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A novel approach to rapidly tracking whole-farm methane emissions

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Abstract

Enteric fermentation and manure from livestock farming are major sources of methane (CH₄) emissions and have a large potential for emissions reduction. However, there is a lack of effective methods for evaluating future emissions reduction efforts, especially at the farm scale. We developed a rapid analysis method to evaluate CH₄ emissions from a large number of dairy cow farms in the Netherlands based on single-transect mobile van measurements of CH₄ concentrations downwind of farms located between 80 and 750 m from the road. Methane emissions from 51 dairy cow farms were determined on four campaign days within a total of 7 measurement hours between November 2017 and November 2018 using an inverse Gaussian approach combined with two different wind datasets and their composite. We found a range of moderate to high correlation (R^2 : minimum 0.42, maximum 0.86) between the estimated CH₄ emission rates for 11–16 farms on each measurement day and the number of animal units (AUs, 1 AU equals 500 kg of animal weight) across four individual days. The whole-farm CH₄ emission factors (including both enteric fermentation and manure) for the four separate campaign days were estimated using the slope between the CH₄ emission rates derived from the composite of two distinct wind datasets and the number of AUs. Daily emission factors for the four campaign days were estimated to be in the range of 0.18–0.50 kgCH₄/d/AU. From the dataset, averaged over each of the four campaign days, we derived an estimate of the whole-farm CH₄ emission factor, with a 95% confidence interval of 0.47 [0.13–0.81] kgCH₄/d/AU. Our results demonstrate that CH₄ emissions from a large number of dairy cow farms can be rapidly estimated, providing an independent way to evaluate country-specific emission factors and a potential way to monitor future emission reductions.

1. Introduction

After carbon dioxide (CO₂), methane (CH₄) is the most important anthropogenic greenhouse gas (GHG) in terms of radiative forcing, with a global warming potential 27 times greater than that of CO₂

over a 100 year span, and a relatively short atmospheric lifetime (9–12 years) (Forster *et al* 2021). The observed increase in its atmospheric concentration by a factor of ~2.6 since the pre-industrial period is attributed to the rising anthropogenic emissions as a consequence of various human activities (Lassey

et al 2007). For the decade 2008–2017, the dominant anthropogenic CH₄ emissions originated from four source types: agriculture (animal husbandry and rice fields), waste management, oil and gas production and distribution, and coal mining (Saunio *et al* 2020). Agriculture is the dominant methane source in the Netherlands, contributing to 69% of the total Dutch methane emissions in 2018 (UNFCCC NIR 2024). Of these, 45% were due to enteric fermentation from the ruminant digestive system and 21% from manure management (Ruyssenaars *et al* 2019).

CH₄ emissions from individual cows, groups of cows, and entire dairy farms have been quantified using various platforms and sampling techniques, such as respiratory chambers (Jungbluth *et al* 2001), backward Lagrangian stochastic inverse-dispersion technique (Flesch *et al* 2009), tracer flux ratios (Arndt *et al* 2018, Vechi *et al* 2022), mobile vans (Hensen *et al* 2006), drones (Vinković *et al* 2022), and aircraft observations (Arndt *et al* 2018, Daube *et al* 2019) downwind of the source, respectively. Enteric fermentation and manure are the two major CH₄ sources on a dairy farm. Since these two emission sources are often collocated, chamber-like measurements are required to estimate emissions from each source individually (Amon *et al* 2001, Zhang *et al* 2005, Ngwabie *et al* 2011). Alternatively, when cows and manure are well separated in space, atmospheric dispersion techniques can be employed to partition the two major CH₄ sources (Arndt *et al* 2018, Daube *et al* 2019). In addition, factors influencing the emission process have been studied by examining farms with different herd types and sizes, diets, environmental conditions (such as animal activity, air temperature, and relative humidity), and manure practices (Amon *et al* 2001, Zhang *et al* 2005, Ngwabie *et al* 2011, Arndt *et al* 2018, Daube *et al* 2019). Such studies contribute to the overall goal of estimating whole-farm CH₄ emissions which includes all animals and their waste, under varying environmental and given specific management conditions.

Previous studies that investigated whole-farm CH₄ emissions included CH₄ emissions from all parts of animal husbandry, including herd size and type, manure handling, and diet (Amon *et al* 2001, Hensen *et al* 2006, McGinn and Beauchemin 2012, VanderZaag *et al* 2014, Zhu *et al* 2014, Arndt *et al* 2018, Bühler *et al* 2021, Vechi *et al* 2022, Vinković *et al* 2022). It remains challenging to investigate CH₄ emissions from a large number of dairy farms, as it requires considerable efforts to understand whole-farm emissions at the individual farm levels. Hensen *et al* (2006) evaluated whole-farm CH₄ emissions from 10 Dutch dairy farms using two different manure management systems (seven slurry-based systems and three straw-based

systems) and compared measurement-based whole-farm emissions with estimates from a Danish whole-farm model, FarmGHG (Olesen *et al* 2006). The fit of modeled versus measured data had a slope of 0.97 and an *R*-squared value of 0.27. On average, measurements and model emission estimates agreed well for large farms, within 30%. However, emissions from small farms were biased by a factor of 3, and CH₄ emissions in winter appeared to be underestimated. Recently, Vechi *et al* (2022) evaluated whole-farm CH₄ emissions from nine cattle farms (seven dairy farms and two beef farms) using the mobile tracer gas dispersion method over a one-year period. According to their study, the modeled whole-farm CH₄ emissions in Denmark may be underestimated on average by 35% when estimated using default inventory models (IPCC 2006 IPCC 2019, Nielsen *et al* 2021). The above-mentioned studies show that it is possible to quantify CH₄ emissions from an entire farm. However, our understanding of whole-farm CH₄ emissions is associated with significant uncertainties, and the number of dairy farms evaluated is still small compared to the total number of dairy farms in a country, e.g. 16 331 dairy farms in the Netherlands in 2017 (van Ministerie 2017). Dairy cow emission measurements in the Netherlands are usually conducted on a small group of animals before extrapolation to the national level (Corré 2002, Van Amstel *et al* 2003). To bridge this gap, independent measurements are needed, which will help improve the accuracy of inventory models by more accurately reflecting the actual farm management conditions, which can vary from individual farms to the country-specific level.

In this study, we aim to evaluate the extent to which whole-farm methane emissions can be rapidly estimated. We developed an analysis method to quantify CH₄ emissions from a large number of dairy farms in the Netherlands using single-transect mobile van observations of CH₄ concentrations downwind of cow farms and evaluated the estimates against country-specific emission factors that better reflect the Dutch situation than the standard IPCC emission factors (Mosquera and Hol 2012, Mosquera *et al* 2021). We estimated the whole-farm CH₄ emission factor for 51 individual farms on four separate measurement days between November 2017 and November 2018 based on the quantified whole-farm CH₄ emission rates and the number of AUs per farm, which allowed us to compare our results with those of previous studies as well as inventory-reported values.

