A basic model to predict enteric methane emission from dairy cows and its application to update operational models for the national inventory in Norway

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Simple Summary: Many techniques exist to quantify enteric methane (CH_4) emissions from dairy cows. Since measurement on the entire national cow populations is not possible, it is necessary to use estimates for national inventory reporting. This study aimed to develop (1) a basic equation of enteric CH_4 emissions from individual animals based on feed intake and nutrient contents of the diet, and (2) to update the operational way of calculation used in the Norwegian National Inventory Report based on milk yield and concentrate share of the diet. An international database containing recently published data was used for this updating process. By this the accuracy of the CH_4 production estimates included in the national inventory was improved.

Abstract: The aim of this study was to develop a basic model to predict enteric methane emission from dairy cows and to update operational calculations for the national inventory in Norway. Basic models were developed using a database with 63 treatment means from 19 studies. The database included records for enteric CH_4 production (MJ/day), dry matter intake (DMI), and dietary nutrient composition. The basic models were evaluated against an external database (n=36, from ten studies) along with other extant models. When evaluated by low root mean square prediction errors and high concordance correlation coefficients, the developed basic models that included DMI, dietary concentrations of fatty acids and neutral detergent fiber performed slightly better in predicting CH_4 emissions than extant models. In order to propose country-specific values for the CH_4 conversion factor Y_m (% of gross energy intake partitioned into CH_4) and thus to carry out the national inventory for Norway, the existing operational model was updated for the prediction of Y_m over a wide range of feeding situations using energy corrected milk and dietary concentrate share as predictor variables. Input values of Y_m were updated based on the results from the basic models. The predicted Y_m ranged from 6.22 to 6.72%. In conclusion, the prediction of CH_4 production from dairy cows was improved with the help of newly published data, which enabled an update of the operational model for calculating the national inventory of CH_4 in Norway.

Keywords: dairy cattle; prediction model; methane conversion factor; dry matter intake; fatty acid; neutral detergent fiber

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1. Introduction

The increase in global average surface temperature over the past half-century cannot be fully explained by natural climate variability. Scientific evidence indicates that the leading cause of climate change in the most recent half century is anthropogenic. Especially damaging is the increase in the concentration of atmospheric greenhouse gases (GHG), including carbon dioxide (CO_2), chlorofluorocarbons (CFCs), methane (CH_4), tropospheric ozone, and nitrous oxide (N_2O) [1]. Animal husbandry is a major source of anthropogenic GHG emission with CH_4 and N_2O as main gases [2]. Through CH_4, dairy production systems account for, expressed in CO_2-equivalents, approximately one-half of the GHG emissions attributed to the agricultural sector. Of this, on average 81% originate from enteric fermentation and 19% from manure [3]. Enteric CH_4 arises mainly as a side-product from rumen microbial fermentation of feed, especially fibre, to volatile fatty acids (VFAs). This fermentation process generates an excess of hydrogen (H_2) that is removed in the rumen by methanogens through reduction of CO_2 to CH_4.

The factors determining the amount of enteric CH_4 produced per animal include feed dry matter intake, diet composition (i.e. digestibility), rumen microbial population, host physiology and host genetics [4]. To identify efficient mitigation strategies, the amount of CH_4 produced by the dairy system needs to be quantified as accurately as possible. Direct measurements of enteric CH_4 production (MJ/day) from cattle can be conducted using various methods, such as respiration chambers, sulphur hexafluoride (SF_6) tracer technique, and the GreenFeed (GF) system (C-Lock Inc., Rapid City, SD, USA; [5]). However, when the total national CH_4 emissions need to be assessed for an inventory these techniques are not feasible due to the sheer number of measurements which would be needed. For this purpose, often quantitative approaches such as empirical modelling have been used to estimate CH_4 production in dairy cows [6-7].

Accurate information about feed intake and dietary composition is required for good prediction but this information is available only from feeding experiments and thus for a limited number of animals, while information about milk yield and dietary concentrate share is available for the Norwegian dairy cow population from the Dairy Herd Recording System (TINE SA, Norway) for a continuous time series starting in 1990 [8]. Thus, the present study involved the development of an accurate basic model for prediction of enteric CH_4 production, and operational models for prediction of the CH_4 conversion factor (Y_m, % of gross energy intake (GEI)). The Y_m is globally used for national GHG emission inventories and research on mitigation strategies [9]. Previously, Nielsen et al. [6] published in 2013 a basic model for the prediction of enteric CH_4 emission from dairy cows based on 47 treatment means from 12 studies. This equation is currently used in the Nordic Feed Evaluation System – NorFor [8]. One year later, Storlien et al. [7] developed another basic model based on 78 treatment means from 21 studies. This later model [7], and an operational model [8] using information about milk yield and concentrate share, are those which are currently used by the Norwegian Environment Agency (Miljødirektoratet) for the National Inventory Report to the United Nations Framework Convention on Climate Change (UNFCCC) and Kyoto Protocol/Paris Agreement.

The objectives of the present study were 1) to extend the database of Storlien et al. [7] with more recent studies; 2) to develop basic models using this extended database, and evaluate them against extant models in their performance in predicting enteric CH_4 production; 3) to use our best performing basic model to predict CH_4 production and to calculate Y_m with the help of the NorFor feed analysis database (NorFor-database) [8]; and 4) to update operational models where energy-corrected milk (ECM) and dietary concentrate share in the diet were used to predict Y_m and GEI, respectively.

