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Short Title: Uncertainty of methane predictions for beef cattle

Estimating enteric methane production for beef cattle using empirical prediction models compared with IPCC Tier 2 methodology

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Escobar-Bahamondes, P., Oba, M., MacDonald D., Kröbel, R. and Beauchemin, K. A. 2017. E**stimating enteric methane production for beef cattle using empirical prediction models compared with IPCC Tier 2 methodology.** Can. J. Anim. Sci. **xx**: xxx-xxx. The IPCC (2006), Tier 2 methodology and 16 empirical models together with dietary information were used to estimate daily Methane (CH_4) production and Ym (CH_4 energy expressed as a percentage of gross energy intake) for mature cows (lactating, dry) and growing steers (backgrounding, grazing, finishing) in Eastern and Western Canada. Monthly simulations accounted for changes in body weight, feed intake and diet composition. Coefficient of variation (CV) and uncertainty (95% confidence interval divided by mean) were used to estimate variability. Estimates of CH_4 (g d^{-1}) and Ym from models differed from IPCC estimates. For models, the CV of Ym ranged from 0.8 to 29.7% and uncertainty from 0.9 to 45.2% over the production phases of the animals in contrast to the fixed Ym used by IPCC. When information on diet composition is lacking, a Ym value of 7.0 to 7.3% can be used for beef cows depending on stage and location, and 6.4 to 6.6% for growing cattle fed high forage diets, while 4.8% is recommended for finishing diets instead of the default values of 6.5% for high forage diets and 3.0% for finishing diets typically used in the IPCC Tier 2 method.

Keywords: Beef cattle, greenhouse gas, methane, modelling

Abbreviations: **ADF**, acid detergent fiber; **BW**, body weight; **CEL**, cellulose; **CP**, crude protein; **CV**, coefficient of variation; **DM**, dry matter; **DMI**, dry matter intake; **CH_4**, enteric methane production; **GE**, gross energy; **GEI**, gross energy intake; **HC**, hemicellulose; **HF**, high forage; **IPCC**, Intergovernmental Panel on Climate Change; **LF**, low forage; **ME**, metabolizable energy; **MEI**, metabolizable energy intake; **MJ**, megajoules; **NASEM,** National Academies of

Sciences, Engineering, and Medicine; **NDF**, neutral detergent fiber; **NFC**, non-fiber carbohydrate; **Ym**, CH_4 conversion rate (% of GEI)

Within the agricultural sector, beef cattle are the largest source of greenhouse gas emissions both in Canada and globally. Beef production contributes 41% of global livestock emissions (Gerber et al. 2013), while beef accounts for about 25% of total agricultural emissions in Canada (Environment and Climate Change Canada 2016).

The Canadian beef production industry is complex (Shepard et al. 2015, Alemu et al. 2016, Legesse et al. 2016). In simple terms, the beef production system starts with breeding herds (cow-calf sector) that produce calves for subsequent backgrounding and finishing. The cows and suckling calves are generally maintained on pasture during the summer grazing period, calves are weaned in the fall, and pregnant cows are over-wintered in confinement in pens, dry-lots, or fenced areas using supplemental feed. Weaned calves are mainly backgrounded on forage-based diets in feedlots or as stocker cattle on pasture for varying lengths of time before they are finished in feedlots using grain-based diets (Beauchemin et al. 2010, Alemu et al. 2016).

Over the lifespan of a beef animal, there are continuous changes in diet ingredient composition, which are driven by the availability of feed and the need to balance diets to meet requirements based on the animal age, physiological stage of maturity and environmental conditions. Diet composition affects dry matter intake (DMI), the ruminal microbial population, and final products of ruminal fermentation, including CH_4 emissions. Enteric CH_4 represents 2 to 12% of gross energy consumed depending upon level of intake and composition of the diet (Johnson and Johnson 1995).

The United Nations Framework Convention on Climate Change requires countries to provide estimates of all GHG emissions and their uncertainties using Intergovernmental Panel on

Climate Change (IPCC, 2006) methodology. Environment Canada uses the IPCC (2006) Tier 2 methodology to produce its national inventory report (Environment Canada 2014). Specifically, yearly mean gross energy intake (GEI) of a representative animal for each class of beef cattle is estimated, and then multiplied by a CH_4 emission factor (Ym, % of GEI). The emission for each class of animal is then multiplied by the population of animals within each class and summed to estimate the total CH_4 emission for the beef sector. The IPCC provides a default Ym value of 6.5 ± 1% for beef cattle consuming diets with less than 900 g concentrate kg^{-1}, and an Ym of 3 ± 1% for finishing cattle consuming more than 900 g of concentrate per kg dry $matter^{-1}$ (DM). Accuracy of the IPCC Tier 2 methodology can be low, and the Ym value used is critical because it has a direct effect on estimated CH_4 production and is the main source of the large uncertainty in estimating cattle emissions in greenhouse gas inventories (15 to 33%; Karimi-Zindashty et al. 2016).

Various empirical models for predicting CH_4 production from beef cattle have been published (Ellis et al. 2007, 2009; Yan et al. 2009; Ricci et al. 2013; Moraes et al. 2014; Escobar-Bahamondes et al. 2017*b*). Escobar-Bahamondes et al. (2017*a*) showed that many equations lacked accuracy, as they were not specific for high-forage or high-grain diets. According to that study, a set of equations was identified that predicted CH_4 production as well as or better than the IPCC Tier 2 methodology.

The difference between using models that account for changes in diet composition compared with IPCC (2006) Tier 2 methodology for estimating CH_4 production from different beef cattle production systems in Canada is unknown. The first objective of this study was to estimate CH_4 emissions (g d^{-1} and Ym) for beef cattle in Eastern compared to Western Canada using empirical models in contrast to the IPCC (2006) Tier 2 methodology. The second objective was to estimate variability of model predictions of CH_4 due to changes in body weight

(BW) of animals, feed intake and diet composition over the production cycle of cattle.

METHODS

General Overview

Most CH_4 prediction models require knowledge of animal class, BW, feed intake and diet composition. Thus, it was necessary to develop scenarios to represent beef cows and growing cattle and their respective diets during their productive lifespan. Typical scenarios were developed monthly for mature beef cows and growing steers in Eastern and Western regions of Canada to reflect differences in diet composition, BW change, and management. Due to their lower population size, bulls and calves were not considered, while it was assumed that model comparisons for growing-finishing heifers would be similar to those for cows. Empirical models that consider diet composition were used to predict daily CH_4 production (g d^{-1} and Ym) of individual animals by month.

The Beef Production System and Diets

The Canadian beef production system is based entirely on *Bos taurus* breeds and is comprised of three distinct components: cow-calf herds that produce calves, calf growing operations (calves and yearlings on pasture, backgrounding in confinement), and finishing feedlots. Cow-calf and calf growing operations utilize high fibre diets including grazed pastures, harvested forages and by-product feeds. The finishing phase is largely conducted in feedlots using high grain diets ($\geq$ 80% of concentrate in diets, DM basis). Many different management practices and diets for growing and finishing cattle are used in Canada (Shepard et al. 2015; Legesse et al. 2016). As the focus of the current study was to explore variability and uncertainties in CH_4 prediction due to the differing calculation approaches suggested by IPPC (2006), it was necessary to develop typical production systems to represent mature cows and growing cattle (steers) and their respective diets throughout the production cycle.

The production systems used for beef cows and steers are based on Legesse et al. (2016) and presented in Figure 1. Each scheme was comprised of individual stages to account for daily changes in BW, diet composition, environmental conditions and management (grazing, confinement). The production system for Eastern and Western Canada differed slightly to reflect regional differences in management and diets (Sheppard et al. 2015). Although both native and tame pastures are grazed by beef cattle in Western Canada, only tame pasture was considered because of the lack of detailed nutritional information for native pasture.

The beef cow simulation was conducted over a 12-month season (parturition in March) with two 6-month stages (lactating, non-lactating) to reflect changes in DMI (due to additional nutrient requirements for lactation), BW and diet composition (Figure 1a). The initial and final BW of cows were obtained from Sheppard et al. (2015). A milk yield during the lactation phase of 1,600 L was assumed, equivalent to 8 kg d^{-1} at peak lactation (Mathison 1993). Beef cows were assumed to be fed a high-forage diet all year under confinement from November to end of February and on pasture from March to October (Figure 1a).

