Development of a dynamic model for prediction of energy in milk protein, lactose, fat and enteric methane emissions in goats based on energy balance and indirect calorimetry studies

Carlos Fernández[†,1] and Juan J. Loor[‡]

[†]Instituto de Ciencia y Tecnología Animal, Universitat Politècnica de Valencia, España.

[‡]Department of Animal Sciences, Division of Nutritional Sciences, University of Illinois, USA.

[1] Corresponding author: cjfernandez@dca.upv.es

Abstract

Feed costs are overwhelmingly the largest expense for dairy producers. Thus, improving milk production efficiency (milk fat and protein are the main incomes for farmers) is of great economic importance in the dairy industry. The main objective of this study was to develop a dynamic energy partitioning model to describe and quantify how dietary energy from carbohydrate, protein and fat is transferred to milk (protein, lactose and fat) in dairy goats. In addition, due to increasing worldwide concerns regarding livestock contribution to global warming, methane (CH_4) emission was quantified. For modeling purposes, 158 individual goat observations were used and randomly split into 2/3 for model development and 1/3 for internal evaluation. For external evaluation, 20 different energy balance studies from the literature (77 observations) were evaluated. The Root Mean Square Prediction Error (RMSPE) was 13.2% for loss of energy in CH_4, 16.8% for energy in fat, 19.4% for energy in protein and 22.3 energy in lactose. Mean bias was around zero for all variables and the slope bias was zero for milk energy in lactose, close to 1% for milk fat (1.01%) and around 3% and 10% for protein and CH_4, respectively. Random bias was greater than 85% for energy in CH_4 and milk energy components indicating non-systematic errors and that the equation in the model fitted the data properly. Analyses of residuals appeared to be randomly distributed around zero. Slopes of regression lines for residuals versus predicted were positive for milk fat energy, zero for lactose and negative for milk energy in protein and CH_4. This model suggested for use with mixed diets and by-products to obtain balanced macronutrient supply, methane emissions and milk performance during mid lactation could be an interesting tool to help farmers simulate scenarios that increase milk fat and protein, evaluate CH_4 emissions, without the costs of running animal trials.

Lay Summary

The present model using mixed diets with different by-products to obtain macronutrient balance, methane emission and milk performance during mid lactation could be an interesting tool to help farmers, without the costs of running animal experiments. The dietary change from grain-based to partial replacement with agro-industrial-byproducts in mid-lactation dairy goats was accompanied by transformations in carbohydrate and fat energy transfer to support production. The output underscored that both oxidation of carbohydrate and fat interact to maintain milk energy output.

Teaser Text

The model allows creating different scenarios with mixed rations and estimating environmental impact (methane emissions) and the partitioning of milk production into fat, protein and lactose. Within milk quality, the cheese extract (fat plus protein) is the main parameter for farmers because the price of milk depends on it.

Keywords: dynamic model, energy transfer, mixed diets, lactation, goats

Abbreviations: CCC, concordance correlation coefficient; CH_4, methane; E, energy; HP, heat production; Hf, heat of fermentation; HPx, heat production from oxidation; OXC, oxidation of carbohydrate; OXF, oxidation of fat; OXP, oxidation of protein; RE, energy retention; RMSPE, Root Mean Square Prediction Error

Introduction

Because feed costs are overwhelmingly the largest expense in dairy farms, higher energy-related production costs can severely affect livestock producers (Bailey et al., 2005). With these scaling costs, today more than ever before, producers and nutritionists should focus on improving feed efficiency without compromising herd health and welfare (Bethard and Stokes, 1999). In recent years, goat milk production has risen markedly in countries such as Spain, which produces 22.6% of the goat's milk in the European Union (FAOSTAT, 2020) ranking second after France (31.9 %). Income over feed cost is a margin that is calculated as milk revenue per ruminant per day minus feed cost per ruminant per day. Even though income over feed cost is an ideal tool to measure the impact of management and feeding decisions, changes in milk component such as fat and protein are not considered in spite of their large economic impact. In Spain, farmers are paid based on two components in the milk; protein and fat (protein plus fat is the cheese extract). Thus, these solids impact milk price and affect the commercial value of milk in a payment system based on cheese extract (Pirisi et al., 2007).

There are growing concerns that ruminants are one of the largest sources of global methane (CH_4) emissions. Methane accounts for 14% of total global greenhouse gas emissions and is 28 times more potent than CO_2 (IPCC, 2014). Enteric CH_4 emissions from farmed ruminants account for 25% of total CH_4 emissions in the United States (2015 data; US EPA, 2021) and also represent a gross energy loss of 4 to 12% to the ruminant animal (Johnson and Johnson, 1995). Although most CH_4 emissions come from cattle (73.8%) and buffalo (11.3%), the remaining 10% comes from small ruminants including sheep and goats (Gerber, 2013). The world goat population is approximately 1.01 billion (FAOSTAT, 2020) and produces around 4.61 million tons of enteric CH_4 (around 4.9% of the total CH_4 emissions from livestock). Likewise, future CH_4 emissions from goats are expected to increase due to enhanced growth of goat populations and demands for milk and meat.

Due to the increase of the feeding costs and concerns about global warming, it is necessary to pay closer attention to improving nutritional efficiency and milk quality while controlling or reducing CH_4 emissions. Traditionally, the energy balance of dairy goats can be estimated by the difference between energy inputs (by feed intake) and the energy outputs, based on milk yield and body weight of the goats. On commercial farms, however, calculation of energy balance requires detailed information and facilities that are not available. These three concerns (nutritional efficiency, milk quality and CH_4 emissions) could be investigated using modeling tools.

The main objective of the present study was to develop a dynamic energy partitioning model for dairy goats to describe and quantify how the energy from dietary carbohydrate, protein and fat is transferred to milk (protein, lactose and fat) and the environment (CH_4 emission).

Materials and methods

Ethics Statement

The experimental procedures were approved (2021/VSC/PEA/0058) by the Committee on Animal Use and Care at the Polytechnic University of Valencia (UPV) (Valencia, Spain), and followed the codes of practice for animals used in experimental work proposed by the European Union (2003). Authors declare that this manuscript does not involve ethical issues or affect any endangered or protected species.

