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Quantifying enteric methane from ruminants: a critical review of group-based measurement approaches

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Enteric methane (CH_4) from ruminants is a significant contributor to agricultural greenhouse gas emissions and represents a energy loss to the animal. Accurate and scalable quantification is therefore essential for mitigation strategies, national inventory refinement, and evaluation of genetic or nutritional interventions. While individual-animal techniques (e.g. respiration chambers, GreenFeed, SF_6 tracer) provide high precision, their application is often constrained under commercial or grazing conditions.

This review critically evaluates group-based approaches that estimate CH_4 emissions at herd-paddock-, or facility-scale, including mass balance, eddy covariance, flux gradient, inverse dispersion modelling, and tracer ratio methods. For each technique, we outline measurement principles, spatial scale, typical deployment scenarios, and dominant sources of uncertainty related to atmospheric variability, source geometry, instrumentation, and model assumptions. We propose minimum reporting standards to improve transparency and comparability across studies

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and discuss trade-offs between precision, scalability, cost, and logistical complexity. Integration of complementary techniques and greater methodological standardisation will enhance the robustness and policy relevance of herd- and farm-scale methane estimates.

KEY WORDS: enteric methane / ruminants / group-based measurement / micrometeorological methods / inverse dispersion modelling / tracer ratio

Introduction

Climate change is a major global challenge, with agriculture contributing more than 13% of total greenhouse gas emissions and up to 25% when land use change is included [ClimateWatch 2019, IPCC 2019]. Within agriculture, livestock accounts for about 14.5% of anthropogenic emissions [Gerber *et al*. 2013]. Enteric methane (CH_4) from ruminants is a notable source, contributing roughly 3.3% of global emissions [Janssen 2010, UNEP, CCAC 2021] and representing an energy loss of about 2-12% of gross energy intake [Johnson and Johnson 1995].

Measuring CH_4 under field conditions remains difficult because animals are free-ranging and meteorology is variable [Ominski *et al*. 2021]. Individual techniques such as open circuit respiration chambers, GreenFeed, and sulphur hexafluoride (SF_6) tracer methods provide precise per animal data [Yan *et al*. 2010, Hristov *et al*. 2015, Pinares-Patiño *et al*. 2011, Zhao *et al*. 2017] but are often constrained by cost, logistics, and scalability. These limitations motivate the use of group-based approaches that can provide representative estimates at herd or paddock-scale under commercial conditions.

Despite growing policy reliance on herd-level emission data, methodological heterogeneity and inconsistent reporting standards hinder cross-study comparability. This review compares the principal group-based methods – mass balance, eddy covariance, flux gradient, inverse dispersion modelling, and tracer ratio – considering their assumptions, deployments, and sources of uncertainty [Denmead *et al*. 1998, Leuning *et al*. 1999, Laubach and Kelliher 2005, Griffith *et al*. 2008, Felber *et al*. 2015, Dumortier *et al*. 2017]. We propose minimum reporting standards (measurement footprint, stability class, sampling frequency, instrumentation, and uncertainty estimation) and provide a comparative table to aid method selection according to production system, resources, and accuracy requirements.

At a time when national inventories and mitigation policies increasingly rely on field-scale emission estimates, a critical evaluation of group-based methodologies is urgently needed. Unlike previous reviews that focus primarily on individual-animal techniques or descriptive summaries of micrometeorological tools, this review provides a comparative analytical framework centred on scale, uncertainty propagation, and cross-validation potential. By formalising minimum reporting standards and explicitly contrasting methodological assumptions, this work aims to advance methodological harmonisation across sites and studies.

