Computers and Electronics in Agriculture 91 (2013) 1–9

Contents lists available at SciVerse ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

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

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ARTICLE INFO

Article history:
Received 12 December 2011
Received in revised form 19 November 2012
Accepted 29 November 2012

Keywords:
Calorimetry
Methane
STELLA
LabVIEW
Goats

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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http://dx.doi.org/10.1016/j.compag.2012.11.013

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:

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

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).

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

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

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

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.

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

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:

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

where

$$\text{MEI} = \text{DEI} - (\text{CH}_4\text{d} + \text{MJurine}) \quad [\text{metabolisable energy intake, MJ/day}]$$

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

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

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

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.

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

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:

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

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

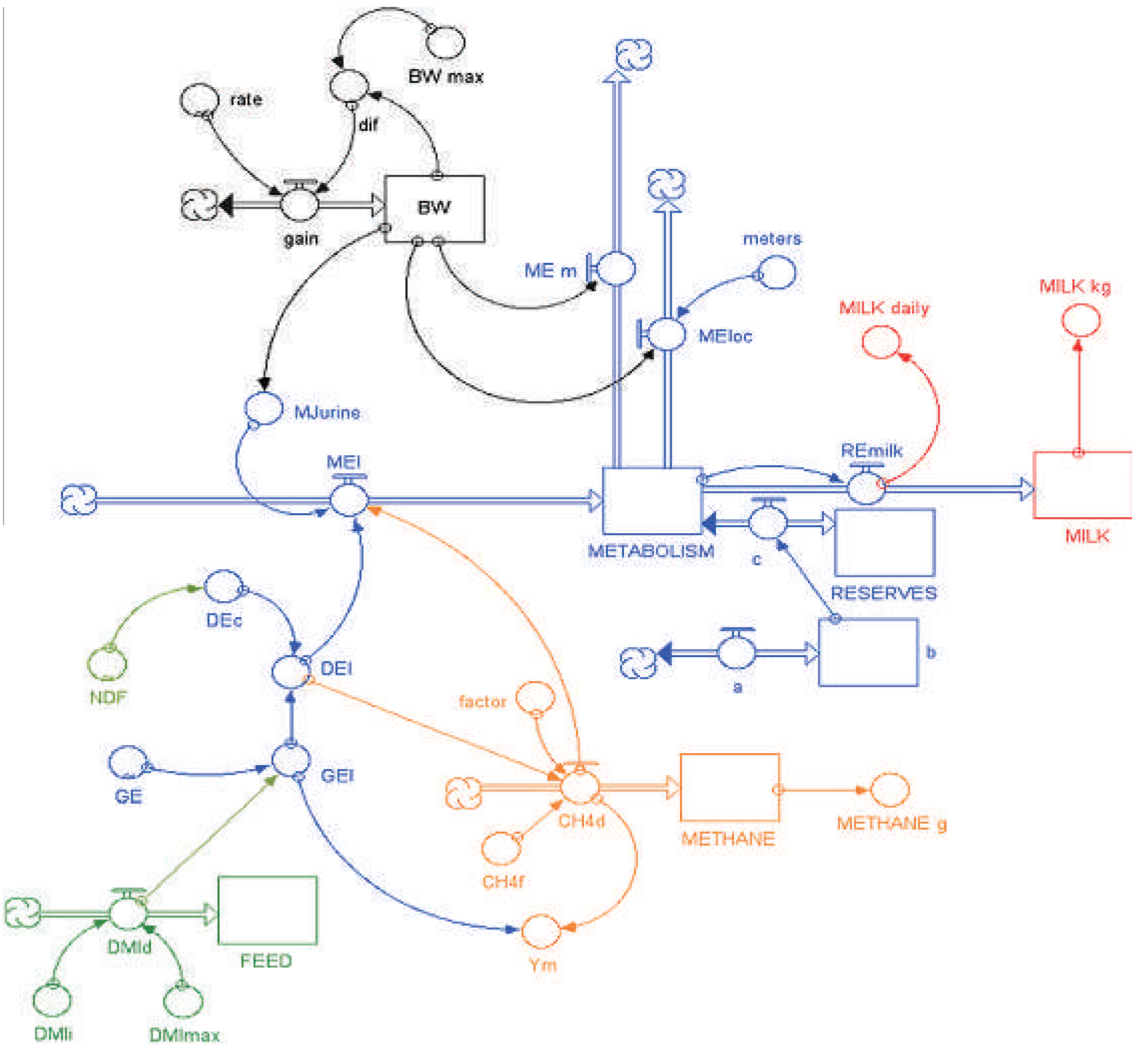

Fig. 1. Diagrammatic representation of the mathematical model. See Table 1 for legend.

constant value independent of diet and affected only by metabolic weight.