Experimental data

The core methodology we used was based on a combination of energy and nitrogen balance with indirect calorimetry. Quantitative measurements of gas exchange in respiration units have been used widely in indirect calorimetry to estimate both heat production and enteric CH_4 emissions (Chwalibog et al., 1997a; 1997b). In addition, this methodology allows the estimation of protein, fat and energy retention and mobilization in the body, oxidation of nutrients and calculation of the energy transfer between protein, carbohydrate and fat at the whole-body level, as well as the partitioning of energy into milk protein, lactose and fat.

The experiment was conducted at the Experimental Farm from the Institute of Animal Science and Technology (Universitat Politècnica de Valencia, Spain). Energy and nitrogen balances were performed in specially designed metabolic cages enabling individual registration of nutrient intake, milk production and excretion of feces and urine. The experiment involved 20 multiparous mature Murciano-Granadina dairy goats in mid-lactation with homogenous body weight (BW; 47 ± 4.4 kg of BW) and milk production in the previous lactation (630 ± 51 kg of milk per 210 ± 30 days of lactation). Two trials with 20 goats per trial in a cross-over design were run with 2 continuous sampling and gas exchange days (2 samples × 20 goats × 2 cross-over × 2 trials = 160 observations). Goats were fed twice a day with a diet containing 1.0 kg/day of alfalfa and 1.5 kg/day of concentrate; crude protein (CP) ranged between 17-20%, neutral detergent fiber (NDF) 21-43% and ether extract (EE) 1.8-4%. Energy and nitrogen balance and real-time gaseous exchange (mobile open-circuit respiration system based on indirect calorimetry) were measured as described by Fernández et al. (2019). Chemical analyses were conducted according to methods from AOAC (2012).

For modeling purposes, of 160 individual goat samples 2 were removed and 158 individual animal observations were used. Data were randomly split in 2/3 for model development (106 observations, Table 1) and 1/3 for internal evaluation (52 observations, Table 2).

Model description

The model simulated individual goat milk production and energy partitioning into fat, protein, lactose, and enteric CH_4 emission at the farm level under an intensive regime where the animals were fed with mixed rations. The model was conceptually based on two established models from indirect calorimetry data; the empirical model of Chwalibog et al. (1997a) was built based on oxidation of nutrients in growing calves and the dynamic model of energy balance in dairy goats from Fernández (2020).

The input of macronutrients (carbohydrates, protein and fat) was measured in balance experiments, and the outputs included feces, urine and gas emissions. The amount of retained protein and fat, and the contribution of different substrates to milk fat, protein and lactose production and the amount of oxidized nutrients were acquired from the combination of energy balance and gas exchange measurements. All values in the model and transfer of energy were expressed in energy terms. The calculation of energy metabolism was carried out with constants and factors accepted in energy metabolism studies (Brouwer, 1965). The model followed the suggestions by Baumgard et al. (2017) where the maternal ability is to partition proportionately more of the absorbed nutrients towards milk synthesis and less into body reserves. The model described below does not describe intermediary pathways of nutrient metabolism, only the general relationships between substrates and products.

The present model consisted of a dynamic system of differential equations and a fourth order Runge-Kutta method with an integration step size of 0.05 hour for numerical integration. The model was run until steady-state was achieved and hour was used as the unit of time. The model contains fourteen pools (kJ/kg $BW^{0.75}$) represented by the capital letter Q followed with the name of the pool; (1. Gross energy intake [GEI], 2. Protein intake [PI], 3. Fat intake [FI], 4. Carbohydrate intake [CI], 5. Methane [CH_4], 6. Ruminal volatile fatty acids [VFA], 7. Protein absorbed [PA], 8. Fat absorbed [FA], 9. Carbohydrate absorbed [CA], 10. Protein retention [RP], 11. Fat retention [RF], 12. Milk protein [MP], 13. Milk lactose [ML], 14. Milk fat [A]). The inputs and outputs to and from the pools are the fluxes (kJ/kg $BW^{0.75}$ per hour) denoted by the abbreviation F. Therefore, the pool changes with time depending on the magnitude of the flux (energy transfer among the pools), and the change is described by a differential equation of the form:

$$\frac{dQ}{dt} = F_{in} - F_{out}$$

We developed a model assuming mass action kinetics as follows:

$$F_i = k_i \, x \, Q_i$$

or

$$F_i = k_i' \, x \, Q_i$$

$$k_i' = k_i \, x \left(\frac{input}{reference\ constant} \right)^n$$

Where *i* is the pool name and *n* the exponent. To increase or decrease the speed of some fluxes, NDF, EE and metabolizability were used (more details below).

Knowledge of the flux and the pool allowed estimation of fractional rate k.

$$k_i = \frac{F_i}{Q_i}$$

Each element of the model is specified by an initial condition derived from actual measurements and published literature, and fractional rates are derived mainly from experimental and empirical information (energy metabolism calculations). Schematic representation of the model is shown in Figure 1 (Stella, 2018). Description of pools and the associated differential equations describing the pool-size change over time are listed below and abbreviations are referenced in Table 3.

1.Gross energy intake pool, Q_GEI (kJ/kg $BW^{0.75}$). This pool includes GEI and has three outputs. The initial amount of energy intake was determined from DM intake (DMI, kg/day) multiplied by the energy content of the diet (GE, MJ/kg DM) and divided by the metabolic BW (kg $BW^{0.75}$), all determined experimentally. Outputs came from splitting of GEI into protein, fat and carbohydrate fluxes according to dietary protein and fat content. Fractional rates to protein intake (k_{GEI_PI}), fat intake (k_{GEI_FI}) and carbohydrate intake (k_{GEI_CI}) were calculated by difference between GEI and PI, FI and CI pools, respectively. The pools Q_PI, Q_FI and Q_CI are defined below.

Gross energy intake Pool, Q_GEI (kJ/kg $BW^{0.75}$).