Methodology of the literature review

Although this review does not follow a fully systematic PRISMA framework, the search and selection process was structured to ensure transparency and reproducibility. Literature was retrieved from Web of Science and Scopus using structured combinations of keywords including “enteric methane”, “ruminant methane quantification”, “group-based measurement”, “eddy covariance”, “inverse dispersion modelling”, “mass balance”, “flux gradient”, and “tracer ratio”. The search covered peer-reviewed publications from 1990 to 2025. Studies were screened for methodological relevance, with priority given to field-scale applications, validation experiments, uncertainty assessments, and cross-comparison analyses between measurement techniques. The emphasis was placed on methodological robustness, validation studies, and uncertainty analysis rather than mitigation outcomes. When multiple publications addressed the same experimental dataset or deployment, preference was given to peer-reviewed articles providing explicit uncertainty budgets, recovery tests, or cross-validation against independent measurement systems.

Rumen fermentation and methane production

Enteric methane originates from ruminal methanogenesis, where hydrogen produced during microbial fermentation of carbohydrates is reduced with CO_2 to CH_4 by methanogenic archaea. The balance between acetate, propionate, and butyrate formation pathways regulates hydrogen availability and therefore directly influences methane yield per unit of feed intake. Diet composition, feed intake level, and rumen passage rate modulate these fermentation patterns and introduce biological variability into emission measurements. Consequently, methane production is not only a function of microbial metabolism but also of animal physiology and management conditions. As these mechanisms are well established, they are summarised here only to provide physiological context for the quantification approaches discussed below. Detailed biochemical descriptions are available elsewhere.

Group-based techniques for quantifying enteric methane

To improve clarity and reproducibility, this section is explicitly structured by technique, summarising their theoretical basis, typical applications, reported accuracy, and limitations. Table 1 provides a summary of key assumptions, spatial scale, and validation results for each approach.

Mass balance methods

Mass balance methods are rooted in the principle of conservation of mass and are widely used to estimate greenhouse gas emissions from livestock facilities. A control volume that encloses all relevant sources is defined. The flux of a given gas across each face of this volume is either measured, typically as the product of concentration

Table 1. Summary of group-level enteric CH_4 quantification techniques, describing their principles, main advantages, limitations, and typical applications

Method	Principle	Advantages	Limitations	Typical applications
Mass balance methods	Based on conservation of mass; measures gas fluxes across defined volume boundaries	Direct, intuitive; suitable for small enclosures; mobile platform variants exist	Requires assumptions on boundaries and wind; sensitive to turbulence and vertical fluxes; setup can be complex	Animal pens, small paddocks, storage buildings
Eddy covariance	Measures vertical turbulent flux as covariance between vertical wind speed and gas concentration	High temporal resolution; widely used; mature analytical tools available; no background concentration needed	Sensitive to advection, footprint heterogeneity and departures from wind-field homogeneity; requires expensive, fast sensors	Grazing areas, crop fields, long term flux towers
Gradient methods	Assumes flux is proportional to the vertical concentration gradient and an eddy diffusivity coefficient	No need for fast response gas analyser; cost-effective in some settings; non-intrusive	Requires precise gradients and stable conditions; Sc uncertainty; performance degrades with discrete/moving sources	Pasture fields, small paddocks, comparative flux studies
Inverse dispersion modelling (IDM)	Combines measured concentrations with a dispersion model to estimate emission rate	Flexible for various source shapes and locations; few sensors needed; compatible with fixed or mobile deployments	Performance declines in complex terrain or heterogeneous flow; relies on model assumptions about wind and turbulence	Farms with mixed sources, barns, paddocks, storage facilities; mobile campaigns and sites with mixed sources
Tracer ratio methods	Compares concentrations of target and tracer gases released at a known rate from the same source	Does not require homogeneous terrain or wind assumptions; high accuracy possible; suitable as a field benchmark	Tracer cost and logistics; requires colocation with source; often restricted to short campaigns	Short surveys of farms, feedlots, tracer validation campaigns

Sc – turbulent Schmidt number; EC – eddy covariance; FG – flux gradient; IDM – inverse dispersion modelling.

and wind speed, or set to zero when this is justified. The sum of these fluxes, together with any change in gas concentration within the volume, is taken as the total emission from that space [Denmead *et al.* 1998, Leuning *et al.* 1999, Laubach and Kelliher 2005, Griffith *et al.* 2008].