For growing beef cattle, the simulation started with weaned calves (November, 8 mo of age). A yearling steer scenario was selected to allow for exploration of various types of diets (high-forage, pasture, and high-concentrate). According to Legesse et al. (2016), this scenario represents about one-third of calf production in Canada. Simulations were conducted for Eastern and Western regions to reflect differences in diet ingredients and age at slaughter (22 and 21 mo, respectively). Backgrounder steers were assumed to be fed a high-forage diet under confinement from November to March when mean ambient temperature was below 0ºC. From April to

October, the steers had access to tame pasture, and from November until the end of their productive life, the steers were fed a high-concentrate diet in a feedlot (Figure 1b). The BW and average daily gain of growing animals during the various phases were from Sheppard et al. (2015) and Legesse et al. (2016).

Diet Composition

Representative diets were selected for each phase of the production systems. These diets accounted for differences in feed sources used in Western and Eastern regions of Canada. In the west, barley grain, barley silage and grass-legume hay were the main feeds, whereas in the east, diets included corn grain, corn silage, alfalfa hay and soybean meal (Mathison 1993, Beauchemin and McGinn 2005, Shepard et al. 2015, Legesse et al. 2016). The forage:concentrate ratio of the diets for the various classes of cattle varied throughout the production cycle as outlined by Legesse et al. (2016).

The chemical composition and nutritional values of dietary ingredients was estimated from Abouguendia (1998), the Beef Cattle Nutrient Requirement Model (National Academies of Sciences, Engineering, and Medicine [NASEM] 2016), Cowbytes 5.0(c) and the National Animal Nutrition Program for America and Canada ([Online] Available: http://nanp-nrsp-9.org [2016 Feb. 01]). A summary of the feed composition data and diets for cows and steers used in the simulations is shown in supplementary Tables S1 and S2.

Most enteric CH_4 prediction equations require an estimate of dry matter intake (DMI), gross energy intake (GEI) or metabolizable energy intake (MEI), which was estimated monthly for each class of cattle using the Beef Cattle Nutrient Requirement Model (NASEM 2016) and representative diets. Representative diets for both regions and animal categories were created using peer-reviewed papers that reported detailed information about beef production in Canada

(Beauchemin and McGinn 2005; Beauchemin et al. 2010; Alemu et al. 2011; Legesse et al. 2011; Sheppard et al. 2015; Legesse et al. 2016). The variables used in the representative diets were: BW (kg), forage intake (% DMI), organic matter (% DM), crude protein (CP, % DM), neutral detergent fiber (NDF, % DM), acid detergent fiber (ADF, % DM), non-fiber carbohydrate (NFC, % DM; NFC = 100 - (NDF + CP + fat + ash)), hemicellulose (HC, % DM; HC = NDF-ADF), cellulose (CEL, % DM; CEL = ADF-ADL), fat (% DM), sugar (% DM), starch (% DM), gross energy (GE, MJ kg^{-1} DM), digestible energy (DE, MJ kg^{-1} DM), metabolizable energy (ME, MJ kg^{-1} DM), and daily intakes of each of the dietary constituents including: DMI (kg d^{-1}), forage (kg DM d^{-1}), CP (kg DM d^{-1}), NDF (kg DM d^{-1}), ADF (kg DM d^{-1}), NFC (kg DM d^{-1}), HC (kg DM d^{-1}), CEL (kg DM d^{-1}), fat (kg DM d^{-1}), sugar (kg DM d^{-1}), starch (kg DM d^{-1}), GEI (MJ d^{-1}), MEI (MJ d^{-1}). The GE content was calculated according to NASEM (2016).

Estimation of Methane Production

IPCC (2006) Tier 2 methodology and 16 models that consider dietary nutrient composition, daily intakes and BW were used to predict enteric CH_4 for cows and steers using the compiled information for diets and intake. The equations used were those identified by Escobar-Bahamondes et al. (2017*a,b*) as being most accurate (best-fit) for high-forage (≥ 40% DM; HF) or low-forage (≤ 20% DM; LF) diets. Detailed descriptions of equations used in this study are shown in Table 1. Not all models are appropriate for beef cows or all phases of steer growth, thus only relevant models were used for each class and phase of cattle production. Specifically, few models have been developed for mature beef cows, and some equations are only accurate for heifers, or for growing cattle fed high- or low-forage diets. Daily CH_4 emissions (g d^{-1}) were calculated monthly using all relevant models for each category of beef cattle. Values of CH_4 were transformed to energy assuming 55.6 MJ kg^{-1} CH_4 and expressed as Ym (as % GEI).

Datasets and Analysis

Datasets were generated for each animal category (cows, steers). Each record (row) within the dataset represented the animal within a region (east, west) on a monthly basis. The variables (columns) provided information on general management, BW, type of diet, dietary forage content (% DM), chemical composition of the diet and nutrient intakes. The dataset for beef cows contained 24 records (12 mo × 2 regions) and 40 variables, whereas the dataset for steers contained 27 records (8-22 mo for east and 8-21 mo for west). The information for each record was then used with the appropriate algorithm to predict CH_4 (g d^{-1} and Ym).

Mean daily CH_4 emissions (g d^{-1}) and Ym values, both estimated monthly, were compared within each phase of production for Eastern vs. Western Canada by averaging over all models. Estimates were compared against the IPCC prediction and among models within each production phase. The variability of Ym between models was determined using coefficient of variation (CV) and uncertainty (%). In climate change, uncertainty of the emission estimate is an estimate of inherent error due to incomplete knowledge and lack of information. In our study uncertainty was calculated according to Karimi-Zindashty et al. (2012) as the 95% confidence interval/mean × 100%. The CV and uncertainty were calculated for each model by production stage for mature cows and growing steers.

All comparisons were conducted using a Kruskal-Wallis test and nonparametric multiple comparisons between means were made by the Steel-Dwass all pairs test or Wilcoxon each pair test. Significance was declared at $P \leq 0.05$. Statistical software used was JMP© 12, SAS Institute, Cary, NC (SAS 2015).

RESULTS AND DISCUSSION

The Models

The models used were organized from lower to higher degree of complexity with indication of the appropriate use for high and low forage diets (Table 1). The models could be categorized into 3 groups: 1) linear models that use one or two basic variables, especially GEI, DMI and BW (e.g., IPCC, SAL, A, SGEL and SDL), 2) linear models that consider a number of dietary variables (e.g., HAL, 14b, iiib, 9b, I and GEI), and 3) polynomial models that are more complex because some variables are expressed as quadratic or cubic functions (e.g., HFOR, HFMC, LFOR and LFMC).

Predictions from the IPCC Tier 2 model are based on GEI; however GE content of feed is not typically reported in feed analysis. The IPCC (2006) suggests using a default value of 18.45 MJ kg^{-1} of DM when GE content of feeds is not available. Using a constant GE value results in the equation being only sensitive to changes in DMI and not to changes in composition of diets, digestibility or rumen fermentation. Thus, using the IPCC model, Ym is constant and changes in CH_4 are strictly due to changes in DMI. The other models were developed using mixed datasets for dairy and beef cows (Ellis et al. 2007, Ricci et al. 2013), and heifers and steers (Ellis et al. 2009, Moraes et al. 2014, Escobar-Bahamondes et al. 2017*b*). These models were selected for use in the present study based on their accuracy and precision for beef cattle fed high forage or high grain diets (Escobar-Bahamondes et al. 2017*a*; Table 1). However, the database used by Escobar-Bahamondes et al. (2017*a*) to evaluate the equations included very few studies using mature cows or grazing cattle. Most studies were conducted with steers or heifers in metabolism studies where growth of cattle was not reported. In addition a small number of studies were conducted with growing cattle in confinement fed backgrounding and finishing diets.

Comparison of Models for Beef Cows

Overall predicted Ym values averaged across models for lactating (mean, 7.0%) and dry (mean, 7.3%) beef cows were similar ($P > 0.05$) for Eastern and Western regions (Table 2). Likewise, for lactating cows the average predicted CH_4 emissions across all models was similar (mean, 265 g d^{-1}; $P > 0.05$) for Eastern and Western regions, but emissions for dry cows were 14% greater (263 vs. 231 g d^{-1}; $P \leq 0.05$) in Western than Eastern Canada. This difference between regions for CH_4 production of dry cows when expressed as g d^{-1} but not when expressed as Ym indicates differences in DMI attributed to differences in the energy content of barley-based diets in the west compared with corn-based diets in the east (Supplementary Table S1).