Differential equation:

$$\frac{dQ\_GEI}{dt} = -F_{GEI\_PI} - F_{GEI\_FI} - F_{GEI\_CI}$$

Outputs:

$$F_{GEI\_PI} = k_{GEI\_PI} \, x \, Q\_GEI$$

$$F_{GEI\_FI} = k_{GEI\_FI} \, x \, Q\_GEI$$

$$F_{GEI\_CI} = k_{GEI\_CI} \, x \, Q\_GEI$$

The gross energy pool size was expressed by the integral equation:

$$GEI = \int_{t0}^{t} \frac{dQ\_GEI}{dt} + iGEI$$

Representing the quantity of energy accumulated from initial time (t_0) to final time (t), with iGEI being the initial pool size (2085 kJ/kg $BW^{0.75}$ according to Table 1).

2.Protein intake pool, Q_PI (kJ/kg BW$^{0.75}$). The protein intake pool includes one input and two outputs. The amount of protein intake was determined from DMI (kg/day) multiplied by the CP content of the diet (g/kg DM) and the heat of combustion of protein (Brouwer, 1965):

$$PI\,(kJ) = DMI(kg) \times CP_{diet}\left(\frac{g}{kgDM}\right) \times 23.86\left(\frac{kj}{g}\right)$$

This expression was divided by the metabolic BW (kg BW$^{0.75}$), all determined experimentally (Table 1). The input (F_{GEI_PI}) was defined previously and the two outputs were the waste of protein intake from the digestive tract to feces (F_{PI_feces}) and the apparent total tract digestibility of protein obtained experimentally (Table 1) and defined as $F_{PI\_PA} = k_{PI\_PA}\, x\, Q\_PI$, with fractional rate being $k_{PI\_PA} = 0.70$ ($k_{PI\_feces} = 1 - k_{PI\_PA}$).

Protein energy intake Pool, Q_PI (kJ/kg BW$^{0.75}$).

Differential equation:

$$\frac{dQ\_PI}{dt} = F_{GEI\_PI} - F_{PI\_feces} - F_{PI\_PA}$$

Input:

$$F_{GEI\_PI} = k_{GEI\_PI}\, x\, Q\_GEI$$

Outputs:

$$F_{PI\_feces} = k_{PI\_feces}\, x\, Q\_PI$$

$$F_{PI\_PA} = k_{PI\_PA}\, x\, Q\_PI$$

The protein energy intake pool size was expressed by the integral equation:

$$PI = \int_{t0}^{t} \frac{dQ\_PI}{dt} + iPI$$

Representing the quantity of energy accumulated from initial time (t_0) to final time (t), with iPI being the initial pool size (0 kJ/kg BW$^{0.75}$).

3.Fat intake pool, Q_FI (kJ/kg BW$^{0.75}$). The fat intake pool includes one input and two outputs. The amount of fat intake was determined from DMI (kg/day) multiplied by the EE content of the diet (g/kg DM) and the fat heat of combustion (Brouwer, 1965):

$$FI\ (kJ) = DMI(kg) \times EE_{diet}\left(\frac{g}{kgDM}\right) \times 39.76\left(\frac{kj}{g}\right)$$

This expression was divided by the metabolic BW (kg BW$^{0.75}$), all determined experimentally (Table 1). The input (F_{GEI_FI}) was defined above and the two outputs were the waste of fat intake from the digestive tract to feces (F_{FI_feces}) and the apparent total tract digestibility of fat obtained experimentally (Table 1) and defined as $F_{FI\_FA} = k_{FI\_FA}$ $x\ Q\_FI$, with fractional rate being $k_{FI\_FA} = 0.67$ ($k_{FI\_feces} = 1 - k_{FI\_FA}$).

Fat energy intake Pool, Q_FI (kJ/kg BW$^{0.75}$).

Differential equation:

$$\frac{dQ\_FI}{dt} = F_{GEI\_PI} - F_{FI\_feces} - F_{FI\_PA}$$

Input:

$$F_{GEI\_FI} = k_{GEI\_FI}\, x\, Q\_GEI$$

Outputs:

$$F_{FI\_feces} = k_{FI\_feces}\, x\, Q\_FI$$

$$F_{FI\_FA} = k_{FI\_FA}\, x\, Q\_FI$$

The fat energy intake pool size was expressed by the integral equation:

$$FI = \int_{t0}^{t} \frac{dQ\_FI}{dt} + iFI$$

Representing the quantity of energy accumulated from initial time (t_0) to final time (t), with iFI being the initial pool size (0 kJ/kg BW$^{0.75}$).

4. Carbohydrate intake pool, Q_CI (kJ/kg $BW^{0.75}$). The carbohydrate intake pool includes one input and three outputs. The amount of carbohydrate intake was determined by difference as follow:

$$CI\ (kJ) = GEI - PI - FI$$

The GEI was obtained experimentally (2085 kJ/kg $BW^{0.75}$, Table 1) and PI and FI were defined previously. This expression was divided by the metabolic BW (kg $BW^{0.75}$). The input (F_{GEI_CI}) was defined above and the three outputs were: the excretion of carbohydrate intake from the digestive tract to feces ($F_{CI\_feces} = k_{CI\_feces}\ x\ Q\_CI$), carbohydrate fermented to VFA ($F_{CI\_VFA} = k_{CI\_VFA}\ x\ Q\_CI$) and carbohydrate that passes to the lower intestinal tract ($F_{CI\_CA} = k_{CI\_CA}\ x\ Q\_CI$). The fractional rate k_{CI_feces} was defined as 1 minus apparent total tract energy digestibility (1-0.67, Table 1). The fractional rate k_{CI_VFA} was obtained according to Demeyer (1992) where it is assumed that 70% of MEI is supplied as VFA and MEI was obtained experimentally (Table 1). The fractional rate k_{CI_CA} was calculated as $k_{CI\_CA} = 1 - k_{CI\_feces} - k_{CI\_VFA}$.

Carbohydrate energy intake Pool, Q_CI (kJ/kg $BW^{0.75}$).

