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Measurements of methane emissions in Icelandic dairy herds, evaluation of methane prediction models and application of results to update calculation methods for the National Inventory in Iceland

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ABSTRACT

The aim of the study was to update methods for calculating dairy cow enteric methane emissions for the National Inventory in Iceland. The first two phases in our study were: 1) to measure methane emissions in Icelandic dairy herds; 2) to use the data obtained to validate several existing models for predicting enteric methane emissions at the on-farm level. These models are developed from accurate information from planned experiments about feed intake, dietary composition and methane emissions that are not available at the country level. One of the two best performing models in this evaluation was the model used by the Norfor ration optimiser at the time of the study. The two later phases in our study were: 3) to create a database with feed plans simulated by the Norfor ration optimiser, covering a wide range of production levels and feed composition, with methane emissions predicted by Norfor's model tested in phase 2; 4) to fit methane emissions predicted in phase 3 to different combinations of explanatory variables available at the country level and select the most applicable model for predicting methane emissions for the National Inventory in Iceland. Our findings suggest that energy corrected milk yield, amount of concentrates per cow and year, and the content of fatty acids in concentrates are the most important input variables for this purpose. Recommendations are presented regarding: a) how these input variables can be obtained at country level, and b) how to update the operational way of calculation used in the Icelandic National Inventory Report.

Keywords: Methane, GHG, dairy cows, Icelandic breed, Norfor, models, predictions.

YFIRLIT

Mælingar á metanlosun frá íslenskum mjólkurkúm, prófun á spálíkönum fyrir metanlosun og notkun niðurstaðna til að uppfæra reikniaðferðir fyrir Loftslagsbókhald Íslands

Markmið rannsóknarinnar var að uppfæra reikniaðferðir Loftslagsbókhalds Íslands fyrir metanlosun (CH_4) frá mjólkandi íslenskum kúm. Fyrstu tveir áfangarnir í rannsókninni voru: 1) Gögnum var safnað á þremur kúabúum um CH_4 losun frá iðragerjun íslenskra mjólkurkúa; 2) Þessi gögn voru notuð til að meta getu nokkurra líkinga til að spá fyrir um metanlosun íslenskra mjólkurkúa. Þessar líkingar eru þróaðar út frá nákvæmum upplýsingum úr skipulögðum tilraunum, um fóðurát, efnasamsetningu fóðurs og metanlosun, sem ekki eru að jafnaði aðgengilegar á landsvísu. Önnur þeirra líkinga sem kom best út í þessum prófunum er sú sem Norfor-fóðurmatskerfið notar. Tveir seinni áfangarnir í verkefninu voru: 3) Að mynda með Norfor-fóðurmatskerfinu gagnagrunn með fóðuráætlunum sem spanna vítt svið framleiðslustigs og fóðursamsetninga þar sem metanlosun frá iðragerjun var metin með áðurnefndri líkingu; 4) Tölfræðileg greining á gagnagrunninum var gerð með það að markmiði að finna sem hentugast vinnulíkan til að meta iðragerjun mjólkurkúa fyrir Loftslagsbókhald Íslands. Á grundvelli niðurstaðna er mælt með að vinnulíkanið hafi eftirfarandi skýribreytur: *árleg* meðalnyt af orkuleiðréttri mjólk, kjarnfóðurmagn *á* kú á *ári* og hlutfall fitusýra í kjarnfóðri. Kynntar eru ráðleggingar um a) hvernig afla má upplýsinga um þessar breytur á landsvísu á hverjum tíma og b) hvernig uppfæra má reikniaðferðir fyrir Loftslagsbókhald Íslands á grunni þessara niðurstaðna.

INTRODUCTION

In ruminants, enteric methane (CH_4) is a byproduct from rumen microbial fermentation of feed to volatile fatty acids (VFA). Ruminal fermentation processes generate an excess of hydrogen that is reduced in the rumen by methanogens with reduction of CO_2 to CH_4. Many factors affect the amount of enteric CH_4 produced. Among them are the animal production level, dry matter intake, diet digestibility, diet composition, rumen microbial population, animal physiology and dietary additives (Ouatahar et al. 2021). The Icelandic breed is the only dairy cow breed in Iceland, and it only exists in Iceland. The cows are smaller and have low yields compared to most dairy cow breeds. Until recently, enteric CH_4 production of Icelandic dairy cows had not been directly measured. It has been assessed by the Environment Agency of Iceland (Umhverfisstofnun) with a generic method for estimating enteric CH_4 from cattle in the National Inventory Report to the United Nations Framework Convention on Climate Change (UNFCCC) and Kyoto Protocol/Paris Agreement. The method, following the simplest Tier 2 methodology (Tier 2a as defined by Vibart et al., 2021) involves calculating Gross Energy (GE) of annual feed intake values. The GE intake is then multiplied by a methane conversion rate (Y_m) of 6.5%, assuming that 6.5% of GE in the feed is converted to CH_4 (Keller et al. 2024).

Due to conversion of all feed values to GE and using a fixed CH_4 conversion rate, the method does not take into account how a difference in feed composition could affect enteric CH_4 emissions. Models for enteric CH_4 emission have been developed to predict CH_4 production more accurately by taking the effect of feed intake and feed composition on Y_m into account. Nielsen et al. (2013) published different models for the prediction of enteric CH_4 emission from dairy cows, based on 12 studies carried out in Norway, Sweden and Denmark. One of these equations is used to predict enteric methane production in the Nordic Feed Evaluation System -NorFor (Norfor 2023). The Nielsen et al. (2013) model is also used by the Swedish Environmental Protection Agency to predict methane emissions from dairy cows. To estimate actual feed intake and composition for predicting methane emissions at the country level, standard diets have been used, when available, together with other surveys concerning feeding of cattle (Carlén et al. 2024). Denmark's National Inventory also uses similar methodology; a model was developed to estimate methane conversion factor (Y_m), based on feed ration information compiled from practical dairy farms (Hellwing et al. 2016, Nielsen et al. 2024).

When dry matter intake (DMI) and chemical composition of the feed rations are known, models including such parameters give a good estimate of enteric CH_4 emission (Nielsen et al. 2013, Niu et al. 2021). In practical situations, information on DMI and chemical composition of the diet is often missing. Therefore, to predict CH_4 emissions with data available on the country level, a different approach may be needed. The methodology applied in the latest Norwegian National Inventory (Rønning et al. 2024) is a good example of this. There, a methane prediction model developed from dairy cow studies included daily DMI and content of fat and neutral detergent fibre (NDF) in the total diet. The operational model for the National Inventory based on this includes an intercept, energy-corrected milk (ECM, kg d^{-1}), concentrate (kg d^{-1}) and concentration of fat in concentrate (g kg DM^{-1}). These variables can all be obtained both at the country and farm levels. The annual methane production is then calculated by multiplying daily production with 305 and using the intercept for the remaining 60 days (Volden et al. 2023).

Iceland currently has no facilities for

measuring individual feed intake of cattle. That has not always been the case. Historically, feed intake of Icelandic dairy cows has been measured in a number of feeding trials. Based on older trials, Baldursdóttir (2010) developed prediction models for intake capacity of Icelandic dairy cows for the NorFor feeding system.

