Published February 9, 2015

Model for estimating enteric methane emissions from United States dairy and feedlot cattle[1]

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ABSTRACT: Methane production from enteric fermentation in cattle is one of the major sources of anthropogenic greenhouse gas emission in the United States and worldwide. National estimates of methane emissions rely on mathematical models such as the one recommended by the Intergovernmental Panel for Climate Change (IPCC). Models used for prediction of methane emissions from cattle range from empirical to mechanistic with varying input requirements. Two empirical and 2 mechanistic models (COWPOLL and MOLLY) were evaluated for their prediction ability using individual cattle measurements. Model selection was based on mean square prediction error (MSPE), concordance correlation coefficient, and residuals vs. predicted values analyses. In dairy cattle, COWPOLL had the lowest root MSPE and greatest accuracy and precision of predicting methane emissions (correlation coefficient estimate = 0.75). The model simulated differences in diet more accurately than the other models, and the residuals vs. predicted value analysis showed no mean bias ($P = 0.71$). In feedlot cattle, MOLLY had the lowest root MSPE with almost all errors from random sources (correlation coefficient estimate = 0.69). The IPCC model also had good agreement with observed values, and no significant mean ($P = 0.74$) or linear bias ($P = 0.11$) was detected when residuals were plotted against predicted values. A fixed methane conversion factor (Ym) might be an easier alternative to diet-dependent variable Ym. Based on the results, the 2 mechanistic models were used to simulate methane emissions from representative US diets and were compared with the IPCC model. The average Ym in dairy cows was 5.63% of GE (range 3.78 to 7.43%) compared with 6.5% ± 1% recommended by IPCC. In feedlot cattle, the average Ym was 3.88% (range 3.36 to 4.56%) compared with 3% ± 1% recommended by IPCC. Based on our simulations, using IPCC values can result in an overestimate of about 12.5% and underestimate of emissions by about 9.8% for dairy and feedlot cattle, respectively. In addition to providing improved estimates of emissions based on diets, mechanistic models can be used to assess mitigation options such as changing source of carbohydrate or addition of fat to decrease methane, which is not possible with empirical models. We recommend national inventories use diet-specific Ym values predicted by mechanistic models to estimate methane emissions from cattle.

Key words: cattle, greenhouse gas, methane, modeling

J. Anim. Sci. 2008. 86:2738–2748
doi:10.2527/jas.2008-0960

INTRODUCTION

Enteric CH_4 production arises principally from microbial fermentation of hydrolyzed dietary carbohydrates. Methane represents loss of energy to the animal and varies between 2 to 12% of GE intake (Johnson and Johnson, 1995). Methane is one of the greenhouse gases emitted from livestock and up to 21 times more potent than CO_2 in its ability to trap heat in the atmosphere. Globally, 287 Mt of CH_4 is released from anthropogenic sources annually, 50% of which is from agriculture, and the largest biogenic source of CH_4 is enteric fermentation from ruminants (US EPA, 2006). Agriculture in the United States contributes about 8% of the total US greenhouse gases emissions and is the second largest CH_4 source in the United States (US EPA, 2007).

Measurement of CH_4 production in animals requires complex and often expensive equipment; therefore, prediction equations are widely used to estimate CH_4 emis-

[1]This research was undertaken thanks to funding from the US Environmental Protection Agency.
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Received February 15, 2008.
Accepted June 2, 2008.

Table 1. Summary of the dairy and feedlot data used to evaluate the models[1]

	Dairy				Feedlot			
Variable	Mean	SD	Min[2]	Max[3]	Mean	SD	Min	Max
CH_4 (MJ/d)	23.5	3.90	15.4	30.3	5.11	1.89	1.62	10.22
DMI (kg/d)	24.5	3.57	16.8	35.9	6.88	0.98	4.32	9.07
CP (% of DM)	16.7	0.40	16.4	17.2	12.4	1.48	9.13	14.2
NDF (% of DM)	26.5	1.06	25.4	27.5	14.6	0.51	13.8	15.2
ADF (% of DM)	18.3	1.64	16.7	20.0	11.4	0.75	9.73	12.1
Fat (% of DM)	3.96	1.65	2.30	5.60	3.89	0.15	3.54	4.13
BW (kg)	707	64.0	590	838	384	61.0	280	526
Milk production (kg/d)	33.1	10.3	14.5	54.3	—	—	—	—

[1]The dairy data were from Johnson et al. (2002) and Westberg et al. (2001), and the feedlot data were from Archibeque et al. (2006, 2007).
[2]Min = minimum value.
[3]Max = maximum value.

sions. Some models have been developed specifically to predict CH_4 emissions from animals (Ellis et al., 2007) and others have either been modified or adapted to estimate CH_4 emission from rumen fermentation (Dijkstra et al., 1992; Baldwin, 1995). At present, mathematical models are used to estimate CH_4 emissions from enteric fermentation at a national and global level. The Intergovernmental Panel on Climate Change (**IPCC**) publishes guidelines (IPCC, 2006) that are used for official estimates of CH_4 emissions. However, accuracy of these models has been challenged (Kebreab et al., 2006b). The US EPA has adopted mechanistic models to estimate CH_4 yield (**Ym**, % of GE) for dairy cattle that are used as inputs to the IPCC tier 2 approach for estimating emission factors (US EPA, 2007). The objectives of this study were to evaluate selected models against observed data for an independent appraisal of the performance of the models in predicting enteric CH_4 emission and to use selected models to develop diet-specific CH_4 emission factors for use in calculating national inventory.

MATERIALS AND METHODS

Animal Care and Use Committee approval was not obtained for this study because the data were obtained from existing data sources, as described.

Data Sources

Dairy Cattle. Methane emission data from dairy cattle from Westberg et al. (2001) and Johnson et al. (2002) were used to evaluate the accuracy of predictions of CH_4 emission by models listed below. These data were individual daily animal CH_4 emissions from animals fed several types of diets. Methane measurements were based on sulfur hexafluoride tracer gas technique (**SF_6**). The data used for evaluation of the models is summarized in Table 1.

