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Review

Challenges and opportunities to capture dietary effects in on-farm greenhouse gas emissions models of ruminant systems

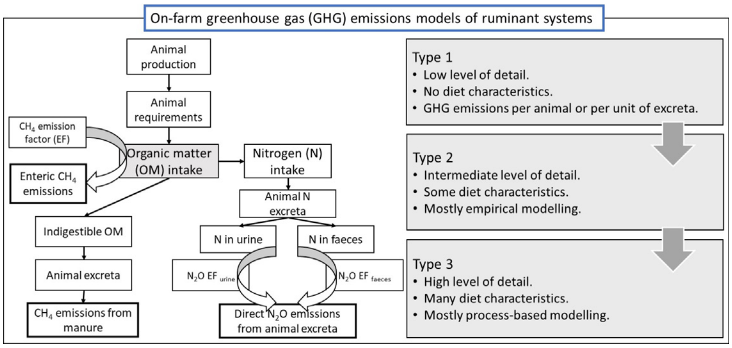
Ronaldo Vibart [a,*], Cecile de Klein [b], Arjan Jonker [a], Tony van der Weerden [b], André Bannink [c], Ali R. Bayat [d], Les Crompton [e], Anais Durand [f], Maguy Eugène [g], Katja Klumpp [h], Björn Kuhla [i], Gary Lanigan [j], Peter Lund [k], Mohammad Ramin [l], Francisco Salazar [m]

[a] *AgResearch Ltd., Grasslands Research Centre, Palmerston North, New Zealand*
[b] *AgResearch Ltd, Invermay Agricultural Centre, Mosgiel, New Zealand*
[c] *Wageningen Livestock Research, Wageningen University & Research, Wageningen, the Netherlands*
[d] *Production Systems, Natural Resources Institute Finland (Luke), Jokioinen, Finland*
[e] *School of Agriculture, Policy and Development, University of Reading, Reading, UK*
[f] *CITEPA, 42 rue Paradis, 75010 Paris, France*
[g] *UMR Herbivores, INRA, VetAgro Sup, Université Clermont Auvergne, Saint-Genès-Champanelle, France*
[h] *UMR Ecosystème Prairial, INRA, Clermont-Ferrand, France*
[i] *Institute of Nutritional Physiology, Leibniz Institute for Farm Animal Biology, Dummerstorf, Mecklenburg-Vorpommern, Germany*
[j] *Teagasc Agriculture and Food Development Authority, Johnstown Castle Environmental Research Centre, Wexford, Ireland*
[k] *Department of Animal Science, AU Foulum, Aarhus University, Blichers Allé 20, DK 8830 Tjele, Denmark*
[l] *Department of Agricultural Research for Northern Sweden, Swedish University of Agricultural Sciences, Sweden*
[m] *Instituto de Investigaciones Agropecuarias, INIA Remehue, Chile*

HIGHLIGHTS

- The effect of diet chemistry on GHG emissions from dairy is often poorly understood.
- The capture of diet-related characteristics ranges from 'none' to 'some' to 'many'.
- The closer the model to rumen function, the closer to diet-related GHG abatement
- All models can improve their ability to predict GHG emissions from ruminant systems.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper reviews existing on-farm GHG accounting models for dairy cattle systems and their ability to capture the effect of dietary strategies in GHG abatement. The focus is on methane (CH_4) emissions from enteric and manure (animal excreta) sources and nitrous oxide (N_2O) emissions from animal excreta. We identified three generic modelling approaches, based on the degree to which models capture diet-related characteristics: from 'none' (Type 1) to 'some' by combining key diet parameters with emission factors (EF) (Type 2) to 'many' by using process-based modelling (Type 3). Most of the selected on-farm GHG models have adopted a Type 2 approach, but a few hybrid Type 2 / Type 3 approaches have been developed recently that combine empirical modelling (through the use of CH_4 and/or N_2O emission factors; EF) and process-based modelling (mostly through rumen and whole tract fermentation and digestion). Empirical models comprising key dietary inputs (i.e., dry matter intake and organic matter digestibility) can predict CH_4 and N_2O emissions with reasonable

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[*] Corresponding author.
E-mail address: ronaldo.vibart@agresearch.co.nz (R. Vibart).

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Effluent
Methane
Nitrous oxide

accuracy. However, the impact of GHG mitigation strategies often needs to be assessed in a more integrated way, and Type 1 and Type 2 models frequently lack the biological foundation to do this. Only Type 3 models represent underlying mechanisms such as ruminal and total-tract digestive processes and excreta composition that can capture dietary effects on GHG emissions in a more biological manner. Overall, the better a model can simulate rumen function, the greater the opportunity to include diet characteristics in addition to commonly used variables, and thus the greater the opportunity to capture dietary mitigation strategies. The value of capturing the effect of additional animal feed characteristics on the prediction of on-farm GHG emissions needs to be carefully balanced against gains in accuracy, the need for additional input and activity data, and the variability encountered on-farm.

Contents

1. Introduction

In recent years, there has been an increasing focus on evaluating the environmental effects of livestock production systems, including their impact on greenhouse gas (GHG) emissions. Although debate remains on the precise contribution of ruminant livestock to anthropogenic methane (CH_4) (Hristov et al., 2018), the role of livestock agriculture as a main contributor to GHG emissions and climate change is undisputed. Climate change and its consequences are currently recognised as one of the major environmental challenges, and the need for GHG mitigation to meet local expectations and international environmental obligations has been globally recognised (Smith et al., 2007). Therefore, it becomes increasingly important to have an enhanced ability to predict on-farm GHG emissions from livestock and assess methods and efficacy of practices to reduce or offset them.

In livestock agriculture, interactions and variability of critical environmental and managerial drivers of GHG emissions contribute to the complexity of extrapolating observed GHG data to a broader range of conditions and scales. Simulation models of on-farm greenhouse gas (GHG) emissions have an important role to play in helping us understand the potential impact of GHG mitigation strategies on farm dynamics, and in using results from experimental measurements of GHG emissions to assess wider implications and potential trade-offs for the system. Models also enable extrapolation of GHG emissions from smaller (i.e., emissions from a site, plot, field, a manure storage facility or from a cow) to larger scales (farm, catchment, region or country) (Schils et al., 2012). In addition to scale, models can also vary depending on the GHG of interest, with some simulating a single GHG (Blaxter and Clapperton, 1965; Wilkerson et al., 1995; Benchaar et al., 2001), while other models include all major agricultural GHG (Wheeler et al., 2008; Hillier et al., 2011).

Given the broad range of GHG accounting tools, the complexity of the issue at hand and the increasing need for accounting of on-farm GHG emissions to meet national or global obligations, there is uncertainty amongst agricultural stakeholders as to which tools (calculators, models, modules) are most appropriate to predict GHG emissions from ruminant systems. The amount of GHG produced within a production system needs to be quantified accurately to allow for alternatives to be explored and emissions to be mitigated (Ellis et al., 2010; Benaouda et al., 2019). In addition to the inherent temporal and spatial variability in emissions, the relative advantages and disadvantages of these tools remain to be fully assessed, especially in light of the difficulty in comparing results obtained from different accounting tools, as these vary in conceptual approaches, reporting units and scope.

Feed management decisions are essential for ruminant production systems, as they impact directly on substrate availability for enteric microbial fermentation and digestion, nutritive value, and ruminant excreta composition. In turn, these processes have a strong influence on the amount and profile of agricultural GHG emissions (Henderson et al., 2015). Major sources of GHG emissions from livestock agriculture include methane (CH_4) emissions from enteric fermentation and stored manure, and nitrous oxide (N_2O) emissions from animal excreta. Accordingly, there is an increasing interest in the use of nutrition and feeding management strategies to reduce GHG emissions. A range of nutritional and feeding management options for CH_4 abatement (Beauchemin et al., 2008; Martin et al., 2010; Caro et al., 2016; Pellerin et al., 2017) and N_2O abatement (de Klein and Eckard, 2008; Monaghan and de Klein, 2014) have been described. Examples of nutrition strategies that have shown promising results in mitigating GHG emissions include increasing grain levels (i.e., greater concentration of degradable starch and soluble carbohydrates in the diet), inclusion of lipids and dietary tannins, reducing dietary crude protein, improving feed digestibility and altering the stage of maturity of harvested forages.

In 2017, a three-year project commenced to bring together the current knowledge on the effect of feed and dietary management on GHG emissions: Capturing the Effects of Diet on Emissions from Ruminant Systems (CEDERS; https://www.eragas.eu/en/eragas/Research-projects/CEDERS-1.htm). The main goal of the project was to examine dietary effects on on-farm GHG emissions and their trade-offs, both at the farm and national scales, with the overall aim of supporting GHG mitigation research and aligning national agricultural GHG inventory research across a consortium of ten countries (Chile, Denmark, Finland, France, Germany, Ireland, Netherlands, New Zealand, Sweden and United Kingdom). Our review is part of this project with the specific objectives to a) identify the most common on-farm GHG accounting tools used by the participant countries, and once identified, b) explore the livestock GHG accounting approach used by these tools, and c) explore the potential benefits of adding diet characteristics to on-farm GHG accounting tools for dairy systems. The focus is on CH_4 emissions from enteric fermentation and manure (animal excreta) and N_2O emissions from animal excreta as on-farm GHG sources.

2. Modelling GHG emissions from ruminant enterprises

Methane and N_2O are colourless and odourless GHG that are 28 and 265 times more potent (100-year horizon) than CO_2 at warming the earth (Myhre et al., 2013). Enteric and manure CH_4 emissions from ruminants, and N_2O emissions from animal excreta are the main GHG from livestock agriculture. The contribution of CO_2 emissions from energy sources and input use are frequently added to GHG budgets, often using a life cycle assessment (LCA) approach. Many mathematical models have been developed to predict these major on-farm GHG.

With a focus on the two main GHG from animal livestock systems (CH_4 and N_2O), different types of models have been developed to predict emissions of these gases. These models vary in the level of detail they capture and range from relatively simple empirical (or statistical) models to more detailed empirical and process-based mechanistic models (herein, mathematical representations of the several underlying processes that characterise the function and integration of biology leading to GHG emissions). The ability to assess the impact of dietary mitigation strategies relies on accurate estimations of enteric and manure CH_4 emissions and N_2O emissions. Estimates of enteric CH_4 emissions are often based on dry matter intake (DMI) and/or the chemical composition or other characteristics of the diet (e.g., organic matter digestibility and fibre concentration), and/or certain characteristics of the animal, such as body weight (BW) or animal product (milk or meat) (Wilkerson et al., 1995). Estimates of N_2O emissions are often based on animal excreta, manure storage and processing, nitrogen (N) fertiliser and soil conditions that favour denitrification (Brown et al., 2001; de Klein and Ledgard, 2005).

Although such equations and predictors provide an estimate of emissions from the animal and animal excreta (CH_4 and N_2O emissions) and from soil conditions (N_2O emissions), these equations are sometimes used in isolation. The variation due to diet types, feeding management and source (e.g., imported vs. on-farm feed) and the extent to which polluting end points are affected (e.g., N in freshwater bodies), are harder to capture, and as a consequence, these equations can still be poor predictors of GHG emissions at a specific farm scale. At the dairy farm scale, a greater complexity with integrated components such as livestock, manure management, housing conditions (barn or on pasture), soil management, and pasture and fodder crop production need to be incorporated in the modelling (Ellis et al., 2010).

