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Application of Models to Predict Methane Emissions by Dairy Cattle

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Abstract: As environmental concerns grow globally, many countries are elaborating upon a plan to reduce greenhouse gas emissions which can result in global climate change. Cattle production is one of the recognized sectors in agriculture that produce a large amount of methane from enteric fermentation, one of the major greenhouse gases being targeted for reduction. Enteric methane production by cattle varies between 2-12% of gross energy intake and a recent statistics showed that it contributes >20% of the total methane emissions in the US dairy cattle is known to produce more enteric methane than beef cattle due to a relatively large amount of forage in the diet and a high level of intake. Therefore, reducing methane emissions by dairy cattle has become one of the most important areas of research in the modern agriculture and accurate quantification of methane emissions by dairy cattle is critical. Direct measurement of methane emissions by dairy herds requires a large amount of time, labor and money and it cannot be practically used to estimate methane emissions from each farm. Application of modeling to predict methane emissions thus could be an alternative and better way of quantifying methane emissions from dairy herds. A common modeling approach is to develop a methane emission model empirically which is heavily dependent on statistical analysis on available data. An Empirical Model is very useful and its predictability may be satisfactory as long as it is built from sufficient and appropriate accumulated data. Interpolation beyond the range of data should be avoided. Many published models can be classified as Empirical Models. A Mechanistic Model, on the contrary, emphasizes more on the underlying mechanism. Experimental data are only used for parameterization of the variables and evaluation of the model. In many cases a Mechanistic Model requires more variabes to be estimated than an Empirical Model which may limit its versatile use. One important feature of a Mechanistic Model is that unlike an Empirical Model it can be easily modified and applied to different conditions (climate, feedstuff, breed and management) without changing the structure of the model. A relatively small number of Mechanistic Models have been published. Each type of models has its pros and cons and one should thus be cautious when choosing a model for a specific condition. According to the model comparisons in literature, the overall predictability of the published models is still low and needs to be improved with further research. More accurate predictions of methane emission by dairy cattle require the development of a more mechanistic model that accounts for more of the biologically important variables that affects methane emissions and this model should be able to integrate all of the farm-specific components. It can be concluded that modeling is very useful to predict the methane emissions by dairy cattle and it is also helpful to find the most appropriate mitigation strategy for a specific condition.

Key words: Methane, modeling, cattle, breed, feed stuff, climate

INTRODUCTION

The Greenhouse Gas (GHG) emissions became one of the major concerns in the modern human society due to their effects on global climate change. It was estimated that the average temperature of the earth could increase 3.6°C by the year 2100 which may possibly increase a sea level >0.9 m. The primary GHG emitted by agriculture are methane (CH_4) and nitrous oxide (N_2O). Enteric methane production, especially is a major contributor to GHG emissions by dairy cattle and also represents a loss of nutrient that can be used for animal production otherwise. Enteric methane production varies between 2-12% of gross energy intake (Johnson and Johnson, 1995). A recent statistics showed that enteric methane emissions from livestock, mostly cattle, represent about 24% of the total methane emissions in the US (EPA, 2009). In 2007, methane emissions from enteric fermentation by beef and dairy cattle were estimated to be 100.2 and 31.9 Tg CO_2 equivalent which contributed 53 and 17% of the methane emissions from the agriculture sector in the US (EPA, 2009). Although, the total amount of methane emissions by beef cattle is larger than by dairy cattle, individual dairy cattle produce more methane than beef cattle, primary due to high feed intake and high forage content in a dairy diet (Ellis *et al*., 2007). There is thus a strong rationale to reduce methane emissions by dairy cattle and accurate estimation is a pre-requisite to find better ways to decrease methane emissions. The most accurate and reliable way of estimating methane emissions may be to directly measure methane emissions from each cow, herd or farm experimentally. Experimental measurement however, requires a large amount of time, money and labor and the measurements vary by methods (Grainger *et al*., 2007). In this regards, modeling can be an alternative approach to estimate methane emissions. By modeling researchers can minimize labor and time-consuming measurements and may be able to find the most efficient way to achieve the goals. For example, application of Cornell Net Carbohydrate and Protein System (CNCPS) into a commercial dairy farm was successful in terms of an increase in productivity and a reduction in nitrogen and phosphorus excretion at the same time (Tylutki *et al*., 2004). There have been attempts to predict methane emission by dairy cattle using mathematical models (Baldwin, 1995; Blaxter and Clapperton; 1965, Ellis *et al*., 2007; Kebreab *et al*., 2008; Kriss, 1930; Mills *et al*., 2003; Moe and Tyrell, 1979). The objective of this review is to summarize these models.