2. Materials and Methods

2.1. Database

The database originally used by Storlien et al. [7] was collated from 21 studies (Nordic, European, intercontinental) published from 1997 to 2013, consisting of 78 treatment means. The database was divided into two subsets, one for model development (n=42) and one for model evaluation (n=36). In the present study, the subset for model development from Storlien et al. [7] was extended by adding data published since 2013 where CH_4 production, forage proportion, dry matter intake (DMI), and contents of ether extract (EE) or fatty acids (FAs) and neutral detergent fiber (NDF) in diets for dairy cows were reported (n=21 treatment means from 8 studies, highlighted with grey background in Table 1; Nordic, European, and intercontinental origin). Treatments investigating impact of feed additives were excluded from the dataset, except for those based on lipids which are commonly used in dairy cows' diet and are frequently represented in the database. The resulting database (n=99, from 29 studies) is described in Table 1, where feed characteristics (roughage and concentrate) and CH_4 production along with corresponding DMI are presented. The roughage was mainly comprised of silage from grass, maize and alfalfa, while barley, maize and soybean meal were the main ingredients of the concentrates. The CH_4 production was determined by the sulfur hexafluoride (SF_6) gas tracer technique in 14 studies, by respiration chambers in 13 studies, by the hood calorimetry technique in one study, and by the GreenFeed system in one study.

Table 1. Summary of database for the basic models.

Data-base[a]	Stage[b]	N[c]	Roughage	Concentrate	Forage proportion (% of DM)	DMI (kg/d)[d]	CH_4 collection technique[e]	CH_4 (MJ/d)[f]	References
D	L	4	Maize silage	Ground maize	50	20	1	20 (14-26)	[10]
D	NL	4	Grass hay or barley silage	Barley grain	95	11	1	12 (11-17)	[11]
D	L	3	Grass silage	Oats, barley, peas and rapeseed cake	69	16	1	17 (16-18)	[12]
D	L	2	Grass silage	Barley, wheat and maize	73	23	1	32 (28-36)	[13]
D	L	3	Grass silage	Barley, wheat and oats	77	20	1	26 (24-28)	[14]
D	L	6	Ryegrass, white and red clover	Pelleted barley	77	19	2	24 (23-26)	[15]
D	L	3	Grass and maize silage	Barley	67	17	2	19 (17-21)	[16]
D	L	3	Alfalfa hay and alfalfa silage	Barley, maize and peas	51	26	1	23 (22-25)	[17]
D	L	4	Grass silage	Barley	70	17	1	25 (21-30)	[18]
D	NL	4	Grass silage	Wheat starch (non-NDF concentrate)	83	8	1	11 (10-12)	[19]
D	L	6	Grass silage	Wheat starch (non-NDF concentrate)	69	15	1	18 (17-19)	[20]
D	L	4	Grass silage	Oats, barley and rye	50	19	1	26 (25-28)	[21]
D	L	2	Rye grass, white clover or mature diverse pasture	0	100	21	4	27 (26-28)	[22]
D	L	1	Grass clover silage	0	100	12	2	17	[23]
D	L	1	Maize, grass/clover silage	Barley, sugar beet pulp and rapeseed cake	50	19	2	18 (16-20)	[24]
D	L	2	Hay, maize silage and grass pellets	Wheat, maize, barley, rapeseed cake	80	21	2	27 (26-28)	[25-26]
D	L	2	Maize and grass/clover silage	Whole cracked rapeseed	55	21	2	25 (23-27)	[27]
D	L	6	Maize, grass silage and hay	Oat, soybean, wheat and apple pulp	50	17	2	22 (18-25)	[3]

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D	L	3	Ryegrass	0	100	15	2	17 (16-19)	[28]
E	L	4	Grass and maize silage	Rapeseed meal, rapeseed cake, cracked rapeseed	51	18	1	20 (17-23)	[29]
E	L	6	Grass silage and maize silage	Rapeseed meal, whole crushed rapeseed	64	17	1	20 (18-22)	[30]
E	L	4	Alfalfa hay and ryegrass silage	Cracked wheat grain	63	20	2	26 (25-28)	[31]
E	L	2	Maize and grass silage	Soybean meal and rolled barley	80	17	1	18 (14-22)	[32]
E	L	2	Maize silage and alfalfa haylage	Cracked wheat grain	67	16	1	23 (21-25)	[33]
E	L	4	Barley silage	Steam rolled barley and pelleted supplement	45	18	2	15 (13-16)	[34]
E	L	2	Haylage, maize silage and high moisture maize	Maize gluten and soybean meal	59	15	3	19 (15-23)	[35]
E	L	4	Hay, grass and maize silage	Barley and wheat bran	75	17	2	22 (18-24)	[36]
E	L	4	Maize and grass silage	Rapeseed meal, sunflower meal, ground wheat and maize gluten feed	56	20	2	23 (22-23)	[37]
E	L	4	Alfalfa silage	High moisture maize and dry maize	88	24	2	25 (24-26)	[38]

[a] D, experiments used for model development; rows with background in grey indicate newly added studies; E, experiments used for model evaluation; [b] Physiological stage defined as either lactating (L) or non-lactating (NL); [c] Number of treatment means in study; [d] Mean value of dry matter intake (DMI) for experiment; [e] 1, tracer gas technique; 2, chamber; 3, head hood; 4, GreenFeed system; [f] Mean (min–max) value for experiment; the following factors were used in converting CH_4 in L/d to g/d and g/d to MJ/d: 1 L CH_4 = 0.716 g; 1 g CH_4 = 0.05565 MJ.