Diets fed to dairy cattle from several states were obtained, and CH_4 emissions from animals fed those diets were estimated by selected models. Several consulting nutritionists and extension personnel in California, Colorado, Kansas, New Mexico, Texas, Washington, and Wisconsin were contacted and asked to provide representative diets for the different classes of cows on a dairy operation. These classes included high milk yield, low milk yield, nonlactating cows, and growing heifers. These individuals were asked to provide nutrient analysis information about the diet as well. The representative samples contained major dietary factors that affect CH_4 production such as type and level of concentrates and various levels of fat supplementation. However, only the data for high-yielding and nonlactating cows were complete and therefore used in this study.

Feedlot Cattle. Methane emissions from feedlot cattle from Archibeque et al. (2006, 2007) were used to evaluate the models. These data were individual daily CH_4 emissions from feedlot steers fed several types of diets. Measurements of CH_4 in these studies were made using the open-circuit chamber method as described by Nienaber and Maddy (1985). The data used for evaluation of the models is summarized in Table 1.

The 2007 Texas Tech University survey (Vasconcelos and Galyean, 2007) was used to generate representative diets that would encompass various extremes as well as average diet compositions. Selected models were then used to estimate CH_4 emissions from cattle fed the diets in the survey.

The Models

There have been several attempts to formulate mathematical models to predict CH_4 emissions from cattle (Wilkerson et al., 1995). The models can be classified into 2 principal groups: empirical (statistical) models that relate nutrient intake to CH_4 output directly and dynamic mechanistic models that attempt to simulate CH_4 emissions based on a mathematical description of ruminal fermentation biochemistry. We chose to evaluate 4 models based on their ease of application, previous usage for preparing inventories, and potential to improve on previous model predictions. The models chosen were IPCC (2006) tier II model, Moe and Tyrrell (1979), 2007 version of MOLLY (Baldwin, 1995), and COWPOLL (Dijkstra et al., 1992; Kebreab et al., 2004).

IPCC. The IPCC in its 2006 national greenhouse gas inventories guidelines (IPCC, 2006) outlines methods for estimating CH_4 emissions from enteric fermentation at 3 levels of detail and complexity. In tier 1, average milk production of 8,400 kg/(animal·yr) is assumed, and the estimated emission factor for North American dairy cows is 121 kg of CH_4/(animal·yr). For feedlot cattle, the emission factor is 53 kg of CH_4/(animal·yr). However, IPCC (2006) recommends the tier 2 (or tier 3, which requires further refinement) method for estimating CH_4 emissions from enteric fermentation for those countries with large cattle populations. Average daily feed intake (in terms of GE content, MJ/d) and CH_4 conversion rates (Ym) are used to estimate CH_4 emissions in the tier 2 method. For dairy cattle, a 6.5% ± 1% of GE intake conversion rate is suggested with the lower bounds recommended for diets with greater digestibility and energy values. Similarly, for feedlot cattle, a 3% ± 1% conversation rate is suggested with the same caveat as in the dairy procedure. Feed intake is estimated from BW, ADG, feeding situation (indoor or outdoor housing, pasture or grazing), milk production per day, average amount of work performed per day, percentage of cows that give birth in a year, and feed digestibility. Using GE estimation equations will introduce a source of error into CH_4 estimates and will not allow a robust assessment of the default Ym values. Therefore, measured GE intake values were used as an input to IPCC (2006) as well as the other models.

Moe and Tyrrell. The model of Moe and Tyrrell (1979) is an empirical model developed using data from US cattle, and the model relates intake of carbohydrate fractions to CH_4 production as follows:

$$\text{Methane (MJ/d)} = 3.41 + 0.51\ \text{NFC} + 1.74\ \text{HC} + 2.65\ \text{C}, \quad [1]$$

where NFC = nonfiber carbohydrate (kg/d); HC = hemicellulose (kg/d); and C = cellulose (kg/d). In cases in which NFC values were not available, it was calculated as NFC = 100 − (CP + ether extract + ash + NDF). Book values were used where HC and C values were not given.

MOLLY. MOLLY (Baldwin, 1995 and its current version MOLLY, 2007) is a dynamic mechanistic model of nutrient utilization in cattle originally developed at the University of California, Davis. Methane production is predicted as described by Baldwin (1995). Briefly, ruminal CH_4 production was predicted based on hydrogen balance. Excess hydrogen produced during fermentation of carbohydrates and protein to lipogenic VFA (acetate and butyrate) is partitioned between use for microbial growth, biohydrogenation of unsaturated fatty acids, and production of glucogenic VFA (propionate and valerate). The assumption is made that the remaining hydrogen is used solely and completely for methanogenesis. The VFA stoichiometry in MOLLY is based on equations developed by Murphy et al. (1982).

COWPOLL. The rumen model of Dijkstra et al. (1992) is the basis for the mechanistic model used in the present evaluation. The model is based on a series of dynamic, deterministic, and nonlinear differential equations. Methane production in the rumen and hindgut was introduced by Mills et al. (2001) following the principles of Baldwin (1995). Later, Kebreab et al. (2004) incorporated the rumen model to a whole-animal model that included nitrogen and phosphorus utilization. Bannink et al. (2006) developed a new stoichiometry for fermentation within the rumen based entirely on experimental observations with lactating dairy cows; therefore, COWPOLL was modified to accommodate these stoichiometric coefficients. One of the fundamental differences in estimating CH_4 emissions between MOLLY and COWPOLL is the representation of microbes in the rumen and the coefficients of fermentation for transformation of substrate to VFA. The MOLLY model uses 1 group of microbes, whereas COWPOLL separates the microbial community into 3 groups: amylolytic, cellulolytic bacteria, and protozoa.