3. Models of on-farm GHG emissions

In addition to models used for GHG inventories (e.g., Ministry for Primary Industries, 2019) and those used for carbon cycle assessments (e.g., Cowie et al., 2012), Denef et al. (2012) classified GHG tools into four major categories: calculators, protocols, guidelines and models. The focus of this review is on on-farm calculators and farm-scale models (herein *on-farm GHG models*) that have been either developed to aid in the representation of enteric fermentation (the prevalent source of GHG from ruminant systems), or that aim to quantify GHG emissions from ruminants (or improve prediction capacity), under varying animal nutrition conditions.

To date, a large number of on-farm GHG models have been developed for use by farmers, farm consultants, environmental authorities and the scientific community. On-farm GHG models can help with i) estimating total emissions for accounting purposes, raising awareness, ii) identifying, developing and encouraging adoption of mitigation strategies, iii) identifying knowledge gaps, and creating and exploring current and alternative scenarios, and iv) scaling-up information, and making future projections and policy development (Smith et al., 2007; Colomb et al., 2012; Milne et al., 2013).

On-farm GHG models offer a broad diversity of scope (i.e., from single GHG to integral assessment of all three major GHG), modelling approach adopted (i.e., from simple empirical approaches to more complex dynamic or process-based models), scale (i.e., from the rumen, soil plot and manure scale to global scale) and emissions source (i.e., horticulture, grazing and livestock, grasslands, orchards, forestry, and other land uses) (Hall et al., 2010; Schils et al., 2012). Although models tend to be characterised as being empirical or mechanistic, often both approaches are followed for different components within a single model. In general, farm-scale models tend to follow hybrid or empirical approaches at wider scopes and at various scales to integrate soil, crop and livestock components into a farm framework (Schils et al., 2012).

The degree to which diet ingredients and diet chemical composition are captured in on-farm GHG models varies considerably. The first step at the animal level of most on-farm models is to estimate daily DMI per animal, derived from estimated animal energy requirements (often based on BW, maintenance needs, tissue growth, milk production, pregnancy, and activity) divided by the energy concentration of the feed. The gross energy (GE; in megajoules MJ) concentration of a feed can be calculated based on crude protein (CP), ether extract (EE), neutral detergent fibre (NDF) and non-fibre carbohydrate (NFC) concentrations. The major component of metabolisable energy (ME) or net energy (NE) of a feed is digestible energy (DE). The DE value of a feed can be estimated from organic matter digestibility (OMD), or from feed chemical composition (from similar components as used for calculation of GE) and corresponding digestibility coefficients published in feed tables for individual ingredients (Beyer et al., 2003; Blok and Spek, 2016; Rinne et al., 2017). Feed DE can also be estimated using prediction equations (NRC, 2001) or be based on a combination of chemical composition data and prediction equations (Fox et al., 2004). These DE or OMD values are often used to calculate total faecal OM output or volatile solids (VS), which are the source of manure CH_4 emissions. However, some more advanced models predict DE, OMD, VS and N digestibility (ND) mechanistically (Illius and Gordon, 1991; Bannink et al., 2018, 2020).

The second step of the animal level model comprises the calculation of a CH_4 conversion factor (MCF or Y_m), which can involve a) multiplying DMI or GE intake (GEI) with a fixed conversion factor [e.g., MCF (% of GE) $= 6.5 \pm 1.0\%$ of GEI (IPCC, 2006)], b) the use of a generic equation, that might include dietary ingredients (e.g., forage and concentrate), chemical composition parameters (e.g., EE, NDF, starch) and digestibility parameters (e.g., OMD) (Nielsen et al., 2013; Jaurena et al., 2015; Eugène et al., 2019), or c) the use of a dynamic and mechanistic model with representation of rumen fermentation and gastrointestinal digestion (Bannink et al., 2011; Beukes et al., 2011; Huhtanen et al., 2015). Input parameters for these dynamic, mechanistic models include DMI, diet chemical composition and ruminal and total tract digestive parameters (Table 1). In these models, rumen H_2 formation is derived from fermented amounts of substrate and associated volatile fatty acid (VFA) stoichiometry (e.g., Bannink et al., 2011; Huhtanen et al., 2015).

The third and final step in capturing dietary effects in on-farm GHG models is an estimation of CH_4 and N_2O emissions from manure storage, land application of manure and direct deposition of faeces and urine by grazing animals. Both CH_4 and N_2O emissions from manures are not only influenced by diet characteristics but also by biotic and abiotic

Table 1
Feed characteristics, digestion processes of enteric methane (CH_4) calculations in selected on-farm models.

Model (main source), country, and model type	Feed characteristics and processes used for enteric CH_4 calculations		
	Feed components and feed characteristics	Digestion kinetics	Enteric CH_4 calculation
Karoline (Danfær et al., 2006) – Denmark / Sweden. Type 3 model.	Forage (for) pdNDF, concentrate (con) pdNDF, for iNDF, con iNDF, starch, lactic acid, NH_3-N, free aa, peptides, soluble CP, insoluble CP, pdCP, for EE, con EE, rest fraction [DM – (ash + NDF + starch + lactic acid + VFA + CP + EE)] (contains WSC, pectins, organic acids, alcohols). VFA for silages.	Feed-specific digestion rates (kd) for pdNDF, insoluble CP and starch. Digestion rate (Kd) of pdNDF adjusted for dietary NFC and feeding level.	Rumen H_2 based on VFA stoichiometry from fermented feed, adjusted for feeding level. H_2 pool adjusted for microbial mass and BH. Includes CH_4 formation in hind gut.
FarmGHG (Olesen et al., 2006) – Denmark. Type 2 model.	CF, NFE, CP, and fat daily intake (kg d^{-1}).		Empirical equation (Kirchgessner et al., 1995).
Valio Carbo® Farm calculator – Finland. Type 2 model.	DMI, OMI, GE, ME, DM, ash, OMD, FOM, CP, EPD, EE, NDF, iNDF, AAT, feed-AAT; PBV, NFC, NFC/CHO lactic acid, VFA, ammonia (g kg^{-1} N), Ca, P, Na, Mg, K, S, Cl, Fe, Cu, Zn, Mn, I, Co, Mo, Se, WSC, starch, iNDF, CF, NFE.	Digestibility of CP, EE, CF, NFE, OM.	Empirical equations (Ramin and Huhtanen, 2013).
FarmSim (Graux et al., 2011) – France. Type 2 model.	For and con NDF, digestibility. Grazing: adjusted for dietary NE intake and animal needs.		IPCC Tier 1 (274 and 279 g CH_4 d^{-1} for European and Dutch dairy cows, respectively) and Tier 2 (MCF = 6% of dietary GEI) (IPCC, 1996).
INRA Method (Eugène et al., 2019) – France. Type 2/3 model.	Not a farm-scale model, but used to progress from Tier 2 to Tier 3 at a national scale. Energetic requirements: GE, DE, NEL. Feed characteristics: DM, OM, CP, NDF, OMD, PC, N balance in the rumen.	Digestibility of OM, NDF, CP, starch, N. Digestive interactions driven by feeding level, DMI and BW. Also includes digestion rates (kd), N and energy use efficiencies.	Empirical equations (Sauvant and Nozière, 2016). Mitigation options (Sauvant et al., 2018).
GAS-EM (Haenel et al., 2020) – Germany. Type 2 model.	GE, DE, NEL, DM, OM, ash, CP (and/or N); OMD, CF, NFE, and fat. No differentiation by seasons and regions.		Empirical equation (Kirchgessner et al., 1994).
The GHG model (O'Brien et al., 2010) – Ireland. Type 2 model.	Dairy cows on conserved forage: proportion of forage in the diet and total DMI. Dairy cows on fresh grass: 0.065 × GEI (IPCC, 2006).		Empirical equations (Mills et al., 2003; IPCC, 2006).
DairyWise (Schils et al., 2007) – Netherlands. Type 2/3 model.	Different EF for con, maize silage and grass products (20, 22 and 27 g CH_4 kg^{-1} DMI, respectively). Updated (Bannink et al., 2020) with EF for different feeds (con ingredients, for qualities and diet types; the latter based on % maize silage in dietary for) derived from Dairy Tier 3 simulation.		CH_4 EF × animal intake (Schils et al., 2006). Updated and corrected CH_4 EF values (Bannink et al., 2020).
Dairy Tier 3 (Dijkstra et al., 1992; Bannink et al., 2011) – Netherlands. Type 3 model.	DMI, aNDFom, starch, SC, CP, non-ammonia CP, crude fat, ash, organic acids (for silages, lactic acid and VFA), and non-allocated OM, now allocated to sugars, starch and aNDFom depending on the ingredient type.	In situ degradation of aNDFom, starch and CP for each diet ingredient [washable fraction (W), potentially degradable (D), and rumen undegradable (U) fraction and fractional degradation rate (kd) of D].	Rumen H_2 based on VFA stoichiometry from fermented substrate (SC, starch, HC, Ce and CP) with an adjustment for dietary for-to-con ratio. H_2 pool adjusted for microbial growth on AA or NH_3-N, and for BH of uFA.
OverseerFM (Wheeler et al., 2008) – New Zealand. Type 2 model.	DM digestibility, ME and N of pastures and supplements. Animal ME requirement from feeding standards (mostly CSIRO, 2007).		EF (21.6 g CH_4 kg^{-1} DMI) × animal intake (IPCC, 2006; Ministry for Primary Industries, 2019).
Whole Farm Model (WFM) (Beukes et al., 2010) – New Zealand. Type 3 model.	Soluble ash, Ce, HC, SC, uFA, starch, large particles in the rumen, lignin, insoluble protein, AA, ammonia.	Microbial biomass and microbes associated with starch and (Ce + HC) fermentation. Ruminal acetate, propionate, butyrate and lactate.	Enteric CH_4 calculation based on H_2 balance from H_2 formation from CHO and AA fermentation, microbial growth, BH of uFA, and VFA profile.
Arla Carbon tool, Arla Foods – Sweden / Denmark / Germany / United Kingdom. Type 2 model.	GE intake, either specified by the farmer or calculated based on NorFor for cows and IPCC (2006) for heifers and bulls, and FA.	Digestibility coefficients: DM, CP, CF, structural and non-structural carbohydrates, FA, DE.	Empirical equation (IPCC, 2006).
NorFor (Nielsen et al., 2013) – Sweden / Denmark. Type 2 model.	DMI and dietary FA and NDF.		Empirical equation (Nielsen et al., 2013).
$SIMS_{DAIRY}$ (del Prado et al., 2011) – UK. Type 2 model.	DMI (g kg^{-1} BW d^{-1} and kg d^{-1}), C18:2 (quantity of linoleic acid in the diet), quantity of FA with a chain length ≥ 20C in the diet.		Empirical equation (Giger-Reverdin et al., 2003).
Farmscoper (Gooday et al., 2014) – UK. Type 2 model.	DMI, ME.		Empirical equation (IPCC, 1996), using default coefficients derived for Western Europe.
AgRE Calc – UK. Type 2 model.			Enteric CH_4 emissions for different livestock classes from IPCC Tier 2 (IPCC, 2006).

