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

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27 Short title: Dairy diet characteristics and on-farm greenhouse gas emission models

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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<sub>4</sub>) emissions from enteric and manure (animal excreta) sources and nitrous oxide (N<sub>2</sub>O) 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<sub>4</sub> and/or N<sub>2</sub>O 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<sub>4</sub> and N<sub>2</sub>O emissions with reasonable 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

63    balanced against gains in accuracy, the need for additional input and activity data,  
64    and the variability encountered on-farm.

65    *Keywords:* Dairy farm system, Diet, Feeding management, Effluent, Methane,  
66    Nitrous oxide.

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## 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<sub>4</sub>) (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<sub>4</sub>) emissions from enteric fermentation and stored manure, and nitrous oxide (N<sub>2</sub>O) 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<sub>4</sub> abatement (Beauchemin *et al.*, 2008; Martin *et al.*, 2010; Caro *et al.*, 2016; Pellerin *et al.*, 2017) and N<sub>2</sub>O 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<sub>4</sub> emissions from enteric fermentation and manure (animal excreta) and N<sub>2</sub>O emissions from animal excreta as on-farm GHG sources.

## **2. Modelling GHG emissions from ruminant enterprises**

Methane and N<sub>2</sub>O are colourless and odourless GHG that are 28 and 265 times more potent (100-year horizon) than CO<sub>2</sub> at warming the earth (Myhre *et al.*, 2013).

Enteric and manure CH<sub>4</sub> emissions from ruminants, and N<sub>2</sub>O emissions from animal excreta are the main GHG from livestock agriculture. The contribution of CO<sub>2</sub> 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<sub>4</sub> and N<sub>2</sub>O), 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<sub>4</sub> emissions and N<sub>2</sub>O emissions. Estimates of enteric CH<sub>4</sub> 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<sub>2</sub>O 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<sub>4</sub> and N<sub>2</sub>O emissions) and from soil conditions (N<sub>2</sub>O 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<sub>4</sub> 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<sub>4</sub> conversion factor (MCF or Y<sub>m</sub>), which can involve a) multiplying DMI or GE intake (GEI) with a fixed conversion factor [e.g., MCF (% of GE) = 6.5 ± 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<sub>2</sub> 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<sub>4</sub> and N<sub>2</sub>O emissions from manure storage, land application of manure and direct deposition of faeces and urine by grazing animals. Both CH<sub>4</sub> and N<sub>2</sub>O emissions from manures are not only influenced by diet characteristics but also by biotic and abiotic factors such as manure storage, soil and climatic conditions. Here we focus on the influence of diet. Manure CH<sub>4</sub> 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) (Figure 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).

