approach with default values of the FOD model (IPCC, 2006) at the national level is not appropriate for estimating landfill CH_4 emissions in Cyprus. Mobile surveys reveal that it is essential to reevaluate and revise the inventory data for the national waste sector.

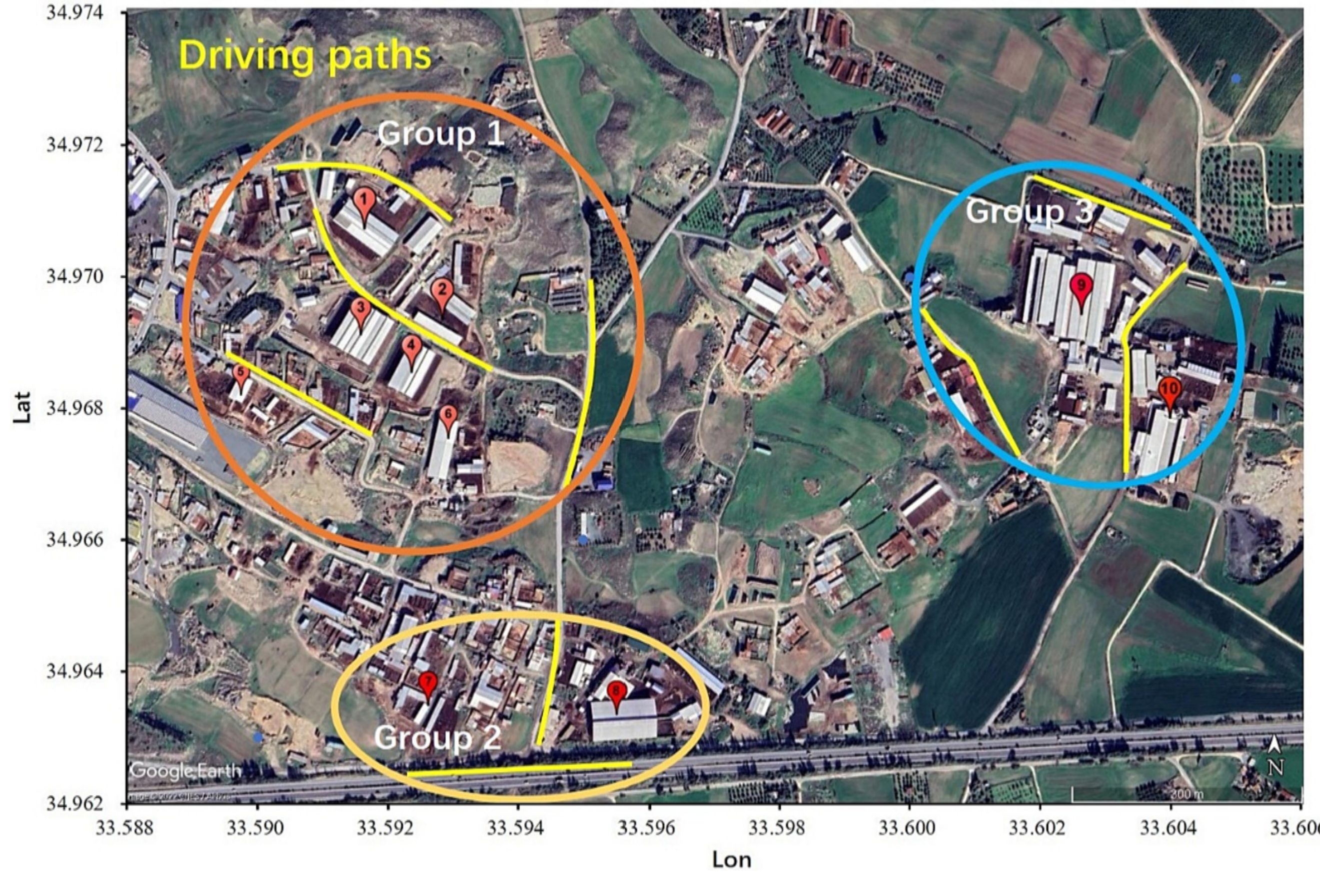

Fig. 4. The selected ten-point sources at the Aradippou area combined with driving paths. The figure includes the driving paths of the vehicle during measurement transects (yellow lines). Base map © Google Earth 2022.