2.2. Development of basic models

CH_4 production was predicted by fitting mixed models to the lmer [39] procedure of R statistical language (R Core Team 2016; version 4.0.2) (Equation I):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_n X_n + R_j + \varepsilon, \quad \text{(I)}$$

where Y denotes the response variable of CH_4 production, β_0 denotes the fixed effect of intercept; X_1 to X_n denote the fixed effects of predictor variables and β_1 to β_n are the corresponding slopes; R_j denotes the random study effects of the experiment; ε denotes the within-experiment error. To account for differing accuracy in observed means, models were fitted using the WEIGHT statement in R, where the data were weighted according to the number of observations [40]. The effect of the categorical factor CH_4 measurement techniques (tracer gas, chamber, headhood, GF) was tested prior to model development and found to be not significant ($P > 0.1$), and thus was not incorporated in the models fitted. The presence of multicollinearity of fitted models was examined based on the variance inflation factor (VIF). A VIF in excess of 5 was considered an indicator of multicollinearity [41]. All parameters included in the developed models presented were significant at $P < 0.05$.

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2.3. Model evaluation

In total, ten models were evaluated, including three models developed in the present study and seven extant models with similar input variables (DMI and dietary nutrient contents). The models were compared through assessing their abilities of predicting CH_4 production, using mean squared prediction error ($MSPE$) and concordance correlation coefficient (CCC). The $MSPE$ was calculated according to Bibby and Toutenburg [42] as shown in Equation (II):

$$MSPE = \frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n} \quad \text{(II)}$$

where Y_i denotes the observed value of the response variable for the ith observation, $\hat{Y}_i$ denotes the predicted value of the response variable for the ith observation, n denotes the number of observations. The root mean square prediction error ($RMSPE$) was used to assess overall model prediction accuracy because its output was in the same unit as the observations. In the present study, $RMSPE$ was reported as a proportion of observed CH_4 production means in order to compare the predictive capability of models with different predicted means. A smaller $RMSPE$ implies a better model performance. The $MSPE$ was decomposed into error in central tendency (ECT), error due to disturbance (ED) or random error, and error due to regression (ER).

The ECT, ED and ER fractions of $MSPE$ were calculated as follows:

$$ECT = (\bar{P} - \bar{O})^2 \quad \text{(III)}$$

$$ED = (1 - R^2) \times S_o^2 \quad \text{(IV)}$$

$$ER = (S_p - R \times S_o)^2 \quad \text{(V)}$$

where $\bar{P}$ and $\bar{O}$ are the predicted and observed means, S_p is the predicted standard deviation, S_o is the observed standard deviation and R is the Pearson correlation coefficient.

According to Lawrence and Lin [43], CCC is the product of a bias correction factor as the measurement of accuracy (C_b) and the precision measurement of Pearson correlation coefficient (r). The CCC was calculated as shown in Equation (VI):

$$CCC = r \times C_b \quad \text{(VI)}$$

where

$$C_b = [(v + 1)/(v + \mu\text{^}2)/2]^{-1}$$

$$v = S_o/S_p$$

$$\mu = (\bar{P} - \bar{O})/(S_o S_p)^{1/2}$$

where $\bar{P}$, $\bar{O}$, S_o, and S_p were defined above, and v indicates a measure of scale shift, and μ indicates a measure of location shift. The CCC evaluates the degree of deviation of the best-fit line from the identity line ($y = x$), and thus, the CCC of a model that is closer to 1, is an indication of better model performance.

2.4. Update of operational models

The equation from Storlien and Harstad [44] presently used for predicting Y_m was based on calculations in NorFor (Table 2), using intervals of 500 kg from 5000 to 12000 kg of ECM. The same database with CH_4 production predicted by the basic models, GEI and Y_m was used in the present study for the development of operational models. The standardized lactation curves in NorFor were employed to predict animal requirement for ECM production through the lactation cycle. Daily DMI was calculated for every second lactation week for each 500 kg interval of the 305-day lactation. Feed energy (GE, metabolizable energy (ME), and net energy (NE)), animal energy requirements, and energy supplementation were calculated based on the Dutch net energy lactation (NEL) system as modified by NorFor [8].

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Table 2. Mean (min-max) value of concentrate share, DMI and GEI throughout a 305-day lactation with various combinations of silages and concentrates at different levels of ECM production[a] in the NorFor-database used for the operational models.

