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# Applying a mechanistic fermentation and digestion model for dairy cows with emission and nutrient cycling inventory and accounting methodology

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*In mitigating greenhouse gas (**GHG**) emissions and reducing the carbon footprint of dairy milk, the use of generic estimates in inventory and accounting methodology at farm level largely ignores variation of on-farm GHG emissions. The present study aimed to implement results of an extant dynamic, mechanistic Tier 3 model for enteric methane (**$CH_4$**) (applied in Dutch national GHG inventory) in order to capture variation in enteric $CH_4$ emission, and in faecal N and organic matter (**OM**) digestibility, ultimately required to predict manure $CH_4$ and ammonia emission. Tier 3 model predictions were translated into calculation rules that could easily be implemented in an annual nutrient cycling assessment tool including GHG emissions, which is currently used by Dutch dairy farmers. Calculations focussed on (1) enteric $CH_4$ emission, (2) apparent faecal OM digestibility and (3) apparent faecal N digestibility. Enteric $CH_4$ was expressed in $CH_4$ yield indicated with the term emission factor (**EF**; g $CH_4$/kg DM) for individual dietary components and feedstuffs. Factors investigated to cover predicted variation in EF value included the level of feed intake, the type of roughage fed (proportions of grass silage and maize silage) and the quality of roughage fed. A minimum number of three classes of roughage type (i.e. 0. 40% and 80% maize silage in roughage DM) appeared necessary to obtain correspondence between interpolated EF values from EF lists and Tier 3 model predictions. A linear decline in EF value with 1% per kg increase in DM intake is adopted based on model simulations. The quality of roughage was represented by the effect of maturity of harvested grass or of the whole plant maize at cutting, based on a survey of modelling as well as experimental work. Also, predictions were assembled for apparent faecal OM digestibility which could be used in national inventory and in farm accounting. Apparent faecal N digestibility (as a major determinant of predicted urinary N excretion) was predicted, to support current Dutch national ammonia emission inventory and to correct the level of N digestibility in farm accounting. Compared to generic values or values retrieved from the Dutch feeding tables, predicted OM and N digestibility and enteric $CH_4$ are better rooted in physiological principles and better reflect observed variation under experimental conditions. The present results apply for conditions with fairly intensive grassland management in temperate regions.*

**Keywords:** enteric methane, nitrogen, digestibility, Tier 3, farm accounting

## Implications

A dairy farm-specific management aiming to reduce the emissions of methane and ammonia requires accurate accounting of emissions. For this reason, a currently applied farm accounting tool used by dairy farmers and by feed and dairy industry was improved to address variation in emissions. This was achieved by translating and implementing results obtained with an extant dynamic, mechanistic model into estimates that fit in the format of this particular farm accounting tool. The approach in principal allows as well the handling of different farming conditions and dietary aspects than studied here. Results also give indications for further improvement of inventory of cow excreta production and related emissions.

## Introduction

Enteric methane (**$CH_4$**) is the largest contributor to greenhouse gas (**GHG**) emissions on dairy farms, followed by $N_2O$ emissions from excreted N and $CH_4$ emission from stored manure (Hristov *et al.*, 2013). Generic $CH_4$ estimates are generally used for these emissions, with a fixed proportion of dietary gross energy intake being emitted as enteric $CH_4$, a

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fixed N digestibility used to estimate excreted N with faeces and urine, and a fixed organic matter (**OM**) digestibility leading to volatile solids (**VSs**), respectively. However, fixed factors to calculate these emissions ignore variation in enteric fermentation, N excretion and manure composition caused by nutritional factors. Moreover, the trade-off of enteric $CH_4$ mitigating measures towards excreted N and related ammonia emissions, and excreted VS needs to be taken into account (Moraes *et al.*, 2012). This means that factors used to estimate these emissions may be inter-dependent rather than fixed. To ensure farm accounting tools are specific and conclusive with respect to the consequences of nutritional measures or changes in farm management, the concept of using generic estimates (i.e. the use of average, fixed values) needs to be abandoned (e.g. Eugène *et al.*, 2019).

Although there is still debate about the precise contribution of livestock to methane emissions of anthropogenic origin (Hristov *et al.*, 2018), its contribution is large and estimated to be about half of the total global GHG emission from agriculture (Gerber *et al.*, 2013). Methane originates from the conversion of OM by anaerobic microbial activity, resulting in the formation of hydrogen that is utilised by methanogens to produce $CH_4$. This process takes places in the enteric environment of the rumen of ruminants and in the large intestine of ruminants and monogastric animals, as well as in stored manure. Although similar principles hold for enteric methanogenesis and methanogenesis in stored manure, substrate and fermentation conditions may differ substantially dependent on diet and animal type and storing conditions. As a result, emission factors (**EFs**) may vary widely and for quantification both sources of $CH_4$ emission need to be treated as being case-specific and inter-dependent. The IPCC (2006) developed guidelines to quantify both sources of $CH_4$ in national inventory of GHG emissions, described by Tier 2 methodology. For enteric $CH_4$, 6.5% of the gross energy ingested with feed is assumed to be emitted as $CH_4$ energy. For stored manure, default EFs for $CH_4$ emission from VS are given, with VS defined as the mass of OM excreted with faeces (undigested feed, microbial biomass and endogenous secretions) and urine (IPCC, 2006). The use of such generic and fixed EFs may suit the purpose of national inventories. It unlikely suits the purpose of accounting for variability and interactions between different on-farm GHG sources (Eugène *et al.*, 2019). It is prerequisite that GHG accounting tools for dairy farming or representation of GHG EFs in Life Cycle Assessment studies have the capacity to capture this variability (Cederberg *et al.*, 2013). Using generic estimates of GHG emission applied in national inventories does not comply with assessment of the variability among farms and with integral assessment of impacts of management and mitigation measures.

The aim of the present study was to derive EFs and calculation rules for dairy cattle for a farm accounting tool, to capture variation in enteric $CH_4$ emission and to capture variation in N and OM digestibility that may ultimately lead to variation in $CH_4$ and ammonia-N emissions. Simulations were performed with an extant Tier 3 model of fermentation and digestion in dairy cattle (Bannink *et al.*, 2018) to derive enteric $CH_4$ yield from feed DM, that is, the EF for enteric $CH_4$ (g $CH_4$/kg DM), and equations to correct for specific dietary conditions. Dietary factors addressed were the rate of DM intake, dietary chemical composition and rumen degradation characteristics, the type of roughage fed and the feeding quality of roughage. Preliminary results were already published in an abstract form (Bannink *et al.*, 2019).