The energy requirements for maintenance (MEm, MJ/d) were estimated using the equation of Lachica and Aguilera (2005):

$$\text{MEm} = 0.401/\text{kg BW}^{0.75}$$

REmilk: ME retained in milk (k_l) was 0.669 (Aguilera et al., 1990) times METABOLIMS.

c was equal to b (see RESERVES below).

The energy cost for locomotion (MEloc, MJ/goat/d) was estimated using the empirical equation of Lachica and Aguilera (2005) for goats:

$$\text{MEloc} = [(0.00335 \times \text{BW} \times \text{meters})/700]$$

The locomotion was assumed to be in horizontal directions and indoors, and for the simulation 1000 m were considered.

METABOLISM(t_0) = 3.59 MJ (initial condition), this value being the amount of ME per kg of milk (Aguilera et al., 1990).

2.1.4. Stock RESERVES (metabolisable energy from reserves, MJ)

During lactation, mobilisation of energy reserves is a key factor influencing milk production. Negative energy balance is a physiological phenomenon in high yielding dairy goats in early lactation. A dairy goat is in negative energy balance from the onset of lactation until 100–120 d afterwards. This is mainly caused by a nutritive deficit due to the non-synchronisation of lactation and feed intake. The flows of ME reserves for mobilisation was estimated using the quadratic model of Fernández et al. (2008) (RESERVES, MJ = $5.401 - 0.093t + 0.032t^2$). The quadratic function was expressed as a stock and flow diagram:

$$\text{RESERVES}(t) = \int_{t_0}^{t} c(s)ds + \text{RESERVES}(t_0)$$

where *c* = *b* = –0.093, *being both the first derivate of the quadratic function RESERVES.*

RESERVES(t_0) was the intercept of the parabolic equation (5.401 MJ).

$$b(t) = \int_{t_0}^{t} a(s)ds + b(t_0)$$

where $a = 0.046$ is the second derivate of the quadratic equation RESERVES.

2.1.5. Stock MILK (milk energy accumulated, MJ)

The quantity of milk produced depends on the net energy available for lactation.

$$\text{MILK}(t) = \int_{t_0}^{t} \text{REmilk}(s)ds + \text{MILK}(t_0)$$

where

Table 1
List of acronyms, parameters and variables used in the model.

Acronym	Description and units	Determination and reference
a	Second derivate from quadratic expression of body reserves (MJ/d)	0.046 (Fernández et al., 2008)
b = *c*	First derivate from quadratic expression of body reserves (MJ)	−0.09313 (Fernández et al., 2008)
BW	Body weight (kg)	30 initial value
BWmax	Body weight maximum (kg)	45
CH_4d	Flow of CH_4 production (MJ/d)	Exponential function (Von Bertalanffy, 1968)
CH_4f	Maximum CH_4 production (MJ/d)	2 (Tovar-Luna et al., 2010)
DEc	Digestible coefficient energy (%)	65–77 (López et al., 2010)
DEI	Digestible energy intake (MJ/d)	GEI × DEc
dif′	Difference between BWmax and BW (kg)	15
DMId	Dry matter intake (kg/d)	Exponential function (Von Bertalanffy, 1968)
DMIi	Initial DMI (kg/d)	0.8 (Fernández et al., 2005)
DMImax	Dry matter intake maximum (kg/d)	2 (Fernández et al., 2005)
factor	Percentage of DEI converted to CH_4	6.5 (López et al., 2010)
FEED	Accumulation of DMI (kg)	0 initial value
GE	Diet gross energy (MJ/kg DM)	18 (FEDNA, 2009)
GEI	Gross energy intake (MJ/d)	DMId × GE
MEI	Metabolizable energy intake (MJ/d)	DEI − (CH_4d + MJurine)
MEloc	Metabolizable energy locomotion (MJ/d)	(0.00335 × BW × meters)/700 (Lachica and Aguilera, 2005)
MEm	Metabolizable energy for maintenance (MJ/d)	0.401 × $BW^{0.75}$(Lachica and Aguilera, 2005)
METABOLISM	ME accumulation (MJ)	3.59 initial value
meters	Distance (m)	User
METHANE	CH_4 accumulation (MJ)	0.7 initial value (López et al., 2010)
METHANE_g	CH_4 accumulation (g)	55.65 kJ/g CH_4 (Blaxter and Clapperton, 1965)
MILK	Milk accumulation (MJ)	0 initial value
MILK_daily	Milk production (kg/d)	REmilk/3.59
MILK_kg	Milk production (kg)	MILK/3.59 MJ/kg milk
MJurine	Urine production (MJ/d)	0.022 × $BW^{0.75}$
NDF	Neutral detergent fiber (g/kg)	355–550 (FEDNA, 2009)
rate	Rate of BW (kg/d)	0–1
RESERVES	ME accumulation (MJ)	5.4 initial value (Fernández et al., 2008)
REmilk	Energy retained in milk (MJ/d)	0.669 × METABOLISM (Aguilera et al., 1990)
Ym	CH_4 conversion factor (%)	CH_4d/GEI × 100

$$\mathrm{REmilk} = 0.669 \times \mathrm{METABOLISM}$$

$$\mathrm{MILK}(t_0) = 0\ \mathrm{MJ}$$

As the units are expressed in MJ, it was converted to mass units. Thus:

The kg of milk produced per day was MILK daily = REmilk/3.59.

