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Evaluation of models of enteric methane emissions in finishing steers

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ABSTRACT

Accurate estimation of enteric CH_4 emissions (i.e., MJ or g of CH_4/ day) in the ruminant sector is necessary for properly determining greenhouse gas emissions and developing measuring, reporting, and verification programs. However, measuring enteric CH_4 emissions under commercial conditions presents challenges due to technical and economic constraints. Thus, using prediction models allows for estimating individual enteric CH_4 emissions according to animal and dietary characteristics. When evaluated in independent datasets, there is limited information regarding the accuracy and precision of the reported equations to predict enteric CH_4 emissions in steers fed a finishing diet. This study evaluated the predictive performance of various reported equations for estimating enteric CH_4 production in finishing steers. Data used to assess the prediction equations came from 446 steers from five experiments during the finishing phase. Gas flux, nutrient consumption, and animal growth performance were evaluated in each experiment. Seventy-two equations were compared based on the mean square prediction error (**MSPE**), the decomposition of the root MSPE (**RMSPE**), and the concordance correlation coefficient (**CCC**). Prediction equations for estimating enteric CH_4 emissions showed lower sensitivity with RMSPE (as a percentage of the observed mean) ranging from 17.79 to 99.21 and CCC ranging from –0.07 to 0.21. The decomposition of the RMSPE showed mean bias (as a percentage of the RMSPE) ranging from 0.14 to 94.87 and slope bias (as a percentage of the RMSPE) ranging from 0 to 25.24. In addition, 49 equations underpredicted (ranging from 0.6 to 50.1%) and 23 overpredicted (ranging from 3.7 to 96.1%) enteric CH_4 emissions. The prediction of enteric CH_4 production showed greater CCC and lower MSPE when the intake of DM and ether extract were included as predictors. These results suggest a limited ability to predict enteric CH_4 by steers during the finishing phase. Further efforts are required to generate sensitive models to accurately predict enteric CH_4 emissions in finishing steers.

Implications

Models have been used to estimate enteric methane emissions from ruminants and develop the national inventories of greenhouse gasses. However, limited information exists regarding the sensitivity of models reported in the literature to represent the methane production in steers during the finishing phase. Retrieved equations from the literature showed lower sensitivity for predicting methane production, suggesting limited ability to represent the actual methane emissions from steers during the finishing phase. Further models are needed to represent the enteric methane emissions appropriately and improve the estimation of greenhouse gas emissions from the ruminant sector.

Introduction

In the last decades, there has been a substantial effort to measure and mitigate enteric methane CH_4 emissions from ruminants (Beauchemin et al., 2022). Enteric CH_4 emissions represent an energy loss by ruminants that ranges between 2 and 12% of the gross energy intake (Johnson and Johnson, 1995), which varies according to animal physiology and behavior, dietary characteristics, and rumen microbial communities (Hristov et al., 2015; Ungerfeld et al., 2022). In addition, CH_4 is a potent greenhouse gas with a global warming potential 28 times greater than CO_2 over a 100-year time frame (Forster et al., 2021). Emissions of enteric CH_4 represent 58% of the greenhouse gas from the ruminant supply chain (FAO, 2021). Therefore, appropriate determination of CH_4 emissions is essential to identifying efficient animals, promoting appropriate productive practices, designing sector recommendations for reducing greenhouse gas emissions, and supporting

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measuring, reporting, and verification programs and regulatory policies.

Determination of enteric CH_4 under commercial conditions is challenging due to technical constraints such as limited measurement techniques and the economic implications of an extensive animal evaluation (Hristov et al., 2013; Beauchemin et al., 2022). Thus, the estimation of enteric CH_4 by applying empirical or mechanistic models has been used to determine enteric CH_4 emission under a variety of conditions (Ellis et al., 2014; Moraes et al., 2014; van Lingen et al., 2019). Indeed, the majority of national inventories for estimating enteric CH_4 production from ruminants used empirical models, where a predefined proportion of the consumed energy is expected to be emitted as enteric CH_4 (Gavrilova et al., 2019). However, there is evidence that those empirical approaches would be inaccurate, under or overestimating enteric CH_4 emissions, mainly when enteric CH_4 is determined outside the limits of the data from which models were developed (Ricci et al., 2013; Ellis et al., 2014; Escobar-Bahamondes et al., 2016).

The literature reports different models for estimating enteric CH_4 emissions from beef cattle. Models used individual or treatment-average data to predict enteric CH_4 emissions (Ellis et al., 2009; Ramin and Huhtanen, 2013; Moraes et al., 2014; Escobar-Bahamondes et al., 2017). Generally, models to estimate enteric CH_4 emissions include a large proportion of forages (54–82% inclusion) (Yan et al., 2009; Ricci et al., 2013; van Lingen et al., 2019), limiting the applicability to feedlot conditions (Ellis et al., 2014). In addition, the Intergovernmental Panel on Climate Change suggests that enteric CH_4 emissions represent between 3 and 4% of the gross energy intake for cattle-feeding finishing diets (Gavrilova et al., 2019). However, there is limited information regarding the accuracy and precision of the reported models to predict enteric CH_4 emissions on steers consuming a finishing diet. Thus, the objective of this work was to evaluate the accuracy and precision of different reported models for estimating enteric CH_4 in finishing steers using an independent dataset. The hypothesis was that the current models have a low agreement when estimating enteric CH_4 emissions from steers during the finishing period.