Abbreviations: AA: amino acids; AAT: amino acids absorbed from the small intestine; BH: biohydrogenation; Ce: cellulose; CF: crude fibre; CHO: carbohydrate; CP: crude protein; aNDFom: neutral detergent fibre assayed with heat stable amylase and expressed exclusive of residual ash; DE: digestible energy; DMI: dry matter intake; DOMI: digestible organic matter intake; EE: ether extract (i.e., crude fat); EPD: effective protein degradability; FA: fatty acids; FL: feeding level; FOM: fermentable organic matter; GE: gross energy; GEI: gross energy intake; HC: hemicellulose; iNDF: indigestible neutral detergent fibre; kd: fractional degradation rate; kp: fractional passage rate; ME: metabolisable energy; N: nitrogen; NDF: neutral detergent fibre; NE: net energy; NFC: non-fibre carbohydrates [calculated as DM – (ash + CP + EE + NDF)]; NFE: nitrogen free extract [calculated as DM – (ash + CP + EE + CF)]; OM: organic matter; OMD: organic matter digestibility; OMI: organic matter intake; PBV: protein balance in the rumen; PC: proportion of concentrate in the diet; pdCP: potentially digestible CP; pdNDF: potentially digestible NDF; uFA: unsaturated FA; VFA: volatile fatty acids; WSC: water soluble carbohydrates.

factors such as manure storage, soil and climatic conditions. Here we focus on the influence of diet. Manure CH_4 emissions are strongly linked to the VS content of the manure and as mentioned above this is often estimated from DE or OMD values. Nitrous oxide emissions are calculated from the amount of N excreted as faeces and urine multiplied by an emission factor (IPCC, 2006). Nitrogen excretion estimates require information on DMI per animal and CP or N concentration of the diet (IPCC, 2006) (Fig. 1), where the N concentration of the diet also influences partitioning of excreta N into faeces and urine (IPCC, 2019). Excretion estimates can be refined further by accounting for improved estimates of apparent faecal ND. Nitrous oxide emission factors will differ according to the method of manure management and, for excreta, the livestock type (e.g., cattle vs. sheep) and form of excreta (faeces vs. urine) (IPCC, 2006).

4. On-farm GHG model approaches to capture dietary effects on GHG emissions from livestock systems

In most ruminant systems, CH_4 is the predominant source of GHG emissions, with the diet having a major impact on enteric CH_4 from fermentation of feed in the rumen; the latter is the prevailing GHG source. For the two most important GHG (CH_4 and N_2O), there are three generic approaches that on-farm models use to estimate the effect of dietary characteristics on GHG emissions from livestock systems. The three approaches (hereafter *Types*) differ in the level and units the model is attempting to predict and quantify, and the degree at which diet-related details are represented, often associated with the number of variables and modelling approach chosen. The three approaches we identified are:

- A *Type 1* approach has a very low level of detail and uses a CH_4 emission factor (EF) per animal and an N_2O EF per unit of animal excreta, similar to a Tier 1 level at a national scale (IPCC, 2006).
- A *Type 2* approach has an intermediate level of detail (Fig. 1). It estimates the energy requirements of the animal (often in terms of ME or NE) based on milk, meat and fibre production, and animal characteristics. These requirements are then used to estimate feed DMI; enteric CH_4 emissions are then estimated using a CH_4 EF (g CH_4 kg^{-1} DMI).
- A *Type* 3 approach has a higher level of detail that often involves process-based modelling, taking into account DMI, diet chemical composition and nutrient supply, along with feed degradation and fermentation characteristics to predict (rather than assume) CH_4 EF according to a mechanistic, dynamic representation.

Type 1 models that use a default EF per animal or per unit of excreta N are not commonly used for on-farm GHG accounting or LCA, and generally only serve at a national level for inventory purposes. However, some on-farm GHG accounting models use country-, region- or farm-specific EF and apply these to the number of animals (e.g., kg CH_4 $animal^{-1}$ $year^{-1}$) or the amount of excreta N (e.g., kg N_2O-N kg^{-1} N excreted) (*diversified* Type 1 models; herein Type 1+ models). The EF for these Type 1+ models can be derived from experimental data (e.g., van der Weerden et al., 2011; Chadwick et al., 2018) or from detailed process-based modelling that could also provide look-up tables of EF (e.g., based on farm system, animal type or region) for such Type 1+ models. Type 1 models that use IPCC default values cannot capture dietary effects as CH_4 and N excreta EF are provided for an *average* animal. However, Type 1+ models could capture dietary effects if experimental data or results from process-based models deliver different EF estimates for an animal (or per unit of N excreta) consuming different diets.

For Type 2 models, a number of alternative approaches have been followed. These include either a) models that calculate energy requirements to estimate DMI with fixed EF and N excreta values, with or without different EF values for different stock classes (e.g., Wheeler et al., 2008), b) models that use prediction equations for enteric CH_4 emissions or for EF estimates based on feeding level, dietary proportion of

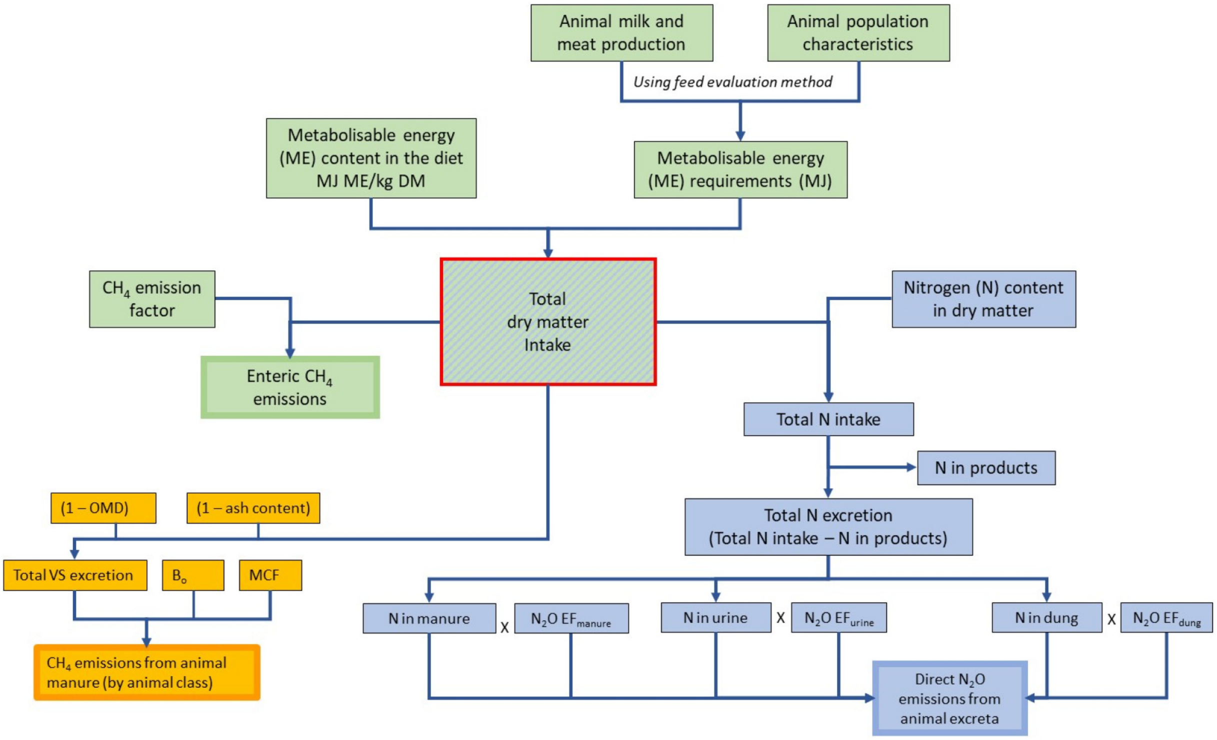

Fig. 1. Schematic overview of a generic Type 2 approach for estimating methane (CH_4) and nitrous oxide (N_2O) emissions from livestock production systems (modified from de Klein et al., 2019). Green boxes refer to enteric CH_4, orange boxes to manure CH_4, and blue boxes to N_2O. ME = metabolisable energy; MJ = mega joules; OMD = organic matter digestibility; VS = volatile solids; B_0 = maximum CH_4 producing capacity of manure; MCF = CH_4 conversion factor; EF = emission factor. The efficiency of use of feed energy and protein modulate these fluxes.

concentrate and OM digestibility (OMD) from a large literature database (e.g., Eugène et al., 2019), or c) a purely experimentally-driven (empirical) estimate of EF rather than a meta-analysis (e.g., Hellwing et al., 2016).

For models using Type 2a approaches, the opportunities to capture GHG abatement from ruminants using diet characteristics are limited. The use of sole indicators of diets or diet components feeding values such as ME, often calculated from chemical composition and OMD (irrespective of feeding level), limits the possibilities of GHG mitigation via nutritional strategies (Waghorn, 2007; Niu et al., 2018). This approach tends to use animal-, rather than feed-driven EF, and appears less accurate in accounting for changes in diet and diet characteristics other than by changes in feeding value. A more detailed alternative to this approach is the use of specific dietary ingredient EF (i.e., different EF for concentrates, supplements and fresh forages). Following this approach, emissions from enteric fermentation are calculated using different EF (g CH_4 kg^{-1} DMI) values for concentrates, maize silage and grass products (Schils et al., 2006), most likely obtained from respiration chambers. Type 2b models have a few more opportunities to capture GHG abatement using diet characteristics. However, these are limited to the predictor variables included in the empirical enteric CH_4 equation (feeding level, OMD and dietary proportion of concentrate) and the characterisation of non-digestible OM (CP, NDF, starch, C/N ratio) and N excretion (urinary and faecal), and its effect on manure EF (INRA, 2018; Eugène et al., 2019). Finally, models that follow Type 2c approaches have greater opportunities to explore GHG abatement using diet characteristics by using different EF based on experimental studies. For example, some experiments have shown that an increased concentration of starch and fat in the diet resulted in a significantly lower CH_4 conversion factor (MCF, % of GEI) (Hellwing et al., 2016; Niu et al., 2018; Sauvant et al., 2018).

Alternatively, process-based models could be used to provide diet-specific EF. For example, Bannink et al. (2020) recently derived lookup tables for specific EF for feeds and dietary ingredients for a range of diet classes (classified according to the proportion of maize silage in forage DM) and estimating DMI from process-based modelling. In this way, the essence of variation predicted by a process-based modelling approach (Type 3) was introduced by differentiation of EF values and correction for DMI and diet class in an otherwise typical Type 2a approach.

In all Type 2 models, estimates of DMI, along with the N concentration of the feed, are used to estimate animal N intake, which provides the basis for estimating N excretion in urine, faeces and manure effluent. Nitrous oxide emissions from these sources are then estimated using source-specific EF (e.g., Wheeler et al., 2008). Furthermore, to explore GHG abatement, the partition between faecal and urinary N fluxes derived from N intake can be estimated (INRA, 2018) along with CH_4 emissions for some mitigating strategies (e.g., for forage diets by Sauvant et al., 2014 in the INRA Method; for various diets by deriving an ND correction factor by Bannink et al., 2018 in DairyWise).

A Type 3 approach considers the effect of feed intake, feed chemical composition, ruminal degradation characteristics and end-products of fermentation, as well as rumen fermentation conditions and physical inflows and outflows of nutrients, to estimate enteric CH_4 emissions (e.g., Bannink et al., 2011; Beukes et al., 2011; Huhtanen et al., 2015). This is often achieved using process-based (mechanistic) models that focus on detailed biological and physical processes with explicit mechanisms being represented, in contrast to the empirical approaches with Type 2 models which are typically simpler, and the mechanisms are made implicit to the model.