Differential equation:

$$\frac{dQ\_CI}{dt} = F_{GEI\_CI} - F_{CI\_feces} - F_{CI\_VFA} - F_{CI\_CA}$$

Input:

$$F_{GEI\_CI} = k_{GEI\_CI}\ x\ Q\_GEI$$

Outputs:

$$F_{CI\_feces} = k_{CI\_feces}\ x\ Q\_CI$$

$$F_{CI\_VFA} = k_{CI\_VFA}\ x\ Q\_CI$$

$$F_{CI\_CA} = k_{CI\_CA}\ x\ Q\_CI$$

The carbohydrate energy intake pool size was expressed by the integral equation:

$$CI = \int_{t0}^{t} \frac{dQ\_CI}{dt} + iCI$$

Representing the quantity of energy accumulated from initial time (t_0) to final time (t), with iCI being the initial pool size (0 kJ/kg $BW^{0.75}$).

5.Methane energy waste pool, Q_CH_4 (kJ/kg $BW^{0.75}$). The CH_4 pool had one input, F_{VFA_CH4}. The CH_4 pool represents the amount of energy losses to the atmosphere from fermentation in the VFA pool (Q_VFA). The quantities of CH_4 produced by goats were obtained experimentally by an open circuit head-hood indirect calorimetry system. Thus, the fractional rate was calculated as: $k_{VFA\_CH4} = \frac{F_{VFA\_CH4}}{Q\_VFA}$. The CH_4 flux (F_{VFA_CH4}) was also corrected by NDF and EE of the diet due to the fact that fiber is the main substrate for methanogens and lipid has an inhibitory effect on ruminal microbial fermentation (Grainger and Beauchemin, 2011). A reference value of 30% and 3% (average values from the trial) for NDF and EE, respectively, was used in this model.

CH_4 energy waste Pool, Q_CH_4 (kJ/kg $BW^{0.75}$).

Differential equation:

$$\frac{dQ\_CH4}{dt} = F_{VFA\_CH4}$$

Input:

$$F_{VFA\_CH4} = k_{VFA\_CH4}\, x \left(\frac{NDF}{30}\right)^{0.011} x \left(\frac{3}{EE}\right)^{0.11} x\, Q\_VFA$$

The CH_4 waste energy pool size was expressed by the integral equation:

$$CH4 = \int_{t0}^{t} \frac{dQ\_CH4}{dt} + iCH4$$

Representing the quantity of energy accumulated from initial time (t_0) to final time (t), with iCH4 being the initial pool size (0 kJ/kg $BW^{0.75}$).

6.VFA energy pool, Q_VFA (kJ/kg BW$^{0.75}$). This pool includes one input and three outputs. The amount of energy in the VFA was determined according to Demeyer (1992) as mentioned above. The input F_{CI_VFA} and the output $F_{VFA\text{-}CH4}$ were described earlier. The flux F_{VFA_Hf} was the heat of fermentation and was calculated as follows:

$$F_{VFA\_Hf} = HP_{total} - HP_x$$

The HP_{total} was the heat production determined from measurements of O_2 consumption, CO_2 and CH_4 production, and urine N (N_{urine}) using the equation of Brouwer (1965):

$$HP_{total}\,(\text{kJ}) = 16.18 \times O_2 + 5.02 \times CO_2 - 2.17 \times CH_4 - 5.99 \times N_{urine}$$

where gases are expressed in liters per day and N_{urine} in grams per day.

The CO_2 production from oxidation (CO_{2x}) was calculated as CO_2 - (2 × CH_4) according to Fahey and Berger (1988). Then, HP from oxidation (HPx) was:

$$HP_x\,(\text{kJ}) = 16.18 \times O_2 + 5.02 \times CO_{2x} - 5.99 \times N_{urine}$$

Gases are expressed in liters per day and N_{urine} in grams per day.

HP_{total} and HP_x were experimentally measured (see Table 1).

The flux of VFA to fat absorption pool was calculated as:

$$F_{VFA\_FA} = (Q\_VFA - F_{VFA\_CH4} - F_{VFA\_Hf})\ x\ 0.6$$

Assuming that 0.6 is the amount of energy from acetic acid that is driving the pool of FA according to Ørskov and Ryle (1998) for mixed diets.

The amount of energy from VFA that enters the carbohydrate absorption pool was obtained by difference.

$$F_{VFA\_CA} = Q\_VFA - F_{VFA-CH4} - F_{VFA\_Hf} - F_{VFA\_FA}$$

VFA energy Pool, Q_VFA (kJ/kg BW$^{0.75}$).

Differential equation:

$$\frac{dQ\_VFA}{dt} = F_{CI\_VFA} - F_{VFA\_CH4} - F_{VFA\_Hf} - F_{VFA\_CA} - F_{VFA\_FA}$$

Input:

$$F_{CI\_VFA} = k_{CI\_VFA}\, x\, Q\_CI$$

Outputs:

$$F_{VFA\_CH4} = k_{VFA\_CH4}\, x \left(\frac{NDF}{30}\right)^{0.011} x \left(\frac{3}{EE}\right)^{0.11} x\, Q\_VFA$$

$$F_{VFA\_Hf} = k_{VFA\_Hf}\, x\, Q\_VFA$$

$$F_{VFA\_CA} = k_{VFA\_CA}\, x\, Q\_VFA$$

$$F_{VFA\_FA} = k_{VFA\_FA}\, x\, Q\_VFA$$

The VFA energy pool size was expressed by the integral equation:

$$VFA = \int_{t0}^{t} \frac{dQ\_VFA}{dt} + iVFA$$

Representing the quantity of energy accumulated from initial time (t_0) to final time (t), with iVFA being the initial pool size (0 kJ/kg $BW^{0.75}$).

