CHARACTERIZING CALIFORNIA-SPECIFIC CATTLE FEED RATIONS AND IMPROVE MODELING OF ENTERIC FERMENTATION FOR CALIFORNIA'S GREENHOUSE GAS INVENTORY

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PO BOX 2815

SACRAMENTO CA 95812

PREPARED BY:

RANGA APPUHAMY[1,2] & ERMIAS KEBREAB[1]

[1]UNIVERSITY OF CALIFORNIA, DAVIS, ONE SHIELDS AVENUE

DAVIS, CA 90210 (530) 752 5907

[2]IOWA STATE UNIVERSITY, AMES, IA 50014

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List of Abbreviations

attNDF	apparent total tract digestible neutral detergent fiber (% dry matter)
CARB	California Air Resources Board
CEFM	Cattle Enteric Fermentation Model
COWPOLL	Mechanistic rumen model developed in Europe
CP	Crude protein (% dry matter)
DDGS	Dry distillers grain with solubles
DE	Digestible energy (MJ)
DMI	Dry matter intake (kg/d)
dNDF	digestible neutral detergent fiber (% dry matter)
EE	Ether extract (% dry matter)
EMU	Energy Metabolism Unit
EPA	Environmental Protection Agency
GEI	Gross energy intake (MJ/d)
GHG	Greenhouse gases
IPCC	Intergovernmental Panel for Climate Change
LIG	Lignin (% dry matter)
MB	Mean bias
MOLLY	Mechanistic rumen model developed at UC Davis
MSPE	Mean square prediction error
NDF	Neutral detergent fiber (% dry matter)
NDICP	Neutral detergent insoluble crude protein (% dry matter)
RB	Random bias
RMSPE	Root mean square prediction error
SB	Slope bias
TMR	Total mixed ration
USDA	United States Department of Agriculture
Y_m	A constant fraction of gross energy intake (GEI, MJ/animal/d) lost as enteric methane from a given animal population

ABSTRACT

The amount of methane (CH4) produced from enteric fermentation depends primarily on feed intake and diet composition. The diet formulated by California's cattle industry has been changing depending on feed availability and cost. Milk production has increased linearly over the last 6 decades with a concomitant increase in feed or dry matter intake (DMI). Methane emissions are expected to decrease per unit of milk produced as feed efficiency increases. It is not possible to measure enteric CH4 production from all animals in the state, therefore, mathematical models are widely used to estimate emissions. However, empirical models developed on low producing cattle or different feed regimen might not be robust enough to use in California. The objectives of this study were (1) to improve the modeling methodology for estimating cattle enteric CH4 emissions in the California Greenhouse Gas Emission Inventory by developing mathematical models, (2) evaluate new and extant emission estimation models, and (3) collect data on California-specific cattle diets and improve enteric CH4 emissions from the state. The study involved three major tasks. The first task was development of a set of equations for predicting enteric CH4 emissions from cattle using DMI and composition data applicable to California cattle systems. The second task evaluated the CH4 emission estimates from newly developed models and the estimates from the methodologies used by US EPA. Both of these tasks were based on measured data on CH4 emission, dietary intake, and diet composition, which was collated from a literature review. Through regression analyses, the study identified the following most important predictor variables for enteric methane emissions: DMI, neutral detergent fiber (NDF) or digestible NDF (dNDF), ether extract (EE), and GEI, depending on the type of cattle considered. The new models for lactating dairy cows developed on California-specific data performed better compared to extant models. For beef cattle, equations developed by Moraes et al. (2014), IPPC (2006) and Nielsen et al. (2013) models had acceptable performance for different categories. All the models chosen are summarized in the report. The third task was collecting feed ingredients, DMI and diet composition of cattle farms in California and applying the models to estimate statewide CH4 emissions from enteric fermentation. Specific equations that are based on California conditions have been developed for each category. The study also updated Ym values from 0.048 to 0.055 or 0.069 for different dairy cow groups. For 2015, the new models estimated 10% higher CH4 emissions due to the higher Ym values compared to the U.S. EPA model, but an overall 5% lower CH4 emissions if both the updated Ym values and feed intake matrix were used. The new models have resulted in more accurate dietary changes in California cattle operations, improved methane emission estimates from California cattle, and can be used to inform the California's Short-Lived Climate Pollutant Reduction Strategies.

Executive Summary

Background

The microbial fermentation process in digestive tract, referred to as enteric fermentation, largely depends on the type of digestive system (ruminants vs. non-ruminants, with ruminants producing much more methane), feed intake (greater feed intake leads to more methane production) and feed composition, particularly the amount of fiber and lipid in the diet. Feed intake is positively correlated with methane emissions and productivity (e.g., milk or average daily gain). Attempts to quantify enteric methane emissions show that feed intake can account for up to 70% of the variability in enteric methane emissions and other dietary or animal variables would be required for a better prediction. The diet formulated by California's cattle industry has been changing depending on feed availability and cost. Milk production has increased linearly over the last 6 decades with a concomitant increase in feed, feed quality and dry matter intake (DMI). The default emission factors (Y_m) for cattle in the United States are 3% ± 1 of gross energy intake for feedlot cattle (fed high-grain diets) and 6.5% ± 1 of gross energy intake for dairy cows (cattle that are primarily fed forages, concentrate feeds, low quality crop residues, and by-products) and grazing cattle (IPCC, 2006). However, the US EPA uses a country specific emission factor, which is 4.8% for dairy cattle. This is substantially lower than the average Y_m reported in several publications (e.g. Appuhamy et al. 2016). Therefore, a better estimation methodology is required to improve the inventory. The aim of the study was to characterize feed intake and diet composition of different cattle groups including dairy, heifers, dry cows, beef cattle and feedlot cattle in California and improve estimates of enteric methane emissions from the state.

Methods

Data on ingredient and nutrient composition of diets, and feed intake of dairy cow herds were obtained from published research and surveys focusing on commercial dairy farms in California. For beef cattle diets, there was a paucity of published data so we collected information from beef cattle nutritionists and environmental specialists. Moreover, some information were retrieved from scientific publications focused on California cattle. Actual CH_4 emission measurements from beef cattle in commercial farms are not available, therefore, we relied on CH_4 emission measurements made on animals with similar characteristics (e.g., similar DMI and diet composition) in experimental settings (e.g., calorimetric or energy metabolism trials). These data were obtained from original experimental databases (measurements from individual animals) or from published literature (treatment means). The experimental data of lactating dairy cows (n = 250) representative of California cow diets were used to develop 3 linear models to predict enteric CH_4 emissions of lactating dairy cows. Forty four CH_4 emission measurements (treatment means) published in literature were used to develop a model to predict CH_4 emissions from feedlot cattle. New models developed to predict CH_4 emissions from lactating dairy cows in this report were evaluated using the literature data (n=77) representative of California cows. Along with new models, several other extant models previously ranked high for lactating cows in North America (Appuhamy et al., 2016) were also evaluated. The population statistics of California cattle groups in 2015 were obtained. These were dairy cattle groups (lactating, dry and replacement heifers) and dairy cattle groups (replacement heifers, stockers beef cows, feedlot and bulls). The CH_4 emissions of each cattle group were estimated using the best prediction models selected from the model evaluations and also new proposed Y_m models.

Results

New models that take into account dietary factors such as digestible neutral detergent fiber (NDF) and animal factors such as milk fat percentage performed better than extant models, particularly for dairy cattle. The average DMI of cows in literature data was 20.6 kg/d, which was closer to the mean DMI of California cows (22.9 kg/d) than the mean DMI of cows in the experimental data set (19.9 kg/d). The average Y_m of 5.7% in the data were close to the average Y_m of 5.6% estimated for US dairy cow populations by Kebreab et al. (2008). New models including dNDF predicted CH_4 production slightly more accurately than that including total NDF. The new feedlot model predicted emissions well when evaluated through cross-validation. The majority of the models in Moraes et al. (2014) successfully predicted CH_4 emissions from beef stockers, when evaluated using the limited number of observations from literature.

Table E1. Summary of models recommended for use to predict CH_4 emissions (g/cow/d) from different cattle groups in California.

	Models chosen by the present study
Dairy cattle	
Cows	
Lactating cows	= 11.2×DMI + 2.18 × dNDF + 32.2 × Milk fat
Dry cows	= 9.6 + 22.1 × DMI
Replacement heifers	= 9.6 + 22.1 × DMI
Beef cattle	
Feedlot	= -54.9 + 12.6 × DMI + 4.46 × NDF - 4.61 × EE
Replacement heifers	= (0.065 × GEI)/0.05565
Stockers	= (-1.487 + 0.046 × GEI + 0.038 × NDF + 0.006 × BW)/0.05565
Cows	= (2.381 + 0.053 × GEI)/0.05565
Dairy & beef Bulls	= (0.065 × GEI)/0.05565

Conclusions

The estimate of enteric methane emissions in the state by the selected models proposed by the present study was 10.4% greater than estimates using the US EPA method at 10.5 Mt/yr for the same amount of feed intake. The majority of this discrepancy was related to the difference between the Y_m used to estimate emission from lactating cows. Gross energy intake and consequently feed intake was overestimated by IPCC-Tier 2 used in US EPA models. Therefore, although the present study had a greater emission factor the total emission estimate is less than that reported by CARB (2013) because GEI in this study is considerably lower compared to IPCC-Tier 2/ US EPA model estimates. The current inventory for enteric methane emissions from cattle in CA is 11.05 MT CO2e eq/yr, which is about 5% greater than estimated in this study. Overall, revising the Y_m value of IPCC-Tier 2/ US EPA models and GEI to match with observed feed intake and dietary characteristics of modern lactating cows in California and adopting proposed new model (or simplified Y_m) would greatly improve the representativeness of enteric CH_4 emission estimates in the GHG inventories from cattle in California.

INTRODUCTION

Global emissions of greenhouse gases (GHG) have risen to unprecedented levels despite a growing number of policies to reduce climate change (IPCC, 2014). Anthropogenic sources account for 58% of global GHG emissions (EPA, 2011a), 18% of which were generated by agriculture-related activities during the 2000–2010 period (Smith et al., 2014). Methane (CH_4) from enteric fermentation of livestock was the largest contributor (40%) to the agricultural GHG emissions (Tubiello et al., 2013). Dairy cattle account for 20% of enteric CH_4 emissions in North America (FAO, 2006a). Enteric emissions comprise the largest known source of CH_4 in California, approximately 30% of inventoried CH_4. In 2012, 96% of total enteric CH_4 in California was generated from cattle, 73% of which was from dairy cattle (CARB, 2017). Although the national dairy cattle populations have generally been decreasing since 1990, some states including California have seen increases in their dairy cattle populations. The National Agricultural Statistics Service estimates there are approximately 1.78 million dairy cows, which is the highest in the nation and 6.3 million cattle including calves, beef cows and feedlot in California (USDA-NASS, 2012).