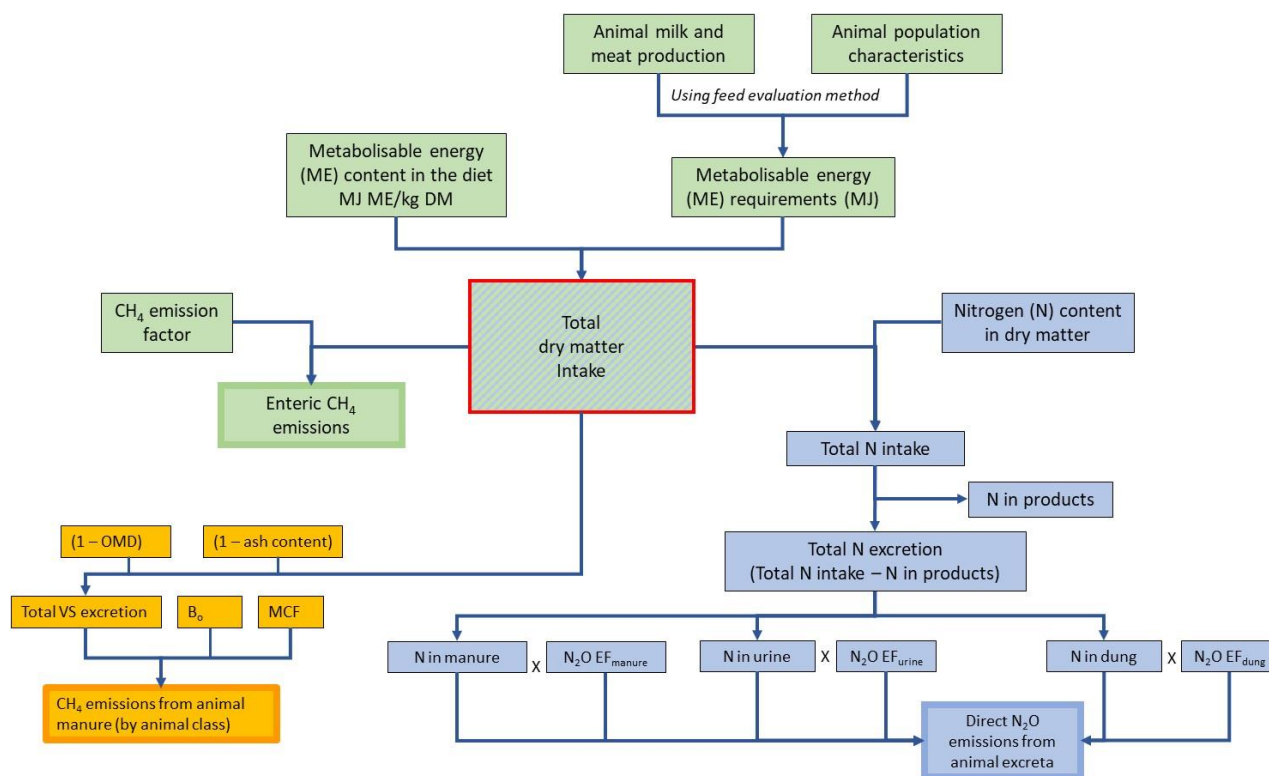
#### **4. On-farm GHG model approaches to capture dietary effects on GHG emissions from livestock systems**

In most ruminant systems, CH<sub>4</sub> is the predominant source of GHG emissions, with the diet having a major impact on enteric CH<sub>4</sub> from fermentation of feed in the rumen; the latter is the prevailing GHG source. For the two most important GHG (CH<sub>4</sub> and N<sub>2</sub>O), 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<sub>4</sub> emission factor (EF) per animal and an N<sub>2</sub>O 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 (Figure 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<sub>4</sub> emissions are then estimated using a CH<sub>4</sub> EF (g CH<sub>4</sub> kg<sup>-1</sup> 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<sub>4</sub> 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<sub>4</sub> animal<sup>-1</sup> year<sup>-1</sup>) or the amount of excreta N (e.g., kg N<sub>2</sub>O-N kg<sup>-1</sup> 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<sub>4</sub> 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.



**Figure 1.** Schematic overview of a generic Type 2 approach for estimating methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) emissions from livestock production systems (modified from de Klein *et al.*, 2019). Green boxes refer to enteric CH<sub>4</sub>, orange boxes to manure CH<sub>4</sub>, and blue boxes to N<sub>2</sub>O. ME = metabolisable energy; MJ = mega joules; OMD = organic matter digestibility; VS = volatile solids; B<sub>0</sub> = maximum CH<sub>4</sub> producing capacity of manure; MCF = CH<sub>4</sub> conversion factor; EF = emission factor. The efficiency of use of feed energy and protein modulate these fluxes.

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<sub>4</sub> emissions or for EF estimates based on feeding level, dietary proportion of 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<sub>4</sub> kg<sup>-1</sup> 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> but also for N excretion and associated N<sub>2</sub>O 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<sub>4</sub>, are described in Table 1. Similarly, the inclusion of diet characteristics in calculating manure-derived CH<sub>4</sub> and N<sub>2</sub>O 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<sub>4</sub> and N<sub>2</sub>O emission factors (EF) or a CH<sub>4</sub> conversion factor (MCF). Recently, a few hybrid Type 2 / Type 3 approaches have been developed that combine empirical modelling (through the use of CH<sub>4</sub> or N<sub>2</sub>O 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<sub>4</sub> emissions. It also leads to predictions of OM excretion (i.e., VS), manure CH<sub>4</sub> emissions, and to predictions of N excretion, in turn a major predictor of N<sub>2</sub>O 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<sub>L</sub> 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<sub>4</sub> per unit of DMI and per unit of faeces at grazing, CH<sub>4</sub> and N<sub>2</sub>O 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<sub>4</sub> is primarily produced in the rumen (87% of total enteric CH<sub>4</sub> 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.

