CSIRO PUBLISHING

REVIEW
https://doi.org/10.1071/AN22051

ANIMAL PRODUCTION SCIENCE

An assessment of global ruminant methane-emission measurements shows bias relative to contributions of farmed species, populations and among continents

M. M. Della Rosa[A,*], G. C. Waghorn[B], R. E. Vibart[A] and A. Jonker[A]

For full list of author affiliations and declarations see end of paper

*Correspondence to:
M. M. Della Rosa
AgResearch Limited, Grasslands Research Centre, Tennent Drive, 11 Dairy Farm Road, Private Bag 11008, Palmerston North 4442, New Zealand
Email: milagros.dellarosa@agresearch.co.nz

Handling Editor:
Ermias Kebreab

Received: 17 February 2022
Accepted: 19 October 2022
Published: 11 November 2022

Cite this:
Della Rosa MM *et al.* (2023)
Animal Production Science, **63**(3), 201–212.
doi:10.1071/AN22051

ABSTRACT

Global ruminant methane (CH_4)-mitigation strategies rely on data from *in vivo* CH_4-emission measurements. This survey of 415 peer-reviewed studies of *in vivo* enteric-CH_4 measurements from farmed ruminants details research objectives, diets, and methodology as well as groups within ruminant species. The survey results have been evaluated in relation to ruminant population data and the contributions of each species to CH_4 emissions. Despite the highest estimated total CH_4 emissions from ruminants in Asia, South America and Africa (accounting for 37%, 23% and 17% of total enteric-CH_4 emissions respectively), the number of *in vivo* studies of CH_4 measurements were 15%, 9% and 1% of global studies respectively. Globally, the most studied species were cattle (64%) and sheep (22%), whereas goats and buffalo accounted for 7% and 5% of studies respectively. These species account for 75%, 7%, 5% and 12% of total enteric-CH_4 emissions respectively. Most cattle studies were with *Bos taurus* and only 12% of the cattle studies were with *Bos indicus*. Respiration chambers have been used in 51% of studies and, despite the development of other methodologies, they remain the dominant technique for measurement of enteric-CH_4 production. Most studies involved animals fed high-forage diets; these were 56% of the studies with cattle, 73% with sheep, 47% for goats, but only 15% of studies with buffalo. The evaluation of diets as a mitigation strategy was the prime objective of all regions. The number of studies that have measured CH_4 from cattle aligns with their contribution to enteric emissions; however, buffalo, *Bos indicus* cattle and mature beef cows were under-represented relative to their global populations and contribution to global emissions. Dominance of measurements from cattle was evident in all continents.

Keywords: agriculture, diets, farmed ruminant species, global distribution of studies, methane measurement techniques, methane mitigation, ruminant methane emissions, trends.

Introduction

Enteric methane (CH_4) from domestic ruminants is a major source of anthropogenic greenhouse gas (GHG; Myhre *et al.* 2013). Methane emissions from livestock and mitigation strategies are reported biennially in a national GHG inventory report from countries associated with the 'Paris Agreement' (United Nations of Climate Change (UNCC) 2015). National CH_4 estimates can be calculated using the Intergovernmental Panel on Climate Change (IPCC) Guidelines (Intergovernmental Panel on Climate Change (IPCC) 2006, 2019), and the level of uncertainty is dependent on the tier level (1–3) used for calculations. The lower and upper uncertainty (95% confidence interval) for global enteric-CH_4 emissions is –11% to 18% (United States Environmental Protection Agency (US EPA) 2017) and this is a consequence of limited local information about livestock numbers, dry-matter intake (DMI), diet chemical composition and CH_4 emissions per unit of DMI (i.e. CH_4 yield; Hristov *et al.* 2018).

Globally, ruminant livestock numbers and current estimates of ruminant enteric-CH_4 emissions (Statistical Database Food and Agriculture Organization of the United Nations (FAOSTAT) 2020) show that emissions are highest from Asia (37%), followed by South

America (SA, 23%), Africa (17%), Europe (10%), North America (NA, 9%) and Oceania (3%). Non-dairy and dairy cattle account for 56% and 19% of estimated enteric emissions respectively, followed by buffalo (12%) sheep (7%), goats (5%) and camelids (1%). Statistical Database Food and Agriculture Organization of the United Nations (FAOSTAT) (2020) data were available only for South American camelids (llama and alpaca) but not for other minor categories such as farmed deer and bison.

Refining and implementing methodology to estimate livestock CH_4 emissions is ongoing, and the aim is to reduce uncertainty of national CH_4 estimates by validating estimates of animal DMI and CH_4 yield (summarised by Intergovernmental Panel on Climate Change (IPCC) 2006, 2019) with measured values. Ruminant CH_4 yield depends on several interacting feed and animal factors, which should be captured by *in vivo* CH_4-emission measurements. Although the United Nations Framework Convention on Climate Change (UNFCCC) (1997) stated that 'comparable methodologies' should be used for compiling the GHG inventory to make national results comparable in a consistent manner, several methods have been developed to determine CH_4 emissions from individual animals. Each method affects the variability of the enteric-CH_4 estimate (Hammond *et al.* 2016*a*; Jonker *et al.* 2020; Della Rosa *et al.* 2021), and all need to be validated against the 'gold standard', respiration chambers (RC). Methodology may contribute variability to CH_4 emission measurements and national inventories.

Global efforts to reduce the rise in anthropogenic GHG emissions require robust data to establish current emissions, develop projections of future emissions as well as identify and evaluate emission-mitigation strategies. The global statistics from Statistical Database Food and Agriculture Organization of the United Nations (FAOSTAT) (2020) give a macro view of ruminant populations and its contribution to CH_4 from ruminant enteric fermentation. These statistics and expert advice guide global and regionalised policies to identify new research areas appropriate for local conditions.

Every published study has its own objective that adds information to the scientific community, but a macro analysis of where, how and what studies were conducted will enable comparisons among ruminant populations and production systems. The objective of this literature survey was to summarise published information on CH_4 measurements performed on farmed ruminant species, categories of feeds, methodology and research aims on six continents, in relation to ruminant populations and the contributions of each species to estimated global CH_4 emissions for each continent.

Materials and methods

A literature search was conducted using Google Scholar, Scopus, and Ovid to retrieve relevant scientific peer-reviewed papers. The keywords used in the literature search were livestock, cattle, beef, dairy, goat, sheep, deer, buffalo, llama, alpaca, methane, chambers, sulfur hexafluoride (SF_6), GreenFeed (GF), laser CH_4 detector, sniffer and words related to continents, such Africa, Asia, etc. Only peer-reviewed papers written in English were considered, not technical notes, conference abstracts or technical reports. Articles published between 1994 and 2018 that reported CH_4 emissions measured using RC, SF_6, GF and 'Other' techniques (face mask (FM), portable accumulation chambers (PAC); hand-held laser CH_4 detector (LMD) and 'sniffer' (SNF)) were considered (n = 415 treatment means; listed in Supplementary material Table S1). Articles that were based on simulated CH_4-emission data were not considered.