2. Material and methods

The CH₄ concentrations downwind of a large number of dairy farms were measured in the Netherlands

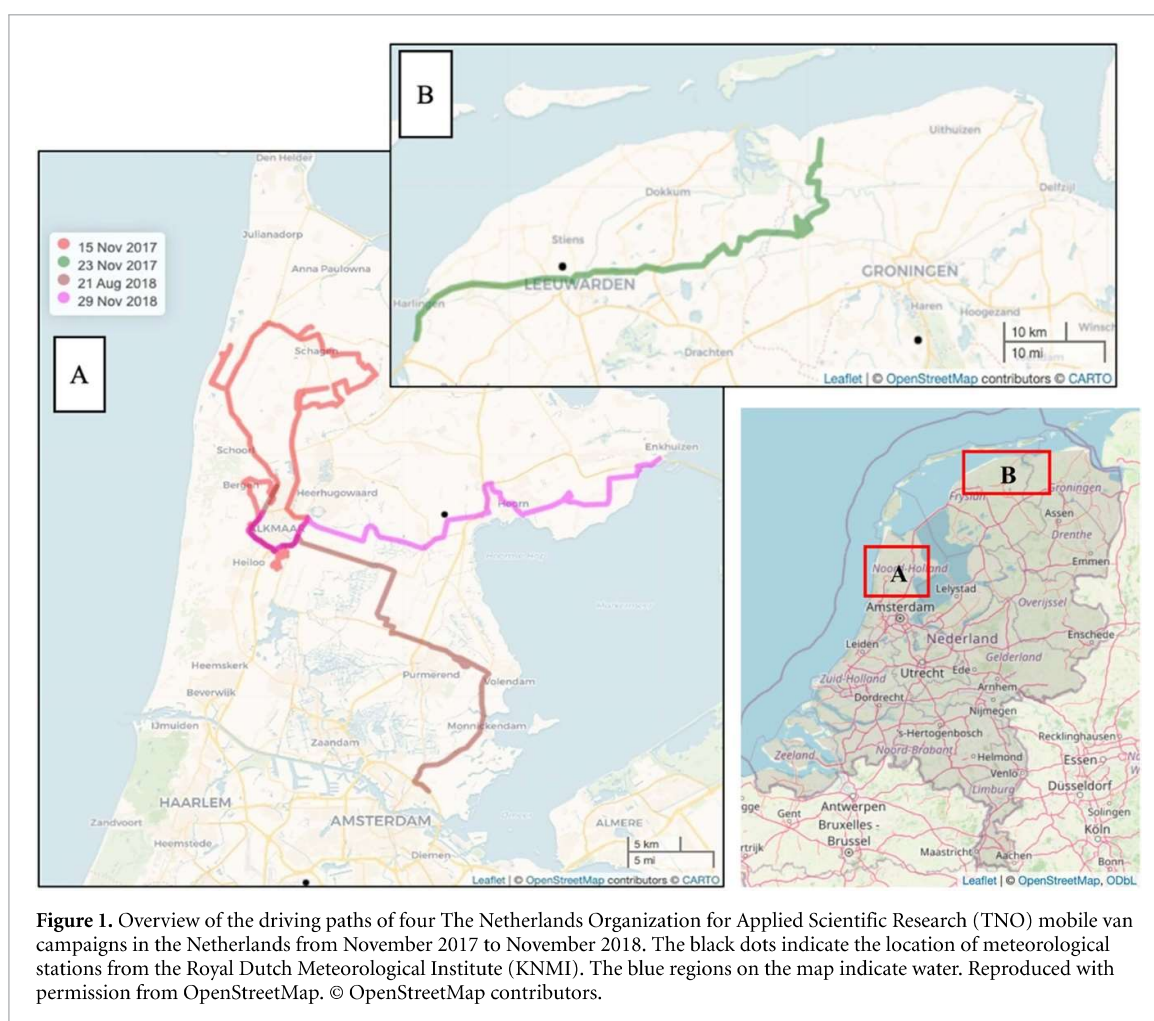


Figure 1. Overview of the driving paths of four The Netherlands Organization for Applied Scientific Research (TNO) mobile van campaigns in the Netherlands from November 2017 to November 2018. The black dots indicate the location of meteorological stations from the Royal Dutch Meteorological Institute (KNMI). The blue regions on the map indicate water. Reproduced with permission from OpenStreetMap. © OpenStreetMap contributors.

(figure 1). We focused on two provinces (Flevoland and Gelderland, already in table 1) in the Netherlands with mainly rural area and a relatively high density of farms. The driving route was selected based on Google Earth and the wind direction on each campaign day to select a route to pass by downwind of as many farms as possible. During the period from November 2017 to November 2018, we carried out mobile van laboratory measurements on four separate days to collect a random emission dataset for dairy cow farms across the Netherlands, without pre-selecting any farms in advance. The recorded in-van geospatial data was used to detect candidate dairy farms along the driven routes after the drives, i.e. to look for CH_4 plumes matching farms located upwind of the driven routes, as shown on Google maps, visual inspection and known location of other sources (e.g. landfills and waste water treatment plants). The locations of the candidate farms were then submitted to the National Institute for Public Health and the Environment (RIVM) for confirmation, and the RIVM provided the number and the type of cows on confirmed farms. The detected farms were located between 80 and 750 m upwind of the driven routes. Four dairy farms were sampled twice and all of these repetitions were completed on the same day. We took

the averages of the two quantified values to represent the emission intensity of the farms. The remaining plumes originated from different sources, such as industrial activities, traffic, households, and other agricultural sources, which were not evaluated in this study.

2.1. Mobile van measurements

Continuous measurements of CH_4 were performed at a flow rate of 6 l min^{-1} with a Tunable Infrared Laser Direct Absorption Spectroscopy analyzer (Aerodyne Research Inc., Billerica, US) located in a mobile van with a trailer. A stainless-steel central entrance tube with a diameter of 60 mm was used to sample ambient air at the front of the trailer from a height of 3 m; from this tube, a $1/4''$ PE tube went to the analyzer, which simultaneously measured CH_4 , C_2H_6 , N_2O , CO_2 , and CO at 1 Hz, with a precision of 2.4, 0.1, 0.1, 390 and 2.5 ppb, respectively. The same setup was used in Vinković *et al* (2022). Calibration was done at the start and the end of each measurement day in the field using two gas standards with a known CH_4 concentration of 4695.0 ppb and 1975.5 ppb, respectively. The standards were calibrated by the Flask and Calibration Laboratory (FCL) of the European infrastructure Integrated Carbon Observing System in

Table 1. Overview of four mobile van campaign info between November 2017 and November 2018, where the start and end times are given in UTC, and the average distance from dairy cow farms to the closest KNMI station in km.

Campaign	Province	Start—End (hh:mm)	Avg. dist (km) (min—max)	KNMI station(s)	Temp. (°C)	Cloud cover (9 = sky invisible)
15 November 2017	North Holland	11:00–15:00	19 [15–25]	Berkhout	10.7	8
23 November 2017	Friesland, Groningen	15:00–16:00	50 [25–72] 16 [2–37]	Eelde Leeuwarden	8.6	2
21 August 2018	North Holland	08:00–09:00	14 [8–25] 28 [16–33]	Berkhout Schiphol	21.4	8
29 November 2018	North Holland	08:00–09:00	7 [2–11]	Berkhout	10.1	8

Jena, Germany, while the CH₄ standards at the FCL are closely aligned with the WMO CH₄ scale maintained at the NOAA global monitoring laboratory.

2.2. Meteorological measurements

Hourly wind speed and direction measurements for all four days were obtained from the nearest meteorological stations of the Royal Netherlands Meteorological Institute (KNMI) along the driving routes shown in figure 1. One or two KNMI stations were selected for each measurement day, which, on average, were 7–50 km away from the farms (table 1).

Furthermore, we also used the ERA5 hourly wind speed and wind direction at $0.25^\circ \times 0.25^\circ$ resolution (Hersbach *et al* 2023) from the European Centre for Medium-Range Weather Forecasts (ECMWF) at each location of the measurements and at a time that was close to the measurement time. The distance between the KNMI stations and the measured farms was relatively large, on average 22 ± 16 km across the four campaign days.

The mean wind direction observed at the KNMI stations can differ from the local wind direction because the farms are located 7–50 km away from the closest KNMI station (table 1). However, it is a good indicator to indicate which farm was the source of each plume. Following Caulton *et al* (2018), we derived the actual on-site wind direction based on the locations of the measured plume and the farm. In practice, the wind direction was obtained by calculating the vector between the farm and the center of the measured plume, which allowed the Gaussian plume model (GPM) to produce a plume at the same location as the measured plume. This procedure did not affect the wind speed estimated using the KNMI stations.

