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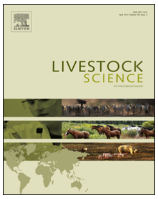

Prediction of the Ym factor for livestock from on-farm accessible data

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ABSTRACT

Methane emission factor (Ym) is directly involved to calculate the worldwide livestock methane inventories, hence it is important to refine the estimation of this parameter for different livestock production systems. The purpose of this work was to generate refined mathematical models to predict CH_4 emissions from an extensive compiled database at on-farm level and to compare them with different models already available in the literature. Methane emission predictive models (expressed as Ym, % gross energy intake; and methane production, **CH_4p**, g an^{-1} d^{-1}) where fitted taken into account the production system, the livestock type and the feed characteristics available at on-farm level within a reasonable uncertainty range. In order to develop the models, only easy available parameters were selected to fit new mathematical models. Hence, the full model included: ruminant types (beef cattle, dairy cattle, and sheep), fibre sources (fresh forage, conserved forage, and straw) and concentrate levels (DM basis) in the diet (Low, $<35\%$; Intermediate, 35–65%; High, $>65\%$). Full models were assessed by the Bayesian Information Criterion (BIC) and terms that did not reach significance level ($P \leq 0.05$) were dropped from the model. Furthermore, predicted results were assessed through correlation and regression analyses considering the model significance. Models developed in this study were compared by the degree of adjustment of a simple regression. Additive and technique terms were initially dropped from the full model used to predict Ym because they did not have effect in the prediction ($P > 0.10$). Therefore, the final equation for Model 1 was: $\text{Ym(a)} = \text{Intercept} - 0.243(\pm 0.051) \times \text{DMI (kg d}^{-1}) + 5.9 \times 10^{-3}(\pm 1.17 \times 10^{-3}) \times \text{NDF (g kg}^{-1}\text{ DM}^{-1}) + 5.7 \times 10^{-3}(\pm 1.63 \times 10^{-3}) \times \text{DMD (g kg}^{-1}\text{ MS}^{-1})$ (BIC=559). All terms of this model, intercept factor (type of cattle × source of fibre × level of concentrate), DMI, NDF, and DMD were significant ($P < 0.0001$). DMI was the term with the greatest weight in the model. The predicted Ym value decreased about 0.243 percentage units ($P < 0.0001$) per each additional kg in DMI. When the equation was compared with previous publicated models, our model showed a satisfactory degree of fitting.

In conclusion, this new model improved the estimation of the Ym factor from beef and dairy production systems, using different forage quality characteristics from on-farm level to increase precision.

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1. Introduction

Methane (**CH_4**), carbon dioxide (**CO_2**) and nitrous oxide (**N_2O**) dominate agricultural greenhouse gas (**GHG**) emissions into the atmosphere (IPCC, 2007). Emissions of CH_4, CO_2 and N_2O associated with livestock are determined mostly by direct emissions (enteric fermentation and effluent decomposition) or indirect (associated with feed for animal consumption and deforestation for cattle use). Methane emissions from livestock are mainly explained by the methanogenic activity of highly specialized archaebacteria dwelling in the gastrointestinal tract of ruminants, which is a natural process associated to the bacterial digestion system that allows ruminants to get energy and nutrients from fibrous-rich feeds. While this is a relevant energy loss for the animal (*c.a.* 2–12% of the daily gross energy intake; Johnson and Johnson, 1995), and consequently restricts potential animal production, it also constitutes an important source of GHG. It is estimated that worldwide agriculture annually produces 205–245 million tonnes of CH_4 and 80 million tonnes of these are a product of enteric fermentation in ruminants (Moss et al., 2000; O'Neil et al., 2011). Other studies have estimated that agriculture accounts for 52% of CH_4 emissions (Smith et al., 2007), and that the contribution of agriculture to total global GHG emissions is around 8–11% (O'Mara, 2011). A different estimation places enteric methane from ruminant's contribution in the range of 17–30% of global anthropogenic CH_4 emissions (Beauchemin et al., 2009).

Despite the complexity and difficulty to accurately measure the flow of GHG, there is evidence that improving agricultural practices could help to reduce them (Grainger and Beauchemin, 2011; Smith et al., 2007). Currently, there is growing concern about climate change consequences, hence governments of many countries are making efforts to reduce the causes and to forecast the necessary adaptations to meet the possible future scenarios (Grainger and Beauchemin, 2011; IPCC, 2007).

An aspect that adds further complexity to the problem of GHG emissions is the discrepancy among different approaches to the issue. Many authors have focused on analysis of the proportion of energy lost from the diet, which conducted to the concept of Ym (methane conversion factor). However, the environmental impact of CH_4 produced by cattle requires the computing of gases emission on a daily basis, which requires taking into account at least the dry matter intake. Other authors prefer to assess the impact of cattle production systems through the amount of CH_4 emitted per unit of product (commonly named intensity of production, and expressed as kg CH_4/kg animal product), or even through a larger scale as a whole system modelling approach such as Life Cycle Assessment (Beauchemin et al., 2010).Methane emission rate is highly variable and depends on several factors linked mainly to animal, feed and interactions between them. The most important factor accounting for CH_4 emissions is dry matter intake (DMI), and although CH_4 emission increases with DMI production per unit of feed ingested, it may decrease with increasing feeding level (Blaxter and Clapperton, 1965; Cambra-López et al., 2008; Johnson and Johnson, 1995). This may explain the frequently observed association with animal age and weight (Reynolds et al., 2010). Feed characteristics may also have an important influence (Grainger and Beauchemin, 2011; IPCC, 2006) through changes in ruminal pH, microbial population, rumen stoichiometry, *etc.* (Johnson and Johnson, 1995). While there is evidence that methane emissions are closely related to fermented diet digestibility (Cambra-López et al., 2008), methanogenic capacity of diets with similar chemical composition may vary widely (Getachew et al., 2005).

Estimations of livestock GHG emissions are frequently calculated following the guidelines established by the IPCC (2006), where the contribution of cattle is computed considering that 6.5% of the gross energy ingested is converted to CH_4 for all bovine categories (Ym – tier 2). Although feedlot systems where concentrates may represent up to 90% of the DMI, they are computed with Ym of 3%; all these Ym values can fluctuate ± 1 percentage units according to diet quality (IPCC, 2006).