The Agricultural University of Iceland recently obtained a GreenFeed (GF) unit for measuring methane emissions of cattle. In comparison to respiratory chambers (RC), which are the "golden standard", a GF system accurately estimates rumen CH_4 and CO_2 emission rates if the number of measurements are sufficient (Hristov et al. 2018, McGinn et al. 2021). Due to its design and compact size, the GF unit is more versatile than RC and can be moved with ease among farms and can get measurements from larger groups. This opened the possibility to collect data that could be used to improve predictions of enteric methane emissions from Icelandic dairy cows.

The objectives of the present study were: 1) to measure methane emissions in Icelandic dairy herds; 2) to use the data obtained to validate several existing models for predicting enteric methane emissions at the on-farm level; 3) to use one of the two best performing methane prediction models with the Norfor ration optimiser to create a database with feed plans and methane predictions covering a wide range of production levels and feed composition; 4) to use methane emissions predicted in phase 3 to fit different combinations of explanatory variables available at the country level and select the most applicable model for predicting methane emissions for the National Inventory in Iceland.

MATERIALS AND METHODS

Phase 1: Measurements of methane emissions in three dairy herds

Farms, animals, management and data collection

Three Icelandic dairy farms collaborated in a study that took place from September 2022 to June 2023. More exactly, September to October 2022 on Farm 1, February to March 2023 on Farm 2 and April to May 2023 on Farm 3. On all three farms, cows of the Icelandic breed were housed, without access to grazing, in free stall barns with one milking robot. The herd size ranged from 50 to 70 lactating cows. Roughage or partially mixed ration (PMR) were offered ad lib on a feed alley, and concentrates were rationed in milking robots and in additional concentrate feeders, based on milk yield of individual cows.

One GreenFeed (GF) unit (C-Lock Inc., Rapid City, SD) was placed in the dairy barn and operated according to manufacturer's instructions, in order to estimate individual cow daily CH_4 and CO_2 emissions. Pelleted concentrates stored in a hopper fitted on the GF unit were used as a bait. Animals were identified by an EID tag placed in an ear or on a neck collar, and sampling was activated when the animals head was located close to the sampling inlet within the feeder. The GF was set to distribute 8 drops of feed (≈ 40 g/drop) every 35 sec per animal and per visit. Daily visits were limited to 4 per day with a minimum of 5-h intervals to ensure good distribution of visits over the day. Exhaled gases from the animal at each visit were collected, filtered for dust, and the air outflow rate was measured. CH_4 and CO_2 concentrations were measured by a nondispersive infrared sensor. CH_4 and CO_2 emissions (g d^{-1}) were calculated from CH_4 and CO_2 concentrations and air flow during the animal's visits to the feeder, corrected by background CH_4 and CO_2 concentrations and air flow and by air temperature. Prior to use, all data from the GF unit were quality checked by the C-Lock data team. If some data were incomplete (visits too short, bad head position, for example), they were excluded from the final data used in the statistical evaluation. Further details of how the GF unit operates are provided by Hammond et al. (2015) and Hristov et al. (2015). All cows in the herd had access to the unit during an adaptation time that was a minimum of 2 weeks.

After the adaptation time within each herd, approximately 40 lactating cows with good attendance (≥10 visits per cow in 2 weeks) to the GF unit were selected for a 3-week data collection period. This group was selected as representative of the herd distribution with respect to lactation number, milk yield and days after calving. Samples were taken from roughages on each farm, representing daily feed offered ad lib. Apart from CO_2 and CH_4 measurements, all data were collected from the herd management systems on the farms: age, parity, days in milk, daily milk yield (kg d^{-1}) and information about concentrates offered (kg d^{-1}) in the GF unit, milking robots and concentrate feeders. On Farm 1, body weight and milk composition during the data collection period were also registered. Available individual cow data were averaged, representing an average day during the data collection period. Seven cows, 1-3 per farm, with fewer than 14 visits to the GF unit were excluded from the dataset. The removal of these cows did not have any considerable effect on how representative the cows in the final dataset were for the farms. The dataset included CH_4 and CO_2 production (g d^{-1}), total amount of different concentrates mixtures fed (kg d^{-1}), days from parturition, parity, milk composition and milk yield (kg d^{-1}). Milk composition was sampled once for each cow in the data collection period, with the exception of 20 cows, from which the milk was not sampled. Milk samples were analysed for protein, fat and lactose using infrared spectrometer CombiFoss 6000 FC (Foss Electric) at the Research Centre for the Milking Industry in Iceland (Rannsóknastofa mjólkuriðnaðarins). The milk composition was used to calculate the energy-corrected milk (ECM), according to Sjaunja et al. (1990). Where milk composition was missing, it was estimated that it contained 4.00% fat, 3.40% protein and 4.53% lactose.

Voluntary intake of feed offered ad lib was estimated on an individual level by the prediction equations of NorFor (Volden et al. 2011). The estimations were based on information in the database about lactation number, live weight, milk yield and days in milk. Cows on Farm 1 were weighed at the beginning of the data collection period, but for cows on Farm 2 and Farm 3, it was estimated 465, 495 and 525 kg for first, second and ≥ third parity cows, respectively (Kristjánsson, 2023).

Diets and feed composition

On all three farms, purchased concentrate mixtures were fed separately in concentrate feeders, milking robots and the GF unit as described above. On Farm 1, only grass silage was offered at the feed table. On the other two farms, partially mixed rations (PMR) offered at the feed table had the following composition, as % of DM:

Farm 2: Grass silage 54.5; annual ryegrass/oat silage 24.5; ensiled barley grain 21.0
Farm 3: Grass silage 75.2; dried barley grain 20.5; fish meal 1.8; Bergafat F-100 1.6, minerals 0.9

Table 1. Nutrient composition of feed offered ad lib at feed table on the three farms.

	Farm 1	**Farm 2**	**Farm 3**
Dry matter (DM) %	39.9	45.4	43.4
Organic matter digestibility %	77.7	79.5	82.5
Fill value (FV)	0.46	0.41	0.41
Chemical composition g/kg DM			
Ash	69	69	63
Neutral detergent fibre (NDF)	461	396	440
Crude protein (CP)	168	156	134
Crude fat (CFat)	35	33	50
Sugars	56	79	76
Starch	0	106	125
Carbohydrate rest fraction	193	175	138
Fermentation products in feedstuff (FPF)	75	66	49
Other measurements:			
Fatty acids in feedstuff g/kg Cfat	690	685	768
Indigestible NDF (iNDF) g/kg NDF	180	199	110

Table 2. Average nutrient composition of the total diet on the three farms.