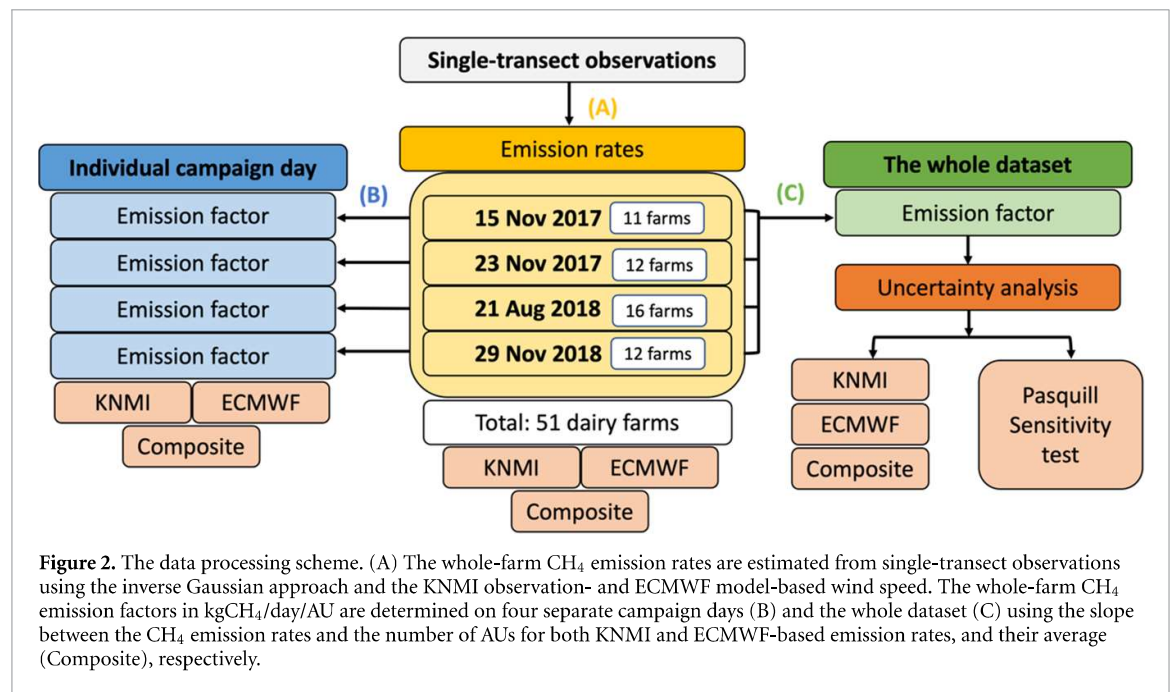
Therefore, we used both the mean wind speed from the closest KNMI stations and the modeled ECMWF wind speed at each location of the measurements and at a time that was close to the measurement time, and the actual wind direction for the GPM simulations to determine the CH₄ emission rates from dairy cow farms, which we present in section 3.1.

2.3. GPM

In this study, the same GPM formulation used by Vinković *et al* (2022) was applied to simulate the CH₄ concentration levels along the sampled transect. The plume concentration transported downwind from the source was estimated as follows:

$$C(x, y, z) = \frac{Q}{2\pi u \sigma_y \sigma_z} e^{\frac{-y^2}{2(\sigma_y)^2}} \left(e^{\frac{-(z-h_s)^2}{2(\sigma_z)^2}} + e^{\frac{-(z+h_s)^2}{2(\sigma_z)^2}} \right) \quad (1)$$

where C (gm⁻³) is the concentration of CH₄ at a given location x (distance parallel to the wind direction) and y (distance perpendicular to x) (m), which are transformed coordinates to ensure that the sampled plume is perpendicular to the wind direction (see figure A1), and z (m) is the height above the ground. Q is the source strength (gs⁻¹), h_s is the height of the emission (m), u is the mean wind (ms⁻¹), and σ_y and σ_z are the dispersion parameters in the cross-wind and vertical direction (m), respectively. The dispersion parameters (σ_y , σ_z) encode the strength of turbulent mixing or diffusivity, as well as the downwind distance over which the mixing is performed, x , which does not appear directly in equation (1). They are calculated according to any of several analytical parameterizations based on Pasquill–Gifford’s stability class scheme (Turner 1970). The plumes were simulated using a point source placed at the center of each farm at a height of 5 m above the ground. In GPM, the stability of the atmosphere is categorized as atmospheric stability classes, e.g. ranging from A (unstable) to F (stable) in Pasquill classes, which is the key factor that determines the dispersion of air pollutants. The stability class on all four campaign days can be described by the stability class D, which represents a neutral condition of the atmosphere, with moderate wind speeds and limited vertical mixing. The stability class affects the horizontal and vertical dispersion parameters (σ_y and σ_z) in equation (1). On all four measurement campaign days, we obtained a complete cloud cover of 7–8 oktas (7 broken clouds; 8 complete



overcast) and a well-defined mean wind speed of 2.8–7.5 ms^{−1} (table A1), which corresponds to the stability class D (neutral).

Farm plumes were obtained from the measured data by subtracting the background derived from the lower 10th percentile of the downwind CH₄ transect measurements, as described by Vinković *et al* (2022). Thus, the emission rate Q_{CH_4} (kgCH₄/d) was obtained from the ratio of the integrated concentration of the measured and modeled concentration plumes per farm multiplied by a source strength Q_{model} (arbitrarily chosen as 1 gCH₄ s^{−1}). The value 86.4 in equation (2) represents the conversion factor from gCH₄ s^{−1} to kgCH₄/d.

$$Q_{\text{CH}_4} = \left[Q_{\text{model}} \cdot \frac{\int C(x, y, z)_{\text{observed plume}}}{\int C(x, y, z)_{\text{modeled plume}}} \right] \cdot 86.4. \quad (2)$$

2.4. Animal unit (AU) per farm

We received data on the number of animals, animal category (dairy/meat, age, sex), and housing type for 51 individual farms from the RIVM based on the GPS coordinates. The animals were divided into three main cattle groups: mature dairy cattle, other mature cattle, and growing cattle (see appendix figure A2). According to the Dutch National Inventory Report, 2021 (Ruyssenaars *et al* 2021), an animal classified as ‘other mature cows’ on average emits ~57% of the amount of CH₄ emitted by mature dairy cows, while for growing cattle this is ~25%. We derived an equivalent number of mature dairy cows by taking the sum of the number of ‘other mature cows’ scaled by 57% and the number of growing cattle scaled by 25%, respectively. In 2017, the average weight of mature dairy cows in the Netherlands was ~650 kg (Van

Bruggen *et al* 2019). With these, we obtained the number of AUs by multiplying the equivalent number of mature dairy cows with the ratio of 650 kg/500 kg, where one AU equals 500 kg of animal weight (USDA (United States Department of Agriculture) 1973). We then converted the estimated CH₄ source strength (kg/d) per farm to the whole-farm CH₄ emission factor per day per AU (kgCH₄/d/AU).