In order to complete the estimations leading to the national inventory of CH_4 emissions, an Annual Emission Factor per animal category is calculated by the product between DMI and the Ym. Hence that estimation is quite sensitive to changes in intake, which is particularly difficult to assess in semi and extensive production conditions. Among others, diet digestibility and composition, changes in digestibility and digestion kinetics in association with DMI are not taken into account to refine the estimates of Ym (IPCC, 2006). For example, the calculation system is "blind" to changes in the sources of carbohydrates (Johnson and Johnson, 1995; IPCC, 2006) or lipid contents (Grainger and Beauchemin, 2011), which have been shown as important sources of variation.

Considering the direct effect of Ym on calculation of the emission factor and the high degree of uncertainty involved in its estimation (Dong et al., 2004; Neftel et al., 2006), it is important to try to refine the value of this parameter. According to the IPCC, in countries where the contribution of livestock is important, it would be desirable to have estimates with a level of refinement equalling IPCC's Level 3. This approach would require "*the development of sophisticated models which consider the composition of the diet in detail*, *the concentration of products resulting from the fermentation in ruminants*, *the seasonal variations of the animal population or the quality and availability of food*, *and possible mitigation strategies. Many of these estimates would result from direct experimental measurements*" (IPCC, 2006).

Given the importance of Ym, a considerable worldwide research activity is currently taking place in order to improve estimates of CH_4 emissions. This aspect becomes more important when considering that Ym estimates are based on data collected from British breeds of cattle (*Bos taurus*), sheep fed temperate forages and dairy cows (Holstein) fed with concentrate diets (Kurihara et al., 1999). In the case of tropical pastures, according to the IPCC, it is essential to improve estimates of Ym, since data are scarce and inaccurate (Kurihara et al., 1999). For example, in a study of *Aristatum dicantium* hay and Rhodes grass supplied *ad libitum* to Brahman heifers, Ym values were estimated *c.a.* 11%, a value substantially higher than 6.5% suggested by the IPCC for Level 2. There have been also sharp reductions in Ym when diet quality was improved by grain supplementation (Kurihara et al., 1999). Other studies showed a greater methanogenic capacity of C4 grasses (Ulyatt et al., 2002), further confirmed by a meta-analysis where tropical grasses produced up to 17% more CH_4 than temperate ones (Archimède et al., 2011).

An additional issue that needs to be addressed is that Ym predictions (or their equivalent) should be made available for each animal category and feeding system. With the purpose of obtaining reliable predictions at a system level for large geographical regions, input data should be reasonably accessible from national system descriptors. With this regard, country and world-wide inventories based on mathematical models also help in enhancing our knowledge of CH_4 production by animals and allow the evaluation of causes of change and variation in enteric CH_4 emission. Although several models already exist in the literature, some of them utilise non-commonly available input variables and others may have difficulty to predict CH_4 production outside the range on which they were carried out. The objective of the present study was to develop a mathematical model capable of predicting CH_4 emissions from data available at on-farm level for a wide range of livestock production systems (dry matter intake and basic feed chemical composition) and to compare against different models already available in the literature.

2. Material and methods

The rationale underpinning this work was to develop methane emission predictive models (expressed as Ym, % gross energy intake; and methane production, **CH_4p**, g an^{-1} d^{-1}) where production system, animal and feed characteristics are available at a farm level within a reasonable uncertainty range.

2.1. Database and calculations

Throughout the paper, 54 scientific studies published in refereed journals were analysed and characterised according to the criteria presented in Table 1. From every article the relevant experimental treatments were included, taking into account a number of variables of interest (animal characteristics and diet quality, Table 2) in order to create predictive models; hence the original database included 179 inputs of which 39 corresponded to treatments with additives used to mitigate methane emissions. In those experiments where chemical composition values were not reported, the values were replaced or calculated using the database from beef (NRC, 1996), dairy (NRC, 2001) and Feedipedia (2013), FAO. For instance, in those feedstuffs where ash contents were not reported, it was assumed as 5% for concentrates and 8% for any other feeds; and ether extract was assumed 2% for straw and 4% for any other forage. Similarly, if Gross Energy (**GE**) of feeds was not published, it was assumed as 4.4 Mcal kg DM^{-1}. Non-fibrous carbohydrates (**NFC**) were calculated as NFC = 100 − (NDF + Ash + EE + CP) (NRC, 2001). When digestibility was reported as Organic Matter Digestibility (**OMD**), the corresponding conversion to Dry Matter Digestibility (**DMD**) was calculated by multiplying OMD by 1.05 or 1.08, as appropriate (*i.e.* concentrates or other feeds as above).

To convert Net Energy of Lactation (**ENL**) into DMD, the equations (2)–(11) from Dairy NRC (NRC, 2001) was used *i.e.*

$$\mathrm{NEL}\left(\mathrm{Mcal\ \ kg^{-1}}\right) = \left[0.703 \times \mathrm{MEp}\left(\mathrm{Mcal\ \ kg^{-1}}\right)\right] - 0.19,$$

$$\text{and } \mathrm{ME}\left(\mathrm{Mcal\ \ kg\,DM^{-1}}\right) = 4.4\ \left(\mathrm{Mcal\ \ GE\ \ kg\,DM^{-1}}\right)$$
$$\times 0.82\ (\mathrm{Mcal\ \ Mcal^{-1}}) \times \mathrm{DMD}\ (\mathrm{kg\ \ kg^{-1}})$$

To standardise the expression of the results found across different literature sources, it was assumed that one Mol of CH_4 weighs 16 g and occupies 22.4 L (under normal conditions of pressure and temperature); each kg of CH_4 yields 55.66 MJoules (13.3 Mcal kg^{-1} × 4.185 MJoules $Mcal^{-1}$). In those cases where the original authors did not report any description of the energy density of the diet, it was calculated from the data of ration composition using tables (Feedipedia, 2013; NRC, 2001).