The microbial fermentation process in digestive tract, referred to as enteric fermentation, produces CH_4 as a byproduct, which can be exhaled or eructated by the animal. The amount of CH_4 produced and emitted by an individual animal depends primarily on the amount and type of feed it consumes. Although emissions from few animals under controlled conditions can be measured, it is not practical to do so at a large scale. Therefore, enteric CH_4 emission estimates for GHG inventories rely on mathematical models. Several mathematical models have been developed to predict enteric CH_4 emissions from cattle, including both empirical and mechanistic models.

The empirical models have provided a better alternative in practical situations because they are simpler and easily applicable in terms of information and computer software requirements. Nonetheless, reliability of enteric CH_4 emission estimates is often questioned because they significantly affect policy guidelines and regulations (Stubbs, 2013). Therefore, models should be evaluated for their accuracy and precision of the predictions before use in policy decisions. Appuhamy et al. (2016) evaluated 40 extant models for dairy cows using data from North America, Europe, and Oceania. They showed that prediction accuracy and precision were markedly dependent on the degree of representativeness of the model parameters to feed intake and dietary nutrient composition of the region of interest.

The Environmental Protection Agency (U.S. EPA) uses Cattle Enteric Fermentation Model (CEFM), which is a spreadsheet-based mathematical model to estimate enteric methane emissions from cattle in USA. The model is based on Intergovernmental Panel for Climate Change (IPCC) Tier 2 equation [$CH_4 = Y_m \times GEI$], where Y_m = methane conversion factor defined as a constant fraction of gross energy intake (GEI, MJ/animal/d) lost as enteric CH_4 from a given animal population. Because obtaining actual measurements of feed intake and GE content of the diets are difficult, GEI is estimated using a cascade of calculations primarily involving constant digestible energy (DE) values for cattle populations in question as described in IPCC Good Practice Guidance (IPCC 2000). Nonetheless, CEFM does not use IPCC Tier 2 Y_m or DE constants. Instead, it uses its own Y_m and DE constants determined using the MOLLY cow model (Baldwin, 1999) pertaining to feed intake and diet-characteristics of seven regions in the US. The DE constants that CEFM uses for California cattle inventories were 69, 66, 63, 65, 65 and 85 for dairy cows, replacement heifer, beef cows, beef replacement, beef stockers and feedlot, respectively. The Y_m used were 4.8, 5.9, 6.5, 6.5, 6.5 and 3.0%, respectively. An uncertainty analysis conducted by U.

S. EPA (EPA, 2016) indicated the CEFM to have a modest amount of uncertainty (-11% to +18% of the predictions) in the final national inventory estimate, although there has been no report on region-wise uncertainty estimates.

Of all the variables in CEFM or IPCC-Tier 2 models, the use of constant Y_m is of special concern as Y_m of a particular cattle group in a given region can vary significantly (Kebreab et al., 2008). For instance, Y_m of dairy cows varies from 3.9 to 10.7% across North America, Europe, and Oceania and from 3.9 to 8.0% in North America (Appuhamy et al., 2016). Level of feed intake and dietary nutrient composition could explain a significant proportion of this variability (Ramin and Huhtanen, 2013). Therefore, applying Y_m representative of dry matter intake (DMI) and dietary nutrient composition is key to successful determination of enteric CH_4 emissions. Even though U.S. EPA attempted to address this variability, the version of MOLLY cow model (Baldwin, 1999) they used to derive those Y_m values was calibrated on data from cows and diets in 1990s at the latest. Given the fact that DMI, diet composition, and energy utilization efficiencies of cattle have changed over time (Moraes et al. 2015), and the MOLLY cow model parameters have undergone considerable revisions after the 1999 version (e.g., Hanigan et al. 2009, 2013), if Y_m and DE constants were to be recalculated based on current cow and diet characteristics, they would likely yield different numbers than those used in CEFM. Nonetheless, U.S. EPA (2014) stated that they evaluated those Y_m values using a more recently developed mechanistic model namely COWPOLL (Kebreab et al., 2008). The COWPOLL model was calibrated for grass silage-based diets so extrapolation to cattle in North America should be done carefully.

The overall objective of the present study was to develop and assess a set of empirical models for predicting enteric CH_4 emissions from different cattle groups in California using recent records on feed intake and diet composition of each group. The specific objectives were: 1) characterize California cattle diets and summarize related feed intake, 2) collate enteric methane emission measurements related to the feed intake levels, and dietary nutrient composition of California cattle, 3) develop new empirical models or assess extant empirical models that predict CH_4 emissions corresponding to California cattle characteristics, and 4) apply those models in determining CH_4 emission factors (kg/animal/yr) and estimating emissions of each cattle group in California.

MATERIALS & METHODS

Data Sources

Dairy cattle diets. Data on ingredient and nutrient composition of diets, and feed intake of dairy cow herds were obtained from published research and surveys focusing on commercial dairy farms in California (Getachew et al., 2005; Swanepoel et al., 2010, 2014; Trillo et al., 2016; Castillo et al., 2013; Rossow et al., 2013). Data for lactating dairy cows included DMI, and ingredient and nutrient composition of 182 diets from 83 farms. Castillo et al. (2013) conducted a survey of 39 commercial dairy farms in Merced County in California, which provided the majority (68%) of lactating dairy cow data. The authors selected those farms to represent the ranges of herd size (from 210 to 2435) and milk yield [from 25 kg/d (10th percentile) to 39 kg/d (90th percentile)] of California dairy cows. All dairies milked Holstein cows and were using total mixed rations (TMR). They obtained ingredient compositions from feed records of each farm. Total mixed ration samples analyzed for nutrient composition (Neutral detergent fiber (NDF), acid detergent fiber (ADF), ether extract (EE), and minerals) were taken by hand from the low, middle, and top portion of the feed pile across the entire length of the feed bunk. Dry matter intake was calculated by subtracting the amount of feed refusals from the total amount of TMR delivered per group, multiplying that by the DM concentration of the TMR, and then dividing by the number of cows in the group (Castillo et al., 2013). Another survey conducted by Trillo et al. (2016) provided ingredient and nutrient composition of lactating dairy cow diets from 26 farms in San Joaquin County with herd size varying from 1,100 to 6,900 cows. Swanepoel et al. (2010) and Swanepoel et al. (2014) provided DMI, and dietary ingredient and nutrient composition of 20 lactating dairy cow diets from 17 farms in Tulare and Kings Counties with herd size varying from 800 to 5000 lactating cows and average milk yield ranging from 33 to 51 kg/d. The authors collected representative TMR and individual feed ingredient samples and analyzed them for nutrient composition. Dry matter intake, and ingredient and nutrient composition of lactating dairy cow diets in six commercial dairy farms in the San Joaquin County and five commercial dairy farms in Tulare and Kings Counties were obtained from Getachew et al. (2005) and Rossow et al. (2013), respectively. Feed intake and dietary ingredient and nutrient composition of dairy heifers and dry cows in California were obtained from Rauch et al. (2014) and a survey (2015 to 2016) conducted by Dr. Heidi Rossow at University of California, Davis (personal communication).

Beef cattle diets. We contacted leading beef cattle nutritionists and environmental specialists including Dr. Richard Zinn, Dr. James Oltjen, Dr. Roberto Sainz, and Dr. Frank Mitloehner in the Department of Animal Science at UC Davis in order to collect information on feed intake, and diet composition of beef cattle groups in California. Moreover, some information were retrieved from scientific publications focused on California cattle (e.g., Klasing et al. 2012, Stackhouse-Lawson et al., 2012).

Methane emissions. Actual CH_4 emission measurements from dairy and beef animals in commercial farms are not available, therefore, we relied on CH_4 emission measurements made on animals with similar characteristics (e.g., similar DMI and diet composition) in experimental settings (e.g., calorimetric or energy metabolism trials). These data were obtained from original experimental databases (measurements from individual animals) or from published literature (treatment means). Fifty calorimetric trials conducted in former Energy Metabolism Unit (EMU) at USDA, Beltsville provided 1025 enteric CH_4 production measurements (g/d) from lactating Holstein cows. When adjusted for feed intake, there was no differences in breed in methane emissions (Moares et al. 2014). A detailed description of the data is available in Moraes et al. (2014) and Appuhamy et al. (2018). However, the majority of the EMU data was not representative of DMI and diet composition of modern cows in California. For instance, the third quantiles of DMI (19.3 kg/d) and dietary EE content (3.0 % of DM) of EMU data were lower than the mean DMI (22.9 kg/d) of EE (4.3 % of DM) content of lactating dairy cows in California. Only 18% of the EMU data (n = 214) were in line with the characteristics of lactating dairy cows in California. Thirty six additional methane emission measurements representative of California cows were obtained from a metabolic trial conducted at University of California, Davis (Niu et al., 2016). So, the final dataset for lactating dairy cows included 250 enteric methane emission measurements from 117 individual lactating cows in 23 experiments. Besides CH_4 production, DMI, and diet composition, the experimental data included apparent total tract digestibility of nutrients.