Nitrous oxide emissions are largely estimated as for Type 2, but feed characteristics are used to estimate faecal N digestibility and N returned to the different soil N pools and processes (Bannink et al., 2018; INRA, 2018). In this way, Type 3 approaches allow for dietary ingredients, feed composition and digestion kinetics to be considered not only for CH_4 but also for N excretion and associated N_2O accounting and mitigation.

5. Selected on-farm GHG models

We have selected a number of (*on-farm and animal*) models from CEDERS participant countries, mostly based on degree of adoption and use, and on published literature. Information on these models was either publicly available or provided by experienced users. A brief description of the selected models is provided as Supplementary Material. The source of the model, the inclusion of diet characteristics and digestion kinetics in calculating enteric CH_4, are described in Table 1. Similarly, the inclusion of diet characteristics in calculating manure-derived CH_4 and N_2O from N excreta, are presented in Table 2.

5.1. Brief summary of the models

Most of the selected on-farm GHG models have adopted a Type 2 approach, generally using CH_4 and N_2O emission factors (EF) or a CH_4 conversion factor (MCF). Recently, a few hybrid Type 2 / Type 3 approaches have been developed that combine empirical modelling (through the use of CH_4 or N_2O EF) and process-based modelling, mostly of rumen and whole tract fermentation and digestion. Obtaining an accurate estimation of DMI is an essential first step to obtain accurate GHG predictions, because this variable is such an overriding factor in enteric CH_4 emissions. It also leads to predictions of OM excretion (i.e., VS), manure CH_4 emissions, and to predictions of N excretion, in turn a major predictor of N_2O emissions. Estimates of DMI in these models are often obtained from either feed tables or nutrition models (energy based or protein-plus-energy based) (e.g., Scandinavian feed units in FarmGHG; the NE_L system in GAS-EM; CSIRO (2007) in OverseerFM) (Type 2 approach) or as an outcome of more sophisticated models. In experimental settings, measuring feed on offer vs feed refused (housing systems), inference from animal performance (housing and grazing systems), and the use of markers and estimates from herbage disappearance (grazing systems), are commonly used to obtain estimates of DMI. In turn, the information collected in these settings provides a feedback loop to keep feed tables, nutrition models and ruminant models relevant and updated.

A second step in this process is the attainment of adequate EF (i.e., CH_4 per unit of DMI and per unit of faeces at grazing, CH_4 and N_2O per unit of animal excreta). Emission factors are often obtained from either literature surveys, databases of experimental data, or based on predictions of process-based models that are able to be explanatory and consider further detail. The choice will depend on country- or region-specific data availability and the possibility of adapting and validating the later models to country- or region-specific conditions.

A subtle distinction can be made between empirical GHG prediction models that potentially represent the most relevant results obtained from experimental work, and mechanistic models that attempt to grasp the underlying mechanisms and processes. In ruminants, enteric CH_4 is primarily produced in the rumen (87% of total enteric CH_4 production) and to a lesser extent in the large intestine (the remaining 13%) (Murray et al., 1976; Torrent and Johnson, 1994; discussed in Ellis et al., 2008). The closer the models are at interpreting and simulating rumen function (ruminal degradation characteristics and end-products of fermentation), the greater the opportunity to capture diet characteristics beyond the sole variables OM or DM intake, and to capture dietary mitigation alternatives.

6. Capturing the effects of diet on emissions from ruminant systems using on-farm GHG models

6.1. Opportunities

Most prediction models of GHG emissions are based on feed (DM or GE) intake derived from feed evaluation systems applied in practice. Although these models consider the main driver of enteric CH_4 emissions,

Table 2
Summary of the approaches used for estimating methane (CH_4) and nitrous oxide (N_2O) emissions from manure (including urine and faeces deposited during grazing) and feed characteristics captured in selected on-farm models.

Model (source) and country	Manure CH_4 (including faeces from grazing)	Manure N_2O (including urine and faeces from grazing)	Feed characteristics captured in the model
FASSET (Olesen et al., 2002) – Denmark.	Does not include estimates of manure CH_4.	Estimates manure N_2O using semi-empirical equations that calculate nitrification and denitrification, and partition the end-products into N_2 and N_2O.	Dietary N.
FarmGHG (Olesen et al., 2006) – Denmark.	IPCC Tier 2: calculates annual CH_4 EF based on VS excretion, B_0, and MCF (for three housing and four storage systems) but uses country specific values and also includes temperature and storage time functions.	Estimates N_2O for three housing and four storage systems as a function of temperature and/or storage time and/or tank surface area.	Dietary N.
Valio Carbo® Farm calculator – Finland.	Algorithm by Sommer et al. (2004) and applying experimentally derived parameters for stored slurry (Elsgaard et al., 2016; Petersen et al., 2016).	EF used for calculation of N_2O from EMEP/EEA (2016) and IPCC (2006) (Grönroos et al., 2017).	Total N, VSD, ash, water, P, TAN, FOM, K.
FarmSim (Salètes et al., 2004; Graux et al., 2011) – France.	IPCC Tier 2 for the calculation of CH_4 emissions from manure and housing systems.	Field: N excreta related to energy needs and diet quality, and C:N ratio of manure. Soil temperature and humidity in a dynamic equation. Barn: IPCC Tier 2 for N_2O from manure and croplands.	OMD, OM, ME and N.
INRA Method (Eugène et al., 2019) – France.	Annual CH_4 EF per animal based on VS excretion (from indigested OM and urinary OM, and IPCC Tier 2), B0, MCF, and MS. Annual manure EF per head: VS × EC × 365.	Eugène et al. (2019) does not describe N_2O approach, but recommend estimations of faecal and urinary N, along with determination of OMD and N digestibility.	OMD, OM, ME and N.
GAS-EM (Haenel et al., 2020) – Germany.	IPCC Tier 2: calculates annual CH_4 EF per head of animal based on VS excretion, B0, MCF, and MS. VS excretion for dairy cows based on DMI, DOM and ash in feed. Country specific values for MCF for different manure storage systems.	Type 1+ with fixed N_2O and NH_3 EF disaggregated for different manure and storage types and IPCC default for indirect N_2O from N leaching.	GE, ME, NEL, OMD, ash and N for key livestock categories
The GHG model (O'Brien et al., 2010) – Ireland.	Type 1+ with fixed CH_4 EF disaggregated for storage (slurry, manure, silage effluent) or soil applied (monthly slurry, manure).	Type 1+ with fixed N_2O EF disaggregated for storage (slurry, manure) or soil applied (urine, faeces, slurry, manure), plus grazing Nex.	Total DMI, OMD, and CP of the diet.
DairyWise (Schils et al., 2007; Bannink et al., 2020) – Netherlands.	Type 1+ with a fixed CH_4 EF for manure storage and one for manure applied to land.	Type 1+ with a fixed N_2O EF for stored manure and EF based on soil type and water level for manure N inputs to soil; and fixed fractions for N leaching and ammonia volatilisation.	Total DMI, OMD, and CP of the diet.
Dairy Tier 3 (Bannink et al., 2018) – Netherlands.	IPCC Tier 2: it calculates annual CH_4 EF per head of animal based on VS excretion, B0, MCF, and MS. VS excretion based on OMD and VSD. Use of a Tier 3 is limited to the prediction of ND and urine N excretion (implemented), and OMD and VS excretion (currently not implemented).	IPCC Tier 2 with EF for urine, faeces and manure storage and land application. IPCC Tier 3 for dairy cattle with prediction of Nex in urine based on N intake, apparent faecal N digestibility and N retention in animal product. Nex = N intake – N retention for all other animal classes.	Tier 2: total DMI, ME, OMD, and CP of the diet. Tier 3: DMI, aNDFom, starch, sugars, CP, non-ammonia CP, crude fat, ash, organic acids (for silages, lactic acid and VFA). In situ degradation of aNDFom, starch and CP [washable (W), potentially degradable (D), and rumen undegradable (U) fraction, and fractional degradation rate (kd) of D].
OverseerFM (Wheeler et al., 2008) – New Zealand.	CH_4 from anaerobic ponds and solids storage, application of stored manure to land, and faeces from grazing livestock. Based on proportion of faecal DM in each component and uses NZ inventory EF and IPCC Tier 2.	Estimates Nex based on DMI, dietary CP, and N in product; then splits between urine and faeces based on dietary N. Proportions urine and faeces to MMS and applies N_2O EF from the NZ inventory.	Total DMI, OMD, ash, CP.
Whole Farm Model (WFM) (Beukes et al., 2010) – New Zealand.	Does not estimate CH_4 from manure, but it does estimate OMD.	Does not estimate N_2O from manure, but it does estimate N excretion in faeces and urine (g N d^{-1})	Total CP intake.
Arla Carbon tool, Arla Foods – Sweden.	Emissions of CH_4 from manure is calculated based on IPCC (2006).	N_2O emitted from manure based on the amount of N in excreta. Animal-N balance. Total N_2O from manure systems calculated as the sum of direct and indirect N_2O emissions.	Total CP intake and VS, in addition to DM, CP, CF, FA, DE, NE. GE is calculated.
SIMSDAIRY (del Prado et al., 2011) – UK.	CH_4 from manure in storage based on IPCC, and manure on land from country specific EF (per animal) derived from Chadwick and Pain (1997) and Yamulki et al. (1999) for applied manure and faeces from grazing.	N_2O from manure storage from EMEP/CORINAIR (2005). N_2O from Nex deposited on soil estimated from mechanistic approach (nitrification and denitrification). Urinary and faecal N split based on dietary N.	Total DMI, OMD, ash, CP.
Cool Farm Tool (Hillier et al., 2011) – UK.	IPCC Tier 2: calculates annual CH_4 EF per head of animal based on VS excretion, B_0, MCF, and MS. Uses IPCC range of MMS and animal categories. Country-specific (rather than IPCC) EF for manure composting.	IPCC Tier 2: calculates annual N_2O from MMS using IPCC N excretion rates for 'animal category by region'. Uses IPCC range of MMS and animal categories. Country-specific (rather than IPCC) EF for manure composting.	Total DMI, OMD, ash, CP.
Farmscoper (Gooday et al., 2014) – UK.	IPCC Tier 2 (IPCC, 1996).	IPCC Tier 2 (IPCC, 1996) but with NH_3 and N leaching losses calculated in the model.	Total DMI, OMD, ash, CP.
AgRE Calc – UK.	IPCC Tier 2: calculates annual CH_4 EF per head of animal based on VS excretion, B_0, MCF, and MS.	IPCC Tier 2: calculates annual N_2O from manure based on livestock numbers, Nex/head, MS, and N_2O EF for each MMS.	Total DMI, OMD, ash, CP.

Abbreviations: B0: maximum CH_4 producing capacity of manure; Faecal DM: faecal dry matter (estimated from DMI and OMD); FOM: fermentable organic matter; MCF: CH_4 conversion factor for each MMS (by climate); MMS: manure management system (including grazing); MS: fraction of livestock handled in different MMS; Nex: N excretion (estimated based on DMI as used for enteric CH_4, N concentration of the diet and N removal in products); OMD: organic matter digestibility; TAN: total ammoniacal N; VS: volatile solids (estimated based on OMD and ash concentration of feed); VSD: volatile solids digestibility.

they are inadequate to capture the effect of dietary chemical components and dietary chemical/physical characteristics on GHG emissions. As a result, these models cannot capture the effect of potential dietary GHG abatement options that alter diet characteristics such as lipid (Grainger and Beauchemin, 2011), fibre (Niu et al., 2018), and starch and sugar concentrations (Hindrichsen et al., 2005), ruminal and whole tract digestibility (Appuhamy et al., 2016), or secondary plant metabolites (Jayanegara et al., 2012; Sauvant et al., 2018). As a consequence, there is an increasing demand for models that take into account feed properties that both improve GHG prediction and can capture nutritional mitigation strategies (Niu et al., 2018; van Lingen et al., 2019; Benaouda et al., 2019).