2.2. Model fitting

To develop the model, only animal or feed characteristics, easily measurable and obtainable, and productive system descriptors were selected to account for the cattle methane emissions. Hence the full model included: ruminant type (beef cattle, dairy cattle, and sheep), fibre source (fresh forage, conserved forage, and straw) and level of concentrate (DM basis) inclusion in the diet (Low, < 35%; Intermediate, 35–65%; and High, > 65%, Table 3).

Likewise, four different types of complete models were initially evaluated:

2.2.1. Model 1a $Ym_{(I)}$

Model to predict Ym (including DMI)

$$\mathrm{Ym_I}(\%\ \mathrm{GE}) = \mathrm{Var}^{-1} + \mathrm{ID} + \mathrm{Type} \times \mathrm{SF} \times \mathrm{Conc} + \mathrm{Tech}$$
$$+ \mathrm{Addit} + \mathrm{DMI} + \mathrm{NDF} + \mathrm{DMD} + \mathrm{Res}$$

Table 1
Factors used to characterise bibliographic data sources.

Variable	Description
Source	Bibliographic source (Journal article)
No. animals	Number of animals used for each methane assessment (*e.g.* Ym)
Ruminants	Beef cattle (33), dairy cattle (16), sheep (5)
Breed	Livestock breed (*e.g.* Holstein, cross-breed)
Age	Age at the time of the experiment
Fibre source (FS)	Conserved forage (hay and silages); fresh forage (zero-grazing or grazing); straw
Fibre proportion	Proportion of FS on the daily dry matter intake
Concentrates proportion	Level of concentrates inclusion in the total dry matter intake as: Low (< 35%), Intermediate (35–65%) and High (> 65%)
Concentrates details	Qualitative description of the concentrates
Additives	Yes or no (plus a qualitative description)

Table 2
Variables extracted from consulted peer-reviewed articles.

Animal characteristics	
LW (kg)	Live weight
DMI (kg animal^{-1} day^{-1})	Dry matter intake (mean and variance)
OMI (kg animal^{-1} day^{-1})	Orgainic matter intake (mean and variance)
DMIc (kg animal^{-1} day^{-1})	Dry matter intake as concentrate
MP (kg day^{-1})	Milk production
Technique	Technique used to measure emission of methane: respiratory chamber or sulphur hexafluoride (SF_6)
Diet characteristics	
DM (g/kg WM)	Dry matter
DMD diet (g kg^{-1} DM^{-1})	Dry matter digestibility (mean and variance)
Ash (g kg^{-1} DM^{-1})	Inorganic matter
CP (g kg^{-1} DM^{-1})	Crude protein
NDF (g kg^{-1} DM^{-1})	Neutral detergent fibre
EE (g kg^{-1} DM^{-1})	Ether extract
Starch (g kg^{-1} DM^{-1})	Starch
GE (Mcal kg DM^{-1})	Gross energy
ME (Mcal kg DM^{-1})	Metabolisable energy
Ym (%)	(Gross energy lost as methane/gross energy intake) × 100

Table 3
Number of bibliographic sources by type of cattle, source of fibre (fresh, conserved forage and straw) and level of inclusion of concentrates in the diet (Low, Intermediate and High on DM basis).

Type of cattle	**Proportion of concentrates in the diet**[a]		
Source of fibre	**Low (< 35% DM)**	**Intermediate (35–65% DM)**	**High (> 65% DM)**
Beef cattle			
Conserved forages	40	14	20
Fresh forages	26	1	0
Straw	1	3	5
Dairy cattle			
Conserved forages	15	14	0
Fresh forages	29	0	0
Straw	0	0	0

[a] DM, dry matter basis.

Thus, daily methane production (CH_4p-Ym_a) was estimated by

2.2.2. *Model 1b $CH_4p_{(I)}$*

Model to predict CH_4p based on $Ym_{(I)}$

$$\begin{aligned}CH_4p\left(I,\ g\ \ d^{-1}\right) = {} & DMI\left(kg\ d^{-1}\right) \times 4.4\left(Mcal\ \ kg\ DM^{-1}\right)\\ & \times Ym_I\left(Mcal\ \ Mcal^{-1}\right)\\ & \times 13.3\left(Mcal\ \ kg\ CH_4^{-1}\right)\\ & \times 1000(g\ \ kg^{-1})\end{aligned}$$

2.2.3. *Model 2a $Ym_{(II)}$*

Model to predict Ym (without DMI)

$$\begin{aligned}Ym_{II}(\%\ GE) = {} & Var^{-1} + ID + Type \times SF\\ & \times Conc + Tech + Addit + NDF + DMD + Res\end{aligned}$$

Thus, daily methane production (CH_4p-$Ym_{(II)}$),was estimated by

2.2.4. *Model 2b $CH_4p_{(II)}$*

Model to predict CH4p based on $Ym_{(II)}$

$$\begin{aligned}CH_4p\left(II,\ g\ \ d^{-1}\right) = {} & DMI\left(kg\ \ d^{-1}\right) \times 4.4\left(Mcal\ \ kg\ DM^{-1}\right)\\ & \times Ym_{II}\left(Mcal\ Mcal^{-1}\right)\\ & \times 13.3\left(Mcal\ \ kg\ \ CH_4^{-1}\right)\\ & \times 1000(g\ \ kg^{-1})\end{aligned}$$

2.2.5. *Model 3 $CH_4p_{(III)}$*

Model to predict CH_4p avoiding the use of Ym

$$\begin{aligned}CH_4p\left(III,\ g\ d^{-1}\right) = {} & Var^{-1} + ID + Type \times SF\\ & \times Conc + Tech + Addit\\ & + DMI + NDF + DMD + Res\end{aligned}$$

2.2.6. *Model 4 $CH_4p_{(IV)}$*

An alternative model to predict CH_4p avoiding the use of Ym

$$\begin{aligned}CH_4p\left(IV,\ g\ d^{-1}\right) = {} & Var^{-1} + ID + Type \times SF\\ & \times Conc + Tech + Addit\\ & + NDF_{int} + NFC_{int} + DMD + Res\end{aligned}$$

where Var^{-1} is the weighing factor, estimate of Ym variance; ID is the bibliographic source (random factor); Type × SF × Conc is the interaction among ruminant species (beef cattle, dairy cattle and sheep), fibre source (conserved forage, fresh forage and straw) and level of concentrate (DM basis) inclusion in the whole diet (Low, < 35%; Intermediate, 35–65%; High, > 65%); Tech is the technique for measurement methane (respiratory chamber or SF_6); Addit is the presence of additives (yes or no); DMI is the dry matter intake (kg d^{-1}); NDF is the neutral detergent insoluble fibre (g kg^{-1}); DMD is the dry matter digestibility (g kg^{-1}); Res is residual; CH_4p is methane production (g animal^{-1} d^{-1}); NDF_{Int} is the neutral detergent insoluble

Table 4
Alternative models found in the literature that were compared against the predictive models proposed in this work.