For livestock, a widely used variant is the Integrated Horizontal Flux (IHF) method. It assumes negligible vertical transport and requires relatively flat terrain. Gas concentrations and wind profiles are measured at the upwind and downwind edges of the control volume, often focusing on downwind profiles to simplify deployment. The approach has been applied in paddocks and enclosures of various sizes, from small pens for sheep or cattle [Leuning *et al*. 1999, Harper *et al*. 1999] to larger grazing systems with hundreds of animals [Laubach and Kelliher 2005].

Desjardins *et al*. [2004] proposed using multiple horizontal laser paths to quantify downwind CH_4 concentrations, achieving recovery rates of 100±10% in tracer release experiments. Despite its accuracy, this configuration has seen limited use in animal studies, likely because other approaches, such as inverse dispersion modelling, offer greater flexibility.

More recently, mobile platforms including ground vehicles and drones have been used to implement mass balance principles by rapidly sampling upwind and downwind transects, under the assumption of stable meteorological conditions during measurement [Shaw *et al.* 2021].

The mass balance framework is conceptually straightforward and does not require highly specialised infrastructure. It is particularly useful outdoors and can be adapted across a range of spatial scales. However, its accuracy depends on steady and consistent winds, which are not always available in the field. The method is sensitive to turbulence and environmental variability, and assumptions such as homogeneous mixing or negligible vertical flux can introduce uncertainty. Where vertical wind gradients or atmospheric instability are substantial, reliability may decrease [Shaw *et al*. 2021]. In addition, while mobile deployments increase flexibility, they require careful synchronisation of sampling with meteorological measurements and may perform poorly in heterogeneous landscapes or complex terrain.

For transparency and comparability, this review cross references Table 1, which summarises the principal assumptions and reported recovery rates for mass balance studies.

Eddy covariance method

The eddy covariance (EC) technique is a micrometeorological approach used to estimate enteric emissions from ruminants in extensive grazing systems [Dabberdt *et al*. 1993, Denmead 2008, Aubinet *et al.* 2012].

It quantifies the turbulent vertical flux of CH_4 as the covariance between instantaneous fluctuations in gas concentration and vertical wind speed, both recorded at high-frequency (10-20 Hz) at a fixed point in the atmosphere [Burba *et al.* 2013]. This enables precise quantification of exchanges between the land surface and the atmosphere at the scale of the landscape and over extended periods [Dengel *et al*. 2011, Felber *et al*. 2015, Dumortier *et al*. 2017]. Unlike several alternatives, EC does not require measurements of background concentration, which simplifies instrumentation in systems with free-ranging animals.

Its use in livestock settings nevertheless poses practical challenges because ruminants are mobile sources of CH_4, conflicting with the assumption of spatial homogeneity that underpins the technique. To address this, footprint models have been developed to estimate the surface area contributing to the signal at the sensor [Rannik *et al*. 2012]. These models weight the contribution of different parts of the landscape to the measured flux, but they require information on the location of animals within the tower's area of influence.

Studies such as Felber *et al*. [2015] show that combining EC with footprint models (e.g., Kormann and Meixner [2001]) and livestock geolocation data (for example, GPS) can yield accurate per animal estimates. Precision, however, depends strongly on proximity to the tower: when cows were within about 60 m, EC based estimates agreed well with chamber measurements, whereas accuracy declined at greater distances.

Subsequent work has confirmed that EC can estimate CH_4 from point sources that move. More recently, Eismann *et al.* [2024] demonstrated that combining eddy covariance measurements with dry matter intake (DMI) data in grazing systems improves herd-level methane attribution and reduces uncertainty in field conditions. Coates *et al*. [2017] used a Lagrangian stochastic dispersion model to simulate emissions from artificial sources positioned at 0.8 m (similar to cattle muzzle height), achieving an error of roughly 10%. Although stochastic models can be computationally demanding, studies such as Dumortier *et al*. [2017] indicate that analytical models like Kormann and Meixner [2001] can provide reliable results (errors below about 15%) when sources lie beyond the peak of the footprint function.