Material and methods

Animals, feed management, and experimental conditions

Data from five independent experiments were used to evaluate animal growth performance and gas flux during the finishing phase. Those evaluations were conducted at the Climate Smart Research Facility at Colorado State University, in Fort Collins, CO, USA. In experiment one, a total of 166 Angus steers (approximately 15 months of age and 518 ± 39.9 kg of initial BW) were offered a finishing total mixed ration (**TMR**) for 69 days (Table 1). Diet samples were collected weekly, dried, composed, and conserved throughout the experiment for further analysis. Individual intake was recorded daily during the evaluation using the SmartFeed intake monitoring system (C-Lock, Rapid City, SD). Steers were weighed on d -1 and 0 to obtain the initial BW and on d 68 and 69 to record the final BW. In addition to the initial and final BW, unshrunk weights were obtained during the evaluation period on days 22 and 45.

In experiment two, a total of 170 Angus steers (approximately 15 months of age and 345 ± 22.3 kg of initial BW) were offered a finishing TMR for 96 days (Table 1). Diet samples were collected weekly, dried, composed, and conserved throughout the experiment for further analysis. Individual intake was recorded during the evaluation using the SmartFeed system. Steers were weighed on d -1 and 0 to obtain the initial BW and on d 179 and 180 to record the final BW. In addition to the initial and final BW, unshrunk weights were obtained during the evaluation period on days 28, 56, 84, 112, and 140.

In experiment three, a total of 51 Angus steers (approximately 15 months of age) were classified according to the initial BW as heavy (n = 23 and 578 ± 24.0 kg) or light (n = 38 and 512 ± 36.5 kg BW) group. Heavy and light steers were offered a finishing TMR for 52 and 80 days, respectively (Table 1). Diet samples were collected weekly, dried, and conserved throughout the experiment for further analysis. Individual intake was recorded daily during the evaluation using SmartFeed system. Steers were weighed on

Table 1
Ingredient inclusion and chemical compositions of the diets offered to finishing steers.

Item	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5
Ingredient (% of DM)					
Steam-flaked corn	60.0	65.0	65.0	65.0	65.0
Corn silage	27.0	20.0	20.0	20.0	20.0
Dry distiller grains with solubles	4.0	7.0	7.0	7.0	7.0
Molasses-based mineral supplement[1]	4.0	4.0	4.0	4.0	4.0
Vitamin/mineral supplement[2]	3.0	–	–	–	–
Vitamin/mineral supplement[3]	–	4.0	4.0	4.0	4.0
Ionophore[4]	2.0	–	–	–	–
Composition[5] (% of DM)					
DM, % As Fed	66.8	63.8	66.5	62.9	63.3
CP	12.8	13.9	13.7	14.5	14.2
NDF	16.8	16.6	17.5	17.1	16.9
ADF	9.9	8.1	8.8	9.5	8.8
Lignin	1.6	1.3	1.4	1.5	1.4
Non-fiber carbohydrates	62.2	61.9	61.3	60.6	61.3
Starch	55.3	51.3	53.8	52.0	51.7
Ether extract	4.3	3.1	3.1	3.2	3.2
Ash	3.9	4.5	4.5	4.6	4.6
Total digestible nutrients	82.1	80.1	81.0	81.0	80.6
Gross energy, Mcal/kg of DM	4.6	4.4	4.4	4.4	4.4
Net energy of maintenance, Mcal/kg of DM	2.0	2.0	2.0	2.0	2.0
Net energy of gain, Mcal/kg of DM	1.4	1.4	1.3	1.4	1.4

[1] MidWest PMS, Englewood, CO.
[2] Without ionophore. Ralco, Marshall, MN.
[3] With ionophore (monensin sodium). Ralco, Marshall, MN.
[4] Proprietary ionophore supplement.
[5] Analyzed by a commercial laboratory using a wet chemistry package (Dairy One, Ithaca, NY).

d -1 and 0 to obtain the initial BW and on d 51 and 52 and d 79 and 80 to record the final BW for the heavy and light groups, respectively. In addition to the initial and final BW, unshrunk weights were obtained during the evaluation period on day 21 for all cattle and on days 42 and 63 for the light group.

In experiment four, a total of 36 Angus steers (approximately 15 months of age and 548 ± 31.2 kg of initial BW) were offered a finishing TMR for 76 days (Table 1). Diet samples were collected weekly, dried, and conserved throughout the experiment for further analysis. Individual intake was recorded daily during the evaluation using the SmartFeed system. Steers were weighed on d -1 and 0 to obtain the initial BW and on d 75 and 76 to record the final BW. In addition to the initial and final BW, unshrunk weights were obtained during the evaluation period on days 21, 42, and 63.