414 **Table 1.** Feed characteristics, digestion processes of enteric methane (CH<sub>4</sub>) calculations in selected on-farm models.

Model (main source), country, and model type	Feed characteristics and processes used for enteric CH <sub>4</sub> calculations		
	Feed components and feed characteristics	Digestion kinetics	Enteric CH <sub>4</sub> calculation
Karoline (Danfær <i>et al.</i> , 2006) – Denmark / Sweden. Type 3 model.	Forage (for) pdNDF, concentrate (con) pdNDF, for iNDF, con iNDF, starch, lactic acid, NH <sub>3</sub> -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 <sub>2</sub> based on VFA stoichiometry from fermented feed, adjusted for feeding level. H <sub>2</sub> pool adjusted for microbial mass and BH. Includes CH <sub>4</sub> formation in hind gut.
FarmGHG (Olesen <i>et al.</i> , 2006) – Denmark. Type 2 model.	CF, NFE, CP, and fat daily intake (kg d <sup>-1</sup> ).		Empirical equation (Kirchgeßner <i>et al.</i> , 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 <sup>-1</sup> 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 <i>et al.</i> , 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 <sub>4</sub> d <sup>-1</sup> for European and Dutch dairy cows, respectively) and Tier 2 (MCF = 6% of dietary GEI) (IPCC, 1996).
INRA Method (Eugène <i>et al.</i> , 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 <i>et al.</i> , 2018).
GAS-EM (Haenel <i>et al.</i> , 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 <i>et al.</i> , 1994).
The GHG model (O'Brien <i>et al.</i> , 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 <i>et al.</i> , 2003; IPCC, 2006).
DairyWise (Schils <i>et al.</i> , 2007) – Netherlands. Type 2/3 model.	Different EF for con, maize silage and grass products (20, 22 and 27 g CH <sub>4</sub> kg <sup>-1</sup> DMI, respectively). Updated (Bannink <i>et al.</i> , 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 <sub>4</sub> EF × animal intake (Schils <i>et al.</i> , 2006). Updated and corrected CH <sub>4</sub> EF values (Bannink <i>et al.</i> , 2020).
Dairy Tier 3 (Dijkstra <i>et al.</i> , 1992; Bannink <i>et al.</i> , 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.	<i>In situ</i> degradation of aNDFom, starch and CP for each diet ingredient [washable fraction (W), potentially degradable (D), and	Rumen H <sub>2</sub> based on VFA stoichiometry from fermented substrate (SC, starch, HC, Ce and CP) with an adjustment for dietary

		rumen undegradable (U) fraction and fractional degradation rate (kd) of DJ].	for-to-con ratio. H <sub>2</sub> pool adjusted for microbial growth on AA or NH <sub>3</sub> -N, and for BH of uFA.
OverseerFM (Wheeler <i>et al.</i> , 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 <sub>4</sub> kg <sup>-1</sup> DMI) × animal intake (IPCC, 2006; Ministry for Primary Industries, 2019).
Whole Farm Model (WFM) (Beukes <i>et al.</i> , 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 <sub>4</sub> calculation based on H <sub>2</sub> balance from H <sub>2</sub> 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 <i>et al.</i> , 2013) – Sweden / Denmark. Type 2 model.	DMI and dietary FA and NDF.		Empirical equation (Nielsen <i>et al.</i> 2015).
SIMS <sub>DAIRY</sub> (del Prado <i>et al.</i> , 2011) – UK. Type 2 model.	DMI (g kg <sup>-1</sup> BW d <sup>-1</sup> and kg d <sup>-1</sup> ), C18:2 (quantity of linoleic acid in the diet), quantity of FA with a chain length ≥ 20 C in the diet.		Empirical equation (Giger-Reverdin <i>et al.</i> , 2003).
Farmscoper (Gooday <i>et al.</i> , 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 <sub>4</sub> 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.