	Farm 1	Farm 2	Farm 3
Organic matter digestibility %	80.0	81.3	82.8
Fill value (FV)	0.35	0.33	0.33
Chemical composition g/kg DM			
Ash	76	81	78
Neutral detergent fibre (NDF)	336	300	324
Crude protein (CP)	167	167	155
Crude Fat (CFat)	45	43	55
Sugars	56	74	73
Starch	171	193	198
Carbohydrate rest fraction	166	179	161
Fermentation products in feedstuff (FPF)	40	38	28
Other measurements/ calculations:			
Fatty acids g/kg Cfat	766	768	826
Fatty acids g/ kg DM	35	33	46
Indigestible NDF (iNDF) g/kg NDF	192	194	144

The average nutrient composition of silage and PMR offered ad lib at the feed table is reported in Table 1, and the corresponding information for the total diet on the three farms is reported in Table 2. Information of nutrient composition of purchased feed products in PMR and concentrate mixtures was found in the Norfor database through the use of TineOptiFor (Tine 2025), i.e., it was not analysed. Forage samples were analysed as following: the DM of the samples was determined with a double step drying method by drying the samples in a hot-air drying cabinet at 60°C for approximately 48 h. After milling, an approximately 3-g sample was put in a hot-air drying cabinet at 103°C, as described in European Commission Regulation EC No. 152/2009. As outlined in the same regulation, crude protein (CP) was analysed with the Kjeldahl method, where ash was analysed at 550°C, and starch was analysed using the polarimetric method (p.47, Commission Regulation EC No. 152/2009). Other parameters (OMD, NDF, iNDF, crude fat, sugars) shown in Tables 1 and 2 were analysed with near infrared reflectance spectroscopy (NIRS), in the laboratory Efnagreining ehf (2025). The carbohydrate rest fraction was calculated as described by Volden (2011), and fill value (FV) as described by Volden et al. (2011).

Phase 2: Statistical evaluation of methane prediction models

Several prediction models for enteric methane production have recently been developed in other Nordic countries. They were chosen for this study as they fit the input variables in the database. The ability of the chosen models to predict CH_4 production was compared by different methods, as recommended by Tedeschi (2006). First, concordance correlation coefficient (CCC) was calculated. According to Lin (1989), CCC is the product of a bias correction factor for the measurement of accuracy (Cb) and the precision measurement of the Pearson correlation coefficient (r). 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. Second, the mean squared prediction error (MSPE) was calculated and decomposed into errors in central tendency (ECT), errors due to deviation of the regression slope from unity (ER), and errors due to the disturbances or random variation (ED), all according to Bibby and Toutenburg (1977). The square root of MSPE was then calculated and expressed as a fraction of the observed mean (RMSPE%).

CH_4 measurements of the GF unit were expressed as grams per day, but the evaluated prediction models express CH_4 production in MJ. For conversion, the following was used: 1 g CH_4 = 0.0565 MJ. The model evaluations reported by the statistical methods described above are based on average daily values for the three-week data collection period for individual cows. This applies to both the observed methane values by the GF unit and the production, feed intake and nutrition composition parameters used as inputs to the prediction models.

Phase 3: Simulated database

The Norfor feed evaluation system (Norfor 2011 & 2023) uses the model of Nielsen et al. (2013) for the prediction of enteric CH_4 emissions from dairy cows. The Norfor feed evaluation system was used to simulate a variety of diets fulfilling nutritional requirements of Icelandic dairy cows with different production levels. The details of the Norfor system are described in various sections of Norfor (2011), and changes made since the book was published are available on their website (Norfor 2023). The Norfor system accounts for differences between dairy breeds, including the Icelandic breed, in feed intake (Volden et al. 2011) and the deposition and mobilisation of body reserves through the lactation cycle (Nielsen & Volden 2011). The standardized lactation curves in NorFor were employed to predict the animal requirement for different levels of ECM production through the lactation cycle. A standard curve of body reserve mobilisation and deposition was also used, assuming that body condition score at calving is 3.5, mobilisation in early lactation (until day 70) is approximately 0.5 units and that body condition has reached 3.5 again at the end of the lactation, at 305 days after (and 60 days before next) calving. Diet optimisations were made at week 2, 4, 8, 12, 20, 30, 40 and 48 of the production year, which was thereby divided up into 8 periods, respectively 21, 21, 28, 42, 63, 70, 60 and 60 days in length. The results of diet optimisations were then multiplied by the respective number of days for each period to arrive at a whole production year diet. In each optimisation this was done for three groups of cows, namely first, second and ≥third parity cows. Based on information from the common national registration system for dairy herds, these three groups are respectively 36%, 24% and 40% of the total dairy cow population in Iceland. These proportions were used to weigh the optimisation results for cows in different parities to achieve a total account of different feeds used, production and emission results over whole production year for a 100-cow farm with 36, 24 and 40 cows in parities 1, 2 and ≥3, respectively. This type of diet optimisation and whole-farm summary was repeated for a total of 64 combinations of yearly production levels and available dietary ingredients. This was done in two study setups:

Setup 1: The forage part was selected by Norfor ration optimiser from a variety of forages (feeds no 1-6 in Table 5): the concentrate part with a) dried barley grain as a part of the concentrates or not and b) the fatty acid content of the diet in lactation either very flexible in the range 18-45 g FA kg DM^{-1} or elevated with the minimum from 31 to 39 (increasing with increasing yearly ECM yield) and maximum 50 g FA kg DM^{-1}. Under these constraints, the Norfor ration planner could choose from 6 concentrates (feeds no 7-11 and 13 in Table 5). See Table 6 for further details on Setup 1.

Setup 2: Three fixed, very different forage qualities were used (feeds no 2, 5 and 6 in Table 5) to reflect a likely range, from a forage with poor digestibility, mainly useful for maintaining feed structure for a normal rumen function with high level of concentrates, to medium and good quality forages, with moderate or high part of the nutrients coming from the forage part. Here, the ration optimiser could select from 5 different concentrates but only chose two: feed 12 and 7 in Table 5, feed 12 representing a major part of the concentrates in all simulated feed plans. See Table 7 for further details on Setup 2.

Phase 4: Analysis of simulated database, development and sensitivity analysis of proposed model for predicting methane emissions for the National Inventory in Iceland

The simulated database, produced by the Norfor ration optimiser, reported in Table 6 (Setup 1) and Table 7 (Setup 2), was analysed by multiple regression analyses, i.e., REG procedure performed with SAS (2015). These regression analyses were performed to fit methane emissions predicted in phase 3 to test different combinations of practically feasible explanatory variables available at the country level, in which the response variable was either EF or GEI, and the possible input (explanatory) variables were ECM; OMD_d, OMD_f, Concentrate, FA_c and FA_d, where EF=Emission factor in kg CH_4 cow^{-1} year^{-1}; GEI=Gross energy intake in MJ cow^{-1} day^{-1}, ECM= energy corrected milk yield in kg cow^{-1} year^{-1}; OMD_d and OMD_f are organic matter digestibility (%) of total diet and the forage part, respectively; Concentrate is the amount of concentrates (including barley grain) in kg DM cow^{-1} year^{-1}; FA_c and FA_d are g fatty acids in kg DM of concentrates and total diet, respectively.