Source	Type of cattle	ID	Equation[a]
Intergovernmental Panel for Climate Change (IPCC, 2006)	*Beef and dairy cattle*	*Ym-IPCC*	CH_4p (g d^{-1})=DMI × 4.4 (Mcal kg^{-1} DM^{-1}) × 0.065 (Mcal $Mcal^{-1}$) × 13.3 (Mcal kg^{-1} CH_4)
Cambra-López et al. (2008)	*Beef and dairy cattle*	*Ym-CLz*	$Ym = -0.0038 \times DMD^2 + 0.3501 \times DMD - 0.8111$
		CH_4p-CLz	CH_4p (g d^{-1})=DMI × 4.4 (Mcal kg^{-1} DM^{-1}) × $Ym_{(CLz)}$ × 13.3 (Mcal kg^{-1} CH_4) × 1000 g kg^{-1}
Ellis et al. (2007)	*Beef and dairy cattle*	*CH_4p-Ellis*	CH_4p (MJ d^{-1})=$3.27_{(SE=0.794)} + 0.736_{(SE=0.0741)} \times DMI$
Mills et al. (2003)	*Dairy cattle*	*CH4p-Mills*	CH4 (MJ d^{-1})=$56.27 \times (1 - e^{[-0.028 \times DMI]})$

[a] CH_4p, methane production; DMI, dry matter intake (kg d^{-1}); Ym, yield methane (Mcal $Mcal^{-1}$); DMD, dry matter digestibility (g kg^{-1} MS^{-1}); SE, standard error.

fibre intake (kg $animal^{-1}$ d^{-1}); NFC_{Int} is the non-fibrous carbohydrates intake (kg $animal^{-1}$ d^{-1}); and Ym is the proportion of gross energy lost as methane (Mcal $Mcal^{-1}$ or Mcal 100 $Mcal^{-1}$).

2.3. *Alternative models to predict Ym*

Results collected from the database were compared against the following models available in the literature (Table 4).

2.4. *Statistical analysis*

The whole database was characterised by descriptive statistical parameters after making a classification by cattle type, source of fibre and proportion of concentrate in the diet. Full models were analysed by Proc Mixed (SAS Institute, 2002) and results were assessed by the Bayesian Information Criterion (BIC) (Schwarz, 1978). The terms that did not achieve the significance level ($P \leq 0.05$) were dropped from the model. The bibliographic source was included in the model as a random effect, and methane production variance from each study was used as a weighting factor.

Furthermore, predicted results were assessed through correlation and regression analysis considering the model significance, the determination coefficient (r^2), and the residuals dispersion. The slope of the model predictions on actual measurements data was tested by $H_0 = 1$. Significance was declared whenever $P \leq 0.05$, but if $0.05 < P \leq 0.10$ the exact P value was also informed. Models developed in this study were compared with the degree of adjustment of a simple regression between predicted and observed values in the database. For these comparisons, regression fitness (predicted *vs* observed) for each model was evaluated through the intercept ($H_0 = 0$), slope ($H_0 = 0$), model significance (slope, $H_0 = 1$), root mean square error (RMSE), and the determination coefficient (r^2).

3. Results

3.1. *Database characteristics*

The initial database analysis was performed on 179 measurements obtained from 54 publications and included data from beef and dairy cattle, as well as from small ruminants. However, sheep and goat experiments were disregarded due to a strong under-representation (only 4 papers, supplying 7 inputs) and a disproportionate influence was evident in the results, lowering the BIC estimate and regression output. An additional publication was also disregarded because of the lack of important basic information.

The final database included 168 treatments (from 49 publications) with 110 measurements from beef cattle and 58 from dairy cows (Table 3). It contained 45% of the diets consisting of forage as the unique feed, and the remaining 55% included concentrates in a proportion ranging between 20% and 60% in 70% of the treatments. Only 7 treatments (*i.e*. 4% of the data) used C4 forages (*i.e. Chloris gayana* and *Brachiaria brizanta*). Descriptive statistical analysis of DMI, DMD, NDF and Ym for every combination of animal type, fibre source and participation of concentrate in the diet indicated that most data came from experiments run with beef cattle fed conserved forages with different proportions of concentrate in their diets, and fresh forages with low proportion of concentrates (Table 5). Meanwhile, data from dairy cattle came from animals fed conserved forages with low or intermediate proportions of concentrate. Those treatments from diets based on fresh forage had only low proportion of concentrates in the final DMI (Table 5).

3.2. *Fitting models*

The full model which was initially used to predict Ym did not detect differences due to additive or technique ($P > 0.10$), hence these terms were dropped from the model and the final estimates (Model 1, $Ym_{(I)}$; BIC=559, 168 treatment inputs) are presented in Table 6. The model intercept factor (type of cattle × source of fibre × level of concentrate interaction) was significant ($P < 0.0001$), and all terms of the equation were significant (DMI, $P < 0.0001$; NDF, $P < 0.0001$ and DMD, $P < 0.01$) for this model. The variable with the highest weight in the model was DMI, and per each incremental kg in DMI, Ym value was decreased about 0.243 percentage units ($P < 0.0001$). Consequently, increasing DMI from 5 to 15 kg DM, it would be expected a reduction in Ym of 2.43 percentage units. On the other hand, NDF and DMD had a similar contribution (5.9×10^{-3} and 5.7×10^{-3}, respectively), *i.e.* an increment of 100 g kg^{-1} in either NDF or DMD would increase Ym *c.a.* 0.6 percentage units.