TYPES OF MODELS: EMPIRICAL VS. MECHANISTIC

All of the published models can be classified into two types: an Empirical or Mechanistic Model. One of the major differences between empirical and mechanistic approaches is that empirical models are more dependent on experimental data and correlations among the variables. On developing an Empirical Model, one should gather data and identify statistical relationships among the variables. In order to develop an Empirical Model to predict methane emissions by dairy cattle, for instance, a modeler first develops a database containing a comprehensive set of data from literature. Several statistical models is then constructed with measurements in the database (feed intake, animal body weight, milk production and diet composition) as explanatory variables and methane emissions as a response variable. Several techniques are available for developing an Empirical Model (linear and nonlinear regressions (Neter *et al*., 1996) and a random coefficient model (Swamy, 1970)).

Mechanistic Models on the contrary, begin with possible mechanisms of a predefined target or response variable. Many Mechanistic Models published in literature for predicting enteric methane emissions are on the basis of the Baldwin's Rumen Model (Baldwin, 1995). In this type of models methane production is predicted by its relationship with rumen pH, microbial population and VFA production which are determined based on animal and dietary characteristics.

Each type of models has pros and cons and it is hardly possible to construct a 100% Empirical or Mechanistic Model. When an Empirical Model developed, a mechanistic approach is needed to select candidate variables and structure of the model. Similarly, parameter estimation in a Mechanistic Model also depends on empirical relationships.

Development of an Empirical Model is relatively easy although it requires much labor and time and it has been widely conceived that an Empirical Model works well within the range of data from which the Empirical Model was built. However, interpolation beyond the range should be done which caution since, inference of a Statistical Model is valid only within the range of data (Neter *et al*., 1996). For instance, an Empirical Model developed on a database containing only grazing data may not be able to be used for cattle fed TMR. Another pitfall of an empirical approach is that a model can be built only on the basis of available data. This could be a problem if the most significant variable that affects the response variable cannot be measured experimentally. Biological values are somehow related each other and thus it is not uncommon to observe a significant model that contains several variables that are not actually relevant to the response variable.

In Mechanistic Models however, relationships among the variables are structured on the basis of sound scientific knowledge and the cause and effect relationships which makes modelers liberalized from data availability. Unlike an Empirical Model, the structure of a model does not need to be changed when it is applied to a different condition although the parameter of the variables may need to be modified. One of the disadvantages of a Mechanistic Model is that most Mechanistic Models require a more detailed description of the input variables that are not commonly measured. For instance, Molly (Baldwin, 1995) and COWPOLL (Kebreab *et al*., 2008) require a comprehensive profile of chemical composition of the diet which includes the analysis of different types of carbohydrates. A Mechanistic Model also depends on available data for developing sub-models or parameter estimation. These empirical relationships thus need to be modified when a Mechanistic Model is applied to other situation than it was originally built for. For instance, the model performance of COWPOLL for feedlot cattle was relatively poor compared to that for dairy cattle mainly because COWPOLL is parameterized for dairy cattle (Kebreab *et al*., 2008). If a Mechanistic Model contains many sub-models or equations, additional extensive and costly studies may be needed.

MODELS TO PREDICT METHANE PRODUCTION FROM DAIRY CATTLE

Since, a full description of Mechanistic Models is lengthy and beyond the scope of this review, only Empirical Models published are shown (Table 1). The

Table 1: List of published models to predict methane production from dairy cattle. Modified from Ellis *et al*. (2007)

Source	Model to predict methane production (MJ day^{-1})*
Kriss (1930)	$75.42+94.28\times DMI$ (kg day^{-1})$\times 0.05524$ (MJ g^{-1} of CH_4)
Axelsson (1949)	$-2.07+2.636\times DMI$ (kg day^{-1})$-0.105\times DMI$ (kg day^{-1})^2
Blaxter and Clapperton (1965)	$5.447+0.469\times$(Energy digestibility at maintenance intake, percentage of GE) + Multiple of maintenance $\times$[$9.930-0.21\times$ (Energy digestibility at maintenance intake, percentage of GE)/$100\times GEI$ (MJ day^{-1})]
Moe and Tyrell (1979)	$0.341+0.511\times NSC$ (kg day^{-1}) + $1.74\times HC$ (kg day^{-1}) + $2.652\times C$ (kg day^{-1})
Mills *et al.* (2003)	(1) $5.93+0.92\times DMI$ (kg day^{-1})
Linear equations	(2) $8.25+0.07\times ME$ intake (MJ day^{-1})
	(3) $1.06+10.27\times$ Forage proportion + $0.87\times DMI$ (kg day^{-1})
Mills *et al.* (2003)	(1) $56.27\times(1-e^{[-0.028\times DMI\ (kg/day)]})$
Nonlinear equations	(2) $45.89\times(1-e^{[-0.003\times MEI\ (MJ/day)]})$
Ellis *et al.* (2007)	$8.56+0.14\times$Forage (%)
	$3.23+0.81\times DMI$ (kg day^{-1})