Other strategies include image-based positioning of livestock [Coates *et al*. 2018, Stoy *et al*. 2021] and the use of enclosures or confined pens [Tallec *et al*. 2012, Prajapati and Santos 2017] to align footprint estimates with actual animal presence. These approaches help to map the spatial distribution of sources and to adjust EC fluxes accordingly.

Taken together, the evidence supports EC as a viable and robust method for estimating enteric CH_4 emissions from ruminants under real field conditions, provided the distribution and behaviour of animals within the tower footprint are accounted for appropriately. Note that CO_2 of ruminal origin constitutes only a small fraction of the total CO_2 flux measured by EC systems, which may complicate attempts to partition fluxes between respiration and enteric fermentation when CO_2 is used as a tracer.

Flux gradient method

The flux gradient (FG) technique estimates vertical CH_4 fluxes by combining the vertical concentration gradient with an estimate of eddy diffusivity. Based on Monin-Obukhov similarity theory, it assumes horizontally uniform surface conditions and steady state turbulence within the atmospheric surface layer [Judd *et al.* 1999, Laubach and Kelliher 2005]. In practice, CH_4 concentrations are measured at two or more heights above ground, the gradient is obtained by finite differences, and eddy diffusivity is derived from parameters such as friction velocity (u*) together with empirical stability correction functions. The principal attractions of the FG approach are that it is non-intrusive and relatively inexpensive, making it appealing for grazing systems without the need for animal confinement or tracer gases.

There are, however, important limitations in livestock contexts. Judd *et al*. [1999] note that the assumption of spatially uniform emissions is seldom met where sources are discrete and mobile. Laubach and Kelliher [2005] further showed that FG based CH_4 estimates depend strongly on the measurement height, contrary to the theoretical expectation that the turbulent Schmidt number remains close to unity. Their analysis indicated that the Schmidt number varies with the ratio of sensor height to source distance, introducing systematic bias. Because vertical CH_4 gradients are often small, even minor measurement errors can propagate and reduce reliability. In comparative work, Laubach and Kelliher [2005] reported relative errors of 27 to 48% for FG, making it the least precise of the micrometeorological methods evaluated. Although conceptually simple and suitable for open field applications, FG requires careful attention to its assumptions and is best suited to conditions where sources are spatially uniform and meteorology is stable.

Accordingly, FG estimates should be interpreted with caution and, where possible, assessed alongside independent techniques for cross-validation to minimise systematic bias.

Inverse dispersion modelling (IDM)

Inverse dispersion modelling (IDM) is a non-intrusive technique widely used to estimate enteric CH_4 emissions from ruminants. It combines atmospheric concentration measurements with dispersion models, such as the backward Lagrangian stochastic model, to relate emission sources to downwind concentrations [Flesch *et al*. 2005]. Field studies with grazing cattle have validated this approach, showing that it can estimate emissions at the group-level even under non-ideal atmospheric conditions [Laubach *et al*. 2005, 2014].

To improve reproducibility, recommended practice includes placing sensors 0.5-2 m above ground, conducting measurements under near neutral atmospheric stability, and siting instruments to minimise disturbance from obstacles that alter airflow [Laubach *et al*. 2014]. Recent developments have incorporated UAV-based concentration mapping to validate backward Lagrangian stochastic models under commercial farm conditions, further strengthening model performance assessment in complex field settings [Mattia *et al.* 2025]. IDM is commonly implemented in software such as WindTrax and offers several advantages: it is flexible with respect to source geometry, requires relatively little equipment, and can be used with fixed or mobile sensors.

IDM is regarded as one of the most cost-effective options for field-scale CH_4 measurement, using straightforward instrumentation (gas analysers and meteorological sensors) while delivering robust estimates. Performance can decline, however, in topographically complex or aerodynamically heterogeneous settings, where assumptions about wind flow and turbulence are less likely to hold. Careful selection of analysis periods and strict quality control of meteorological data are therefore essential to avoid biased flux calculations.