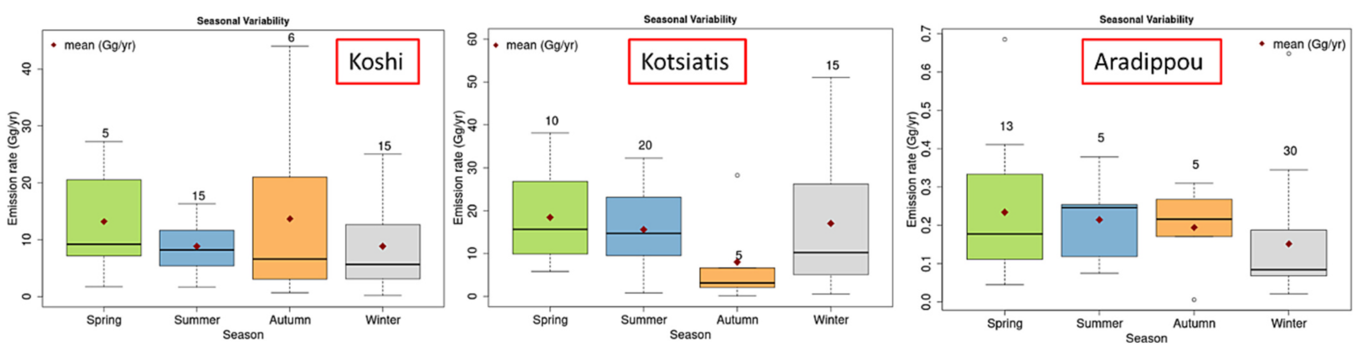

Fig. 5. Seasonal variabilities of the three sites, from left to right respectively Koshi, Kotsiatis, and Aradippou. The numbers on top of each bar present the transect numbers.

For livestock, methane emissions from enteric fermentation estimated using in situ measurements are 40 % greater than that reported in the national inventory. The result is comparable to that reported by Hiller et al. (2014) and Vechi et al. (2022) for other areas. However, the bottom-up estimate is within the lower end of the confidence interval of our top-down estimate. The possible reasons for this difference include i) time variability in the number of animals, ii) non-specific emission factors, iii) diurnal variation in the strength of cattle enteric fermentation, and iv) the measured emission rates may contain a fraction of manure methane emissions.

4. Conclusions and implications for national inventories

This study provides site-level atmospheric methane observations during the course of one year, at three selected hotspots, representing 28 % of Cyprus national methane emissions. It sheds light on the discrepancies between bottom-up and top-down estimation approaches. After extrapolation, our calculated top-down estimates of methane waste and livestock emissions for Cyprus were 129 % and 40 % larger than the reported values in the bottom-up national inventory. Due to the ambient meteorological conditions of the subtropical climate, we expect only small seasonal changes in biogenic methane emissions from landfills and cattle farms.