In addition to individual cow data, an extensive literature search was conducted to retrieve relevant data. The search used Science Direct, Journal of Dairy Science, and Journal of Animal Science online databases for research articles on dairy and beef cattle published in English from January 2000 to April 2015. The oldest publication year was set to 2000 to collect data representative of modern cattle. The title and abstracts of retrieved articles were further screened for *in vivo* studies measuring enteric CH_4 emissions. We considered primarily the studies examining the impact of changes in basic dietary nutrient composition on enteric CH_4 emissions from cattle. In studies testing the impact of feed additive supplementations (e.g., 3-nitrooxypropanol, fibrolytic enzymes, plant bioactive compounds, monensin, fatty acids, and nitrate), CH_4 emission measurements (treatment means) of the control treatments and only those supplementation treatments not significantly affecting CH_4 yields (per kg of DMI) were included in the datasets. When duplicates were excluded, the searches resulted in 74, 10, 32, and 4 articles containing 280, 31, 132, and 10 treatment means of enteric CH_4 emission measurements of lactating dairy cows, non-lactating cows (dry cows and heifers together), beef heifers and steers, and beef bulls, respectively. When CH_4 emissions were reported in L/cow/d, they were converted to g/cow/d considering 16.0 g molar mass and 22.4 L molar volume [CH_4 (g/cow/d) = CH_4 (L/cow/d) × (16.0/22.4)]. Missing dietary nutrient composition values were estimated from the National Research Council dietary requirement for dairy cattle (NRC, 2001) and Feedpedia (www.feedipedia.org) feed ingredient composition tables. When apparent total tract digestibility of NDF (attNDF) was missing, it was calculated using following equation in NRC (2001).

$$\text{attNDF} = 0.75 \times [(\text{NDF} - \text{NDICP}) - \text{LIG}] \times (1 - [\text{LIG} / (\text{NDF} - \text{NDICP})]^{0.667}) \qquad [1]$$

where NDF = NDF content, NDICP = neutral detergent insoluble crude protein content, LIG = lignin content (all as % of DM). The methane emission measurements related to DMI, dietary forage, NDF and EE contents, which did not fall within the ranges of California cattle were excluded. These variables were chosen as they have been often shown to be significantly associated with CH_4 production in the rumen. The final data sets for lactating dairy cows, feedlot cattle (steers and heifers receiving diets with < 20% of forage), beef replacement heifers, beef stockers (growing steers and heifers on pasture), and beef bulls included 77, 44, 32, 10 and 10 treatment means of enteric CH_4 emission measurements, respectively. Moreover, 28 CH_4 emission treatment means from grazing dairy cows having similar characteristics of beef cows in California were used to find a suitable model for beef cows.

Model Development

Lactating cows. The experimental data of lactating dairy cows (n = 250) representative California cow diets were used to develop linear models to predict enteric CH_4 emissions. Dry matter intake, dietary CP, NDF, ADF, and total ash contents (% of DM), milk yield (kg/d) and milk protein and fat percentages, and BW (kg/cow) were considered as potential predictor variables. Appuhamy et al. (2016) demonstrated that inclusion of apparent total tract digestible NDF content (dNDF) in place of total NDF content improved accuracy of the CH_4 emission predictions for lactating dairy cows in North America.

$$\text{dNDF (\% of DM)} = \text{total NDF (\% of DM)} \times \text{attNDF}/100 \qquad [2]$$

The model development process was repeated twice with and without considering dNDF as an additional predictor variable. Correlated variables ($|r| \geq 0.5$) were not regressed together in order to minimise multi-collinearity issues such as inaccurate model parameters, decreased statistical power and risk for excluding variables having significant effects during model construction. For instance, in models for lactating cows, milk yield and DMI (r = 0.65), dietary ADF and NDF contents (r = 0.65), and dietary NDF and dNDF (r = 0.86) were not regressed together. Therefore, several secondary pools including uncorrelated candidate variables had to be formed. All possible combinations of variables in each secondary pool were regressed separately against CH_4 production measurements (g/d). For example, one of the pools had 9 variables (P = 9), which led to 512 potential regression models ($2^P = 2^9 = 512$). Each regression was carried out accounting for random animal and study effects as shown in following linear mixed-effects model:

$$Y_{ijk} = \beta_0 + \beta_1 X_{1ijk} + ...\beta_p X_{pijk} + \alpha_i + \gamma_j + \varepsilon_{ijk} \qquad [3]$$

where Y_{ijk} = the *k*th CH_4 emission measurement of *i*th cow in *j*th study, β_0 = intercept, X_{1ijk} to X_{pijk} = *k*th measurement of the explanatory variables (total number of the explanatory variables = *p*) pertaining to *i*th cow in *j*th study, β_1 to β_p = fixed effects (regression coefficients) of the explanatory variables, α_i = the random effect associated with the *i*th cow (*i* = 1,., 117), γ_j is the random effect associated with the *j*th study (*j* = 1, …, 23) and ε_{ijk} is the random error. Interactions and polynomial effects of the explanatory variables were not included in the models in order to promote model simplicity and avoid an impact of multicollinearity on model parameters (Appuhamy et al., 2014). All the mixed-models in each pool were fitted first to data using the *lme4* package in R (version 2.12.2, R Foundation for Statistical Computing, Vienna, Austria) and then ranked by descending Bayesian information criterion (BIC; Schwarz, 1978) values. Lower BIC values imply proper balance between model complexity and model fit (Myung, 2000). Three models associated with the least BIC values were chosen as the final models to predict CH_4 emissions with or without dNDF. A comprehensive description of the variable and model selection procedure is available in Appuhamy et al. (2014).

Feedlot cattle. Forty four CH_4 emission measurements (treatment means) published in literature were used to develop a model to predict CH_4 emissions from feedlot cattle. The measurements were made on cattle with DMI and dietary nutrient compositions that were similar to feedlot cattle in California. The model was developed following the meta-analysis approach previously described in Appuhamy et al. (2013). Briefly, mixed-effect meta-regression models including fixed effect of explanatory variables and random study effects were fitted against the CH_4 emission measurements (treatment means). The explanatory variables included in the analysis were DMI, BW, and dietary forage, NDF, ADF, CP and EE contents. First, the individual explanatory variables were regressed separately against the CH_4 emissions. Variables with considerable effects ($P < 0.10$), when regressed individually were then regressed together in one model. Again, correlated variables (e.g., NDF and ADF) were not regressed together to avoid multicollinearity issues. This resulted in more than one regression models having similar potential to predict the emissions accurately (e.g., similar likelihood statistics). The model associated with the least BIC was chosen as the final model as our objective was to develop a simple model which is still capable of best predicting the emissions. The meta-analysis was carried out using *metafor* package (Viechtbauer, 2010) in R (version 2.12.2, R Foundation for Statistical Computing, Vienna, Austria).

Model Evaluation

New models developed in this report to predict CH_4 emissions from lactating dairy cows were evaluated using the literature data (n=77) representative of California cows. Along with new models, several other extant models previously ranked high for lactating cows in North America (Appuhamy et al., 2016) were also evaluated. These extant models were: IPCC-Tier 2 model that U.S. EPA use for dairy cows in California (Y_m = 4.8%), and models in Nielsen et al. (2013), Moate et al. (2011), Ellis et al. (2007), and Moe and Tyrrell et al. (1979). Models in Moraes et al. (2014) developed using non-lactating cow data, Jiao et al. (2014) model for dairy heifers, and IPCC-Tier 2 model used for replacement dairy heifers in California (Y_m = 5.9%) were evaluated using the literature data on non-lactating dairy cows including both dry cows and heifers (n=31). The new model to predict CH_4 emissions from feedlot cattle was evaluated through cross-validation procedures due to lack of data. Besides the new model, we also evaluated the model in NRC (2016) for cattle on low-forage diets and IPCC-Tier 2 model used by U.S. EPA for California feedlot cattle (Y_m = 3.0%). The models developed by Moraes et al. (2014) and Ellis et al. (2007) for beef cattle, NRC (2016) models for cattle on high forage diets, and the IPCC-Tier 2 model used by U.S. EPA (Y_m = 6.5%) were evaluated with the literature data set for beef replacement heifers (n = 32), beef stockers (n = 10), beef cows (n = 28), and beef bulls (n = 10). The overall agreement between model predictions and the data were determined by calculating the mean square prediction error (MSPE).

$$MSPE = \frac{1}{n} \cdot \sum_{i=1}^{n} (O_i - P_i)^2 \qquad [4]$$

where n = number of observations, O_i = observed response of ith study treatment, P_i = corresponding predicted response. As the square root of MSPE (RMSPE) carries the same unit of observed values, RMSPE was expressed as a percentage of average observed value. The RMSPE quantifies overall agreement between predicted and observed values. Moreover, the mean square prediction error was decomposed into systematic biases such as mean bias (MB) and slope bias (SB), and bias due to random causes (RB) to have insight into the magnitude of sources of prediction error. Those biases were calculated according to Bibby and Toutenburg (1977). The sources of errors can also be assessed using the observed vs. predicted value plots with unity and scatter regression lines indicating perfect and actual relationships between observed and predicted values, respectively. For example, the scatter regression line running notably away from the unity line indicates the presence of a mean bias.

Estimate of Emissions from Cattle Groups in California

Cattle population statistics. The population statistics of California cattle groups in 2015 were obtained from California Department of Food and Agriculture (CDFA). Some adjustments were done to the CDFA statistics in line with the adjustments by California Air Resource Board (CARB, 2003). The categories of stockers and feedlot cattle were converted from the CDFA categories of “other heifers” and “steers”. According to reports from U.S. EPA and the California Cattlemen’s Association (CAA), stockers and feedlot cattle are two consecutive stages for final meat production, and the typical time cattle are at each stage is approximately the same (four months). This implies that these two groups may have equal populations. However, additional information from CCA and University of California Cooperative Extension indicates that some heavy weight calves are placed into feedlots directly without grazing as stockers (CARB, 2003). This is especially true in the Imperial Valley (Imperial County), where calves in or out of the valley are sent to feedlots following weaning and fattened for about seven months. With exclusion of 22,000 head of feeders in Imperial Valley, the statewide stocker population is estimated as half of the remainder (CARB, 2003). The calculations, explained in following equations, resulted in 234,000 stockers and 456,000 feedlot cattle.

$$\text{Stockers} = (\text{Other Heifers} + \text{Steers} - 22{,}000)/\ 2 \qquad [5]$$

$$\text{Feeders} = (\text{Other Heifers} + \text{Steers}) - \text{Stockers} \qquad [6]$$

Estimating emission factors and population emissions. Daily CH_4 emissions (g/d) of each cattle group were estimated first using the best prediction models selected from the model evaluations. Those daily emissions were then converted to yearly emissions multiplying by 365 to determine the emission factors (kg/yr). In estimating the average emission factor for dairy cows, we assumed every year of cow life to have a 305 d lactation period and 60 d dry period. Average daily emission during lactation and dry periods were estimated using the best performing models from lactating and non-lactating cow model evaluations, respectively. Once the average daily emissions (g/d) were known, the emission factor (kg/yr) was calculated as shown below.

$$CH_4\ (\text{kg/yr}) = [CH_4\text{-lactation (g/d)} \times 305 + CH_4\text{-dry period (g/d)} \times 60]/1000 \qquad [7]$$

The emission factors were then multiplied by the corresponding population size to estimate annual total emissions of each cattle group. The emissions from each cattle group were also estimated using IPCC-Tier 2 models used by U.S. EPA. Consistent with IPCC-Tier 2 approach, we assumed zero emissions from dairy and beef calves.