Total kg of milk produced was; MILK kg = MILK/3.59.

2.1.6. Stock METHANE (CH$_4$ accumulated, MJ)

The stock METHANE is the concentration of CH_4 or its accumulation. The integral equation is:

$$\mathrm{METHANE}(t) = \int_{t_0}^{t} \mathrm{CH_4d}(s)ds + \mathrm{METHANE}(t_0)$$

The methane produced dairy (MJ/d) followed the Von Bertalanffy (1968) exponential model, based on the assumption that CH_4 production is proportional to the difference between initial and theoretical maximum CH_4 production. The expression is as follow:

$$\mathrm{CH_4d} = (\mathrm{factor} \times \mathrm{DEI} - \mathrm{CH_4f}) \times e^{(-0.0025 \times t)} + \mathrm{CH_4f}$$

Differences in enteric CH_4 emissions become more pronounced when expressed per unit of digested feed (Dijkstra et al., 2011) instead of unit of feed intake, our initial CH_4 production was factor times DEI. From the study of López et al. (2010) in dry and non-pregnant Murciano-Grandinas goats fed total mixed rations, we assumed a factor of 0.065. For CH_4f a maximum value considered was 2 MJ/d based on the studies of Tovar-Luna et al. (2010) in Alpina dairy goat during lactation.

The METHANE(t_0) considered was 0.7 MJ based on the study of López et al. (2010) with dry Murciano-Granadina goats fed mixed rations.

To express energy values of CH_4 on mass units, we assumed a value of 55.65 kJ/g CH_4 according to Blaxter and Clapperton (1965).

$$\mathrm{METHANE\ g} = \mathrm{METHANE}/0.05565$$

In addition, the CH_4 conversion factor (CH_4/GEI) was obtained:

$$\mathrm{Ym} = (\mathrm{CH_4d}/\mathrm{GEI}) \times 100$$

As we observed, the physiological flows (material unit per day) or stocks (material unit) were converted to net energy flows (MJ/d) or net energy (MJ) and viceversa with the set of parameters needed for conversion.

2.2. Validation of the mathematical model

2.2.1. Lactation trial

The protocol for experimental procedures was approved by the Committee on Animal Use and Care at the Polytechnic University of Valencia (Spain) and followed the codes of practice for animals used in experiment proposed by the EU (2003). The validation trial was conducted at the Experimental Farm of the Animal Science Department (Institute for Animal Science and Technology), Valencia, Spain. A homogenous group of 24 Murciano-Granadina dairy goats from a herd of 200 goats was selected to evaluate the model. The group was homogeneous in terms of lactation number (5.0), litter size (1.9 kids), milk production in the previous lactation (610 kg/lactation per goat) and body weight (42.8 kg). The experiment had a lactation period of 150 d, and during this time milk yield (kg/d) was recorded once per week. The goats were offered 3 kg/d per goat of a mixed ration based on chopped alfalfa hay, barley, corn, sunflower, soy meal and premix (forage concentrate ratio 40:60). The diet contained 18 MJ GE/kg DM and 16% CP (AOAC, 2000) and the energy and protein recommendation was based on Lachica and Aguilera (2005) and FEDNA (2009). Goats had water freely available at all times and milking took place ones per day.

2.2.2. Gas measurements

Respiration calorimetry based on open circuit mask system for measuring O_2 consumption, CO_2 and CH_4 production (Taylor et al., 1982) was used for respiratory gas measurements. The open circuit respiration device was designed to fit small ruminants and installed on a trolley to increase the mobility of the unit through the farm. All analytical instrumentation was mounted on a kart on wheels, with exterior plumbing readily accessible. The rotameters, flow meters and fan were mounted on the bottom of the unit. Gas analyzer and computer were mounted on top of the unit as shown in Fig. 2a and b. A description of the system is found in López et al. (2010) and Fernández et al. (2012).