427 **Table 2.** Summary of the approaches used for estimating methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) emissions from manure (including urine and faeces  
428 deposited during grazing) and feed characteristics captured in selected on-farm models.  
429

Model (source) and country	Manure CH <sub>4</sub> (including faeces from grazing)	Manure N <sub>2</sub> O (including urine and faeces from grazing)	Feed characteristics captured in the model
FASSET (Olesen <i>et al.</i> , 2002) – Denmark.	Does not include estimates of manure CH <sub>4</sub> .	Estimates manure N <sub>2</sub> O using semi-empirical equations that calculate nitrification and denitrification, and partition the end-products into N <sub>2</sub> and N <sub>2</sub> O.	Dietary N.
FarmGHG (Olesen <i>et al.</i> , 2006) – Denmark.	IPCC Tier 2: calculates annual CH <sub>4</sub> EF based on VS excretion, B <sub>0</sub> , and MCF (for three housing and four storage systems) but uses country specific values and also includes temperature and storage time functions.	Estimates N <sub>2</sub> O 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 <i>et al.</i> (2004) and applying experimentally derived parameters for stored slurry (Elsgaard <i>et al.</i> , 2016; Petersen <i>et al.</i> , 2016).	EF used for calculation of N <sub>2</sub> O from EMEP/EEA (2016) and IPCC (2006) (Grönroos <i>et al.</i> , 2017).	Total N, VSD, ash, water, P, TAN, FOM, K.
FarmSim (Salètes <i>et al.</i> , 2004; Graux <i>et al.</i> , 2011) – France.	IPCC Tier 2 for the calculation of CH <sub>4</sub> 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 <sub>2</sub> O from manure and croplands.	OMD, OM, ME and N.
INRA Method (Eugène <i>et al.</i> , 2019) – France.	Annual CH <sub>4</sub> EF per animal based on VS excretion (from indigested OM and urinary OM, and IPCC Tier 2), B <sub>0</sub> , MCF, and MS. Annual manure EF per head: VS × EC × 365.	Eugène <i>et al.</i> (2019) does not describe N <sub>2</sub> O 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 <i>et al.</i> , 2020) – Germany.	IPCC Tier 2: calculates annual CH <sub>4</sub> EF per head of animal based on VS excretion, B <sub>0</sub> , 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 <sub>2</sub> O and NH <sub>3</sub> EF disaggregated for different manure and storage types and IPCC default for indirect N <sub>2</sub> O from N leaching.	GE, ME, NEL, OMD, ash and N for key livestock categories
The GHG model (O'Brien <i>et al.</i> , 2010) – Ireland.	Type 1+ with fixed CH <sub>4</sub> EF disaggregated for storage (slurry, manure, silage effluent) or soil applied (monthly slurry, manure).	Type 1+ with fixed N <sub>2</sub> O 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 <i>et al.</i> , 2007; Bannink <i>et al.</i> , 2020) – Netherlands.	Type 1+ with a fixed CH <sub>4</sub> EF for manure storage and one for manure applied to land.	Type 1+ with a fixed N <sub>2</sub> O 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 <i>et al.</i> , 2018) – Netherlands.	IPCC Tier 2: it calculates annual CH <sub>4</sub> EF per head of animal based on VS excretion, B <sub>0</sub> , 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). <i>In situ</i> 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 <i>et al.</i> , 2008) – New Zealand.	CH <sub>4</sub> 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 <sub>2</sub> O EF from the NZ inventory.	Total DMI, OMD, ash, CP.
Whole Farm Model (WFM) (Beukes <i>et al.</i> , 2010) – New Zealand.	Does not estimate CH <sub>4</sub> from manure, but it does estimate OMD.	Does not estimate N <sub>2</sub> O from manure, but it does estimate N excretion in faeces and urine (g N d <sup>-1</sup> )	Total CP intake.
Arla Carbon tool, Arla Foods – Sweden.	Emissions of CH <sub>4</sub> from manure is calculated based on IPCC (2006).	N <sub>2</sub> O emitted from manure based on the amount of N in excreta. Animal-N balance. Total N <sub>2</sub> O from manure systems calculated as the sum of direct and indirect N <sub>2</sub> O emissions.	Total CP intake and VS, in addition to DM, CP, CF, FA, DE, NE. GE is calculated.
SIMSDAIRY (del Prado <i>et al.</i> , 2011) – UK.	CH <sub>4</sub> 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 <i>et al.</i> (1999) for applied manure and faeces from grazing.	N <sub>2</sub> O from manure storage from EMEP/CORINAIR (2005). N <sub>2</sub> O 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 <i>et al.</i> , 2011) – UK.	IPCC Tier 2: calculates annual CH <sub>4</sub> EF per head of animal based on VS excretion, B <sub>0</sub> , 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 <sub>2</sub> O 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 (Goody <i>et al.</i> , 2014) – UK.	IPCC Tier 2 (IPCC, 1996).	IPCC Tier 2 (IPCC, 1996) but with NH <sub>3</sub> and N leaching losses calculated in the model.	Total DMI, OMD, ash, CP.
AgRE Calc – UK.	IPCC Tier 2: calculates annual CH <sub>4</sub> EF per head of animal based on VS excretion, B <sub>0</sub> , MCF, and MS.	IPCC Tier 2: calculates annual N <sub>2</sub> O from manure based on livestock numbers, Nex/head, MS, and N <sub>2</sub> O EF for each MMS.	Total DMI, OMD, ash, CP.

