Norwegian University of Life Sciences
Faculty of biosciences

2023

Report

Models to predict enteric methane emission from dairy cows to be used in the Norwegian inventory calculations.

Harald Volden, Puchun Niu and Egil Prestløkken

Summary

The aim of this report is to describe models to predict enteric methane (CH4) emission from dairy cows. A basic model was developed to study nutritional factors affecting CH4 emission. Based on this an operational model to be used in the national inventory in Norway was developed. The dominant forage in Norway is grass silage and therefore a database containing grass silage as the dominating forage was constructed. In the model development, only dietary treatments where grass silage consisted of 50% or more of the forage was used. The dataset used to develop the basic model consisted of 203 treatments, whereas the data set for the operational model had 110 treatments. Only variables that had a significant contribution in the prediction of CH4 were included. The basic model consisted of the variables dry matter intake and total diet neutral detergent fiber (NDF) and crude fat content. The operational model showing the lowest root mean square prediction error (RMSPE) and highest concordance correlation coefficient included the variables daily energy corrected milk yield (ECM, kg/d), daily concentrate intake (kg DM/d) and crude fat in concentrate compound feed (g/kg DM). The RMSPE (expressed in %) was 14.6% and the uncertainty was estimated to be 27.6%. Model for predicting gross energy intake and the methane conversion factor Ym (% og gross energy intake partitioned into methane) were also developed. Simulations showed that Ym ranged from 6.9 to 6.3% when annual milk yield ranged from 7000 to 11000 kg, respectively, which are in accordance with other studies, and at the same level as previous Norwegian inventory models.

Content

1. Introduction

In Norway, today's models for calculating methane (CH4) emissions from dairy cows are based on a combination of empirical equations (basic models) developed from experiments in which CH4 production is measured, and computer simulations with TINE OptiFôr (operational model) where different feed rations and production levels are included (Niu et al., 2021). When dry matter intake (DMI) and chemical composition of the feed rations are known, the empirical equations give a good estimate of enteric CH4 emission (Nielsen et al., 2013; Ramin and Huhtanen, 2013; Storlien et al., 2014). However, in practical farm situations, information on DMI and chemical composition of the diet, including digestibility is deficient. Moreover, when the total national methane emissions need to be assessed for an inventory purpose these models are not feasible due to limited information and data that are not robust enough. Calculation of enteric methane production under practical production conditions must therefore be done indirectly through related input variables, or proxies.

Grass silage and grass-based pasture is the dominant roughage type in Norwegian cattle production and consists of more than 90% of the roughage intake. The national inventory calculations are based on a combination of a basic model and an operational model. Thus, to improve the robustness it is of vital importance that the models used to predict CH4 emission from experimental data is based on grass forage diets.

The aim of this report is to: 1) describe a basic model with grass silage as the dominant forage to predict CH4 production, to calculate CH4 conversion factor (Ym) and gross energy intake (GEI) and 2) to present an operational model where proxies that can be easily obtained are used to predict CH4 production, Ym and GEI. The proxies used were energy corrected milk (ECM, kg/d)), concentrate intake (kg DM/d) and concentrate crude fat concentration (g/kg DM).

2. Materials and Methods

A comprehensive literature search with a focus on studies feeding grass silage to dairy cows, resulted in a database of 260 treatment means from 66 studies. The database contains information of DMI, ECM, dietary composition, and methane production. An additional criterion was that organic matter digestibility (OMD) was known either for the forage or for the total feed ration.

Basic model

Two subsets from the database were created, each containing information of variables required for the development of the basic and operational equations. For the basic model the dataset consisted of 203 treatment means published in the period 2016-2021. Only treatments where grass silage consisted more than 50% of the forage was used. Methane production (MJ/day) was predicted using the lmer procedure of R statistical language according to the following model:

$$CH4_{pred} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_n X_n + R_j + \varepsilon$$

Where:

$CH4_{pred}$ = Response variable of CH4 prediction, MJ/day

β_0 = the fixed effect of intercept

$X_1 - X_n$ = the fixed effects of predictor variables

B1 – Bn = the corresponding parameter values of *X*

Rj = the random study effect of the experiment

ε = the within experiment error.