The portable respiration device was used as an indirect open calorimeter, since it was equipped with an air entry and a calibrated flow meter (3000 L/h; Thermal Mass Flowmeter Sensyflow with totaliser VT-S, ABB Inc., Alzenau, Germany) that was connected to a centrifugal fan (CST60 Soler Palau Inc., Parets del Vallès, Barcelona, Spain). The system automatically totalises the air volume and by means of a membrane pump (250 L/h; ABB Inc., Alzenau, Germany) sends an aliquot sample into a gas analyser. Before conducting the air sample to the gas analyser, samples are filtered and pass through a 0.5-liter flask containing 100% (W/V) silica gel (J.T. Baker Analyzed Reagent, Capitol Scientific, Inc., Phillipsburg, NJ, USA) to absorb moisture.

The concentration of O_2 in exhaled and atmospheric air was measured by an oxygen analyser based on the paramagnetic principle. CO_2 and CH_4 concentration in atmospheric air were measured by using an infrared analyser. An autocalibrated analyser model Easyflow 3020 (ABB Inc., Alzenau, Germany) determined the three gases.

This analyser was controlled by MODBUS with a PC (Fujitsu Siemens Lifebook Sseries, Pentium 4 laptop, Munich, Germany) under a LabVIEW (http://www.ni.com/labview) environment in order to save the data to hard disk. The data acquisition frequency was one recording per minute because the PC memory was able to store nearly an unlimited amount of data. The flow meter was monitored by a 10 bits Analog to Digital Converter, model DS2438 (Maxim Integrated Products, Inc., Sunnyvale, CA, USA) with a built-in temperature sensor. The electronics prototyping platform Arduino (www.arduino.cc) was selected to control it and send data from gas analyser to LabVIEW by RS-232 protocol in real time (Fig. 3).

Final calculations used in open circuit followed the Haldane transformation (Willmore and Costill, 1973). The whole respiration system was calibrated. For 75 min and 1 h pure gas N_2 (99.99%) and CH_4 (99.99%) were injected, respectively. The N_2 recovery of the system was assessed gravimetrically by injecting 85 g of N_2 and 40 g of CH_4 into the mask (McLean and Tobin, 1990) and considering the density of N_2 as 1.2509 g/L and CH_4 as 0.7162 g/L, respectively. The N_2 and CH_4 cylinders were weighted on an electronic scale before and at the end of the recovery test. The amount of N_2 consumed was calculated as the reduction in O_2 multiplied by air flow (50 L/min) and time. A correction factor (volume of gases injected and detected by the system) was obtained for N_2 and CH_4.

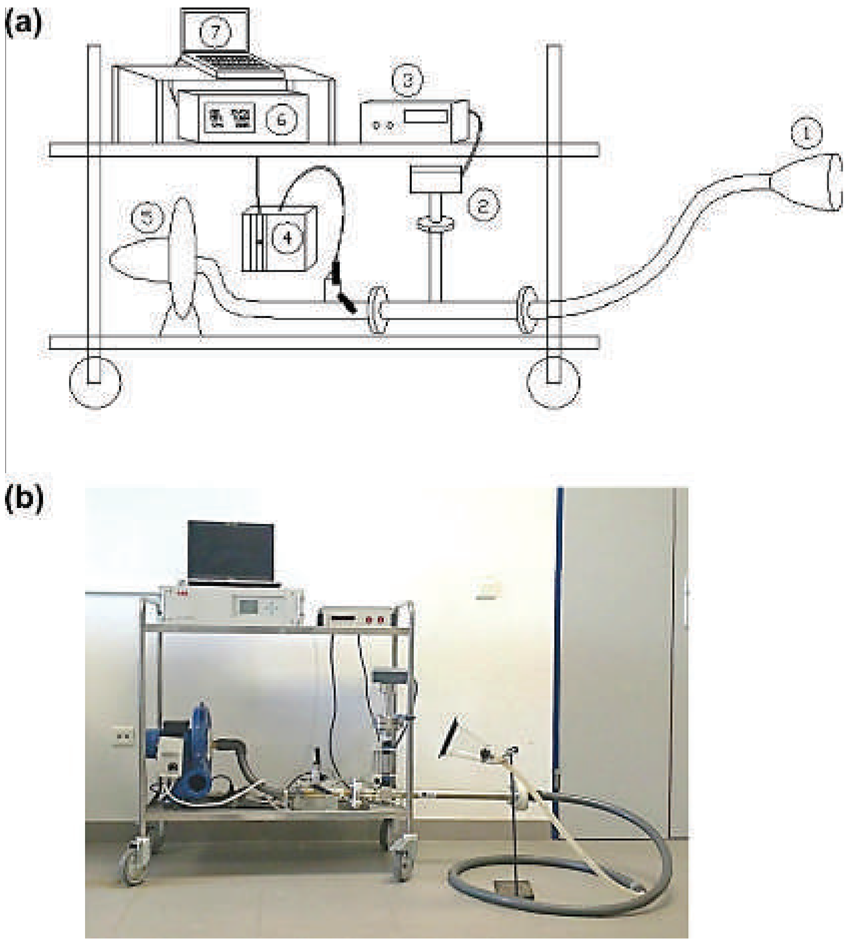

Fig. 2. Diagrammatic representation of the respiration mask device. (a) 1 – mask; 2 – thermal mass flow meter; 3 – transduccer and totaliser; 4 – pump and flow meter; 5 – fan; 6 – gas analyser; 7 – labtop with software included. (b) Picture of the system.