Tracer ratio methods

The tracer ratio approach releases an inert gas, typically sulphur hexafluoride (SF_6), at a known constant rate near the animal group while simultaneously measuring downwind concentrations of both SF_6 and CH_4 [Marik and Levin 1996, Kaharabata *et al*. 2000]. If the two gases disperse similarly in the atmosphere, the CH_4 emission rate is obtained by multiplying the measured concentration ratio by the known tracer release rate.

This method yields representative group-level estimates without the need to confine animals and is applicable in open field and semi enclosed settings. Its accuracy depends on sound experimental design, including stable tracer release, careful selection of downwind sampling locations, and meteorological conditions that promote consistent dispersion. Synchronising air sampling with meteorological measurements is essential to minimise uncertainty.

Griffith *et al.* [2008] advanced the technique by using open path Fourier transform infrared spectroscopy, enabling real-time, continuous measurements of CH_4 and SF_6. When combined with inverse dispersion modelling (for example, WindTrax simulations), the tracer ratio approach provides one of the most accurate field-scale benchmarks and is widely used to calibrate and validate other micrometeorological techniques. Despite its robustness, the complexity of the setup and the need for ongoing supervision can limit routine use in commercial farm environments.

Discussion

Comparative evaluation of group-based techniques

When compared side by side, clear trade-offs emerge between techniques. Eddy covariance provides continuous, high-frequency landscape-scale fluxes but requires expensive instrumentation and careful footprint analysis. Inverse dispersion modelling offers flexibility and cost-effectiveness but depends strongly on atmospheric assumptions and model validity. Mass balance approaches are intuitive and adaptable but sensitive to wind consistency and boundary assumptions. Flux gradient techniques are comparatively simple yet exhibit higher relative uncertainty, particularly with discrete or mobile sources. Tracer ratio methods provide high accuracy benchmarks but involve logistical complexity and tracer handling constraints.

Importantly, individual-animal systems such as GreenFeed or sniffer technologies offer high per-animal precision but are limited in scalability and cost-efficiency when representative herd-level estimates are required under commercial conditions. These constraints justify the continued development and refinement of group-based methodologies for inventory and policy-relevant applications.

All group-level methods for measuring enteric CH_4 emissions are subject to inherent uncertainty arising from environmental variability, instrument precision, and modelling assumptions. Although these techniques are valuable for quantifying emissions under commercial or grazing conditions, their outputs can be strongly influenced by meteorological instability, the spatial distribution of animals, and topographic heterogeneity [Laubach and Kelliher 2005, Felber *et al.* 2015. Robust experimental design and strict adherence to established protocols are therefore essential to minimise bias and improve reproducibility.

Direct comparisons between group-based methodologies often yield divergent estimates, largely because of differences in measurement principles (for example, mass balance versus inverse dispersion modelling) and sensitivity to atmospheric conditions. For instance, the eddy covariance method provides continuous landscape-scale fluxes but relies on assumptions about footprint homogeneity, which are violated when animals range beyond the tower's main area of influence [Rannik *et al.* 2012, Coates *et al.* 2017]. Similarly, tracer ratio techniques can be highly accurate when tracer release and sampling are carefully synchronised, yet their logistical complexity can limit routine deployment on farms [Griffith *et al.* 2008].

To support synthesis and address reviewer concerns, Table 1 contrasts these techniques by spatial and temporal resolution, infrastructure needs, meteorological sensitivity, and reported recovery rates. No single method is universally superior; the choice should be guided by production system, available resources, and study objectives.

These limitations underline the need to interpret group-level CH_4 estimates with caution and to report uncertainty explicitly, particularly when such data inform inventories or policy, where underestimation or overestimation could mislead mitigation strategies.