2.5. Determination of CH₄ emission factor

Data processing consisted of the following three steps: (a) estimation of individual whole-farm emission rates using both the KNMI and ECMWF winds; (b) determination of the whole-farm emission factors using the emission per farm and the AUs for each of the four separate days; and (c) calculation of an overall emission factor based on all farms from all four campaign days. Emission factors from both separate campaign days and the entire dataset were estimated using the KNMI- and ECMWF-based emissions per farm and the AUs, respectively, as well as the average of KNMI and ECMWF emissions per farm and the AUs, which we refer to as a ‘Composite’ throughout the text. The data-processing scheme is shown in figure 2. The estimated single-transect emission rates did not include the measurement uncertainty of each observation. As indicated by Caulton *et al* (2018), the estimated emission rate based on single-transect observations can be 0.05–6.5 times the actual emission rate, and 0.5–2.7 times for sites with 10+ transects. Similarly, the uncertainty of the estimated mean emission rate based on single-transect observations downwind of a number of farms is expected to be significantly reduced relative to the uncertainty of the estimated emission rate based on a single transect. We estimated the whole-farm CH₄ emission factors for

each measurement day using the slope of a linear fit between the CH₄ emission rates and the number of AU per farm. The uncertainty of the estimates is given as a 95% confidence interval (CI). Furthermore, we use the slope of the linear fit between averaged CH₄ emission rates and averaged numbers of AUs on individual days (a total of four days) to derive an overall whole-farm methane emission factor.

2.6. Analysis uncertainties

Several parameters define the dispersion of the plume in the model, such as source, receptor height, roughness length, and stability class. Therefore, to assess the uncertainty of the whole-farm CH₄ emission factor from the complete dataset, we estimated the slope between the averaged emissions rates and averaged numbers of AUs using two additional Pasquill stability classes, E (slightly stable) and C (slightly unstable), which represent the minimum (*E*) and maximum (*C*) emission estimates, respectively. Furthermore, a Monte Carlo simulation (10 000 samples) was used to generate random values for the averaged CH₄ emission rates per day for stability class D. It is based on the regression coefficients of the emission rates versus the number of AUs, i.e. emission factors and assumes a normal distribution of random errors in a simple regression model. This allowed us to explore the uncertainty in the slope estimates per day under different realizations of the error term. The estimated whole-farm CH₄ emission factors for all four separate days and the complete dataset were compared with estimates reported in previous studies on whole-farm CH₄ emissions. Furthermore, a full statistical description of the four single-measurement days and the complete dataset is presented in this study, including the minimum, maximum, mean, median, variance, skew, and kurtosis.

3. Results and discussion

3.1. CH₄ emission rates from individual farms and campaign days

Our results showed a wide range of estimated CH₄ emission rates from individual farms. The estimated CH₄ emission rates from individual farms, based on the KNMI observation-based wind, ranged from 11 to 680 kg CH₄/d, whereas for the ECMWF-model-based wind, the range was 9–1068 kg CH₄/d (see table A3). However, the comparison is meaningful only when the number of AUs per farm is considered, because the number of AUs drives emissions, given that CH₄ emissions from cattle are a consequence of their metabolism. Therefore, a (wide) range of farm emission rates is expected, as the number of AUs per farm ranges from 34 to 1026 with an average of 339 AUs.

For each measurement day, the estimated CH₄ emission rates from the individual farms were positively correlated with the number of AUs. Three out

of four mobile van measurement days showed a high correlation, with an R^2 value between 0.63 and 0.89 across the two sets of CH₄ emission rates (figure 3). The dataset from 23 November 2017 has the lowest R^2 value ranging between 0.40 (KNMI) and 0.43 (ECMWF), where the correlation is reduced by four farms with an emission rate of between 297 and 1069 kg/d. Excluding these four farms, the R^2 values increased to 0.61 (KNMI) and 0.65 (ECMWF), respectively. No ethane plumes were observed near any of the four farms. As ethane is a tracer for natural gas emissions (Visschedijk *et al* 2018), this implies that there is no additional contribution from natural gas leakage to potentially explain the elevated emissions from the four farms. We cannot exclude the impact of a plume from an upwind methane source or methane emissions from the larger amount of manure on the four farms compared to other farms. However, as the so-called transect-to-transect emission rate variability can be between 0.05 and 6.5 times the true emission rate as shown by Caulton *et al* (2018), the observed variability in our single-transect CH₄ emission rates is most likely caused by atmospheric variability.

Owing to the sampling strategy and, in general, the lack of manure management information on each farm, we were not able to distinguish manure-related emissions from enteric fermentation emissions. Therefore, this study focuses on whole-farm CH₄ emissions per AU, which include the two main CH₄ emission contributors: enteric fermentation and manure emissions. We later discuss the possible role of manure emissions in the comparison, based on limited manure management info available.

3.2. Methane emission factors from dairy cows

The estimated whole-farm CH₄ emission factors (both enteric fermentation and manure emissions) varied by a factor of ~ 2.7 over the four measurement days, and were in the range of 0.18–0.50 kgCH₄/d/AU (see table 2). Note that the derived emission factors include the contribution of CH₄ emissions from the manure. Since the manure practice on individual farms is not known, we cannot estimate the CH₄ emissions from manure onsite to derive the emission factors for dairy cows only, as was done by Vinković *et al* (2022).

According to Caulton *et al* (2018), a minimum of 10 transects should be used to constrain the atmospheric variability for the inverse Gaussian approach. As our single-transect measurements were short-term observations that were not performed under controlled and replicable conditions, the derived CH₄ emissions for individual farms were associated with large uncertainties. However, when a large number of sites were investigated, the uncertainty caused by atmospheric variability was reduced by averaging over multiple farms. The whole-farm CH₄ emission factor with 95% CI for the whole