Continents, animals, measurement techniques and aim of studies

Information extracted from each publication included year of publication (1994–2018), country where the trial was conducted, animal species/type, the technique used to determine CH_4 (RC, SF_6, GF and Other techniques), as well as the aims of each study and animal diets. Animals were categorised as cattle, buffalo, goat, sheep and other species (deer, alpaca, llama, etc.). Cattle were further categorised as either dairy (growing, lactating and non-lactating) or beef cattle (growing and mature) and either *Bos indicus* or *Bos taurus*. If the studies reported a cross between *Bos taurus* and *Bos indicus*, they were included as *Bos indicus*.

The countries where the studies were conducted were grouped into continents as follows: Asia, Africa, Europe, North America (including Mexico; NA), South America (including Caribbean, except Mexico, SA) and Oceania. The aims of the research studies were classified into the following four groups: diet evaluation (Diet); technique/s (Tech), involving comparisons among, or modifications within a technique to measure CH_4; animal efficiency (Efficiency) for animals with divergent feed efficiency (residual feed intake), CH_4 emissions or breeds and 'Other objectives', such as vaccines, defaunation, etc.

Diet classification

Information on composition of diets fed during CH_4 measurements was used to identify the following three subgroups: 'High-forage diets' when fresh or conserved forage, i.e. hay, haylage and silage, represented 65% or more of the diet; 'High-concentrate diets', when energy and/or protein concentrates represented 65% or more of the total diet; and 'mixed diets', when there was no-clear dominance of either forages or concentrates. If a comparison was made between two contrasting diets such as forage versus concentrate, or if diets changed from high forage to high concentrate (or mixed) or *vice versa*, then the two extreme diet types were recorded within the same study.

Within each diet subgroup, further classification was performed. Diets were grouped as 'Supplement' when any type of forage/concentrate (e.g. different plant species, oils, seeds, lipids or different combinations of dietary components) was added or substituted in the control diet. Diets were grouped as 'Additive' if bio-active extracts or compounds such as ionophores, urea, tannins, mix of herbs, saponins, nitrate, CH_4 inhibitors, and/or essential oils were tested. If the aim of a study was to test different proportions of ingredients in a diet (e.g. compare an unbalanced diet with a nutrient-balanced diet), or forage qualities/types (e.g. C3 vs C4 species, ryegrass vs clover) or feeding frequencies, they were classified as 'Nothing added'. If the combination of components classified as 'Supplement' or 'Additive' were tested in the same study, it was stated as 'Both'.

Data processing and presentation

Because of the nature of the data and the scope of this survey, statistical comparisons were neither possible nor required. Data were collected and organised in Microsoft Excel. Each Excel row entry (unit of evaluation) contained the following information: authors, publication year, journal, CH_4 measurement technique, continent, livestock species, productive state and subspecies of beef and dairy cattle, study aims and type of diet. If one study included more than one CH_4 measurement technique, livestock species, study aim or diet, the same study was counted as many times as variations showed for that classification criteria. For example, a study using three CH_4 measurement techniques in cattle was counted three times for technique classification and one time for livestock species. Although 415 publications were collected for the current evaluation, there were 450 entries for technique by continent, because 28 publications used two or more techniques to measure CH_4. There were 435 entries for the evaluation of species by continent, 467 entries for the evaluation of techniques by species and 446 entries for study aim combined with continent. Only studies that were classified as 'Diet' by their aim were used to analyse diet by continent and animal species, resulting in 348 entries for diet by continent and 360 entries for diet by animal species.

Only data from cattle were further classified by subspecies (*Bos taurus*, *Bos indicus*), production type and physiological state, i.e. dairy (growing, lactating, non-lactating) and beef (growing, mature). For cattle, 292 entries were available for the evaluation. Twenty-three publications with cattle did not report subspecies and one did not report the physiological state of the animals and these were not included in the cattle subclassification.

So as to have a reference point and to aid interpretation, data from Statistical Database Food and Agriculture Organization of the United Nations (FAOSTAT) (2020) were included. Classification of countries from Statistical Database Food and Agriculture Organization of the United Nations (FAOSTAT) (2020) was summarised as continents. 'Africa' included near east as well as northern and sub-Saharan Africa; 'Asia' included eastern Asia, Russian Federation and southern Asia regions; western Europe, eastern Europe were grouped as 'Europe'; North America, plus Mexico as NA; Latin America and the Caribbean (Central America), excluding Mexico as 'SA' and Oceania as 'Oceania'. Then, the number of animals per species and emissions per species per continent were summarised from Statistical Database Food and Agriculture Organization of the United Nations (FAOSTAT) (2020).

Results and discussion

This survey defined disparities between continents and animal species in trials involving CH_4 measurements, as well as the focus of research across regions and the methodology used. This survey did not evaluate CH_4-emission values, and the accuracy of published data was not judged. However, the survey did provide details concerning the scarcity of measurements in some continents, bias regarding some ruminant species, production systems and feed type. Identifying these shortcomings provides an insight for future research measurements, to address the current imbalance of global information, enabling progress towards an integrated CH_4-emission mitigation program. The current study considered only papers published in English language in peer-reviewed journals and therefore excluded information from publications published in local languages and published in reports and conference proceedings.

Methane measurement techniques used between 1994 and 2018

Between 1994 and 2018, approximately half (51%) of the published studies used RC to measure CH_4 emissions, followed by 36% with SF_6 and 7% with GF. The remaining 6%, mostly from Europe, comprised 2% FM, 2% SNF, 1% PAC (from Oceania), and 1% LMD (9, 9, 4 and 6 studies respectively) and have been categorised as 'Other tech' in Table 1. From 2006, there was an increase in annual studies of ruminant CH_4 emissions and numbers of studies using RC and SF_6 were similar from 1994 until 2011, after which the number of studies with RC increased at a greater rate (Fig. 1).

Respiration chambers provide accurate and precise measurements of CH_4 emitted by individual animals (Pinares Patiño and Waghorn 2014), but RC facilities are not available in many countries. The need to measure CH_4 emissions under conditions more representative of livestock farming led to the development of methods including SF_6 tracer technique in the early 1990s (Johnson and Johnson 1995) and GF spot-sampling in the past decade. These methods enable CH_4 emissions to be estimated on-farm or while animals are grazing (Della Rosa *et al.* 2021), but

Table 1. Continental summary of studies published from 1994 to 2018, classified by methane measurement techniques, study aims and ruminant species.