A close examination of several enteric CH_4 prediction equations for dairy cows used in on-farm GHG models showed that equations based on important aspects of diet composition performed better (i.e., having a greater accuracy) than those based on simpler, generic parameters or Type 1 / 2 equations (Ellis et al., 2010). These findings are in agreement with the widely spread notion that enteric CH_4 production is primarily driven by both amount and composition of feed consumed. More specifically, equations that included important aspects of diet composition, such as carbohydrate components [non-structural carbohydrates (NSC), hemicellulose (HC) and cellulose (Ce) (Moe and Tyrrell, 1979)] were more accurate in their predictions of enteric CH_4 emissions compared with other equations (Ellis et al., 2010). The Moe and Tyrrell (1979) equation was used in an early version of the Molly model (Baldwin, 1995) to predict CH_4 emissions (Palliser and Woodward, 2002). Ellis et al., (2010) examined other equations including those of Blaxter and Clapperton (1965) (also tested in Molly), Kirchgessner et al. (1995) used in FarmGHG, Giger-Reverdin et al. (2003) used in $SIMS_{DAIRY}$, Corré (2002) used in Schils et al. (2005), Schils et al. (2006) used in DairyWise (recently updated based on Bannink et al., 2020), and a Type 1 (Tier 1) and a Type 2 (Tier 2) model from IPCC (1996), used in FarmSim and Phetteplace et al. (2001), respectively.

Due to the inclusion of diet composition information, the Moe and Tyrrell (1979) equation was the best performing in a direct comparison with other empirical equations (Ellis et al., 2010), as most of these equations did not include such information. Although the Moe and Tyrrell equation includes some important aspects of chemical composition (and an indirect estimate of feed intake level), other dietary characteristics that have proven effective in CH_4 mitigation (i.e., lipid, starch and fibre concentration, OM digestibility; Dijkstra et al., 2010; Bannink et al., 2016), are not. Furthermore, the equation assumes a constant CH_4 yield per unit of NSC, HC and Ce, as discussed in Ellis et al. (2008). The implications of this assumption is that it excludes differential ruminal fermentability and passage rate of these components associated with variations in feed intake level, in turn affecting efficiency of microbial synthesis, VFA production, ruminal pH, VFA profile and CH_4 production (Hindrichsen et al., 2005; Dijkstra et al., 2010). Overall, the use of fixed CH_4 conversion factors led to low CH_4 prediction accuracy and imposes severe limits to opportunities for nutritional mitigation of GHG emissions (Ellis et al., 2010). Consistent with these findings, Jentsch et al. (2007) concluded that a major component of CH_4 production could not be explained solely by DMI. Consideration of all digestible nutrients in the diet revealed that the carbohydrate fraction, particularly digestible (crude) fibre and digestible N-free residuals contributed the most to CH_4 production, whereas digestible fat had an inhibitory effect (Jentsch et al., 2007).

More recently, Niu et al. (2018) identified the main predictor variables of dairy CH_4 production (g CH_4 cow^{-1} day^{-1}), and examined the trade-offs between the availability of input variables (including diet characteristics) and the accuracy of models (assessed with several measures of model predictive ability) using the large dairy CH_4 database from the international collaborative initiative GLOBAL NETWORK (https://globalresearchalliance.org/research/livestock/collaborative-activities/global-research-project/). Along with records of enteric CH_4 production, milk yield, milk composition and BW, the database includes dietary concentrations of GE, CP, EE, NDF, ash and measured (or estimated) DMI. In addition to supporting the well-established notion that DMI is the most important variable to predict CH_4 production from dairy cows, the inclusion of diet characteristics such as NDF and EE concentration improved the accuracy of prediction of enteric CH_4 production (Ramin and Huhtanen, 2013; Niu et al., 2018).

The GLOBAL NETWORK project data were also used by Benaouda et al. (2019) to examine the predictive ability of existing enteric CH_4 equations compared with measurements obtained from calorimetry chambers, the SF_6 tracer technique and automated head chambers across ruminant species. Enteric CH_4 emissions (g CH_4 d^{-1}) from dairy cattle were suitably predicted by equations that included feed intake (DMI, GEI) and/or feed level (DMI/BW) as predictors (Mills et al., 2003; Ramin and Huhtanen, 2013; Charmley et al., 2016). However, the best performing equation (Ramin and Huhtanen, 2013) included GE digestibility and lipid concentration (EE), in addition to feeding level (Benaouda et al., 2019). Although most equations that include digestibility use digestible OM rather than digestible GE, both variables have been well established predictors of enteric CH_4 emissions (Blaxter and Clapperton, 1965; Sauvant and Nozière, 2016).

Ellis et al. (2010) showed that the accuracy of enteric CH_4 predictions using a fixed CH_4 energy conversion factor was low. In addition to limiting the possibility of implementing nutritional mitigation strategies (as mentioned above), the use of such fixed conversion factors can potentially introduce substantial error at the farm scale. These errors can escalate at larger scales (e.g. in GHG inventories) and may lead to unsuitable mitigation recommendations or inaccurate projections of CH_4 emissions over time (Bannink et al., 2011).

The effect of dietary strategies on N_2O emissions are largely driven by total N intake, or more importantly, the total N output in excreta or manure. Dietary N concentration is therefore a key parameter that needs to be captured, as is the case in most on-farm GHG models. In addition, the partitioning of N between urine and faeces affects N_2O emissions, as it is well-accepted that N_2O emissions from urine are greater than those from faeces (IPCC, 2019). Diet characteristics that affect N partitioning in urine and faeces include, amongst others, DMI, N intake, rumen-fermentable OM leading to the synthesis of microbial N, DM digestibility, CP concentration, and the presence of secondary metabolites such as tannins. Dry matter digestibility and CP are negatively related to N partitioning in faeces, whereas tannin concentration is positively related to the proportion of N excreted as faecal N (de Klein and Eckard, 2008; Sauvant et al., 2014). All the on-farm GHG models reviewed in this paper capture DMI, dietary DMD and CP (or N) concentration, but very few (if any) take account of more detailed aspects such as the effect of differing profiles of N disappearance (ruminal and whole-tract) or the concentration of plant secondary metabolites such as tannins in the diet.

In a meta-analysis by Sauvant et al. (2014), relationships between CH_4 and urinary outputs were derived for ruminants fed forages (temperate and tropical forages) as their sole diet. It was shown that CH_4 production was closely related to digestible OM intake when both variables were expressed per unit of DMI or LW. This suggests that digestible OM intake is a key parameter to be captured in models for estimating CH_4 emissions from forage-fed ruminants. In agreement with these findings, Warner et al. (2017) reported that enteric CH_4 methane emissions were clearly affected by grass silage quality (based on harvesting leafy to late-heading grass maturity stages), more so than by DMI level (based on stage of lactation). Per unit of OM or NDF digested, CH_4 yields were similar between DMI levels, but noticeable increases were seen when reported on a digestible OM intake basis (Warner et al., 2017). Sauvant et al. (2014) also showed that, when animals are managed indoors with an anaerobic slurry storage, mitigation of enteric CH_4 appeared to be partly offset by a higher production of CH_4 from manure.

The use of dynamic mechanistic modelling in the simulation of enteric CH_4 emissions and N_2O emissions from animal excreta, has resulted in more accurate predictions than simple regression equations (Benchaar et al., 1998). Although the INRA/ IPCC (2006) ratio for enteric CH_4 emissions was close to unity and estimates did not differ between models for adult cows (i.e., most cattle in France), the use of dietary characteristics such as digestible OM intake (corrected for feeding level and proportion of concentrate in the diet) in the prediction allows for different mitigation strategies to be tested (Sauvant et al., 2018; Eugène et al., 2019). Furthermore, mechanistic modelling of methanogenesis in particular, has allowed for IPCC Tier 3 approaches to go beyond the farm scale (Bannink et al., 2011; Huhtanen et al., 2015). In addition, the use of a country-specific (i.e., Dutch studies only) Tier 3 approach to predict faecal N digestibility (Bannink et al., 2018) resulted in more accurate predictions than using feeding tables (CVB model; CVB, 2011), in particular for Dutch studies for which more accurate estimates of model inputs on rumen degradability of substrates were available. The over-prediction of the CVB model would lead to an over-prediction of urine or ammoniacal N excretion, in turn leading to biased estimations of the N mitigation potential from nutritional strategies (Bannink et al., 2018).

6.2. Challenges

Overall, on-farm models that predict enteric CH_4 emissions are based on a few animal and feed characteristics, but DMI is typically the key parameter to consider. Analyses of large datasets of individual dairy cows have shown that simplified equations based on DMI alone or in combination with a few feed and/or animal related variables can predict mean enteric CH_4 emissions with a similar accuracy to that of more detailed empirical equations (Hristov et al., 2018; Niu et al., 2018). Although reliable for national emission inventory purposes, these approaches do not allow for exploring nutritional mitigation options on specific farms.

Accurate predictions of DMI are essential to achieve accurate predictions of livestock emissions, including enteric and manure CH_4, and N_2O emissions. In some confinement-type feeding systems where predictions of DMI can rely on robust and frequently-updated feed evaluation systems, the issue of prediction accuracy becomes of less concern. For example, using data from North America, model equations that used estimates of DMI could predict enteric CH_4 emissions as accurately as when using measured DMI data, provided DMI could be estimated with reasonable accuracy (Appuhamy et al., 2016), and prediction accuracy was not improved by further addition of diet characteristics to the model (Niu et al., 2018). Using European data, estimates rather than measured DMI provided for acceptable predictions (RMSPE $\leq$ 15%; CCC $\geq$ 0.50), whereas using estimates of DMI for Australia and New Zealand provided for poor predictive performance of enteric CH_4 emissions (RMSPE > 25%; CCC < 0.40) (Appuhamy et al., 2016). The differences in accuracy were most likely attributed to the DMI prediction models used, based on North American data that are unlikely to address diets with a high proportion of forage (Appuhamy et al., 2016; Hristov et al., 2018). As expected, forages (offered either fresh or conserved) dominated the diets used in Australia and New Zealand (mean values of 88% vs. 52% and 64% for North American and European diets, respectively). Obtaining reasonable estimates of herbage DMI in a grazing situation can be challenging, as results obtained from different methods (e.g., the use of markers, herbage disappearance and inferences from animal performance) can vary substantially and can potentially be misleading (Macoon et al., 2003).

The type of livestock farming system is also an important consideration when assessing the value of refining on-farm GHG models to capture more details concerning dietary strategies. In fully housed livestock systems, where animals are fed a total mixed ration for example, dietary measures to reduce GHG emissions can be more easily adopted compared with systems that rely on grazing-based diets to varying degrees. In reality, it is highly unlikely that one feed constituent (e.g., NDF concentration) will vary while others remain unchanged, due to the inherent association between diet constituents in diet formulation, but any goal-directed change is easier to achieve in confinement-type diets or through supplemental feeding than in grazing situations. The latter also offer dynamic changes (seasonal, daily, hourly) in herbage quantity, composition, nutritive value, and animal preference, which add complexity to DMI predictions from pasture-based systems.