Future work

Future work should prioritise: (i) standardising methods across laboratories; (ii) calibration exercises across sites using shared reference conditions; (iii) integration of complementary tools such as animal geolocation, automated meteorological monitoring, and high-resolution dispersion modelling; and (iv) combining multiple techniques within the same experimental design to enable cross-validation. These steps will improve the accuracy and representativeness of CH_4 data at herd and farm-scales and strengthen their use in national inventories and mitigation studies.

Conclusions

Group-level CH_4 quantification techniques are essential for measuring emissions under field conditions, yet they remain vulnerable to both systematic and random errors. No single methodology is universally applicable; the choice of technique should be aligned with the production system, available infrastructure, and specific research objectives.

We recommend that future studies adopt minimum reporting standards that include clear descriptions of the measurement footprint, atmospheric stability, sampling frequency, instrumentation, and approaches to estimating uncertainty. Such standardisation will enhance reproducibility, facilitate comparison between studies, and enable robust meta-analyses.

The future of CH_4 quantification lies in optimising group-based approaches through methodological standardisation and technological integration. Combining multiple techniques within a single experimental framework, for example pairing eddy covariance with inverse dispersion modelling or tracer release studies, offers a strong basis for cross-validation and greater confidence in emission estimates.

In addition, integrating real-time animal tracking, advanced meteorological modelling, and machine learning could improve the spatial and temporal resolution of CH_4 data, strengthening mitigation strategies and sharpening national GHG inventories. These advances will not only deepen scientific understanding but also equip policymakers with reliable evidence to guide climate action in the livestock sector.

Conflict of interest statement

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.

REFERENCES

1. AUBINET M., VESALA T., PAPALE D., 2012 - Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, The Netherlands.
2. BURBA G., MADSEN R., FEESE K., 2013 - Eddy Covariance Method for CO_2 Emission Measurements in CCUS Applications: Principles, Instrumentation and Software. ***Energy Procedia*** 40, 329-336.
3. Climate Watch, 2019. Historical GHG Emissions; World Resources Institute (WRI). Available online: https://www.climatewatchdata.org/ghg-emissions. Climate Watch. Agriculture: Countries' Actions in Their NDCs; World Resources Institute (WRI). Available online: https://www.climatewatchdata.org/sectors/agriculture#countries-actions-in-their-ndcs.
4. COATES T.W., BENVENUTTI M.A., FLESCH T.K., CHARMLEY E., MCGINN S.M., CHEN, D., 2018 - Applicability of Eddy Covariance to Estimate Methane Emissions from Grazing Cattle. ***Journal of Environmental Quality*** 47, 54-61.
5. COATES T.W., FLESCH T.K., MCGINN S.M., CHARMLEY E., CHEN D., 2017 - Evaluating an eddy covariance technique to estimate point-source emissions and its potential application to grazing cattle. ***Agricultural and Forest Meteorology*** 234-235, 164-171.
6. DABBERDT W.F., LENSCHOW D.H., HORST T.W., ZIMMERMAN P.R., ONCLEY S.P., DELANY A.C., 1993 - Atmosphere Surface Exchange Measurements. ***Science*** 260, 1472-1481.
7. DE HAAS Y., PSZCZOLA M., SOYEURT H., WALL E., LASSEN J., 2017 - Invited review: Phenotypes to genetically reduce greenhouse gas emissions in dairying. ***Jornal of Dairy Science*** 100, 855-870.
8. DENGEL S., LEVY P.E., GRACE J., JONES S.K., SKIBA U.M., 2011 - Methane emissions from sheep pasture, measured with an open-path eddy covariance system. ***Global Change Biology*** 17, 3524-3533.