RESULTS & DISCUSSION

Feed intake and dietary characteristics of California cattle

Lactating dairy cows: Alfalfa hay, corn silage, wheat silage, and alfalfa silage were the most frequently used forage types and included in 98, 85, 31, and 25% of the diets (data not shown), respectively. The inclusion rates of corresponding forage types were as high as 56, 38, 26, and 27% of DM, respectively (Table 1). Corn grain (ground, rolled, or steam-flaked), whole cotton seeds, canola meal, almond hulls, and dry distillers grain with soluble (DDGS) were the most frequently used concentrate ingredients with inclusion rates as high as 20 to 27% of DM. Summary of DMI and nutrition content of the diet is given in Table 2. Dry matter intake varied from 17.5 to 30.1 kg/d with a mean of 22.9 kg/d. Some farms had separate diets for low and high producing cows with mean DMI of 25.8 and 21.4 kg/d, respectively (data not shown). Forage content varied from 24 to 74% of DM with a mean of 50% of DM (Table 2). Almond hull content was a significant determinant of dNDF as it had significantly negative relationship with attNDF and explained 55% of the variability of attNDF (Figure 1). Crude fat (EE) content of the diet decreased with increasing forage content and ranged from 2.4 to 10.4% of DM with a mean of 4.8% of DM.

The data is representative of the most common diets. However, there are differences in diet for example organic vs conventional and based on location on the state so further refinement can be done by collecting specific data and population.

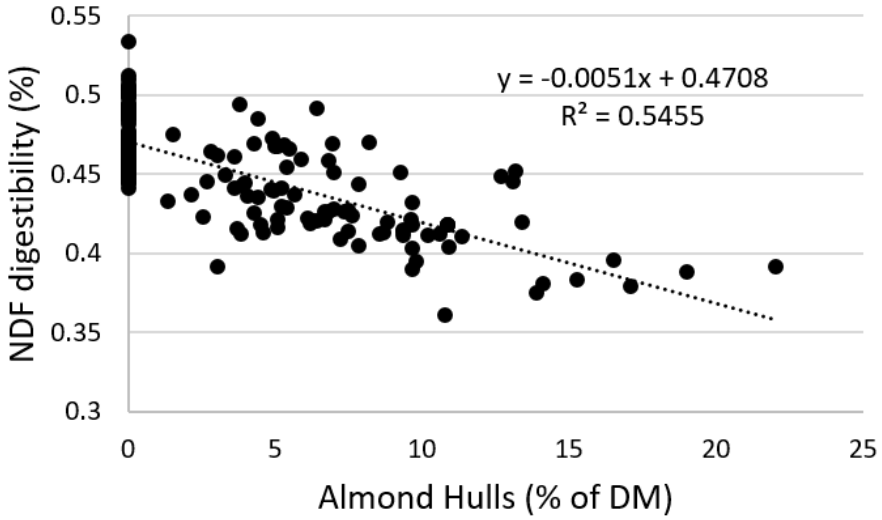

Figure 1. Relationship between apparent total tract digestibility of NDF and dietary almond hull content in lactating dairy cow diets in California

Table 1. Frequently used ingredients in lactating dairy cow diets in California

Ingredients	Inclusion rate (% of DM)
Forage	
Alfalfa hay	0 - 56
Corn silage	0 - 38
Wheat silage	0 - 26
Alfalfa silage	0 - 27
Oat hay	0 - 7
Wheat straw	0 - 6
Concentrate	
Corn grain (ground/flaked/rolled)	0 - 27
Almond hulls	0 - 22
Whole cotton seed	0 -14
Canola meal	0 - 20
Dry distillers grain	0 - 20
Wet distillers grain	0 - 15
Soybean hulls	0 - 11
Corn gluten meal	0 - 13
Whey powder	0 - 12
Wheat millings	0 - 10
Soybean meal	0 - 9
Molasses	0 - 8

Table 2. A summary of DMI and dietary nutrient composition of lactating dairy cows in California

Variable[1]	Mean	Median	Minimum	Maximum
DMI, kg/d	22.9	23.0	17.5	30.1
GEI, MJ/d	423.7	425.5	323.8	556.9
Forage, DM %	49.6	48.3	24.0	74.3
CP, DM %	17.2	17.2	13.0	22.2
Total NDF , DM %	33.5	33.4	25.0	43.5
Digestible NDF, DM %	15.1	15.0	11.5	20.6
ADF, DM %	22.4	22.7	17.5	30.4
EE, DM %	4.8	4.7	2.4	10.4
Ash, DM %	8.3	8.1	5.1	13.1
attNDF, %	45.0	45.1	36.1	53.4

[1] GEI = gross energy intake, attNDF = apparent total tract digestibility of NDF

Dairy heifers and dry cows. Feed intake and dietary characteristics of dairy heifers and dry cows in California are given in Table 3. Dry matter intake of dairy heifers ranged from 6.0 to 22.8 kg/d with a mean of 9.9 kg/d. The average GEI of the dairy heifers was 181.2 MJ/d. Corn silage, alfalfa hay, and wheat straw were the most frequently used forage types in dairy heifer diets (data not shown). Canola meal and almond hulls were the most frequently used byproduct feeds. The majority of heifer diets included feeds pushed out from lactating cow pens at an average rate of 10% of DM (data not shown). Mean total NDF, CP, and EE contents of heifer diets were 47.9, 14.2, and 3.2 % of DM, respectively. The average DMI and GEI of dry cows were 13.5 kg/d, and 248 MJ/d respectively. All the dry cow diets included alfalfa hay at an average rate of 14% of DM (data not shown). They intermittently included triticale (52% of DM), corn silage (38% of DM), wheat straw (9% of DM), and wheat hay (11% of DM). Almond hulls (7% of DM), DDGS (10% of DM), canola meal (12% of DM) and corn grain (10% of DM) were the major concentrate ingredients (data not shown). About 50% of the diets included bakery wastes (7% of DM). Total NDF content of dry cow diets varied from 36.4 to 50.8 % of DM with a mean of 45.9% of DM. Mean CP, and EE contents of dry cow diets were 15.0, and 3.6% of DM, respectively.

Table 3. Diet characteristics of dairy heifers and dry cows in California, and relevant data from non-lactating dairy cows from several energy metabolism experiments involving measuring enteric methane emissions.

	Literature data			California dry cow data			California heifer data		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
DMI, kg/d	10.3	4.1	14.6	13.5	13.2	13.6	9.9	6.0	22.8
Gross energy intake, MJ/d	173.0	76.7	266	248.2	241.6	248.9	181.2	109.8	417.2
Forage, DM %	75.5	45.0	100	67.1	57.2	73.9	62.5	45.1	74.3
CP, DM%	15.6	11.8	22.5	15.0	13.8	16.5	14.2	12.2	16.6
total NDF, DM%	45.8	30.6	60.9	45.9	36.4	50.8	47.9	43.6	54.3
ADF, DM%	27.4	18.5	41.5	30.4	24.9	33.9	33.5	29.1	37.3
EE, DM%	3.4	2.1	7.7	3.6	2.9	4.3	3.2	2.7	3.9
Gross energy, MJ/DM kg	18.2	16.7.	19.0	18.4	18.1	18.7	18.3	17.6	18.9
BW, kg	587	175	868	--	--	--	--	--	--
CH_4 production (g/d)	235	90	397	--	--	--	--	--	--
CH_4 yield (g/DMI kg)	23.8	12.9	30.2	--	--	--	--	--	--
Ym (% of GEI)	7.20	3.9	9.2	--	--	--	--	--	--

Beef cattle groups. When averaged across the values obtained from published literature (Stackhouse-Lawson et al., 2012) and via personal communications (Richard Zinn at University of California-Davis), the mean DMI of feedlot cattle in California was 7.3 kg/d. The feedlot diets included 8 to 20% of forage mainly composed of alfalfa hay (Table 4). Steam-flaked corn (50 to 75 % of DM), DDGS (20 to 30 % of DM), and cotton seed (0 to 5 % of DM) accounted for the majority of the concentrates. Total NDF content varied between 18 and 24 with a mean of 20% of DM. Dietary EE ranged from 4.5 to 8.0% with a mean of 7% of DM. We could not find representative data on DMI of beef stockers, replacement heifers, cows, and bulls in California. The respective groups had average DMI of 5.2, 7.3, 15.4, and 8.6 kg/d in our literature data set (data not shown). Moreover, based on a nation-wide survey, Westberg et al. (2001) reported similar average DMI of 6.3, 7.2, 14.4, and 10.0 kg/d, respectively for those cattle groups in US. Therefore, we adopted the averages of those two sets of values (5.8, 7.3, 14.9, and 9.3 kg/d, respectively) as DMI for the beef stockers, replacement heifers, cows, and bulls, respectively.

Stockers in California receive 100% forage-based diets predominantly composed of alfalfa hay and thus have NDF, CP, and EE contents of 51, 18, and 2% of DM, respectively (data not shown). The beef cows and bulls eat diets usually composed of alfalfa hay (about 90% of DM), corn grain (about 5% of DM), and wheat grain (about 5% of DM). So, the calculated average NDF, CP, and EE contents of the cow and bull diets were 40, 20, and 2.2% of DM, respectively (data not shown). We could not find representative data on diet composition for beef replacement heifers in California. So, the average dietary characteristics in California were assumed to be similar to the characteristics of other beef replacement heifer populations, for instance those published in the literature. The average total NDF, CP, EE, and GE contents in literature were 39.1, 14.5, and 3.2 % of DM, and 18.4 MJ/kg of DM, respectively (data not shown).

Table 4. Data sources and diet characteristics of California feedlot cattle

	Klasing et al. (2012)	Stackhouse-Lawson et al. (2012)	Roberto Sainz*	Frank Mitloehner*
Ingredient (% of DM)				
Corn flaked	51 to 53	75	58	57 to 60
DDGS	0 to 30	0	25	21
Corn silage	0	0	0	0
Wheat	4.3 to 9.9	0	0	0
Soybean meal, 48%	0	0	0	0
Rice bran	3.2 to 7.7	0	0	0
Wheat middling	4.2 to 7.4	0	0	0
Cotton seed meal	0 to 4.4	5	0	0
Wheat straw	3.9 to 7.7	0	0	0
Alfalfa hay	3.7 to 4.4	20	8	8 to 10
Sorgham-sudan grass	3.7 to 6.6	0	0	0
Animal/vegetable fat	2 to 4	0	3	1.7
Molasses and minerals	1.2 to 1.4	0	6	0
Liquid premix	0	0	0	7
Urea	0 to 0.13	0	0	0

Nutrient (% of DM)				
NDF	24	18	19	19
NFC	53	63	57	58
CP	14	12.5	15	15
EE	8	4.5	8	7

*personal communication

Model development

Diet characteristics for lactating dairy cows used for model development are given in Table 5. The characteristics were close to cows in California. For instance, the mean (43.2% of DM) and median (44.7% of DM) attNDF was similar to those of California cows (45.0 and 45.1 % of DM, respectively). Consequently, the average dNDF of the data were nearly identical to that of California data [14.9 % (Table 5) vs. 15.1 % (Table 2)]. Overall, DMI was lower than the DMI of California cows (mean = 19.9 vs. 22.9 kg/d). The amount of feed the animal consumes primarily determines the extent of rumen fermentation and thereby the amount of CH_4 produced in the rumen.