## Material and methods

An extant model was used to calculate the variation in EF of enteric $CH_4$ in dairy cows under varying nutritional conditions, and in apparent faecal OM digestibility (as main determinant of VS excreted) and the apparent faecal N digestibility (determining digested N and main determinant of N excreted in urine, often referred with the term ammoniacal N). The model is currently applied as a Tier 3 approach in the Dutch GHG inventory (Bannink *et al.*, 2011; Vonk *et al.*, 2016). The model is a dynamic, mechanistic representation of rumen fermentation developed by Dijkstra *et al.* (1992), adapted by Mills *et al.* (2001) on post-ruminal digestion of nutrients and fermentation in the hindgut, and subsequently adapted by Bannink *et al.* (2008) on the representation of the stoichiometry of production of volatile fatty acids from fermented substrate (soluble carbohydrates, starch, hemi-cellulose, cellulose and CP). Recently, the model was adapted to improve its prediction of apparent faecal N digestibility, albeit without any consequence for predicted enteric $CH_4$ (Bannink *et al.*, 2018).

The model is a dynamic model including nonlinear relationships and dependency of rates of conversion on predicted concentrations of substrates, metabolites and microbial material in the rumen volume. By this representation, the concept of additivity of rumen degradability and the contribution of individual dietary components to microbial protein and absorbed nutrients are abandoned (Dijkstra *et al.*, 1992). This also holds for the contribution of individual dietary components to the EF of whole diet DM. As a result, the predicted EF value and faecal digestibility of a dietary component are diet-specific and depend on feed DM intake and diet characteristics. In this respect, the Tier 3 model differs from most other mechanistic models (as reviewed by Tedeschi *et al.*, 2014) as despite their mechanistic nature these adopt the concept of additivity, and they hence are to be considered static models instead of dynamic (Bannink *et al.*, 2016).

### *Calculating variation in enteric methane*

*Diet types.* The proportion of grass and maize silage in the diet is the main variant in Dutch diets for dairy cows and together they cover the roughage part of the diet almost entirely. Therefore, based on the annual cow performance in 2014, a series of five basal diets were formulated with an incremental proportion of maize silage in roughage DM from 0% to 20%, 40%, 60% and 80% maize silage in roughage DM. These diets showed a continuous increase in estimated DM intake from 16.8 to 18.7 kg/day and in fat- and

**Table 1** *Description of five basal diets for dairy cattle in 2014 in The Netherlands based on the cow model of Zom* et al. *(2012), differing in proportion of maize silage in roughage DM, DM intake and fat- and protein-corrected milk yield*

| | 0% maize silage | 20% maize silage | 40% maize silage | 60% maize silage | 80% maize silage |
|---|---|---|---|---|---|
| FPCM (kg/cow per day) | 22.3 | 23.0 | 23.3 | 23.6 | 23.9 |
| DM intake (kg DM/cow per day) | 16.8 | 17.5 | 17.8 | 18.3 | 18.6 |
| Diet composition (% DM) | | | | | |
| Rumen-resistant soybean meal | 0.0 | 2.1 | 4.6 | 5.5 | 6.5 |
| Low-CP concentrate meal NL | 26.7 | 24.6 | 22.0 | 20.8 | 19.9 |
| Total concentrate | 26.7 | 26.7 | 26.6 | 26.4 | 26.4 |
| Maize silage (BLGG, 2014) | 0.0 | 15.0 | 29.7 | 44.7 | 58.5 |
| Grass silage autumn (BLGG, 2014) | 22.6 | 17.9 | 12.4 | 7.0 | 1.8 |
| Grass silage spring (BLGG, 2014) | 27.1 | 21.7 | 15.0 | 8.4 | 2.1 |
| Grass silage summer (BLGG, 2014) | 22.6 | 17.9 | 12.4 | 7.0 | 1.8 |
| Urea | 0.0 | 0.0 | 0.0 | 0.4 | 0.6 |
| Wheat straw | 1.0 | 0.9 | 4.0 | 6.3 | 8.9 |
| Chemical composition (g/kg DM), unless indicated otherwise | | | | | |
| VEM (VEM unit) | 931 | 948 | 952 | 953 | 954 |
| DVE+ | 75 | 80 | 85 | 85 | 85 |
| OEB+ | 35 | 22 | 8 | 4 | −3 |
| CP | 176 | 167 | 156 | 152 | 143 |
| DOM | 695 | 707 | 709 | 709 | 708 |
| FOMp+ | 553 | 549 | 535 | 523 | 511 |
| Crude fibre | 223 | 229 | 240 | 249 | 259 |
| Crude ash | 101 | 89 | 77 | 64 | 53 |
| DCOM (%) | 80 | 80 | 80 | 79 | 78 |
| Sugars | 83 | 73 | 61 | 49 | 37 |
| Starch | 26 | 82 | 137 | 194 | 247 |
| Satiety value (SV unit)[1] | 0.84 | 0.81 | 0.80 | 0.78 | 0.77 |
| NDF | 451 | 427 | 409 | 391 | 376 |
| ADF | 255 | 241 | 233 | 224 | 217 |
| ADL | 24 | 23 | 23 | 23 | 24 |
| Crude fat | 40 | 39 | 37 | 35 | 34 |

FPCM = fat- and protein-corrected milk; NL = Netherlands; VEM = net energy of lactation (1 VEM = 6.9 kJ; Van Es, 1978); DVE+ = intestinal digested protein; OEB+ = rumen protein balance; FOMp+ = rumen fermentable organic matter '(updated DVE/OEB-system; Van Duinkerken *et al.*, 2011); DOM = digestible organic matter, according to feed analysis and feeding tables; DCOM = digestibility coefficient organic matter, according to feed analysis and feeding tables.
[1]Satiety value (Zom *et al.*, 2012).

protein-corrected milk yield from 22.3 to 23.9 kg/day. Diets always contained between 73% to 74% of roughage DM and 26% to 27% of concentrate DM and were formulated with the cow model of Zom *et al.* (2012). Further details on dietary composition and feeding values are indicated in Table 1. For a detailed description of the Tier 3 model inputs and assumptions made on rumen *in situ* degradation characteristics, the reader is referred to Bannink *et al.* (2011).

*Feedstuff emission factor value.* For every feedstuff in the Dutch feeding tables (CVB, 2011), an EF value was derived by exchanging 5% (see further explanation for this choice below) of the average annual diet DM for DM of the feedstuff the EF value had to be derived for. The change in simulated enteric $CH_4$ emission was assumed to be caused entirely by the exchanged DM, from which the EF value could be calculated. It was assumed that $CH_4$ from the remaining 95% DM of the basal diet remained the same (as well as DM intake), and hence the EF value could be derived in a comparable manner to that of taking the derivative of a function (see Figure 1 for a schematic explanation).