Yield (ECM, kg)	Silage[b]	Concentrate[c]	Concentrate share, % DM	DMI, kg/d	GEI, MJ/d
5000	1	I	11 (0-37)	15 (12-17)	279 (232-312)
	2	II	20 (0-53)	15 (12-17)	282 (228-327)
	3	II	25 (0-50)	16 (12-18)	292 (233-340)
5500	1	III	13 (0-40)	15 (13-17)	289 (242-323)
	2	III	16 (0-38)	16 (13-17)	292 (245-323)
	3	II	29 (10-51)	16 (12-19)	305 (232-355)
6000	1	III	14 (0-40)	16 (14-18)	300 (255-331)
	2	I	23 (3-47)	16 (14-19)	307 (253-352)
	3	II	32 (9-52)	17 (14-20)	319 (252-368)
6500	1	III	16 (0-43)	17 (14-18)	310 (261-342)
	2	I	22 (4-47)	17 (14-19)	316 (268-350)
	3	III	35 (11-52)	18 (14-20)	333 (267-383)
7000	1	II	21 (1-53)	17 (15-19)	324 (276-359)
	2	III	23 (7-45)	17 (15-19)	322 (276-354)
	3	II	39 (16-55)	19 (15-21)	347 (279-398)
7500	1	III	20 (4-47)	18 (15-19)	330 (284-362)
	2	I	32 (15-53)	18 (15-21)	345 (278-394)
	3	II	42 (21-57)	19 (16-22)	361 (292-412)
8000	1	III	22 (7-49)	18 (16-20)	340 (294-371)
	2	I	35 (17-54)	19 (16-22)	359 (291-407)
	3	II	45 (26-59)	20 (16-23)	376 (307-427)
8500	1	III	24 (10-50)	19 (16-20)	350 (303-383)
	2	I	37 (18-55)	20 (16-22)	372 (308-422)
	3	II	47 (30-61)	21 (17-24)	390 (320-442)
9000	1	III	26 (12-52)	19 (17-21)	360 (313-393)
	2	I	40 (21-57)	21 (17-23)	386 (319-436)
	3	II	50 (34-63)	22 (18-24)	405 (334-457)
9500	1	I	38 (23-59)	21 (17-23)	387 (315-437)
	2	I	43 (25-59)	21 (18-24)	400 (332-451)
	3	I	49 (35-61)	22 (18-25)	413 (346-464)
10000	1	I	39 (23-60)	21 (18-24)	401 (332-452)
	2	I	45 (29-60)	22 (18-25)	414 (346-466)
	3	I	52 (38-62)	23 (19-25)	427 (358-477)
10500	1	I	41 (23-62)	22 (19-25)	415 (348-467)
	2	I	48 (32-61)	23 (19-25)	429 (359-480)
	3	I	54 (41-64)	23 (20-26)	441 (370-491)
11000	1	I	43 (25-63)	23 (19-26)	429 (358-480)
	2	I	50 (35-62)	24 (20-26)	443 (372-495)
	3	I	57 (43-67)	24 (20-27)	454 (381-504)
11500	1	I	46 (29-64)	24 (20-26)	443 (373-496)
	2	I	52 (38-63)	24 (21-27)	457 (388-510)
	3	I	59 (46-70)	25 (21-27)	468 (393-518)
12000	1	I	48 (32-65)	24 (21-27)	458 (387-511)
	2	I	54 (41-65)	25 (21-28)	472 (401-525)
	3	I	59 (48-68)	26 (21-28)	484 (404-537)

[a] The standardized lactation curves in the Norfor-database were employed to predict animal requirement for ECM production through the lactation cycle; [b] 1, 2 and 3 refer to code for silages in Table 3; [c] I, II and III refer to code for concentrates in Table 3. Silages 1, 2 and 3 represent a normal range in forage qualities found in the Norwegian cattle production; the combinations of silage and concentrate were determined on the basis of minimum cost when the energy requirements of the animal are met.

The data predicts standard feed rations during a 305-day lactation at different lactation yield, using three different forage qualities (Table 3), 5.7, 6.1 and 7.0 MJ NEL per kg DM, representing low, medium, and very high energy content, respectively. Three complimentary concentrate mixtures, which are representative of what is used in practical diet formulation in Norway, were used in the diet formulation to meet the animal energy requirement (Table 3).

Table 3. Chemical composition (per kg of dry matter) of silages and concentrates in the NorFor[a]-database used for the operational models.

Feed type	Code	Nutritional value	DM (g/kg)	Ash (g)	Crude protein (g)	Crude fat (g)	NDF[b] (g)	Total acids (g)	Sugar (g)	Starch (g)	Net energy for lactation (MJ)
Silage	1	Very high	332	77	167	39	436	62	92	n.d.	7.0
	2	Medium	325	70	157	35	511	63	53	n.d.	6.1
	3	Low	320	68	150	34	538	64	43	n.d.	5.7
Concentrate[c]	I	High	879	83	200	59	182	n.d.	n.d.	301	8.0
	II	Medium	873	76	194	52	208	n.d.	n.d.	307	7.7
	III	Low	873	76	182	46	202	n.d.	n.d.	390	7.5

[a] NorFor: Nordic Feed Evaluation System [8]; [b] NDF: Neutral detergent fiber; [c] Concentrates with high (I), medium (II) and low (III) net energy content were FORMEL Energi Premium 80, FORMEL Elite 80 and FORMEL Favør 80, respectively (Felleskjøpet Agri, Lillestrøm, Norway); n.d.: not determined.

To observe the effects of different basic models on the output of operational models, the basic model that performed the best in predicting CH_4 production, and models from Storlien et al. [7] and Nielsen et al. [6] were selected to predict CH_4 production, respectively, and thus to calculate Y_m in the NorFor-database. Three operational models were therefore developed, in which the response variable was Y_m, and the input variables were ECM and concentrate share in the diet. Moreover, GEI was also predicted with the same input variables. The Y_m and GEI were estimated by fitting a mixed effect model using the lmer [40] procedure of R statistical language (R Core Team 2016; version 4.0.2). The model employed is shown in Equation (VII):

$$Y = b_0 + b_1X_1 + b_2X_2 + b_nX_n + S_j + \epsilon, \quad \text{(VII)}$$

where Y denotes the response variable of Y_m or GEI, b_0 denotes the fixed effect of intercept; X_1 to X_n denote the fixed effects of predictor variables and b_1 to b_n are the corresponding slopes; S_j denotes the repeated effect of days after lactation at each ECM production level; ϵ denotes the error within a lactation cycle. The following equation was used to calculate the CH_4 emission factor (EF) for 365 days, which can be used for estimating national CH_4 emissions when the number of animals is known:

$$\text{EF} = (\text{GEI} \cdot Y_m \cdot 365\ \text{days/yr}) / 55.65\ \text{MJ/kg}\ CH_4 \quad \text{(VIII)}$$

where EF denotes emission factor (kg CH_4/head/year); GEI denotes gross energy intake (MJ/head/day); Y_m denotes CH_4 conversion rate, which is the fraction of gross energy in feed converted to CH_4.