In experiment five, a total of 23 Angus steers (approximately 16 months of age and 608 ± 51.4 kg of initial BW) were offered a finishing TMR for 49 days (Table 1). Diet samples were collected weekly, dried, and conserved throughout the experiment for further analysis. Individual intake was recorded daily during the evaluation using the SmartFeed system. Steers were weighed on d -1 and 0 to obtain the initial BW and on d 48 and 49 to record the final BW. In addition to the initial and final BW, unshrunk weights were obtained during the evaluation period on day 21.

Gas flux determination

In each experiment, steers were located in pens containing one automated head-chamber system (**AHCS**, GreenFeed, C-Lock, Rapid City, SD) for gas flux collection (CH_4, CO_2, and O_2). Before using the AHCS, steers individually received a radio frequency electronic ID (Allflex, Madison, WI). Steers were exposed to the AHCS during an acclimation period of approximately 2 weeks before data collection. After the acclimation period, headbox wings and cattle panels were used to insure that only one animal had access to the AHCS.

Steers were allowed to visit the AHCS every 4 h (up to six visits per day) and consume up to six drops of alfalfa pellet (approximately 35 g as fed/drop) per visit with 30-second intervals between drops. This encouraged animals to visit the units throughout the day and insured they stayed at the AHCS for an appropriate gas flux collection. Gas flux was calculated as reported by Huhtanen et al., 2015.

Recovery tests of CO_2 were performed monthly throughout the experiment and at the beginning and end of each experiment. Additionally, the manufacturer performed zero and span calibrations of the CH_4, CO_2, and O_2 gas analyzers every 3 days via an onboard autocalibration system. Raw collection data were validated by C-Lock Inc., which included appropriate head proximity, visit length, and airflow and wind corrections. Data were excluded when the length of the visit was less than two min and the airflow was less than 26 L/s (Arthur et al., 2017; Gunter and Beck, 2018). In addition, the evaluated growing steers visited the AHCS at least 55 times during each phase, as recommended by Vargas et al., 2024.

Models for predicting enteric methane in beef cattle

The literature reports different models for predicted enteric CH_4 emissions in ruminants (Ellis et al., 2007; Ellis et al., 2009). In this analysis, 72 linear and non-linear equations were retrieved from the literature to predict enteric CH_4 emissions (MJ/d) from beef cattle (Supplementary Table S1). Criteria for selecting those equations were based on the available covariates or those that could be calculated in the present database. Consequently, the concentration of hemicellulose was calculated as the difference between NDF and ADF, cellulose as the difference between ADF and lignin, and non-structural carbohydrates was calculated as the difference between the DM and the content of CP, NDF, ash, and ether extract (Van Soest, 1994). The digestible energy intake was determined as the product of the total digestible nutrient intake and 18.41 MJ of DE/kg of total digestible nutrients (NASEM, 2016). Metabolized energy intake was calculated as the product between digestible energy intake and 0.82 (NASEM, 2016). The requirement of net energy for maintenance (**NEm**) was calculated as the product between 0.077 and metabolic BW (NASEM, 2016). Finally, the intake level was determined as the ratio between the intake and the requirement of the NEm (Hales et al., 2022).

Calculation, chemical analysis, and model evaluation

Animal growth was determined by linear regressions of the shrunk BW (0.96 × BW) against time, and the calculated slope was considered the average daily gain (Vargas et al., 2024). The dry matter intake (**DMI**) was calculated as the average feed intake (i.e., TMR and pellets) corrected by the DM concentration of the TMR and pellets during the experimental period. The chemical composition of the diets (i.e., CP, NDF, ADF, lignin, starch, EE, ash, total digestible nutrients) was determined by a commercial laboratory using a wet chemistry package (Dairy One, Ithaca, NY). The data describing enteric CH_4 emissions, animal growth performance, and nutrient intake are reported in Table 2. In addition, the correlation of animal growth performance, nutrient intake, and enteric CH_4 emissions was analyzed using the Corr procedure of SAS 9.4 (SAS, Institute Inc.).

Models were evaluated using RStudio (v. 2024.09.0) with R Statistical Language (v. 4.1; R Core Team, 2020). The data were analyzed using a linear mixed model fitted with lmer (lme4 package) (Bates et al., 2015). The mean square prediction error (**MSPE**) was calculated as:

$$MSPE = \sum_{i=1}^{n} (Oi - Pi)^2 / n$$

Where Oi is the observed value, and Pi is the predicted value. The root of the MSPE (**RMSPE**), expressed as a percentage of the observed mean, estimates the overall predicted error. The RMSPE was decomposed into error due to overall bias (**ECT**), error due to deviation of the regression slope from unity (**ER**), and random error (**ED**) (Tedeschi, 2006). Additionally, the correlation coefficient analyses (**CCC**) were performed (Lin, 1989) and calculated as follows:

$$CCC = P \times Cb$$

Where P is the Pearson correlation coefficient, which is given a measure of precision, and Cb is the bias correction factor, which is given a measure of accuracy.