Item	Africa	Asia	Europe	N America	S America	Oceania	Total
Measurement technique (number of studies)							
RC	0	35	81	56	7	51	230
SF_6	3	25	36	25	34	39	162
GF	0	1	8	8	0	13	30
Other tech.	1	4	18	0	1	4	28
Total	4	65	143	89	42	107	450
Study aim (number of studies)							
Efficiency	0	3	24	6	5	25	63
Diet	4	61	102	71	35	56	329
Tech	0	1	16	8	1	18	44
Other obj.	0	1	2	0	0	7	10
Total	4	66	144	85	41	106	446
Ruminant species (number of studies)							
Buffalo	0	21	0	0	0	0	21
Cattle	3	26	96	75	29	49	278
Goat	1	11	13	5	2	0	32
Sheep	0	13	22	2	9	49	95
Other spp.	0	2	1	3	0	3	9
Total	4	73	132	85	40	101	435

Abbreviations: Continent; N America, North America (including Mexico); S America, South America (including all other countries not in N America); RC, respiration chamber; SF_6, sulfur hexafluoride; GF, GreenFeed; Other tech. includes face mask, sniffer, laser methane detector and portable accumulation chamber.
Regarding study aims; Efficiency, refers to a range of parameters relating to the efficiency of animal production, e.g. breed, feed utilisation; Diet, effects of diet on methane emissions; Tech, assessing variations within/among techniques; Other obj., other objectives include evaluation of rumen fauna, heat stress, anti-methanogenic vaccination.
Other spp., including alpaca, llama, deer, bison.

intakes of grazing animals cannot be determined accurately (Undi *et al.* 2008).

The SF_6 and GF methods have an acceptable accuracy for CH_4 measurement (Grainger *et al.* 2007; Hammond *et al.* 2016*a*; Jonker *et al.* 2020), and PAC has an acceptable precision for ranking animals, when compared with results from RC (Jonker *et al.* 2018). Other spot-sampling methods to measure CH_4 emission from individual animals provide less accurate or precise estimates of daily CH_4 production and have been developed with a view to screening and selection of individual animals, these are FM (Hammond *et al.* 2016*b*), LMD and SNF (Garnsworthy *et al.* 2012; Chagunda 2013).

Prior to 1990, most research involving RC for CH_4 determinations was to evaluate energetic metabolism in ruminants (Lassey 2007). The increasing number of studies addressing CH_4 emissions since 1990, and especially from 2006 onward, aligns with international efforts and interests to quantify and reduce GHG emissions from livestock in relation to global warming. These include the international environmental treaty under the United Nations Framework Convention on Climate Change (UNFCCC) which was adopted in 1992 at the Rio de Janeiro Earth Summit, followed by the Kyoto Protocol agreements that came into force in 2005, with a second commitment period after 2012.

Techniques used for CH_4 studies per continent

Most animal-CH_4 measurement studies were from Europe (32%), followed by Oceania (23%), North America (20%), Asia (15%), South America (9%), and Africa (1%). When considering cattle data only (Europe, 35%; North America 27%, Oceania 18%, South America 10%, Asia 9%, Africa 1%), the distribution of the number of studies by region was similar to the number of studies providing CH_4 data from dairy and beef cattle to the 'GLOBAL NETWORK' database (Europe 49%, North America 38%, South America 7%, Oceania 6%, Asia <1%; Niu *et al.* 2018; van Lingen *et al.* 2019), although with relatively more studies from Oceania, South America and Asia in the current study. In contrast, the largest total emissions of enteric CH_4 from ruminant livestock are produced in Asia, SA and Africa, which also have the largest ruminant livestock populations (Table 2). The increase in total CH_4 emissions from the ruminant livestock

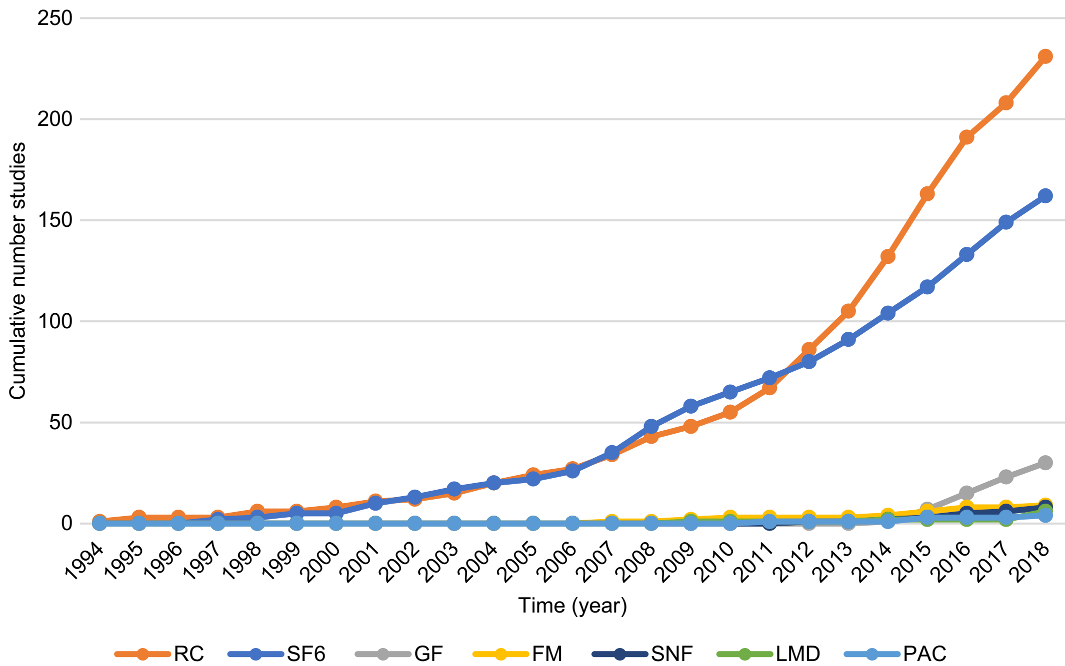

Fig. 1. Cumulative number of published studies from 1994 to 2018, with seven *in vivo* methane measurement techniques. RC, respiration chamber; SF_6, sulfur hexafluoride; GF, GreenFeed; FM, face mask; PAC, portable accumulation chamber; LMD, laser methane detector; SNF, sniffer.

sector from 1890 to 2014, estimated using Tier 2 IPCC guidelines, was mainly due to increased emissions from livestock in Africa, Asia and SA (Dangal *et al.* 2017). In addition to the numbers of ruminants, the high proportion of cattle in SA, relative to Asia and Africa, accounts for the high emissions relative to total ruminant numbers in SA.

With regard to measurement technique (Table 1), RC has been the most used (percentage of total measurements) in Asia (54%), Europe (57%), NA (63%) and also Oceania (48%) but has been used only in 17% of SA studies. The SF_6 tracer technique has been used in all continents (Table 1) and has the advantage over RC in that it can be used with free-ranging and grazing animals (Johnson and Johnson 1995). The GF system has mainly been used in Oceania, Europe and NA and the other spot-sampling techniques have mainly been reported in Europe (Table 1).

The development and increased use of spot-sampling methods reported in the literature are a response to the need to measure larger number of animals for genetic selection or to measure emissions on commercial farms, and most of these methods require less technical expertise by the user (Hammond *et al.* 2016*a*; Garnsworthy *et al.* 2019). However, some of these spot-sampling methods (i.e. FM, LMD and SNF) require further investigation due to high variance and uncertainty regarding accuracy (Oss *et al.* 2016; Hristov *et al.* 2018). Differences among continents in the techniques used for determination of CH_4 emissions are indicative of available infrastructure (RC especially), but also ruminant species and production systems. Sharing of capability among countries could enable development of strategic research alliances, enabling research gaps to be filled, especially in Africa, Asia and SA. Such initiatives are in progress with projects through, for example, the Global Research Alliance on Agricultural Greenhouse Gasses (globalresearchalliance.org) and Research Program on Climate Change, Agriculture and Food Security (ccafs.cgiar.org).