To account for differing accuracy in observed means, the model was fitted using the WEIGHT statement in R, where the data were weighted according to the number of observations.

The Ym and GEI were predicted using the same input variables ($X_1 - X_n$) as in the $CH4_{pred}$ model by fitting a mixed effect model using the Imer procedure of R statistical language.

Operational model

An important prerequisite for the operational model is that it contains variables that are robust and possible to obtain at a national level, primarily from the national herd recording system. The dataset contains 236 treatments means from 59 studies. However, to obtain variables that are available from a practical perspective, a refined dataset was formed where only studies that it is possible to obtain the contents of ECM, concentrate intake, concentrate crude fat (conCFat) and forage NDF (foNDF) were included. Only treatments where grass silage consisted more than 50 % of the forage was used. The refined dataset contains 110 treatment means. Information from the basic model will provide information about which variables should be directly or indirectly included in an operational model. Methane production

(MJ/day) was predicted using the lmer procedure of R statistical language according to the following model:

$$CH4_{pred} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_n X_n + R_j + \varepsilon$$

Where:

$CH4_{pred}$ = Response variable of CH4 prediction, MJ/day

β_0 = the fixed effect of intercept

$X_1 – X_n$ = the fixed effects of predictor variables

B1 – Bn = the corresponding parameter values of *X*

Rj = the random study effect of the experiment

ε = the within experiment error.

All variables included in the developed models were significant at P<0.05. To select and evaluate the models for accuracy and robustness a cross validation method using leave-one out (LOOCV) was used. Models with the lowest LOOCV-based rot mean square prediction error (RMSPE, %) and concordance correlation coefficient (CCC) were chosen as the recommended models. The RMSPE was used to evaluate for overall model prediction accuracy, expressed in percentage of CH4 predicted mean. The CCC is the product of a bias correction factor as the measurement of accuracy and the prediction measurement of Pearson correlation coefficient. The CCC evaluates the degree of deviation of the best fit line from the line y = x, and thus the CCC of a model that is closer to 1, is an indication of better model performance.

To estimate the national CH4 emission factor (EF) for a dairy cow for 365 days the following equation is used:

$$EF = (CH4_{predL} \cdot 305 \text{ days} + CH4_{predD} \cdot 60 \text{ days})/55.65$$

Where:

EF = emission factor, kg CH4/animal/year

CH4predL = CH4 in the lactation period, MJ/day

CH4predD = CH4 in the dry period, MJ/day

305 days = lactation period, days

60 days = non lactation period, days

55.65 = conversion of CH4 from MJ to kg.

In the EF equation it is assumed a lactation period of 305 days and no lactation (dry period) of 60 days.

When calculating Ym on an annual basis (365 days) the calculated daily GEI is divided in GEI from the lactation period (GEI*predL*) and from the dry period (GEI*predD*):

$$GEI = (GEI_{predL} \cdot 305 \text{ days} + GEI_{predD} \cdot 60 \text{ days})/365$$

Where:

GEI = gross energy intake, MJ/day

GEIpredL = gross energy intake in the lactation period, MJ/day

GEIpredD = gross energy intake in the dry period, MJ/day

305 days = lactation period, days

60 days = non lactation period, days

3. Results

3.1 Basic model

Table 1 present the descriptive statistics used in the development of the basic model. The dataset shows a large variation both in DMI and chemical composition of the diet. The chemical composition is the diet means and the OMD is in the forage.

Table 1. Descriptive statistics of data used to develop the basic models. A total of 203 treatment means.

Item	Average	STD[1]	Minimum	Maximum
Dry matter intake, kg/day	18.5	3.7	7.3	28.1
Forage intake, kg DM/day	11.4	2.5	4.4	21.3
Concentrate intake, kg DM/day	7.4	3.0	0.0	15.5
Forage proportion in the diet, %	63.6	14.0	35.0	100
Crude protein, g/kg DM	173	26	122	264
NDF, g/kg DM	372	61	192	597
Starch, g/kg DM	154	74	5	318
Crude fat, g/kg DM	39	14	17	85
OMD[2], g/kg DM	742	48	451	848
ECM[3], kg/day	27.7	6.2	9.1	45.7
Methane, MJ/day	22.5	4.2	10.2	36.6