In addition to a 5% exchange of dietary DM, also simulations were performed with a 10% exchange of dietary DM, but calculated EF values remained rather similar to those obtained with 5% exchange (meaning 5% and 10% exchange delivered similar 'derivative' values; Figure 1). The small differences in estimated EF value with 5% and 10% exchange of DM indicated that simulated changes in enteric $CH_4$ with a 5% exchange of DM were not too small to obtain accurate EF estimates or to obtain specific EF values for the type of basal diet DM was exchanged with. Because a smaller percentage of exchange must be expected to deliver the more accurate 'derivate' estimates, EF values obtained with 5% exchange were considered most accurate and used in the present study.

*Effect of diet/roughage type on emission factor.* It was investigated whether deriving a separate list of EF values for feedstuffs listed in the Dutch feeding tables (CVB, 2011) for the two basal diets differing most in roughage type (0% *v.* 80% maize silage in roughage DM) was sufficient to reproduce enteric $CH_4$ emissions as simulated with the Tier 3 model. To examine this, the EF values of diets with an intermediate

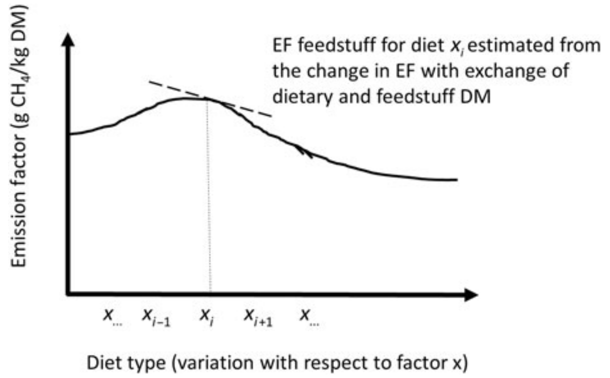


**Figure 1** A schematic representation of the method used to retrieve the dairy cattle emission factor (EF) value for a feedstuff or dietary component (DM basis) by exchanging its DM with dietary DM, from simulations with the Tier 3 model for a specific diet $x_i$ in a range of diets which vary with respect to factor *x*. The method compares to taking the derivative of the EF function at location $x_i$. Factor *x* may involve the proportion of maize silage in roughage DM (as used in the present study) but also may refer to other factors such as dietary CP content, NDF content or diet digestibility.

proportion of maize silage in roughage (20%, 40% and 60% of DM) were derived by interpolation of EF from the list derived for the 0% and 80% maize silage diets. If interpolation did not reproduce outcomes with the original Tier 3 model within 1% difference, an extra EF list was created for the basal diet with an intermediate proportion of maize silage in roughage. By this approach, it was ensured that interpolation of EF values from the available lists matched with Tier 3 model simulation results.

*Dry matter intake.* Next to type of feedstuff and diet, also the level of DM intake affects predicted enteric $CH_4$ yield, causing a decrease in EF value with increase of DM intake. The effect of DMI on whole diet EF value was investigated with Tier 3 model simulations by simulating the effect of varying DM intake from 14 to 24 kg/day for the two most differing basal diets (0% and 80% maize silage in roughage DM). From these simulation results, a general correction factor was derived for the whole diet EF value.

*Roughage quality.* The effect of characteristics of grass silage and maize silage (indicated as roughage quality) on enteric $CH_4$ was estimated based on survey of recent information gathered by modelling as well as experimentation. *In vivo* observations were used from trials in climate-controlled respiration chambers, which were specifically designed to determine the variation in EF value due to roughage quality (Warner *et al*., 2015, 2016 and 2017; Hatew *et al*., 2016). The observed variation in EF values for the grass silages was related to several of the feed characteristics listed in Table 1, as indicated in the overview in Table 2. Furthermore, observations of the *in situ* rumen degradation characteristics of these roughages (Heeren *et al*., 2016) were used to predict EF values for grass silage and grass herbage with the Tier 3 model as realistic as possible (Bannink *et al*., 2016). Also previous modelling work (with different assumptions; Bannink *et al*., 2010) was used and compared to outcomes of the more recent experimental and modelling work.

**Table 2** *Relationship between observed grass silage composition and feeding values and observed emission factor (EF) value in lactating dairy cows for 10 dietary treatments (14 observations) including 70% (Warner* et al.*, 2017) or 80% (Warner* et al.*, 2016) grass silage in dietary DM, assuming the change in EF was caused entirely by grass silage*

| Change in grass silage characteristic | g $CH_4$/kg DM Total diet | g $CH_4$/kg DM Corrected to grass silage DM | $R^2$ |
|---|---|---|---|
| +100 g NDF/kg DM | 2.2 | 3.0 | 0.72 |
| +100 g Sugar/kg DM | 1.4 | 1.9 | 0.12 |
| +100 g CP/kg DM | −2.1 | −2.8 | 0.68 |
| +100 g OEB+/kg DM | −2.5 | −3.4 | 0.68 |
| +100 g DVE+/kg DM | −7.9 | −10.7 | 0.39 |
| +100 VEM/kg DM | −1.8 | −2.4 | 0.56 |
| +10 g Crude fat/kg DM | −1.8 | −2.4 | 0.63 |
| +10% DCOM | −1.1 | −1.5 | 0.07 |

DVE+ = intestinal digested protein; OEB+ = rumen protein balance (updated DVE/OEB-system; Van Duinkerken *et al*., 2011); VEM = net energy of lactation (1 VEM = 6.9 kJ; Van Es, 1978); DCOM = digestibility coefficient of organic matter.

### *Calculating variation in apparent faecal nitrogen and organic matter digestibility*

Bannink *et al*. (2018) described how the current Tier 3 model was adapted to accommodate it more for use in ammonia inventory. A new representation was introduced for the effect of endogenous N secretion and for degradability of endogenous and microbial N in the large intestine. In particular for Dutch feeding trials, prediction accuracy improved substantially compared to the previous inventory methodology that was based on values available from feed analysis in practice and feeding tables (CVB, 2011). The Tier 3 model was used to predict variation in apparent faecal N digestion, which is pivotal for calculation of the amount of digested N and of urine excreted N (Van Bruggen *et al*., 2019), and ultimately for emission of ammonia N.