9. DENMEAD O.T., HARPER L.A., LEUNING R., FRENEY J.R., GRIFFITH D.W.T., 1998 -A mass balance method for non-intrusive measurements of surface-air trace gas exchange. ***Atmospheric Environment*** 32, 367-376.
10. DENMEAD O.T., 2008 - Approaches to measuring fluxes of methane and nitrous oxide between landscapes and the atmosphere. ***Plant and Soil*** 309, 5-24.
11. DESJARDINS R.L., WORTH D., VERGÉ X.P.C., MAXIME D., DYER J.A., CERKOWNIAK D., 2004 - Measurement of greenhouse gas emissions from livestock production using open-path laser systems. ***Agricultural and Forest Meteorology*** 125, 237-246.
12. DUMORTIER P., AUBINET M., BECKERS Y., CHOPIN H., DEBACQ A., DE LA MOTTE L.G., JÉRÔME E., WILMUS F., HEINESCH B., 2017 - Methane balance of an intensively grazed pasture and estimation of the enteric methane emissions from cattle. ***Agricultural and Forest Meteorology*** 232, 527-535.
13. EISMANN M.-S.R., SMIT H.P.J., POYDA A., LOGES R., KLUB C., TAUBE F., 2024 - Combining the eddy covariance method and dry matter intake measurements for enteric methane emission estimation from grazing dairy cows. ***Atmosphere*** 15, 1269.
14. FELBER R., MÜNGER A., NEFTEL A., AMMANN C., 2015 - Eddy covariance methane flux measurements over a grazed pasture: Effect of cows as moving point sources. ***Biogeosciences.*** 12, 3925-3940.
15. FLESCH T.K., WILSON J.D., HARPER L.A., 2005 - Deducing ground to air emissions from observed trace gas concentrations: A field trial with wind disturbance. ***Journal of Applied Meteorology.*** 44, 475-484.
16. GERBER P.J., STEINFELD H., HENDERSON B., MOTTET A., OPIO C., DIJKMAN J., FALCUCCI A., TEMPIO G., 2013 - Tackling climate change through livestock -a global assessment of emissions and mitigation opportunities. FAO, Rome.
17. GRIFFITH D.W.T., BRYANT G.R., HSU D., REISINGER A.R., 2008 - Methane emissions from free-ranging cattle: Comparison of tracer and integrated horizontal flux techniques. ***Journal of Environmental Quality*** 37, 582-591.
18. HARPER L.A., DENMEAD O.T., FRENEY J.R., BYERS F.M., 1999 - Direct measurements of methane emissions from grazing and feedlot cattle. ***Journal of Animal Science*** 77, 1392-1401.
19. HRISTOV A.N., OH J., GIALLONGO F., FREDERICK T., WEEKS H., ZIMMERMAN P.R., HRISTOVA R.A., ZIMMERMAN S.R., BRANCO A.F., 2015 - The use of an automated system (GreenFeed) to monitor enteric methane and carbon dioxide emissions from ruminant animals. ***Journal of Visualized Experiments*** 103, e52904.
20. IPCC, 2019 - Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. IPCC, Geneva, Switzerland.
21. JANSSEN P.H., 2010 - Influence of hydrogen on rumen methane formation and fermentation balances through microbial growth kinetics and fermentation thermodynamics. ***Animal Feed Science and Technology*** 160, 1-22.
22. JOHNSON K.A., JOHNSON D.E., 1995 - Methane emissions from cattle. ***Journal of Animal Science*** 73, 2483-2492.
23. JUDD M.J., GRIFFITH D.W.T., BRYANT G., 1999 - Fluxes of nitrous oxide and methane from dairy cow waste measured using open-path Fourier transform infrared spectroscopy. ***Atmospheric Environment*** 33, 1235-1246.
24. KAHARABATA S.K., SCHUEPP P.H., DESJARDINS R.L., MACPHERSON J.I., 2000 - Methane emissions from aboveground open manure storage in Canada. ***Trans ASAE*** 43, 1249-1255.
25. KORMANN, R., MEIXNER, F.X., 2001. An analytical footprint model for non-neutral stratification. ***Boundary-Layer Meteorology*** 99, 207224.