The performance of seven different model combinations was compared with respect to R^2 and the root of mean squared prediction error (RMSPE), and the significance of the effects of explanatory variables in the models. After selecting the most feasible model based on that evaluation, it was further tested by sensitivity analysis. To be able to work with realistic values in that analysis, data on the average fatty acid concentration of concentrates purchased by Icelandic dairy farmers was obtained from feed companies, and data on average concentrate quantity fed to dairy cows was obtained from the common dairy herd registration system (Icelandic Agricultural Advisory Centre (RML), Guðmundur Jóhannesson, personal communication, February 16, 2025).

RESULTS AND MODEL DEVELOPMENT

Phase 1: Measurements of methane emissions in three dairy herds

In total, 111 cows from the three farms finished the study, covering a wide range in milk yield, feed intake and methane emissions (Table 3).

Phase 2: Statistical evaluation of methane prediction models

Of the models accessed, the five best performing models with addition of the model currently used for the National Inventory (Keller et al. 2024) are reported in Table 4. The model from Storlien et al. (2014) with only DMI (kg d^{-1}), and FA (g/kg DM) as input variables predicted enteric CH_4 emissions most accurately of the models accessed, judged by CCC (0.535) and RMSPE (13.4%). The model of Nielsen et al. (2013) with DMI (kg/d), NDF (g/kg DM) and FA (g/kg DM) followed closely, according to CCC (0.529) and RMSPE (13.8%) outcomes. All five models presented here predict enteric CH_4 emissions considerably better than the Keller et al. (2024) model, judging by both CCC and RMSPE, where also the ER fraction of the prediction error outperforms other models considerably. This highlights shortcomings of that simple model to describe animal and dietary effects on methane emissions, although the average predicted value coincides well with the average observed value, as the low ECT% value demonstrates.

Table 3. Number of dairy cows included in the database and their mean values (standard deviation; min-max values in parentheses) of days in milk, feed intake, milk yield, observed CH_4 emissions and milk yield within the three week recording period.

	Farm 1	**Farm 2**	**Farm 3**
Number of animals	39	36	36
Number of visits per animal	68.3 (29.0;15-137)	61.1 (23.5;14-112)	58.9 (19.5;18-105)
Days in milk	189 (113.4;10-402)	161 (71.4;29-349)	201 (102.8;47-540)
Milk yield, kg cow^{-1} d^{-1}	19.1 (8.3; 2.6-36.0)	22.3 (7.9;12.1-39.4)	25.3 (7.4;12.9-42.0)
Roughage/PMR (predicted), kg DM cow^{-1} d^{-1}	9.6 (1.0;7.8-12.1)	11.8 (1.2;9.7-14.2)	10.0 (1.1;8.0-12.1)
Concentrate, kg DM cow^{-1} d^{-1}	5.2 (3.2;1.2-12.4)	4.8 (2.7;1.0-10.7)	6.1 (2.2;1.9-9.8)
CH_4 production, g cow^{-1} d^{-1}	332 (42.6; 227-447)	371 (47.1; 274-471)	354 (45.7; 249-451)
CH_4 yield (Y_m), % of GEI	6.9 (1.0;4.6-9.3)	6.9 (1.3;4.7-9.7)	6.6 (1.2;4.8-9.6)

Table 4. Evaluation of CH_4 emission prediction models based on measured methane emissions in three Icelandic dairy herds, ranked by decreasing CCC

Source*)	n	Prediction Equation	CCC	RMSPE	ECT	ER	ED
1	111	CH_4 = 6.8+1.09*DMI-0.15*FAs	0.535	13.4%	3.2%	26.5%	70.3%
2	111	CH_4 = 1.23*DMI-0.145*FAs+0.012*NDF	0.529	13.8%	3.8%	29.2%	67.1%
3	111	CH_4 = 4.92+1.13*DMI-0.118*FAs	0.516	14.4%	5.8%	32.2%	61.9%
4	111	CH_4 = -3.01+1.19*DMI-0.103*FAs+0.017*NDF	0.495	14.3%	12.3%	24.4%	63.4%
5	111	CH_4 = 1.13*DMI-0.114*FAs+0.012*NDF	0.493	14.2%	15.5%	21.0%	63.6%
6	111	CH_4 = GE*0.065	0.474	16.9%	1.5%	51.5%	47.0%

n, number of treatment means; CH_4, methane (MJ/day); DMI, dry matter intake (kg/day); FAs, fatty acid content (g/kg DM); NDF, neutral detergent fiber content (g/kg DM) ; $RMSPE$, root mean squared prediction error expressed as a percentage of the observed mean; CCC, concordance correlation coefficient.
*) 1: Storlien et al. 2014; 2: Nielsen et al. 2013; 3: Niu et al. 2021- Model 1; 4: Niu et al. 2021- Model 2; 5: Niu et al. 2021- Model 3; 6: Keller et al. 2024

Table 5. Chemical composition of feeds used in Norfor feed plans to create database for development of operational models.

				g kg DM^{-1}								
Feed no	Feed type	OMD %	DM g kg feed^{-1}	Ash	Crude Protein	Crude Fat	NDF	Total Acids	Sugar	Starch	Rest fraction	Fill value
1	CGS	79.2	372	104	177	42	436	62	92	0	204	0.44
2	GS	80.0	350	71	179	35	452	27	76	0	230	0.45
3	GS	76.0	400	75	158	35	486	27	76	0	213	0.49
4	GS	81.0	517	59	135	35	463	20	65	0	282	0.45
5	GS	74.5	388	75	162	30	501	27	92	0	199	0.50
6	GS	64.0	400	76	125	35	532	27	76	0	199	0.56
7	CM	86.4	877	85	217	49	154	0	69	347	148	0.22
8	CM	83.3	876	83	176	51	199	0	60	382	109	0.22
9	CM	83.6	877	83	210	50	201	0	66	319	137	0.22
10	CM	84.3	880	89	176	63	230	0	67	279	163	0.22
11	CM	84.5	879	89	209	64	205	0	78	254	179	0.22
12	CM	82.8	873	84	173	41	208	0	61	391	103	0.22
13	B	86.0	863	23	115	32	196	0	20	602	25	0.22

[1)]CGS: Clover grass silage; GS: Grass silage; CM: Concentrate mixture; B: Dried barley grain

Table 6. Setup 1: Farm-production year summaries of CH_4 emissions estimated by Norfor and diet parameters of importance for development of operational models, according to Norfor feed plans made at 9 different ECM production levels, either with barley grain as part of the concentrate (+) or not (-) and with either high (+) or moderate (-) level of allowed fat addition in concentrate. The ration optimiser could select from 8 different forages and 6 different concentrates.