In Dutch GHG emission inventory, $CH_4$ emission from manure is calculated according to an adapted version of the IPCC Tier 2 approach (IPCC, 2006). Default values are used for the gross energy content of dietary DM and energy digestibility to calculate VS according to the IPCC Tier 2. These energy-based calculations were replaced by calculations of the amount of OM excreted with faeces and urine (Zom and Groenestein, 2015). In the present study, the Tier 3 model was used to investigate variation in predictions of apparent faecal OM digestibility as the main driver of excreted OM (VS) next to OM intake, and hence of $CH_4$ emitted from manure (Van Bruggen *et al*., 2019).

## Results

### *Variation in enteric methane*

Using the process-based Tier 3 model, in first instance, EF values were derived for every feedstuff in the Dutch feeding

**Table 3** *List of emission factor (EF) values for typical roughages (on top) and concentrate feedstuffs in alphabetical order (A to L) from the Dutch feeding tables for dairy cattle (CVB, 2011), separately for the basal diet including 0%, 40% and 80% maize silage in dietary roughage DM (to be continued for feedstuffs M to Z in Table 3)*

| | g $CH_4$/kg feedstuff DM | | |
|---|---|---|---|
| Roughage/feedstuff | 0% maize silage | 40% maize silage | 80% maize silage |
| Grass silage | 19.5[1] | 19.5[1] | 21.0[1] |
| Maize silage | 18.4[1] | 17.5 [1] | 16.2[1] |
| Straws | | *17*[2] | |
| Lucerne | | *20*[2] | |
| Barley | 22.8 | 22.1 | 20.7 |
| Barley feed. high grade | 19.7 | 19.2 | 18.7 |
| Barley mill by-product | 19.1 | 18.6 | 18.1 |
| Beet pulp SU < 100 | 25.2 | 25.6 | 28.5 |
| Beet pulp SU 100 to 150 | 25.6 | 25.8 | 28.5 |
| Beet pulp SU > 200 | 26.3 | 25.9 | 28.1 |
| Beans (phaseolus) heat treated | 21.3 | 20.9 | 21.4 |
| Bread meal | 23.0 | 23.5 | 23.2 |
| Brewer's grains dried | 16.7 | 16.4 | 16.3 |
| Brewer's yeast dried | 19.7 | 18.6 | 18.6 |
| Casein | 18.3 | 16.7 | 16.8 |
| Chicory pulp dried | 25.0 | 25.2 | 27.9 |
| Citrus pulp | 27.0 | 26.4 | 28.0 |
| Carob | 27.2 | 26.1 | 26.4 |
| Cottonseed expeller, partly w. husk | 15.9 | 15.9 | 17.4 |
| Cottonseed expeller | 15.8 | 16.0 | 17.6 |
| Cottonseed expeller, without husk | 13.9 | 14.0 | 15.4 |
| Cottonseed extracted, partly w.husk | 17.5 | 17.7 | 19.9 |
| Cottonseed extracted, with husk | 18.0 | 18.2 | 20.3 |
| Cottonseed extracted, without husk | 17.4 | 17.4 | 19.5 |
| Cottonseed, with husk | 17.8 | 16.8 | 16.9 |
| Cottonseed, without husk | 10.4 | 10.1 | 11.3 |
| Coconut extracted | 20.8 | 21.2 | 23.2 |
| Coconut expeller CFa < 100 | 18.7 | 19.1 | 20.9 |
| Coconut expeller CFa > 100 | 17.0 | 17.5 | 19.4 |
| Grass meal CP < 160 | 20.4 | 20.2 | 21.0 |
| Grass meal CP 160 to 200 | 20.2 | 19.9 | 20.6 |
| Grass meal CP > 200 | 19.6 | 19.4 | 20.1 |
| Grass seeds | 22.3 | 21.5 | 19.9 |
| Hempseed | 9.9 | 10.0 | 11.3 |
| Lentils | 22.3 | 20.9 | 19.8 |
| Linseed | 8.6 | 9.0 | 10.7 |
| Linseed expeller | 18.4 | 18.6 | 21.0 |
| Linseed extracted | 20.6 | 20.7 | 23.2 |
| Lucerne meal CP < 140 | 20.9 | 21.1 | 22.5 |
| Lucerne meal CP > 180 | 19.7 | 19.8 | 21.2 |
| Lucerne meal CP 140 to 160 | 19.8 | 20.1 | 21.5 |
| Lupins CFa < 70 CP < 335 | 21.9 | 21.5 | 23.2 |
| Lupins CFa < 70 CP > 335 | 20.8 | 20.5 | 22.2 |

CFa = crude fat; SU = sugars; w. husk = without husk.
[1]The EF values indicated are for the average grass silage and maize silage harvested in the Netherlands. The Tier 3 model does allow to prediction variation in EF with quality of grass silage (see Bannink *et al*., 2010) and of maize silage. The reader is referred to the paragraph *Roughage Quality* in 'Material & Methods' section how variation in EF value for grass silage and maize silage was accounted for.
[2]Fixed values are currently adopted for straw and Lucerne across diet types.

tables for the basal diets containing 0% and 80% of maize silage in roughage DM (Tables 3 and 4). Substantial differences in EF values were obtained for feedstuffs, with generally low EF values for feedstuffs with a high content of starch, CP or fat, whereas EF values were higher for feedstuffs with a high content of sugars and NDF. Across basal diets, the calculated EF value was on average 19.7 g $CH_4$/kg DM with a SD of 3.90, indicative of the substantial variation between feedstuffs in their calculated contribution to enteric $CH_4$. Besides chemical composition, also the rumen degradation characteristics had an impact on

**Table 4** *List of emission factor (EF) values for concentrate feedstuffs in alphabetical order (M to Z) from the Dutch feeding tables for dairy cattle (CVB, 2011), separately for the basal diet including 0%, 40% and 80% maize silage in dietary roughage DM (continuation of Table 2 with values for feedstuffs A to L)*