Table 5. A summary of experimental data, and a summary of literature data used respectively for developing and evaluating CH_4 prediction equations for lactating dairy cows

	Model development (n = 250)				Model evaluation (n = 77)			
	Mean	Median	Min.	Max.	Mean	Median	Min.	Max.
DMI, kg/d	19.9	19.5	16	28	20.6	20.1	15.2	28.6
Gross energy intake, MJ/d	381	376	296	527	388	380	284	546
Forage content (% of DM)	51.7	50.0	27.2	71.3	49.8	52.1	30.0	68.6
Nutrient composition (% DM)								
CP	16.2	16.3	10.6	20.2	16.3	16.3	13.1	20.8
NDF	34.1	33.7	24.5	45.9	33.9	33.3	26.5	39
Digestible NDF	14.9	14.7	7.6	29.3	15.9	15.7	10.5	21.5
ADF	21.5	20.3	13.2	34.5	21.1	20.2	16.6	26.4
EE	3.2	3	2.5	5.8	4.7	4.3	2.5	9.9
Ash	6.4	6.3	4.1	8.6	7.1	7	5.2	10.5
Lignin	5	4.9	2.2	9	3.8	3.9	1.8	6.2
Digestibility of NDF, %	43.2	44.7	30	67	46.9	47.5	32.4	53
Animal characteristics								
BW, kg	631	628	493	807	633	620	473	762
DIM	151	146	27	356	118	113	45	247
Milk yield, kg/d	29.5	28.5	12.6	50.5	30.7	30.1	14.9	45.2
Milk fat, %	3.6	3.6	1.7	5.8	3.8	3.7	2.7	4.8
Methane emissions								
Production (g/d)	375	375	222	542	392	397	206	547
Yield (g/DMI)	19	19.2	12.1	26.6	19.1	18.9	12.4	28.6
Y_m (% of gross energy intake)	5.53	5.57	3.58	8	5.66	5.64	3.2	8.2

Consequently, most of the CH_4 emission prediction models include DMI as a predictor variable. Dry matter intake could also regulate the extent of rumen fermentation and thus CH_4 production via its ability to regulate the passage rate. Therefore, different DMI could have different CH_4 yields (CH_4 produced per kg of DMI) and different parameter estimates for the relationship between CH_4 production and DMI in models. Nonetheless, the similar dNDF values between the experimental data and California cow population suggest that the impact of the DMI discrepancy on model parameter estimates of DMI could be marginal. On the other hand, models including both DMI and dNDF would carry the power of predicting accurately the CH_4 production across several populations even though the DMI can be different among them. The average Y_m of the literature data (5.5%), was nearly identical to that of Kebreab et al. (2008) (average Y_m = 5.6%) determined for commercial dairy cow populations in US.

The new models selected to predict CH_4 production (g/d) and Y_m in lactating dairy cattle included DMI (kg/d), dNDF (% of DM), and milk fat content (%) as predictor variables.

$$CH_4 = 11.2 \pm 0.8 \times \text{DMI} + 2.18 \pm 0.8 \times \text{dNDF} + 32.2 \pm 4.2 \times \text{milk fat} \qquad [8]$$

$$Y_m = 6.85 \pm 0.49 - 0.14 \pm 0.02 \times \text{DMI} + 0.38 \pm 0.08 \times \text{milk fat} \qquad [9]$$

The positive relationship between DMI and the CH_4 production is expected as the amount of feed consumed is the primary driver for the extent of rumen fermentation and thus the amount of CH_4 produced in the rumen. The positive association between dNDF and CH_4 production highlights further the importance of cellulose and hemicellulose fermentation particularly in terms of supplying hydrogen for methanogenesis in the rumen (Moe and Tyrrell, 1979). The positive relationship between CH_4 production and milk fat percentage, which was independent of DMI, agrees with the similar relationship previously demonstrated by Moraes et al. (2014). Inclusion of milk fat content into the model already having DMI explained 10% more variability in CH_4 production (data not shown). Nonetheless, van Lingen et al. (2014) showed individual milk fatty acids rather than just the total milk fat percentage to explain a greater percentage of the variability.

New models were developed for feedlot cattle as extant models were not found to be adequate in California conditions. The new model developed using literature data (Table 6) included a positive relationships of DMI (kg/d) and dietary NDF content (% of DM) and a negative relationship of dietary fat (EE, % of DM) with enteric CH_4 production (g/d).

$$CH_4 = -54.9 \pm 22.3 + (12.6 \pm 1.9 \times \text{DMI}) + (4.46 \pm 0.93 \times \text{NDF}) + (-4.61 \pm 1.75 \times \text{EE}) \qquad [10]$$

Increasing dietary fat particularly at the expense of carbohydrate would reduce CH_4 production in the rumen by reducing fermentable biomass. It might also negatively affect CH_4 production by reducing DMI and NDF digestibility as observed by Eugene et al. (2008) and Hollman et al. (2013). However, the inclusion of both EE and DMI in the present model indicates that dietary fat could have an effect on methane production in the rumen independent of DMI.

Table 6. A summary of literature data (n = 44) used to develop a model for California feedlot cattle

	Mean	Minimum	Maximum
DMI, kg/d	7.52	3.47	14.1

Dietary nutrients (% of DM)			
Forage	10.3	0	22.7
NDF	18.3	11.5	26.7
ADF	9.9	3.5	15.4
CP	15.1	12.2	22.4
EE	4.8	1.5	11
BW	466	320	730
CH_4 (g/d)	103.8	34.6	200
CH_4/kg of DMI	13.5	7.7	27.2
Y_m (% of gross energy intake)	3.7	2.0	6.3

Due to paucity of California specific data and availability of extant models, new models for replacement beef heifers, stockers, beef cows and bulls were not developed. However, extant models have been evaluated and given in the next section with recommendations for use in California.

Model evaluation

Lactating dairy cows. A summary of data used for model evaluation is given in Table 5. The data were reasonably representative of feed intake and dietary characteristics of dairy cows in California (Table 2 vs. Table 5). Forage content of the diets varied from 30 to 69% of DM with a mean of 50% of DM, which is close to forage content in California diets ranging from 24 to 74% of DM with a mean of 50% of DM. The CP, NDF, ADF, and EE contents (% of DM) varied within similar ranges and had similar mean values compared to those of lactating cows in California. Corn silage, alfalfa hay, corn grain, and canola meal were included in >50% of the diets respectively. The attNDF had a similar range (32.4 to 53.0% vs. 36.1 to 53.4%) and a similar mean value (46.9% vs. 45.0%) compared to that of California cows. Nearly half of the attNDF (44% of total values) in literature data were actual measurements, while the rest was estimated as described above. Mean (45%) and variability (32.4 to 52.6%) of the measured attNDF (data not shown) were also in line with the values of California cows. Consequently dNDF had similar distributions for literature data (10.5 to 21.5 with a mean of 15.9% of DM) and California cow data (11.5 to 20.6 with a mean of 15.1% of DM). The average DMI of cows in literature data was 20.6 kg/d, which was closer to the mean DMI of California cows (22.9 kg/d) than the mean DMI of cows in the experimental data set (19.9 kg/d). The average Y_m of 5.7% in the data were close to the average Y_m of 5.6% estimated for US dairy cow populations by Kebreab et al. (2008).

Performance of the new model evaluated with data used in its development is given in Table 7. Predicted values from new models vs. the data (observed values) are presented in Figure 2. The new models fitted to the data well (RMSPE <15% of the average observed value) and with negligible systematic bias (mean and slope bias < 10% of total bias) indicating satisfactory parameter estimates for the relationship of DMI, dNDF, and milk fat content in the models. New model including dNDF predicted CH_4 production slightly more accurately than that including total NDF as indicated by lower RMSPE (11.1 vs. 11.3%) and lower systematic bias (e.g., mean bias = 3.6 vs. 4.5% of total bias). When evaluated with independent data, again, the model including dNDF more accurately predicted CH_4 production than the one including total NDF (16.2 vs. 16.5%, Table 8). Nonetheless, dNDF is not a routinely available information compared to the total

NDF. The satisfactory performance of the model including total NDF points out the possibility to use the model to predict CH_4 accurately in many cattle populations (with uncertainty of about 11%).

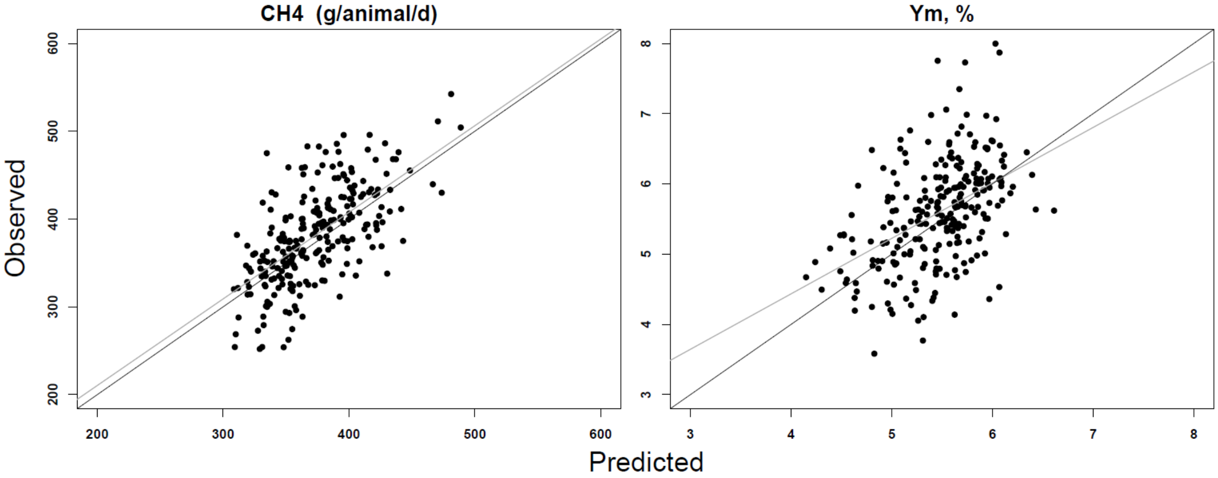

Figure 2. Predicted CH_4 production and Y_m of lactating dairy cows from new models compared to experimental data (observed values) used for developing the models.