3. Results

3.1. Development and evaluation of basic models

Models 1, 2 and 3, which were developed in the present study, and other extant models, are presented in Table 4 with results of model evaluations. The models were arranged in descending order of CCC. Overall, the developed models and models from Storlien et al. [7] and Nielsen et al. [6] performed better than other extant models with respect to prediction accuracy ($RMSPE$ & CCC), except that the lowest $RMSPE$ was found in one of the models from Niu et al. [9] yet with low CCC. The overall performance of the extant models using only DMI as input variable did not perform as

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good as models where dietary FAs and/or NDF were included as input variables in addition to DMI. Model 1 slightly outperformed the model from Storlien et al. [7], judged by $RMSPE$ (15.0 versus 15.3), owing to smaller ER. When NDF together with DMI and FAs was included as input variables in the models, evaluation through CCC and $RMSPE$ indicated that model performances were improved (Model 2 and 3, as well as the Nielsen et al. [6] model). Model 2 and 3 performed even better, indicated by lower $RMSPE$ and higher CCC, compared to the Nielsen et al. [6] model. It was assumed that cows are not emitting nor inhaling CH_4 if they are not eating, hence the intercept was forced to zero in Model 2 to have Model 3 developed. The performance was somewhat compromised for Model 3 as compared to Model 2 mainly due to increased ED (Table 4).

Table 4. Evaluation of developed and extant basic models ordered by decreasing CCC.

Model	n	Prediction equation	$RMSPE$, %	ECT, %	ED, %	ER, %	CCC	r	C_b
Model 2	36	CH_4 = – 3.01 + 1.19 × DMI – 0.103 × FAs + 0.017 × NDF	13.8	0.2	86.1	13.7	0.703	0.70	1.00
Model 3	36	CH_4 = 1.13 × DMI – 0.114 × FAs + 0.012 × NDF	13.9	0.1	87.3	12.6	0.694	0.69	1.00
[6]	36	CH_4 = 1.23 × DMI – 0.145 × FAs + 0.012 × NDF	15.3	3.1	73.1	23.8	0.677	0.69	0.99
Model 1	36	CH_4 = 4.92 + 1.13 × DMI – 0.118 × FAs	15.0	0.9	82.8	16.3	0.650	0.65	1.00
[7]	36	CH_4 = 6.80 + 1.09 × DMI – 0.15 × FAs	15.3	0.6	79.3	20.1	0.649	0.65	1.00
[9]	36	CH_4 = 26.0 + 15.3 × DMI + 3.42 × NDF/10 × 0.05565	13.0	0.0	97.6	2.40	0.611	0.70	0.87
[46]	36	CH_4 = (38.0 + 19.22 × DMI) × 0.05565	15.6	5.2	89.0	5.80	0.547	0.58	0.95
[9]	36	CH_4 = [160 + 14.2 × DMI – 13.5 × EE/10] × 0.05565	15.6	14.8	84.0	1.20	0.528	0.60	0.87
[9]	36	CH_4 = (107 + 14.5 × DMI) × 0.05565	14.8	0.7	99.2	0.00	0.504	0.58	0.87
[47]	36	CH_4 = (20 + 35.8 × DMI – 0.5 × DMI^2) × 0.716 × 0.05565	15.4	8.2	90.9	0.90	0.434	0.57	0.76

n, number of treatment means; CH_4, methane (MJ/d); DMI, dry matter intake (kg/d); EE, ether extract content (g/kg DM); FAs, fatty acid content (g/kg DM); NDF, neutral detergent fiber content (g/kg DM) if not indicated otherwise; $RMSPE$, root mean squared prediction error expressed as a percentage of the observed mean and in MJ; ECT, error due to bias, as a percentage of total $MSPE$; ER, error due to regression, as a percentage of total $MSPE$; ED, error due to the disturbance, as a percentage of total $MSPE$; CCC, concordance correlation coefficient; r, Pearson correlation coefficient; C_b, bias correction factor;

Plots of observed versus predicted values of enteric CH_4 production and the residuals (observed minus predicted) for Model 3 and models from Storlien et al. [7] and Nielsen et al. [6] are presented in Figure 1. These three models were selected to calculate CH_4 production in the NorFor-database, respectively.