Abbreviations: B<sub>0</sub>: maximum CH<sub>4</sub> producing capacity of manure; Faecal DM: faecal dry matter (estimated from DMI and OMD); FOM: fermentable organic matter; MCF: CH<sub>4</sub> 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<sub>4</sub>, 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.

## **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<sub>4</sub> emissions, 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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<sub>DAIRY</sub>, 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> production (Hindrichsen *et al.*, 2005; Dijkstra *et al.*, 2010). Overall, the use of fixed CH<sub>4</sub> conversion factors led to low CH<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> production (g CH<sub>4</sub> cow<sup>-1</sup> day<sup>-1</sup>), 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<sub>4</sub> database from the international collaborative initiative GLOBAL NETWORK (<https://globalresearchalliance.org/research/livestock/collaborative-activities/global-research-project/>). Along with records of enteric CH<sub>4</sub> 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<sub>4</sub> production from dairy cows, the inclusion of diet characteristics such as NDF and EE concentration improved the accuracy of prediction of enteric CH<sub>4</sub> 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<sub>4</sub> equations compared with measurements obtained from calorimetry chambers, the SF<sub>6</sub> tracer technique and automated head chambers across ruminant species. Enteric CH<sub>4</sub> emissions (g CH<sub>4</sub> d<sup>-1</sup>) 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

507 Huhtanen, 2013; Charmley *et al.*, 2016). However, the best performing equation  
508 (Ramin and Huhtanen, 2013) included GE digestibility and lipid concentration (EE),  
509 in addition to feeding level (Benaouda *et al.*, 2019). Although most equations that  
510 include digestibility use digestible OM rather than digestible GE, both variables have  
511 been well established predictors of enteric CH<sub>4</sub> emissions (Blaxter and Clapperton,  
512 1965; Sauvant and Nozière, 2016).

513 Ellis *et al.* (2010) showed that the accuracy of enteric CH<sub>4</sub> predictions using a fixed  
514 CH<sub>4</sub> energy conversion factor was low. In addition to limiting the possibility of  
515 implementing nutritional mitigation strategies (as mentioned above), the use of such  
516 fixed conversion factors can potentially introduce substantial error at the farm scale.  
517 These errors can escalate at larger scales (e.g. in GHG inventories) and may lead to  
518 unsuitable mitigation recommendations or inaccurate projections of CH<sub>4</sub> emissions  
519 over time (Bannink *et al.*, 2011).