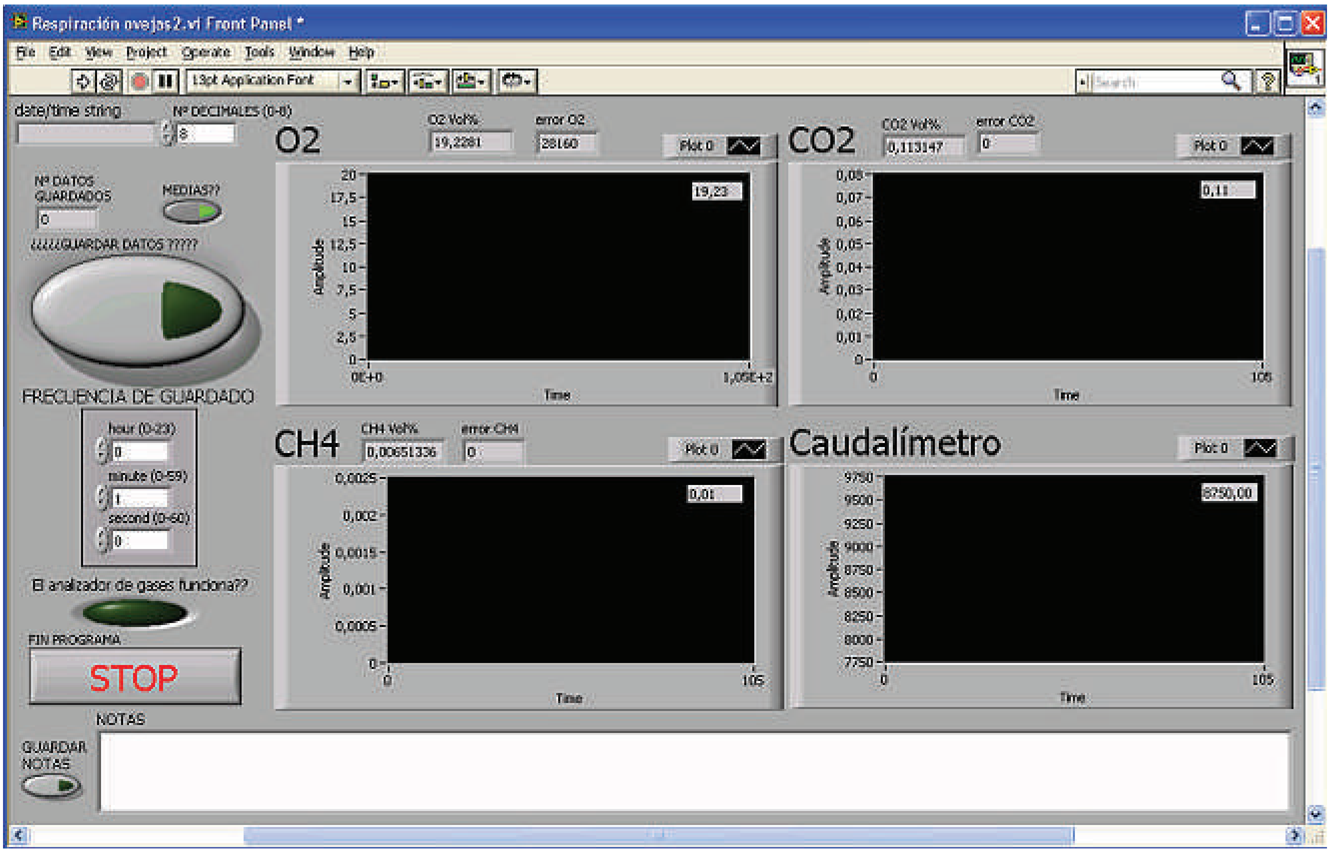

Fig. 3. Panel of the LabVIEW program for monitoring gas analyser and the flow meter.

Gas measurements were recorded on day 7th and 14th of lactation and then every 14 d of lactation (28, 42 until 140 d). Eight of the 24 goats were selected randomly and the same 8 goats were always used for gas measurements, while the 16 goats left were used only for milk yield records. Gas exchange was measured for each goat for 15 min/h and repeated every 3 h for 24 h (8 measures/d with 4 goats/h).