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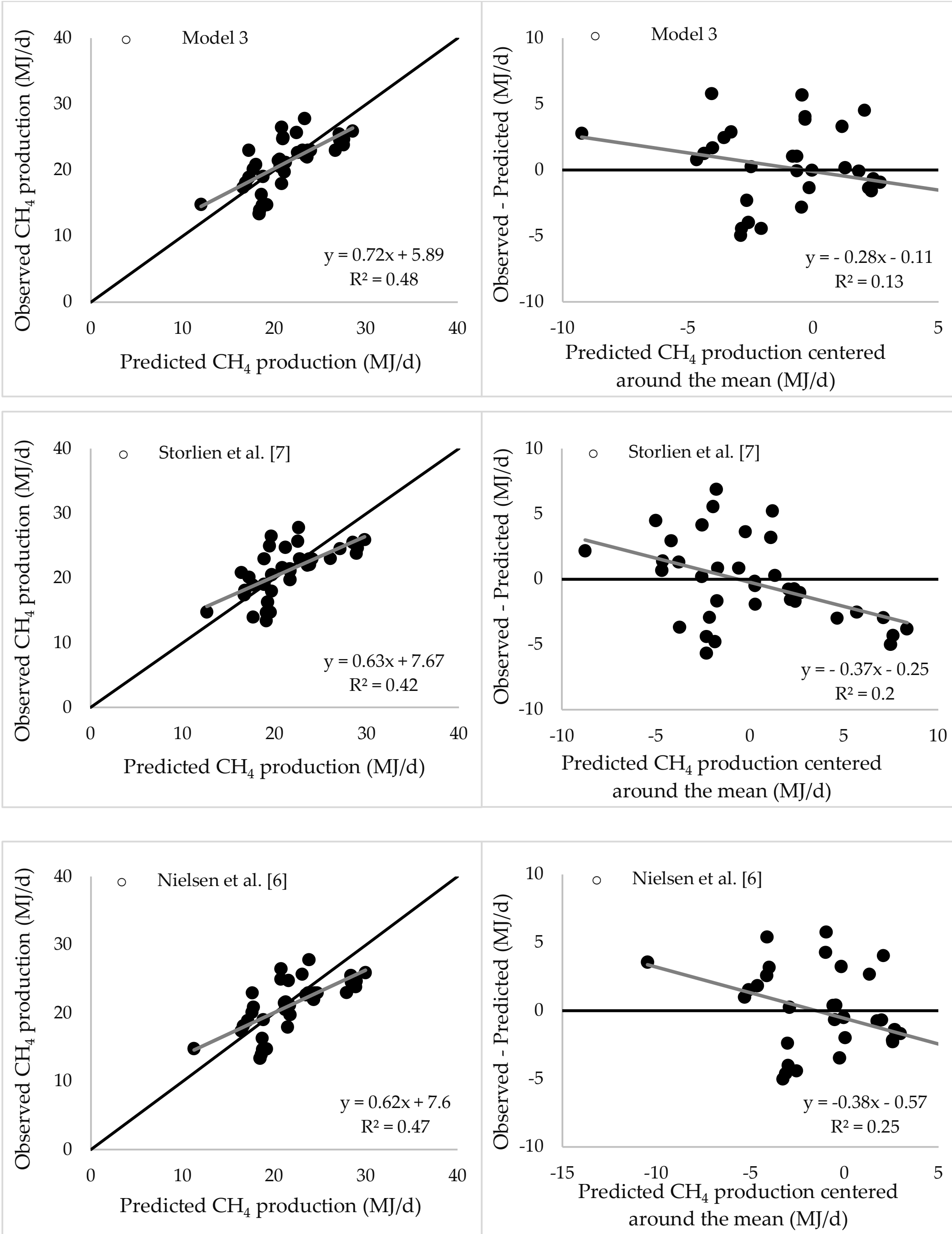

Figure 1. Observed versus predicted values of enteric CH_4 production and the residuals (observed minus predicted) for basic models currently used in Norway and the Model 3 developed in the present study. The graphs to the left show that the models overestimate CH_4 emissions at the lower range and underestimate emissions at the upper range. The graphs to the right show the presence of a linear bias (slope) and the presence of a mean bias (intercept).

3.2. Update of operational models

The operational models for the prediction of Y_m and GEI are presented in Table 5. There was a significant positive relationship between GEI and both ECM and concentrate share. When estimating Y_m, both predictor variables were negatively correlated to the response variable.

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Table 5 shows the annual production of CH_4 assuming an annual milk yield of 6000, 8000 and 10000 kg ECM and an averaged concentrate share of 38.0, 43.5 and 50.0%, respectively. These are typical concentrate shares in Norway where concentrate is used on all dairy farms. When milk yield and concentrate share were increased, Y_m was predicted to decrease in all models, whereas GEI and the CH_4 emission factor were predicted and calculated to increase, respectively. At a production level of 6000 kg ECM and a 38% concentrate share, when the prediction of Y_m was obtained through the model from Storlien et al. [7], the prediction of $Y_{m(S)}$ (see footnote to Table 5) and the CH_4 emission factor (127.7 kg/year per cow) were the lowest. On the contrary, using the model from Nielsen et al. [6] to predict CH_4 production and Y_m under the same conditions with the NorFor-database led to the highest predicted values of both $Y_{m(N)}$ (see footnotes to Table 5) and the CH_4 emission factor. The same ranking for both Y_m and the CH_4 emission factor was found at a production level of 8000 kg ECM and a 43.5% concentrate share, while the differences among predictions of $Y_{m(S)}$, $Y_{m(M)}$ (see footnotes to Table 5) and $Y_{m(N)}$ were decreased. At a production level of 10,000 kg ECM and a 50% concentrate share, predictions of $Y_{m(M)}$ and correspondingly the CH_4 emission factor were the lowest, which were 6.22 and 163.7 kg/year per cow, respectively.