Recently, Niu et al. (2018) highlighted the potential effects of increased intake and associated effects such as increased passage rate and reduced time for ruminal digesta retention, which in turn can reduce OM digestibility and CH_4 production per unit of feed (i.e., a reduction in g CH_4 kg^{-1} DMI) (Van Soest, 1994). Feed intake is a consequence of feed on offer, animal production demand and digestibility of nutrients. In contrast with Type 3 models where the effect is captured, Type 2 models do not account for the effect of changes in feeding level, often expressed as multipliers of maintenance energy levels (e.g., NRC, 2001).

Another challenge for on-farm GHG models to capture dietary strategies is the accuracy and availability of input data to run the models. Availability of data and transparency in the description and adoption of methodological procedures are essential to make informed decisions on GHG abatement strategies, and even more so when these tools are to inform policy (Hall et al., 2010). The more detailed the model in terms of inclusion of dietary characteristics, the higher the level of detail that is required for the input and activity data. This not only includes detail on diet composition (e.g., proportions of different feed types), but also on diet characteristics within each ration ingredient or feed type. In many cases, the complexity of obtaining or recording additional input data needs to be carefully balanced against the benefit of being able to capture the effect of a given dietary strategy in the model. Nevertheless, in many cases of intensive farming systems, reasonable estimates or feed table values can be used as inputs, or obtained from commercial lab ‘high-throughput’ analysis of nutritional value (e.g. Near Infra-Red Spectroscopy). These estimates or feed table values can be more *generic* than detailed measurements as an input, but they still offer potential to capture more of the variation in GHG emissions, as these estimates are based on variation in feed chemical composition.

Empirical models that include commonly measured dietary inputs can be fairly successful in predicting CH_4 emissions (Ellis et al., 2007). However, the impact of mitigation strategies to reduce CH_4 emissions needs to be assessed in a more integrated way, and often empirical models do not have the biological basis for such assessment. Mathematical models of fermentation and digestion have become extremely useful to simulate the complex digestive processes in the rumen, to increase our understanding of the complexity of systems and to identify areas where knowledge is lacking and more research is required to improve both understanding and accuracy of predictions (Ellis et al., 2008). Dynamic components of CH_4 predictions have been added to these mechanistic models (e.g., Benchaar et al., 1998; Mills et al., 2001) and delivered improved prediction of the effect of specific mitigation measures. However, limitations in the accuracy of CH_4 predictions continue to surface (Bannink et al., 2016). Earlier work in search for causes of inaccurate simulation of rumen function (leading to inaccurate predictions of enteric CH_4) already identified the need for accurate estimates of stoichiometry of VFA production with substrate fermentation and VFA absorption kinetics (Bannink et al., 1997) and interspecies H_2 transfer (Ellis et al., 2008).

Finally, it is important to note that most of the models available (and those selected in this review) have been developed for temperate conditions and related animal breeds and feed nutritive values, often involving adult Holstein-Friesian and Jersey cattle with ad libitum access to feed and quality drinking water (i.e., low nitrate concentrations) under European and New Zealand conditions. Models have been developed for diets or dietary ingredients with a common mineral, DM and OM concentration including typical grass / legume mixed pastures (fresh and conserved), maize (grain and silage), other grains, concentrates and by-products, with feed nutritive values described in various feed tables. Development and evaluation of models for livestock production systems in arid and tropical regions is extremely limited to date, highlighting the need for greater effort by the international research community in this area.

7. Conclusions

The models reviewed in this paper generally include Type 2 or combinations of Type 2 and Type 3 approaches depending on livestock class, GHG considered and emissions source involved. The majority of enteric CH_4 models use a Type 2 approach to estimate DMI from production data and animal population characteristics, whereas a limited number of models use the more detailed mechanistic Type 3 approach. Type 2 models can capture a varying range of diet characteristics, including total DMI, DM or OM digestibility, ME/GE, and CP concentration. Most models then use a CH_4 EF (g CH_4 kg^{-1} DMI) and a N_2O EF (N_2O-N emitted as % of N excreted) to estimate GHG emissions. Some models include different CH_4 EF for different diets or dietary ingredients (e.g., DairyWise, with EF values derived from a Type 3 approach) rather than CH_4 EF purely based on animal species (e.g., OverseerFM). Only Type 3 models represent underlying mechanisms such as ruminal fermentation and total-tract digestive processes (e.g., Karoline, Dairy Tier 3, Whole Farm Model). Prior to a proper representation of these processes, ruminal digestibility of, and competition for, different substrates, bypass fractions, and the rate (faster fermentation, lesser CH_4 production) and extent of fermentation, along with adequate descriptions of OM chemical composition, need to be captured by these models. Other aspects such as the effect of secondary metabolites on CH_4 EF also need to become apparent.

There are opportunities for all models to improve their ability to capture dietary mitigation strategies, but the value of doing so should be carefully balanced against gains in accuracy of the estimates, the need for additional input and activity data, the variability actually encountered on-farm and amongst farms, and the need for consistency between different approaches that are to be used for different purposes (inventory vs. on-farm accounting vs. life cycle analysis).

Declaration of competing interest

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

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Appendix A. Supplementary data

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References

Appuhamy, J.A.D.R.N., France, J., Kebreab, E., 2016. Models for predicting enteric methane emissions from dairy cows in North America, Europe, and Australia and New Zealand. Glob. Chang. Biol. 22, 3039–3056.

Baldwin, R.L., 1995. Modeling Ruminant Digestion and Metabolism Chapman & Hall. UK, London.

Bannink, A., De Visser, H., Klop, A., Dijkstra, J., France, J., 1997. Causes of inaccurate prediction of volatile fatty acids by simulation models of rumen function in lactating cows. J. Theor. Biol. 189, 353–366.

Bannink, A., van Schijndel, M.W., Dijkstra, J., 2011. A model of enteric fermentation in dairy cows to estimate methane emission for the Dutch National Inventory Report using the IPCC Tier 3 approach. Animal Feed Science & Technology 166-167, 603–618.

Bannink, A., van Lingen, H.J., Ellis, J.L., France, J., Dijkstra, J., 2016. The contribution of mathematical modeling to understanding dynamic aspects of rumen metabolism. Front. Microbiol. 7, 1820.

Bannink, A., Spek, W.J., Dijkstra, J., Šebek, L.B.J., 2018. A tier 3 method for enteric methane in dairy cows applied for fecal N digestibility in the ammonia inventory. Frontiers in Sustainable Food Systems 2, 66.

Bannink, A., Zom, R.L.G., Groenestein, K.C., Dijkstra, J., Sebek, L.B.J., 2020. Applying a mechanistic fermentation and digestion model for dairy cows with emission and nutrient cycling inventory and accounting methodology. Animal 14 (S2), s406–s416.

Beauchemin, K.A., Kreuzer, M., O'Mara, F., McAllister, T.A., 2008. Nutritional management for enteric methane abatement: a review. Aust. J. Exp. Agric. 48, 21–27.

Benaouda, M., Martin, C., Li, X., Kebreab, E., Hristov, A.N., Yu, Z., Yáñez-Ruiz, D.R., Reynolds, C.K., Crompton, L.A., Dijkstra, J., Bannink, A., Schwarm, A., Kreuzer, M., McGee, M., Lund, P., Hellwing, A.L.F., Weisbjerg, M.R., Moate, P.J., Bayat, A.R., Shingfield, K.J., Peiren, N., Eugène, M., 2019. Evaluation of the performance of existing mathematical models predicting enteric methane emissions from ruminants: animal categories and dietary mitigation strategies. Animal Feed Science & Technology 255, 114207.

Benchaar, C., Rivest, J., Pomar, C., Chiquette, J., 1998. Prediction of methane production from dairy cows using existing mechanistic models and regression equations. J. Anim. Sci. 76, 617–627.

Benchaar, C., Pomar, C., Chiquette, J., 2001. Evaluation of dietary strategies to reduce methane production in ruminants: a modelling approach. Can. J. Anim. Sci. 81, 563–574.

Beukes, P.C., Gregorini, P., Romera, A.J., Levy, G., Waghorn, G.C., 2010. Improving production efficiency as a strategy to mitigate greenhouse gas emissions on pastoral dairy farms in New Zealand. Agric. Ecosyst. Environ. 136, 358–365.

Beukes, P.C., Gregorini, P., Romera, A.J., 2011. Estimating greenhouse gas emissions from New Zealand dairy systems using a mechanistic whole farm model and inventory methodology. Animal Feed Science & Technology 166, 708–720.

Beyer, M., Chudy, A., Hoffmann, L., Jentsch, W., Laube, W., Nehring, K., Schiemann, R., 2003. Rostock Feed Evaluation System: Reference Numbers of Feed Value and Requirement on the Base of Net Energy. Plexus-Verlag, Miltenberg.

Blaxter, K.L., Clapperton, J.L., 1965. Prediction of the amount of methane produced by ruminants. Br. J. Nutr. 19, 511–521.

Blok, M.C., Spek, J.W., 2016. CVB Veevoedertabel 2016: chemische samenstellingen en nutritionele waarden van voedermiddelen. CVB, Netherlands Available at:. https://edepot.wur.nl/379631.

Brown, L., Jarvis, S.C., Headon, D., 2001. A farm-scale basis for predicting nitrous oxide emissions from dairy farms. Nutr. Cycl. Agroecosyst. 60, 149–158.

Caro, D., Kebreab, E., Mitloehner, F.M., 2016. Mitigation of enteric methane emissions from global livestock systems through nutrition strategies. Climate Change 137, 467–480.

Chadwick, D.R., Pain, B.F., 1997. Methane fluxes following slurry applications to grassland soils: laboratory experiments. Agric. Ecosyst. Environ. 63, 51–60.

Chadwick, D.R., Cardenas, L.M., Dhanoa, M.S., Donovan, N., Misselbrook, T., Williams, J.R., Thorman, R.E., McGeough, K.L., Watson, C.J., Bell, M., Anthony, S.G., Rees, R.M., 2018. The contribution of cattle urine and dung to nitrous oxide emissions: quantification of country specific emission factors and implications for national inventories. Sci. Total Environ. 635, 607–617.

Charmley, E., Williams, S.R.O., Moate, P.J., Hegarty, R.S., Herd, R.M., Oddy, V.H., Reyenga, P., Staunton, K.M., Anderson, A., Hannah, M.C., 2016. A universal equation to predict methane production of forage-fed cattle in Australia. Anim. Prod. Sci. 56, 169–180.

Colomb, V., Bernoux, M., Bockel, L., Chotte, J.-L., Martin, S., Martin-Phipps, C., Mousset, J., Tinlot, M., Touchemoulin, O., 2012. Review of GHG calculators in agriculture and forestry sectors. A guideline for appropriate choice and use of landscape based tools. FAO EX-ACT team (EX-Ante Carbon-balance tool - www.fao.org/tc/exact), The Joint Research Unit Eco&Sols (Functional Ecology and Biogeochemistry of Soils & Agro-ecosystems - http://www.montpellier.inra.fr/ecosols) and the ADEME ClimAgri programme (www.ademe.fr).