Statistical Analysis

A database containing diets that had measured CH_4 values reported in the literature (Table 1) were used to evaluate the models. For a perfect model, CH_4 predicted will be equal to CH_4 observed. An assessment of the error of prediction was made by calculation of the mean square prediction error (**MSPE**):

$$\text{MSPE} = \sum_{i=1}^{n} (O_i - P_i)^2 / n,$$

where n = the number of runs and O_i and P_i = the observed and predicted CH_4 emissions, respectively. The MSPE was decomposed into error due to overall bias of prediction, error due to deviation of the regression slope from unity, and error due to the disturbance (random variation; Bibby and Toutenburg, 1977). Root MSPE (**RMSPE**) was used as a measure of accuracy of prediction.

Concordance correlation coefficient or reproducibility index (**CCC**; Lin, 1989) was also used to evaluate the precision and accuracy of CH_4 prediction against observed values for each model. The CCC can be represented as a product of 2 components. The first component is the correlation coefficient (r) that measures precision. This coefficient may vary from 0 to 1, where 1 indicates perfect fit. The second component is the bias correction factor (C_b) that indicates how far the regression line deviates from the line of unity. This value also ranges from 0 to 1, and 1 indicates that no deviation from the line of unity has occurred. Finally, the estimate μ measures location shift relative to the scale (difference of the means relative to the square root of the

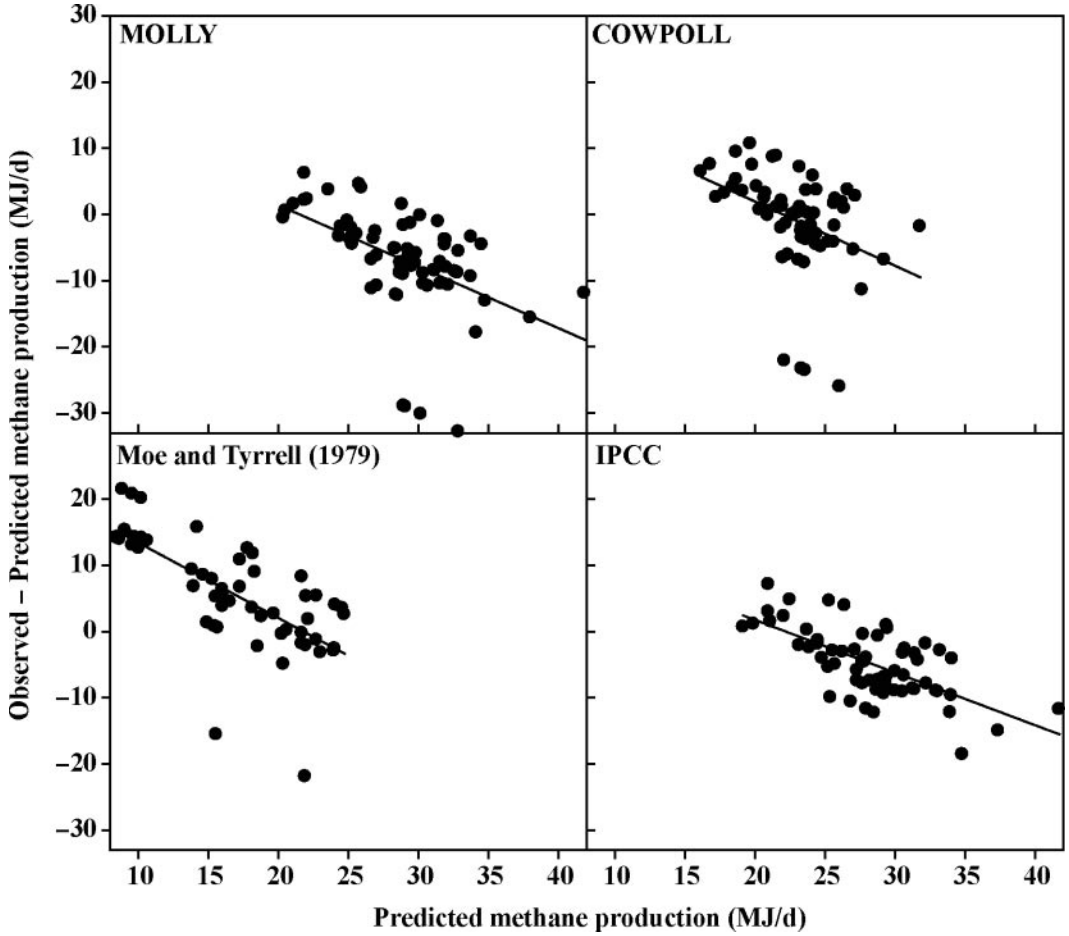

Figure 1. Plot of observed minus predicted methane production vs. predicted methane production from US dairy cattle. The independent variable (predicted methane production) was centered around the mean predicted value before the residuals were regressed on the predicted values. The equations for MOLLY were Y = −7.28 (±0.84) − 0.93 (±0.21) (X − 29.3), R^2 = 0.24, $P < 0.001$; COWPOLL Y = −1.17 (±0.85) − 0.97 (±0.29) (X − 23.2), R^2 = 0.15, P = 0.0014; Moe and Tyrrell (1979) Y = 5.80 (±0.80) − 1.14 (±0.16) (X − 16.7), R^2 = 0.49, $P < 0.001$; IPCC Y = −5.17 (±0.49) + 0.79 (±0.11) (X − 28.7), R^2 = 0.45, $P < 0.001$. IPCC = Intergovernmental Panel for Climate Change.

product of 2 standard deviations). This value ranges from −1 to 1, with positive numbers indicating underprediction and negative numbers indicated overprediction.

An assessment of prediction bias has been presented in the form of residual plots in which the residuals (observed − predicted) were plotted against predicted values (Figures 1 and 2). The independent variable predicted CH_4 production was centered around the mean predicted value before the residuals were regressed on the predicted value. Mean centered bias and bias at the minimum and maximum values were determined as described by St-Pierre (2003).