Table 5
Description of variables classified by type of cattle (beef or dairy), source of fibre (fresh, conserved forage and straw) and level of inclusion of concentrates in the diet (Low, Intermediate and High on DM basis).

	Proportion of concentrates in the diet[a]											
	Low (< 35% DM)				**Intermediate (35–65% DM)**				**High (> 65% DM)**			
	DMI[b] kg DM d^{-1}	NDF[c] g kg^{-1} DM^{-1}	DMD[d] g kg^{-1} DM^{-1}	Ym[e] % EB	DMI[b] kg DM d^{-1}	NDF[c] g kg^{-1} DM^{-1}	DMD[d] g kg^{-1} DM^{-1}	Ym[e] % EB	DMI[b] kg DM d^{-1}	NDF[c] g kg^{-1} DM^{-1}	DMD[d] g kg^{-1} DM^{-1}	Ym[e] % EB
Beef cattle												
Conserved forages												
N	40	40	40	40	16	16	13	15	20	20	20	19
Minimum	3.5	350	385	3.8	4.6	310	660	3.4	4.1	130	692	2.8
Maximum	11.9	800	830	11.4	11.3	610	784	10.3	14.1	260	871	9.8
Mean	7.0	450	606	6.9	8.1	408	713	6.5	8.5	206	755	5.4
S	2.20	126.2	75.5	1.50	1.83	67.5	33.9	1.67	2.56	32.7	51.3	1.74
Fresh forages												
N	26	26	26	26	1	1	1	1	*nd*	*nd*	*nd*	*nd*
Minimum	4.0	310	414	4.1	10.2	540	705	8.4	*nd*	*nd*	*nd*	*nd*
Maximum	14.9	820	815	9.9	10.2	540	705	8.4	*nd*	*nd*	*nd*	*nd*
Mean	10.2	605	614	6.9	10.2	540	705	8.4	*nd*	*nd*	*nd*	*nd*
S	2.69	129.3	114.9	1.87	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*
Straw												
N	1	1	1	1	3	3	3	3	5	5	5	5
Minimum	10.6	430	600	8.9	11.0	270	650	6.8	6.3	160	622	2.3
Maximum	10.6	430	600	8.9	11.4	370	700	8.5	7.9	270	798	10.1
Mean	10.6	430	600	8.9	11.3	320	673	7.9	7.2	194	750	4.6
S	*nd*	*nd*	*nd*	*nd*	0.23	50	25.17	0.92	0.82	45.1	76.7	3.13
Dairy cattle												
Conserved forrage												
N	15	15	15	15	14	14	6	14	*nd*	*nd*	*nd*	*nd*
Minimum	8.2	390	502	6.1	14.2	300	566	5.1	*nd*	*nd*	*nd*	*nd*
Maximum	17.9	600	864	8.8	19.7	520	722	8.6	*nd*	*nd*	*nd*	*nd*
Mean	13.7	453	738	7.3	16.6	381	666	6.8	*nd*	*nd*	*nd*	*nd*
S	4.29	72.5	139.1	0.91	1.80	65.1	53.5	0.92	*nd*	*nd*	*nd*	*nd*
Fresh forage												
N	29	29	29	29	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*
Minimum	6.8	230	626	4.3	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*
Maximum	20.5	700	911	8.6	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*
Mean	12.7	541	752	6.7	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*
S	3.76	121.8	76.9	0.98	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*

nd, not determined.

[a] Dry matter basis.

[b] Dry matter intake.

[c] Neutral detergent fibre.

[d] Dry matter digestibility.

[e] Proportion of ingested gross energy eliminated as methane, Mcal/Mcal.

Table 6
Predicting model for different types of cattle, source of fibre (SF) and concentrate intake as proportion of daily dry matter intake (level of concentrate).

ID	**Source of fibre**	**Level of Concentrate**[a]	**Model parameters Intercept (standard error)**	
			Model 1a, $Ym_{(I)}$[b] **(% GE)**	**Model 2a, $Ym_{(II)}$**[c] **(% GE)**
Beef cattle				
1	Fresh forage	Low	2.0 (1.77)^{ns}	0.1 (1.81)^{ns}
2	Fresh forage	Intermediate	4.1 (1.96)*	2.7 (2.07)^{ns}
3	Conserved forages	Low	3.1 (1.55)*	1.8 (1.61)^{ns}
4	Conserved forages	Intermediate	2.3 (1.56)^{ns}	0.8 (1.63)^{ns}
5	Conserved forages	High	1.5 (1.51)^{ns}	0.3 (1.57)^{ns}
6	Straw	Low	5.1 (1.62)**	3.4 (1.69)*
7	Straw	Intermediate	4.4 (1.51)**	2.7 (1.56)†
8	Straw	High	1.0 (1.52)^{ns}	−0.1 (1.60)^{ns}
Dairy cattle				
9	Fresh forage	Low	3.1 (1.97)^{ns}	0.1 (1.93)^{ns}
10	Conserved forages	Low	3.7 (1.83)*	0.8 (1.81)^{ns}
11	Conserved forages	Intermediate	3.5 (1.86)†	0.5 (1.81)^{ns}
Probability				
Type of cattle × source of fibre × level of concentrate			0.0002	0.0062

DMI, dry matter intake; NDF, neutral detergent fibre of total diet; DMD, apparent dry matter digestibility. Standard error of the parameters is reported between brackets (). Probability of Ym=0; ns, non-significant.

† $P < 0.10$.

* $P < 0.05$.

** $P < 0.01$.

[a] Level of concentrate: Low, less than 35% of dry matter intake; Intermediate, between 35% and 65%; High, more than 65% of the ingested dry matter.

[b] $Ym_{(I)}$ (% GE)=Intercept−0.243(0.051)*** × DMI (kg d^{-1})+5.9 × 10^{-3} (1.17 × 10^{-3})*** × NDF (g kg^{-1} DM^{-1})+5.7 × 10^{-3}(1.63 × 10^{-3})** × DMD (g kg^{-1} MS^{-1}).

[c] $Ym_{(II)}$ (% GE)=Intercept+6.3 × 10^{-3} (1.27 × 10^{-3})*** × NDF (g kg^{-1} DM^{-1})+4.7 × 10^{-3} (1.77 × 10^{-3})** × DMD (g kg^{-1} MS^{-1}).