Ruminant species studied globally and their contribution to global enteric-CH_4 emissions

The distribution of published studies concerning CH_4 measurement from animal species and across continents is summarised in Table 1. Most studies have been conducted with cattle (64%) and sheep (22%), with only 7% from goats and 5% from buffalo and 2% from other ruminants (alpaca, bison, llama, deer). The large number of studies with cattle is likely to reflect their dominance in numbers, importance in global agriculture and contribution to the total enteric-CH_4 emissions from ruminant livestock (76%, Table 2).

The relatively large number of studies with sheep, compared with other livestock, is likely to reflect their productive value for some continents (e.g. Europe and Oceania) and the ease of measurement, although sheep contribute only 7% of livestock enteric-CH_4 emissions (Table 2). Sheep are often used to explore mitigation options for ruminants in general, possibly because of lower

Table 2. Continental summary of animal numbers (millions), annual enteric-methane emissions (CO_2-equiv; million tons) by species (Statistical Database Food and Agriculture Organization of the United Nations (FAOSTAT) 2020).

Item	Africa	Asia	Europe	N America	S America	Oceania	Total
Animal numbers (millions)							
Buffalo	3.4	197.0	0.5	0	0	0	200.9
Cattle	354.0	462.0	119.0	141.0	373.0	37.1	1486.1
Goats	440.0	562.0	16.4	11.4	22.9	4.1	1056.1
Sheep	389.0	519.0	130.0	14.8	64.6	97.4	1214.8
Other	0	0	0	0	9.1	0	9.1
Total	1186.4	1740.0	265.9	167.2	469.6	138.6	3981.0
Methane as CO_2 equiv. from ruminant enteric fermentation (million tons)							
Buffalo	4.0	232.5	0.5	0	1.6	0	238.6
Cattle	252.8	388.4	182.3	176.1	449.6	50.8	1510.8
Dairy	65.2	135.7	81.1	31.9	48.3	12.5	376.2
Non-dairy	187.6	252.7	101.1	144.2	401.3	38.3	1134.6
Goats	46.0	57.6	1.8	1.2	2.4	0.4	109.8
Sheep	40.3	54.1	22.0	1.9	6.9	16.4	141.7
Other	0	0	0	0	5.6	0	5.6
Total	343.2	732.5	206.5	179.2	460.4	67.6	2001.0

Global populations and emissions in each continent, based on data from Statistical Database Food and Agriculture Organization of the United Nations (FAOSTAT) (2020).
Abbreviations; N America, North America (including Mexico); S America, South America (including Caribbean, except Mexico, SA); Other includes alpaca and llama.

costs than with cattle studies. However, goats are not studied as much as sheep, despite large global numbers (1.06×10^9). The percentage of studies involving goats (7%) was similar to their contribution to ruminant enteric-CH_4 emissions (5%; Table 2). The imbalance between studies and emissions for sheep versus goats is also evident for cattle versus buffalo. Buffalo is responsible for approximately 12% of ruminant enteric-CH_4 emissions, yet only 21 studies have been published (5% of the total). This assessment shows little affiliation between the number of studies on individual species and either animal numbers or their contribution to ruminant enteric-CH_4 emissions.

Ruminant species studied per continent and their contribution to enteric-CH_4 emissions

The species from which CH_4 measurements have been made, within continents, do not relate to their contribution to emissions. This is illustrated in Fig. 2, where both the quantity of emissions and the number of studies have been expressed on a percentage basis for each continent for cattle, sheep and goats. Most apparent is the low number of studies undertaken in Africa over the assessment period. Asia is responsible for 37% of enteric emissions and, although all measurements from buffalo have been undertaken in that continent, studies with sheep, goats and cattle are substantially under-represented in a global context. In SA, cattle are by far the dominant emitters and, although most studies have been undertaken with cattle (Table 1), numbers have been low but are most likely to grow in the near future (Congio *et al.* 2021). In NA, cattle are also the dominant ruminant species and, although the numbers are less than half of those for SA, the number of studies undertaken are more than twice that for SA (Fig. 2). In contrast, the percentage of studies with goats and cattle in Europe far exceeds their contribution to global emissions for those species. Similarly, for sheep and cattle in Oceania, where the number of studies accounted for 52% and 18% of those undertaken globally, corresponding emissions accounted for 12% and 3% of global emissions.

Although global populations of sheep and goats exceed those of cattle (Table 2) the percentage of total emissions from cattle are highest across all continents (Africa 74%, Asia 53%, Europe 88%, NA 98%, SA 98% and Oceania 75%) and this would suggest that most evaluations should be from cattle. This was the case in Europe, NA and SA where 73%, 88% and 73% of studies were with cattle, and although in Asia 37% of studies were with cattle, another 30% were with buffalo. In Oceania, 48% of studies were with cattle; so, globally and also regionally, most studies have been undertaken with the highest-emitting species.

Only 13% of global enteric-CH_4 emissions come from sheep, goats and camelids, with 44% of this from Asia, yet studies with sheep and goats from this continent are only 19% of global studies with these species (Table 1). Sheep and goats from Africa account for 34% of global emissions