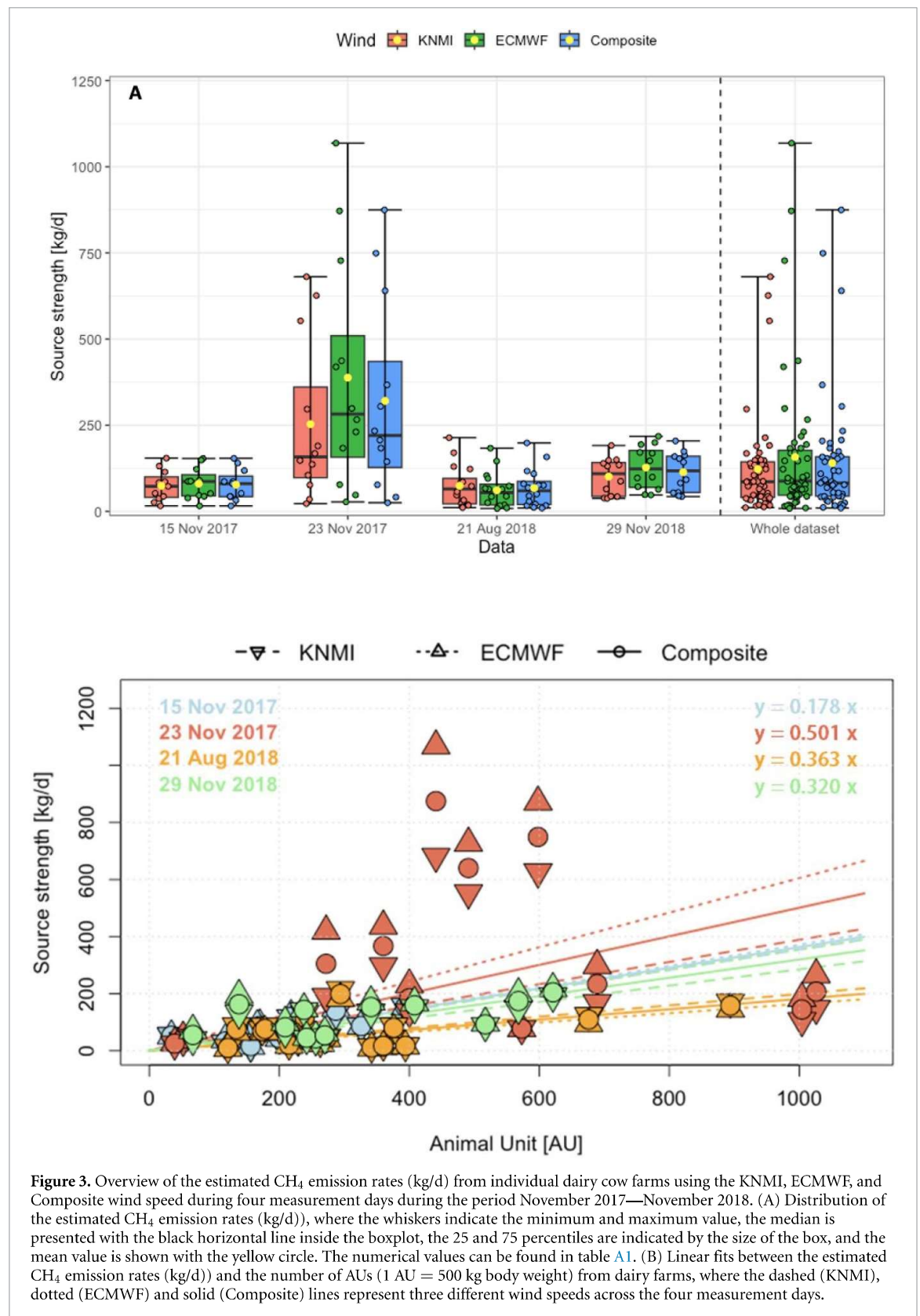


Figure 3. Overview of the estimated CH₄ emission rates (kg/d) from individual dairy cow farms using the KNMI, ECMWF, and Composite wind speed during four measurement days during the period November 2017–November 2018. (A) Distribution of the estimated CH₄ emission rates (kg/d), where the whiskers indicate the minimum and maximum value, the median is presented with the black horizontal line inside the boxplot, the 25 and 75 percentiles are indicated by the size of the box, and the mean value is shown with the yellow circle. The numerical values can be found in table A1. (B) Linear fits between the estimated CH₄ emission rates (kg/d) and the number of AUs (1 AU = 500 kg body weight) from dairy farms, where the dashed (KNMI), dotted (ECMWF) and solid (Composite) lines represent three different wind speeds across the four measurement days.

averaged dataset (composite) equals 0.47 [0.13–0.81] kgCH₄/d/AU.

3.3. Uncertainty analysis

Our analyses show that the chosen stability class and relatively large errors on individual farm emissions

did not strongly affect the presented emission rates in this work. The farm-scale CH₄ emission factors, derived from sensitivity tests for two Pasquill stability classes (E and C), result in estimates ranging from 0.38 to 0.57 kg CH₄/d/AU. Based on sensitivity testing, we found that the 5th percentile background and

Table 2. Summary of the emission factor (EF) with a 95% CI (kgCH₄/d/AU) and R^2 per individual campaign, and the AU statistics, as well as the averaged data over four campaigns (Avg. dataset) for the average of KNMI- and ECMWF-based based CH₄ emission rates (Composite).

Campaign	Dataset	EF (kgCH ₄ /d/AU)	95% CI (kgCH ₄ /d/AU)	R^2 (N)	Ave. AU (min–max)
15 November 2017	Composite	0.36	[0.27–0.46]	0.86 (11)	209 [34–394]
23 November 2017	Composite	0.50	[0.15–0.85]	0.42 (12)	495 [39–1026]
21 August 2018	Composite	0.18	[0.11–0.26]	0.63 (16)	232 [121–894]
29 November 2018	Composite	0.32	[0.23–0.41]	0.82 (12)	323 [67–621]
Avg. dataset	Composite	0.47	[0.13–0.81]	0.82 (4)	339 [34–1026]

the 20th percentile background would affect the emission factor by 2.4% and 2.5%, respectively. The averaged animal weight of dairy cows may be a potential source of uncertainty. We took the value of 650 kg from the Dutch Agricultural Emissions Report 2017. Note that the value was the estimated average weight of dairy cows in the Netherlands in 2017, and may change from year to year.

The mean wind and mean direction from the nearest KNMI stations (mean values of one or more KNMI stations for each campaign within a period of one or several hours; table A1) were compared with the ECMWF model-based wind at the KNMI stations and at the exact farm locations (mean values of all wind speeds at the exact measurement location close to the measurement time for each measurement campaign day) (figure A3). The difference between the KNMI observation- and ECMWF model-based dataset for KNMI stations ranged from 13%–30% for wind speed, while for the wind direction was in the range of 1% and 9% across the four measurement campaign days from November 2017 to November 2018. The wind speed sensitivity test suggests an estimate of 0.40–0.54 kg CH₄/d/AU, while the Monte Carlo analysis yields estimates within the 95% CI range of 0.23–0.71 kg CH₄/d/AU for the average emissions factor over all farms.

The inverse GPM is mostly sensitive to atmospheric variability, followed by wind speed. We assessed the impact of the selection of the meteorological stations on the quantification of emission rates for 23 November 2017. The average wind speeds at the Leeuwarden and Eelde stations during the observation period were 6 m s^{−1} and 5 m s^{−1}, respectively. Comparing to the average of 5.5 m s^{−1} used for estimating the emission rates, the use of the wind speeds from either of the two stations will result in a 9% difference in the estimated emission rates. To this end, on-site windspeed measurements are highly recommended. An improvement of our method could be the use of location-specific wind speed measurements. In addition, using a tracer at or near multiple farm sites will further decrease the uncertainty in the individual estimates, and simultaneous measurements of CH₄ and NH₃ may help to partition whole-farm CH₄ emissions into dairy cow and manure emissions (Ngwabie *et al* 2011, Barrancos *et al* 2013).

3.4. Comparison of the whole-farm CH₄ emissions reported in the literature

The whole-farm CH₄ emission factors of 0.47 [0.13–0.81] kgCH₄/d/AU derived in this study are within the range of previously reported whole-farm emission values (see table 3). The average EF of 0.47 is close to the highest estimate on 23 November 2017 and higher than any other campaigns. This can be explained by the fact that the average number of cows on 23 November 2017 was significantly higher than other campaigns (see figure A5). Our whole-farm CH₄ emission results were compared only to those of previous studies in Europe due to similar climatic conditions and manure-handling practices. However, we have to be careful when comparing with other studies because of the scarcity of such measurements, the lack of compatibility between different methodologies, and the fact that only a few studies (Amon *et al* 2001, Vechi *et al* 2022) have systematically measured emissions over one year to capture seasonal variations.

The whole-farm CH₄ emission factor over the averaged dataset of 51 dairy cow farms found in this study was within ~27% with the emission factor reported in the Dutch National Inventory (Ruyssenaars *et al* 2021), and ~49% with the IPCC (2006) for dairy cows (see details in the appendix, table A3). Note that in the two inventories mentioned above, the CH₄ emission factor for dairy cows has been converted from per cow to per AU for easier comparison using the average cow weight of 650 kg (Van Bruggen *et al* 2017). The main reason for the difference between the two inventories is that the IPCC uses a Tier 1 methodology, which is not country-specific and therefore may not represent the actual characteristics of the country's livestock. The National Emission Model for Agriculture (NEMA), which was used by The Dutch National Inventory, combines Tier 3 information on dietary composition, regional differences in milk production levels and feed use to model emission factors and emissions from dairy farms. Furthermore, the whole-farm CH₄ emissions estimated by the Dutch National Inventory in North Holland and Friesland are ~28% lower compared with the measured CH₄ emissions in this study. This finding is consistent with that of Vechi *et al* (2022), who similarly suggest that the inventory-estimated

Table 3. Overview of the whole-farm CH₄ emission factors from dairy cow farms. Whole-farm emissions are the sum of enteric fermentation and manure emissions. Measurement-based values from previous whole-farm studies, along with the country and number of investigated dairy cow farms, and the method used to quantify whole-farm CH₄ emissions.