Results

Dietary characteristics and animal growth performance

Experimental diets were formulated using similar ingredients. Steam-flaked corn varied between 60 and 65% of inclusion, while corn silage ranged between 20 and 27%, which was the forage source (Table 1). Diet formulation intended to provide similar nutrient concentration, with an average of 13.8% CP, 17.0% NDF, 52.8% starch, and 8.4 and 5.7 MJ/kg of DM of NEm and net energy of gain, respectively. Steer BW ranged between 396.3 and 782.2 kg, while the average daily gain ranged between 0.88 and 2.95 kg (Table 2). Daily DMI ranged between 7.86 and 15.89 kg, representing an average of 2.0 kg of DM per 100 kg of BW. Enteric CH_4 emissions varied between 6.31 and 16.69 MJ daily.

The production of CH_4 was positive and significantly associated with BW (0.34), average daily gain (0.17), and DMI (0.18), resulting in a positive relationship with CP, NDF, hemicellulose, non-

Table 2
Enteric methane emissions, animal growth performance, and nutrient intake description of finishing steers.

Variable	Mean	Median	SD	Min	Max	r[1]
CH4, MJ/d	9.9	9.7	1.77	6.3	16.7	–
CH_4, g/d	178	173	31.8	113	299	–
BW, kg	552	551	59.9	396	782	0.34***
ADG, kg/d	1.97	1.98	0.34	0.88	2.95	0.17***
DMI, kg/d	11.3	11.1	1.23	7.9	15.9	0.18***
CP, kg/d	1.52	1.50	0.16	1.01	2.29	0.32***
NDF, kg/d	1.90	1.88	0.21	1.32	2.72	0.20***
Hem, kg/d	0.89	0.89	0.10	0.54	1.34	0.41***
ADF, kg/d	1.01	0.96	0.17	0.68	1.43	0.00 ns
Lig, kg/d	0.16	0.15	0.03	0.10	0.23	−0.01 ns
Cel, kg/d	0.85	0.81	0.14	0.57	1.20	0.00 ns
NFC, kg/d	6.97	6.85	0.75	4.89	9.56	0.14**
Sta, kg/d	6.02	5.87	0.76	4.29	8.36	0.10*
EE, kg/d	0.41	0.35	0.10	0.26	0.62	−0.04 ns
Ash, kg/d	0.48	0.47	0.05	0.31	0.73	0.38***
GE, MJ/d	211	206	25.4	151	294	0.12**
DE, MJ/d	168	164	19.0	117	239	0.18***
ME, MJ/d	137	134	15.5	96	196	0.18***
Forage, %	21.8	20.0	4.15	20.0	26.6	−0.27***

Abbreviations: ADG = Average daily gain. DMI = DM intake. Hem = Hemicellulose intake. ADF = ADF intake. Lig = Lignin intake. Cel = Cellulose intake. NFC = Non-fiber carbohydrate intake. Sta = Starch intake. EE = Ether extract intake. Ash = Ash intake. GE = Gross energy intake. DE = Digestible energy intake. ME = Metabolize energy intake. Forage = Forage proportion.

[1] Pearson correlation between measured variables and CH_4 production. ns = non-significant; * = $P < 0.05$; ** = $P < 0.01$, *** $P < 0.001$.

structural carbohydrates, starch, ash, and energy intake (Table 2). However, intake of cellulose, ADF, lignin, and ether extract did not show a significant association with CH_4 emissions. In addition, the forage proportion in the diet was negatively and significantly associated with enteric CH_4 emissions (−0.27).

Model evaluation for predicting enteric methane emissions

Residual estimation and decomposition showed large variability regarding the evaluated model (Fig. 1). Model 3, where CH_4 prediction was based on the Intergovernmental Panel on Climate ChangeF Tier I methodology (Gavrilova et al., 2019), and model 68 (Ellis et al., 2007), where CH_4 prediction was based on DM and ether extract intake, showed lower RMSPE (Table 3). In addition, ED was larger in models 11 (van Lingen et al., 2019), 34 (Ellis et al., 2009), and 63 (Ellis et al., 2007). In contrast, model 30 (Yan et al., 2009), where CH_4 prediction was based on energy concentration and DMI, showed the largest RMSPE. Models 28–33 (Yan et al., 2009) showed the highest ECT, while models 39 and 41 (Ellis et al., 2009) resulted in the highest ER. In general, CCC was low in every model (< 0.15), except for model 68 (Ellis et al., 2007), where the CCC was 0.21.

