J. Dairy Sci. 98:1–15
http://dx.doi.org/10.3168/jds.2014-9138

Modeling the trade-off between diet costs and methane emissions: A goal programming approach

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ABSTRACT

Enteric methane emission is a major greenhouse gas from livestock production systems worldwide. Dietary manipulation may be an effective emission-reduction tool; however, the associated costs may preclude its use as a mitigation strategy. Several studies have identified dietary manipulation strategies for the mitigation of emissions, but studies examining the costs of reducing methane by manipulating diets are scarce. Furthermore, the trade-off between increase in dietary costs and reduction in methane emissions has only been determined for a limited number of production scenarios. The objective of this study was to develop an optimization framework for the joint minimization of dietary costs and methane emissions based on the identification of a set of feasible solutions for various levels of trade-off between emissions and costs. Such a set of solutions was created by the specification of a systematic grid of goal programming weights, enabling the decision maker to choose the solution that achieves the desired trade-off level. Moreover, the model enables the calculation of emission-mitigation costs imputing a trading value for methane emissions. Emission imputed costs can be used in emission-unit trading schemes, such as cap-and-trade policy designs. An application of the model using data from lactating cows from dairies in the California Central Valley is presented to illustrate the use of model-generated results in the identification of optimal diets when reducing emissions. The optimization framework is flexible and can be adapted to jointly minimize diet costs and other potential environmental impacts (e.g., nitrogen excretion). It is also flexible so that dietary costs, feed nutrient composition, and animal nutrient requirements can be altered to accommodate various production systems.

Key words: environmental impact, methane, diet formulation, linear programming

INTRODUCTION

Dietary factors associated with methane (CH_4) emissions have been traditionally examined with the objective of determining nutritional characteristics associated with gaseous energy losses (Blaxter and Clapperton, 1965; Moe and Tyrrell, 1979). In recent years, research on CH_4 emissions has been redirected to the reduction of greenhouse gas (**GHG**) emissions because CH_4 emission from livestock production is an important GHG source worldwide. For instance, in 2012 CH_4 emissions from enteric fermentation accounted for 25% of total US CH_4 emissions from anthropogenic sources (EPA, 2014). Although representative, it is important to point out that the agriculture sector as a whole is only responsible for 8.1% of total US GHG emissions, and its main contributor is agricultural soil management (EPA, 2014). In this context, several studies have been conducted to identify and review technical options for mitigating CH_4 emissions (e.g., Boadi et al., 2004; Martin et al., 2010; Gerber et al., 2013; Hristov et al., 2013), and dietary manipulation has been suggested as a key mitigation tool (Kebreab et al., 2010). Recently, interest has increased on practical aspects related to the implementation of mitigation strategies and also on the associated mitigation costs (e.g., Doreau et al., 2014; Pacheco et al., 2014). Mathematical models play a major role in the determination of costs associated with CH_4 mitigation and also in the investigation of the compromise between reducing CH_4 emissions and increased mineral and nitrogen excretion (Moraes et al., 2012; Dijkstra et al., 2013; Sauvant et al., 2014). Several models have been developed to predict CH_4 emissions from various classes of animals and to identify central processes in the ruminal digestion of carbohydrates that may be altered to mitigate emissions (Moe and Tyrrell, 1979; Baldwin, 1995; Kebreab et al., 2004; Moraes et al., 2014). However, only a limited number

Received December 21, 2014.
Accepted March 7, 2015.
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of studies have examined the application of decision-making models for mitigating CH_4 emissions from dairy systems through dietary manipulation.

Mathematical programming models have been used to optimize the use of scarce resources in various economic sectors (e.g., Dantzig, 1963; Kennedy, 1986). In the livestock industry, such models have been mostly developed to optimize diets (St-Pierre and Harvey, 1986; Tedeschi et al., 2000), to examine optimal policies in reproductive-management programs (De Vries, 2006; Giordano et al., 2012), and to identify optimal animal-replacement strategies (Kristensen, 1992; Nielsen et al., 2010). The application of decision-making models to improve the sustainability of the livestock industry has frequently focused on minimizing and managing mineral and nitrogen balance and excretion. For instance, Jean dit Bailleul et al. (2001) and Pomar et al. (2007) modified the least cost diet algorithm to minimize nitrogen and phosphorus excretion by pigs. Dubeau et al. (2011) proposed multicriteria programming models to reduce nitrogen and phosphorus excretion by pigs based on the observation that a trade-off existed between diet cost and environmental impacts of pig production. Moreover, Cabrera (2010) developed a Markovian model to optimize replacement policies and dairy-herd net income for diets and nitrogen excretion. The demand for these optimization models is driven by the increase in the establishment of environmental policies regulating the livestock industry (Oenema, 2004). In California, a cap-and-trade system to reduce GHG emissions has already been implemented by the California Air Resources Board (CARB, 2008). The potential application of a cap-and-trade policy scheme to the dairy industry was examined by Moraes et al. (2012), who showed that mitigating CH_4 emissions from US dairy cows by dietary manipulation may be expensive. The same authors advocated that optimization models may assist dairy producers when complying with CH_4-emission regulatory policies in an optimal manner. Therefore, the objective of this study was to develop an optimization framework for the joint minimization of dietary costs and CH_4 emissions through the identification of the set of feasible solutions for various levels of trade-offs between dietary costs and emissions. This framework extends the model from Moraes et al. (2012) and provides the decision maker the opportunity to select the most desired solution according to current feed prices and policy regulations.

MATERIALS AND METHODS

General Framework

The model was structured in 3 sequential parts. In the first part, an equation was developed to predict CH_4 emissions from lactating dairy cows using a large database of indirect calorimetry records. In the second part, 2 linear programming models were developed and solved for the individual minimization of dietary costs and CH_4 emissions. In the third part, a weighted goal programming model was developed and solved for the joint minimization of diet costs and CH_4 emissions from lactating dairy cows. The CH_4 prediction equation from the first part was used in both the linear programming and goal programming models. Likewise, the 2 linear programming models were used to determine the targets and goal constraints in the goal programming model.

Prediction of Methane Emissions

The objective of this section was to develop a model that could predict CH_4 emissions from lactating dairy cows and could be directly adapted to a constraint equation or objective function from a linear programming model. The main assumptions of linear programming models are proportionality and additivity (Winston and Venkataramanan, 2002). The proportionality assumption requires that the contribution of each decision variable to the objective function or constraint is proportional to the value of the variable itself. Similarly, the additivity assumption requires that the contribution of each decision variable is independent of the value of the other variables (Winston and Venkataramanan, 2002). The prediction model was therefore developed using nutrient intakes as independent variables because those would result in a model with proportional and additive decision variables representing intakes of feeds. A systematic and sequential model-selection strategy was used to identify the independent variables that were fundamental in predicting CH_4 emissions. First, all possible models resulting from the use of NDF, ether extract (**EE**), CP, and ME intakes as independent variables were constructed, and the condition indexes of the design matrices were determined with the perturb package in the software R (Hendrickx, 2012). Models for which the largest index was greater than 10 were discarded because possible issues with multicollinearity arise when the condition number is between 10 and 30 and the presence of multicollinearity is severe when the condition number is greater than 30 (Belsley et al., 1980). The remaining models were fitted, and the model with the smallest deviance information criterion was selected (Spiegelhalter et al., 2002).

The data used for model development were from the database of lactating cows described by Moraes et al. (2014). Multiple records on the database originated from the same animal and were grouped into various studies. A mixed effects model was therefore used to