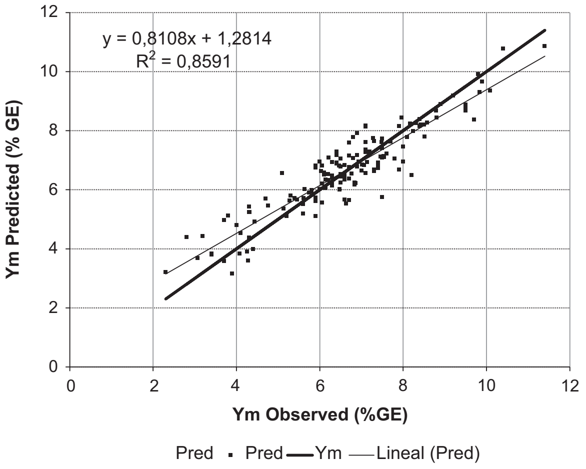

Fig. 1. Regression of predicted Ym by the model on observed data.

Predicted results had a significant degree of correspondence with the observed data as shown by the linear regression adjusted model (Fig. 1):

Model 1a $Ym_{(I)}$ (BIC 559; $r^2=0.84$)

$$Ym_{Pred} = 1.37_{(SE\ =\ 0.187;P<0.0001)} + 0.80_{(SE\ =\ 0.028;\ P<0.0001)} \times Ym_{Obs}$$

where Ym_{Pred} (%GE) is $Ym_{(I)}$ predicted by the model; SE is the standard error of the parameter, and Ym_{Obs} (%GE) is Ym observed.

According to the high agreement between predicted and observed data, a test on the slope of the regression indicated that it was not different from 1 ($H_0=1$; $P=0.13$). This model was also assessed by dropping the DMI term (Model 2 $Ym_{(II)}$, which raised BIC to 574, Table 6), but regression analysis of predicted results on observed data also had a significant degree of correspondence.

Model 2a $Ym_{(II)}$ (BIC 574; $r^2=0.81$)

$$Ym_{Pred} = 1.73_{(SE\ =\ 0.193;\ P<0.0001)} + 0.75_{(SE\ =\ 0.028;\ P<0.0001)} \times Ym_{Obs}$$

where $Ym_{(II)Pred}$ (%GE) is Ym predicted by the model, SE is the standard error of the parameter, and Ym_{Obs} (%GE) is Ym observed.

Models developed to predict CH_4p (Table 7) had satisfactory correspondence between observed and predicted data:

Model 3 $CH_4p_{(III)}$ (BIC 1609; $r^2=0.94$)

$$CH_4p_{Pred} = 20.5_{(SE\ =\ 4.19;\ P<0.0001)} + 0.91_{(SE\ =\ 0.017;P<0.0001)} \times CH_4p_{Obs}$$

Model 4 $CH_4p_{(IV)}$ (BIC 1615; $r^2=0.92$)

$$CH_4p_{Pred} = 22.5_{(SE\ =\ 4.82;\ P<0.0001)} + 0.90_{(SE\ =\ 0.020;\ P<0.0001)} \times CH_4p_{Obs}$$

where CH_4p_{Pred} (g d^{-1}) is the methane production predicted by the model, SE is the standard error of the parameter, and CH_4p_{Obs} (g d^{-1}) is the observed methane production.

Table 7
Predicting model for methane production (PCH_4, g an^{-1} d^{-1}) for different types of cattle, source of fibre (SF) and concentrate intake as proportion of daily dry matter intake (level of concentrate).

ID	Source of fibre	Level of concentrate[a]	Model parameters Intercept (standard error)	
			Model 3 $CH_4p_{(III)}$[b]	Model 4 $CH_4p_{(IV)}$[c]
Beef cattle				
1	Fresh forage	Low	-59 (41.6)^{ns}	-158 (72.0)*
2	Fresh forage	Intermediate	22 (52.1)^{ns}	-104 (80.3)^{ns}
3	Conserved forages	Low	-31 (35.8)^{ns}	-151 (64.8)*
4	Conserved forages	Intermediate	-46 (46.3)^{ns}	-166 (66.6)*
5	Conserved forages	High	-84 (40.2)*	-207 (64.6)**
6	Straw	Low	48 (44.8)^{ns}	-52 (68.0)^{ns}
7	Straw	Intermediate	21 (41.0)^{ns}	76 (64.0)^{ns}
8	Straw	High	-93 (42.5)*	-231 (66.4)***
Dairy cattle				
9	Fresh forage	Low	-13 (54.0)^{ns}	-107 (80.8)^{ns}
10	Conserved forages	Low	-1 (50.1)^{ns}	-111 (78.9)^{ns}
11	Conserved forages	Intermediate	2 (52.7)^{ns}	-117 (80.2)^{ns}
Probability				
Type of cattle × source of fibre × level of concentrate			$< 0.0001^{\dagger}$	< 0.0001

BW, body weight; NDFI, neutral detergent fibre intake; NFCI, non fibrous carbohydrate intake; DMD, apparent dry matter digestibility. Standard error of the parameters is reported between brackets (). Probability of Ym=0; ns, non-significant.

† $P < 0.10$.

* $P < 0.05$.

** $P < 0.01$.

*** $P < 0.001$.

[a] Level of concentrate: Low, less than 35 dry matter intake; Intermediate, between 35% and 65%; High, more than 65% of the ingested dry matter.

[b] $CH_4p_{(III)} = \text{Intercept} + 24\ (2.78)^{***} \times \text{NDFI (kg d}^{-1}) + 10\ (3.58)^{**} \times \text{NFCI (g kg}^{-1}\text{ DM}^{-1}) + 0.184\ (0.050)^{**} \times \text{DMD (g kg}^{-1}\text{ MS}^{-1})$.

[c] $CH_4p_{(IV)} = \text{Intercept} + 0.387\ (0.0792)^{***} \times \text{BW (kg)} + 0.100\ (0.0458)^{*} \times \text{NDF (g kg}^{-1}\text{ DM}^{-1}) + 0.216\ (0.0638)^{***} \times \text{DMD (g kg}^{-1}\text{ MS}^{-1})$.