2.2.3. Statistical analysis

Data from the simulation and validation studies were used to evaluate the mathematical model. The coefficient of determination (R^2), slopes and intercept between observed and simulated values were used to gauge the quality of the prediction. The prediction error was assessed by calculating the mean square prediction error (MSPE). The MSPE was decomposed (Bibby and Toutenburg, 1977) into error in central tendency (ECT), error due to regression (ER), and error due to disturbances (ED). Root MSPE was used as a measure of accuracy of prediction (RMSPE). All calculations were performed by SPSS v16 (2008).

3. Results and discussion

3.1. Model prediction and validation

The mathematical simulation model was calibrated to obtain a milk production pattern for Murciano-Granadina dairy goats with a BW of 30 kg postpartum (maximum BW = 45 kg) that were milked once daily throughout 150 d of lactation period. The initial DMI was 0.8 kg/d and the goal seeking was of 2 kg/d. The concentration of NDF in diets is negatively correlated with energy concentrations and affects the digestibility (NRC, 2001). GEI and NDF of the diet followed opposites tendencies during lactation as previously indicated and recommend by FEDNA (2009). Initial CH_4 production considered in our simulation was 0.7 MJ/d based on the study of López et al. (2010) with dry Murciano-Granadina goats fed mixed rations.

Under these steady state conditions, the mathematical simulation model predicted milk production that reached a peak of 3.6 kg/d at about 60 d of lactation and then slightly declined as lactation advance, as described Fernández et al. (2002, 2006). The simulation results for milk production are shown in Fig. 4a. The average value of the simulated lactation (2.9 kg/d) is comparable to the estimates reported by Vidal et al. (2008) for Murciano-Granadina dairy goat herds under the Spanish Official Milk Control system. Results of the regression between observed and predicted milk production with the model developed are presented in Fig. 4b. This model underestimated milk production up to 2.9 kg/d and then overestimated it after that. The coefficient of determination was 0.94 and the error of prediction (RMSPE) was 0.563, as shown in Fig. 4b and Table 2.

The daily CH_4 production simulated during 150 d of lactation went from 0.96 to 1.77 MJ/goat at the beginning and mid-end of lactation, respectively (see Fig. 5a). For the validation trial the calibration factor for O_2 and CH_4 were close to one: 1.0039 ± 0.0020 and 1.1980 ± 0.0303 respectively, showing the adequacy of the whole system (open circuit respiration mask), which confirms the absence of leaks and good performance of the analysers. The average simulated value was 1.554 MJ/d and the value observed during the validation trial was 1.51, both values considering 150 d of lactation. Results of the regression for observed versus predicted CH_4 production are shown in Fig. 5b and Table 2. The

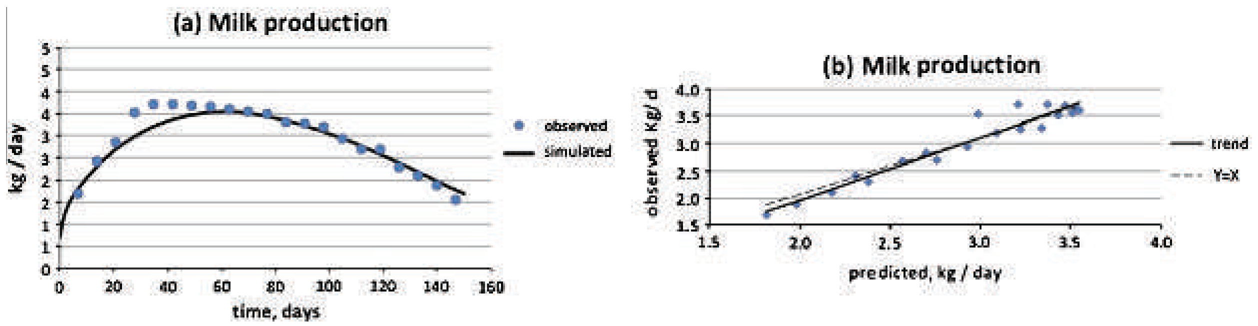

Fig. 4. Model validation: (a) milk production over 150 d of lactation, (b) observed vs. predicted milk production during first 150 d of lactation. Mean predicted milk production (kg/d) = 2.86; root mean square prediction error = 0.563; error in central tendency (ECT) = 0.006; error due to regression (ER) = 0.009; and error due to disturbances (ED) = 0.025. Regression line (trend); line of equality ($Y = X$).

Table 2
Observed vs. predicted regression coefficients and goodness of fit of data from milk yield (kg/d) and methane production (MJ/d) during 150 d of lactation.

Variable	Average	α[a]	β	R^2	RMSPE	ECT	ER	ED
MY[b], kg/d	2.86	−0.328	1.145	0.936	0.563	0.006	0.007	0.025
Line of equality		1.036	0.927					
CH_4, MJ/d	1.55	−0.781	1.481	0.959	0.253	0.001	0.016	0.007
Line of equality		0.991	0.854					

[a] Regression coefficients: Observed = $\alpha + \beta$ Predicted. R^2 = coefficient of determination. RMSPE = root mean square prediction error. ECT = error in central tendency. ER = error due to regression. ED = error due to disturbances.
[b] MY = milk production. CH_4 = methane production.