7.Protein absorbed pool, Q_PA (kJ/kg $BW^{0.75}$). The protein absorbed pool includes two input and five outputs. The amount of protein absorbed was determined as follow:

$$PA\,(kJ) = PI\left(\frac{kJ}{kg\ BW^{0.75}}\right) \times \left(\frac{CP_{digestibility}}{100}\right)$$

It is assumed that the protein pool is equal to the amount of digested protein, represented by the input F_{PI_PA} that was defined previously, and it could represent the amount of absorbed amino acids which could be used for milk protein (F_{PA_MP}), protein retention (F_{PA_RP}) or be deaminated (F_{RP_PA}) and oxidized (F_{PA_OXP}) with concomitant excretion of energy with nitrogenous substances in urine (F_{PA_UEN}) and transferred of energy to carbohydrate metabolism (F_{PA_CA}). Feeding systems such as AFRC (1993) and

INRA (2018) use metabolizability (qm = ME/GE) in the predictions of the efficiency of ME use for production. The qm of the diets was utilized to adjust the flux and a reference value of 0.6, obtained from this study, was contemplated (see Tables 1 and 2). The flux F_{PA_CA} was an estimation of glucogenesis (generation of glucose from non-carbohydrate carbon substrates) and was adjusted by qm. The fractional rates of F_{PA_RP}, F_{PA_MP} and F_{PA_CA} were calculated as $k = \frac{Flux}{Q\_pool}$. See Table 4 for details.

The F_{PA_OXP} is the energy associated with oxidation of protein and calculated by published methods for ruminants (Brouwer, 1958; Chwalibog et al., 1997a);

$$F_{PA\_OXP}\ (kJ) = 6.25\ \times\ N_{urine}(g)\ \times\ 18.42\left(\frac{kJ}{g}\right)$$

The fractional rate was calculated from bioenergetic equations and constants. This expression was divided by the metabolic BW (kg $BW^{0.75}$). The F_{PA_UEN} was the loss of energy nitrogen in urine and calculate according to Chwalibog et al. (1997a; 2004):

$$F_{PA\_UEN}(kJ) =\ N_{urine}(g) \times\ 0.9\ \times\ 24.9\left(\frac{kJ}{g}\right)$$

This expression was divided by the metabolic BW (kg $BW^{0.75}$).

Protein energy Pool, Q_PA (kJ/kg BW$^{0.75}$).

Differential equation:

$$\frac{dQ\_PA}{dt} = F_{PI\_PA} + F_{RP\_PA} - F_{PA\_MP} - F_{PA\_RP} - F_{PA\_OXP} - F_{PA\_UEN} - F_{PA\_CA}$$

Input:

$$F_{PI\_PA}\ =\ k_{PI\_PA}\ x\ Q\_PI$$

$$F_{RP\_PA}\ =\ k_{RP\_PA}\ x\ Q\_RP$$

Outputs:

$$F_{PA\_MP}\ =\ k_{PA\_MP}\ x\ Q\_PA$$

$$F_{PA\_RP}\ =\ k_{PA\_RP}\ x\ Q\_PA$$

$$F_{PA\_OXP} = k_{PA\_OXP} \, x \, Q\_PA$$

$$F_{PA\_UEN} = k_{PA\_UEN} \, x \, Q\_PA$$

$$F_{PA\_CA} = k_{PA\_CA} \, x \left(\frac{0.6}{qm}\right) x \, Q\_PA$$

The protein energy pool size was expressed by the integral equation:

$$PA = \int_{t0}^{t} \frac{dQ\_PA}{dt} + iPA$$

Representing the quantity of energy accumulated from initial time (t_0) to final time (t), with iPA being the initial pool size (0 kJ/kg $BW^{0.75}$).

8.Fat absorbed pool, Q_FA (kJ/kg $BW^{0.75}$). The fat absorbed pool includes four input and four outputs. The amount of fat absorbed was determined as follows:

$$FA\,(kJ) = FI\left(\frac{kJ}{kg\ BW^{0.75}}\right) \times \left(\frac{EE_{digestibility}}{100}\right)$$

It is assumed that the fat pool is equal to the amount of digested fat that was previously defined by the flux F_{FI_FA}. This pool is constituted by the next inputs: digested fat (F_{FI_FA}), VFA as acetic acid from ruminal fermentation (F_{VFA_FA}), energy transfer from the carbohydrate pool to FA (F_{CA_FA}), and the mobilization of fat reserves to the fat pool (F_{RF_FA}). The flux F_{CA_FA} was an estimation of lipogenesis (process of producing palmitic acid and triacylglycerol) and was corrected by qm; when diet qm is high, the F_{CA_FA} is lower and vice versa. The outputs represent the amount of absorbed fatty acids and energy which could be used for milk fat synthesis (F_{FA_MF}), fat retention (F_{FA_RF}) or mobilization and oxidation (F_{FA_OXF}) with concomitant excretion of energy-free nitrogen in urine ($F_{FA\_UENfree}$). Because fiber stimulates milk fat synthesis, provides lipogenic substrates in the form of acetate and hydroxybutyrate (Van Knegsel et al., 2007), the flux F_{FA_MF} was corrected by NDF.

The F_{FA_OXF} is the energy associated with the oxidation of fat and calculated by published methods for ruminants (Brouwer, 1958; Chwalibog et al., 1997a);

$$F_{FA\_OXF}\,(kJ) = \left(1.719\times O_2 - 1.719\times CO_{2x} - 1.963\times N_{urine}\right)\times 39.76\left(\frac{kJ}{g}\right)$$

This expression was divided by the metabolic BW (kg BW$^{0.75}$). The speed of energy transfer from the flux F_{FA_OXF} to the environment was adjusted by qm (being 0.6 the reference value). The $F_{FA\_UENfree}$ was the loss of nitrogen energy in urine and calculated according to Chwalibog et al. (1997a; 2004):

$$F_{FA\_UENfree}(kJ) = UE_{calorimetric\ bomb}\,(kJ) - F_{PA\_UEN}$$

Where UE was the heat of combustion of urea energy determined in a bomb calorimeter. This expression was divided by the metabolic BW (kg BW$^{0.75}$).

The fractional rate of the remaining fluxes was calculated as $k = \frac{Flux}{Q\_pool}$. See Table 3 and 4 for details.

Fat energy Pool, Q_FA (kJ/kg BW$^{0.75}$).

