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Representation of a mathematical model to predict methane output in dairy goats

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ABSTRACT

Ruminants may contribute to global warming through the release of methane (CH_4) gas by enteric fermentation. Most CH_4 emissions from ruminants are estimated using simple regression equations. Thus a mechanistic dynamic model to predict CH_4 output by goats was developed by using a computer-aided simulation device via object-oriented modeling. The model was structured into seven stocks; body weight, feed, metabolism, milk, methane and reserves (with two stocks). The goat model was set up to simulate indoor facilities in which the goat was fed a mixed ration. Then, 24 goats were used to evaluate the model during 150 days of lactation. A calorimetry system based on an open circuit respiration mask was used for quantification of respiratory CH_4 production, as a way to validate the CH_4 simulated. The mathematical simulation model estimated an average CH_4 conversion factor (Ym) value of 5.3%, and an average daily CH_4 production of 1.55 MJ/d. The average daily CH_4 production for the validation group of goats was 1.51 MJ/d. Based on our simulation over 5 months of lactation for a mixed diet, use of the Intergovernmental Panel for Climate Change values (Ym = 6.5) could result in an overestimation of enteric CH_4 for dairy goats fed concentrate diets.

1. Introduction

Global warming, caused by increasing atmospheric concentrations of greenhouse gases, is a major worldwide environmental, economic and social threat (Intergovernmental Panel on Climate Change (IPCC), 2007). Dietary modifications (McAllister et al., 1996; Moss et al., 2000; Beauchemin et al., 2008) may help to mitigate both methane (CH_4) emissions and nitrogen (N_2) excretions.

To develop strategies to mitigate ruminant CH_4 emissions, it is necessary to quantify CH_4 production under a wide range of circumstances. Different techniques are currently available to measure CH_4 produced by ruminants; however, their application is complex and requires costly installations (Johnson and Johnson, 1995). Therefore, mathematical relationships have been developed to predict CH_4 emissions. In the widely used IPCC Tier 2 method, CH_4 production is a fixed fraction of gross energy intake. Other empirical equations are based on feed characteristics or digestibility of feed components (Blaxter and Clapperton, 1965; Moe and Tyrrell, 1979). All of them represent a particular phenomenon at a point of time. In contrast to these empirical models, mechanistic models are sensitive to dietary changes and take into account fermentative processes at a more detailed level (Dijkstra et al., 2011). Other approaches, such as dynamic systems, represent the change of a determined phenomenon over time. A dynamic system modeling approach can be helpful in evaluating the impact of different interventions in CH_4 production of a whole animal as a system (Benchaar et al., 1998; Kebreab et al., 2008).

The aim of this study was to develop, represent and assess a mathematical model for dairy goats which, using as inputs nutritional information from mixed rations, could (a) predict daily changes of CH_4 emissions over the lactation period and (b) quantify the total amount of dry matter intake, milk produced and CH_4 emitted during a period of time.

2. Materials and methods

To represent and develop the mathematical model we used the main components of a system dynamic software (computer-aided simulation via object-oriented modeling), although the model proposed was a mechanistic dynamic model. The most important elements of the system were the state variables. State variables were indicators of the current status of the system. They were the variables on which all the other calculations in the model are based. A state variable represents an accumulation or stock of mass or en-

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ergy, for instance. These stocks were created and destroyed by the result of the control variables in the system. System elements that represent the action or change in a state variable were called flows or control variables. The remaining set of variables in any model might be classed as converters or transforming variables. Therefore, we were developed and represented a dynamic model of CH_4 production by goats and their change over the lactation period based on stocks and flows component of a system dynamic software.

The goat model was set up to simulate indoor facilities in which animals are grouped in pens by their production potential. All parameters considered in this study assumed values from intensive nutrition system in Spain, as indicate by FEDNA (2009). Each element of the model is specified by initial conditions. The initial conditions may derive from actual measurements or estimates. The estimates, in turn, could be derived from empirical information. To develop and represent the model, information from experiments conducted by Aguilera et al. (1990), Lachica and Aguilera (2005), Fernández et al. (2005, 2008) and López et al. (2010) were used, while the remaining information was found in the literature. To evaluate the goat model, a dairy goat lactation trial was conducted at the University facilities.

2.1. Model development and structure

Recent advances in computer simulation allow development and representation of dynamic models. The dynamic model described in this section is a deterministic type, which means that any perturbations of the system are assumed to be absent. The state of a given variable at any time is entirely determined by previous states of that variable as well as the other variables upon which it is dependent.

To develop a dynamic model, we used Stella 9 (High Performance System, Inc., Hanover, New Hampshire, 1997). In this language, stocks and flows were building blocks (objects) and simulated, respectively, the state variables and the relative rates of change. Stocks were accumulations within the system. Flows were the movement of content throughout the system, whereas flows were regulated by valves (converters) and connectors, which link the various part of the model.