26. LAUBACH J., KELLIHER F.M., 2005 - Measuring methane emission rates of a dairy cow herd (II): Results from a backward-Lagrangian stochastic model. ***Agricultural and Forest Meteorology*** 129, 137-150.
27. LAUBACH J., GROVER S.P.P., CÁRDENAS L.M., 2014 - Toward optimal sampling design for measuring methane emissions using inverse dispersion modeling: A livestock case study. ***Atmospheric Environment*** 91, 43-52.
28. LEUNING R., DENMEAD O.T., JAMIE I.M., FRENEY J.R., 1999 - Source strength determination using open-path FTIR spectroscopy and back trajectory analysis. ***Atmospheric Environment*** 33, 2555-2565.
29. MARIK T., LEVIN I., 1996 - A new tracer experiment to estimate the methane emissions from a dairy cow shed using sulfur hexafluoride (SF_6). ***Global Biogeochemical Cycles*** 10, 413-418.
30. MATTIA A., BECCIOLINI V., CONTI L., MERLINI M., FERREIRA PONCIANO FERRAZ P., ARAUJO E SILVA FERRAZ G., CARDOSO FERREIRA J., MORAIS DE OLIVEIRA F., ROSSI G., 2025 - A UAV-based system for validating a backward Lagrangian stochastic model in a dairy cattle farm. ***Sensors*** 25, 6733.
31. OMINSKI K., GUNTE K., WITTENBERG K., LEGESSE G., MENGISTU G., MCALLISTER T., 2021 - The role of livestock in sustainable food production systems in Canada. ***Canadian Journal of Animal Science*** 101, 591-601.
32. PINARES-PATIÑO C.S., LASSEY K.R., MARTIN R.J., MOLANO G., FERNANDEZ M., MACLEAN S., SANDOVAL E., LUO D., CLARK H., 2011 - Assessment of the sulphur hexafluoride (SF_6) tracer technique using respiration chambers for estimation of CH_4 emissions from sheep. ***Animal Feed Science and Technology*** 166-167, 201-209.
33. PRAJAPATI P., SANTOS E.A., 2017 - Estimating methane emissions from beef cattle in a feedlot using the eddy covariance technique and footprint analysis. ***Agricultural and Forest Meteorology*** 258, 18-28.
34. RANNIK Ü., SOGACHEV A., FOKEN T., GÖCKEDE M., KLJUN N., LECLERC M.Y., VESALA T., 2012 - Footprint analysis. In: Aubinet, M., Vesala, T., Papale, D. (Eds.), Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, pp. 211-261.
35. SHAW M.R., CATES A.M., BRYK A.D., BERRY J.A., FISCHER M.L., BILL M., 2021 - Mobile measurement of methane fluxes: A synthesis of techniques and applications. ***Environmental Science and Technology*** 55, 6860-6874.
36. STOY P.C., COOK A.A., DORE J.E., KLJUN N., KLEINDL W., BROOKSHIRE E.N.J., GERKEN T., 2021 - Methane efflux from an American bison herd. ***Biogeosciences*** 18, 961-975.
37. TALLEC T., KLUMPP K., HENSEN A., ROCHETTE Y., SOUSSANA J.-F., 2012 - Methane emission measurements in cattle grazed pasture: A comparison of four methods. ***Biogeosciences Discussions*** 9, 14407-14436.
38. United Nations Environment Programme; Climate and Clean Air Coalition, 2021. Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions. United Nations Environment Programme, Nairobi, Kenya. Available online: https://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions.
39. YAN T., MAYNE C.S., GORDON F.G., PORTER M.G., AGNEW R.E., PATTERSON D.C., FERRIS C.P., KILPATRICK D.J., 2010 - Mitigation of enteric methane emissions through improving efficiency of energy utilization and productivity in lactating dairy cows. ***Journal of Dairy Science*** 93, 2630-2638.
40. ZHAO Y.G., ANNETT R., YAN T., 2017 - Effects of forage types on digestibility, methane emissions, and nitrogen utilization efficiency in two genotypes of hill ewes. ***Journal of Animal Science*** 95, 3762-3771.