Differential equation:

$$\frac{dQ\_FA}{dt} = F_{FI\_FA} + F_{VFA\_FA} + F_{CA\_FA} + F_{RF\_FA} - F_{FA\_MF} - F_{FA\_RF} - F_{FA\_OXF} - F_{FA\_UENfree}$$

Input:

$$F_{FI\_FA} = k_{FI\_FA}\,x\,Q\_FI$$

$$F_{VFA\_FA} = k_{VFA\_FA}\,x\,Q\_VFA$$

$$F_{CA\_FA} = k_{CA\_FA}\,x\left(\frac{0.6}{qm}\right)x\,Q\_CA$$

$$F_{RF\_FA} = k_{RF\_FA}\,x\,Q\_RF$$

Outputs:

$$F_{FA\_MF} = k_{FA\_MF}\, x \left(\frac{NDF}{30}\right)^{0.01} x\, Q\_FA$$

$$F_{FA\_RF} = k_{FA\_RF}\, x\, Q\_FA$$

$$F_{FA\_OXF} = k_{FA\_OXF}\, x \left(\frac{0.6}{qm}\right) x\, Q\_FA$$

$$F_{FA\_UENfree} = k_{FA\_UENfree}\, x\, Q\_FA$$

The fat energy pool size was expressed by the integral equation:

$$FA = \int_{t0}^{t} \frac{dQ\_FA}{dt} + iFA$$

Representing the quantity of energy accumulated from initial time (t_0) to final time (t), with iFA being the initial pool size (0 kJ/kg $BW^{0.75}$).

9.Carbohydrate absorbed pool, Q_CA (kJ/kg $BW^{0.75}$). The carbohydrate absorbed pool includes three inputs and four outputs. The amount of carbohydrate absorbed was determined as follows:

$$CA\ (kJ) = DE\left(\frac{kJ}{kg\ BW^{0.75}}\right) - PA - FA$$

Where DE is the digestible energy. This carbohydrate pool includes the contribution of energy from digested carbohydrates (F_{CI_CA}), from ruminal fermentation (F_{VFA_CA}) and glucogenesis (F_{PA_CA}), and it is assumed that under normal feeding conditions the daily net value of glycogen depots remains constant. The carbohydrate pool outputs released energy into milk lactose (F_{CA_ML}), and energy used for lipogenesis (F_{CA_FA}), which is evaluated as the amount of energy transferred from carbohydrate to fat pool. This pool also represent energy-containing products excreted with urine ($F_{CA\_UENfree}$) and oxidized carbohydrate (F_{CA_OXC}).

The F_{CA_OXC} is the energy associated with oxidation of carbohydrates and calculated by published methods for ruminants (Brouwer, 1958; Chwalibog et al., 1997a);

$$F_{CA\_OXC}\,(kJ) = (-2.968\,\times O_2 + 4.174\,\times CO_{2x} - 2.446\,\times N_{urine}) \times 17.85\left(\frac{kJ}{g}\right)$$

This expression was divided by the metabolic BW (kg BW$^{0.75}$). This calculation was needed to obtain the fractional rate and the flux was corrected with qm. The $F_{CA\_UENfree}$ is the loss of nitrogen energy in urine and calculated according to Chwalibog et al. (1997a; 2004):

$$F_{CA\_UENfree}(kJ) = UE_{calorimetric\,bomb}\,(kJ) - F_{PA\_UEN}$$

Where UE was the heat of combustion of urea energy determined in a bomb calorimeter. This expression was divided by the metabolic BW (kg BW$^{0.75}$).

The fractional rate of the remaining fluxes was calculated as $k = \frac{Flux}{Q\_pool}$. See Table 3 for details.

Carbohydrate energy Pool, Q_CA (kJ/kg BW$^{0.75}$).

Differential equation:

$$\frac{dQ\_CA}{dt} = F_{CI\_CA} + F_{VFA\_CA} + F_{PA\_CA} - F_{CA\_ML} - F_{CA\_FA} - F_{CA\_OXC} - F_{CA\_UENfree}$$

Input:

$$F_{CI\_CA} = k_{CI\_CA}\,x\,Q\_CI$$

$$F_{VFA\_CA} = k_{VFA\_CA}\,x\,Q\_VFA$$

$$F_{PA\_CA} = k_{PA\_CA}\,x\left(\frac{0.6}{qm}\right)x\,Q\_PA$$

Outputs:

$$F_{CA\_ML} = k_{CA\_ML}\,x\,Q\_CA$$

$$F_{CA\_FA} = k_{CA\_FA}\,x\left(\frac{0.6}{qm}\right)x\,Q\_CA$$

$$F_{CA\_OXC} = k_{CA\_OXC}\ x \left(\frac{qm}{0.6}\right) x\ Q\_CA$$

$$F_{CA\_UENfree} = k_{CA\_UENfree}\ x\ Q\_CA$$

The carbohydrate energy pool size was expressed by the integral equation:

$$CA = \int_{t0}^{t} \frac{dQ\_CA}{dt} + iCA$$

Representing the quantity of energy accumulated from initial time (t_0) to final time (t), with iCA being the initial pool size (0 kJ/kg $BW^{0.75}$).

10.Protein retention pool, Q_RP (kJ/kg $BW^{0.75}$). The protein-retained pool includes one input and one output. The amount of protein retained was determined as follows:

$$RP\ (kJ) = N_{retained}(g) \times 6.25 \left(\frac{g\ Protein}{g\ of\ N}\right) \times 23.86 \left(\frac{kJ}{g\ Protein}\right)$$

This expression was divided by the metabolic BW (kg $BW^{0.75}$). The input was F_{PA_RP} and the output F_{RP_FA}, both defined previously.

Protein retention Pool, Q_RP (kJ/kg $BW^{0.75}$).

Differential equation:

$$\frac{dQ\_RP}{dt} = F_{PA\_RP} - F_{RP\_FA}$$

Input:

$$F_{PA\_RP} = k_{PA\_RP}\ x\ Q\_PA$$

Outputs:

$$F_{RP\_FA} = k_{RP\_FA}\ x\ Q\_RP$$

The protein retention pool size was expressed by the integral equation:

$$RP = \int_{t0}^{t} \frac{dQ\_RP}{dt} + iRP$$

Representing the quantity of energy accumulated from initial time (t_0) to final time (t), with iRP being the initial pool size (28 kJ/kg $BW^{0.75}$, see Table 1).