Table 5. Operational models: CH_4 emission factors (kg/year per cow), Y_m, and GEI, estimated using selected basic models at production levels of 6000, 8000 and 10,000 kg energy corrected milk (ECM) assuming 38.0, 43.5 and 50.0% concentrate share in the rations, respectively.

Model[a]	CH_4, kg/year per cow[b]	Y_m[c], %	GEI[d], MJ/cow and day
GEI = 159 + 0.02 × ECM + 1.39 × conc.share			
	6000 kg ECM and 38.0 % concentrate share		
$Y_{m(S)} = 7.11 - 7 \times 10^{-5} \times ECM - 4.1 \times 10^{-3} \times$ conc.share	127.7	6.53	298
$Y_{m(M)} = 7.65 - 1.1 \times 10^{-4} \times ECM - 5.4 \times 10^{-3} \times$ conc.share	130.2	6.66	298
$Y_{m(N)} = 7.71 - 1 \times 10^{-4} \times ECM - 4.4 \times 10^{-3} \times$ conc.share	131.5	6.72	298
	8000 kg ECM and 43.5 % concentrate share		
$Y_{m(S)} = 7.11 - 7 \times 10^{-5} \times ECM - 4.1 \times 10^{-3} \times$ conc.share	146.5	6.40	349
$Y_{m(M)} = 7.65 - 1.1 \times 10^{-4} \times ECM - 5.4 \times 10^{-3} \times$ conc.share	147.8	6.45	349
$Y_{m(N)} = 7.71 - 1 \times 10^{-4} \times ECM - 4.4 \times 10^{-3} \times$ conc.share	150.6	6.57	349
	10,000 kg ECM and 50.0 % concentrate hare		
$Y_{m(S)} = 7.11 - 7 \times 10^{-5} \times ECM - 4.1 \times 10^{-3} \times$ conc.share	164.5	6.25	401
$Y_{m(M)} = 7.65 - 1.1 \times 10^{-4} \times ECM - 5.4 \times 10^{-3} \times$ conc.share	163.7	6.22	401
$Y_{m(N)} = 7.71 - 1 \times 10^{-4} \times ECM - 4.4 \times 10^{-3} \times$ conc.share	168.2	6.39	401

[a] $Y_{m(S)}$, $Y_{m(M)}$ and $Y_{m(N)}$ denotes Y_m calculated based on GEI (Norfor-database) and CH_4 production which was predicted using the model from Storlien et al. [7], Model 3 and the model from Nielsen et al. [6], respectively; [b] Including 60 d of dry period through inclusion of dry cows in the model for predicting daily CH_4 production (MJ); [c] Y_m, methane conversion factor (% of GEI); [d] GEI: gross energy intake.

4. Discussion

The aims of the present study were to develop a basic model which can be used as a method for the accurate calculation of enteric CH_4 emissions from individual dairy cows, and to update the existing operational model for the prediction of Y_m and the CH_4 emission factor to be used in the national GHG inventory in Norway.

4.1. Relationship between methane production and dietary factors in the basic models

In the present study, DMI and dietary concentrations of FAs and NDF were used and confirmed as key predictor variables for CH_4 production in dairy cows. DMI was the most important variable for the prediction of enteric CH_4 production in all models evaluated. The significant positive relationship is consistent with the knowledge that CH_4 production increases with feed intake due to the greater availability of substrate for microbial fermentation [8,48,49]. A linear relationship between DMI and CH_4 production has been observed in many studies [6,7,46]. However, an increased intake potentially increases passage rate of feed through the rumen, resulting in a decline in rumen

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fermentation and CH_4 production per unit of feed [50]. Subsequently, the percentage of gross energy lost as CH_4 declines [9], but at the same time digestibility may decline resulting in an unchanged methane emission intensity per unit of milk or meat produced. Nevertheless, the first assumption implies that in theory a model of CH_4 production based on DMI, GEI or MEI, should be nonlinear [8]. The only nonlinear model [47] that was evaluated in the present study did not perform as robust as others, which may be due to that only feed intake was accounted for in their model. This could be justified by Bell et al. [51], where the residual variation (difference between observed and predicted values) in CH_4 emission was notably reduced after incorporating the significant fixed effects of dietary characteristics on CH_4 yield, in addition to the effect of feeding level.

In the present study, the accuracy of prediction was better with the inclusion of dietary fat content in the equation compared to extant models where only DMI was used, and there was a significant negative relationship between fat and CH_4 production. This was facilitated by not excluding experiments where fat had been supplemented. Indeed, CH_4 production decreases through fat supplementation in the diet, as reviewed and studied by several groups [11,34,51]. The mode of action of fat on CH_4 mitigation has been extensively studied. The effect is based on the following components. 1) Biohydrogenation of unsaturated fatty acids utilizes H_2 available for CH_4 production. However, the complete biohydrogenation of one mol of linoleic acid can reduce CH_4 production only by one mol and thus this is not quantitatively important [47]. 2) As fat is not fermentable, part of the reduced CH_4 production with increased dietary fat concentration can be accredited to decreased supply of fermentable substrate for the microorganisms also reducing hydrogen production [53]. 3) The most important component is a direct toxicity of fatty acids, especially that of lauric and myristic acid and polyunsaturated fatty acids, exhibiting against the archaeal methanogens [54]. 4) Finally, dietary fat concentration directly influences rumen fermentation by favouring propionate production at a cost of acetate or butyrate, or both, because protozoa are inhibited as well which results in declines in fibre digestion and hydrogen supply [55].