A diagrammatic representation of the relationship among stocks (compartments) of the conceptual model is shown in Fig. 1 (stock and flow diagram). The dairy goat simulation model was divided in seven stocks that represent the state variables of the model: BW = body weight, FEED = accumulation of dry matter intake, METABOLISM = metabolisable energy available for work, two stocks for RESERVES = metabolisable energy accumulated in body reserves, MILK = milk energy accumulated and, METHANE = CH_4 accumulation. The physiological flows (material unit per time) were converted in energy (MJ) per material unit and time.

Duration of lactation was fixed at 150 days (d), and the simulation time unit was "days", so a long-term time horizon of 5 months was therefore considered. The time step (dt) was of 0.25 and Runge–Kutta4 was the integration method used in this study. Acronyms, variables and parameters used here are listed in Table 1. The diagrammatic representation of the model is shown in Fig. 1. The structure represented in Fig. 1 corresponds exactly to the following integral equation, although in general the flows are functions of the stock and other state variables and parameters:

$$\mathrm{Stock}(t) = \int_{t_0}^{t} [\mathrm{Inflow}(s) - \mathrm{Outflow}(s)]ds + \mathrm{Stock}(t_0)$$

where Inflow(s) represents the value of the inflow at any time s between the initial time t_0 and the current time t.

2.1.1. Stock BW (body weight, kg)

Evolution of BW (kg) during lactation was expressed by the integral equation, following the pattern described by Fernández et al. (2008) for Murciano-Granadina dairy goats (initial and maximum BW were 30 and 45 kg, respectively).

$$\mathrm{BW}(t) = \int_{t_0}^{t} [\mathrm{gain}(s)]ds + \mathrm{BW}(t_0)$$

where the inflow gain (kg/d) was; gain = dif′ × rate, being dif′ = BW maximum − BW actual, and rate range between 0.0 and 1.0.

2.1.2. Stock FEED (dry matter intake accumulation, kg)

The stock FEED (kg) represents the quantity of dry matter intake (DMI) accumulated during the lactation period and was expressed as an integral equation

$$\mathrm{FEED}(t) = \int_{t_0}^{t} [\mathrm{DMId}(s)]ds + \mathrm{FEED}(t_0)$$

As stock integrate their flows, in this case the inflow DMId (kg/d) was described by the Von Bertalanffy (1968) growth function, based on the assumption that DMI is proportional to the difference between initial DMI and maximum DMI. Initial DMI (DMIi) and maximum (DMImax) were obtained from a trial conducted in Murciano-Granadina goats during lactation (Fernández et al., 2005); 0.8 and 2 kg/d respectively.

$$\mathrm{DMI} = [\mathrm{DMIi} - \mathrm{DMImax}] \times \mathrm{e}^{(-0.025\times t)} + \mathrm{DMImax}$$

2.1.3. Stock METABOLISM (metabolisable energy available for work, MJ)

The energy requirements were expressed as metabolisable energy (ME) with MJ as units. The integral equation is:

$$\mathrm{METABOLISM}(t) = \int_{t_0}^{t} [\mathrm{MEI}(s) - (\mathrm{MEm}(s) + \mathrm{REmilk}(s) - c(s) - \mathrm{MEloc}(s))]ds + \mathrm{METABOLISM}(t_0)$$

where

$$\mathrm{MEI} = \mathrm{DEI} - (\mathrm{CH_4d} + \mathrm{MJurine}) \quad [\text{metabolisable energy intake, MJ/day}]$$

c is a parameter described below and equal to −0.093.

MEloc is the metabolisable energy for locomotion, also described below.

$$\mathrm{DEI} = \mathrm{DEc} \times \mathrm{GEI} \ [\text{digestible energy intake, MJ/d}]$$

DEc; apparent digestibility coefficient of energy that range between 0.65 and 0.77 and it was obtained experimentally from López et al. (2010) for mixed rations and Murciano-Granadina goats.

$$\mathrm{GEI} = \mathrm{DMId} \times \mathrm{GE} \quad [\text{gross energy intake, MJ/d}]$$

GE; gross energy was 18 MJ/kg DM and neutral detergent fiber (NDF) ranged from 355 to 550 g/kg DM according to FEDNA (2009) recommendation for Spanish feeding systems. NRC (2001) reported lower digestibility when increase the level of fiber; lower NDF at the beginning of lactation with higher DEc was assumed in our study. The linear relationship between DEc and NDF on the simulation model was:

$$\mathrm{DEc} = 1.0213 - 0.0007 \times \mathrm{NDF}$$

Being this equation based on data from López et al. (2010) and FEDNA (2009).

CH_4d; see below [MJ CH_4/d].

MJurine = 0.022 × kg $BW^{0.75}$ experimentally obtained by López et al. (2010) for mixed diets [urine energy]. We assumed a