| | g $CH_4$/kg feedstuff DM | | |
|---|---|---|---|
| Feedstuff | 0% maize silage | 40% maize silage | 80% maize silage |
| Maize chemical/heat treated | 22.6 | 22.9 | 21.2 |
| Maize gluten meal | 16.6 | 15.2 | 13.3 |
| Maize gluten feed CP < 200 | 20.6 | 20.0 | 19.5 |
| Maize gluten feed CP 200 to 230 | 20.3 | 19.8 | 19.4 |
| Maize gluten feed CP > 230 | 20.1 | 19.5 | 19.2 |
| Maize germ meal expeller | 19.0 | 18.9 | 19.7 |
| Maize germ meal, solv. extr. 3[33]extractedextracted | 21.1 | 21.5 | 23.7 |
| Maize germ meal feed expeller | 20.2 | 19.8 | 20.1 |
| Maize germ meal feed, solv. extr. | 21.2 | 21.5 | 23.5 |
| Maize solubles dehydrated | 19.4 | 20.1 | 22.9 |
| Maize feed flour | 23.1 | 21.5 | 19.3 |
| Maize feed meal | 20.7 | 19.6 | 18.1 |
| Maize feed meal, solv. extr. | 22.4 | 21.4 | 20.5 |
| Maize bran | 22.1 | 21.4 | 20.5 |
| Maize starch | 23.9 | 22.0 | 22.7 |
| Molasses cane SU < 475 | 29.6 | 22.0 | 22.7 |
| Molasses cane SU > 475 | 30.0 | 22.1 | 19.6 |
| Oats grain | 19.7 | 19.8 | 19.8 |
| Oats grain, peeled | 21.1 | 20.8 | 20.4 |
| Oats husk meal | 17.3 | 17.8 | 18.1 |
| Oats mill feed, high grade | 18.9 | 19.2 | 19.4 |
| Palm pit expeller CFi < 220 | 17.0 | 17.4 | 18.5 |
| Palm pit expeller CFi > 220 | 16.7 | 17.4 | 18.6 |
| Peanuts | 3.6 | 4.0 | 5.6 |
| Peanut hulls partly with shell | 17.6 | 17.7 | 20.0 |
| Peanut hulls with shell | 14.1 | 14.7 | 17.2 |
| Peanut hulls without shell | 18.0 | 18.0 | 20.1 |
| Peanut meal partly with shell | 17.8 | 18.0 | 20.3 |
| Peanut meal without shell | 21.0 | 20.9 | 23.3 |
| Peanut with shell | 8.4 | 9.1 | 11.5 |
| Peas | 22.8 | 22.0 | 22.1 |
| Potato pulp CP < 95 | 22.0 | 21.6 | 20.8 |
| Potato pulp CP 95 to 140 | 21.3 | 20.9 | 20.1 |
| Potato starch dehydrated | 24.0 | 22.3 | 20.2 |
| Potato crisps | 12.1 | 12.3 | 11.4 |
| Potato protein CA < 10 | 16.5 | 14.8 | 14.0 |
| Potato protein CA > 10 | 16.3 | 14.7 | 14.0 |
| Potato dehydrated | 22.7 | 21.5 | 20.5 |
| Potato sweet, dehydrated | 24.6 | 23.6 | 22.1 |
| Rapeseed meal CFi < 380 | 18.7 | 19.3 | 22.8 |
| Soybean hulls CFi > 360 | 23.8 | 23.4 | 24.0 |
| Soybean meal CFi 50 to 70 CP > 440 | 21.2 | 20.6 | 22.5 |
| Soybean meal MervoBest | 20.6 | 19.4 | 19.0 |
| Sunflower meal CFi < 160 | 19.2 | 19.5 | 22.4 |
| Wheat | 23.4 | 23.0 | 22.5 |
| Wheat middlings | 20.4 | 20.6 | 22.0 |

CFi = crude fibre; CA = crude ash; SU = sugars; Solv. extr. = solvent extracted.

calculated EF value. For example, starch-rich feedstuffs such as wheat and barley received relatively high EF values between 20.7 and 23.4 g $CH_4$/kg DM which is more than the values obtained for the average feedstuff. Although maize had a comparable starch content to wheat and barley, its EF value was lower (17.8 to 21.2 g/kg DM) due to lower rumen starch degradability and a higher proportion of starch predicted to bypass rumen fermentation. Depending on the type of feedstuff, there were also significant differences in calculated EF values within feedstuff for the two basal diets of 0% and 80% maize silage in roughage DM. The EF values in the list for 80% maize silage basal diet differed from that for 0% maize silage basal diet by $0.2 \pm 2.37$ g $CH_4$/kg DM (Tables 3 and 4), indicating that the difference depended on the type of feedstuff and its chemical composition and rumen degradation characteristics.

Interpolated EF values for 20%, 40% and 60% maize silage basal diets from the EF lists of basal diets 0% and 80% maize silage differed from Tier 3 predicted EF values by +1.8% (Figure 2a). An additional EF list was derived for the intermediate 40% maize silage basal diet to correct this inaccuracy. Interpolation from the three EF lists for basal diets 0%, 40% and 80% maize silage to obtain EF values for the 20% and 60% maize silage basal diet reproduced the Tier 3 predicted EF values well (Figure 2b) with interpolated values differing by −0.5% only.

*Effect of dry matter intake.* Tier 3 simulations indicated a nonlinear decline in EF value with increase in feed intake from 14 to 24 kg DM/day for the 0% as well as the 80% maize silage basal diet (Figure 3). Assuming a linear response, the decline was estimated to be −0.20 and −0.22 g $CH_4$/kg DM per kg increase in daily DM intake with the 0% and the 80% maize silage basal diet, respectively (Figure 3). This means, on average, a 1.1% decline in EF value per kg increase in DM intake.

*Effect of roughage quality.* The first modelling effort with the Tier 3 model to investigate the effect of grass quality by Bannink *et al.* (2010) indicated that number of days of regrowth, or sward weight, has a strong effect on EF value of grass silage in cows. For the diet including 60% grass silage at the highest DM intake of 23 kg/day, the EF value was 4 g/kg DM lower for grass silage obtained with high N fertilisation and early cutting compared with low N fertilisation and late cutting. The recent *in vivo* observations in trials with lactating cows matched this modelled range in EF value. Trials were conducted with diets containing 70% or 80% grass silage in dietary DM (Warner *et al.*, 2016 and 2017). The observations indicated an increase with 0.1 g/kg DM per extra day of grass regrowth (after cutting) (results not shown). From a basal value at the youngest growth stage of 18.7 g/kg DM, a period of 30 and 60 days of regrowth made EF increase to 21.7 and 24.7 g/kg DM, but this was considered to be a wider range than what is common in Dutch farming practice. Subsequent Tier 3 model predictions were performed with the observed *in situ* rumen widerthantextarea