Only a few studies have measured CH_4 production from mature cows under production conditions. Pinares-Patiño et al. (2003) used Charolais dry cows (BW, 712 kg) grazing pastures of timothy at four stages of maturity (early vegetative, heading, flowering, and senescence) and reported a range of 204 - 273 g d^{-1} of CH_4 with Ym ranging from 5.9 - 6.7%. These values are within the range reported in the present study. The overall CV resulting from the range in model estimates of Ym for lactating cows due to monthly changes in DMI and diet composition was 24% in the east and 29% in the west (Table 2). The slightly lower variability for dry cows (CV = 16 to 20%) was attributed to smaller changes in DMI and diet composition over the 6-month period compared with diets consumed during lactation.

There were important differences among models for predicting Ym values (Table 3) for lactating and dry beef cows in both Eastern and Western Canada. For lactating cows in both regions, equations HAL and iiib predicted Ym values that were similar ($P > 0.05$) to those generated using IPCC methodology (Table 3). In contrast, in both regions HFMC predicted considerably greater ($P \leq 0.05$) Ym values compared with all other models, while HFOR predicted greater ($P \leq 0.05$) Ym values compared to IPCC. This difference in prediction could be attributed to the low proportion of data from mature beef cows used when developing the models, as well as the possibility that the Monte Carlo procedure used to amplify the original database in developing the model also amplified error variations in the original variables. Equations 14b and N estimated lower Ym values than IPCC. In case of daily CH_4 production (Table 4) for lactating beef cows, IPCC (2006) estimated a daily emission in the east of 248 g d^{-1}, which was similar to the range of estimates (208 to 237 g d^{-1}; $P > 0.05$) for all models except HFOR (287 g d^{-1}) and HFMC (376 g d^{-1}), which were considerably greater ($P \leq 0.05$; Table 4). For lactating cows in the west, IPCC estimated an emission of 257 g d^{-1}, which was similar to iiib, but greater ($P \leq 0.05$) than estimates generated by models 14b, N, and HAL and lower ($P > 0.05$) than estimates generated by HFMC and HFOR.

Regardless of region, no model predicted an Ym value similar to that of IPCC ($P \leq 0.05$; Table 3) for dry cows. In the east, models HFMC, HFOR, iiib and HAL predicted values greater than IPCC (9.5, 8.0, 7.6 and 7.0 vs. 6.5%, respectively). For models 14b and N predicted values were lower ($P \leq 0.05$) than IPCC. In the west, model performance for Ym was similar to that in the east. The IPCC model estimated 220 g d^{-1} of CH_4 for dry cows in the east, similar to estimates generated by HFOR, iiib and HAL (252, 241, 220 g d^{-1}, respectively; $P > 0.05$; Table 4) but greater than those generated by 14b and N (195 and 190 g d^{-1}; $P \leq 0.05$) and less than HFMC (299 g d^{-1}; $P \leq 0.05$). For dry cows in the west, IPCC predicted 250 g d^{-1}, which was only similar to iiib (273 g d^{-1}; $P \leq 0.05$). Other models predicted greater (HFMC, HFOR; $P \leq 0.05$) or lower estimates (HAL, 14b, N; $P \leq 0.05$).

When used for mature beef cows, the models differed in their sensitivity to changes in dietary components, as evidenced by the CV reported in Table 3 (Ym) and Table 4 (g d^{-1}) and the range in Ym shown in Supplementary file Figure S1. Equations HAL and N had greatest stability and lower variations in their responses within phase (CV < 5.6%) and across locations with HAL being closest to IPCC estimates. Although they considered variables such as NDF content, GEI

(HAL only) and BW (HAL only), those equations were not very sensitive to changes in inputs and estimates of Ym were relatively constant within each of these models. Equation 14b uses MEI, ADF content, and lignin content as inputs, and despite changes in these inputs across the production phases, the predicted values were relatively constant, except for Western lactating cows because dietary ADF content exhibited greater variability (Table S1) as pasture matured during the grazing season. Models HFMC and HFOR consistently predicted greater Ym and CH_4 compared to IPCC, and estimates from these models were also more variable within production phase. Both these models incorporate DMI and HC (NDF-ADF) as inputs expressed as polynomial variables, and BW, which varied across the year. Model iiib uses ratios between different types of energy, thus variation in DE, ME and GE content of diets across the season caused this model to have greater variation in Ym values.

The Ym values were slightly less variable for a given equation for dry versus lactating cows (Supplementary file figure S1) because DMI and contents of NDF, ADF, starch and GE of dry cow diets were less variable than for lactating cow diets (Table S1). Some models such as iiib and HFOR were sensitive to these changes, and Ym within production phase varied for those models due to changes in nutrient intake.

Comparisons of Predictions for Growing Steers

There was no difference ($P > 0.05$) in the overall mean for predicted values of Ym between Eastern and Western regions for growing steers during backgrounding (mean, 6.5% ± 0.99), grazing (mean, 6.6% ± 1.34) and finishing (mean, 4.8% ± 0.86; Table 2). However, average CH_4 production differed between Eastern and Western regions during backgrounding (116 vs. 148 g d^{-1}; $P \leq 0.05$) and grazing (209 vs. 232 g d^{-1}; $P \leq 0.05$), with no differences between regions for finishing (mean, 155 g d^{-1}; $P = 0.38$). Differences in prediction of CH_4 production during backgrounding and grazing phases, despite no difference in Ym, indicates that the differences were mainly due to differences in DMI. Because average daily gain differed in the previous stage, steers in the west had greater initial BW at the start of the grazing phase compared with those in the east (424 vs. 384 kg), which led to greater CH_4 production in the west due to increased DMI. The models did not detect differences in Ym values between regions during the finishing phase even though Western steers consumed barley diets rather than corn diets, finished one month earlier than Eastern steers and had lower average DMI (9.5 vs. 10.0 kg d^{-1}, respectively) for the period, likely due to use of Ym as a percentage (narrow scale) and the use of a nonparametric multiple comparisons test, which is less powerful in detecting differences compared with a standard ANOVA test.

Backgrounding in confinement. Models differed in predicted values of Ym in both Eastern (4.5 to 8.2%) and Western (5.2 to 8.3%) Canada (Table 5). In the east, all models differed from IPCC (6.5%) with greater Ym values for iiib (8.2%), 14b (7.3%) and HFOR (6.9%) and lower values for N (6.1%), SAL (6.0%) and HFMC (4.5%). In the west, 14 b (6.6%) and HFOR (6.5%) were similar to, while iiib (8.3%), N (6.0%), SAL (5.9%) and HFMC (5.2%) were less than IPCC. The CV indicated that HFMC was highly sensitive to monthly changes in inputs, while 14b was variable in the east but not in the west with the opposite for HFOR. Similar to IPCC, iiib was not sensitive to changes in nutrient intakes over the growing period likely because the model also uses GEI.

When calculated as CH_4 production, estimates ranged from 80 to 145 g d^{-1} in the east and from 119 to 188 g d^{-1} in the west (Table 6). Differences were detected among models in both locations. In the east, predicted values from 14b and HFOR (128 and 122 g d^{-1}) were similar to IPCC (121 g d^{-1}, $P > 0.05$), while those from N, HFMC, SAL and iiib (107, 80, 106 and 145 g d^{-}

[1]; $P \leq 0.05$) differed from IPCC. In the west, all predicted values differed from IPCC. Emissions were generally more variable in the east compared with the west during the backgrounding in confinement phase, as indicated by the larger CV (4.5 to 15.4% vs. 1.67 to 8.4%; Table 6). The variability was greatest for HFMC (east and west) and SAL (east). In both cases, the models were able to show differences due to variability in composition of diets.

An important difference between regions was the source of feed; corn grain and corn silage were used in the east and barley grain and barley silage were used in the west (Table S2). Barley crop is the mainstay of the Western Canadian feedlot industry, both as a grain and silage crop, whereas in Eastern Canada corn grain and corn silage are predominant in diets due to agronomic differences between the regions as well as proximity in the east to corn production in the United States. Steers in the west consumed more fiber and less NFC than steers in the east, which is usually associated with greater CH_4 production however, when the CH_4 response was expressed as Ym, the models surprisingly did not predict differences due to feed source. While in our study overall predicted Ym values were similar in both regions (Table 2), some models performed differently between the two regions because the models (HFMC, HFOR, 14b and SAL) that use dietary components and/or BW to estimate CH_4 were more sensitive to changes in these inputs and hence showed more variability. In contrast, other models such as iiib, which consider GEI, DE and ME, showed less variability (Table 5, Supplementary file figure S2).