Study	Study country	Season	Nr. of farms	Method	Whole-farm emission factor [kgCH ₄ /d/AU] ^(a)
Amon <i>et al</i> (2001)	Austria	Whole year	1	^(b) VR·(CH _{4in} -CH _{4out})	0.27–0.36
Hensen <i>et al</i> (2006)	Netherlands	Spring, summer	10	IGA ^(c)	0.67–1.21
Bühler <i>et al</i> (2021)	Switzerland	Fall	1	IDM ^(d) , iTRM ^(e)	0.26–0.34
Vinković <i>et al</i> (2022)	Netherlands	Spring, fall	1	MBA ^(f)	0.21–0.52
Vechi <i>et al</i> (2022)	Denmark	Whole year	7	TDM ^(g)	0.34–1.30
This study	Netherlands	Summer, fall	51	IGA	0.18–0.50

^a AU = Animal unit (500 kg).

^b VR = Ventilation rate.

^c IGA = Inverse Gaussian approach.

^d IDM = Inverse dispersion method.

^e iTRM = Inhouse tracer ratio measurements.

^f MBA = Mass balance approach.

^g TDM = Tracer dispersion method.

whole-farm CH₄ emissions in Denmark are, on average, underestimated by 35%.

Since the majority (75%) of our single-day campaigns were carried out in the cold season (November), our results may underestimate the whole-farm emissions. In fact, it is reasonable to presume that in November, there is a relatively small amount of manure in manure cellars because they were completely emptied by late August according to Dutch regulations that no manure can be spread on fields between September and mid-February. Furthermore, in August 2018, we estimated the lowest whole-farm CH₄ emission factor (0.18 [0.11–0.26] kgCH₄/d/AU), which is in line with the empty manure cellars owing to the above-described manure practice in the Netherlands. Unfortunately, we were unable to draw conclusions regarding the seasonality of whole-farm CH₄ emissions in this study because our measurements were performed only in August and November. Therefore, further studies are encouraged to perform and/or repeat our single-transect sampling strategy in different seasons of the year to capture the seasonality of whole-farm CH₄ emissions together with more accurate wind measurements (wind speed and wind direction) to significantly reduce the uncertainty of the estimates.

4. Conclusions

In this study, we demonstrated a rapid analysis method to estimate the total farm-scale CH₄ emissions from a large number of dairy cow farms in the Netherlands. Single-transect atmospheric measurements of CH₄ concentrations downwind of 51 farms were obtained using a mobile van, which was

subsequently used to derive CH₄ emission estimates using the inverse Gaussian approach.

The moderate to high R^2 value ranging from 0.42 to 0.86 confirms that the number of AU is driving the CH₄ emission rates, with the estimated whole-farm CH₄ emission factor of 0.47 [0.13–0.81] kgCH₄/d/AU over the Composite dataset, which was within ~27% of the country-specific emission value reported in the Dutch National Inventory (2021) and was approximately 49% higher than the IPCC (2006) default value. We note however that given the large role of this number in upscaling dairy farm CH₄ emissions to country-level, a 27% increase would present a large extra challenge for GHG mitigation.

The use of single-transect observations, as in this study, may cause a lack of measurements in different seasons over a year. Over different seasons, dairy cow emissions are unlikely to change, but manure management may change due to a cyclic management system (VanderZaag *et al* 2014). In future studies, it is advisable to aim for a better distribution over different seasons or months. An important recommendation is to have on-site windspeed measurements for this type of emission study because the uncertainty in the wind speed has a strong impact on the uncertainty in the emission estimate. Our results demonstrate that CH₄ emissions from a large number of dairy cow farms can be estimated rapidly. Provided that the sufficient number and distribution of farms are sampled, the approach presented in this study may provide an independent evaluation of (country-specific) emission factors used in CH₄ reporting and potentially useful to track on-farm emissions reductions with changes to manure or feeding management.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

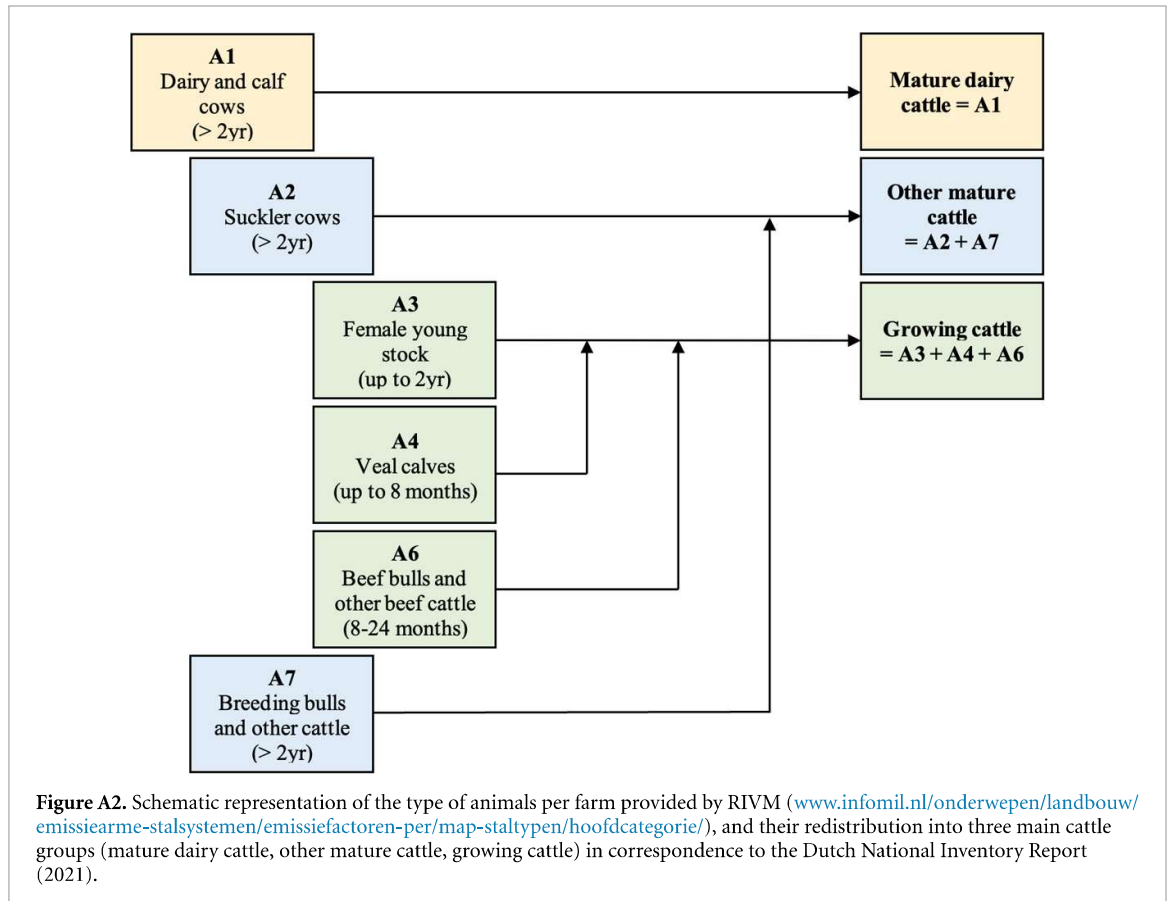
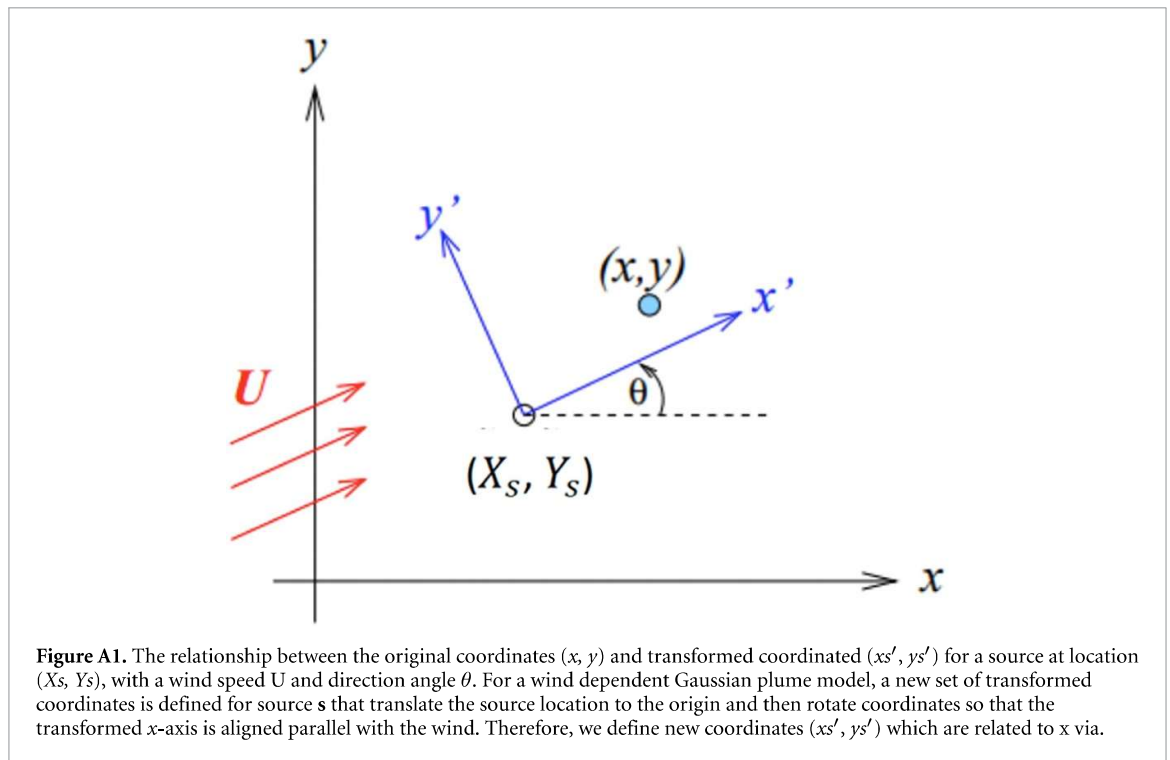
The authors declare that they have NO affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript.