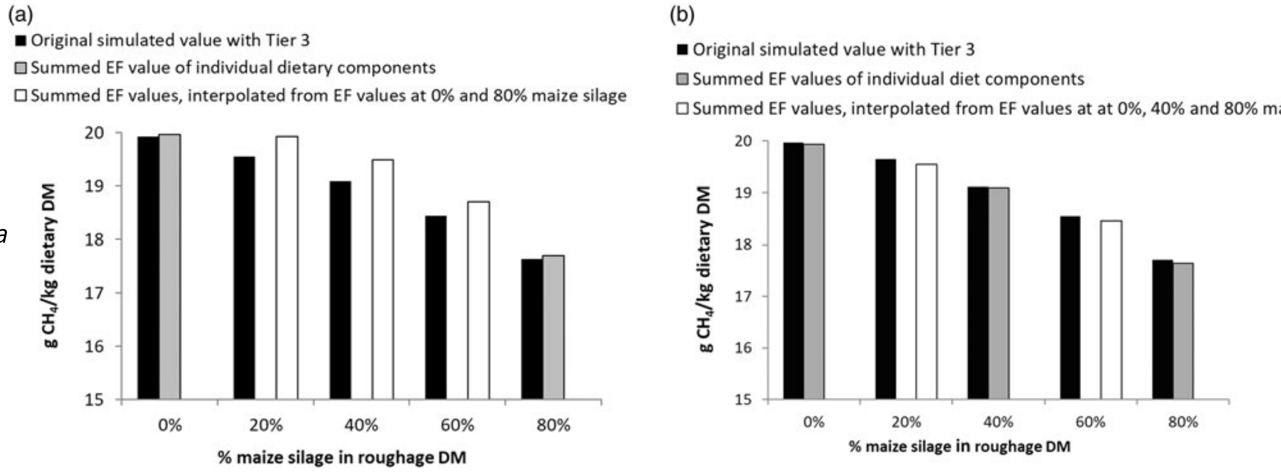


**Figure 2** A comparison of dairy cattle enteric methane emission factor (EF) values simulated with the Tier 3 model, of EF values obtained through interpolation of EF values from (a) the EF lists of the basal diets containing 0% and 80% maize silage in roughage DM and of EF values obtained through interpolation of EF values from (b) the EF lists of the basal diets containing 0%, 40% and 80%

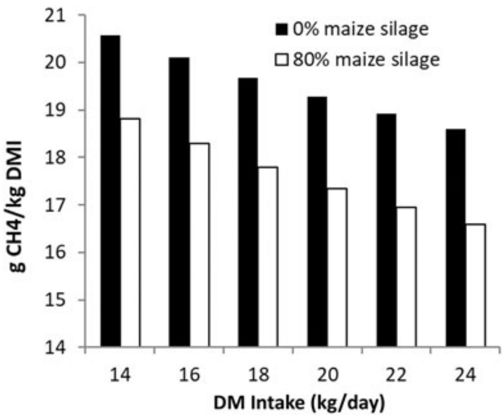


**Figure 3** Effect of DM intake on simulated dairy cattle enteric methane emission factor (EF) values for the basal diet containing either 0% or 80% maize silage in roughage DM.

degradation characteristics in these same trials as the most realistic model input (Bannink *et al.*, 2016). The results confirmed that the model captures part of the variation in EF values observed, and that the model reproduces the direction of change in EF with grass maturation. For grass herbage the predictions were less conclusive, but observed EF values were reported not to differ significantly (Warner *et al.*, 2015) in contrast to the highly significant effects established for the grass silages.

Also the EF value of maize silage was observed to change with the growth stage at which the maize crop was cut, ranging from 25% to 40% DM in the whole maize plant. A range of 3.6 g/kg DM was obtained for EF (Hatew *et al.*, 2016). Discarding the unrealistically low 25% DM, the EF decreased with 0.49 g/kg maize silage DM per 10 g increase in starch content or with 0.83 g/kg DM per 10 g decrease in NDF content.

### *Variation in apparent faecal nitrogen and organic matter digestibility*

The Tier 3 model was used to estimate apparent faecal digestibility of N and OM, and these results were compared with digestibility derived from the Dutch feeding tables (CVB, 2011) and reported roughage analysis. Instead of adopting constant digestibility values for feedstuffs and dietary components, the Tier 3 model takes into account the effect of level of N intake on predicted N digestibility as demonstrated in Figure 4a. With the decline in N intake levels from 1990 till recently, partly related to an increase in maize silage proportion of the average diet, the apparent N digestibility reduced from 75% in 1990 to the lowest value of 66% in 2012 (Figure 4a), together with an increase of DM intake and milk yield (latter results not shown). Due to increased N intake, in more recent years, predicted apparent N digestibility increased again to 69% in 2017. These trends were not reproduced by the previous method with values of N digestibility retrieved from feeding tables and roughage analysis in practice (performed till 2014). Although the latter values demonstrated a similar decline in time, they showed much less variation due to dietary changes and they were much higher than Tier 3 model predictions, on average a 6% unit of digestibility higher value (Figure 4a).

With respect to apparent faecal OM digestibility, the Tier 3 model predicted a gradual decline from 83% in 1990 to 78% in 2017 (Figure 4b), together with an increase in OM intake and milk yield (latter results not shown). Values derived from feeding tables appeared much more constant between 78% and 80% from 1990 till 2017 and compared to the Tier 3 model predictions were lower than the Tier 3 predictions for 1990 till 1997 in particular (Figure 4b). Although predicted EF value (Figure 4c) with the Tier 3 model followed the decline in N digestibility (Figure 4a) and OM digestibility (Figure 4b), the simulated variation in EF appeared not to be identical and the decline appeared to be more gradual.

## Discussion

The present study demonstrates the capacity of the Tier 3 model to predict variation in enteric $CH_4$ emissions, and in $CH_4$ and ammonia emissions from excreta and manure as a function of dietary characteristics and cow performance widerthantextarea

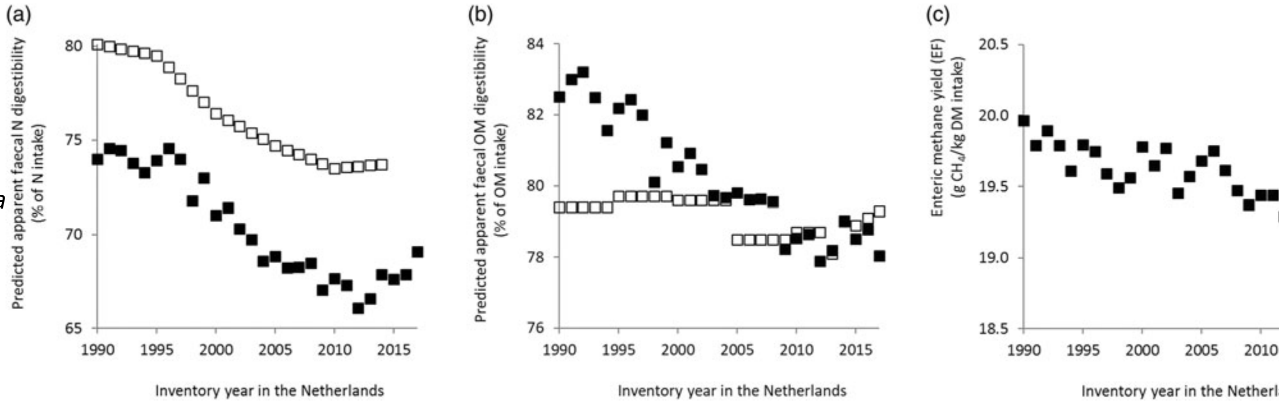


**Figure 4** Tier 3 simulated values (closed symbols) against values adopted in previous inventory (open symbols) for apparent faecal N digestibility (a; the previous inventory method stopped after 2014, currently the Tier 3 is used), for apparent faecal digestibility of organic matter (OM) (b; current inventory does not use Tier 3 predictions) and for enteric methane ($CH_4$) 'yield (c; current inventory uses Tier 3 predictions) in dairy cattle.