Table 8
Summary of the degree of adjustment of regression of Ym predicted values through the models on the observed ones.

Model[a]	Regression parameters (standard error) (*P* value)		$\sqrt{MSE}$[b]	Model[c] ($H_0=1$)	Adj. R[d]
	Intercept ($H_0=0$)	Slope ($H_0=0$)			
Performance of models predicting gross energy lost as methane (Ym)					
Ym – Model 1a	-0.4 (0.25) ($P=0.10$)	1.05 (0.036) ($P<0.0001$)	0.65	$P=0.13$	0.84
Ym – Model 2a	-0.6 (0.28) ($P=0.027$)	1.09 (0.041) ($P<0.0001$)	0.71	$P=0.04$	0.86
Ym – CLz	-0.5 (0.35) ($P<0.0001$)	0.22 (0.067) ($P=0.001$)	1.58	$P<0.0001$	0.06
Performance of models predicting methane production (CH_4p, g d^{-1})					
CH_4p – Model 1b	-3.6 (4.48) ($P=0.42$)	1.01 (0.018) ($P<0.0001$)	22.6	$P=0.47$	0.95
CH_4p – Model 2b	0.8 (4.85) ($P=0.87$)	0.98 (0.019) ($P<0.0001$)	24.7	$P=0.44$	0.94
CH_4p – Model 3	-9.0 (4.72) ($P=0.06$)	1.03 (0.019) ($P<0.0001$)	23.3	$P=0.08$	0.94
CH_4p – Model 4	-6.9 (5.49) ($P=0.29$)	1.03 (0.023) ($P<0.0001$)	26.7	$P=0.16$	0.92
Other models (CH_4p, g d^{-1})					
$CH_4p\text{-IPCC}_{(Ym=6.5\%)}$	5.9 (10.59) ($P=0.58$)	0.99 (0.045) ($P<0.0001$)	50.0	$P>0.05$	0.74
CH_4p-CLz	133.6 (16.68) ($P<0.0001$)	0.58 (0.099) ($P<0.0001$)	90.4	$P<0.0001$	0.17
CH_4p-Ellis	-88.6 (14.68) ($P<0.0001$)	1.61 (0.073) ($P<0.0001$)	50.0	$P<0.0001$	0.74
CH_4p-Mills	-11.1 (11.31) ($P=0.32$)	0.94 (0.043) ($P<0.0001$)	50.0	$P>0.05$	0.74

[a] Ym and CH_4p models 1–4 proposed in this report. Ym and CH_4p-CLz, Model proposed by Cambra-López et al. (2008). CH_4p-IPCC, Tier 2 proposed by IPCC (2006). CH_4p-Ellis, Model [equation 2c] proposed by Ellis et al. (2007); CH_4p-Mills, Model proposed by Mills et al. (2003).

[b] Root mean square error of the prediction.

[c] Significance of the model.

[d] Adjusted *R* squared.

3.3. *Comparison with other models*

The CH_4p-IPCC (Ym=6.5%) was compared by regression analysis against the actual methane emissions reported in the database (Table 8), which indicated a satisfactory degree of fitting. The performance of models 1 and 2 of this work (Ym – Model 1a and Model 2a) as predictors of Ym factor performed better compared with the model proposed by Cambra-López et al. (2008); Ym-CLz, taking into account the determination coefficients (r^2, 0.84 and 0.86 *vs* 0.06) and the RMSE (0.65 and 0.71 *vs* 1.58, Table 8). Moreover, in order to evaluate the models that predict methane production (CH_4p, g d^{-1}) we noted that those here proposed had a very good degree of adjustment ($r^2=0.92$–0.95), low RMSE (22.6–26.7), with a slope equal to one, (testing $H_0=1$, $P>0.05$; $H_0=0$, $P<0.0001$) and the intercept equal to zero.

In contrast, other CH_4p prediction models had higher RMSE (*i.e.* 50–0.4). Ellis et al. (2007) and Cambra-López et al. (2008) models performed similarly between them. These models had a slope different to one and zero (testing $H_0=0$ and $H_0=1$, $P<0.0001$) and an intercept different from zero (*i.e.* CH_4p-CLz, $+133.6$, CH_4p-Ellis, -88.6, $P<0.0001$). The Ellis model had a reasonable degree of adjustment ($r^2=0.74$), while the Cambra Lopez model fitting was poor ($r^2=$ 0.17). Predictor Models of the IPCC, 2007 (using Tier 2; Ym=6.5%) and Mills et al. (2003) performed reasonably well ($r^2=0.74$, RMSE=50.0 for 2 models), and the intercept was equal to zero and the slope did not differ from one (*i.e.* $P>0.05$ for 2 models, Table 8), indicating that these models were the best adjusted predictions, altogether with the models proposed in this work.

4. Discussion

The quality of the diets was quite variable and representative of the ample variations found in different livestock production systems. Within the "low concentrate" category for beef cattle, NDF varied between 350 and 800, 310 and 820 g kg^{-1} DM for conserved forages and fresh forages, respectively. Similarly for dairy cattle and the same type of forages, the variation was between 390 and 600, and 230 and 700 g kg^{-1}. A similar pattern was observed for DMD and DMI.

The main purpose of this work was to develop a mathematical model capable of predicting CH_4 emissions from data accessible at on-farm level and sensitive to different feeding system input parameters as type of livestock and feed quality. This kind of models could also be useful to assess the technical, energetic and even economical impact of feeding changes, when comparing the current ones against potential emissions, or mitigation strategies. The model was also compared against different models already available in the literature and the estimation proposed by the IPCC (2006).

According to the tier 2 (IPCC, 2006) of the presently proposed estimate (Ym=6.5 ± 1%), the Ym is not sensitive to changes in diet quality, though the actual figure can be set within 5.5–7.5 range according to the user's judgment. On the contrary, the model herein developed allows predicting the Ym parameter according to changes in intake, DMD and NDF, three animal-feed characteristics that have frequently been signalled as of upmost importance to predict methane emissions (Johnson and Johnson, 1995; Moe and Tyrrell, 1979).

The outstanding weight of DMI on predicted cattle methane emission (g d^{-1}) is revealed by the reasonable fitting observed for every model as shown in Table 8, where even the predictions by the IPCC model accounts for 74% of variability.