Discussion

This analysis evaluated 72 retrieved equations for predicting enteric CH_4 emissions using data from 446 growing steers during the finishing phase fed similar grain-based diets commonly used

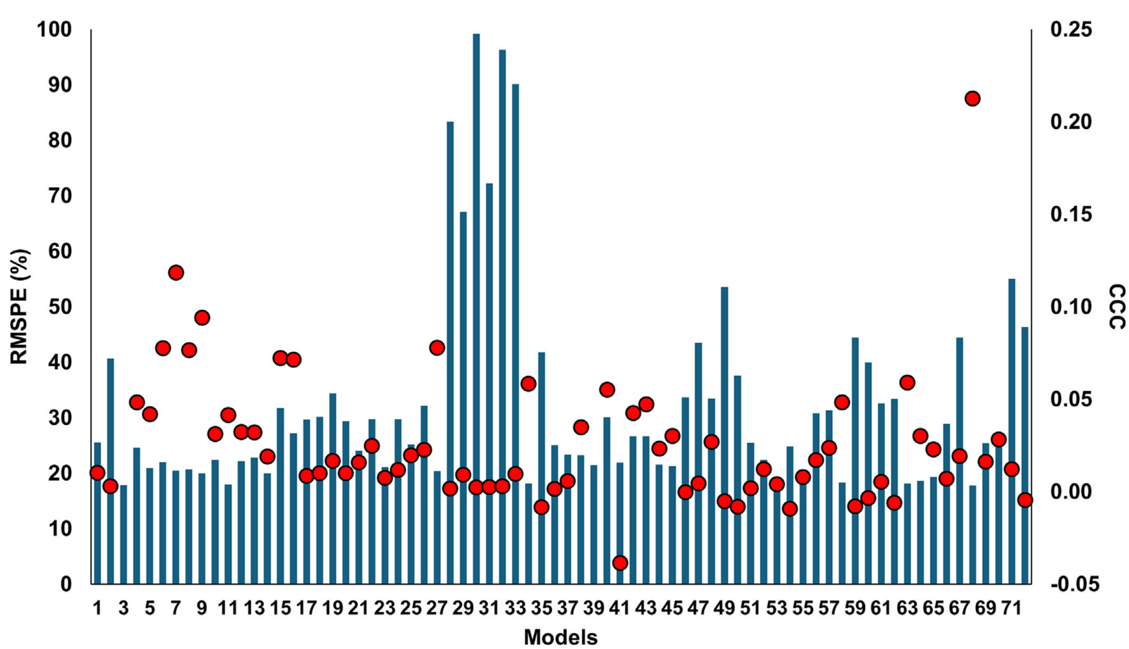

Fig. 1. Description of the root mean square prediction error, as a percentage of the observed mean (RMSPE [%], bars), and the concordance correlation coefficient (CCC, dots) from assessed models for predicting enteric methane emissions in finishing steers.

Table 3
Model evaluation for estimating enteric methane emissions in finishing steers.