*GE = Gross Energy; GEI = Gross Energy Intake; HC = Hemicelluloses; C = Cellulose; NSC = Nonstructural Carbohydrate

most critical variables in predicting methane production from dairy cattle were dry matter intake and the proportion of forage in a diet (Table 1). It is reasonable that feed intake and methane production are positively correlated and inefficient use of ingested feed is increased by the level of forage intake. Although, Empirical Models are useful to assess the amount of methane production from dairy cattle, it should be noted that based on the Empirical Models the only possible solution for reducing methane emissions by dairy cattle is to decrease cattle numbers and feed intake. As Kebreab *et al*. (2006) pointed out using Mechanistic Models the effectiveness of various mitigation strategies can be accessed.

Another disadvantage of the use of Empirical Models to predict methane emissions is that it is quite sensitive to the database used for model development. The major difference among the models shown in Table 1 is that they used different sets of data for the model development. With similar model structure and variables, the models estimated the parameters diversely. This implies that these models may not be able to predict methane emissions accurately by the dairy cattle in different location, feed or management from those in the database used for model development. For example, the predictabilities of the models by Mills *et al.* (2003) were variable among different sets of data.

As recommended by IPCC (2006), it is good practice to choose or develop an appropriate model for predicting methane emissions in a specific condition (Fig. 1). Different models may give different answers for the same model inputs (Kebreab *et al*., 2008). Based on the evaluations of the published models conducted by various researchers (Benchaar *et al*., 1998; Ellis *et al*., 2007; Kebreab *et al*., 2008; Mills *et al*., 2003) the overall predictability of the current models is still low. The low predictability may be because the input variables required by the models were not adequately presented in the evaluation database or the models were inadequate or excessively simplified (Benchaar *et al*., 1998).

Especially, the predictability of a Mechanistic Model is influenced by the accuracy of the input parameters

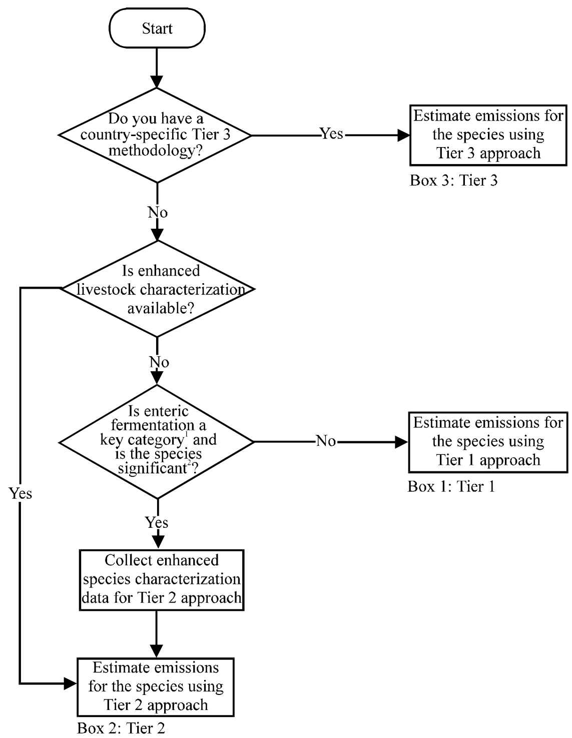

Fig. 1: Decision tree for models to predict methane emissions from enteric fermentation. Adapted from IPCC (2006)

such as chemical composition of the diet and digestion and passage rates of feed components (Benchaar *et al*., 1998). Although, COWPOLL, based on a Mechanistic Rumen Model, predicted more accurately than others models methane emissions from dairy cattle with a wide variety of feed ingredients (Kebreab *et al*., 2008) the predictability of the model still needs to be improved: concordance correlation coefficient estimate was <0.8. Further research is required to predict methane emission by dairy cattle more accurately. An improved model should account for more of the biologically important variables that affect methane emissions.

CONCLUSION

Different types of models can be used to quantify enteric methane emissions by dairy cattle. Each type of models has its pros and cons. One should thus be careful when choosing a model for a specific condition. For instance, if accumulated data are sufficient and cover a wide range of the possible model variables, an Empirical Model with simple input variables would be suitable. However, if insufficient data are available and more accurate estimation is needed, a Mechanistic Model would be preferred. Although, there are several published models that can be used to predict methane emissions by dairy cattle, they are not readily applicable to a situation other than the models were originally built from. Moreover, the overall predictability of the current models is still low and needs to be improved with further research. More accurate predictions of methane emission by dairy cattle require the development of a more mechanistic model that accounts for more of the biologically important variables that affects methane emissions and this model should be able to integrate all of the farm-specific components. It can be concluded that modeling is very useful to predict the methane emissions by dairy cattle and helpful to find the most appropriate mitigation strategy.

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