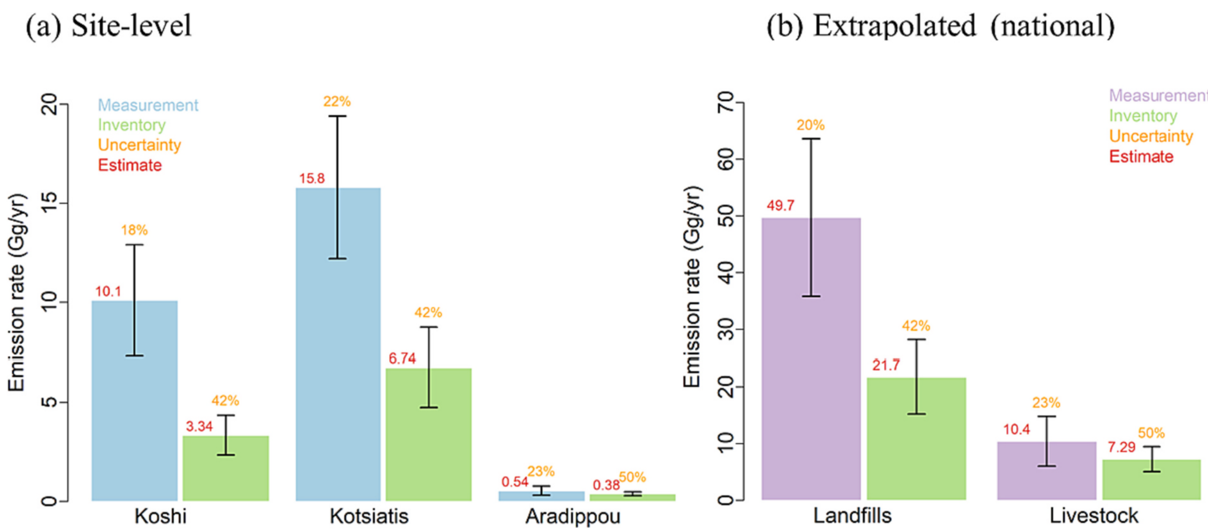

Fig. 6. Methane emission rates calculated from in situ CH_4 measurements and bottom-up inventory estimates: (a) presents the site scale and (b) presents the extrapolated estimates (national scale).

Table 2
The results from mobile in-situ measurements and the comparison with the bottom-up inventory.

Site	Measurement (uncertainty %)	Inventory (uncertainty %)	Category	Measurement (uncertainty %)	Inventory (uncertainty %)
Koshi	10.1 (18 %)	3.34 (42 %)	Landfills	49.7 (20 %)	21.7 (42 %)
Kotsiatis	15.8(22 %)	6.74(42 %)			
Aradippou	0.54 (23 %)	3.34 (50 %)	Livestock	10.4 (23 %)	7.29 (50 %)

For livestock, this study provides a method to quantify enteric methane emissions from cattle bridging the site scale to the national scale, whereas previous studies focused essentially on animal- or farm-scale (Storm et al., 2012; Golston et al., 2020; Vinković et al., 2022). Our study assumed that the dairy and non-dairy cattle distribution at the surveyed area is representative of the national-level dairy and non-dairy cattle population distribution, which may have a significant impact on national estimates of enteric CH_4 emissions from livestock.

Our study also highlights closed landfills may be a significant, underestimated CH_4 emission source, even if active landfills are properly accounted for. Therefore, to achieve efficient mitigation of CH_4 emissions, closed landfills should be monitored regularly and targeted by mitigation approaches.

Additional measurements would be required to cover more emission source categories and extend our understanding of local to national methane emissions in Cyprus.

Furthermore, different observation platforms and calculation methods could complement top-down estimates of this study and help to move towards a top-down vs. bottom-up reconciliation (Guha et al., 2020). For example, aircraft mass balance estimates for methane have been found to be 1.4–2.8 times higher than a city inventory (Lamb et al., 2016). Our findings indicate that the bottom-up methane emissions from solid waste disposal are clearly underestimated by a factor of 2.3 for Cyprus. The development of an inventory including more site-specific and more contemporary emission factors is equally vital in reconciling top-down/bottom-up approaches, as hinted by Lyon et al. (2015) and Amini et al. (2022).

This survey method can be applied for other regions or small-surface countries aiming to assess the methane emission structure independently from inventories and support policymakers in designing and implementing efficient mitigation action. The use of commercially available sensors, car platforms and open-source modeling ensure easy reproduction. Indeed, the method presented here is suitable for countries where it is possible to directly estimate a significant and representative amount of the total emissions of major emitting sectors. In order to obtain comparable data, it is necessary to select the largest and most representative emission sources and areas. Actually, with only slightly more resources it would be feasible to monitor almost 100 % of Cyprus methane emissions and therefore make more robust top-down estimates but also test the extrapolation hypotheses for different fractions of partial monitoring.

This approach is suitable for methane in livestock and waste sectors, with point sources and limited seasonal variability. The method would be easily applied to upstream and mid-stream fossil fuel methane emissions but would be more challenging in cases with more diffuse leaks of natural gas distribution networks. The method covers a large fraction of global emissions and is promising for many developing countries which have limited resources to develop atmospheric networks or sophisticated inventories.

CRediT authorship contribution statement

JDP conceived the study. YL led field measurements, data analysis and writing of the manuscript. JDP, MV, PB and JS contributed to project advising, reviewing and editing the manuscript. PYQ and MD contributed to conduct field measurements and data collection. JK, FD and DD contributed to the calculation of bottom-up inventory estimates, review and editing of the manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data obtained from mobile measurements that support the findings of this study is open access at the following link: doi: https://doi.org/10.5281/zenodo.7287249.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.165896.

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