Model	Predicted CH_4, MJ/d	RMSPE, MJ/d	RMSPE, %	ECT	ER	ED	CCC
1	8.22	2.53	25.57	44.31	7.23	48.45	0.010
2	6.33	4.03	40.65	79.19	1.63	19.18	0.003
3	9.76	1.77	17.87	0.75	–	–	–
4	11.48	2.44	24.66	41.13	7.26	51.61	0.048
5	8.85	2.07	20.94	25.89	2.55	71.56	0.042
6	8.60	2.18	21.97	36.17	0.85	62.97	0.078
7	8.75	2.03	20.47	32.49	0.40	67.11	0.118
8	8.92	2.05	20.70	23.41	4.15	72.44	0.077
9	8.97	1.98	20.00	22.40	1.42	76.17	0.094
10	8.58	2.22	22.38	36.03	1.34	62.63	0.031
11	9.75	1.79	18.02	0.85	2.33	96.82	0.041
12	8.62	2.20	22.19	34.66	1.58	63.76	0.032
13	8.49	2.23	22.83	39.69	0.45	59.86	0.032
14	9.49	1.98	19.98	4.54	16.06	79.40	0.019
15	7.24	3.14	31.73	71.88	0.06	28.06	0.072
16	7.87	2.69	27.19	57.31	1.77	40.92	0.071
17	12.05	2.94	29.67	52.75	11.24	36.01	0.009
18	12.13	2.99	30.20	54.95	10.31	34.74	0.010
19	12.66	3.41	34.41	64.89	8.40	26.70	0.017
20	12.04	2.91	29.38	53.62	9.67	36.71	0.010
21	11.23	2.38	24.04	30.76	14.40	54.83	0.016
22	12.06	2.95	29.76	53.20	11.13	35.68	0.025
23	8.83	2.09	21.10	26.50	2.31	71.20	0.008
24	7.54	2.95	29.77	64.46	0.13	35.41	0.012
25	8.14	2.50	25.22	50.35	0.36	49.29	0.020
26	7.29	3.19	32.18	67.67	2.06	30.28	0.023
27	10.82	2.02	20.43	20.28	5.22	74.50	0.078
28	17.92	8.26	83.36	92.88	1.56	4.56	0.002
29	16.25	6.65	67.12	90.93	2.11	6.96	0.009
30	19.44	9.83	99.21	93.84	2.94	3.22	0.002
31	16.71	7.16	72.24	90.10	3.83	6.07	0.003
32	19.16	9.54	96.31	93.81	2.77	3.41	0.003
33	18.61	9.93	90.11	94.87	1.32	3.81	0.010
34	9.84	1.80	18.12	0.14	4.28	95.58	0.058
35	6.21	4.14	41.81	79.85	2.15	18.00	−0.008
36	11.53	2.48	25.02	42.47	6.87	50.66	0.001
37	8.41	2.31	23.35	41.86	0.12	58.02	0.006
38	8.59	2.31	23.30	32.67	9.20	58.13	0.035
39	10.45	2.13	21.45	6.45	25.24	68.32	−0.069
40	7.44	2.98	30.08	68.56	0.20	31.24	0.055
41	9.21	2.17	21.88	10.33	23.61	66.05	−0.038
42	7.98	2.65	26.71	53.41	2.89	43.70	0.043
43	7.94	2.65	26.71	55.56	1.23	43.21	0.047
44	8.94	2.14	21.57	20.41	11.55	68.03	0.023
45	8.94	2.11	21.29	21.38	8.84	69.78	0.030
46	7.08	3.34	33.65	71.98	0.26	27.76	0.000
47	5.97	4.32	43.54	83.45	0.01	16.54	0.004
48	7.06	3.31	33.43	74.02	2.54	23.43	0.027
49	4.95	5.31	53.53	87.49	1.51	10.99	−0.005
50	6.67	3.73	37.61	75.80	1.95	22.26	−0.008
51	8.10	2.53	25.51	51.38	0.00	48.62	0.002
52	8.56	2.22	22.38	36.81	0.24	62.96	0.012
53	9.55	1.80	18.13	3.98	6.69	89.33	0.004
54	8.30	2.44	24.81	43.56	4.03	52.41	−0.009
55	10.38	1.82	18.37	6.75	0.52	92.73	0.008
56	7.41	3.05	30.81	67.33	0.02	32.65	0.017
57	12.43	3.10	31.33	66.00	2.05	31.95	0.024
58	10.29	1.82	18.33	4.25	2.40	93.35	0.048
59	5.89	4.41	44.46	83.06	2.08	14.86	−0.008
60	6.38	3.96	39.93	79.59	0.68	19.73	−0.003
61	7.19	3.23	32.63	70.61	0.10	29.29	0.005
62	7.13	3.31	33.42	70.63	1.20	28.17	−0.006
63	9.67	1.80	18.15	1.75	3.15	95.09	0.059
64	9.62	1.84	18.61	2.45	6.24	91.31	0.030
65	9.60	1.92	19.35	2.60	12.83	84.58	0.023
66	7.74	2.87	28.93	57.40	4.74	37.87	0.007
67	13.92	4.41	44.47	82.82	1.45	15.72	0.019
68	9.34	1.76	17.79	10.52	0.48	89.00	0.213
69	8.20	2.52	25.41	46.14	4.88	48.99	0.016
70	11.77	2.62	26.47	50.08	4.96	44.96	0.028
71	15.01	5.46	55.06	87.26	2.39	10.35	0.012
72	14.14	4.60	46.39	84.74	1.08	14.18	−0.004

Abbreviations: RMSPE = Root mean square prediction error (RMSPE). ECT = Error due to overall bias as a percentage of total RMSPE. ER = Error due to deviation of the regression slope from unity as a percentage of total RMSPE. ED = Random error as a percentage of total RMSPE. CCC = Concordance correlation coefficient.

in commercial feedyards in the United States. The retrieved equations showed low agreement for predicting enteric CH_4 emissions with RMSPE values ranging from 17.79 to 99.21 and CCC values ranging from –0.07 to 0.21 (Ellis et al., 2010). A total of 49 equations underpredicted (ranging from 0.6 to 50.1%) and 23 overpredicted (ranging from 3.7 to 96.1%) enteric CH_4 emissions (Fig. 2). This analysis did not intend to develop a new model due to the similar experimental conditions and the narrow variability of the animal and dietary characteristics among the five experiments (Table 1). Instead, it examined the constraints of the current models for predicting CH_4 emissions under feedlot conditions and highlighted the importance of developing new models for this production phase (Moraes et al., 2014; Escobar-Bahamondes et al., 2016; van Lingen et al., 2019).

In this analysis, DMI was positively and significantly associated with enteric CH_4 production in finishing steers (0.18; Table 2). Dry matter intake has been reported as an important factor in predicting enteric CH_4 emissions because it is related to the amount of organic matter potentially fermented in the rumen (Ellis et al., 2007; Ricci et al., 2013; van Lingen et al., 2019). Ruminants with greater DMI are expected to produce more total enteric CH_4 emissions. The reported DMI in the retrieved models ranged from 1.62 to 14.4 kg/day (Ellis et al., 2007; Ellis et al., 2009; Yan et al., 2009; Moraes et al., 2014; Escobar-Bahamondes et al., 2016; van Lingen et al., 2019; Hales et al., 2022). Conversely, the DMI ranged between 7.86 and 15.89 kg/day in this study (Table 2). Differences in DMI between the animals used for developing the retrieved models and steers in this analysis can result in a larger ECT due to a systematic underprediction of enteric CH_4 emissions (Tedeschi, 2006).