[1]STD= standard deviation;[2]OMD= organic matter digestibility in the forage;[3]ECM= energy corrected milk

The model which included variables with a significant ($P<0.05$) contribution in the prediction of CH4, lowest RMSPE and the highest CCC was selected as the basic model. The following model was selected:

$$CH4 = 4.81 + 0.921 \cdot DMI - 0.066 \cdot Fat + 0.0088 \cdot NDF$$

Where:

CH4 = methane, MJ/day

DMI = dry matter intake, kg/day

Fat = crude fat in the total diet, g/kg dry matter

NDF = Neutral Detergent Fiber in total diet, g/kg dry matter

Dry matter intake is the most important variable predicting methane production, however, it does not perform as well as a model where dietary fat and NDF were included as input variables. Standard error vas 2.4 MJ/day, which gave a RMSPE of 11,0%. The mean predicted CH4 production was 21.5 MJ/day, and the observed value was 22.4 MJ/day, which gives a general bias of -0.9 MJ/day.

3.2 Operational model

In Norwegian dairy production DMI intake is not available on a regular basis. The same applies to NDF, where approximately 40% of the dairy farmers carry out forage analyzes on a regular basis. For crude fat, the feed industry reports the fat content in the commercial compound concentrate feed in a common feed database, which make this information available on a national level. Since DMI is not available in practice, a substitute for feed intake must be found for the operational model. Based on the data set used to develop the basic model, a high correlation (r=0,70) was found between daily DMI and daily ECM production. Thus, an operational model with ECM as an input variable was developed.

In Norway, 98% of all dairy cows participate in the national herd recording system. Individual daily milk yield is recorded 11 times per year and individual milk chemical composition is measured 6 to 11 times per year. In the database, individual concentrate intake is registered at the same time as milk is recorded.

Table 2 present the descriptive statistics used in the development and evaluation of the operational model. The dataset includes experiments performed in the period from 2016 to 2021. Thus, it represents cows with an up-to-date genetic merit and a high production level. Daily ECM production showed a treatment means from 0 (dry cows) to 45.7 kg, which demonstrate that the dataset represents a wide range in production level, and thus is representative for Norwegian milk production. The large variation in milk production also reflects the large variation in DMI. Concentrate intake has a variation from 1.7 to 15.1 kg/day, which causes a large variation in forage proportion and chemical composition of the diet. The major contribution to crude fat in the feed ration is ingredients in the compound feed. In Norway approximately 95% of the cows are fed commercial concentrate mixtures, which have a crude fat content from 20-100 g/kg DM with a normal range of 40 to 65 g/kg DM. Crude fat content in commercial concentrate mixtures is reported in a common feed database (http://feedstuffs.norfor.info/).

Table 2. Descriptive statistics of data used to develop and evaluate the operational model. A total of 110 treatment means.

Item	Average	STD[1]	Minimum	Maximum
Dry matter intake, kg/day	19.5	3.3	13.3	28.1
Forage intake, kg DM/day	11.5	1.7	7.1	14.7
Concentrate intake, kg DM/day	8.0	3.0	2.9	15.5
Forage proportion in the diet, %	60.7	10.0	42.1	80.0
Crude protein, g/kg DM	176	24	133	251
NDF, g/kg DM	368	54	272	518
Starch, g/kg DM	144	62	43	278
Crude fat ration, g/kg DM	41	15	21	85
Crude fat concentrate, g/kg DM	54	31	6	149
ECM[2], kg/day	29.9	6.2	17.1	45.7
Methane, MJ/day	22.1	3.6	14.1	34.2

[1]STD= standard deviation; [2]ECM= energy corrected milk

In the operational model, daily ECM production, daily concentrate intake and crude fat in the concentrate all showed a significant contribution in the prediction of CH4. The model with the lowest RMSPE and highest CCC was:

$$CH4\mathit{predL} = 12.89 + 0.243 \cdot ECM + 0.665 \cdot concentrate - 0.0504\ conCFat$$

Where:

CH4*predL* = methane, MJ/day in the lactation period

ECM = energy corrected milk, kg/day

Concentrate = concentrate feed, kg dry matter/day

conCFat = crude fat in the concentrate, g/kg dry matter

Based on cross validation RMSE and CCC were 14.6% and 0.604, respectively. The general bias (predicted mean – observed mean) was 0.2 MJ/day.