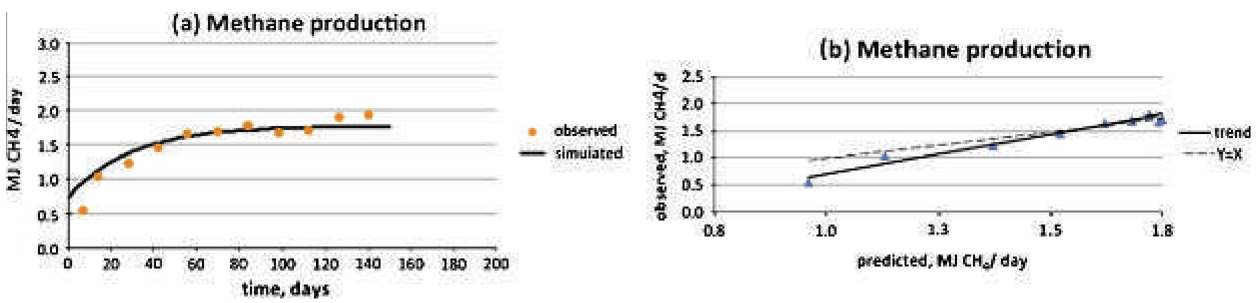

Fig. 5. Model validation: (a) CH_4 production over 150 d of lactation, (b) observed vs. predicted CH_4 production during 150 d of lactation. Mean predicted CH_4 production (MJ CH_4/goat and day) = 1.554; root mean square prediction error = 0.253; error in central tendency (ECT) = 0.001; error due to regression (ER) = 0.016; and error due to disturbances (ED) = 0.007. Regression line (trend); line of equality ($Y = X$).

coefficient of determination was 0.96 and the prediction error was 0.253. The mathematical simulation model underestimates CH_4 production below 1.6 MJ/d. Good accuracy was obtained for CH_4 production during 21 weeks of lactation, with error in central tendency of 0.001; error due to regression of 0.016 and error due to disturbances of 0.007 (Fig. 5a, b and Table 2).

Tovar-Luna et al. (2010) compared Alpine dairy goats during lactation fed *ad libitum* and near maintenance. CH_4 emission was considerably less with consumption near MEm than with *ad libitum*. CH_4 emission was approximately twice as great in late lactation than in early and mid lactation in does consuming *ad libitum* (0.94 MJ/d and 1.01 vs. 2.12 for early, mid and late lactation respectively), and CH_4 emission was significantly lower in early lactation compared with mid and late lactation in does consuming near MEm (0.24 MJ/d vs. 0.95 and 0.98 for early, mid and late lactation respectively). Tovar-Luna et al. (2011), studying the effect of level of feeding on energy utilization by Angora goats when diets had 60% concentrate, observed that CH_4 emissions ranged from 0.41 (low level of feeding) to 0.46 (high level of feeding) MJ/d, and no significant differences were observed in comparison to Angora does fed near the ME requirement for maintenance. The same authors found that the energy losses in CH_4 by Angora does with different feeding levels were 0.55, 0.60 and 0.64 MJ/d for level of feeding low, medium and high respectively. Although the whole lactation period according to the Spanish Official Milk Control is 210 d, our study considers 150 d. So, we found simulated values of 0.96 MJ CH_4/d at 7 d of lactation, 1.68 MJ/d at 70 d and 1.77 MJ/d at 140 d of lactation, similar to those observed by Tovar-Luna et al. (2010) with Alpine dairy goats and different level of feeding.

3.2. Model prediction and applications

The IPCC (2007) national greenhouse inventory guidelines outlines methods for estimating CH_4 emissions from enteric fermentation. Enteric CH_4 emissions from ruminants are proportional to DMI and thus usually normalised by expressing them on the basis of DMI, either as g CH_4/kg DMI or as a percentage of GEI (also called Ym factor, IPCC, 2007). Kebreab et al. (2008) predicted daily emissions for lactating dairy cows that ranged from 15 to 35 g CH_4/kg DMI, while Shibata and Terada (2009) found values of 36 and 37 g CH_4/kg DMI for sheep and goats, respectively. In our simulation for dairy goats, this value averaged 16.78 g CH_4/kg DMI, lower values that these authors with diets based on timothy and alfalfa hay. Differences in enteric CH_4 emission commonly become more pronounced when expressed per unit of digested feed (Dijkstra et al., 2011). For example, Pinares-Patino et al. (2003) evaluated CH_4 emissions of beef cows grazing on timothy at four stages of maturity. Methane production per unit feed intake did not differ (21.0 and 22.1 g/kg DM in vegetative and senescent stage, respectively) but differences in CH_4 production were much more pronounced when expressed per unit of digested feed (27.0 and 39.2 g/kg digested DM, respectively). Since only digested nutrients are ultimately available for metabolism in the body of the animal, such differences in CH_4 production when expressed per unit digested feed are of greater interest, and this is the reason our mathematical model estimated CH_4 emissions from digested feed rather than DM intake.