Of all the extant models, the model in Moate et al. (2011) including DMI and dietary EE content best predicted CH_4 emissions but the prediction accuracy was still a little lower than that of the new model including dNDF (RMSPE = 16.2 vs. 16.7%, Table 7). The Neilsen et al. (2013) model including dNDF content was able to best predict the emissions (RMSPE = 17.4%) next to the Moate et al. (2011) model. Moreover, Appuhamy et al. (2016) found this model to predict CH_4 emissions from cows in North America more accurately than many other extant models. Consistently, in the present model evaluation, the Neilsen et al. (2013) model including total NDF was associated with larger prediction error than the model including dNDF (RMSPE = 19.9 vs. 17.4%). Overall, the new model including dNDF has a potential to predict CH_4 production from lactating dairy cows in California. If information on dNDF is not available, the new model with total NDF in place of dNDF could still be able to predict the emissions accurately. The model used by U.S. EPA with a constant Y_m of 0.048 was associated with a significant mean bias (22.6% of total bias, Table 7) for the methane emissions to be under-predicted by 15% (335 vs. 392 g/cow/d, data not shown).

Table 7. Performance of new and extant models to predict CH_4 production and Y_m of lactating dairy cows with similar DMI and diets to California cows.

Model[1]	RMSPE%	MB%	SB%	RB%
----------------------------------Evaluating new models with data used in their development---------------------------------------				
CH_4 (g/cow/d)				
$= 11.2 \pm 0.8 \times \text{DMI} + 2.18 \pm 0.8 \times \text{NDFd} + 32.2 \pm 4.2 \times \text{Milk fat}$	11.1	3.6	0	96.4
$= 11.0 \pm 0.9 \times \text{DMI} + 1.06 \pm 0.56 \times \text{NDF} + 32.2 \pm 4.6 \times \text{Milk fat}$	11.3	4.5	0.1	95.4
Y_m (% of gross energy intake)				
$= 6.85 \pm 0.49 – 0.14 \pm 0.02 \times \text{DMI} + 0.38 \pm 0.08 \times \text{Milk fat}$	12.1	3.5	1.9	94.6
-----------------------------------Evaluating new and extant models with independent data--				
New models				
CH_4 (g/cow/d)				
$= 11.2 \times \text{DMI} + 2.18 \times \text{dNDF} + 32.2 \times \text{Milk fat}$	16.2	1	5.8	93.1
$= 11.0 \times \text{DMI} + 1.06 \times \text{NDF} + 32.2 \times \text{Milk fat}$	16.5	2.1	6.6	91.3
$= ((6.85 – 0.14 \times \text{DMI} + 0.38 \times \text{Milk fat})/100) \times \text{GEI}$	18.9	7.5	5.2	87.3
Extant models				
CH_4 (g/cow/d)				
U.S. EPA model for California : $= [0.048 \times \text{GEI}]/0.05565$	22.6	42	0.1	57.9
Nielsen et al. (2013): $= [1.23 \times \text{DMI} - 1.45 \times \text{FA} + 0.017 \times \text{NDFdg}]/0.05565$	17.4	6.3	23.5	70.1
Moate *et al*. (2011): $= [\exp\{3.15 - 0.035 \times \text{EE}\}] \text{ x DMI}$	16.7	6	7.2	86.8
Ellis et al. (2007): $= [1.64 + 0.04 \times \text{MEI} + 1.45 \times \text{NDFI}] / 0.05565$	18.1	11.4	0.5	89.1
Moe and Tyrrell (1979): $= [3.41 + 0.52 \times \text{NSC} + 1.74 \times \text{HC} + 2.65 \times \text{CEL}]/0.05565$	18.3	2.4	4.4	93.1
Nielsen et al. (2013): $= [1.23 \times \text{DMI} - 1.45 \times \text{FA} + 0.012 \times \text{NDF}]/0.05565$	19.9	27.9	17.6	54.5

[1] DMI in kg/d, NDFd=apparent total tract digestible NDF (% of DM), Milk fat in %, NDF in % of DM, GEI =gross energy intake (MJ/d), FA = fatty acid content (g per kg of DM), NDFdg = NDFd in g per kg of DM, MEI = metabolizable energy intake (MJ/d), NDFI= total NDF intake (kg/d), NSC = non-structural carbohydrate intake (kg/d), HC = hemicellulose intake (kg/d), CEL = cellulose intake (kg/d), and EE = dietary ether extract content (% of DM)

Non-lactating dairy cows. A summary of literature data used to evaluate models for dairy heifers and dry cows is given in Table 3. The CH_4 emission measurements (n = 31) made on dairy heifers and dry cows ranged from 90 to 397 g/d corresponding to DMI ranging from 4.1 kg/d to 14.6 kg/d. Methane yield varied from 12.9 to 30.2 g per kg of DMI with a mean of 23.8 g per kg of DMI, which was equivalent to mean Y_m of 7.2. Body weight varied from 175 kg (Holstein heifer) to 868 kg (Holstein dry cow). The range of DMI and dietary nutrient compositions were in line with means and ranges of DMI and dietary nutrient composition of California heifer and dry cows in our data (Table 3).

Prediction performance of extant models evaluated using the literature data on heifers and dry cows are given in Table 8. Of all extant models available for non-lactating cows, the model in Jiao et al. (2014) including only DMI best predicted the enteric CH_4 emissions. The model was associated with a satisfactory RMSPE of 16.6% with majority (75.7%) of the error coming from random variability of data. The Jiao et al. (2014) model had relatively smaller mean bias (5.9% of total bias) and thus able to predict average CH_4 production reasonably close to the observed average (219 vs. 229g/d, data not shown). The literature data set had four treatment means of CH_4 measurements representing the data used by Jiao et al. (2014) to develop the model. This might potentially enhance overall performance of the model compared to the other models in the present evaluation. However, when the model evaluation was repeated removing those 4 observations from the data set, Jiao et al. (2014) model still performed better than the other models (RMSPE = 16.9%, data not shown). Even though the performance were not in par with those of Jiao et al. (2014) model, predictions from the IPCC-Tier 2 models, and the models in Moraes et al. (2014) were also in reasonable agreement with observed values as indicated by RMSPE varying between 20 to 22% (Table 8). The latter models were however related to large mean bias representing 18 to 32% of total bias. Overall, Jiao et al. (2014) model can be recommended to predict enteric CH_4 emissions from dairy heifers and dry cows in California.

Table 8. Performance of extant models to predict CH_4 production (g/cow/d) of heifers and dry cows having DMI and diets similar to California cattle.

Source	Model	RMSPE	MB	SB	RB
IPCC-Tier 2	$= [0.065 \times GEI]/0.05565$	20.5	31.7	20.4	47.8
U.S. EPA (dairy heifers)	$= [0.059 \times GEI]/0.05565$	26.3	43.7	22.0	34.3
Jiao et al. (2014)	$= 9.6 + 22.1 \times DMI$	16.6	5.9	18.4	75.7
Moraes et al. (2014)	$= [2.38 + 0.053 \times GEI]/0.05565$	21.5	18.1	38.5	43.4
	$= [2.88 + 0.053 \times GEI - 0.190 \times EE]/0.05565$	21.8	21.9	39.9	38.2

Feedlot cattle. A summary of literature data used to develop a new model for feedlot cattle [11] is given in Table 6. In an agreement with the California feedlot cattle diets (Table 4), the average forage content of the diets in literature data varied from 0 to 22.3% with an average of 10.7% of DM. Half of the diets contained corn grain as the major concentrate ingredient, while for the other diets barley was the main grain source. About 60% of the diets contained alfalfa as major forage source and the rest of the diets included cereal (barley and wheat) hay or barley silage as major forage source. Dry matter intake of the feedlot cattle in literature data were quite similar to DMI of feedlot cattle in California (e.g., mean DMI = 7.52 vs. 7.30 kg/d). Dietary nutrient composition;

for instance the mean NDF and CP contents (18.3 and 15.1 % of DM, respectively) were similar to that of California feedlot cattle diets (18 to 24, and 14 to 15 % of DM, respectively). However, EE contents of the diets in literature data were on average lower than (mean = 4.8 vs. 7% of DM) the values in California feedlot cattle diets.

$$CH_4 \text{ (g/cow/d)} = 54.9 + 12.6 \times DMI + 4.46 \times NDF - 4.61 \times EE \qquad [11]$$

The new feedlot model had a relatively small RMSPE of 18.3%, when evaluated through cross-validation. Moreover, the systematic biases such as mean bias and slope bias were negligible (Figure 3). The average EE content of literature data (4.8 % of DM) was less than the average EE content of California feedlot diets (7% of DM). However, the model still performed well on a subset of data (n = 22), the average EE content of which was 7% of DM. This indicates the potential of the model to predict CH_4 emissions successfully across a wide range of diet compositions. Along with the new model, we also evaluated two models recommended by NRC (2016) for beef cattle on low forage diets, and IPCC-Tier 2 model used by U. S. EPA for California. One of the two models in NRC (2016) was developed by Escobar-Bahamondes et al. (2016) and the other was by Ellis et al. (2007). Even though the new model has an advantage of performing well on data involved in its development, the extant models were associated with much larger RMSPE (40% to 42%). The IPCC-Tier 2 model (Y_m of 0.03) under-predicted the emissions by about 25 % (75 vs. 104 g/d, data not shown). This could be due to the fact that Y_m of 3.0% in the IPCC-Tier 2 model was about 25% less than the average Y_m of 3.9% in the data. Overall, the new model could be recommended to predict accurately enteric CH_4 emissions from feedlot cattle in California.