In the dry period with no milk production and concentrate supplementation the predicted methane production (CH4*predD*) is the intercept of 12.86 MJ/day assuming no use of concentrate.

The Ym factor is calculated as the ratio of predicted CH4 production and GEI. Based on the same input variables as in the operational model the following equation is used to predict daily GEI:

GEI*predL* = 135.82 + 4.31·ECM + 14.51·concentrate – 0.234· conCFat

Where:

GEI*predL* = predicted gross energy intake in the lactation period, MJ/day

ECM = energy corrected milk, kg/day

Concentrate = concentrate feed, kg dry matter/day

conCFat = crude fat in the concentrate, g/kg dry matter

In the dry period the GEI (GEIpredD) is set to 135.82 MJ/day

Diet chemical composition is not available in practice and the gross energy level in one kg of DM is set to a fixed level of 18.9 MJ. The value of 18.9 is according to the NorFor feed evaluation system and represent an average feed ration with grass silage and a concentrate mixture. Table 3 present simulations of daily CH4 production and Ym at different milk yields and concentrate levels. The conCFat is fixed to 50 g/kg DM, which is close to the average in Norwegian concentrate mixtures to dairy cows. The feed intake is calculated according to the NorFor feed evaluation system. Two different silage qualities, high and low energy content, are used to achieve differences in concentrate intake. The DMI and thus the GEI, is lower for a given quantity of milk when the silage has a higher energy content than a lower energy content. This results in a lower daily methane production and, also a reduced emission of methane per kg ECM. However, the Ym is higher, which can be explained by a higher concentrate proportion for the low energy silage. This affects the rumen fermentation profile towards a higher ruminal propionate production, reducing the CH4 production. The level of Ym in Table 3 fits well with the values calculated in the NorFor's energy system, which is the most used feed evaluation system for dairy cattle in Norway. The Ym decreases with increased milk yield.

Table 3. Calculated gross energy intake (GEI), methane (CH4) production, CH4 conversion factor (Ym) and CH4 per kg energy corrected milk (ECM) at different milk yields and concentrate intake.

ECM yield, kg/day	Silage quality	Concentrate, kg /day	GEI, MJ/day	Methane, MJ/day	Ym, %	Methane per kg ECM
20	High[1]	2,1	244	16,4	6,75	0.82
20	Low[2]	4.2	274	17,7	6,44	0.88
26	High	5.9	325	20.1	6.19	0.77
26	Low	7.9	354	21,3	6.01	0.82
32	High	9.7	406	23.8	5.85	0.74
32	Low	11.6	433	24.9	5.74	0.78

[1]High silage quality: Net energy lactation = 6.13 MJ/kg dry matter; [2]Low silage quality: Net energy lactation = 5.78 MJ/kg dry matter

The EF factor is used in the national inventory report to calculate the annual enteric CH4 emission. In combination with the number of cows, information on average daily ECM yield, concentrate intake and fat content in concentrate feed the annual emission is calculated. In the EF calculation it is assumed a lactation period of 305 days and a dry period of 60 days. Table 4 present examples of annual CH4 production (kg/cow/year) at 7000, 9000 and 11000 kg ECM per cow and year, which represent an average of daily ECM of 23.0, 29.1 and 35.3 kg, respectively. In the simulations, a forage quality representing the present national average was used. Daily concentrate intake at 7000, 9000 and 11000 Kg ECM were 5.3, 9.0 and 12.6 kg, respectively. The crude fat content in the concentrate mixture was set to 50 g/kg DM.

Table 4. Annual methane (CH4) production (kg/year) per cow at different 305 days energy corrected milk yield (ECM). Assuming a 60-day dry period

ECM yield, 305 days	Average daily ECM, kg	Average daily Concentrate, kg	CH4, kg/cow/year	Ym, %
7000	23.0	5.3	118	6.79
9000	29.1	9.0	138	6.44
11000	35.3	12.6	158	6.22

In Table 4, CH4 and Ym is presented on an annual basis, including the dry period in the predicted values. This results in a lower CH4 production and a higher Ym than presented in Table 3, reflecting daily lactation situations.