RESULTS AND DISCUSSION

Model Evaluation

Dairy. Table 2 gives summary statistics for the performance of each model in predicting CH_4 emissions. For the dairy cow data, COWPOLL had the lowest RMSPE (3.41 MJ) and the Moe and Tyrrell (1979) model had the greatest (9.51 MJ). The MOLLY and IPCC models showed intermediate RMSPE values (7.42 and 8.94, respectively). Decomposition of the MSPE indicated that COWPOLL-based predictions had nearly 95% of their errors coming from random sources. For the other 3 models, the overall bias of prediction component contributed most to the MSPE (50 to 65%). The CCC analysis revealed that COWPOLL was more precise (r = 0.75) and more accurate (C_b = 0.95) than the other 3 models (r between 0.43 and 0.50 and C_b between 0.47 and 0.55). There was a small overall mean underprediction of CH_4 emission by COWPOLL (μ = 0.11). The MOLLY and IPCC models tended to overpredict (μ = −0.34 and −0.27, respectively) and Moe and Tyrrell (1979) to underpredict (μ = 0.48) overall CH_4 emissions. Predictions from IPCC were slightly better than MOLLY mainly because the mean predictions from IPCC are closer to the observed data (mean bias 17.5% for IPCC compared with 20.4% for MOLLY; Table 2). Results of residuals plotted against predicted value (Figure 1) showed a significant mean and linear biases ($P < 0.001$) for all models except COWPOLL, in which there was only significant linear bias ($P = 0.02$). The magnitude of the linear bias for COWPOLL was less than 5.7 MJ/d at the minimum (16.2 MJ/d) and 9.5 MJ/d at the maximum (31.8 MJ/d) predicted CH_4 emission values. One of the main differences between the 2 dynamic mechanistic models was the VFA stoichiometry used to predict VFA profile from nutrients. The MOLLY model uses Murphy et al. (1982) equations, which describe the stoichiometry of the production of acetic, propionic, butyric, and valeric acids with fermentation of soluble carbohydrate, starch, hemicelluloses, cellulose, and protein. The updated version of MOLLY uses these coefficient estimates but with 1.0 mol of propionic acid and 0.5 mol of butyric acid substituted for 1.0 mol of valeric acid, and VFA coefficients were also dependent on rumen pH (Argyle and Baldwin, 1988). The COWPOLL model on the other hand uses the equations developed by Bannink et al. (2006) that were based on dairy cow experiments and have different stoichiometric coefficients. Benchaar et al. (1998) also showed that COWPOLL (before the modifications were made) agreed with observed data better than MOLLY or other empirical models.

Feedlot. Statistical analysis showed that for feedlot cattle, MOLLY had the lowest RMSPE and COWPOLL had the greatest (Table 3), although the differences were not as large as those observed for dairy cattle. The IPCC and Moe and Tyrrell (1979) models had intermediate RMSPE values. The breakdown of errors indicated that most of the errors from MOLLY and IPCC were random (99.6 and 84.8%, respectively). In contrast, the overall bias of prediction component contributed most to the MSPE in COWPOLL (60.7%) and was a significant component in the Moe and Tyrrell (1979) model (31.0%). The results are supported by the CCC analysis, which showed that MOLLY was more precise ($r = 0.69$) and accurate ($C_b = 0.66$) compared with the other models (r between 0.39 and 0.51 and C_b between 0.41 and 0.55). Results of residuals vs. predicted values showed absence of mean bias for MOLLY ($P = 0.94$) and IPCC ($P = 0.74$) and no linear bias for COWPOLL ($P = 0.74$), Moe and Tyrrell (1979; $P = 0.32$), and IPCC models ($P =$