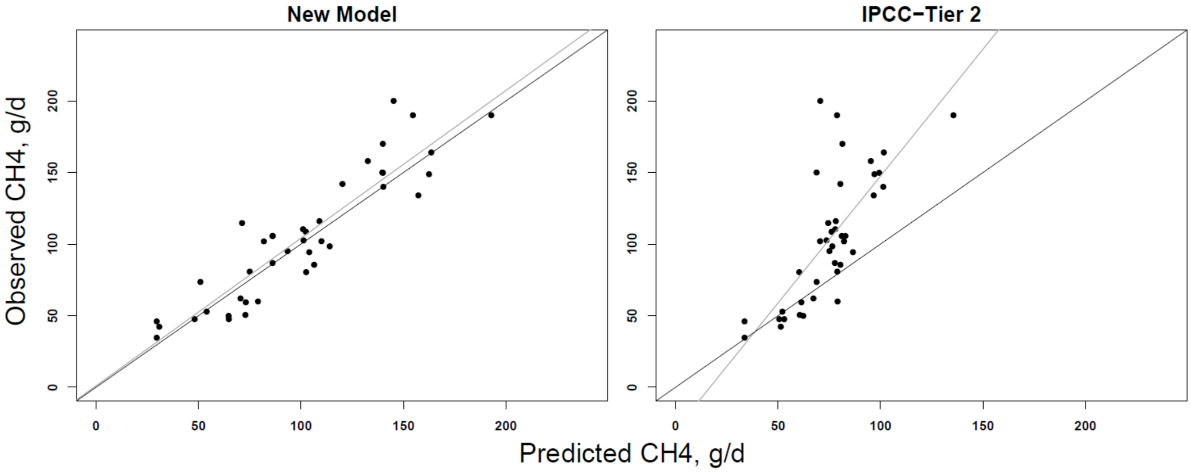

Figure 3. Predicted CH_4 production of feedlot cattle from the new model and the IPCC-Tier 2 model compared to literature data (observed values) used for developing the new model.

Replacement beef and stockers. Literature data (n = 10) used to evaluate models for stockers were fairly representative of beef stockers in California in terms of dietary nutrient composition. For instance, NDF (median = 47 % of DM) and EE (median = 2.0 % of DM) contents previously shown to have significant impact on enteric CH_4 yields (g per kg of DMI) were similar to average dietary characteristics of stocker cattle in California (51 and 2.0% of DM, respectively). The literature data (n = 28) on grazing dairy cows (the majority in Australia and New Zealand) used to evaluate models for beef cows had mean NDF, CP, and EE of 45.8, 19.8, and 2.7 % of DM, respectively. Those values were in line with the mean nutrient composition of California beef cow diets (data not shown). The literature data (n = 32) on replacement beef heifers included measurements made on heifer cattle not belonging to stocker and feedlot cattle groups (data not shown). Body weight of heifers ranged from 254 to 549 kg and was related to DMI ranging from 5.2 to 9.2 kg/d with a mean of 7.4 kg/d. Diets included primarily cereal and grass silages representing 36 to 75% of DM. The mean NDF, ADF, CP, and EE content in diets were 37.6, 21.5, 14.6, and 3.5 % of DM, respectively. The CH_4 production of the beef replacement heifers ranged from 99 to 228 g/d. The mean methane yield was 22.2 g/kg of DMI and mean Y_m was 6.6% for beef replacement heifers.

Moraes et al. (2014) developed a set of models to predict CH_4 emissions from beef heifers and steers separately. The majority of data involved in the model development was related to diets with forage contents greater than 50% of DM suggesting that the models would better perform emissions from replacement heifers and perhaps stockers than feedlot cattle. Consistently, the models in Moraes et al. (2014) models more accurately predicted the emissions from beef replacement heifers (RMSPE = 18 to 19%, Table 10) than heifers and steers in feedlot operations (RMSPE > 40%). Nonetheless, the models in Moraes et al. (2014) had a mean bias (33 to 37% of total bias) to under-predict the emissions from beef replacement heifers by 11% (148 vs. 166 g/d, data not shown). The Ellis et al. (2007) models had even larger mean bias (e.g., 50.3% in Table 10) and thus larger prediction error (e.g., RMSPE = 28.9%, Table 10). On the other hand, the IPCC-Tier 2 model with a constant Y_m of 6.5% was able to predict the emissions more closely to observed values and was associated with smaller mean bias (9.3%) and RMSPE (14.9%).

The majority of the models in Moraes et al. (2014) successfully predicted CH_4 emissions from beef stockers (RMSPE = 11 to 19%, Table 10), when evaluated using the limited number of observations from literature (n = 10). Inclusion of BW or dietary NDF content besides GE intake in the models greatly improved the performance (RMSPE = 13 to 19% vs. 25.8%, Table 9). Consequently, the Moraes et al. (2014) model including GEI, dietary NDF, and BW most accurately predicted the emissions with the least RMSPE of 11.7%. The IPCC-Tier 2 model with constant Y_m of 6.5% had a large slope bias representing 48.2% of total prediction error (Table 9). Dietary NDF content explained 53% of the variability in the prediction error showing the importance of accounting for differences in NDF content of pastures (data not shown). The NRC (2016) model for beef cattle fed high-forage diets (Escobar-Bahamondes et al., 2016) did not perform well on the data and had a large RMSPE of 49.7%.

Beef cows and bulls. When evaluated using the literature data for dairy cows on pasture (n = 28), the Moraes et al. (2014) model based only on GEI had the smallest RMSPE (15.9%, Table 10) with negligible systematic bias (< 1% of total bias). The Moraes et al. (2014) model was developed using data from non-lactating cows fed high-forage diets. The IPCC-Tier 2 model using Y_m of 6.5% also predicted the emissions well (RMSPE = 17.4%, Table 10) but had a mean bias for over-predicting the emissions by 20 g (327 vs. 307 g/d, data not shown). The new model developed for lactating dairy cows in California did not perform well for the cows on pasture and was associated with a large mean bias for over-predicting emissions by 60 g. The performance of the other models developed for lactating dairy cows such as the ones in Nielsen et al. (2013) were also not satisfactory (RMSPE = 23 to 28%). However, again, the Nielsen et al. (2013) model including dNDF performed better than their model including total NDF. Overall, the results indicated that the empirical models developed using data from one particular production system (e.g., concentrated dairy operations with TMR diets) would not be able to successfully predict the CH_4 emissions from a different system (e.g., grazing system).

Table 9. Performance of extant models to predict CH_4 emissions (g/animal/d) from beef cattle, when evaluated on literature data representative of beef cattle groups in California.

Source	Models[1]	RMSPE%	MB%	SB%	RB%
Beef Replacement Heifers (n = 35)					
Moraes et al. (2014)	= [1.289 + 0.051 × GEI]/0.05565	18.4	36.4	4	59.6
	= [-0.163 + 0.051 × GEI + 0.038 × NDF]/0.05565	18.7	33	8.5	58.5
	= [-1.487 + 0.046 × GEI + 0.038 × NDF + 0.006 × BW]/0.05565	18.8	35.1	0	64.9
IPCC (2006)	= [0.065 × GEI]/0.05565	14.9	9.3	0	90.7
Ellis et al. (2003)	= [2.7 + 1.16 × GEI – 15.8 × EEI]/0.05565	29.8	50.3	2	47.7
Beef Stockers (n = 10)					
Moraes et al. (2014)	= [1.289 + 0.051 × GEI]/0.05565	18.8	44.8	20.9	34.3
	= [-0.163 + 0.051 × GEI + 0.038 × NDF]/0.05565	13.1	21.9	39.7	38.4
	= [-1.487 + 0.046 × GEI + 0.038 × NDF + 0.006 × BW]/0.05565	11.7	0.2	0.7	99.1
	= [0.743 + 0.050 × GEI]/0.05565	25.8	71.8	9.9	18.3
	= [-0.221 + 0.048 × GEI + 0.005 × BW]/0.05565	18.1	18.6	13.2	68.1
IPCC (2006)	= [0.065 × GEI]/0.05565	23	28.7	48.2	23.1
NRC (2016)-high forage	= 71.5 + 0.12 × BW + 0.10 × DMI^3 – 244.8 × EEI	49.7	17.6	65.7	16.7
Cows on pasture (n = 28)					
Beef cattle models					
Moraes et al. (2014)	= [2.381 + 0.053 × GEI]/0.05565	15.9	0.4	0.1	99.5
IPCC (2006)	= [0.065 × GEI]/0.05565	17.4	15.1	1.9	83
Dairy cow models					
New model	= 11.2×DMI + 2.18×dNDF + 32.2×Milk fat	25.6	66.3	2.4	31.3
Nielsen et al. (2013)	= [1.23×DMI - 1.45×FA + 0.017×NDFdg]/0.05565	23.6	58	7.8	34.2
	= [1.23×DMI - 1.45×FA + 0.012×NDF]/0.05565	28.0	74.7	2.8	22.5

[1] DMI in kg/d, NDF as a % of DM, BW in kg, NDFd=apparent total tract digestible NDF (% of DM), Milk fat in %, NDF in % of DM, GEI =gross energy intake (MJ/d), FA = fatty acid content (g per kg of DM), NDFdg = NDFd in g per kg of DM, EEI = dietary ether extract intake (kg/d)

Three studies in literature provided 9 treatment means of enteric CH_4 emission measurements from beef bulls. All the extant models for beef cattle in Moraes et al. (2014) and the IPCC-Tier 2 model with a constant Y_m of 6.5% were evaluated on those 9 observations. The IPCC-Tier 2 model had the smallest RMSPE of 34% compared to the other models (38-58%, data not shown). The high RMSPE value is due to a large variability of the measured emissions across the three studies (CV=49%). Therefore, the IPCC-Tier 2 model can be recommended to predict enteric CH_4 emissions from bulls. The models recommended by the present study and the models used by U.S. EPA to predict enteric CH_4 emissions from different cattle groups in California are given in Table 10.

Table 10. Models proposed by the present study and the models used by U.S. EPA to predict CH_4 emissions (g/cow/d) from different cattle groups in California.