kg ECM cow^{-1} year^{-1}	Barley	Added fat	Forages used	Concentrates used	OMD % forage	OMD % diet	concentrate kg DM cow^{-1} year^{-1}	% conc. of DM	Fatty acids in concentrates g kg DM^{-1}	Fatty acids in diet g kg DM^{-1}	Emission kg CH_4 cow^{-1} year^{-1}	Gross energy MJ cow^{-1} day^{-1}
5686	+	-	3,2,6,4	13,9,7,11	74.5	78.1	1496.6	32.4	28.4	24.5	110.5	237.2
	-	-	4,2,6,3	8,7,9,11	77.8	79.3	1197.2	26.3	42.2	27.8	106.7	233.3
	+	+	1,3,4,6,2	13,11,7,9	76.2	78.8	1318.4	28.9	39.2	28.9	104.9	232.7
	-	+	4,1,6,2	8,7,11,9	77.3	79.1	1260.9	27.6	43.0	29.3	104.9	232.4
5969	+	-	3,2,6,4	13,9,11,7	75.2	78.6	1575.9	33.4	29.8	25.1	111.7	242.6
	-	-	4,2,6,3	8,9,11,7	77.9	79.5	1350.2	28.9	42.9	28.6	108.2	239.6
	+	+	1,3,4,6	13,11,9,7	76.2	79.1	1466.8	31.3	40.1	29.6	106.6	239.2
	-	+	4,1,6,3,2	8,11,7,9	77.4	79.3	1418.0	30.3	43.8	30.1	106.4	238.8
6253	+	-	3,2,6,4	13,9,11,7	75.2	78.7	1726.0	35.6	30.9	25.6	113.7	249.3
	-	-	4,6,2,3	8,9,11,7	77.9	79.7	1513.6	31.5	43.1	29.2	110.0	246.3
	+	+	1,3,4,6	11,13,9,10,7	76.2	79.2	1625.0	33.8	40.8	30.3	108.5	246.0
	-	+	4,1,6,3,2	8,11,9,7,10	77.4	79.4	1586.0	32.9	44.2	30.9	108.2	245.5
6538	+	-	3,2,6	13,9,11	75.3	78.9	1865.4	37.5	31.3	26.0	115.8	255.9
	-	-	4,6,2,3	8,9,11	77.9	79.8	1675.9	34.0	42.9	29.6	112.1	252.9
	+	+	1,3,6,4	11,13,9,10	76.2	79.4	1779.8	36.0	41.2	30.8	110.5	252.7
	-	+	4,1,6,3,2	8,11,9,10	77.3	79.5	1748.8	35.3	44.3	31.4	110.2	252.2
6820	+	-	3,2,6,4	13,9,11	75.3	79.1	2017.1	39.5	31.5	26.2	118.1	262.7
	-	-	4,6,2,3	8,9,11	77.9	79.9	1837.2	36.3	42.5	29.9	114.3	259.6
	+	+	1,3,4,6	11,13,9,10	76.2	79.6	1928.2	38.1	41.5	31.2	112.7	259.4
	-	+	4,1,6,3,2	8,11,9,10	77.3	79.6	1911.7	37.6	44.4	31.9	112.3	259.1
7104	+	-	3,2,6,4	13,9,11	75.0	79.1	2194.5	41.9	31.5	26.4	120.6	270.0
	-	-	4,6,2,3	8,9,11	77.9	80.0	2000.8	38.5	42.2	30.2	116.5	266.4
	+	+	1,3,4,6,2	11,13,9,10	76.3	79.7	2085.6	40.1	41.9	31.7	114.9	266.3
	-	+	4,1,6,3,2	8,11,9,10	77.2	79.7	2078.2	39.9	44.6	32.5	114.4	265.9
7389	+	-	3,2,6,4	9,13,11	75.2	79.4	2321.5	43.3	31.8	26.7	122.7	276.4
	-	-	4,6,2,3	8,9,11	77.9	80.1	2161.7	40.6	42.0	30.6	118.7	273.1
	+	+	1,3,6,4	13,11,10,9	76.1	79.8	2266.5	42.4	42.2	32.2	117.3	273.7
	-	+	4,1,6,3,2	8,10,9,11	77.2	79.9	2243.7	41.9	45.0	33.1	116.6	272.9
7672	+	-	3,2,6,4	9,13	75.2	79.5	2470.6	45.0	32.1	26.9	125.0	283.2
	-	-	4,6,2,3	8,9	77.9	80.2	2319.8	42.5	42.0	30.9	120.9	279.9
	+	+	1,3,6,4,2	13,11,10,9	76.0	79.9	2433.0	44.4	42.8	32.8	119.6	280.8
	-	+	1,4,6,3,2	8,10,9,11	77.2	80.0	2407.4	43.9	45.6	33.8	118.7	279.9
7956	+	-	3,2,6,4	9,13	75.2	79.6	2628.9	46.7	32.3	27.2	127.5	290.2
	-	-	4,6,2,3	8,9	77.9	80.3	2479.7	44.4	42.0	31.3	123.2	286.6
	+	+	1,3,6,4,2	10,13,11,9	75.8	80.0	2606.9	46.4	43.3	33.4	122.0	288.2
	-	+	1,4,6,3,2	8,10,9,11	77.1	80.1	2573.9	45.8	46.1	34.5	120.9	286.9

Phase 3: Simulated database

As reported in Table 6 (Setup 1) and Table 7 (Setup 2), the database created by the Norfor ration optimiser covers a wide range of production levels and diet compositions with respect to important variables like forage digestibility, amount of concentrates in total diet, fatty acid content of concentrates, etc.

Table 7. Setup 2: Farm-production year summaries of CH_4 emissions estimated by Norfor and diet parameters of importance for development of operational models, according to Norfor feed plans made at 9 different ECM production levels, with fixed forage quality at three different levels; where good, medium and poor quality are feeds 2,5 and 6 in Table 5, respectively.

kg ECM cow^{-1} year^{-1}	Forage	OMD % forage	OMD % diet	concentrate kg DM cow^{-1} year^{-1}	% conc. of DM	Fatty acids in concentrates g kg DM^{-1}	Fatty acids in diet g kg DM^{-1}	Emission kg CH_4 cow^{-1} year^{-1}	Gross energy MJ cow-1 year-1
	Good	80.0	80.8	1146.0	25.8	33.0	25.4	105.5	227.5
5686	Medium	74.5	77.8	1796.0	38.4	32.9	24.7	111.5	237.5
	Poor	64.0	72.8	2397.0	46.6	32.7	27.4	118.5	260.2
	Good	80.0	80.9	1383.0	30.2	32.9	25.8	107.0	234.0
5969	Medium	74.5	78.0	1955.0	40.6	32.9	24.9	113.7	244.3
	Poor	64.0	73.2	2548.0	48.3	32.7	27.6	120.9	267.1
	Good	80.0	81.0	1579.0	33.6	32.9	26.2	108.8	240.3
6253	Medium	74.5	78.1	2115.0	42.7	32.8	25.2	116.0	251.1
	Poor	64.0	73.5	2699.0	49.9	32.7	27.8	123.4	273.9
	Good	80.0	81.1	1750.0	36.2	32.9	26.4	111.0	246.9
6538	Medium	74.5	78.3	2273.0	44.7	32.8	25.5	118.4	258.0
	Poor	64.0	73.8	2848.0	51.4	32.8	27.9	125.8	280.7
	Good	80.0	81.2	1921.0	38.7	32.9	26.7	113.3	253.8
6820	Medium	74.5	78.5	2430.0	46.6	32.8	25.7	120.8	264.9
	Poor	64.0	74.1	2996.0	52.8	32.9	28.1	128.3	287.6
	Good	80.0	81.3	2096.0	41.1	32.9	26.9	115.6	260.6
7104	Medium	74.5	78.6	2588.0	48.4	32.9	26.0	123.2	271.8
	Poor	64.0	74.3	3138.0	54.1	33.1	28.3	130.7	294.3
	Good	80.0	81.3	2274.0	43.5	32.9	27.2	118.1	267.6
7389	Medium	74.5	78.8	2745.0	50.0	32.9	26.2	125.6	278.7
	Poor	64.0	74.6	3274.0	55.2	33.5	28.6	132.9	300.9
	Good	80.0	81.4	2450.0	45.6	32.9	27.4	120.5	274.5
7672	Medium	74.5	78.9	2895.0	51.5	33.1	26.5	128.0	285.5
	Poor	64.0	74.9	3408.0	56.2	33.8	28.9	135.1	307.5
	Good	80.0	81.4	2626.0	47.7	32.9	27.6	123.1	281.6
7956	Medium	74.5	79.1	3041.0	52.9	33.4	26.8	130.3	292.3
	Poor	64.0	75.2	3535.0	57.2	34.3	29.2	137.3	313.9