Corré, W.J., 2002. Agricultural Land Use and Emissions of Methane and Nitrous Oxide in Europe. Report 40, Plant Research International, Wageningen, the Netherlands. 29 pp.

Cowie, A., Eckard, R., Eady, S., 2012. Greenhouse gas accounting for inventory, emissions trading and life cycle assessment in the land-based sector: a review. Crop & Pasture Science 63, 284–296.

CSIRO, 2007. Nutrient Requirements of Domesticated Ruminants. CSIRO Publishing, Victoria, Australia.

CVB, 2011. Table of Feedstuffs: Information about Composition, Digestibility, and Feeding Values. Centraal Veevoederbureau, Product Board Animal Feed, The Hague.

Danfær, A., Huhtanen, P., Uden, P., Sveinbjornsson, J., Volden, H., 2006. The Nordic dairy cow model, Karoline - description. In: Kebreab, E., Dijkstra, J., Bannink, A., Gerrits, W.J., France, J. (Eds.), Nutrient Digestion and Utilization in Farm Animals: Modelling Approaches. CABI Publishing, Wallingford, pp. 383–406.

Denef, K., Paustian, K., Archibeque, S., Biggar, S., Pape, D., 2012. Report of Greenhouse Gas Accounting Tools for Agriculture and Forestry Sectors. Interim Report to USDA under Contract No. GS23F8182H.

Dijkstra, J., Neal, H.D.S.C., Beever, D.E., France, J., 1992. Simulation of nutrient digestion, absorption and outflow in the rumen: model description. J. Nutr. 122, 2239–2256.

Dijkstra, J., France, J., Ellis, J.L., Kebreab, E., Lopez, S., Reijs, J.W., Bannink, A., 2010. Effects of nutritional strategies on simulated nitrogen excretion and methane emission in dairy cattle. Modelling Nutrient Digestion and Utilisation in Farm Animals, pp. 394–402.

Ellis, J.L., Kebreab, E., Odongo, N.E., McBride, B.W., Okine, E.K., France, J., 2007. Prediction of methane production from dairy and beef cattle. J. Dairy Sci. 90, 3456–3466.

Ellis, J.L., Dijkstra, J., Kebreab, E., Bannink, A., Odongo, N.E., McBride, B.W., France, J., 2008. Aspects of rumen microbiology central to mechanistic modelling of methane production in cattle. J. Agric. Sci. 146, 213–233.

Ellis, J.L., Bannink, A., France, J., Kebreab, E., Dijkstra, J., 2010. Evaluation of enteric methane prediction equations for dairy cows used in whole farm models. Glob. Chang. Biol. 16, 3246–3256.

Elsgaard, L., Olsen, A.B., Petersen, S.O., 2016. Temperature response of methane production in liquid manures and co-digestates. Sci. Total Environ. 539, 78–84.

EMEP/CORINAIR, 2005. Emission Inventory Guidebook. fourth ed. European Environment Agency, Copenhagen, Denmark.

EMEP/EEA. 2016. EMEP/EEA air pollutant emission inventory Guidebook 2016. 3.B Manure management. Copenhagen, European Environment Agency. EEA Report No 21/2016.

Eugène, M., Sauvant, D., Nozière, P., Viallard, D., Oueslati, K., Lherm, M., Mathias, E., Doreau, M., 2019. A new Tier 3 method to calculate methane emission inventory for ruminants. J. Environ. Manag. 231, 982–988.

Fox, D.G., Tedeschi, L.O., Tylutki, T.P., Russell, J.B., Van Amburgh, M.E., Chase, L.E., Pell, A.N., Overton, T.R., 2004. The Cornell Net Carbohydrate and Protein System model for evaluating herd nutrition and nutrient excretion. Animal Feed Science & Technology 112, 29–78.

Giger-Reverdin, S., Morand-Fehr, P., Tran, G., 2003. Literature survey of the influence of dietary fat composition on methane production in dairy cattle. Livest. Prod. Sci. 82, 73–79.

Gooday, R.D., Anthony, S.G., Chadwick, D.R., Newell-Price, P., Harris, D., Duethmann, D., Fish, R., Collins, A.L., Winter, M., 2014. Modelling the cost-effectiveness of mitigation methods for multiple pollutants at farm scale. Sci. Total Environ. 468-469, 1198–1209.

Grainger, C., Beauchemin, K.A., 2011. Can enteric methane emissions from ruminants be lowered without lowering their production? Animal Feed Science & Technology 166–167, 308–320.

Graux, A.I., Gaurut, M., Agabriel, J., Baumont, R., Delagarde, R., Delaby, L., Soussana, J.F., 2011. Development of the pasture simulation model for assessing livestock production under climate change. Agric. Ecosyst. Environ. 144, 69–91.

Grönroos, J., J. Munther and S. Luostarinen. 2017. Calculation of atmospheric nitrogen and NMVOC emissions from Finnish Agriculture – Description of the revised model, Reports of the Finnish environment institute 37, ISBN 978-952-11-4902-3.

Haenel, H.-D., Rösemann, C., Dämmgen, U., Döring, U., Wulf, S., Eurich-Menden, B., Freibauer, A., Döhler, H., Schreiner, C., Osterburg, B., Fuß, R., 2020. Calculations of gaseous and particulate emissions from German agriculture 1990 – 2018: report on methods and data (RMD) Submission 2020. Braunschweig: Johann Heinrich von Thünen-Insti tut, 448 p, Thünen Rep 77, DOI:10.3220/REP1584363708000.

Hall, P., Holmes-Ling, P., Stewart, K., Sheane, R., 2010. A Scottish Farm-based Greenhouse Gas Accounting Tool. A review of existing tools and recommendations for improved emissions accounting and reporting within agriculture and horticulture. Prepared by Laurence Gould Partnership Ltd. and Best Foot Forward for the Scottish Government, Edinburgh, Scotland.

Hellwing, A.L.F., Weisbjerg, M.R., Brask, M., Alstrup, L., Johansen, M., Hymøller, L., Larsen, M.K., Lund, P., 2016. Prediction of the methane conversion factor (Y_m) for dairy cows on the basis of national farm data. Anim. Prod. Sci. 56, 535–540.

Henderson, G., Cox, F., Ganesh, S., et al., 2015. Rumen microbial community composition varies with diet and host, but a core microbiome is found across a wide geographical range. Sci. Rep. 5, 14567. https://doi.org/10.1038/srep14567.

Hillier, J., Walter, C., Malin, D., Garcia-Suarez, T., Mila-i-Canals, L., Smith, P., 2011. A farm-focused calculator for emissions from crop and livestock production. Environ. Model. Softw. 26, 1070–1078.

Hindrichsen, I.K., Wettstein, H.R., Machmüller, A., Jörg, B., Kreuzer, M., 2005. Effect of the carbohydrate composition of feed concentrates on methane emission from dairy cows and their slurry. Environ. Monit. Assess. 107, 329–350.

Hristov, A.N., Kebreab, E., Niu, M., Oh, J., Bannink, A., Bayat, A.R., Boland, T.M., Brito, A.F., Casper, D.P., Crompton, L.A., Dijkstra, J., Eugène, M., Garnsworthy, P.C., Haque, N., Hellwing, A.L.F., Huhtanen, P., Kreuzer, M., Kuhla, B., Lund, P., Madsen, J., Martin, C., Moate, P.J., Muetzel, S., Muñoz, C., Peiren, N., Powell, J.M., Reynolds, C.K., Schwarm, A., Shingfield, K.J., Storlien, T.M., Weisbjerg, M.R., Yáñez-Ruiz, D.R., Yu, Z., 2018. Symposium review: uncertainties in enteric methane inventories, measurement techniques, and prediction models. J. Dairy Sci. 101, 6655–6674.

Huhtanen, P., Ramin, M., Udén, P., 2015. Nordic dairy cow model Karoline in predicting methane emissions: 1. Model description and sensitivity analysis. Livest. Sci. 178, 71–80.

Illius, A.W., Gordon, I.J., 1991. Prediction of intake and digestion in ruminants by a model of rumen kinetics integrating animal size and plant characteristics. J. Agric. Sci. 116, 145–157.

INRA, 2018. INRA Feeding System for Ruminants. Wageningen Academic Publishers, NLD (640 p).

IPCC, 1996. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Greenhouse Gas Inventory Reference Manual. Volume 3. Hadley Centre, Bracknell, UK.

IPCC, 2006. Chapter 10 Emissions from Livestock and Manure Management. In 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Vol 4. Agriculture, Forestry and Other Land Use, Prepared by the National Greenhouse Gas Inventories Programme. In: Eggleston, S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), Japan: IGES. http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html.

IPCC, 2019. Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Available at: https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch11_Soils_N2O_CO2.pdf.

Jaurena, G., Cantet, J.M., Arroquy, J.I., Palladino, R.A., Wawrzkiewicz, M., Colombatto, D., 2015. Prediction of the Ym factor for livestock from on-farm accessible data. Livest. Sci. 177, 52–62.

Jayanegara, A., Leiber, F., Kreuzer, M., 2012. Meta-analysis of the relationship between dietary tannin level and methane formation in ruminants from *in vivo* and *in vitro* experiments. J. Anim. Physiol. Anim. Nutr. 96, 365–375.

Jentsch, W., Schweigel, M., Weissbach, F., Scholze, H., Pitroff, W., Derno, M., 2007. Methane production in cattle calculated by the nutrient composition of the diet. Arch. Anim. Nutr. 61, 10–19.

Kirchgessner, M., Windisch, W., Muller, H.L., 1994. Methane release from dairy cows and pigs. In: Aguilera, J.F. (Ed.), Proceedings of the 8th Symposium on Energy Metabolism of Farm Animals. EAAP Publication No vol. 76, pp. 399–402.

Kirchgessner, M., Windisch, W., Müller, H.L., 1995. Nutritional factors for the quantification of methane production. In: Engelhardt, W.V., Leonhard-Marek, S., Breves, G., Giesecke, D. (Eds.), Ruminant physiology: digestion, metabolism, growth and reproduction. Proceedings of the Eighth International Symposium on Ruminant Physiology, Ferdinand Enke Verlag: Stuttgart, Germany, pp. 333-348.

de Klein, C.A.M., Eckard, R.J., 2008. Targeted technologies for nitrous oxide abatement from animal agriculture. Aust. J. Exp. Agric. 48, 14–20.

de Klein, C.A.M., Ledgard, S.F., 2005. Nitrous oxide emissions from New Zealand agriculture - key sources and mitigation strategies. Nutr. Cycl. Agroecosyst. 72, 77–85.

de Klein, C.A.M., Rollo, M., van der Weerden, T.J., 2019. Assessment of tools for estimating on-farm GHG emissions – final report. Report for the Ministry for Primary Industries, Wellington, New Zealand 29 Pages. https://www.mpi.govt.nz/dmsdocument/39092-assessment-of-tools-for-estimating-on-farm-ghg-emissions-pdf.

van Lingen, H.J., Niu, M., Kebreab, E., Valadares Filho, S.C., Rooke, J.A., Duthie, C.-A., Schwarm, A., Kreuzer, M., Hynd, P.I., Caetano, M., Eugène, M., Martin, C., McGee, M., O'Kiely, P., Hünerberg, M., McAllister, T.A., Berchielli, T.T., Messana, J.D., Peiren, N., Chaves, A.V., Charmley, E., Cole, N.A., Hales, K.E., Lee, S.-S., Berndt, A., Reynolds, C.K., Crompton, L.A., Bayat, A.-R., Yáñez-Ruiz, D.R., Yu, Z., Bannink, A., Dijkstra, J., Casper, D.P., Hristov, A.N., 2019. Prediction of enteric methane production, yield and intensity of beef cattle using an intercontinental database. Agric. Ecosyst. Environ. 283, 106575.