Individual DMI is affected by internal and external factors of the animal such as the gut capacity associated with the BW and the chemical composition of the diet, respectively (NASEM, 2016). Larger animals are expected to consume more feed than small ones, resulting in greater enteric CH_4 emissions. Kriss (1930) and Axelsson (1949), cited by Wilkerson et al., 1995, developed models for predicting enteric CH_4 emissions using adult cattle. Those models showed a large ECT (approximately 85%) due to the differences in DMI relative to the steers in this study. Thus, greater enteric CH_4 prediction is expected using those models than the observed in this analysis with data derived from growing steers due to a systematic overprediction of enteric CH_4 emissions (Tedeschi, 2006).

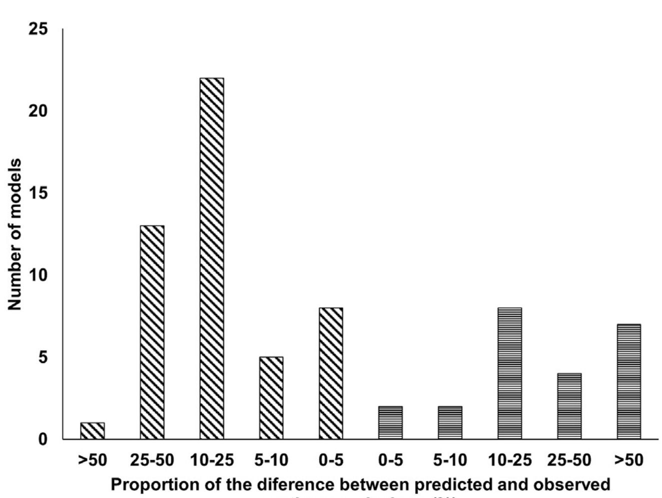

Fig. 2. Number of models according to the proportion difference between predicted and observed methane emissions in finishing steers (left panel: underprediction, n = 49, diagonally hatched bars; right panel: overprediction, n = 23, horizontally hatched bars).

The determination of enteric CH_4 emissions has been conducted using respiration chambers, sulfur hexafluoride trace technique, hood calorimetry, and AHCS (Ellis et al., 2009; van Lingen et al., 2019; Hales et al., 2022). Some of these techniques require animal movement restriction, impairing normal feeding behavior and potentially reducing the DMI compared to unrestricted conditions (Llonch et al., 2018). Although including the methodology for measuring CH_4 did not improve the enteric CH_4 prediction, it has been postulated that it could affect the enteric CH_4 determination (van Lingen et al., 2019). In this study, enteric CH_4 emissions were determined using the AHCS. The AHCS captures the exhaled or eructed CH_4 through the nostrils and mouth of the animal, which represents more than 90% of the CH_4 production (Murray et al., 1976), resulting in a potential underestimation of the individual CH_4 emission. However, the use of AHCS allows the animal to exhibit unrestricted feeding behavior while determining enteric CH_4 emissions. In addition, the evaluated steers visited the AHCS more than 55 times during the finishing period in this study, ensuring the appropriate determination of enteric CH_4 emissions under confined conditions (Vargas et al., 2024). Determining enteric CH_4 emissions using techniques that modify DMI can result in an inaccurate CH_4 determination limiting the ability to compare with unrestricted conditions.

The literature reports greater enteric CH_4 emissions from ruminants consuming forage-based than grain-based diets (Johnson and Johnson, 1995). Indeed, Gavrilova et al. (2019) report that the emission factor (i.e., energy loss as CH_4 relative to the gross energy intake) varies between 3–4% when ruminants consume diets with more than 85% concentrate in the diet relative to 6.3–7.0% when the diet has lower concentrate inclusion. Some models for predicting enteric CH_4 emissions were developed using diets with 31–81% forage inclusion (Ellis et al., 2009; Yan et al., 2009; Ricci et al., 2013), while in this analysis, the average corn-silage inclusion was 21.3% (Table 1). In addition, the NDF concentration in beef cattle's diet in Moraes et al., 2014 and Hales et al., 2022 was 38%, greater than the 17% average NDF concentration in the current study analysis. A greater proportion of forage results in greater fiber concentration in the diet. In the rumen, fiber fermentation increases acetate and butyrate resulting in greater hydrogen production (Moss et al., 2000). In addition, the passage rate in the rumen decreases when the fiber concentration increases in the diet (Huhtanen et al., 2006). Therefore, greater hydrogen availability and lower passage rate promote rumen methanogenesis (Janssen, 2010; Ungerfeld, 2020). Thus, retrieved models using diets with greater fiber concentration were expected to overestimate the enteric CH_4 emissions because they were developed using different forage inclusions.