Phase 4: Analysis of simulated database, development and sensitivity analysis of proposed model for predicting methane emissions for the National Inventory in Iceland

Tables 8 and 9 report seven different regression model combinations for predicting methane emissions (EF, Table 8) and gross energy intake (GEI, Table 9). Model 1 has corresponding explanatory variables to the operational model currently used (Keller et al. 2024), i.e., milk yield (ECM) and digestibility of total diet. For both response variables, Model 1 has better predictive ability than Model 2, which only has ECM but not OMD_d as an explanatory variable, judging both from higher R^2 and lower RMSPE. However, by replacing OMD_d from Model 1 with the yearly amount of concentrates in Model 3, but still keeping ECM, the predictive ability is improved for EF but not for GEI. From Model 3, prediction is improved in Model 4 for both EF and GEI by adding fatty acid content in concentrates (FA_c). By including OMD_d again as the fourth explanatory variable (Model 5), some further improvement was achieved, judging from R^2 and RMSPE, and even more so by using FA_d instead of FA_c (Model 6). The effect of replacing OMD_d with OMD_f (Model 7) is negative for the prediction of EF but decreases RMSPE in the case of GEI. However, the influence of some explanatory variables included are statistically insignificant for EF in the case of models 2 and 6, and for GEI in the cases of models 5, 6 and 7. Based on this, the best composition of variables for models for analogously predicting EF (Table 8) and GEI (Table 9) is as in Model 4.

The concentration of FA in Icelandic forages is relatively stable, mostly in the range 20-25 g FA kg DM^{-1}. The concentrates are more variable in this respect, often in the range 20-60 g FA kg DM^{-1}. We received data from feed companies covering the majority of concentrates purchased for dairy cows in Iceland. Based on recent reports (Sturludóttir & Sveinbjörnsson 2021, Gautason et al. 2023), it was estimated that home-grown barley makes up 12.3% of the concentrates used for dairy cows in Iceland. Based on these data and the reported FA content of the feeds in the Norfor database, we found the weighed average to be 41.5 g FA kg DM^{-1} in concentrates fed to dairy cows in Iceland.

The amount of concentrates in the total diet is also an important input variable in the regression equations presented in Tables 8 and 9. Furthermore, from the simulated database in Tables 6 and 7, it is clear that a certain level of ECM yield can be reached with different levels of concentrates, depending to a great extent on forage quality, of which OMD_f is the single best predictor. For final development and application of an operational model for EF and GEI, it is

Table 8. Coefficients a (intercept), b1, b2, b3,...bn (slopes) for the (multiple) linear regressions predicting methane emissions (EF kg CH_4 cow^{-1} $year^{-1}$) from different combinations of explanatory variables, based on analysis of the simulated dairy herds data in Tables 6 and 7

Model	intercept	Slope parameter values kg ECM cow^{-1} $year^{-1}$	OMD_d (%)	OMD_f (%)	Concentrates, kg DM cow^{-1} $year^{-1}$	FA_c, g kg conc. DM^{-1}	FA_d, g kg diet DM^{-1}	RMSPE	R^2
1	236.5****	0.00901****	-2.29****					2.18	0.924
2	64.3****	0.00776****						5.35	0.539
3	86.0****	0.00048^{NS}			0.0130****			1.61	0.959
4	89.8****	0.00129**			0.0118****	-0.181****		1.18	0.970
5	185.0****	0.00657****	-1.39****		0.0039**	-0.299****		0.939	0.981
6	233.8****	0.00937****	-2.02****		0.0011^{NS}		-0.828****	0.533	0.993
7	140.9****	0.00073****		-0.77****	0.0026**		-0.738****	0.712	0.992

OMD_d: diet organic matter digestibility; OMD_f: forage organic matter digestibility; FA_c: fatty acids in concentrates; FA_d: Fatty acids in diet desirable to be able to relate the parameters ECM, OMD_f and quantity of concentrates fed to each other in a simple manner. Therefore, from the database reported in Tables 6 and 7, the following regression equation was fitted:

Equation 1: Concentrates, kg DM cow^{-1} $year^{-1}$ = 4006.9+0.558*kg ECM -75.53 * OMD_f

A further use of this relationship is dependent on the assumption that Norfor feed plans are realistic in predicting the quantity of concentrates needed to reach a certain ECM yield level at a certain average forage quality. To validate this assumption, data were obtained from the Icelandic Agricultural Advisory Centre (RML):

1. The average ECM yield according to reports from the common registration system was 6527, 6628 and 6772 kg cow^{-1} $year^{-1}$ in the years 2022, 2023 and 2024, repectively (RML 2025a) – the most recent year reported in the National Inventory is 2022 (Keller et al. 2024).
2. The average forage organic matter digestibility (OMD_f, %) according to analysis of forages, predominantly from dairy farms, in the years 2022-2023 was in the range 76-79% (RML 2025b).
3. Data on concentrate quantity was registered in circa one third of the herds in the common registration system in 2024 (Icelandic Agricultural Advisory Centre (RML), Guðmundur Jóhannesson, personal communication, February 16, 2025). The quality of these data is variable, but after validation at different levels (normality check etc.) 54 farms with good quality data and yield in the range 5500-7500 (average 6275) kg ECM cow^{-1} $year^{-1}$ were left. On average, these farms used 0.25 kg DM concentrates kg ECM^{-1}. One farm with very accurate registration of ECM yield and concentrate use delivered data for three recent years (2022-2024). The average yield was 6612 kg ECM cow^{-1} $year^{-1}$ and concentrate use was 0.27 kg DM kg ECM^{-1}.

A sensitivity analysis is presented in Table 10, of Model 4 from Table 8 and 9 for EF and GE, respectively, to changes in yield (ECM cow^{-1} $year^{-1}$) from 5750 to 7750 and within each yield category to changes in forage digestibility (OMD_f, %). This is all based on the relationship of concentrate use with ECM and OMD_f presented by Equation 1 above.