Macoon, B., Sollenberger, L.E., Moore, J.E., Staples, C.R., Fike, J.H., Portier, K.M., 2003. Comparison of three techniques for estimating the forage intake of lactating dairy cows on pasture. J. Anim. Sci. 81, 2357–2366.

Martin, C., Morgavi, D.P., Doreau, M., 2010. Methane mitigation in ruminants: from microbe to the farm scale. Animal 4, 351–365. https://doi.org/10.1017/S1751731109990620.

Mills, J.A.N., Dijkstra, J., Bannink, A., Cammell, S.B., Kebreab, E., France, J., 2001. A mechanistic model of whole-tract digestion and methanogenesis in the lactating dairy cow: model development, evaluation, and application. J. Anim. Sci. 79, 1584–1597.

Mills, J.A.N., Kebreab, E., Yates, C.M., Crompton, L.A., Cammell, S.B., Dhanoa, M.S., Agnew, R.E., France, J., 2003. Alternative approaches to predicting methane emissions from dairy cows. J. Anim. Sci. 81, 3141–3150.

Milne, E., Neufeldt, H., Rosenstock, T., Smalligan, M., Cerri, C.E., Malin, D., Easter, M., Bernoux, M., Ogle, S., Casarim, F., Pearson, T., Bird, D.N., Steglich, E., Ostwald, M., Denef, K., Paustian, K., 2013. Methods for the quantification of GHG emissions at the landscape level for developing countries in smallholder contexts. Environ. Res. Lett. 8, 1–9.

Ministry for Primary Industries, 2019. Methodology for calculation of New Zealand's agricultural greenhouse gas emissions. Version 5 MPI Technical Paper No: 2019/18. This publication is available on the Ministry for Primary Industries website at http://www.mpi.govt.nz/news-and-resources/publications/.

Moe, P.W., Tyrrell, H.F., 1979. Methane production in dairy cows. J. Dairy Sci. 62, 1583–1586.

Monaghan, R.M., de Klein, C.A.M., 2014. Integration of measures to mitigate reactive nitrogen losses to the environment from grazed pastoral dairy systems. The Journal of Agricultural Science, 1-12.

Murray, R.M., Bryant, A.M., Leng, R.A., 1976. Rates of production of methane in the rumen and large intestines of sheep. Br. J. Nutr. 36, 1–14.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2013. Anthropogenic and natural radiative forcing. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Nielsen, N.I., Volden, H., Åkerlind, M., Brask, M., Hellwing, A.L.F., Storlien, T., Bertilsson, J., 2013. A prediction equation for enteric methane emission from dairy cows for use in NorFor. Acta Agriculturae Scandinavica, Section A — Animal Science 63, 126–130.

Niu, M., Kebreab, E., Hristov, A.N., Oh, J., Arndt, C., Bannink, A., Bayat, A.R., Brito, A.F., Boland, T., Casper, D., Crompton, L.A., Dijkstra, J., Eugene, M.A., Garnsworthy, P.C., Haque, M.N., Hellwing, A.L.F., Huhtanen, P., Kreuzer, M., Kuhla, B., Lund, P., Madsen, J., Martin, C., McClelland, S.C., McGee, M., Moate, P.J., Muetzel, S., Munoz, C., O'Kiely, P., Peiren, N., Reynolds, C.K., Schwarm, A., Shingfield, K.J., Storlien, T.M., Weisbjerg, M.R., Yanez-Ruiz, D.R., Yu, Z., 2018. Prediction of enteric methane production, yield, and intensity in dairy cattle using an intercontinental database. Glob. Chang. Biol. 24, 3368–3389.

NRC, 2001. National Research Council. Nutrient Requirements for Dairy Cattle. National Academy Press, Washington, DC, Seventh Revised Edition.

O'Brien, D., Shalloo, L., Grainger, C., Buckley, F., Horan, B., Wallace, M., 2010. The influence of strain of Holstein-Friesian cow and feeding system on greenhouse gas emissions from pastoral dairy farms. J. Dairy Sci. 93, 3390–3402.

Olesen, J.E., Petersen, B.M., Berntsen, J., Hansen, S., Jamieson, P.D., Thomsen, A.G., 2002. Comparison of methods for simulating effects of nitrogen on green area index and dry matter growth in winter wheat. Field Crop Res. 74, 131–149.

Olesen, J.E., Schelde, K., Weiske, A., Weisbjerg, M.R., Asman, W.A.H., Djurhuus, J., 2006. Modelling greenhouse gas emissions from European conventional and organic dairy farms. (special issue: mitigation of greenhouse gas emissions from livestock production). Agriculture, Ecosystems and Environment 112, 207–220.

Palliser, C.C., Woodward, S.L., 2002. Using models to predict methane reduction in pasture-fed dairy cows. In: Rizzoli, A.E., Jakeman, A.J. (Eds.), Integrated Assessment and Decision Support, Proceedings of the 1st Biennial Meeting of the iEMSs. Lugano, Switzerland, pp. 162–167.

Pellerin, S., Bamière, L., Angers, D., Béline, F., Benoit, M., Butault, J.-P., Chenu, C., Colnenne-David, C., De Cara, S., Delame, N., Doreau, M., Dupraz, P., Faverdin, P., Garcia-Launay, F., Hassouna, M., Hénault, C., Jeuffroy, M.-H., Klumpp, K., Metay, A., Moran, D., Recous, S., Samson, E., Savini, I., Pardon, L., Chemineau, P., 2017. Identifying cost-competitive greenhouse gas mitigation potential of French agriculture. Environ. Sci. Pol. 77, 130–139.

Petersen, S.O., Olsen, A.B., Elsgaard, L., Triolo, J.M., Sommer, S.G., 2016. Estimation of methane emissions from slurry pits below pig and cattle confinements. PLoS One 11, e0160968.

Phetteplace, H.W., Johnson, D.E., Seidl, A.F., 2001. Greenhouse gas emissions from simulated beef and dairy livestock systems in the United States. Nutr. Cycl. Agroecosyst. 60, 99–102.

del Prado, A., Misselbrook, T., Chadwick, D., Hopkins, A., Dewhurst, R.J., Davison, P., Butler, A., Schröder, J., Scholefield, D., 2011. SIMSDAIRY: a modelling framework to identify sustainable dairy farms in the UK. Framework description and test for organic systems and N fertiliser optimisation. Science of the Total Environment 409, 3993–4009.

Ramin, M., Huhtanen, P., 2013. Development of equations for predicting methane emissions from ruminants. J. Dairy Sci. 96, 2476–2493.

Rinne, M., Kuoppala, K., Vanhatalo, A., Huhtamäki, T., Nousiainen, J., Huhtanen, P., 2017. Finnish feed evaluation system and Feed Tables. Proceedings of the 8th Nordic Feed Science Conference, 97–102. Uppsala, Sweden.

Salètes, S., Fiorelli, J.-L., Vuichard, N., Cambou, J., Olesen, J.E., Hacala, S., Sutton, M., Fuhrer, J., Soussana, J.-F., 2004. Greenhouse gas balance of cattle breeding farms and assessment of mitigation options. In: Weiske, A. (Ed.), Proceedings of the International Conference: Greenhouse Gas Emissions from Agriculture Mitigation Options and Strategies. Institute for Energy and Environment, Leipzig, Germany, pp. 203–208.

Sauvant, D., Nozière, P., 2016. Quantification of the main digestive processes in ruminants: the equations involved in the renewed energy and protein feed evaluation systems. Animal 10, 755–770.

Sauvant, D., Eugène, M., Giger-Reverdin, S., Archimède, H., Doreau, M., 2014. Relationship between CH_4 and urinary N outputs in ruminants fed forages: a meta-analysis of the literature. Anim. Prod. Sci. 54, 1423–1427.

Sauvant, D., Giger-Reverdin, S., Eugène, M., 2018. Enteric methane emissions. In: Sauvant, D., Delaby, L., Nozière, P. (Eds.), INRA Feeding System for Ruminants. Wageningen Academic Publishers, Wageningen, Netherlands, pp. 209–212.

Schils, R.L.M., Verhagen, A., Aarts, H.F.M., Sebek, L.B.J., 2005. A farm level approach to define successful mitigation strategies for GHG emissions from ruminant livestock systems. Nutr. Cycl. Agroecosyst. 71, 163–175.

Schils, R.L.M., Verhagen, A., Aarts, H.F.M., Kuikman, P.J., Šebek, L.B.J., 2006. Effect of improved nitrogen management on greenhouse gas emissions from intensive dairy systems in the Netherlands. Glob. Chang. Biol. 12, 382–391.

Schils, R.L.M., de Haan, M.H.A., Hemmer, J.G.A., van den Pol-van Dasselaar, A., de Boer, J.A., Evers, A.G., Holshof, G., van Middelkoop, J.C., Zom, R.L.G., 2007. DairyWise, a whole-farm dairy model. J. Dairy Sci. 90, 5334–5346.

Schils, R.L.M., Ellis, J.L., de Klein, C.A.M., Lesschen, J.P., Petersen, S.O., Sommer, S.G., 2012. Mitigation of greenhouse gases from agriculture: role of models. Acta Agriculturae Scandinavica. Section A, Animal Science 62, 212–224.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., 2007. Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture. Agric. Ecosyst. Environ. 118, 6–28.

Sommer, S.G., Petersen, S.O., Møller, H.B., 2004. Algorithms for calculating methane and nitrous oxide emissions from manure management. Nutr. Cycl. Agroecosyst. 69, 143–154.

Torrent, J., Johnson, D.E., 1994. Methane production in the large intestine of sheep. In: Aguilera, J.F. (Ed.), Energy Metabolism of Farm Animals. CSIC, Granada, Spain, pp. 391–394.

Van Soest, P.J., 1994. Nutritional Ecology of the Ruminant. Cornell University Press, Ithaca, New York.

Waghorn, G.C., 2007. What is dietary metabolisable energy? Proceedings of the New Zealand Grassland Association 69, 153–159.

Warner, D., Bannink, A., Hatew, B., van Laar, H., Dijkstra, J., 2017. Effects of grass silage quality and level of feed intake on enteric methane production in lactating dairy cows. J. Anim. Sci. 95, 3687–3699.

van der Weerden, T.J., Luo, J., de Klein, C.A.M., Hoogendoorn, C.J., Littlejohn, R.P., Rys, G.J., 2011. Disaggregating nitrous oxide emission factors for ruminant urine and dung deposited onto pastoral soils. Agric. Ecosyst. Environ. 141, 426–436.

Wheeler, D.M., Ledgard, S.F., de Klein, C.A.M., 2008. Using the OVERSEER nutrient budget model to estimate on-farm greenhouse gas emissions. Aust. J. Exp. Agric. 48, 99–103.

Wilkerson, V.A., Casper, D.P., Mertens, D.R., 1995. The prediction of methane production of Holstein cows by several equations. J. Dairy Sci. 78, 2402–2414.

Yamulki, S., Jarvis, S.C., Owen, P., 1999. Methane emission and uptake from soils as influenced by excreta deposition from grazing animals. J. Environ. Qual. 28, 676–682.