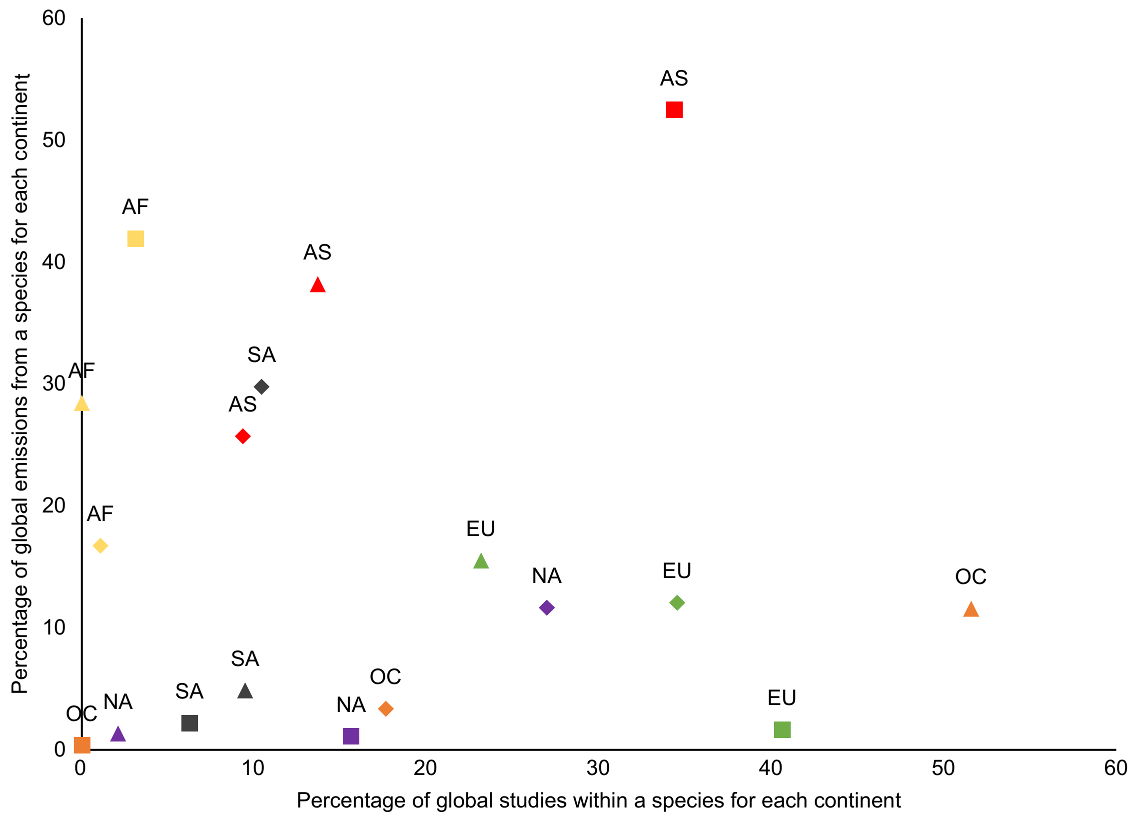

Fig. 2. Relationship between ruminant enteric-methane emissions and number of studies in six continents for cattle (◆), sheep (▲) and goats (■). Continents are as follows: AF, (yellow) Africa; AS, (red) Asia; EU, (green) Europe; NA, (violet) North America; SA, (black) South America; and OC, (orange) Oceania.

from these species, and only one study has been published. Given differences in breeds and diets available to sheep and goats in Africa and Asia, compared with Europe and Oceania, it is important that more studies with these species are undertaken to achieve defensible estimates of emissions.

Overall, number of studies appear to be related to infrastructure and wealth of continents and there are limited associations between the number of studies and either species CH_4 emissions (Fig. 2) or species numbers. Although it may be argued that CH_4 yields are similar for all ruminants when given similar diets, 'typical diets' used in each continent differ among species, as do responses in CH_4 yield to the level of intake. Differences in diet, digestive physiology, animal management and levels of production justify the requirement for species-specific data (van Gastelen *et al.* 2019), so as to achieve defensible global estimates of CH_4 emissions and increase accuracy to reduce uncertainty. It is also clear that small populations of large ruminants (e.g. buffalo) can contribute with higher amounts of CH_4 than do large populations of small ruminants (i.e. goat and sheep), suggesting that measurements from large emitters (cattle and buffalo) could be a priority. Achieving accurate estimates of CH_4 emissions across all species, diets and continents will guide future global research.

Cattle: subspecies, production type and physiological state

Bos indicus cattle represent more than half the global cattle population and are dominant in tropical and subtropical regions (Utsunomiya *et al.* 2019), yet only 12% of CH_4 measurement studies with cattle have been undertaken with *Bos indicus*, compared with *Bos taurus* (79%). Twenty-four studies (9%) did not specify breed or physiological state, so they were not included in the classification. Most studies with *Bos indicus* were undertaken in growing beef cattle (87% of studies), while dairy cattle were studied only in 13% of the publications (3% growing, 5% lactating and 5% non-lactating). In contrast, most studies with *Bos taurus* were with dairy cattle (62% of studies; 4% growing, 50% lactating, 8% non-lactating) and 38% of studies were with beef cattle (35% growing and 3% mature).

Given the genomic and phenotypic differences, such as heat tolerance, a faster rumen fermentation rate, shorter rumen retention time and higher protozoa populations, as well as diet, there may be differences in CH_4 emissions between *Bos indicus* and *Bos taurus* (Hegarty 2004). Estimates (Table 2) indicated that non-dairy cattle were the largest contributor (75%) to global enteric-CH_4 emissions, followed by dairy cattle (25%). However, beef cows have been poorly addressed in published studies. Therefore, to improve the accuracy of CH_4 estimates, the database of beef cattle needs to be increased, including data for mature (breeding) cows. Beef cows are an essential category for beef production, but their diet quality is often poor, compared with dairy cows, and this is likely to affect CH_4 yields. Addressing these imbalances will improve the accuracy of global emission data from ruminants, as indicated in the assessment by Cottle and Eckard (2018).

Techniques used to measure CH_4 emissions within species

The SF_6 and RC techniques were used to determine CH_4 emissions with most ruminant species. RC was the most commonly used technique with cattle (45%), goats (70%) and sheep (64%), while the SF_6 tracer technique was the most commonly used technique in buffalo (67%; Table 3). The less frequent use of RC in large ruminants than in small ruminants is probably associated with experiment costs, limited number of RC units for large animals per laboratory and greater development and use of alternative methods in cattle. Although measurements from grazing cattle may be better suited to the SF_6 tracer technique or GF spot-sampling, there remains the challenge of determining feed intake. The increasing use of RC to measure CH_4 emissions for all species maybe explained by their accuracy and precision in measurements of both CH_4 and feed intake (Jonker *et al.* 2020).

Within the spot-sampling methods, GF, LMD and FM were used with large and small ruminants, while SNF was used only with cattle and PAC was used only with sheep. The SNF technique was developed for dairy cattle (Garnsworthy *et al.* 2012), whereas the PAC technique was developed for sheep (Goopy *et al.* 2011). The SNF and LMD methods record only CH_4 concentrations, which limits their wider application to generate accurate CH_4-emission estimates. Although some spot-sampling methods are still under evaluation to assess their capability to provide accurate emission-factor estimates (FM and PAC), the accuracy of GF has been demonstrated for cattle (Jonker *et al.* 2020) and may enable more measurements from less studied species, such as, for example, camelids, and buffaloes, so as to provide reliable data in continents where these species are common.

Table 3. Number of studies from 1994 to 2018, classified by ruminant methane-measurement techniques and ruminant species evaluated using each technique.

Species (number of studies)	RC	SF_6	GF	FM	PAC	LMD	SNF	Total
Buffalo	7	14	0	0	0	0	0	21
Cattle	139	123	28	3	0	4	9	306
Goat	21	3	0	4	0	2	0	30
Sheep	65	27	2	2	4	1	0	101
Other	6	3	0	0	0	0	0	9
Total	238	170	30	9	4	7	9	467

RC, respiration chamber; SF_6, sulfur hexafluoride; GF, GreenFeed; FM, face mask; PAC, portable accumulation chamber; LMD, laser methane detector; SNF, sniffer; Other refers to alpaca, llama, deer, bison.