Average daily feed intake (to determine GE intake) and CH_4 conversion factor (Ym) are used to estimate CH_4 emissions (IPCC, 2007). Using IPCC Tier 2 (2007) methodology for dairy cattle, a Ym of 6.5% of GEI is suggested With diets consisting primarily of grains, the percentage of GEI that is converted to CH_4 in the rumen is typically less than 4% compared with 6.5% or more, which is common for animals fed primarily forages (Beauchemin et al., 2009). Kebreab et al. (2008) using a mechanistic model (COWPOLL) for dairy cows, found a lower value for CH_4 emissions (5.6% of GE on average, ranging from 3.8 to 5.6) than IPCC (2007). Torres et al. (2006), using IPCC (2007) methodology suggested Ym values of 5.5% for dairy cattle with high DE diets, as in our situation. Merino et al. (2001) reported that Ym ranged from 4% to 7% for dairy ewes. When the predicted CH_4 production was expressed as percentage of GEI, the average value obtained in our goat mathematical simulation model was 5.3%, lower than the IPCC (2007) recommendation. Johnson and Johnson (1995), feeding beef cattle and dairy cows a range of diets, claimed that the Ym value varies from 2% (concentrate diets) to 12% (forage diets). The IPCC Tier 2 (2007) calculated CH_4 emissions as 6.5% of GEI except if diets contain more than 90% grain, in which case 3% of GEI is lost as CH_4. When using forage diets, there are some dietary mitigation options to reduce CH_4 emissions, so Animut et al. (2008), feeding Boer whether goats fed different levels of *Kobe ledespera* and sorghum-Sudan grass range (differing in amount of condensed tannins) values from 3.2% to 8.8% of GEI.

Therefore, application of the average Ym values for dairy goats fed concentrate mixed rations within this mathematical simulation model will result in lower total emissions compared with estimate using IPCC Tier 2 (2007) methodology. Based on our simulations (mixed ration with 40:60 forage concentrate ration), the IPCC (2007) Ym conversion factor overestimates CH_4 production from goats (1.4 points). Kebreab et al. (2008) also use a mechanistic model for dairy cows and found an overestimation of CH_4 production by IPCC (2007) of about 13%.

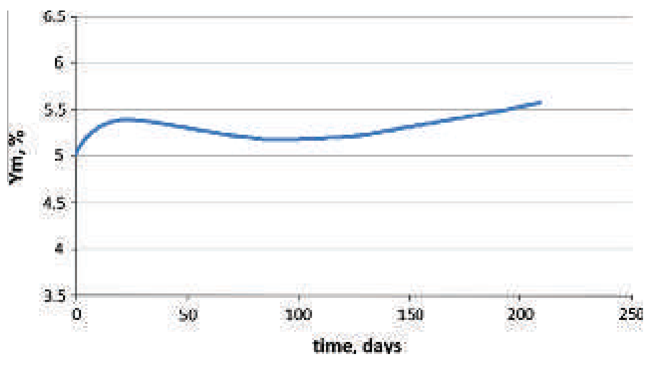

Fig. 6. Simulation of the methane conversion factor (Ym, %) during 210 d of lactation.

Using the present simulation model we can use as input the initial conditions at the beginning of lactation. So, we can consider initial body weight as 30 kg and if we use total mixed ration we could incorporate GE of the diet of 18 MJ/kg DM, an initial energy digestibility value of 77%, DMI of 0.8 kg and NDF of 355 g/kg DM. Under this scenario the total amount of DMI consumed per goat during the first 150 d of lactation would be 253.1 kg, with 443.1 kg of milk accumulated during 150 d of lactation and total amount of CH_4 emission of 4.05 kg. Moreover, it is possible to represent the CH_4 conversion factor simulated during lactation, as shown in Fig. 6.

4. Conclusions

A mechanistic dynamic model to predict CH_4 output by goats was developed using a computer-aided simulation device via object-oriented modeling. The goat model was set up to simulate indoor facilities in which the goat was fed mixed rations. The integration of information generated from isolated experiments and literature into the simulation model contributed to a more dynamic understanding of the system under study. 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. Result of simulation studies help researchers to identify specific nutritional aspects to refining, providing data for improving the usefulness of the model.

Acknowledgment

This study was support by INIA Project (Ref. RTA2011-00107-C02-02).

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