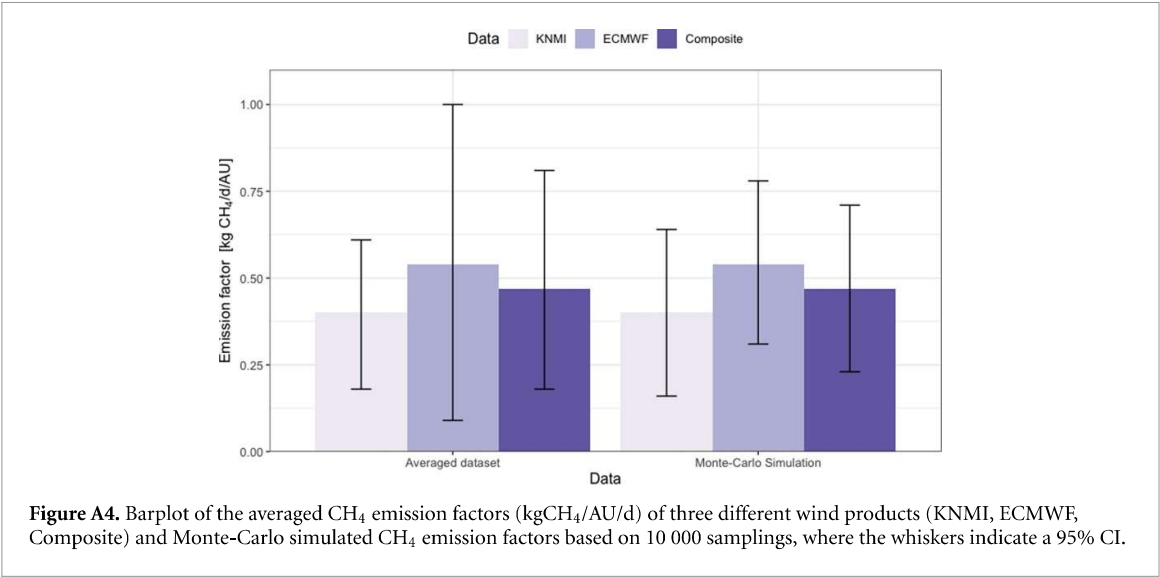
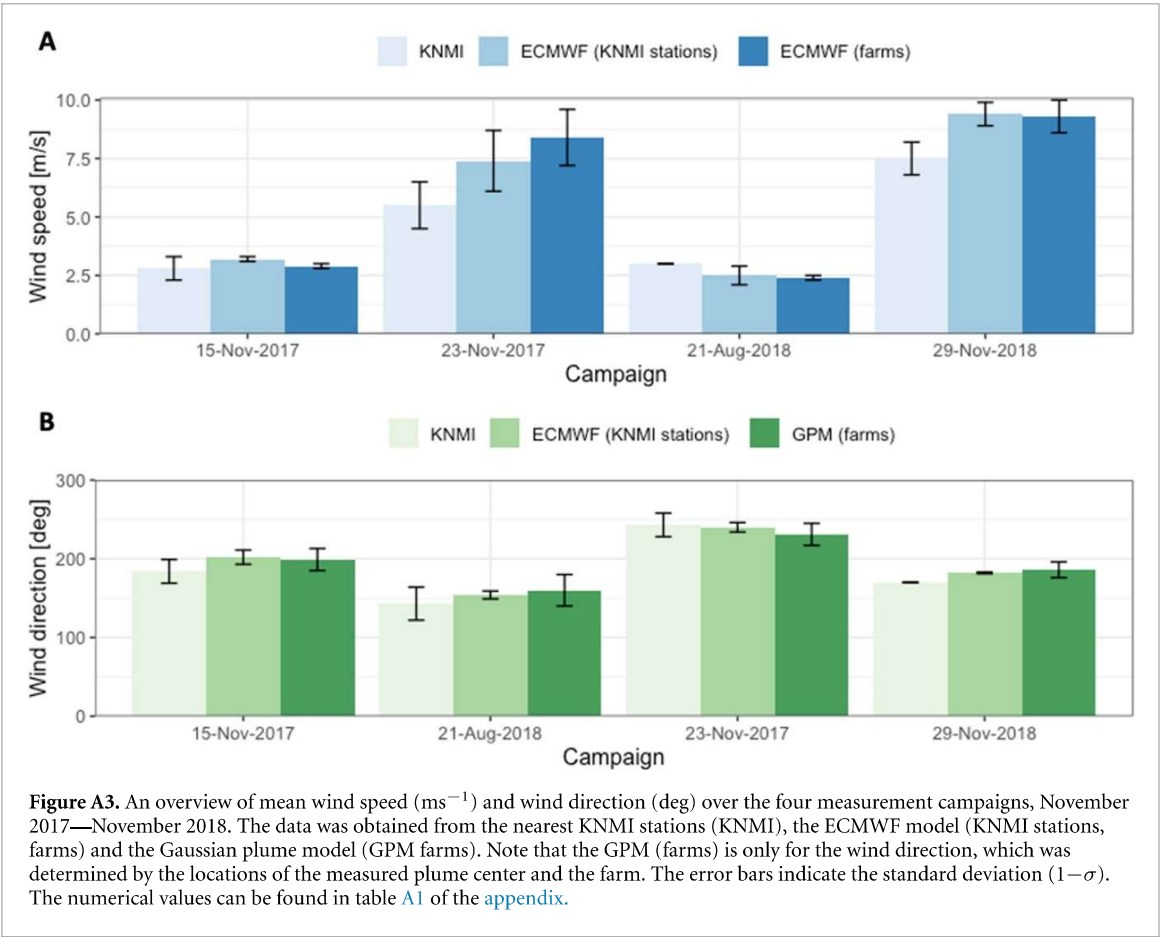
Appendix

$$\begin{pmatrix} x'_s \\ y'_s \end{pmatrix} = R_\theta \begin{pmatrix} x - X_s \\ y - Y_s \end{pmatrix}$$

$$R_\theta = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

where corresponds to the angle the wind direction vector makes with the x -axis, and R_θ represents the 2×2 matrix that rotates vectors through an angle θ in x,y —plane (Figure A1). The resulting coordinates have an xs' -axis that is aligned with the wind direction (Lushi and Stockie 2010). The illustration is originally posted in Lushi and Stockie (2010).