Aims and objectives of studies measuring ruminant CH_4

In terms of study objectives, the majority of CH_4 measurement studies evaluated diet as the main study aim (Africa 100%, Asia 92%, Europe 71%, NA 84%, SA 85%, Oceania 53%) whereas animal efficiency was the second-most studied strategy (Asia 5%, Europe 17%, NA 7%, SA 12%, Oceania 24%; Table 1). Oceania and Europe also reported a higher number of studies that evaluated CH_4 measurement techniques, than did other continents. The focus of studying diets as a mitigation strategy may have been a response to obtaining emission factors for inventories, especially as dietary strategies can be a method ready to be applied to reduce CH_4 emissions (Martin *et al.* 2010) through the use of supplements and additives. In the past decade, studies have also attempted to identify animals that vary in efficiency for production and also low CH_4 emitters, both of which could provide options to reduce CH_4 emissions, provided these characteristics are heritable (Thompson and Rowntree 2020), as shown in sheep and cattle (Lassen and Løvendahl 2016; Hayes *et al.* 2016; Jonker *et al.* 2018).

Diets fed for CH_4 measurements by continent and species

Diets used for animal production are dependent on feed sources available, animal species and affordability. Globally, CH_4 measurement studies reporting diet composition comprised 197 high-forage (fibrous), 35 high-concentrate (grain) and 116 mixed diets (Table 4). The high-forage diets were the most common in evaluations undertaken in Africa (100%), Europe (55%), NA (44%), SA (72%) and Oceania (86%), while mixed diets were the most prevalent in Asia (56%), and although few in number, most high-concentrate diets were evaluated in Europe and NA. Forage is less expensive than grain and it is the main dietary component (86%) of ruminant diets (Mottet *et al.* 2017), especially in Africa, SA and Oceania (Seré and Steinfeld 1995). Forages are important in less intensive farming systems in all continents; however, it is expected that intensification of production systems continues and changes in diets offered to ruminants will be most evident in continents with extensive systems (Thornton *et al.* 2009; McAllister *et al.* 2020).

Most (72%) diets fed during studies of CH_4 emissions included supplements that provided energy or protein, but which differed from the main components and/or additives,

Table 4. Continental distribution of studies published from 1994 to 2018 of ruminant feeding, expressed in terms of the basal diets with supplements and additives fed during methane measurements.

Item	Africa	Asia	Europe	N America	S America	Oceania	Total
High-forage diets (number of studies)							
Nothing added	1	5	28	7	9	23	73
Supplement	2	9	26	16	11	13	77
Additive	0	8	6	10	3	11	38
Both	1	2	2	0	3	1	9
Total	4	24	62	33	26	48	197
High-concentrate diets (number of studies)							
Nothing added	0	1	5	0	1	0	7
Supplement	0	1	2	4	3	0	10
Additive	0	2	2	8	0	3	15
Both	0	0	3	0	0	0	3
Total	0	4	12	12	4	3	35
Mixed diets (number of studies)							
Nothing added	0	10	3	1	1	1	16
Supplement	0	9	17	14	3	2	45
Additive	0	15	14	15	2	2	48
Both	0	2	5	0	0	0	7
Total	0	36	39	30	6	5	116

Diets have been defined on the basis of main components; 'High-forage diets' contain more than 65% of dry matter as high-fibre components; 'High-concentrate diets' contain more than 65% of the dry matter as high-energy protein ingredients and 'Mixed diets' contain less than 65% forage or concentrate. The diet may contain additional components, which have been defined as follows: 'Supplement', which is any type of forage/concentrate different from the main component, including different plant species and/or in combination with oils, seeds, lipids etc.; 'Additive', which comprises compounds affecting digestion, such as ionophores, urea, tannins, herbal mixtures, saponins, nitrate, methane inhibitors or essential oils; and 'Both', which refers to inclusion of both additives and supplements.

such as ionophores, nitrate, CH_4 inhibitors, etc. (Table 4). Their use was widespread in CH_4 studies and only 73 of 197 studies with high-forage diets did not include supplements or additives (these were 100% forage). Half or more of studies with sheep, goats and cattle fed high-forage diets included addition of supplements or other additives (Table 5) as did most studies with high-concentrate diets (most of these were with cattle) and mixed diets. The supplements provide nutrients to meet animal requirements and the choice depends on the main dietary component, level of production and are species-specific, whereas many additives may have been included in an effort to reduce methanogenesis.

The analysis of the diet type per species shows that a wide range of feedstuffs has been evaluated, perhaps reflecting the diversity in farming systems, or in anticipation of changes to future feeding. The 'high-forage' diets were dominant in studies with sheep (73%) and cattle (56%), while the 'mixed' diet was most prevalent with buffalo (78%) and both 'high-forage' and 'mixed' diets dominated goat studies (Table 5). Although 'high-concentrate' diets were the least studied diet types in all species, their use was most prevalent with cattle. Mixed diets dominated buffalo studies because they are fed agricultural crop-residues and industrial by-products to ensure low-cost production (Deb *et al.* 2016). In summary, a wide spectrum of diets has been evaluated (Table 5), providing a broad base of emission data and supplements and additives that were in common use.

Conclusions

Overall, the number of studies that have measured CH_4 from cattle align with their contribution to enteric emissions. However, buffalo, *Bos indicus* cattle and mature beef cows were under-represented relative to their global populations and contribution to global emissions. The second-largest contributor to global CH_4 emissions are buffaloes, which globally produce a similar quantity of CH_4 as do sheep and goats combined, yet only 14% of studies from these three species were from buffaloes.

Most published research has focused on evaluating the effect of diets on CH_4 emissions. High-forage diets were the most evaluated across species. Current trends include studies of individual variation within species and suggest a change in focus, along with increased implementation of spot-sampling methods for estimation of CH_4 emissions.

Table 5. Number of studies published from 1994 to 2018 classified by animal species and diets fed during methane measurements, expressed in terms of the basal diets with supplements and additives.

Item	Buffalo	Cattle	Goat	Sheep	Other	Total
High-forage diets (number of studies)						
Nothing added	3	46	2	26	1	77
Supplement	0	54	10	13	1	78
Additive	0	24	2	12	0	39
Both	0	8	0	1	0	9
Total	3	132	14	52	2	203
High-concentrate diets (number of studies)						
Nothing added	1	6	1	0	0	8
Supplement	0	8	1	1	1	11
Additive	0	14	0	1	0	15
Both	0	3	0	0	0	3
Total	1	31	2	2	1	37
Mixed diets (number of studies)						
Nothing added	5	11	2	1	1	20
Supplement	6	30	6	3	0	45
Additive	4	29	6	9	0	48
Both	0	3	0	4	0	7
Total	15	73	14	17	1	120

Diets have been defined on the basis of main components; 'High-forage diets' contain more than 65% of dry matter as high-fibre components; 'High-concentrate diets' contain more than 65% of the dry matter as high energy-protein ingredients and 'Mixed diets' contain less than 65% forage or concentrate. The diet may contain additional components, which have been defined as either. 'Supplement', which are any type of forage/concentrate different to the main component, including different plant species and/or in combination with oils, seeds, lipids etc. 'Additive', comprise compounds affecting digestion, such as ionophores, urea, tannins, herbal mixtures, saponins, nitrate, methane inhibitors or essential oils. 'Both', refers to inclusion of both additives and supplements.