(DM intake and milk yield). The Tier 3 model shows more potential to capture variability compared to the use of table values. It captures the effect of DM intake and dietary composition on apparent faecal N and OM digestibility and dietary EF for enteric $CH_4$.

*Accounting enteric methane emission*

Outcomes of the Tier 3 model were translated into a feedstuff EF value for enteric $CH_4$ yield for a specific type of basal diet. An approach was adopted similar to that of taking the derivative of a function, by examining the change in simulated EF due to exchange of a small fraction dietary DM by the DM of the feedstuff or dietary component of interest. It is concluded that this approach allows the formulation of EF lists for specific diet types which can easily be adopted in a farm accounting tool, and also can be used by the feed industry to derive an EF value when formulating compound feed and advising farmers. For use of modelling results in practice, such a simplification is needed as well as restriction to some main diet types. Although other choices are certainly worth investigating in the future, the primary factor in which diets differ between farms and between regions in the Netherlands is the proportion of maize silage in the diet. By varying this particular factor, it appeared that a minimum of three lists of EF values for different maize silage proportions had to be derived to ensure that summation and interpolation of EF values matched with Tier 3 model predictions. With another choice of discriminatory factor to identify diet types, different EF lists will be generated and perhaps also a different number of lists are needed to reproduce Tier 3 model results. The acidifying effect of a diet on the rumen may be considered for example, with different diet types causing different rumen pH values. The Tier 3 model accounts for the effect of rumen pH on enteric $CH_4$ emission from fermented sugars and starch as reported by Bannink *et al.* (2011). In effect, the more acidifying the diet, the lower the predicted EF of a feedstuff which was simulated to decrease −3.1% with a decrease of pH by 0.1. Such effects hence have a strong impact on predicted EF values. Such effects are realistic as demonstrated by the results of Moate *et al.* (2017), who observed 30% lower $CH_4$ yield for a wheat diet with strong acidifying effect on the rumen, milk fat depression and a very high trans-10 fatty acid proportion in milk fat, as compared to the corn and barley diet. Normally, dairy cow diets are formulated however to prevent extreme acidification and milk fat depression does not occur to this extent. Nevertheless, to be able to predict accurate EF values for various levels of rumen acidification, a separate EF list for each level of rumen acidification can be created following the same approach as used in the present study. Alternative methods to predict $CH_4$ yield have been published; however, they do not serve the same purpose as the present study. With a more indirect representation of the acidifying effect of a diet, Eugène *et al.* (2019) employed an empirical equation that predicts a decline in $CH_4$ yield with increased dietary proportion of concentrate. As this equation with a generic purpose of application (Eugène *et al.*, 2019) only accounts for roughage : concentrate proportion and level of feed intake, it will be more difficult to calculate case-specific EF values. The aim of the present study was to generate specific EF values of individual feedstuffs for a specific diet type, as well as to account for differences in roughage quality. Several alternative equations have been developed with various combinations of explanatory variables, but they also cannot serve the purpose of the present study. Also Benaouda *et al.* (2019) developed empirical equations to account for the effect of dietary measures to mitigate enteric $CH_4$. They concluded that current IPCC models performed moderately under different mitigation strategies because they do not account for differences in dietary lipid, NDF and starch contents, and the effects of diet quality (i.e. digestibility). The approach in the present study can take those effects into account however. Moreover, Benaouda *et al.* (2019) concluded that for better prediction with various dietary measures, models should include feed intake, digestibility and additional information on dietary concentrations of lipid, structural and non-structural carbohydrates. These aspects are addressed by the approach in the present study.

The EF lists derived in the present study have been introduced in the farm accounting tool (the annual nutrient cycling assessment tool) which is used by farmers and the feed and dairy sector in the Netherlands (Aarts *et al*., 2015). The method allows the farm accounting tool to closely match prediction by the Tier 3 model without the need to incorporate the Tier 3 model itself with all its complexity. In this way, it is also ensured that predictions by the Tier 3 model as in Dutch national inventory of enteric $CH_4$ match with methodology adopted in the farm accounting tool. Introducing the average national dairy cow diet as an input to the farm accounting tool would deliver rather similar predictions as the Tier 3 model.

The fact that the farm accounting tool matches the Tier 3 model does not preclude prediction error. Nevertheless, the present study and previous modelling work (Bannink *et al*., 2010, 2016 and 2018) showed the Tier 3 model is capable to capture some important sources of variation in EF. This includes the differences in EF between feedstuffs, the effect of DM intake level, as well as the effect of roughage characteristics, which have all been observed as important sources of variation in EF. A recent meta-analysis of Van Gastelen *et al*. (2019) confirms the predicted effects of silage characteristics on enteric $CH_4$ with change in EF value due to chemical composition and OM digestibility pointing in the same direction as predictions by the Tier 3 model. An IPCC Tier 2 approach (IPCC, 2006), or adoption of such Tier 2 with differential EF values for various farming conditions, is still less flexible compared to the approach in the present study. This is demonstrated by the predicted small, but gradual decline in EF of enteric $CH_4$ in time (Figure 4c), reflecting increase in DM intake and milk yield, whereas the IPCC Tier 2 approach would typically adopt a constant EF. This drop in EF value associated with increase in DM intake has been demonstrated before in reviews on observed enteric $CH_4$ yield (e.g. Reynolds *et al*., 2010).

Further studies are needed to evaluate accuracy of $CH_4$ predictions by the Tier 3 model as well as the EF lists. This includes the evaluation of predicted EF values for individual feedstuffs, given a certain diet. In particular, the number of studies on variation of roughage characteristics on EF value is scarce, whereas it is the main component of dairy diets. Furthermore, it needs to be investigated what other basal diets and EF lists would be preferred or necessary, and whether these can be applied in farm accounting. With the attention to reduce N emissions to the environment, it is thinkable that also multiple EF lists are preferred for conditions of varying CP supply. It is noted that methods used in the present study do not accommodate effects of enteric $CH_4$ mitigating feed additives. Their effect needs to be accounted for independently of the present EF lists. The effect of supplemented fats (as well as feedstuffs rich in fat) is already accommodated for. Finally, results shown here apply for conditions with fairly intensive grassland management in temperate regions (north-western Europe) and they might not hold for extreme growing conditions and regions with widely different production conditions.