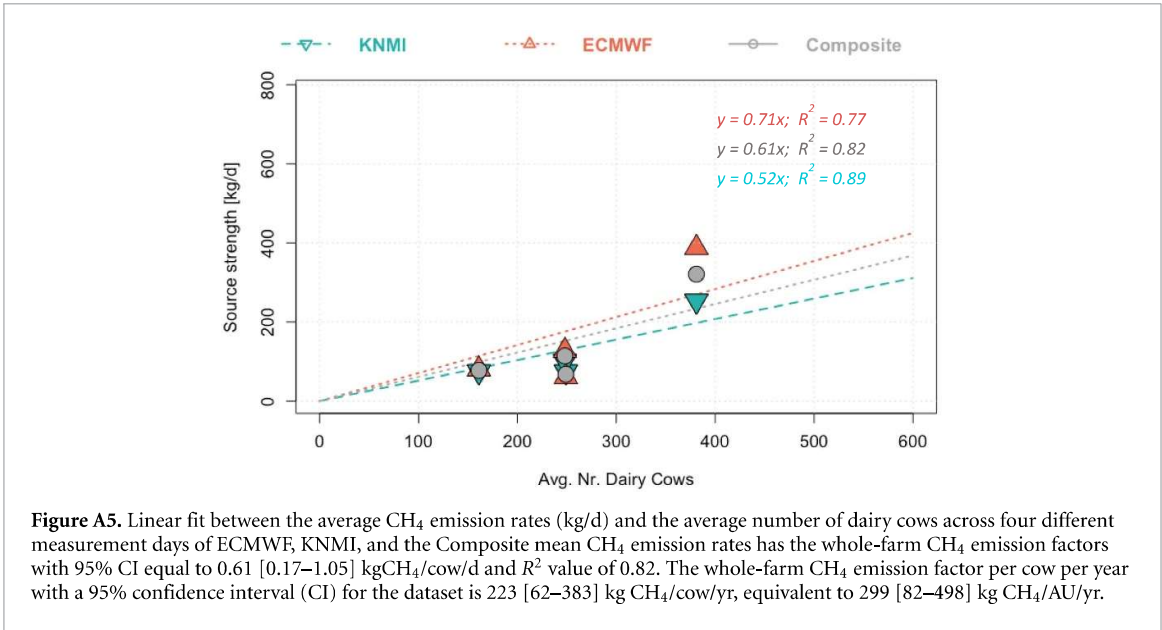


Table A1. Overview of the mean wind speed (ms^{-1}) and wind direction ($^{\circ}$) values from the nearest KNMI stations and modeled by ECMWF over the four measurement campaigns, November 2017—November 2018.

Campaign	KNMI stations ^(a)			ECMWF (KNMI stations) ^(b)		ECMWF (farms) ^(c)	GPM (farms) ^(d)
	ws (ms^{-1})	wd ($^{\circ}$)	Cloud cover	ws (ms^{-1})	wd ($^{\circ}$)	ws (ms^{-1})	wd ($^{\circ}$)
15 November 2017	2.8 ± 0.5	184 ± 15	8	3.2 ± 0.1	202 ± 9	2.9 ± 0.1	199 ± 14
23 November 2017	5.5 ± 1.0	243 ± 15	8	7.4 ± 1.3	240 ± 6	8.4 ± 1.2	231 ± 14
21 August 2018	3.0 ± 0.0	143 ± 21	8	2.5 ± 0.4	154 ± 5	2.4 ± 0.1	160 ± 20
29 November 2018	7.5 ± 0.7	170 ± 0	7–8	9.4 ± 0.5	182 ± 1	1.3 ± 0.7	186 ± 10

^a KNMI stations = mean values of one or more KNMI stations for each campaign.
^b ECMWF (KNMI stations) = ECMWF-model-based mean values of one or more KNMI stations for each campaign.
^c ECMWF (farms) = ECMWF-model-based mean values of wind speed at the exact measurement location for each campaign.
^d GPM (farms) = actual wind direction determined using the vector between the source location and plume center. The $\pm$ sign represents the standard deviation.

Table A2. Overview of descriptive statistics of farm-scale CH₄ emission rates (kgCH₄/d) from three different datasets (KNMI, ECMWF, Composite), on four individual campaigns in the Netherlands, November 2017–November 2018.

(A) ECMWF								
CH ₄ emission rates (kgCH ₄ /d)								
Campaign	Nr. of farms	Min	Max	Mean	Median	Variance	Skew	Kurtosis
15 November 2017	11	16	154	81	87	25	30	164
23 November 2017	12	28	1068	388	283	1312	72	216
21 August 2018	16	9	183	61	55	30	89	286
29 November 2018	12	48	218	127	123	46	4	126
(B) KNMI								
CH ₄ emission rates (kgCH ₄ /d)								
Campaign	Nr. of farms	Min	Max	Mean	Median	Variance	Skew	Kurtosis
15 November 2017	11	16	155	74	73	23	37	176
23 November 2017	12	23	681	253	158	635	78	193
21 August 2018	16	11	214	74	65	42	78	256
29 November 2018	12	38	191	101	110	34	8	135
(C) Composite								
CH ₄ emission rates (kgCH ₄ /d)								
Campaign	Nr. of farms	Min	Max	Mean	Median	Variance	Skew	Kurtosis
15 November 2017	11	16	154	78	80	24	33	168
23 November 2017	12	25	875	321	220	936	75	206
21 August 2018	16	10	199	68	60	35	83	269
29 November 2018	12	43	205	114	118	39	4	127

Table A3. Summary of descriptive statistics of the estimated CH₄ emission rates (kgCH₄/d) per farm over the whole dataset ($N = 51$ farms) for the KNMI observation- (KNMI) and ECMWF model-based (ECMWF) estimates, and the average of KNMI- and ECMWF-based estimates (Composite).

CH ₄ emission rates (kgCH ₄ /d)				
Whole dataset	Min	Max	Mean	Median
KNMI	11	680	123	86
ECMWF	9	1068	158	88
Composite	10	875	140	82

Table A4. The inventory-inventory reported whole-farm CH₄ emission factors from dairy cow farms and the measurement-based value from this study.

Emission factor [kg/AU/yr]	Inventory		This study
	IPCC (2006)	DNIR ^(b)	
Enteric fermentation	152 [±50%]	176 [±38%]	—
Manure management	30 [±30%]	51 [±33%]	—
Whole-farm ^(a)	182 [98–268]	227 [143–309]	299 [82–498] ^(c)

^a Whole-farm emissions = sum of enteric fermentation and manure emissions.

^b DNIR = Dutch National Inventory Report (Ruyssenaars *et al* 2021).

^c The uncertainty range is given as 95% CI based on the linear fit in figure A5.

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