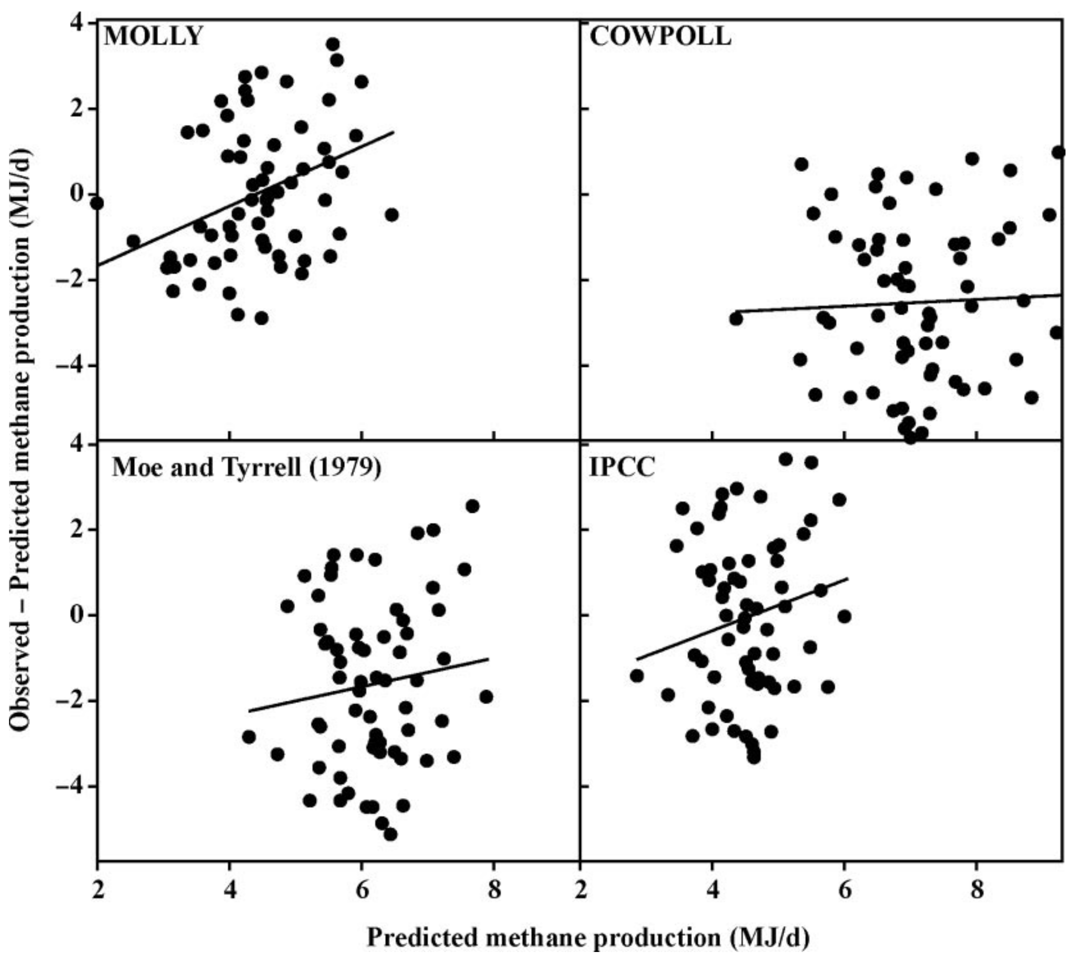

Figure 2. Plot of observed minus predicted methane production vs. predicted methane production from US feedlot cattle. The independent variable (predicted methane production) was centered around the mean predicted value before the residuals were regressed on the predicted values. The equations for MOLLY were Y = 0.069 (±0.19) + 0.69 (±0.22) (X − 4.49), $R^2 = 0.14$, $P = 0.003$; COWPOLL Y = −2.52 (±0.24) + 0.079 (±0.24) (X − 7.09), $R^2 = 0.0018$, $P = 0.74$; Moe and Tyrrell (1979) Y = −1.61 (±0.24) + 0.34 (±0.33) (X − 6.17), $R^2 = 0.014$, $P = 0.32$; IPCC Y = −0.016 (±0.24) + 0.59 (±0.35) (X − 4.58), $R^2 = 0.04$, $P = 0.11$. IPCC = Intergovernmental Panel for Climate Change.

Table 2. Comparison of model performance using dairy cattle diets summarized in Table 1

	Models			
Item	MOLLY	COWPOLL	Moe and Tyrrell (1979)	IPCC[1]
MSPE[2]				
RMSPE (MJ)	7.42	3.41	9.51	8.94
ECT (%)	53.47	1.37	50.07	64.62
ER (%)	20.43	3.91	24.37	17.52
ED (%)	26.10	94.72	25.56	17.56
CCC[3]				
r	0.50	0.75	0.43	0.50
C_b	0.52	0.95	0.47	0.55
μ	−0.34	0.11	0.48	−0.27

[1]IPCC = Intergovernmental Panel for Climate Change.

[2]MSPE = mean square prediction error; RMSPE = root MSPE (MJ); ECT = MSPE decomposed into error due to overall bias of prediction; ER = error due to deviation of the regression slope from unity; ED = error due to the disturbance or random variation.

[3]CCC = concordance correlation coefficient; r = correlation coefficient estimate; C_b = bias correction factor; μ = location shift relative to the scale (squared difference of the means relative to the product of 2 standard deviations).

0.11). There was a significant mean bias for COWPOLL and Moe and Tyrrell (1979) models (P < 0.001). The magnitude of linear bias was 1.6 MJ/d at the minimum (2.01 MJ/d) and 1.4 MJ/d at the maximum (6.47 MJ/d) predicted CH_4 emission values. Although COWPOLL was developed and parameterized for lactating dairy cows, CH_4 emissions from the rumen were expected to be predicted better than the use of other models. Feedlot diets used for evaluation were mostly concentrates, and the VFA stoichiometry used in COWPOLL might not have represented VFA production well. Table 3 shows a systematic overprediction by the COWPOLL model (μ = −0.35) that could be due to underestimation of propionate production in high-concentrate diets. The IPCC model with fixed Ym can be used as a simple alternative to mechanistic models to estimate CH_4 emissions for feedlot diets, because its predictions showed neither mean nor linear bias (Figure 2).

Estimates of Enteric CH_4 Emissions from Dairy Cattle

Based on the comparison of models, COWPOLL was used to predict CH_4 emissions from representative diets across the United States. Most countries use the IPCC model for their CH_4 emissions inventory; therefore, calculations using the IPCC method were also made to compare with the results of COWPOLL predictions.

Various diets from Wisconsin (Shaver and Kaiser, 2004), Texas, New Mexico, Kansas, and Washington states were evaluated (Tables 4 and 5). Different diets for mature and dry cows were used to estimate CH_4 emissions. Methane emissions from mature cows were consistently greater when estimated using the IPCC compared with COWPOLL methods. In contrast, CH_4 emissions from dry cows were consistently less with the IPCC method compared with COWPOLL. The

Table 3. Comparison of model performance using feedlot cattle diets summarized in Table 1

	Models			
Item	MOLLY	COWPOLL	Moe and Tyrrell (1979)	IPCC[1]
MSPE[2]				
RMSPE (MJ)	1.14	2.74	2.26	1.98
ECT (%)	0.29	60.74	30.99	9.67
ER (%)	0.15	0.37	0.10	5.52
ED (%)	99.56	38.89	68.91	84.81
CCC[3]				
r	0.69	0.39	0.51	0.51
C_b	0.66	0.41	0.48	0.55
μ	0.08	−0.35	−0.27	0.14

[1]IPCC = Intergovernmental Panel for Climate Change.

[2]MSPE = mean square prediction error; RMSPE = root MSPE (MJ); ECT = MSPE decomposed into error due to overall bias of prediction; ER = error due to deviation of the regression slope from unity; ED = error due to the disturbance or random variation.

[3]CCC = concordance correlation coefficient; r = correlation coefficient estimate; C_b = bias correction factor; μ = location shift relative to the scale (squared difference of the means relative to the product of 2 standard deviations).