Table 9. Coefficients a (intercept), b1, b2, b3,...bn (slopes) for the (multiple) linear regressions predicting gross energy intake (GEI, MJ cow^{-1} $year^{-1}$) from different combinations of explanatory variables, based on analysis of the simulated dairy herds data in Tables 6 and 7

		Slope parameter values							
Model	**intercept**	**kg ECM cow^{-1} $year^{-1}$**	**OMD_d (%)**	**OMD_f (%)**	**Concentrates, kg DM cow^{-1} $year^{-1}$**	**FA_c, g kg conc. DM^{-1}**	**FA_d, g kg diet DM^{-1}**	**RMSPE**	**R^2**
1	457.3^{****}	0.0265^{****}	-4.75^{****}					1.17	0.997
2	100.9^{****}	0.0239^{****}						10.19	0.754
3	141.7^{****}	0.0102^{****}			0.0244^{****}			3.50	0.971
4	134.4^{****}	0.0087^{**}			0.0268^{****}	0.344^{***}		1.19	0.977
5	460.7^{****}	0.0268^{****}	-4.77^{****}		-0.0005^{NS}		-0.0622^{NS}	1.15	0.997
6	471.4^{****}	0.0274^{****}	-4.91^{****}		-0.0011^{NS}		-0.1757^{*}	1.14	0.997
7	251.9^{****}	0.0232^{****}		-1.98^{****}	0.0013^{NS}		0.0017^{NS}	1.07	0.997

OMD_d: diet organic matter digestibility; OMD_f: forage organic matter digestibility; FA_c: fatty acids in concentrates; FA_d: Fatty acids in diet

Table 10. Sensitivity analysis of suggested operation models (Model 4, Table 8 and 9 for EF and GE, respectively) to changes in yield (ECM cow^{-1} $year^{-1}$) and forage organic matter digestibility (OMD_f %), based on the regression of ECM and OMDf on concentrate quantity per cow presented in Equation 1 (see Reults, Phase 4)

ECM cow^{-1} $year^{-1}$	OMDf %	kg DM conc. cow^{-1} year-1	kg DM conc. kg ECM^{-1}	EF kg CH4 cow^{-1} $year^{-1}$	GE MJ cow^{-1} $year^{-1}$	Ym %	kg CH_4 kg ECM^{-1}	Scenario no.
5750	65.0	2306	0.40	117.2	260.0	6.9	0.0204	**1**
	70.0	1928	0.34	112.7	249.9	6.9	0.0196	**2**
	75.0	1551	0.27	108.3	239.8	6.9	0.0188	**3**
	80.0	1173	0.20	103.8	229.6	6.9	0.0181	**4**
6000	65.0	2445	0.41	119.2	265.9	6.8	0.0199	**5**
	70.0	2068	0.34	114.7	255.8	6.8	0.0191	**6**
	75.0	1690	0.28	110.3	245.7	6.8	0.0184	**7**
	80.0	1313	0.22	105.8	235.6	6.8	0.0176	**8**
6250	65.0	2585	0.41	121.1	271.8	6.8	0.0194	**9**
	70.0	2207	0.35	116.7	261.7	6.8	0.0187	**10**
	75.0	1830	0.29	112.2	251.6	6.8	0.0180	**11**
	80.0	1452	0.23	107.8	241.5	6.8	0.0172	**12**
6500	65.0	2724	0.42	123.1	277.7	6.8	0.0189	**13**
	70.0	2347	0.36	118.6	267.6	6.8	0.0183	**14**
	75.0	1969	0.30	114.2	257.5	6.8	0.0176	**15**
	80.0	1592	0.24	109.7	247.4	6.8	0.0169	**16**
6750	65.0	2864	0.42	125.1	283.7	6.7	0.0185	**17**
	70.0	2486	0.37	120.6	273.5	6.7	0.0179	**18**
	75.0	2109	0.31	116.2	263.4	6.7	0.0172	**19**
	80.0	1731	0.26	111.7	253.3	6.7	0.0165	**20**
7000	65.0	3003	0.43	127.0	289.6	6.7	0.0181	**21**
	70.0	2626	0.38	122.6	279.4	6.7	0.0175	**22**
	75.0	2248	0.32	118.1	269.3	6.7	0.0169	**23**
	80.0	1871	0.27	113.7	259.2	6.7	0.0162	**24**
7250	65.0	3143	0.43	129.0	295.5	6.7	0.0178	**25**
	70.0	2765	0.38	124.5	285.4	6.7	0.0172	**26**
	75.0	2388	0.33	120.1	275.2	6.7	0.0166	**27**
	80.0	2010	0.28	115.6	265.1	6.6	0.0159	**28**
7500	65.0	3282	0.44	131.0	301.4	6.6	0.0175	**29**
	70.0	2905	0.39	126.5	291.3	6.6	0.0169	**30**
	75.0	2527	0.34	122.1	281.2	6.6	0.0163	**31**
	80.0	2150	0.29	117.6	271.0	6.6	0.0157	**32**
7750	65.0	3422	0.44	132.9	307.3	6.6	0.0172	**33**
	70.0	3044	0.39	128.5	297.2	6.6	0.0166	**34**
	75.0	2667	0.34	124.0	287.1	6.6	0.0160	**35**
	80.0	2289	0.30	119.6	276.9	6.6	0.0154	**36**

DISCUSSION

Many different types of models have been developed to predict methane (CH_4) emissions from dairy cows. On-farm models used for this purpose are generally developed in order to capture in some detail the effects of animal production level and diet composition on emissions. Country-level models for prediction of emissions for national inventories can never have as many input (explanatory) variables as the most detailed on-farm models, because the information accessible at a country level is normally not as detailed as the farm-level information. Still, it is desirable that the models used for a National Inventory are based on the most important input information at the farm level that can also be applied at the country level. This is important not only to predict with best possible accuracy the methane emissions from dairy cows at the country level for the National Inventory but also for consistency between country- and farm-level messages regarding means of reducing methane emissions per unit of milk produced.

In Norway, models for calculating methane emissions from dairy cows were updated (Niu et al. 2021,) based on a combination of empirical equations (basic models) developed from experiments in which CH_4 production was measured and on (operational models) computer simulations with TINE OptiFor, which is the national client software for the Norfor system (Volden 2011, Norfor 2023) used in Norway and Iceland. A further update was made for the 2024 NIR submission in Norway, based on a report from Volden et al. (2023), where the operational model is based on experimental data, and its input variables are proxies that can be easily obtained, i.e., energy corrected milk yield (ECM), concentrate intake and crude fat content in concentrates.