Finally, it is well known that there have been fewer studies in continents with lower per capita incomes, but, in general, their research follows global trends regarding measurements from animal species. The use of spot-sampling methods to measure CH_4 emissions may accelerate the research in geographical areas of data scarcity. Additionally, identifying the typical diets used to feed the predominant CH_4-emitting species within each macro region will contribute to more accurate CH_4 estimates on a global and regional scales.

Supplementary material

Supplementary material is available online.

References

Chagunda MGG (2013) Opportunities and challenges in the use of the Laser Methane Detector to monitor enteric methane emissions from ruminants. *Animal* **7**, 394–400. doi:10.1017/S1751731113000724

Congio GF, Bannink A, Mogollón OLM, Latin America Methane Project Collaborators, Hristov AN (2021) Enteric methane mitigation strategies for ruminant livestock systems in the Latin America and Caribbean region: a meta-analysis. *Journal of Cleaner Production* **312**, 127693. doi:10.1016/j.jclepro.2021.127693

Cottle DJ, Eckard RJ (2018) Global beef cattle methane emissions: yield prediction by cluster and meta-analyses. *Animal Production Science* **58**, 2167–2177. doi:10.1071/AN17832

Dangal SRS, Tian H, Zhang B, Pan S, Lu C, Yang J (2017) Methane emission from global livestock sector during 1890–2014: magnitude, trends and spatiotemporal patterns. *Global Change Biology* **23**, 4147–4161. doi:10.1111/gcb.13709

Deb GK, Nahar TN, Duran PG, Presicce GA (2016) Safe and sustainable traditional production: the water buffalo in Asia. *Frontiers in Environment Science* **4**, 38. doi:10.3389/fenvs.2016.00038

Della Rosa MM, Jonker A, Waghorn GC (2021) A review of technical variations and protocols used to measure methane emissions from ruminants using respiration chambers, SF6 tracer technique and GreenFeed, to facilitate global integration of published data. *Animal Feed Science and Technology* **279**, 115018. doi:10.1016/j.anifeedsci.2021.115018

Garnsworthy PC, Craigon J, Hernandez-Medrano JH, Saunders N (2012) On-farm methane measurements during milking correlate with total methane production by individual dairy cows. *Journal of Dairy Science* **95**, 3166–3180. doi:10.3168/jds.2011-4605

Garnsworthy PC, Difford GF, Bell MJ, Bayat AR, Huhtanen P, Kuhla B, Lassen J, Peiren N, Pszczola M, Sorg D, Visker MHPW, Yan T (2019) Comparison of methods to measure methane for use in genetic evaluation of dairy cattle. *Animals* **9**, 837. doi:10.3390/ani9100837

Goopy JP, Woodgate R, Donaldson A, Robinson DL, Hegarty RS (2011) Validation of a short-term methane measurement using portable static chambers to estimate daily methane production in sheep. *Animal Feed Science and Technology* **166–167**, 219–226. doi:10.1016/j.anifeedsci.2011.04.012

Grainger C, Clarke T, McGinn SM, Auldist MJ, Beauchemin KA, Hannah MC, Waghorn GC, Clark H, Eckard RJ (2007) Methane emissions from dairy cows measured using the sulfur hexafluoride (SF6) tracer and chamber techniques. *Journal of Dairy Science* **90**, 2755–2766 doi:10.3168/jds.2006-697

Hammond KJ, Crompton LA, Bannink A, Dijkstra J, Yáñez-Ruiz DR, O'Kiely P, Kebreab E, Eugène MA, Yu Z, Shingfield KJ, Schwarm A, Hristov AN, Reynolds CK (2016*a*) Review of current *in vivo* measurement techniques for quantifying enteric methane emission from ruminants. *Animal Feed Science and Technology* **219**, 13–30. doi:10.1016/j.anifeedsci.2016.05.018

Hammond KJ, Waghorn GC, Hegarty RS (2016*b*) The GreenFeed system for measurement of enteric methane emission from cattle. *Animal Production Science* **56**, 181–189. doi:10.1071/AN15631

Hayes BJ, Donoghue KA, Reich CM, Mason BA, Bird-Gardiner T, Herd RM, Arthur PF (2016) Genomic heritabilities and genomic estimated breeding values for methane traits in Angus cattle. *Journal of Animal Science* **94**, 902–908. doi:10.2527/jas.2015-0078

Hegarty RS (2004) Genotype differences and their impact on digestive tract function of ruminants: a review. *Australian Journal of Experimental Agriculture* **44**, 459–467. doi:10.1071/EA02148

Hristov AN, Kebreab E, Niu M, Oh J, Bannink A, Bayat AR, Boland TM, Brito AF, Casper DP, Crompton LA, Dijkstra J, Eugène M, Garnsworthy PC, Haque N, Hellwing ALF, Huhtanen P, Kreuzer M, Kuhla B, Lund P, Madsen J, Martin C, Moate PJ, Muetzel S, Muñoz C, Peiren N, Powell JM, Reynolds CK, Schwarm A, Shingfield KJ, Storlien TM, Weisbjerg MR, Yáñez-Ruiz DR, Yu Z (2018) *Symposium review*: uncertainties in enteric methane inventories, measurement techniques, and prediction models. *Journal of Dairy Science* **101**, 6655–6674. doi:10.3168/jds.2017-13536

Intergovernmental Panel on Climate Change (IPCC) (2006) Emissions from Livestock and Manure Management. In 'Guidelines for national greenhouse gas inventories'. Chapter 10. (Eds H Dong, J Mangino, TA McAllister). Available at https://wwwipcc-nggipigesorjp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestockpdf [verified 3 June 2021]

Intergovernmental Panel on Climate Change (IPCC) (2019) Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. (Eds E Calvo Buendia, K Tanabe, A Kranjc, J Baasansuren, M Fukuda, S Ngarize, A Osako, Y Pyrozhenko, P Shermanau, S Federici). (IPCC: Switzerland). Available at https://wwwipccch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/ [verified 3 June 2021]

Johnson KA, Johnson DE (1995) Methane emissions from cattle. *Journal of Animal Science* **73**, 2483–2492. doi:10.2527/1995.7382483x

Jonker A, Hickey SM, Rowe SJ, Janssen PH, Shackell GH, Elmes S, Bain WE, Wing J, Greer GJ, Bryson B, MacLean S, Dodds KG, Pinares Patiño CS, Young EA, Knowler K, Pickering NK, McEwan JC (2018) Genetic parameters of methane emissions determined using portable accumulation chambers in lambs and ewes grazing pasture and genetic correlations with emissions determined in respiration chambers. *Journal of Animal Science* **96**, 3031–3042. doi:10.1093/jas/sky187

Jonker A, Green P, Waghorn G, van der Weerden T, Pacheco D, de Klein C (2020) A meta-analysis comparing four measurement methods to determine the relationship between methane emissions and dry-matter intake in New Zealand dairy cattle. *Animal Production Science* **60**, 96–101. doi:10.1071/AN18573

Lassey KR (2007) Livestock methane emission: from the individual grazing animal through national inventories to the global methane cycle. *Agricultural and Forest Meteorology* **142**, 120–132. doi:10.1016/j.agrformet.2006.03.028