Table 4. Representative diets from Wisconsin used to estimate methane emissions, DM basis

Item	Diet 1		Diet 2		Diet 3		Diet 4		Diet 5		Diet 6	
	Mature cows	Dry cows	Mature cows	Dry cows	Mature cows	Dry cows	Mature cows	Dry cows	Mature cows	Dry cows	Mature cows	Dry cows
Ingredient, % of DM												
Wheat straw	1.5	5	—	—	—	—	—	—	0.6	—	—	9.7
Baled hay	7.2	9.3	—	—	—	—	—	—	2.6	11	4.4	—
Haylage	9.9	53.3	20.4	26.7	24.0	29.0	16	57.0	19.5	28	26.6	—
Corn silage	23.4	31.1	24.5	5.6	22.0	31.0	34	36	23.3	54	21.9	36.2
Corn stalkage	—	—	—	32.4	—	—	—	—	—	—	—	—
Oatlage	—	—	—	—	—	38.0	—	6.1	—	—	—	36.9
Dry shelled corn	—	—	24.4	—	26.1	—	7.7	—	—	—	—	8.7
High moisture shelled corn	29.6	—	—	—	—	—	9.8	—	21.6	2.4	20.5	—
Soy hulls	—	—	—	30.2	—	—	7.2	—	3.9	—	—	—
Corn starch	0.8	—	—	—	—	—	—	—	—	—	—	—
Corn gluten feed	2.3	—	3.4	—	—	—	—	—	5.5	—	—	—
Corn gluten meal, 60%	—	—	—	—	0.7	—	0.5	—	—	—	—	—
Whole cottonseed	9.2	—	7.3	—	9.5	—	2.6	—	6.7	—	—	—
Beet pulp	—	—	—	—	—	—	—	—	6.2	—	—	—
Liquid feed supplement	1.7	—	—	—	2.9	—	4.9	—	—	—	—	—
Soybean meal, 48%	6.5	—	—	—	7.0	—	7.2	—	6.0	—	—	4.8
Distillers dried grains	3.1	—	—	—	0.7	—	—	—	—	—	—	—
Roasted soybeans	1.7	—	11.4	—	2.3	—	5.2	—	—	—	6.0	—
Linseed meal	6.5	—	2.9	—	—	—	—	—	—	—	—	—
Feather meal	3.1	—	0.4	—	—	—	—	—	—	—	—	—
Blood meal	1.2	—	1.2	—	1.1	—	0.7	—	—	—	—	—
Fish meal	—	—	—	—	—	—	—	—	0.7	—	—	—
Dry cow mix	—	—	—	—	—	—	—	—	—	4.6	—	—
Purina milking custom[1]	—	—	—	—	—	—	—	—	—	—	20.6	—
Purina dry cow custom[1]	—	—	—	—	—	—	—	—	—	—	—	2.9
Urea	0.2	—	—	0.2	—	—	—	—	0.1	—	—	—
Tallow	0.2	—	—	—	0.4	—	—	—	0.6	—	—	—
Megalac[2]	0.4	—	—	—	—	—	0.5	—	—	—	—	—
Energy booster[3]	—	—	—	—	1.0	—	—	—	—	—	—	—
Minerals-vitamins-additives	2.8	1.3	4.1	4.9	2.3	—	3.7	0.9	2.7	—	—	0.8
Cow performance												
DMI (kg/cow per day)	27.3	12.7	25.0	11.36	25.00	13.64	25.45	13.64	30.91	13.64	26.36	12.27
Milk (kg)	48.6	—	39.6	—	42.50	—	44.04	—	53.78	—	44.82	—
Model predictions												
GE (MJ/kg)	19.33	18.54	19.83	18.37	19.62	18.54	19.16	18.54	19.12	18.41	19.20	18.45
Methane (MJ/d)	26.11	14.06	19.25	15.77	24.77	12.80	29.37	15.69	35.77	14.94	30.38	15.61
Ym[4] (COWPOLL)	4.93	5.84	3.86	7.43	5.01	4.98	5.98	6.11	6.01	5.86	5.96	6.78
IPCC (MJ/d; Ym = 6.5)	34.31	15.31	32.22	13.56	31.88	16.44	31.71	16.44	38.41	16.32	32.89	14.73

[1]Land O' Lakes Purina Feed LLC, St. Paul, MN.
[2]Arm & Hammer Animal Nutrition, Princeton, NJ.
[3]MSC Specialty Nutrition, Dundee, IL.
[4]Ym = methane conversion factor (% of GE).

Table 5. Representative diets from Texas, New Mexico, Kansas, and Washington states used to estimate methane emissions, DM basis

Item	Texas		New Mexico		Kansas		Washington
	Mature cows	Dry cows	Mature cows	Dry cows	Mature cows	Dry cows	Mature cows
Ingredient (% of DM)							
Wheat straw	—	—	—	—	—	17.1	—
Alfalfa hay	7.66	—	13.37	21.2	13.7	10.1	23.9
Oat hay	—	—	—	11.6	—	—	—
Ground hay	—	37.5	—	—	—	—	—
Corn silage	—	—	45.1	18.7	49.1	10.5	15.6
Wheat silage	32.0	50.0	—	—	—	—	—
Sorghum silage	20.4	—	—	—	—	54.9	—
Triticale silage	—	—	6.38	38.9	—	—	6.04
Canola	—	—	—	—	6.44	—	4.65
Soy hulls	—	—	1.3	6.98	—	—	4.85
Soy Plus[1]	—	—	1.3	—	—	—	—
Corn grain flaked	17.6	—	6.99	—	14.1	—	6.87
Corn grain ground	—	—	6.84	—	—	—	16.3
Corn gluten feed	2.94	7.5	—	—	—	—	—
Whole cottonseed	2.55	—	7.69	—	6.44	—	4.84
Beet pulp	—	—	3.24	—	—	—	4.21
High-fat pellet	7.02	—	—	—	—	—	—
Soybean meal, 48%	5.11	—	5.24	1.18	—	—	3.12
Distillers dried grains	3.19	3.75	—	—	1.95	7.03	6.08
Molasses	—	—	—	0.6	—	—	—
Blood meal	—	—	—	—	—	—	0.78
Sweet bran[2]	—	—	—	—	5.92	—	—
Minerals-vitamins-additives	1.59	1.25	2.54	0.92	2.41	0.54	2.8
Model predictions							
GE (MJ/kg)	20.71	18.62	19.37	19.08	19.25	18.79	19.50
Methane (MJ/d)	19.66	17.03	26.11	11.88	26.94	15.61	26.65
Ym[3] (COWPOLL)	3.78	7.20	5.36	4.91	5.57	6.53	5.43
IPCC (MJ/d; Ym = 6.5)	33.64	15.15	31.46	15.52	31.30	15.27	31.67