The accuracy of prediction was further improved when dietary NDF concentration was included in the equations along with DMI and fat, and there was a significant positive relationship between NDF and CH_4 production as expected from earlier studies [6,56]. Studies focusing on the effect of different types of carbohydrates, indicate that high concentrations of starch and sugar (non-fibrous carbohydrates) increase the production of propionate but decrease that of acetate and butyrate, and the opposite is true for NDF (fibrous carbohydrates) [53,56]. The CH_4 production is thus related to the VFA profile in such a way that higher NDF increases CH_4 production by shifting short chain fatty acid proportion towards acetate which is associated with a higher hydrogen release [57].

Model 3 was developed from Model 2 by applying biologically sensible constraints, e.g. zero CH_4 at zero intake [8]. In the current study, Model 3 was selected based on model performance as the updated model over models from Nielsen et al. [6] and Storlien et al. [7]. Different from the Storlien et al. [7] equation, Model 3 allows for considering effects of NDF concentration in the feed in addition to fat concentration. The concentration of NDF will vary with forage proportion and quality in the diet. A positive coefficient for NDF reflected reduced CH_4 production by earlier harvesting of grass for silage as NDF concentration in grass increases with harvesting time. Model 3 has the same input variables as the Nielsen et al. [6] equation but yields slightly lower estimates of the comparatively high CH_4 emission factor in Norway (Table 5).

4.2. Update of operational models

The NorFor-database applied in the present approach is still the same as that used by Storlien and Harstad [44], and the calculation of GEI remained unchanged. No major changes in milk yield and quality of silage and concentrate have taken place since 2015 (pers. com. TINE and Felleskjøpet Fôrutvikling), and therefore, it was considered to be not necessary to recalculate the NorFor-data, except for values of CH_4 production. However, since input data of predicted enteric CH_4 production was changed, equations for prediction of Y_m based on ECM and concentrate share also changed. Many studies have suggested using factors such as fibre digestion [58-59] and dietary lipid content [60], either as the single or multiple variables of a Y_m model. However, in the present study a country-

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specific approach was used for the prediction of Y_m using the same method as Storlien and Harstad [44]. This approach allows for the incorporation of country-specific information in the development of equations, whereas data on fibre and lipids are not readily available. In the Norwegian cow recording system (CRS) individual milk yield and concentrate supplementation is reported 11 times per cow per year, and data from 1.16 million individual cow observations are available [8]. In order to develop representative Y_m for the about 200,000 Norwegian dairy cows it was essential to take into account the effect of dietary composition and the experiments using grass-based diets which were considered when updating CH_4 production in the NorFor-database. From Table 5 the predicted Y_m ranged from 6.22 to 6.72%, which is within the range of the IPCC default Y_m of 6.5% ± 1% [61]. This default value is recommended by IPCC [61] for all types of cattle and buffalo, except feedlot cattle fed at least 90% concentrate. However, the lowest predicted value 6.22% was yet higher than that given by Hellwing et al. [62] for Danish dairy cows, which was 6.02% and 5.98% of GE intake for Holstein and Jersey cows, respectively. Accordingly, Lesschen et al. [63] concluded that within the EU countries, the GHG emission per kilogram milk produced was lowest in Denmark. The discrepancies across countries can possibly be explained by differences in diet composition, as there is a higher dietary proportion of forage in Norway, and milk yield is moderate compared to other European countries and USA. With increasing milk yield and concentrate share, Y_m decreases, whereas the CH_4 emission factor increases. This is due to the fact that more energy is allocated to milk production, as the CH_4 emission in kg per kg ECM decreased. These results are in accordance with those reported by Kirchgessner [64] and Volden and Nes [8]. Accordingly, CH_4 emission decreases by 2.8 g/kg milk and 41.4% of total CH_4/milk per day when milk production is increased from 4000 to 6000 kg and from 5000 to 9000 kg, respectively.

The value of operational models is dependent on correct and annually updated reporting of average annual milk yield and concentrate share of dry matter intake. In addition, an updated basic model could help refining the estimates of CH_4 production, which could ultimately improve the estimate of Y_m. As discussed above, it is possible by using the above information to develop a robust model for use in Norway for the calculation of enteric CH_4 emission from dairy cows. Further, the recommended equation is well suited for improving the CH_4 emissions estimates of the farm level net GHG model HolosNor [65]. The HolosNor is used as an advisory tool [66], and the implementation of Model 3 developed in the current work will be helpful for quantifying and advising mitigation strategies at farm level. In the current models developed, the effects of dietary changes were considered only indirectly through calculation of Y_m using basic models. Therefore, a further improvement in the prediction accuracy might be expected for a tier 3 model that includes also a dynamic and mechanistic model of fermentation biochemistry to calculate enteric CH_4 emission inventories [67,68].

5. Conclusions

Three basic models were developed in this study. Among them, Model 3 with DMI, dietary concentrations of FAs and NDF as input variables, turned out to predict CH_4 production more accurately than the extant models from Nielsen et al. [6] and Storlien et al. [7]. The updated operational model includes region-specific Y_m in the national inventory. Using a basic model database containing recently published data improved CH_4 production estimates in the operational model. Hence, this basic (Model 3) and updated operational equation for calculation of enteric CH_4 emission from individual dairy cows in Norway is currently used by the Norwegian Environment Agency (Miljødirektoratet) since 2019. This is essential to improve accuracy of carbon footprint assessment of dairy cattle production systems and to help quantify and communicate effective mitigation strategies.

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