Most studies that have measured CH_4 production of beef cattle used high forage diets, although many studies evaluated feed additives or ingredients (e.g., lipids, nitrate, tannins, enzymes, organic acids, vegetable oils and meals, distillers dried grains) as mitigation strategies (e.g. Beauchemin and McGinn 2006, Chung et al. 2011, Hales et al. 2012, Hunerberg et al. 2013), besides, studies that used diets similar to those used in Eastern Canada, CH_4 production ranged from 105 (Staerfl et al. 2012; corn silage and concentrate; mean BW, 304 kg) to 170 g d^{-1}

(Beauchemin and McGinn 2005; corn silage and corn grain; mean BW, 328 kg), and Ym from 5.1 to 5.9%, similar to values predicted by average models in our study. Studies with diets representative of those fed in Western Canada reported values from 99 g d^{-1} (Beauchemin et al. 2007; barley silage; mean BW, 222 kg) to 221 g d^{-1} (McGinn et al. 2009; barley silage; mean BW, 381 kg), with Ym ranging from 5.5 to 7.1%.

Grazing phase. The main differences between regions during this phase were the time the cattle remained on pasture (5 mo in east, 4 mo in west) and initial and final BW of steers (Table 2). In the east, the predicted values of Ym for models HFOR (6.7%), 14b (6.4%) and iiib (5.8%) were similar ($P > 0.05$) to IPCC, while HFMC (9.1%), SAL (6.0%) and N (5.9%) differed ($P \leq 0.05$) from IPCC (6.5; Table 5). In the east, HFOR (7.3%) and 14b (6.7%) were similar ($P > 0.05$) to IPCC, while HFMC (8.9%), SAL (5.9%), N (5.8%) and iiib (4.4%) differed ($P \leq 0.05$).

Seasonal variation in composition and quality of pasture and changes in DMI of cattle can affect CH_4 emissions during the grazing phase (Boadi et al. 2001, Ulyatt et al. 2002). Variability in CH_4 production during the grazing season was accounted for only by the models that include dietary components as predictors. The greatest variability in predicted Ym was observed for iiib (east, 27.8%; west, 24.3%) and 14b (east, 7.3%, west, 12.1%; Table 5). The other models were comparatively less responsive to changes during the grazing phase with CV < 7.3%. The evaluated models use different inputs associated with methanogenesis; iiib considers ratios between different types of energy, HFMC uses BW, DMI, HC and fat; HFOR uses BW, DMI, and fat; and 14b uses MEI, ADF and lignin. In contrast, IPCC, N and SAL were not sensitive to changes in forage composition over the grazing season. Few studies have measured CH_4 production from grazing cattle because of the difficulty of measuring CH_4 and DMI on pasture. Experiments that used diets with 100% of forage differed in type of animal, composition and quality of pasture during the grazing phase, but those studies reported values consistent with predicted values from this study. For example, using Hereford x Friesian bulls (mean BW, 272 kg) for several months grazing pastures of rye grass and white clover (DM digestibility, 64.3-83.7) Molano et al. (2006) reported CH_4 emissions ranging from 89 to 222 g d^{-1}. Fitzsimons et al. (2013) reported CH_4 production of 260 to 297 g d^{-1} equivalent to 12.6% of Ym using non-pregnant Simmental heifers (mean BW, 489 kg) grazing perennial ryegrass (in vitro DM digestibility, 76.6 ± 11.4). This estimate is similar to 11.3% of Ym reported by Ominski et al. (2006) using British × Continental crossbred steers grazing grass based pasture in summer and alfalfa-grass silage in winter (NDF, 46.4 - 68.8% of dry matter).

Finishing phase. Despite the feeding of corn grain in Eastern Canada and barley grain in Western Canada, there were no differences in the overall average predicted values of Ym (mean, 4.8%; $P > 0.05$; Table 2) and CH_4 predictions between the regions (mean, 155 g d^{-1}; $P > 0.05$; Table 2) when averaged across models. Likewise, the variability in Eastern and Western regions for Ym (18.1 and 17.5%, respectively) and CH_4 production were similar (19.1 and 17.6%, respectively).

The Ym values for the finishing phase were lower than those obtained for cattle backgrounded in confinement or during the grazing phase. However, in both regions all models predicted greater Ym values than IPCC (Table 5).

Experiments that used low proportion of forage (e.g., ≤ 10%) and barley grain similar to Western finishing diets report CH_4 production from 119 to 136 g d^{-1} with Ym of 4.0 to 5.0% (Hünerberg et al. 2013) and 101 to 116 g CH_4 d^{-1} with Ym of 4.3 to 4.5% (Vyas et al. 2015). This range in Ym with high grain diets is consistent with values in the current study, where the range was 4.4 to 5.8% for barley-based diets. Beauchemin and McGinn (2005) reported a significant difference in Ym value for finishing heifers fed diets based on dry rolled corn (2.8%) as compared to steam-rolled barley grain (4.0%). Hales et al. (2012) reported a very low emission of 45.8 g CH_4 d^{-1}, equivalent to Ym of 2.4%, from steers fed a diet of mainly steam flaked corn. Lower values of Ym of finishing cattle occur when steam flaked corn is fed due to the rapid rate of rumen availability of starch. However, the low Ym values obtained for steam flaked corn by Hales et al. (2012) are not consistent with values predicted for models in our study for Eastern Canada (4.1 to 5.8%) because none of the models was developed using diets with a substantial proportion of steam flaked corn (> 90% of steam flaked corn DM basis). More recently, Vyas et al. (2014) using dry rolled corn reported values ranging 132 to 151 g CH_4 d^{-1} equivalent to Ym of 3.9 to 4.9%, closer to the model predicted values that are reported in this study. Although the models used in the present study to predict Ym values for finishing cattle were selected from Escobar-Bahamondes et al. (2017*a*) to be accurate for high grain diets, the models were not sensitive to type of grain fed.

Model Assessment and Uncertainties

Compared to the fixed CH_4 conversion factors (Ym = 6.5% for diets > 90 g forage kg^{-1} or 3.0% for diets ≤ 90 g forage kg^{-1}) recommended by IPCC (2006), our study showed greater variability in estimations of Ym values for beef cows and growing steers across their production cycle. The models used in the present study were those selected as best-fit for forage and grain based diets as well as new equations developed by Escobar-Bahamondes et al. (2017*a,b*). Yet, there was large variation in predicted Ym values from models ranging from 5.5 to 11.4% (mean: 8.4%) for lactating beef cows, 5.9 to 10.2% (mean: 8.0%) for dry cows, 4.5 to 8.3% (mean: 6.4%) for steers in confined backgrounding (226 to 393 kg, 8 to 12 mo), 4.4 to 9.1% (mean: 6.8%) during grazing (384 to 518 kg, 13 to 18 mo), and 3.0 to 5.8% (mean: 4.4%) for finishing cattle (564 to 708 kg, 19 to 22 mo). It is difficult to compare these estimated Ym values to observed values because of the lack of data for beef cattle in various production scenarios representative of those in Eastern and Western Canada. Thus, the Ym for each category of beef cattle fed various diets is uncertain because the state of the animals and the diet composition are constantly changing.

Uncertainty within models suitable for high forage diets ranged from 0 to 45.2% (Table 7). Uncertainty represents the responsiveness of the model to changes in input variables (e.g., intake, diet composition), and is independent from accuracy (prediction of actual values) and precision (consistent prediction of the same value). Larger uncertainty range indicates that CH_4 production and Ym are not static throughout the production cycle in contrast to the assumption of the IPCC methodology. The range of uncertainty for Ym was smaller when variables within a particular model fluctuated minimally during the production phase of the animal. For example, use of SAL or HAL from Moraes et al. (2014) averaged across animal stages for high forage diets had low uncertainties (2.4 and 3.4%, respectively). The SAL model only considers GEI, which increased at a constant rate with changes in BW within each phase, thus the estimation of CH_4 was consistent and uncertainty was low. In comparison, SAL and HAL models incorporate NDF (%), which changed throughout the grazing phase thereby introducing more variability in CH_4 estimation, and hence more uncertainty. Likewise, the average range of uncertainty through animal stages for high forage diets was lower for models that used ratios between variables to adjust other variables (e.g., N from Ellis et al. 2009; 2.4%). In contrast, inclusion of more variables in models especially when inputs for these variables increased and/or decreased over time, led to greater uncertainties (e.g., HFMC from Escobar-Bahamondes et al. 2017*b*).

In contrast to high forage diets, low forage diets were high in energy content and nutrient contents (e.g., starch, fiber) were less variable over the finishing phase. As a result, the uncertainties of CH_4 predictions were less than for models used for high forage diets, and ranged from 0 to 15.3%. Uncertainty was mainly affected by DMI rather than feed composition, and similar to high forage models the uncertainty was lower for models with few variables and greater for models that use more variables.