11.Fat retention pool, Q_RF (kJ/kg $BW^{0.75}$). The fat-retained pool includes one input and one output. The amount of fat retained was determined as follows:

$$RF\ (kJ) = RE\ (kJ) - RP\ (kJ)$$

Where RE is the retention of energy and RP the retention of protein (Table 1). This expression was divided by the metabolic BW (kg $BW^{0.75}$). The input was F_{FA_RF} and the output F_{RF_FA}, from which energy is retained in body fat or released, respectively. We have observed during the trial that the level of ME of the diet influenced the degree of energy mobilization or deposition in the body (retention of energy negative or positive). As AFRC (1993) and INRA (2018) submitted that tissue gain or mobilization depend of qm, we have corrected as follows: when qm > 0.6 it indicated a positive energy balance in which dietary energy was used for milk production and accumulation of reserve. When qm < 0.6 it indicated a negative energy balance and that energy reserves were used for milk production. Thus, fractional rates changed with qm as follows:

if (qm ≧ 0.6)

{$k_{FA\_RF} = 0.84$

$k_{RF\_FA} = 0.66$

else

$k_{FA\_RF} = 0.66$

$k_{RF\_FA} = 0.84$}

The fractional rate constant values used were those proposed by Kebreab et al. (2003) for dairy cows, i.e. 0.84 for efficiency of energy gain and 0.66 for efficiency of tissue energy mobilization.

Fat retention Pool, Q_RF (kJ/kg BW$^{0.75}$).

Differential equation:

$$\frac{dQ\_RF}{dt} = F_{FA\_RF} - F_{RF\_FA}$$

Input:

$$F_{FA\_RF} = k_{FA\_RF}\, x\, Q\_FA$$

Outputs:

$$F_{RF\_FA} = k_{RF\_FA}\, x\, Q\_RF$$

The fat retention pool size was expressed by the integral equation:

$$RF = \int_{t0}^{t} \frac{dQ\_RF}{dt} + iRP$$

Representing the quantity of energy accumulated from initial time (t_0) to final time (t), with iRF being the initial pool size (100 kJ/kg BW$^{0.75}$, see Table 1).

12.Milk protein energy pool, Q_MP (kJ/kg BW$^{0.75}$). This pool is the energy accumulated in the milk protein fraction and had one input, F_{PA_MP}. The energy flux was described as a mass action type. MP was the energy content in milk observed from milk protein in the trial and it was used as reference to calculate the fractional rate k_{PA_MP}. MP was calculated experimentally as follows:

$$MP = MY\left(\frac{g}{d}\right) x\ Milk\ Protein\left(\frac{g}{100g}\right) x\ 23.64\left(\frac{kJ}{g}\right)$$

Where MY was milk production and this expression was divided by the metabolic BW (kg BW$^{0.75}$).

Milk protein energy Pool, Q_MP (kJ/kg BW$^{0.75}$).

Differential equation:

$$\frac{dQ\_MP}{dt} = F_{PA\_MP}$$

Input:

$$F_{PA\_MP} = k_{PA\_MP} \; x \; Q\_PA$$

The MP energy pool size was expressed by the integral equation:

$$MP = \int_{t0}^{t} \frac{dQ\_MP}{dt} + iMP$$

Representing the quantity of energy accumulated from initial time (t_0) to final time (t), with iMP being the initial pool size (0 kJ/kg BW$^{0.75}$).

13.Milk lactose energy pool, Q_ML (kJ/kg BW$^{0.75}$). This pool is the energy accumulated in the milk lactose fraction and had one input, F_{CA_ML}. The energy flux was described as a mass action type. ML was the energy content in milk observed from milk lactose in the trial and was used as reference to calculate the fractional rate k_{CA_ML}. ML was calculated experimentally as follows:

$$ML = MY\left(\frac{g}{d}\right) x \; Milk \; Lactose \left(\frac{g}{100g}\right) x \; 17.36 \left(\frac{kJ}{g}\right)$$

Where MY was milk production and this expression was divided by the metabolic BW (kg BW$^{0.75}$).

Milk lactose energy Pool, Q_ML (kJ/kg BW$^{0.75}$).

Differential equation:

$$\frac{dQ\_ML}{dt} = F_{CA\_ML}$$

Input:

$$F_{CA\_ML} = k_{CA\_ML}\ x\ Q\_CA$$

The ML energy pool size was expressed by the integral equation:

$$ML = \int_{t0}^{t} \frac{dQ\_ML}{dt} + iML$$

Representing the quantity of energy accumulated from initial time (t_0) to final time (t), with iML being the initial pool size (0 kJ/kg $BW^{0.75}$).

14.Milk fat energy pool, Q_MF (kJ/kg $BW^{0.75}$). This pool is the energy accumulated in the milk fat fraction and had one input, F_{FA_MF}. MF was the energy content in milk observed from milk fat in the trial and it was used as a reference to calculate the fractional rate k_{FA_MF}. MF was calculated experimentally as follows:

$$MF = MY\left(\frac{g}{d}\right)x\ Milk\ Fat\left(\frac{g}{100g}\right)x\ 39.33\left(\frac{kJ}{g}\right)$$

Where MY was milk production and this expression was divided by the metabolic BW (kg $BW^{0.75}$).

Milk fat energy Pool, Q_ML (kJ/kg $BW^{0.75}$).

Differential equation:

$$\frac{dQ\_MF}{dt} = F_{FA\_MF}$$

Input:

$$F_{FA\_MF} = k_{FA\_MF}\ x\left(\frac{NDF}{30}\right)^{0.01} x\ Q\_FA$$

The MF energy pool size was expressed by the integral equation:

$$MF = \int_{t0}^{t} \frac{dQ\_MF}{dt} + iMF$$

Representing the quantity of energy accumulated from initial time (t_0) to final time (t), with iMF being the initial pool size (0 kJ/kg $BW^{0.75}$).

Parameter estimation

The dynamic model used the function *ode()* of the deSolve (solving differential equations) package for numerical solutions of initial first order problems and was implemented in R software (2016). The solution was achieved using the lsoda integration method with absolute and relative error tolerance of 10^{-6}. The parameter estimation was performed by minimizing the negative log likelihood using the function *optim()* from R (2016, v.1.1.447) and the method used for optimization was Broyden Fletcher Goldfarb Shanno algorithm (L-BFGS-B).