This evaluation demonstrated a negative association between forage proportion and total enteric CH_4 emissions (Table 2). In finishing diets, forage is included to maintain ruminal integrity (i.e., anatomical functionality) and microbial fermentation (Galyean and Goetsch, 1993). However, forage has a lower fermentation because it is composed of structural carbohydrates, which have lower fermentability than other dietary components such as soluble carbohydrates (Van Soest, 1994). In addition, finishing diets promote a lower ruminal pH, limiting ruminal methanogen activity and enteric CH_4 synthesis (Ungerfeld et al., 2020). In diets with less concentrate, forage inclusion has been associated with greater CH_4 emissions because it promotes the synthesis of acetate and butyrate, reduces the passage rate, and increases the ruminal pH, resulting in greater CH_4 synthesis (Janssen, 2010; Ungerfeld, 2020). Future analyses should consider contrasting forage inclusion in finishing diets.

In this analysis, the intake of EE, ADF, cellulose, and lignin was not significantly associated with the production of enteric CH_4 emissions (Table 2). However, when enteric CH_4 emission was predicted using the intake of DM and ether extract (Ellis et al., 2007), it showed the greatest CCC (0.21, Table 3). Dietary fat supplementation in ruminant diets has been reported as a practical strategy to reduce enteric CH_4 (Hristov et al., 2013; Beauchemin et al., 2022). Indeed, Grainger and Beauchemin, 2011 reported that by increasing the concentration of ether extract by 1% in the diet, the enteric CH_4 yield (i.e., g of CH_4 per kg of DMI) was reduced between 4.7 and 5.1% depending on the fat concentration of the basal diet. Fat modulates rumen fermentation, reducing the fermentability of the organic matter, capturing hydrogens during the biohydrogenation, or affecting the methanogenic population through the toxic effect of some fatty acids, which affects the enteric CH_4 synthesis (Ramin and Huhtanen, 2013).

Beef cattle production presents large variability due to differences in production conditions such as management practices, resource availability, or geographical localization (Ellis et al., 2007). In this regard, defining a unique model to predict enteric CH_4 emissions is not a simple task because enteric CH_4 emissions in ruminants are modulated by different conditions, as previously discussed. The literature reports the limited ability of the current models to predict enteric CH_4 emissions from ruminants in finishing diets because those conditions were not well represented in the data used to develop the reported models (van Lingen et al., 2019). It has been proposed that enteric CH_4 prediction is modulated in ruminants consuming diets with different forage levels (Escobar-Bahamondes et al., 2016; NASEM, 2016; van Lingen et al., 2019). However, limited information exists regarding animal physiological conditions (e.g., growing vs mature or male vs female) or additive supplementation (e.g., ionophore inclusion) that can modulate animal nutrient requirements and DMI, resulting in different enteric CH_4 emissions (Ricci et al., 2013). In this study, finishing steers were supplemented with an ionophore as a routine feeding practice (Table 1). Ionophore supplementation had contrasting results on CH_4 emissions (NASEM, 2016). The evaluation of CH_4 emissions may be overestimated by ionophore supplementation, especially when comparing with models developed using animals without ionophore supplementation. Thus, future analysis integrating data from finishing steers under current management practices will allow a better estimation of CH_4 emissions.

Models are valuable tools to represent biological systems mathematically. However, they require the use of a representative sample to allow the estimation of accurate and precise values in a different population. In general, empirical models rely on the statistical association between measured and predicted variables, while mechanistic models intend to represent the underlying mechanisms (Ellis et al., 2010; Moraes et al., 2014). In this analysis, neither empirical nor mechanistic models adequately describe the enteric CH_4 emissions from finishing steers.

Conclusion

In conclusion, retrieved models for estimating enteric CH_4 emissions showed lower sensitivity, with RMSPE values ranging from 17.79 to 99.21 and CCC values ranging from −0.07 to 0.21. The decomposition of the RMSPE showed mean bias ranging from 0.14 to 94.87 and slope bias ranging from 0 to 25.24. In addition, 49 equations underpredicted, while 23 overpredicted enteric CH_4 emissions. The prediction of enteric CH_4 production showed greater CCC and lower MSPE when the intake of DM and ether extract was included as predictors. This suggests a limited ability of the retrieved models to predict enteric CH_4 by steers during the finishing phase. Thus, further efforts are necessary to generate sensitive models to predict enteric CH_4 emissions in finishing steers.

Supplementary material

Supplementary Material for this article (https://doi.org/10.1016/j.animal.2025.101536) can be found at the foot of the online page, in the Appendix section.

Ethics approval

Data from five independent experiments were used to evaluate animal growth performance and gas flux during the finishing phase. Those evaluations were conducted at the Climate Smart Research Facility at Colorado State University, CO. The Colorado State University Institutional Animal Care and Use Committee approved all animal evaluation procedures (experiment one: 4072, experiment two: 3712-13, experiment three: 4689, experiment four: 4689, experiment five: 5403).

Data and model availability statement

The data that support the findings of this study are openly available in Dryad at https://doi.org/10.5061/dryad.qnk98sfsn. Information can be made available from the authors upon request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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Declaration of interest

None.

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