520 The effect of dietary strategies on N<sub>2</sub>O emissions are largely driven by total N intake,  
521 or more importantly, the total N output in excreta or manure. Dietary N concentration  
522 is therefore a key parameter that needs to be captured, as is the case in most on-  
523 farm GHG models. In addition, the partitioning of N between urine and faeces affects  
524 N<sub>2</sub>O emissions, as it is well-accepted that N<sub>2</sub>O emissions from urine are greater than  
525 those from faeces (IPCC, 2019). Diet characteristics that affect N partitioning in urine  
526 and faeces include, amongst others, DMI, N intake, rumen-fermentable OM leading  
527 to the synthesis of microbial N, DM digestibility, CP concentration, and the presence  
528 of secondary metabolites such as tannins. Dry matter digestibility and CP are  
529 negatively related to N partitioning in faeces, whereas tannin concentration is  
530 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<sub>4</sub> and urinary outputs were derived for ruminants fed forages (temperate and tropical forages) as their sole diet. It was shown that CH<sub>4</sub> 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<sub>4</sub> emissions from forage-fed ruminants. In agreement with these findings, Warner *et al.* (2017) reported that enteric CH<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> appeared to be partly offset by a higher production of CH<sub>4</sub> from manure.

The use of dynamic mechanistic modelling in the simulation of enteric CH<sub>4</sub> emissions and N<sub>2</sub>O 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub>, and N<sub>2</sub>O 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<sub>4</sub> 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<sub>4</sub> 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 (Macon *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



604 varying degrees. In reality, it is highly unlikely that one feed constituent (e.g., NDF  
605 concentration) will vary while others remain unchanged, due to the inherent  
606 association between diet constituents in diet formulation, but any goal-directed  
607 change is easier to achieve in confinement-type diets or through supplemental  
608 feeding than in grazing situations. The latter also offer dynamic changes (seasonal,  
609 daily, hourly) in herbage quantity, composition, nutritive value, and animal  
610 preference, which add complexity to DMI predictions from pasture-based systems.

611 Recently, Niu *et al.* (2018) highlighted the potential effects of increased intake and  
612 associated effects such as increased passage rate and reduced time for ruminal  
613 digesta retention, which in turn can reduce OM digestibility and CH<sub>4</sub> production per  
614 unit of feed (i.e., a reduction in g CH<sub>4</sub> kg<sup>-1</sup> DMI) (Van Soest, 1994). Feed intake is a  
615 consequence of feed on offer, animal production demand and digestibility of  
616 nutrients. In contrast with Type 3 models where the effect is captured, Type 2  
617 models do not account for the effect of changes in feeding level, often expressed as  
618 multipliers of maintenance energy levels (e.g., NRC, 2001).

619 Another challenge for on-farm GHG models to capture dietary strategies is the  
620 accuracy and availability of input data to run the models. Availability of data and  
621 transparency in the description and adoption of methodological procedures are  
622 essential to make informed decisions on GHG abatement strategies, and even more  
623 so when these tools are to inform policy (Hall *et al.*, 2010). The more detailed the  
624 model in terms of inclusion of dietary characteristics, the higher the level of detail  
625 that is required for the input and activity data. This not only includes detail on diet  
626 composition (e.g., proportions of different feed types), but also on diet characteristics  
627 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<sub>4</sub> emissions (Ellis *et al.*, 2007). However, the impact of mitigation strategies to reduce CH<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub>) 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<sub>2</sub> 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<sub>4</sub> 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<sub>4</sub> EF (g CH<sub>4</sub> kg<sup>-1</sup> DMI) and a N<sub>2</sub>O EF (N<sub>2</sub>O-N emitted as % of N excreted) to estimate GHG emissions. Some models include different CH<sub>4</sub> EF for different diets or dietary ingredients (e.g., DairyWise, with EF values derived from a Type 3 approach) rather than CH<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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 among 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).

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