The Icelandic breed is the only dairy cow breed in Iceland. It is defined as a special breed in the Norfor feed evaluation system, which accounts for differences among dairy breeds in feed intake (Volden et al., 2011) and the deposition and mobilisation of body reserves through the lactation cycle (Nielsen and Volden, 2011). The specific parameter values for the Icelandic breed are based on data available from dairy cow experiments where feed intake, feed composition, animal production level, live weight and other important parameters were measured (Norfor, 2011 & 2023). Unfortunately, no experimental data with all those parameters together with methane emission measurements are available for Icelandic dairy cows. Currently, there are no experimental facilities in Iceland to measure feed intake on an individual cow basis. The current study (Phase 1) therefore relied on the capability of the Norfor system to predict dry matter intake from information about the animal and its diet. In a study by Jensen et al. (2015), where the accuracy of five models predicting dry matter intake (DMI) was tested against experimental data, Norfor had the second lowest prediction error: RMSPE: 1.5 kg DM d^{-1}; and, with the average observed DMI = 21.3 kg d^{-1}, the proportional prediction error was 7.04%. Appuhamy et al. (2016) evaluated the performance of different existing models in predicting enteric CH_4 emissions from dairy cows across different global regions and concluded that emissions can be predicted successfully (RMSPE<15%) if DMI can be estimated with reasonable accuracy (RMSPE<10%). From the available evidence (Jensen et al. 2015), it can be assumed that Norfor fulfills these criteria regarding DMI prediction in general, and specifically also for the Icelandic breed according to a test made by Baldursdóttir (2010) when the breed-specific parameters were adapted. The consistency between methane emission measured by GreenFeed and predicted by equations 1-5 in Table 4 is acceptable (RMSPE <15%), although DMI is predicted by Norfor but not measured in our study.

Although the model from Storlien et al. (2014) with only dry matter intake (DMI kg d^{-1}) and fatty acids (FA g kg DM^{-1}) as input variables predicted enteric CH_4 emissions slightly better (Table 4) than the model of Nielsen et al. (2013), which had one more input variable (NDF g kg DM^{-1}), we decided to use Nielsen et al. (2013) for development of a model for predicting methane emissions for the National Inventory in Iceland. An important factor in that decision was that the Norfor ration optimiser at the time of our study used that model, and its methane emission predictions can easily be included as a part of the optimisation criteria in practical feed planning on Icelandic dairy farms. The methods for estimating enteric methane emissions from dairy cows in Iceland, as suggested by the present paper, can be updated in the future when new or updated methane prediction equations for Norfor are published.

The databases created by simulations with the Norfor feed ration optimiser cover a rather wide range in expected diet compositions for dairy cows in Iceland. Grass silage or haylage is the dominant forage for dairy cows in Iceland, mainly from perennial grasses but partly also from annual ryegrass, oats and some other annual crops. Clover still has a relatively little share as its growing conditions are limited by low summer temperatures. That is also the main reason for the low availability of home-grown cereals. However, barley is commonly grown as dairy cow feed in the areas best suitable. In summary, the typical diet for Icelandic dairy farms is mostly grass-based forage, then different ratios of available concentrate mixtures, with or without home-grown barley as the third main ingredient in the diet. The concentrate mixtures sold for dairy cows in Iceland are mostly made in Iceland from imported feedstuffs, but some are also imported as mixtures ready for use. An important variable regarding the concentrate is its fatty acid content. Due to increased demand for milk fat, there has been a development towards using more added fat in the concentrate feeds, as certain of these additions have proven to elevate milk fat ratio, along with other dietary additions that work more indirectly in the same manner (Weisbjerg et al. 2013, Sveinbjörnsson & Baldursdóttir 2020).

Our recommendations regarding calculations of GHG emissions from dairy cows for the Icelandic National Inventory report are based on practical as well as theoretical considerations. We propose to use models no. 4 in Tables 8 and 9 for the calculations of EF and GE, respectively, from energy corrected milk yield (ECM), fatty acid level in concentrates (FAc) and amount of concentrates in kg DM cow^{-1} year^{-1}, calculated by Equation 1 as described below. Information on average ECM yield per dairy cow per year is published annually by the Icelandic Acgricultural Advisory Centre (RML 2025a). We estimated average fatty acid level in concentrates (FA_c) from information about feed composition and sales figures of different concentrate mixtures, as well as the estimated amount of home-grown barley used in dairy cow diets. The FA_c should not be expected to vary much from year to year but needs to be updated at least at several-year intervals. That process would be easier if there was an official database where feed companies would report the necessary data for these calculations, as is the case in Norway where a similar model is used (Volden et al. 2023).

Furthermore, we propose that Equation 1 reported above should be used to calculate the expected amount of concentrates in kg DM cow^{-1} year^{-1}. For that calculation, data are needed on average ECM yield, published annually as already discussed; but also the average forage organic matter digestibility (OMD_f). That variable can be estimated from annual reports from the Icelandic Agricultural Advisory Centre (RML).

The above proposed update of the methods for estimating enteric methane emissions from dairy cows in Iceland should be an improvement on current methods, especially in capturing the effect of diet composition and milk yield per animal on methane emissions. This should make the reporting of enteric GHG emissions in the National Inventory more accurate. Furthermore, the proposed method has a pedagogical power in the sense that it demonstrates the effects of the most influential variables on methane emissions per unit of product. It should be easier for Icelandic dairy farmers to reduce methane emissions per kg ECM if there is a clear message from the National Inventory calculations that this can be influenced by the quality of forage, concentrate composition and overall efficiency in diet formulation and milk production. All these influences would be much better captured by the proposed updates. For example, the sensitivity analysis in Table 10 demonstrates that for a 5% increase in forage organic matter digestibility (OMD_f), methane emissions per kg ECM will be reduced by around 4%. Similar reduction in methane emissions per kg ECM can be achieved by elevating the yearly ECM yield by 500 kg by increasing concentrate amount by around 280 kg DM per year, with OMD_f unchanged. Concentrate prices are high in Iceland due to the limited domestic production of cereals. On the other hand, conditions for producing high quality grass-based forage are favorable. The proposed methodology for estimating enteric methane emissions indicates to prioritize improved quality of forage for Icelandic dairy cows, rather than placing the greater emphasis on increasing the amount of concentrate feed to increase annual yield and reduce methane emissions per kg ECM. Increased fatty acid level in concentrates will, according to the models we suggest to use, decrease methane emission per kg ECM. It must however be kept in mind that some fatty acid sources can have high carbon footprint for other reasons than methane emissions (Olijhoek et al., 2025).

The most obvious weakness in the foundations of our suggested updates is that they are not directly based on dairy cow production studies with simultaneous records on an individual cow basis of feed intake, diet composition, milk production and methane emissions, as is the case for operational models in neighbouring countries (Carlén et al. 2024, Nielsen et al. 2024, Rønning et al. 2024). The reason for this is a current lack of research facilities in Iceland, especially for measuring feed intake on an individual level. When this situation has been improved, hopefully not in too distant future, it will take awhile to gather the necessary data for an adequate database. Until then, further improvements in addition to what is proposed above can be made by continued co-operation with our Nordic neighbours through the Norfor-system. First, by improving further the feed intake equations parameters for Icelandic dairy cows by utilizing data from experiments that were not available for the study of Baldursdóttir (2010), i.e., studies by Guðnadóttir (2014) and Sveinbjörnsson & Baldursdóttir (2020). Second, by following future updates of Norfor‘s methane prediction equations and testing them with methane emission data from on-farm Icelandic dairy cow studies, as was done in the first part of this study. These two types of improvements can be done and utilized within the frame of the methodology that was proposed above.

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