4. Uncertainty

The uncertainty for the operational model was estimated using the 2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories. Following the guidelines, a 95% confidence interval was derived around the standard deviation (σ) and the predicted global average parameter (μ) using the formula:

$$\text{Uncertainty} = \pm \left[\frac{1.96 * \sigma}{\mu}\right] * 100,$$

The standard deviation was estimated as:

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_i - \mu)^2}, \text{ where:}$$

n is number of observations; x_i is the observed value; and μ is the predicted value for each n.

The number of observations was 158, the global predicted average was 22.3 MJ/d, and the standard deviation was 3.14. Using the formula, the uncertainty was then estimated to be 27.6 %. If normally distributed, 95 percent of observed values will then be within 1.96 standard deviations of the mean, whereas the remaining 5 percent will be equally distributed above and below these limits.

5. Data sources

To calculate enteric CH4 and GEI in the operational model, data on milk yield, concentrate intake and crude fat content in concentrate are needed. Daily milk yield as ECM and daily concentrate intake are obtained from the national herd recording system provided by the company Mimiro. Information on crude fat content in compound feed is found in the NorFor FAS feed table, which contain information on chemical composition of commercial concentrate mixtures. The crude fat content in concentrate mixtures has gradually increased from 1990 until today. It has increased from 40 g/kg DM to 55 g/kg DM in the period. It is suggested to implement a linear increase in crude fat content in the period from 1990 to 2022 in the dataset.

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Appendix I

Table 1. Input data to calculate methane (CH4), gross energy intake (GEI) and methane conversion factor (Ym) in the period 1990 to 2021.

Year	ECM[1], kg/cow/day	Concentrate, kg/cow/day	conCFat[2], g/kg DM[3]	GEI, MJ/day	CH4, MJ/day	Ym, %
1990	20.8	4.8	40.0	261	18.1	6.93
1991	20.5	4.8	40.5	260	18.0	6.93
1992	20.7	5.0	40.9	262	18.2	6.91
1993	21.0	5.1	41.4	265	18.3	6.88
1994	20.9	5.0	41.9	264	18.2	6.88
1995	20.7	5.0	42.3	263	18.2	6.88
1996	20.5	5.1	42.8	263	18.2	6.87
1997	20.7	5.1	43.3	264	18.3	6.86
1998	20.5	5.1	43.8	263	18.2	6.86
1999	20.0	5.0	43.3	260	18.0	6.88
2000	20.2	5.0	44.7	260	18.1	6.87
2001	20.1	4.9	45.2	259	18.0	6.87
2002	20.6	5.0	45.6	261	18.1	6.86
2003	21.0	5.1	46.1	264	18.3	6.83
2004	21.6	5.2	46.6	268	18.5	6.81
2005	22.1	5.3	47.0	270	18.6	6.78
2006	22.1	5.5	47.5	273	18.8	6.76
2007	22.8	5.7	48.0	278	19.0	6.72
2008	23.4	5.9	48.4	282	19.2	6.69
2009	23.8	6.0	48.9	285	19.4	6.67
2010	24.2	6.2	49.4	289	19.6	6.64
2011	24.0	6.4	49.8	290	19.6	6.63
2012	24.6	6.6	50.3	295	19.9	6.60
2013	25.4	6.8	50.8	300	20.2	6.56
2014	26.0	7.2	51.3	306	20.5	6.53
2015	26.7	7.1	51.7	308	20.6	6.52
2016	27.1	7.0	52.2	308	20.6	6.52
2017	26.6	7.1	52.7	308	20.6	6.51
2018	27.5	7.6	53.1	316	21.0	6.46
2019	28.2	7.5	53.6	318	21.1	6.46
2020	28.4	7.6	54.1	319	21.2	6.45
2021	28.4	7.6	54.5	320	21.2	6.44
2022	27.9	7.4	55.0	316	21.0	6.45

1ECM = energy corrected milk; [2]conCFat = Crude fat in concentrate feed;[3]DM = dry matter