[1]Soybean meal, West Central, Ralston, IA.
[2]Wet corn gluten feed, Cargill, Minneapolis, MN.
[3]Ym = methane conversion factor (% of GE).

main reason for these differences is that the IPCC is heavily dependent on the amount of DMI and does not respond to the types of nutrients supplied to the cows. For example, in dry cows fed 53% haylage and 31% corn silage as part of the forage portion of diet (diet 1 in Table 4), IPCC predicted 15.3 MJ/d of CH_4 (272 g/d) emission, whereas COWPOLL predicted 14.1 MJ (248 g/d; DMI = 12.7 kg/d). When the haylage was decreased by half and substituted by oatlage (diet 3 in Table 4), IPCC predicted 16.4 MJ/d (292 g/d), whereas COWPOLL predicted 12.8 MJ/d (227 g/d; DMI = 13.6 kg/d). On a Ym basis, COWPOLL suggested CH_4 emission of 5.84% for the first diet and 4.98% of GE for the second diet compared with 6.5% for both diets in IPCC. For Wisconsin diets, COWPOLL suggests an average Ym value of 5.2% for lactating cows and 6.2% for dry cows. Considering the number of cows and the amount of feed consumed, these changes will make a significant difference in the CH_4 inventory of each state. Based on available information of diets, COWPOLL estimates Ym values for Texas diets to be 3.78% for lactating cows and 7.2% for dry cows. The differences are due to a greater proportion of forage (up to 88%) in dry cow diets compared with 60% in lactating cow diets. For diets from New Mexico, Ym values of 5.36 and 4.91% were predicted for lactating and dry cows, respectively, and for diets from Kansas, 5.57% for lactating cows and 6.53% for dry cows. Only lactating cow diet information was available for Washington diets, which was estimated to be 5.43%. It is important to note that the Ym values are diet-specific and would likely change for different diets in a given region or state.

Estimates of Enteric CH_4 Emissions from Feedlot Cattle

The results of model comparison based on MSPE and CCC showed that MOLLY predicted CH_4 emissions from feedlot cattle better than the other 3 models; therefore, MOLLY was used to estimate CH_4 emissions from feedlot cattle fed various types of diets that are representative of different regions of the United States. The IPCC model also showed comparable results to MOLLY and has been included in the comparison of predictions. The main difference among the diets

Table 6. Representative feedlot cattle diets used to estimate methane emissions, DM basis

	Diet number														
Item	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Ingredient															
Corn silage	8.65	8.65	8.65	8.65	8.65	8.65	8.65	—	—	—	—	—	—	—	4.65
Alfalfa	—	—	—	—	—	—	—	8.65	8.65	8.65	8.65	8.65	8.65	8.65	4
Steam-flaked corn	85	—	—	—	—	—	—	85	—	—	—	—	—	—	85
Dry-rolled corn	—	85	—	—	—	—	—	—	85	—	—	—	—	—	—
High-moisture corn	—	—	85	—	—	—	—	—	—	85	—	—	—	—	—
Barley	—	—	—	85	—	—	—	—	—	—	85	—	—	—	—
Rolled sorghum grain	—	—	—	—	85	—	—	—	—	—	—	85	—	—	—
Wheat	—	—	—	—	—	85	—	—	—	—	—	—	85	—	—
Flaked sorghum grain	—	—	—	—	—	—	85	—	—	—	—	—	—	85	—
Liquid supplement	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2
Fat supplement	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
Model predictions															
GE (MJ/kg)	19.33	19.41	18.87	18.87	18.66	18.66	18.58	19.33	19.41	18.91	18.87	18.70	18.70	18.62	19.33
Methane (MJ/d)	5.06	4.98	5.36	6.15	5.86	5.86	6.02	5.31	5.23	5.59	6.44	5.94	6.53	6.02	5.19
Ym (MOLLY)	3.43	3.36	3.70	4.30	4.10	4.10	4.35	3.58	3.50	3.86	4.44	4.14	4.56	4.31	3.50
IPPC (MJ/d; Ym = 3.5)	5.08	5.10	4.95	4.95	4.90	4.90	4.88	5.08	5.10	4.97	4.95	4.91	4.91	4.89	5.08

	Diet number														
Ingredient	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Corn silage	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	7.5	4.65	4.65	20.9	14.75	9.55
Alfalfa	4	4	4	4	4	4	4	4	4	6	4	4	19	14.75	9.55
Steam-flaked corn	50	68.5	80	68.5	80	68.5	80	68.5	80	—	86.15	81.65	53.75	64.15	74.55
Rolled sorghum grain	—	—	—	—	—	—	—	—	—	81.3	—	—	—	—	—
Wet distillers grains	35	16.5	5	—	—	—	—	—	—	—	—	—	—	—	—
Dry distillers grains	—	—	—	16.5	5	—	—	—	—	—	—	—	—	—	—
Wet corn gluten feed	—	—	—	—	—	16.5	5	—	—	—	—	—	—	—	—
Dry corn gluten feed	—	—	—	—	—	—	—	16.5	5	—	—	—	—	—	—
Liquid supplement[1]	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2
Fat supplement[1]	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	—	—	4.5	1.15	1.15	1.15
Model predictions															
GE (MJ/kg)	19.83	19.58	19.41	19.62	19.41	19.20	19.29	19.33	19.33	18.41	19.08	20.04	19.16	19.16	19.25
Methane (MJ/d)	6.32	5.69	5.36	5.73	5.36	5.65	4.35	5.69	5.31	6.11	5.19	5.17	6.32	5.73	5.46
Ym[2] (MOLLY)	4.15	3.81	3.59	3.81	3.60	3.85	3.60	3.84	3.60	4.33	3.55	3.37	4.33	3.90	3.70
IPPC (MJ/d; Ym = 3.5)	5.20	5.14	5.10	5.15	5.10	5.04	5.06	5.08	5.08	4.83	5.01	5.26	5.03	5.03	5.05