Based on the results from our study we suggest that when diet composition is known and data for animals are available (e.g., BW and DMI) use of complex models, as evaluated and recommended by Escobar-Bahamondes et al. (2017*a,b*), can be used with a high degree of accuracy when predicted values of CH_4 are expressed as g d^{-1}. However in dynamic conditions the performance of the models showed more uncertainty because CH_4 production by animals varies with changes in intake and diet composition. Accuracy is decreased when CH_4 is calculated based on Ym, as is the case with IPCC Tier 2 methodology. Inversely, uncertainty of prediction is less when models only consider one variable and the range of input variables is small. Escobar-Bahamondes et al. (2017*a,b*) developed, evaluated and ranked models for their accuracy in predicting CH_4 emissions for beef production systems using high and low forage diets, and the best-fit models were used in the present study. A condition used to select best-fit models was that predicted values were close to observed values, and hence models showed high accuracy and precision. If the purpose is to obtain estimates of CH_4 production for national inventory purposes representing cattle over a range of geographical regions where information on diet composition is lacking, depending on stage and location use of average Ym of 7.0 to 7.3% for beef cow and 6.4 to 6.6% for growing cattle are recommended when consuming high forage diets. An average Ym of 4.8% is recommended for finishing cattle fed high grain diets.

CONCLUSIONS

There were substantial differences in predicted CH_4 production of beef cattle across all models selected based on accuracy and precision for beef cows during the lactating and nonlactating stage, growing steers fed backgrounding diets or grazing pasture, and feedlot finishing cattle. Furthermore, estimated daily CH_4 production and Ym from models are distinct from IPCC Tier 2 estimates. The variability in predicted CH_4 and Ym was greater for models that considered more dietary components as predictors. The variability due to models was greatest for grazing cattle (cows and growing steers) because of fluctuations in dietary composition (e.g., especially fibre content), intake, and BW during the productive cycle. Models that use fixed factors as predictors, such as DMI or GEI are more stable and show less uncertainty but are less sensitive to changes in diet composition that affect CH_4 production. The average Ym values derived from the best-fit equations were 7.0 to 7.3% for beef cows depending upon stage and location, and 6.4 to 6.6% for growing cattle consuming high-forage diets, while a mean of 4.8% was observed for beef cattle consuming finishing diets.

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REFERENCES

Abouguendia, Z. 1998. Nutrient content and digestibility of Saskatchewan range plants. Technical report on ADF Project #94000114. Grazing and Pasture Technology Program. Regina, SK, Canada.

Alemu, A.W., Dijkstra, J., Bannink, A., France, J., and Kebreab, E. 2011. Rumen stoichiometric models and their contribution and challenges in predicting enteric methane production. Anim. Feed Sci. Technol. **166-167**: 761-778.

Alemu, A.W., Amiro, B.D., Bittman, S., MacDonald, D., and Ominski, K. 2016. A typological characterization of Canadian beef cattle farms based on a producer survey. Can. J. Anim. Sci. **96**: 187-202.

Beauchemin, K.A., and McGinn, S.M. 2005. Methane emissions from feedlot cattle fed barley or corn diets. J. Anim. Sci. **83**: 653-661.

Beauchemin, K.A., and McGinn, S.M. 2006. Methane emissions from beef cattle: Effects of fumaric acid, essential oil, and canola oil. J. Anim. Sci. **84**: 1489-1496.

Beauchemin, K.A. McGinn, S. M., Martinez, T. F., and McAllister T. A. 2007. Use of condensed tannin extract from quebracho trees to reduce methane emissions from cattle. J. Anim. Sci. **85**: 1990-1996.

Beauchemin, K.A., Janzen, H.H., Little, S.M., McAllister, T.A., and McGinn, S.M. 2010. Life cycle assessment of greenhouse gas emissions from beef production in Western Canada: A case study. Agric. Sys. **103**: 371-379.

Boadi, D.A., Wittenberg, K.M., and McCaughey, W. 2001. Effects of grain supplementation on methane production of grazing steers using the sulphur (SF6) tracer gas technique. Can. J. Anim. Sci. **82**: 1-9.

Chung, Y.H., Walker, N.D., McGinn, S.M., and Beauchemin, K.A. 2011. Differing effects of 2 active dried yeast (*Saccharomyces cerevisiae*) strains on ruminal acidosis and methane production in nonlactating dairy cows. J. Dairy. Sci. **94**, 2431-2439.

Ellis, J.L., Kebreab, E., Odongo, N.E., McBride, B.W., Okine, E.K., and France, J. 2007. Prediction of methane production from dairy and beef cattle. J. Dairy. Sci. **90**: 3456-3467.

Ellis, J.L., Kebreab, E., Odongo, N.E., Beauchemin, K.A., McGinn, S.M.S., Nkrumah, J.D., Moore, S.S., Christopherson, R., Murdoch, G.K., McBride, B.W., Okine, E.K., and France, J.

2009. Modeling methane production from beef cattle using linear and nonlinear approaches. J. Anim. Sci. **87**: 1334-1345.

Environment and Climate Change Canada. 2016. National Inventory Report 1990-2014: Greenhouse Gas Sources and Sinks in Canada. 14p.

Environment Canada. 2014. National Inventory Report 1990-2012: Greenhouse Gas Sources and Sinks in Canada. 188p.

Escobar-Bahamondes, P., Oba, M., and Beauchemin, K.A. 2017*a*. An evaluation of the accuracy and precision of methane prediction equations for beef cattle fed high-forage and high grain diets. Animal. **11**:68-77

Escobar-Bahamondes, P., Oba, M., and Beauchemin, K.A. 2017*b*. Universally applicable methane prediction equations for beef cattle fed high- or low-forage diets. Can. J. Anim. Sci. **97**:83-94

Fitzsimons, C., Kenny, D., Deighton, D., Fahey, A., and McGee, M. 2013. Methane emissions, body composition, and rumen fermentation traits of beef heifers differing in residual feed intake. J. Anim Sci. **91**: 5789-5800.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., and Tempio, G. 2013. Tackling climate change through livestock - A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome. 116 pp.

Hales, K.E., Cole, N.A., and Macdonald, J.C., 2012. Effects of corn processing method and dietary inclusion of wet distillers grains with solubles on energy metabolism, carbon-nitrogen balance, and methane emissions of cattle. J. Anim. Sci. **90**: 3174-3185.

Hünerberg, M., McGinn, S. M., Beauchemin, K. A., Okine, E. K., Harstad, O. M., and McAllister, T. A. 2013. Effect of dried distillers' grains with solubles on enteric methane emissions and nitrogen excretion from finishing beef cattle. Can. J. Anim. Sci. **93**: 373-385.

IPCC 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). IGES, Japan.

Karimi-Zindashty, Y., MacDonald J. D., Desjardins, R. L., Worth, D. E., Hutchinson, J. J., and Vergé, X. P. C. 2012. Sources of uncertainty in the IPCC Tier 2 Canadian livestock model. J. Agric. Sci. **150**: 556-569.

Johnson, K.A., and Johnson, D.E. 1995. Methane emissions from cattle. J. Anim. Sci. **73**: 2483-2492.

Legesse, G., Small, J.A., Scott, S.L., Crow, G.H., Block, H.C., Alemu, A.W., Robins, C.D., and Kebreab, E. 2011. Predictions of enteric methane emissions for various summer pasture and winter feeding strategies for cow calf production. Anim. Feed Sci. Technol. **166-67**: 678-687.

Legesse, G., Beauchemin, K.A., Ominski, K.H., McGeough, E.J., Kroebel, R., MacDonald, D., Little, S.M., and McAllister, T.A. 2016. Greenhouse gas emissions of Canadian beef production in 1981 as compared with 2011. Anim. Prod. Sci. **56**: 153-168.

Mathison, G.W. 1993. The beef industry. Pages 35-74 in Martin, J., Hudson, R.J. and B.A. Young, eds. Animal production in Canada. University of Alberta, Faculty of Extension, Edmonton, Canada.

McGinn, S.M., Chung Y.-H., Beauchemin K.A., Iwaasa, A.D., and Grainger, C. 2009. Use of corn distillers' dried grains to reduce enteric methane loss from beef cattle. Can. J. Anim. Sci. **89**: 409-413.

Molano, G., Clark, H., Knight, T., and Cavanagh, A. 2006. Methane emissions from growing beef cattle grazing hill country pasture. In Proceedings of the New Zealand Society of Animal Production. **66**: 172-175.

Moraes, L.E., Strathe, A.B., Fadel, J.G., Casper, D.P., and Kebreab. E. 2014. Prediction of enteric methane emissions from cattle. Glob. Chang. Biol. **20**: 2140-2148.