Lassen J, Løvendahl P (2016) Heritability estimates for enteric methane emissions from Holstein cattle measured using non-invasive methods. *Journal of Dairy Science* **99**, 1959–1967 doi:10.3168/jds.2015-10012

Martin C, Morgavi DP, Doreau M (2010) Methane mitigation in ruminants: from microbe to the farm scale. *Animal* **4**, 351–365 doi:10.1017/S1751731109990620

McAllister TA, Stanford K, Chaves AV, Evans PR, de Souza Figueiredo EE, Ribeiro G. (2020) Nutrition, feeding and management of beef cattle in intensive and extensive production systems. In 'Animal agriculture'. (Eds FW Bazer, G Cliff Lamb, G Wu) pp. 75–98. (Academic Press) doi:10.1016/B978-0-12-817052-6.00005-7

Mottet A, de Haan C, Falcucci A, Tempio G, Opio C, Gerber P (2017) Livestock: on our plates or eating at our table? A new analysis of the feed/food debate. *Global Food Security* **14**, 1–8. doi:10.1016/j.gfs.2017.01.001

Myhre G, Shindell D, Bréon FM, Collins W, Fuglestvedt J, Huang J, Koch D, Lamarque JF, Lee D, Mendoza B, Nakajima T, Zhang H (2013) Anthropogenic and Natural Radiative Forcing. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Eds TF Stocker, D Qin, G-K Plattner, M Tignor, SK Allen, J Boschung, A Nauels, Y Xia, V Bex, PM Midgley). (Cambridge University Press: Cambridge, UK)

Niu M, Kebreab E, Hristov AN, Oh J, Arndt C, Bannink A, Brito F, Boland T, Casper D, Crompton LA, Dijkstra J, Eugène MA, Garnsworthy PC, Haque MN, Hellwing, ALF, Huhtanen P, Kreuzer M, Kuhla B, Lund P, Madsen J, Martin M, McClelland SC, McGee M, Moate PJ, Muetzel S, Muñoz C, O'Kiely P, Peiren N, Reynolds CK, Schwarm A, Shingfield KJ, Storlien TM, Weisbjerg MR, Yáñez-Ruiz DR, Yu Z (2018) Prediction of enteric methane production, yield, and intensity in dairy cattle using an intercontinental database *Global Change Biology* **24**, 3368–3389 doi:10.1111/gcb.14094

Oss DB, Marcondes MI, Machado FS, Pereira LGR, Tomich TR, Ribeiro GO Jr, Chizzotti ML, Ferreira AL, Campos MM, Maurício RM, Chaves AV, McAllister TA (2016) An evaluation of the face mask system based on short-term measurements compared with the sulfur hexafluoride (SF6) tracer, and respiration chamber techniques for measuring CH4 emissions. *Animal Feed Science and Technology* **216**, 49–57 doi:10.1016/j.anifeedsci.2016.03.008

Pinares Patiño CS, Waghorn GC (2014) Technical Manual on Respiration Chamber Designs New Zealand, Ministry of Agriculture and Forestry. Available at https://www.globalresearchalliance.org/wp-content/uploads/2012/03/GRA-MAN-Facility-BestPract-2012-FINAL.pdf [verified 23 January 2022]

Seré C, Steinfeld H (1995) World livestock production systems current status, issues and trends. FAO Animal production and health paper No 127. Available at https://www.fao.org/3/w0027e/w0027e.pdf [verified 24 January 2022]

Statistical Database Food and Agriculture Organization of the United Nations (FAOSTAT) (2020) Food and Agriculture data. Available at http://www.fao.org/faostat/en/#home [verified 2 June 2020]

Thompson LR, Rowntree JE (2020) Invited review: methane sources, quantification, and mitigation in grazing beef systems. *Applied Animal Science* **36**, 556–573. doi:10.15232/aas.2019-01951

Thornton PK, van de Steeg J, Notenbaert A, Herrero M (2009) The impacts of climate change on livestock and livestock systems in developing countries: a review of what we know and what we need to know. *Agricultural systems* **101**, 113–127. doi:10.1016/j.agsy.2009.05.002

Undi M, Wilson C, Ominski KH, Wittenberg KM (2008) Comparison of techniques for estimation of forage dry matter intake by grazing beef cattle. *Canadian Journal of Animal Science* **88**, 693–701. doi:10.4141/CJAS08041

United Nations of Climate Change (UNCC) (2015) Paris Agreement-Status of Ratification. Available at https://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english_.pdf [verified 24 August 2022]

United Nations Framework Convention on Climate Change (UNFCCC) (1997) Kyoto Protocol to the United Nations Framework Convention on Climate Change. Available at https://treatiesunorg/pages/ViewDetailsaspx?src=TREATYmtdsg_no=XXVII-7-achapter=27lang=en [verified 22 October 2019]

United States Environmental Protection Agency (US EPA) (2017) Inventory of US greenhouse gas emissions and sinks: 1990–2015. Available at https://wwwepagov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2015 [verified 4 June 2021]

Utsunomiya YT, Milanesi M, Fortes MRS, Porto-Neto LR, Utsunomiya ATH, Silva MVGB, Garcia JF, Ajmone-Marsan P (2019) Genomic clues of the evolutionary history of Bos indicus cattle. *Animal Genetics* **50**, 557–568. doi:10.1111/age.12836

van Gastelen S, Dijkstra J, Bannink A (2019) Are dietary strategies to mitigate enteric methane emission equally effective across dairy cattle, beef cattle, and sheep? *Journal of Dairy Science* **102**, 6109–6130. doi:10.3168/jds.2018-15785

van Lingen HJ, Niu M, Kebreab E, Valadares Filho SC, Rooke JA, Duthie C-A, Schwarm A, Kreuzer M, Hynd PI, Caetano M, Eugène M, Martin C, McGee M, O'Kiely P, Hünerberg M, McAllister TA, Berchielli TT, Messana JD, Peiren N, Chaves AV, Charmley E, Cole NA, Hales KE, Lee SS, Berndt A, Reynolds CK, Crompton LA, Bayat A-R, Yáñez-Ruiz DR, Yu Z, Bannink A, Dijkstra J, Casper DP, Hristov AN (2019) Prediction of enteric methane production, yield and intensity of beef cattle using an intercontinental database. *Agricultural Ecosystems and Environment* **283**, 106575. doi:101016/jagee2019106575

Data availability. The data that support this study are available in the article and the list of studies retrieved are included as supplementary material.

Conflicts of interest. The authors declare that they do not have conflicts of interest.

Declaration of funding. Maria M. Della Rosa was financially supported by the New Zealand Government through the Global Research Alliance Livestock Emissions and Abatement Research Network (LEARN) awards program (https://livestockemissions.net/). The information contained within this paper should not be taken to represent the views of the Alliance as a whole or its partners.

Author affiliations

[A]AgResearch Limited, Grasslands Research Centre, Tennent Drive, 11 Dairy Farm Road, Private Bag 11008, Palmerston North 4442, New Zealand.

[B]Independent Scientist (retired), 6 Berkley Avenue, Hamilton 3216, New Zealand.