[1]The liquid and fat supplements indicated in these diets represent general supplements as indicated by the survey of Vasconcelos and Galyean (2007).
[2]Ym = methane conversion factor (% of GE).

used for prediction of CH_4 emission was the proportion and type of grain and silage included (Table 6). The average Ym values from all diets predicted by MOLLY (3.88%) was within the range recommended by IPCC (3 ± 1% for feedlot cattle). However, MOLLY was responsive to dietary changes, and its effect on CH_4 emissions and the Ym values predicted ranged from 3.36 to 4.56% of GE. The MOLLY method predicted that diets based on corn had lesser Ym values (average 3.5%) compared with those based on barley, sorghum, and wheat (4.2%; Table 6).

Mills et al. (2001) showed that utilizing corn starch increased total tract starch digestion in the small intestine compared with wheat starch, which contributed to decreased CH_4 production of corn. The authors recommended the use of corn starch compared with wheat or barley, because for similar energy availability, corn provides less CH_4 production and therefore is more environmentally desirable. Castillo et al. (2001) suggested that wheat- or barley-based diets support greater microbial protein synthesis than corn-based diets by providing more rumen-fermentable energy. Greater Ym values were estimated for diets based on wheat (4.56% with alfalfa and 4.10% with corn silage; Table 6). The greater Ym value in a diet with alfalfa may be associated with quick availability of nutrients in the rumen that might not be efficiently utilized by the microbes compared with a corn silage-based diet. Roughage diets are also greater in cellulose, which stimulates extensive digestion by cellulolytic microbes that result in greater acetate production, therefore, greater CH_4 emission (Owens and Goetsch, 1988).

The model was also sensitive to differences in fat supplementation. The advantages of adding fat to the diet is well documented and has recently been summarized by Kebreab et al. (2006a). Odongo et al. (2007) reported that adding myristic acid in the diet decreased CH_4 emissions by 36% and addition of sunflower oil to the diet decreased CH_4 emissions by 21% in steers (McGinn et al., 2004). One of the representative diets (diet 27; Table 6) had 4.5% fat for that diet; the model estimated one of the lowest Ym values for CH_4 emission (3.37%). The MOLLY model takes into account biohydrogenation as an alternative method of using excess hydrogen in the rumen, which decreases CH_4 production.

Methane emission values used in this study were measured using indirect calorimetry (feedlot data) and the SF_6 tracer technique (dairy data). Comparison of models for their accuracy of prediction of CH_4 emissions depends not only on the models themselves but also on the quality of the measured values. The technique used to measure CH_4 emissions from cattle has a significant effect on absolute values measured. For example, Grainger et al. (2007) compared CH_4 emissions measured using indirect calorimetry chambers and the SF_6 tracer technique and found that the latter underestimates emissions by about 8%, mainly because emissions through the rectum are not accounted for in the measurements. However, the authors concluded that the SF_6 technique can be used with reasonable accuracy for inventory purposes. Kebreab et al. (2006a) reviewed studies that compared measurement techniques and found similar systematic differences. Pasture-based dairy and grazing beef animals are not included in the study mainly due to paucity of reliable CH_4 emission measurements and variables that affect emissions such as DMI and detailed diet composition.

Application of the average Ym values for dairy cows and feedlot cattle from the mechanistic models results in a considerable difference in total emissions compared with IPCC tier II calculations when using default Ym values. Assuming a dairy cow consuming 25 kg of DM/d of a diet with an energy concentration of 18 MJ/kg, daily CH_4 emissions would be 29.3 and 25.3 MJ according to IPCC and COWPOLL, respectively. The National Agricultural Statistics Service reported that there were 9.2 million lactating cows in 2007 (NASS, 2007), which means that based on the IPCC Ym value, in a 305-d lactation, the annual CH_4 emissions would be overestimated by an average of 12.5% by IPCC compared with COWPOLL (assuming an average Ym). Similarly, there is a considerable difference in annual CH_4 emission estimates from feedlot cattle. From the 12 million feedlot cattle (in feedlots of >1,000 animals) in the United States (NASS, 2007), using IPCC values would underestimate emissions by about 9.8% compared with what the average Ym value from MOLLY would indicate. Clearly, the mechanistic models are diet-specific; therefore, average values are used here to emphasize the magnitude of differences in CH_4 emissions when using apparently similar Ym values to estimate national inventory.

Another advantage of using mechanistic models compared with empirical models is that mitigation options implemented at a farm or national level can be assessed for their effectiveness. The only reductions in emissions that can be assessed using empirical models are decline in cattle numbers and feed intake (amount and energy concentration). The mechanistic models are ideal to investigate mitigation options that have been summarized in the literature (Boadi et al., 2004; Kebreab et al., 2006a).

The study has demonstrated that national CH_4 emissions inventories are more accurately estimated by mechanistic models that are diet- specific and, hence, should be considered as the preferred approach in preparing inventories. Given the complexities of the models, generating national inventory estimates may not be feasible; however, mechanistic models can be used to generate Ym values that can be used in national inventory models. Additionally, future studies to improve the reliability of these models will eventually help in assessing CH_4 reductions on a farm, state, or national basis. If incentives are introduced (either financial or through legislation), to mitigate CH_4 emissions at a farm level, mechanistic models would be excellent tools to make reliable estimates of enteric CH_4 emissions.

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