National Academies of Sciences, Engineering, and Medicine (NASEM). 2016. Nutrient Requirements of Beef Cattle, Eight Revised Edition, The National Academy Press, Washington, DC. 494p.

Ominski, K.H., Boadi, D.A. and Wittenberg, K.M. 2006. Enteric methane emissions from backgrounded cattle consuming all-forage diets. Can. J. Anim. Sci. **86**: 393-400.

Pinares-Patiño, C.S., Baumont, R., and Martin, C. 2003. Methane emissions by Charolais cows grazing a monospecific pasture of timothy at four stages of maturity. Can. J. Anim. Sci. **83**: 769-777.

Ricci, P., Rooke, J.A., Nevison, I., and Waterhouse, A. 2013. Methane emissions from beef and dairy cattle: Quantifying the effect of physiological stage and diet characteristics. J. Anim. Sci. **91**: 5379-5389.

SAS 2015. JMP® 12 Basic Analysis. SAS Institute Inc., Cary, NC, USA.

Sheppard, S.C., Bittman, S., Donohoe, G., Flaten, D., Wittenberg, K.M., Small, J., Berthiaume, R., McAllister, T.A., Beauchemin, K., McKinnon, J., Amiro, B., MacDonald, D., Mattos, F., and Ominski, K.H. 2015. Beef cattle husbandry practices across ecoregions of Canada in 2011. Can. J. Animal Sci. **95**: 305-321.

Staerfl, S.M., Zeitz, J. O., Kreuzer, M., and Soliva, C. R. 2012. Methane conversion rate of bulls fattened on grass or maize silage as compared with the IPCC default values, and the long-term methane mitigation efficiency of adding acacia tannin, garlic, maca and lupine. Agric. Ecosys. Env. **148**: 111-120.

Ulyatt, M., Lassey, K., Shelton, I., and Walker, C. 2002. Seasonal variation in methane emission from dairy cows and breeding ewes grazing ryegrass/white clover pasture in New Zealand. NZ J. Agric. Res. **45**: 217-226.

Vyas, D., McGeough, E.J., Mohammed, R., McGinn, S.M., McAllister, T.A., and Beauchemin, K.A. 2014. Effects of Propionibacterium strains on ruminal fermentation, nutrient digestibility and methane emissions in beef cattle fed a corn grain finishing diet. Animal **8**: 1807-1815.

Vyas, D., Alazzeh, A., McGinn, S.M., McAllister, T.A., Harstad, O.M., Holo, H., and Beauchemin, K.A. 2015. Enteric methane emissions in response to ruminal inoculation of Propionibacterium strains in beef cattle fed a mixed diet. Animal Production Science **56**: 1035-1040.

Yan, T., Porter, M.G., and Mayne, C.S. 2009. Prediction of methane emission from beef cattle using data measured in indirect open-circuit respiration calorimeters. Animal **3**: 1455-1462.

Table 1. Equations used to predict enteric CH_4 production

Id and Source		[a]Model	[b]Complexity of models	Use in this study
High forage diets				
IPCC (2006) - Tier 2	CH_4 =	(DMI × 18.5 (MJ/kg DM) × Y_m) /55.65 (MJ/kg CH_4)	1	Cow and steers
SAL - Moraes et al. (2014)	CH_4 =	-0.221 + 0.048 × GEI + 0.005 × BW	1	Steers
N - Ellis et al. (2009)	CH_4 =	2.68 - 1.14 × (starch:NDF) + 0.786 × DMI	2	Cows or steers
HAL - Moraes et al. (2014),	CH_4 =	-1.487 + 0.046 × GEI + 0.032 × NDF (%) + 0.006 × BW	2	Cows
14b - Ellis et al. (2007)	CH_4 =	2.94 + 0.0585 × MEI + 1.44 × ADF - 4.16 × lignin	2	Cow and steers
iiib - Yan et al. (2009)	CH_4 =	[[1.749 – 12.18 ME/GE + 10.74 DE/GE] GEI – 14.0] × 0.66] × 0.0556	3	Cow and steers
HFOR - Escobar-Bahamondes et al. (2017*b*)	CH_4 =	71.5(± 11.45) + 0.12(± 0.03) × BW + 0.10(± 0.01) × DMI^3 - 244.8(± 56.44) × fat^3	3	Cow and steers
HFMC - Escobar-Bahamondes et al. (2017*b*)	CH_4 =	25.9(± 0.54) + 0.13(±0.001) × BW + 145.4 (±1.31) × fat + 10.3(±0.16) × $(NDF\text{-}ADF)^2$ + 0.1(±0.00) × DMI^3 - 27.4 (±0.20) × (starch:NDF)	3	Cow and steers
Finishing diets				
IPCC (2006) - Tier 2	CH_4 =	(DMI × 18.5 (MJ/kg DM) × Y_m) /55.65 (MJ/kg CH_4)	1	Steers
A - Ellis et al. (2009)	CH_4 =	2.29 + 0.670 × DMI	1	Steers
SGEL - Moraes et al. (2014)	CH_4 =	0.743 + 0.054 × GEI	1	Steers
SDL - Moraes et al. (2014)	CH_4 =	0.743 + 0.054 × GEI	1	Steers
9b - Ellis et al. (2007)	CH_4 =	0.357 + 0.0591 × MEI + 0.0500 × forage (%)	2	Steers
I - Ellis et al. (2009)	CH_4 =	2.72 + 0.0937 × MEI + 4.31 × CEL - 6.49 × HC - 7.44 × fat	2	Steers
GEI - Ricci et al. (2013)	CH_4 =	74.34 + 0.57 × GEI - 10.61 × feed - 69.67 × stage - 0.22 × GEI × feed + 0.57 × GEI × stage	2	Steers
LFOR - Escobar-Bahamondes et al. (2017*b*)	CH_4 =	-26.4(±20.17) + 0.21(±0.04) × BW + 30.1(±11.83) × CP - 70.5(±25.48) × fat^2 + 10.1(±5.12) × $(NDF\text{-}ADF)^3$	3	Steers
LFMC - Escobar-Bahamondes et al. (2017*b*)	CH_4 =	-10.1(±0.62) + 0.21(± 0.001)×BW + 0.36(±0.003)×DMI^2 - 69.2(±1.65)×fat^3 + 13.0(±0.45)×(CP:NDF) - 4.9(±0.07) × (starch:NDF)	3	Steers

Note: [a] ADF, acid detergent fiber (kg d^{-1}); AL, animal level; BW, body weight (kg); CEL, cellulose (kg d^{-1}); DE, digestible energy (MJ kg^{-1} DM); DL, dietary level; DMI, dry matter intake (kg d^{-1}); GE, gross energy (MJ kg^{-1} DM); GEI, gross energy intake (MJ d^{-1}); GEL, gross energy level; HC, hemicellulose;

ME, metabolizable energy (MJ kg^{-1} DM); MEI, metabolizable energy intake (MJ d^{-1}); NDF, neutral detergent fiber (kg d^{-1}); stage, physiological stage (nonlactating or lactating); Y_m, Methane conversion factor (6.5% for diets > 90 g forage kg^{-1} DM, 3.0% for diets ≤ 90 g forage kg^{-1} DM).

[b] Level 1, linear models that use one or two basic variables; level 2, linear models that consider a number of dietary variables; level 3, polynomial models.

Table 2. Period, BW range and predicted values (mean± SD, coefficient of variation, %) of CH_4 averaged across all models by region and production stage for beef cows and growing steers

	Eastern region	Western region
Beef cows		
Lactating stage		
Period (months)	6	6
BW, kg (min - max)	600 - 617	578 - 602
Overall[a] Ym (%; mean ± SD, CV)	7.0a ± 1.69, 24.0	7.1a ± 2.09, 29.4
Overall CH_4 (g d^{-1}; mean ± SD, CV)	258a ± 66.4, 25.7	271a ± 79.6, 29.4
Dry stage		
Period (months)	6	6
BW, kg (min - max)	617 - 663	602 – 654
Overall Ym (%)	7.2a ± 1.18, 16.4	7.3a ± 1.48, 20.3
Overall CH_4 (g d^{-1})	231a ± 40.3, 17.5	263b ± 53.5, 20.3
Growing steers		
Backgrounder phase		
Period (months)	6	6
BW, kg (min - max)	226 - 341	245 - 393
Overall Ym (%)	6.5a ± 1.08, 16.6	6.4a ± 0.89, 13.9
Overall CH_4 (g d^{-1})	116a ± 20.9, 18.0	148b ± 21.2, 14.3
Grazing phase		
Period (months)	5	4
BW, kg (min - max)	384 - 518	424 - 514
Overall Ym (%)	6.6a ± 1.25, 18.9	6.5a ± 1.43, 22.0
Overall CH_4 (g d^{-1})	209a ± 46.2, 22.1	232b ± 52.6, 22.7
Finishing phase		
Period (months)	4	3
BW, kg (min - max)	564 - 708	564 - 667
Overall Ym (%)	4.8a ± 0.87, 18.1	4.8a ± 0.84, 17.5
Overall CH_4 (g d^{-1})	152a ± 29.1, 19.1	158a ± 27.8, 17.6

[a] Means within a row without the same letter are different ($P \leq 0.05$).