Model 1a to predict Ym showed a reduction in Ym at a rate of 0.243 kg^{-1} DMI^{-1}, indicating that as daily intake raises, the proportion of gross energy lost through the methane pathway decreases. Then, as daily methane production is the product of Ym times DMI, it predicts that daily CH_4p increases with intake but at a decreasing rate (Fig. 2). This outcome agrees with early and recent observations (Blaxter and Clapperton, 1965; Johnson and Johnson, 1995; Sauvant and Giger-Reverdin, 2009).

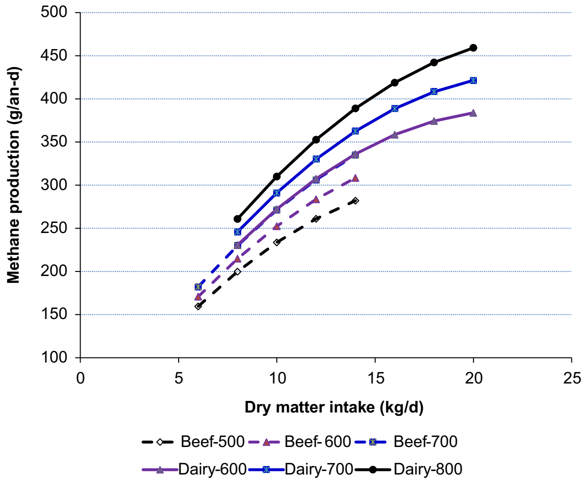

Fig. 2. Predicted methane production for beef and dairy cattle at three different dry matter digestibilities (Beef: 500, 600 and 700 g kg^{-1} DM^{-1}; dairy: 600, 700, 800 g kg^{-1} DM^{-1}). Model Ym(a) for NDF=600 g kg^{-1} DM^{-1}.

The outstanding importance of daily DMI to predict CH_4p was in agreement with previously published studies (Johnson and Johnson, 1995, Mills et al., 2003, Ellis et al., 2007). This fact is also made evident by the good agreement found with Model IPCC as it is arithmetically a constant, hence CH_4p is simply a function of DMI. Similarly, Machmüller and Clarck (2006) in a meta-analysis study carried out to estimate methane emissions for New Zealand, observed a main impact of feed intake associated with their predictive models. The diminishing contribution factor of Ym as intake increases is associated with the well known reduction in DMD in response to increased gastrointestinal flow rate promoted by higher intake (McAllister et al., 1996).

Although the Ym model by the IPCC (2006) has shown good results in comparative analysis (Ellis et al., 2010), it has been criticised due to its lack of capacity to fully describe changes in diet composition (it is a proportion of gross energy intake) as for example in fat content of the diet (Hristov and Tricaricco, 2013). The present model ($Ym_{(I)}$) included diet characteristics through different ways (considering the source of fibre, *i.e.* fresh forage, conserved forage or straw; the level of concentrate inclusion in the diet, NDF concentration and DMD). It has been pointed out that in order to predict CH_4 emissions from livestock, the production systems ought to be grouped according to the type of feeds used (Hagemann et al., 2011).

Increments in any of the two variables associated to diet quality (NDF and DMD) increased Ym prediction in a similar magnitude, but it must be taken into account that both diet characteristics are usually negatively associated, as found within this database (DMD, (g kg^{-1} DM^{-1})= 831–0.325 × NDF (g kg^{-1} DM^{-1}), $r^2=0.23$, $P<0.001$). The inclusion of diet characteristics in addition to DMI improves the prediction quality with respect to those models based exclusively in DMI (Wilkerson et al., 1995).

Fibrous carbohydrates are usually strongly associated with energy losses as methane (Moe and Tyrrell, 1979), hence this issue was considered of particular interest for the purposes of this work. Ruminal fermentation biochemistry studies have shown that NFC usually results in higher concentrations of propionic acid, which precludes the flow of hydrogen towards the methane synthesis (Moss et al., 2000). Coincidently, $CH_4p_{(I)}$ showed a high degree of concordance between observed and predicted results.

Generally, the variability in methane loss increases with the digestibility of the diet, as a probable consequence of the change in the amount of carbohydrates fermented in the reticulum–rumen due to alteration in the balance between digestion and rate of passage. Secondly, as the composition of volatile fatty acids changes, increasing the quantity of propionic and valeric acids in relation to acetic and butyric acids reduces the amount of H_2 available for reducing CO_2, and hence reduces methane production (Baldwin, 1995; Johnson and Johnson, 1995). Theoretically, if all carbohydrates are fermented to acetic acid, the energy loss as methane would be 33%; on the contrary, it would become zero when acetic:propionic acid ratio is 0.5 (Johnson and Johnson, 1995; Wolin and Miller, 1988). Another source of variation is accounted for the relevance of alternative hydrogen sinks as oxygen, unsaturated fatty acids, nitrates, sulphates and microbial growth as well as ruminal pH reduction after feed ingestion (Mills et al., 2001).

According to our results, Ym (%) increased in 0.0057 per g kg^{-1} DM increment in DMD, which turns out quite similar to results previously obtained from sheep fed at maintenance level: Blaxter and Clapperton, 1965; $Ym = 3.67 + 0.0062\ D$ ($kcal \times 1000\ kcal^{-1}$ GE).

5. Conclusions

An improved model for estimating the Ym factor from beef and dairy production systems was developed, using animal and feed quality characteristics to increase the accuracy and sensitivity of the model to changes in the animal production systems. The novelty of this study is the introduction of a refined approach to the IPCC level 3 using an accessible on-farm data, and its potential use for a wide range of livestock production systems. Firstly, methane prediction was explained by the DMI, followed by ivDMD and NDF. Predictors models of Ym development here (*i.e.* models 1a and 2a) had the best adjusted predictions, together with the ones proposed by IPCC (2007) and Mills et al. (2003).

Also, considering the lack of C4 grasses methane emissions data, the herein presented model included parameters that could be useful for predicting methane emissions from C4 grasses. These grasses show unique characteristics of their cell walls that warrant further studies on their methanogenic capacity.

Conflict of interest

None.

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