*Accounting manure methane and ammonia emissions*
Only the calculation of apparent faecal N digestibility by the Tier 3 model is used in current Dutch inventory. Although predictions are not directly implemented in the farm accounting tool (Aarts *et al*., 2015), values derived from feeding tables and roughage analysis are corrected up to the level of N digestibility as predicted by the Tier 3 model. Bannink *et al*. (2018) demonstrated the Tier 3 model predictions were accurate for Dutch feeding conditions in particular. The predicted general decline in N digestibility in time up to 2012 (Figure 4a) is due to the increase of DM intake and milk yield, contributing a larger fraction of microbial and endogenous N in faeces, combined with a reduction of dietary N content. As a result, the proportion of ingested N excreted with faeces increases and excreted with urine decreases, and apparent faecal N digestibility declines.

With respect to predicted OM digestibility, these results are not used in the farm accounting tool nor in current national inventory of $CH_4$ emissions from manure (or VS). Currently, values of OM digestibility are retrieved from feeding tables and roughage analysis. Current level of predicted OM digestibility closely matches the values predicted by the Tier 3 model for recent years (Figure 4b). However, current values appear rather constant and static, whereas the Tier 3 model appears to predict more realistically the expected gradual decline in OM digestibility with increase in DM intake and milk yield of cows. Similarly, Potts *et al*. (2017) reported declines in apparent DM and CP digestibility of 0.07 and 0.04 percentage units per year (period 1970 to 2014). They concluded that the apparent decline in DM digestibility could be mostly accounted for by simultaneous increases in level of DM intake.

*Future efforts and wider application*
To comply with national reduction goals for both $CH_4$ and ammonia emissions, dairy farmers need access to an integral evaluation of the effects on enteric $CH_4$, manure $CH_4$ and ammonia emission (leading to indirect $N_2O$ emission). Such an integral evaluation would benefit from including the translation of predicted variation in N and OM digestibility into the farm accounting tools (translation of predicted EF for enteric $CH_4$ already being accommodated). Instead of adding unnecessary detail and complexity, the aim should be to introduce the most important sources of variation in a consistent manner, acknowledging the underlying causal mechanisms. Making use of the Tier 3 model may help to achieve consistency, as the model predicts the consequences of enteric fermentation as well as OM and N excretion. Not only farm accounting tools should benefit from this work, also conclusions drawn from studies that adopt a Life Cycle Analysis approach to evaluate farm management strategies may become more accurate and meaningful when leaving assumptions typically made at the much higher level of national inventory. An example of this is the study of Van Middelaar *et al.* (2014) on the comparison of three different GHG mitigation strategies on a dairy farm, including nitrate supplementation, supplementation of extruded linseed and reducing maturity of grass herbage with grazing and of grass cut for ensiling.

Future efforts may include the improvement of EF predictions, but should also include studying a further discrimination of basal diet types for which EF lists are derived. When new, detailed observations come forward which are not captured by the Tier 3 model, these have to be added to accounting and inventory methodology. For example, the effects of $CH_4$ mitigating feed additives are not covered by the Tier 3 model and hence would have to be captured separately, presuming they can be treated relatively independently from the processes already captured by the Tier 3 model (i.e. enteric fermentation, degradability characteristics and microbial metabolism). If not, the interactions with enteric fermentation processes need to become clear first.

Also prediction of processes taking place in stored manure may benefit from the type of modelling work presented here. Sommer *et al*. (2004) distinguished between $CH_4$ emission from degradable and non-degradable VS fractions in manure. Kafle and Chen (2016) addressed the lack in literature on $CH_4$ emissions potential of several livestock manures under the same anaerobic digestion conditions (same inoculum, temperature, time and size of the digester) and established relationships between $CH_4$ and chemical composition of digested manures from various species. It hence seems relevant to be able to quantify the effect of nutrition on manure chemical composition and its digestion/degradation characteristics. Dijkstra *et al*. (2018) already demonstrated how the Tier 3 model can be used to quantify the different fractions in urine and faeces and the consequences for manure characteristics that may have a bearing on subsequent emissions and fertiliser value. Like in the Tier 3 model for enteric $CH_4$, such principles are also represented in manure storage models such as DNDC-Manure of Li *et al*. (2012). Next to conditional aspects of manure storage, which can be most determinant for $CH_4$ emission, also three fractions of OM are identified in the model of Li *et al*. (2012) representing a very labile fraction, a labile decomposable fraction and a resistant organic carbon fraction, which is in analogy to the washable, degradable and non-degradable fraction identified with *in situ* techniques for rumen digestion. Although Li *et al*. (2012) state that, ideally, fresh faeces are characterised on their chemical composition in detail in analogy to what is used in rumen models (identifying starch, cell wall material and CP), they aggregated this into separate fractions of organic carbon in fresh faeces. It is possible to quantify and address more details by the Tier 3 model as discussed by Dijkstra *et al*. (2018). This modelling effort demonstrated that variation in different VS fractions can be quantified, and that a distinction can be made between excreted N probably not contributing to manure $CH_4$ emission (urea-like components) and excreted N which does (organic N-containing compounds).

## Conclusions

Translating results from a dynamic, mechanistic model towards a farm accounting methodology in order to capture variation in EF values for enteric $CH_4$ is promising. A similar approach could be taken for predicted apparent faecal N and OM digestibility. With respect to faecal N, this allows more accurate estimation of N excretion with urine and consequently ammonia emission; with respect to faecal OM, this allows more accurate estimation of VS excretion and consequently manure $CH_4$ emissions. Application of the adapted farm accounting tool becomes more realistic if efforts are made to account for variation in various on-farm emission sources instead of using constant and generic values. Thereby, the tool allows dairy farmers and the feed and dairy industry to make a more realistic integral assessment of the effect of nutritional measures on $CH_4$ and ammonia emissions. Finally, results of the present study should not be taken as a thorough evaluation of prediction accuracy of enteric and manure $CH_4$ emissions and ammonia emission, and they apply mainly to the fairly intensive grassland management and feeding practices in temperate regions.


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## Declaration of interest

The authors declare no conflict of interest or competing interest.


## Ethics statement

Not applicable.

## Software and data repository resources

Not applicable.

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