Table 3. Ym (% GEI) predicted from different models for mature beef cows by region and stage of production

Models[a]	Eastern region			Western region		
	Average	SD[b]	CV[c]	Average	SD	CV
Lactating stage						
IPCC (2006) -Tier 2	6.5c	0.00	0.00	6.5c	0.00	0.00
14b - Ellis et al. (2007)	6.0d	0.27	4.50	5.5d	0.94	17.09
N - Ellis et al. (2009)	5.7e	0.11	1.93	5.7d	0.09	1.58
HFMC - Escobar et al. (2017*b*)	10.2a	1.46	14.31	11.4a	0.98	8.60
HFOR - Escobar et al. (2017*b*)	7.8b	0.52	6.67	7.9b	0.51	6.46
HAL - Moraes et al. (2014)	6.5c	0.16	2.46	6.4c	0.11	1.72
iiib - Yan et al. (2009)	6.5bcde	1.92	29.54	6.5bcd	1.93	29.69
Dry stage						
IPCC (2006) -Tier 2	6.5d	0.00	0.00	6.5d	0.00	0.00
14b - Ellis et al. (2007)	6.2e	0.05	0.81	6.0e	0.09	1.50
N - Ellis et al. (2009)	6.0f	0.06	1.00	5.9f	0.06	1.02
HFMC - Escobar et al. (2017*b*)	9.5a	0.19	2.00	10.2a	0.34	3.33
HFOR - Escobar et al. (2017*b*)	8.0b	0.34	4.25	8.3b	0.39	4.70
HAL - Moraes et al. (2014)	7.0c	0.14	2.00	6.7c	0.05	0.75
iiib - Yan et al. (2009)	7.6bc	0.85	11.18	7.7bc	0.83	10.78

Note: [a] Within a column, models with different letters differ ($P \leq 0.05$).
[b] Standard deviation.
[c] Coefficient of variation (%).

Table 4. Methane (g d^{-1}) predicted from different models for beef cows by region and stage

Models[a]	Eastern region			Western region		
	Average	SD[b]	CV[c]	Average	SD	CV
Lactating cows						
IPCC (2006) -Tier 2	248c	18.7	7.54	257c	9.6	3.74
14b - Ellis et al. (2007)	220c	21.7	9.86	209de	37.4	17.89
N - Ellis et al. (2009)	208c	11.6	5.58	214e	5.2	2.43
HFMC - Escobar et al. (2017*b*)	376a	77.3	20.56	432a	44.7	10.35
HFOR - Escobar et al. (2017*b*)	287b	33.2	1.11	300b	21.5	7.17
HAL - Moraes et al. (2014)	237c	13.2	5.57	241d	6.9	2.86
iiib - Yan et al. (2009)	235bc	65.0	27.66	246bcde	71.2	28.94
Dry cows						
IPCC (2006) -Tier 2	220b	16.7	7.59	250c	9.9	3.96
14b - Ellis et al. (2007)	195cd	10.7	5.49	214e	6.2	2.90
N - Ellis et al. (2009)	190d	9.8	5.16	209f	6.1	2.92
HFMC - Escobar et al. (2017*b*)	299a	23.4	7.83	364a	25.1	6.90
HFOR - Escobar et al. (2017*b*)	252b	25.4	10.08	296b	21.9	7.40
HAL - Moraes et al. (2014)	220b	9.3	4.23	238d	6.8	2.86
iiib - Yan et al. (2009)	241bcd	39.6	16.43	273bcd	31.4	11.50

Note: [a] Within a column, models with different letters differ ($P \leq 0.05$).
[b] Standard deviation.
[c] Coefficient of variation (%).

Table 5. Ym (% GEI) predicted from different models by production phase and region for growing beef steers

Models[a]	Eastern region			Western region		
	Average	SD[b]	CV[c]	Average	SD	CV
Backgrounding in confinement phase						
IPCC 2006	6.5c	0.00	0.00	6.5b	0.00	0.00
14b - Ellis et al. (2007)	7.3b	0.23	3.15	6.6b	0.06	0.91
N - Ellis et al. (2009)	6.1d	0.12	1.97	6.0c	0.04	0.67
HFMC - Escobar et al. (2017*b*)	4.5d	0.35	7.78	5.2d	0.29	5.58
HFOR - Escobar et al. (2017*b*)	6.9b	0.04	0.58	6.5b	0.19	2.92
SAL - Moraes et al. (2014)	6.0d	0.14	2.33	5.9c	0.15	2.54
iiib - Yan et al. (2009)	8.2ab	0.05	0.61	8.3a	0.01	0.12
Grazing phase						
IPCC 2006	6.5b	0.00	0.00	6.5b	0.00	0.00
14b - Ellis et al. (2007)	6.4bc	0.47	7.34	6.7b	0.81	12.09
N - Ellis et al. (2009)	5.9c	0.12	2.03	5.8d	0.04	0.69
HFMC - Escobar et al. (2017*b*)	9.1a	0.46	5.05	8.9a	0.50	5.62
HFOR - Escobar et al. (2017*b*)	6.7b	0.47	7.01	7.3b	0.36	4.93
SAL - Moraes et al. (2014)	6.0c	0.03	0.50	5.9d	0.04	0.68
iiib - Yan et al. (2009)	5.8bc	1.61	27.76	4.4e	1.07	24.32
Finishing phase						
IPCC 2006	3.0f	0.00	0.00	3.0e	0.00	0.00
LFMC - Escobar et al. (2017*b*)	4.1e	0.20	4.88	4.4d	0.18	4.09
LFOR - Escobar et al. (2017*b*)	4.4de	0.14	3.18	5.0d	0.21	4.20
9b - Ellis et al. (2009)	4.6d	0.04	0.87	4.4d	0.02	0.45
A - Ellis et al. (2009)	4.9c	0.10	2.04	4.9c	0.05	1.02
I - Ellis et al. (2009)	5.1c	0.12	2.35	4.5c	0.08	1.78
SDL - Moraes et al. (2014)	5.8a	0.03	0.52	5.8a	0.02	0.34

SGEL - Moraes et al. (2014)	5.8a	0.03	0.52	5.8a	0.02	0.34
GEI - Ricci et al. (2013)	5.5b	0.18	3.27	5.4b	0.10	1.85

Note: [a] Within a column, models with different letters differ ($P \leq 0.05$).
[b] Standard deviation.
[c] Coefficient of variation (%).

Table 6. Methane (g d^{-1}) predicted from different models by production phase and region for growing steers

Models[a]	*Eastern region*			*Western region*		
	Average	SD[b]	CV[c]	Average	SD	CV
Backgrounding in confinement phase						
IPCC 2006	121b	9.3	7.69	157b	4.0	2.55
14b - Ellis et al. (2007)	128b	5.8	4.53	150c	2.5	1.67
N - Ellis et al. (2009)	107c	6.1	5.70	136d	2.6	1.91
HFMC - Escobar et al. (2017*b*)	80d	12.3	15.38	119f	10.0	8.40
HFOR - Escobar et al. (2017*b*)	122b	9.3	7.62	149c	8.4	5.64
SAL - Moraes et al. (2014)	106c	10.6	10.00	135e	7.0	5.19
iiib - Yan et al. (2009)	145a	11.8	8.14	188a	5.1	2.71
Grazing phase						
IPCC 2006	210b	23.7	11.29	242b	13.1	5.41
14b - Ellis et al. (2007)	198b	7.7	3.89	236bc	21.6	9.15
N - Ellis et al. (2009)	185b	15.4	8.32	205cd	8.5	4.15
HFMC - Escobar et al. (2017*b*)	286a	39.2	13.71	317a	34.1	10.76
HFOR - Escobar et al. (2017*b*)	212b	35.9	16.93	259ab	26.0	10.04
SAL - Moraes et al. (2014)	187b	20.1	10.75	207cd	11.5	5.56
iiib - Yan et al. (2009)	184b	65.5	35.60	157d	47.5	30.25
Finishing phase						
IPCC 2006	94d	7.3	7.77	100e	4.5	4.50
LFMC - Escobar et al. (2017*b*)	132c	16.6	12.58	144d	12.3	8.54
LFOR - Escobar et al. (2017*b*)	139c	15.3	11.01	165bc	14.4	8.73
9b - Ellis et al. (2009)	145c	10.0	6.90	147d	5.9	4.01
A - Ellis et al. (2009)	155bc	8.8	5.68	162c	5.9	3.64
I - Ellis et al. (2009)	162abc	8.7	8.70	146d	3.9	2.67
SDL - Moraes et al. (2014)	184a	13.1	7.12	190a	7.9	4.16

SGEL - Moraes et al. (2014)	184a	13.1	7.12	190a	7.9	4.16
GEI - Ricci et al. (2013)	174ab	7.7	4.43	178b	4.7	2.64

Note: [a] Within a column, models with different letters differ ($P \leq 0.05$).
[b] Standard deviation.
[c] Coefficient of variation (%).