	Models chosen by the present study	U.S. EPA models	Average Y_m based best fit models
Dairy cattle			
Cows		= (0.048 × GEI)/0.05565	
Lactating cows	= 11.2×DMI + 2.18 × dNDF + 32.2 × Milk fat		(0.055 × GEI)/0.05565
Dry cows	= 9.6 + 22.1 × DMI		(0.069 × GEI)/0.05565
Replacement heifers	= 9.6 + 22.1 × DMI	= (0.059 × GEI)/0.05565	(0.069 × GEI)/0.05565
Beef cattle			
Feedlot	= -54.9 + 12.6 × DMI + 4.46 × NDF - 4.61 × EE	= (0.030 × GEI)/0.05565	(0.039 × GEI)/0.05565
Replacement heifers	= (0.065 × GEI)/0.05565	= (0.065 × GEI)/0.05565	(0.065 × GEI)/0.05565
Stockers	= (-1.487 + 0.046 × GEI + 0.038 × NDF + 0.006 × BW)/0.05565	= (0.065 × GEI)/0.05565	(0.067 × GEI)/0.05565
Cows	= (2.381 + 0.053 × GEI)/0.05565	= (0.065 × GEI)/0.05565	(0.060 × GEI)/0.05565
Dairy & beef Bulls	= (0.065 × GEI)/0.05565	= (0.065 × GEI)/0.05565	(0.068 × GEI)/0.05565

Enteric CH_4 emission estimates for California cattle groups

Dairy cows. Based on the new model [Eq. 8], an average lactating dairy cow in California consuming 22.9 kg DM/d with 15.1% of dNDF and producing milk with 3.6% of fat (Havlin et al., 2015; Niu et al., 2016; Rauch et al., 2012; Swanepoel et al., 2014) was estimated to produce on average 405 g of enteric CH_4 per day over a during her 305 d lactation (Table 11). The IPCC-Tier 2 model used by U.S. EPA for California cows would estimate 365 g/d or about 10% lower. This discrepancy is due to Y_m constant (4.8%) in the IPCC-Tier 2 model being less than the average Y_m, which was 5.6% in our data (Table 3). Among a few studies measuring enteric methane production in California cows, Niu et al. (2016) reported recently some enteric CH_4 emission measurements related to Holstein cows (average milk yield = 31.2 kg/d, milk fat = 3.6%, and BW = 655 kg) receiving TMR diets with alfalfa hay (37 to 53%), steam-flaked corn (19 to 42%), soybean meal (0 to 12%) , whole cotton seed (5.5%), DDGS (2 to 6%), and almond hulls (2.6%). Those cows had an average DMI of 22.1 kg/d and average CH_4 production of 415 g/d, which led to an average Y_m of 5.6%.

We estimated an average dry cow in California (mean DMI = 13.5 kg/d and mean GEI = 248 MJ/d) to produce daily 308 g/d of enteric CH_4. When accounting for an average lactation period length of 305 d and an average dry period length of 60 d, we estimated an average dairy cow in California to produce 142 kg/yr of CH_4. Consequently, the total 1,780,000 dairy cows in California were estimated to emit 252,936 t/yr of enteric CH_4 (Table 11). The U.S. EPA uses one model (= 0.048 × GEI) for all dairy cows, without accounting for the distinction between lactating cows and dry cows. Dry cows consume 41% less DM (13.5 vs. 22.9 kg/d), which itself has an impact on Y_m. For instance the new model for predicting Y_m of lactating cows (Table 7) indicates that lower DMI would be related to greater Y_m. Moreover, increasing forage and thus NDF content, and decreasing EE content were shown to increase enteric CH_4 independent of feed intake (Moraes et al., 2014; Nielsen et al., 2013) suggesting improvements in Y_m. Therefore, the average Y_m of dry cows could be greater than the average Y_m of lactating cows as dry cow diets contain more forage and thus more NDF, and lower EE (Table 2 vs. Table 3). Nonetheless, the U.S. EPA model ($Y_m = 0.048$) applied to dry cows would estimate 214 g/d of CH_4, which was less than what we estimated (308 g/d) from the model chosen in the present study (Table 11). Accounting for a 305d lactation and a 60d dry period, the U.S. EPA model resulted in an emission factor of 124 kg/yr for an average dairy cow in California (Table 11). This was 12.6% less than the emission factor estimate from the models chosen by the present study (220,923 vs. 252,936 t/yr, respectively). Overall, the results suggest that U.S. EPA might need to adapt the models proposed by the present study or revise Y_m constant of the IPCC-Tier 2 models to obtain more representative enteric CH_4 emission estimates for dairy cows in California.

Dairy heifers. According to the model chosen by the present study, the average daily enteric methane production of dairy heifers having average DMI of 9.9 kg/d (Table 3) was 228 g/d (Table 11). This value led to an emission factor of 83 kg/yr (total =64,189 t/yr). The IPCC-Tier 2 model used by U.S. EPA determined the daily emission to be 192 and thus the emission factor to be 70.0 kg/yr. These estimates were 16% less than the estimates given by the model in this study suggesting that the Y_m value of US EPA model (5.9%) could be lower than the average Y_m of dairy heifers in California. Consistently, the US EPA model under-predicted the average CH_4 emissions by 16% (192 vs. 228 g/d), when evaluated with literature data representative of California dairy heifers (Table 3). It is noteworthy that about 50% of the literature data came from animals on diets with forage contents greater than 75%, which was the maximum forage content for heifers in

California (Table 3). However, even when data related to forage contents > 75% were removed, the U.S. EPA model still under-predicted the emissions by >10% (data not shown). Moreover, the original IPCC-Tier 2 model with Y_m of 6.5% predicted the emissions more close to the observed values (data not shown) indicating that U.S. EPA might need to raise Y_m (5.9%) to its original Y_m (6.5%) to accurately predict the emissions from dairy heifers in California. Overall, total annual emission estimate for dairy cattle (excluding calves and bulls) from US EPA model was 13.3% less than the estimate from the models chosen by the present study (274,856 vs. 317,125 t/yr).

Feedlot Cattle. According to the new model, an average feedlot cattle consuming 7.3 kg/d of DM containing on average 20% of NDF and 7% of EE (Table 4) was estimated to produce 92.2 g/d of enteric CH_4 (Table 11). This estimate led to an emission factor of 33.7 kg/yr and total population emission estimate of 15,352 t/yr. The corresponding daily CH_4 production, emission factor, and the population emission estimates from the US EPA model (Table 11) were at 73.2 g/d, 26.8 kg/yr, and 12,203 t/yr, respectively, which 21% lower than our estimates. The IPCC-Tier 2 model uses a constant Y_m value of 3.0% for feedlot cattle receiving less than 10% forage. A recent literature review by Liu et al. (2017) concluded that the average Y_m of such cattle was greater at 3.8%, which is similar to the mean Y_m of 3.7% in the literature data representative of California feedlot cattle (Table 6). Moreover, the data in Stackhouse-Lawson et al. (2012) suggests that there could be a considerable number of farms with feedlot diets containing more than 10% of forage in California (e.g., 20% of alfalfa hay). Until a comprehensive survey on DMI and diet composition California cattle is conducted to determine the actual Y_m, the new models including DMI, dietary NDF, and dietary EE shown to regulate Y_m could be used to predict successfully the CH_4 emissions.

Table 11. Average CH_4 production by individual animals in and the total population (pop) in 2015 of different cattle groups in California estimated with models chosen by the present study and the models used by U.S. EPA

		This study			U.S. EPA based method			Proposed Y_m (% GEI) based method			
	Population (×1000)	g/d	kg/animal/ yr	ton/pop/ yr	g/d	kg/animal/ yr	ton/pop/ yr	Y_m	g/d	kg/animal/ yr	ton/pop/ yr
Dairy cattle											
Cows	1,780		142	252,936		124	220,923			146	259,681
lactating		405			365			5.5	418		
dry		308			214			6.9	309		
Heifers	770	228	83.4	64,189	192	70.0	53,932	6.9	226	82.7	63,650
Beef cattle											
Feedlot	456	92.2	33.7	15,352	73.2	26.8	12,203	3.9	94.4	34.5	15,710
Heifers	130	157	57.1	7,427	157	57.1	7,427	6.5	157	57.4	7,465
Stockers	234	129	47.0	11,003	120	43.9	10,275	6.7	129	47.0	11,004
Cows	590	297	108	63,974	308	113	66,404	6.0	296	108	63,828
Dairy and beef bulls	70	210	76.7	5,372	210	76.7	5,372	6.8	210	76.5	5,357
TOTAL	**4,030**			**420,253**			**376,536**				**426,695**

Other beef cattle groups. The IPCC-Tier 2 model ($Y_m = 6.5\%$) used by U.S. EPA, and also by the present study predicted the average CH_4 emissions of replacement heifers and bulls to be 157 and 210 g/d, respectively (Table 11). Consequently, the heifer and bull populations were related to total emissions of 7,427 and 5,372 t/yr, respectively. The average daily CH_4 production estimates for beef cows and stockers from Moraes et al. (2014) models (Table 11) were 4% lower (297 vs. 308 g/d), and 6% greater (129 vs. 120 g/d) than those from IPCC-Tier 2 models, respectively. Stockers and beef cow emissions are 11,003 and 63,974 t/yr, respectively. Therefore, the emission factors and population emissions were different from each other in the same way (Table 11). The annual emission estimate of total beef cattle population (excluding bulls and calves) from IPCC-Tier 2 models and the models chosen by the present study were similar at 96,309 and 97,756 t/yr, respectively.

Our estimate of emissions using US EPA methodology is different from those reported by CARB (2017). This is mainly a reflection of the estimate in GEI. The IPCC (2006) model used as a base by US EPA was evaluated by Appuhamy et al. (2018) and reported that it had a large RMSPE, the majority of which came from a mean bias for GE to be over predicted. The over prediction was estimated to be about 16% (Appuhamy et al. 2018), which increase emission estimates considerably. Therefore, although US EPA uses a lower Y_m value than this study, because it uses greater GEI compared to observed values, the total emissions in the inventory are larger compared to this study and US EPA method that uses a representative DMI of cows in California.

SUMMARY

This study characterized feed intake and diet composition of different cattle groups in California. A considerable success was achieved in characterizing dairy cattle compared to beef cattle, owing to a significant amount of available data on lactating dairy cows. When evaluated using CH_4 emission measurements from cows with characteristics similar to those of California cows, new models developed in the present study and some extant models better predicted enteric CH_4 emissions from different cattle groups compared to IPCC-Tier 2/US EPA models. Using a population structure similar to CARB, the US EPA models (with observed DMI) estimated the total enteric CH_4 emission from whole California cattle population to be 376,536 t/yr. The estimate from the models proposed by the present study was 10.4% greater at 420,253 t/yr. The majority of this discrepancy was related to the difference between the Y_m used to estimate emission from lactating cows. Gross energy intake and consequently feed intake was overestimated by IPCC-Tier 2/ US EPA models. Therefore, although the present study had a greater emission factor the total emission estimate is less than that reported by CARB because GEI in this study is considerably lower compared to IPCC-Tier 2/ US EPA model estimates. The current inventory for enteric methane emissions from cattle in CA is 11.05 MT CO_2e eq/yr, which is about 5% greater than estimated in this study. Overall, revising the Y_m value of IPCC-Tier 2/ US EPA models and GEI to match with observed feed intake and dietary characteristics of modern lactating cows in California and adopting proposed new model (or simplified Y_m) would greatly improve the representativeness of enteric CH_4 emission estimates in the GHG inventories from cattle in California.

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