Table 7. Uncertainty of Ym for the models by production phase of mature cows (lactating and dry) and growing cattle (backgrounding, grazing, finishing)

Models	Average	Upper 95% mean[a]	Lower 95% mean[a]	Uncertainty (%)
Lactating stage				
IPCC 2006	6.5	6.5	6.5	0.0
14b - Ellis et al. (2007)	5.8	6.2	5.3	15.7
N - Ellis et al. (2009)	5.7	5.7	5.6	2.2
HFMC - Escobar-Bahamondes et al. (2017*b*)	10.8	11.7	10.0	15.7
HFOR - Escobar-Bahamondes et al. (2017*b*)	7.9	8.2	7.6	7.9
HAL - Moraes et al. (2014)	6.4	6.5	6.3	2.9
iiib - Yan et al. (2009)	6.5	7.7	5.3	35.9
Dry stage				
IPCC 2006	6.5	6.5	6.5	0.0
14b - Ellis et al. (2007)	6.1	6.2	6.0	2.7
N - Ellis et al. (2009)	5.9	6.0	5.9	2.4
HFMC - Escobar-Bahamondes et al. (2017*b*)	9.8	10.1	9.6	5.8
HFOR - Escobar-Bahamondes et al. (2017*b*)	8.1	8.4	7.9	5.9
HAL - Moraes et al. (2014)	6.8	7.0	6.7	3.8
iiib - Yan et al. (2009)	7.6	8.1	7.1	13.3
Backgrounding in confinement phase				
IPCC 2006	6.5	6.5	6.5	0.0
14b - Ellis et al. (2007)	6.9	7.2	6.7	6.9
N - Ellis et al. (2009)	6.1	6.1	6.0	2.2
HFMC - Escobar-Bahamondes et al. (2017*b*)	4.9	5.2	4.6	12.5
HFOR - Escobar-Bahamondes et al. (2017*b*)	6.7	6.9	6.6	4.7
SAL - Moraes et al. (2014)	6.0	6.1	5.9	3.1
iiib - Yan et al. (2009)	8.2	8.3	8.2	0.9
Grazing phase				
IPCC 2006	6.5	6.5	6.5	0.0

14b - Ellis et al. (2007)	6.5	7.0	6.0	15.6
N - Ellis et al. (2009)	5.9	5.9	5.8	2.7
HFMC - Escobar-Bahamondes et al. (2017*b*)	9.1	9.4	8.7	8.0
HFOR - Escobar-Bahamondes et al. (2017*b*)	7.0	7.4	6.6	11.3
SAL - Moraes et al. (2014)	5.9	6.0	5.9	1.6
iiib - Yan et al. (2009)	5.2	6.3	4.0	45.2
Finishing phase				
IPCC 2006	3.0	3.0	3.0	0.0
LFMC - Escobar-Bahamondes et al. (2017*b*)	4.3	4.5	4.1	9.6
LFOR - Escobar-Bahamondes et al. (2017*b*)	4.7	5.0	4.3	15.3
9b - Ellis et al. (2007)	4.6	4.6	4.5	2.8
A - Ellis et al. (2009)	4.9	5.0	4.9	3.1
I - Ellis et al. (2009)	4.9	5.2	4.5	13.9
SDL - Moraes et al. (2014)	5.8	5.8	5.8	0.9
SGEL - Moraes et al. (2014)	5.8	5.8	5.8	0.9
GEI - Ricci et al. (2013)	5.5	5.6	5.4	5.2

Note: [a] Upper and lower 95% mean indicate 95% confidence limits about the mean of model prediction.

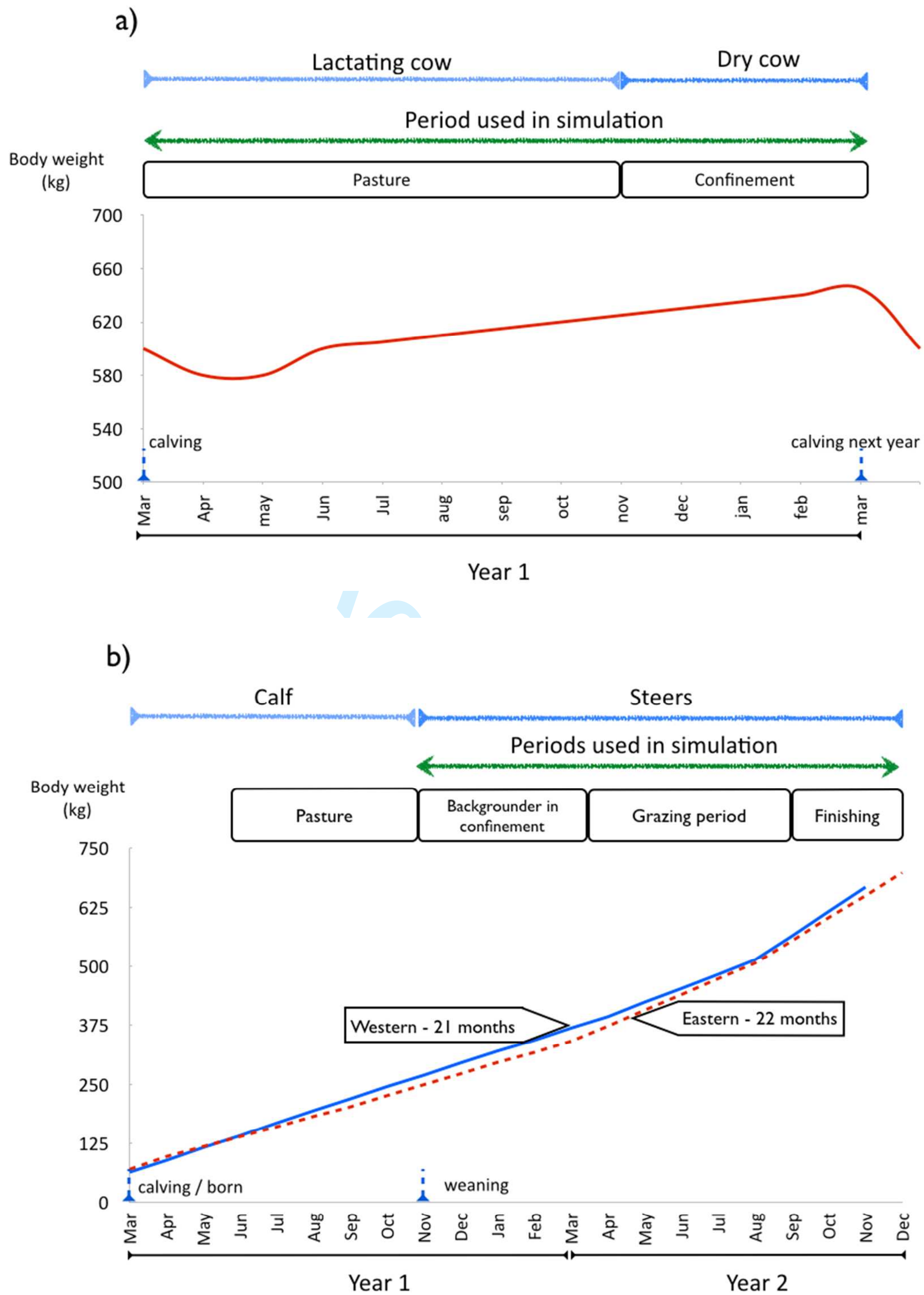

Figure 1. Production systems used in the simulations for a) beef cows and b) growing steers