To characterize model inadequacy (i.e. bias) in the range of our observations, the observed values of MP, ML, MF and CH_4 emissions were compared with model predictions and the discrepancy was calculated as the root mean square prediction error (RMSPE). The RMSPE was decomposed into error due to overall bias of prediction (mean bias), error due to deviation of the regression slope from unity (slope bias), and error due to disturbances or random variations (random bias) (Bibby and Toutenburg, 1977). The adequacy of the best-fitting model was further assessed outside the range of our observations by fitting a regression line between observed and predicted values and considering the intercept and slope deviation from 0 and 1, respectively. This exercise extrapolates to zero and beyond the maximum observed values and, thus, quantifies the applicability domain for the model under consideration.

Residual plots [(observed – predicted) versus predicted values] verifying the assumptions that errors are normally and identically distributed around zero with constant variance were examined. Since residuals are not correlated with predictions, if the model is unbiased, the slope of the regression of residuals on predictions must be zero.

Furthermore, RMSPE and concordance correlation coefficients (CCC) were also used to evaluate the precision and accuracy of predicted versus observed values for the model (Lin, 1989). The CCC estimate represents the product of two components. The first component is the Pearson correlation coefficient that measures precision (deviation of observations from the best fit line). The second component is the bias correction factor that indicates accuracy (i.e. how far the regression line deviates from the unity line).

Evaluation of the mathematical model

From the 158 individual animal observations obtained during the experiment, 2/3 were used to develop the model (106 observations, Table 1) and 1/3 were used for internal evaluation (52 observations, see Table 2 for details). For external evaluation, the model was evaluated with data from 20 different energy balance studies from the literature (77 observations, Table 5).

Model internal and external evaluation.

Residual analysis was assessed for adequacy of the model. Comparisons between observed and model prediction values were performed for MP, ML, MF and CH_4 emissions. An assessment of the error of the predicted relative to the observed values was made by calculation of the RMSPE. The prediction error was assessed by calculating the MSPE. The MSPE was decomposed into mean, slope and random bias, as previously described. Residual plots verifying the assumptions that errors are normally and identically distributed around zero with constant variance were examined. The CCC, described above, evaluates the degree of deviation between the best fit line and the identity line (y=x), thus, the CCC of a model that is closer to 1 is an indicator of better model performance.

Results

Model development

The model achieved the steady-state at 24 hours. The model had four parameters and was fitted using observations from 106 data. From the input's (body weight, gross energy, qm, protein, carbohydrate and fat intake and digestibility), fractional rates and reference constants (Table 4), we obtained the outputs: milk energy partition into protein (MP), lactose (ML), fat (MF) and CH_4 emissions. Initial and final values of optimized parameters, obtained by RMSPE, with their SD and coefficient of variation (CV) are shown in Table 4. The parameters k_{VFA_CH4} had a CV of 18% and less than 10% for parameters related with milk composition k_{PA_MP}, k_{CA_ML}, k_{FA_MF}. The prediction errors are shown in Table 6. From lower to higher, the RMSPE were 13.2% for loss of energy in CH_4, 16.8% for MF, 19.4% for MP and 22.3% ML. Evaluation through CCC was in agreement with RMSPE, with the largest CCC for milk CH_4 energy (0.643) followed by MF (0.574), MP (0.514) and ML (0.464). Mean bias was around zero for all variables and the slope bias was zero for energy ML, close to 1% for MF (1.01%) and around 3% and 10% for MP and CH_4, respectively. Random bias was greater than 85% for energy in CH_4 and milk energy components indicating the absence of non-systematic error, and that the equation in the model fitted the data properly.

Figure 2 displays observed versus predicted values and the corresponding unity regression equation (i.e. observed = predicted). The model had the least bias for MP data in the range 80-125 kJ/kg $BW^{0.75}$ per day, but below this range it underestimated and above this range it overestimated (Figure 2a). For ML, the model bias was minimal (Figure 2b). MF also had a nearly unbiased fit to data from 240-280 kJ/kg $BW^{0.75}$ per day (Figure 2c), and below this range it overestimated and above it underestimated. For energy in CH_4 with a narrow range about 80-90 kJ/kg $BW^{0.75}$ per day, the model bias was minimal, but below and above this range it underestimated and overestimated, respectively (Figure 2d). The residual standard error for MP, ML, MF and energy in CH_4 was off by 23.08, 22.22, 43.84 and 11.36 kJ/kg $BW^{0.75}$ per day, respectively.

Analyses of residuals are shown in Figure 3. Results are consistent with the biases illustrated in Figure 2. The ranges shown before residuals appeared to be randomly distributed about 0. Slopes of regression lines for residuals versus predicted were negative for MP (Figure 3a) and CH_4 (Figure 3d) indicating that the model overpredicted as the prediction increased. For ML the slope was 0 (Figure 3b). Slope of regression lines for residuals versus predicted was positive for the MF pool (Figure 3c) indicating that the model underpredicted amounts of energy in milk as the prediction increased. Therefore, extrapolating outside the above ranges may yield increasingly-biased predictions.

Internal model evaluation

One third of the data obtained from the study was used for internal evaluation (n = 52 observations). The prediction errors are shown in Table 7. From lower to higher, the RMSPE were 13.7% for loss of energy in CH_4, 18.5% for MP, 22.9% for ML and 19.2% for MF energy. RMSPE greater than 20% indicated that some significant variation of ML energy still remained to be explained. Evaluation through CCC was in agreement with RMSPE, with the largest CCC for MP and CH_4 and lowest for ML and MF. Mean bias was around 0 for ML and MF, 0.19% for MP and 0.39% for CH_4. The slope bias was lower for ML and MF (0.84% and 2.54%, respectively) and greater for CH_4 and MP (5.90% and 10.46%, respectively). A slope bias different from 0 indicated a lack of precision with the internal validation data set. Therefore, random bias was greater for ML (99.11%) and MF (97.44%) and lower for CH_4 (93.71%) and MP (89.35%). Random bias around 89% indicated systematic errors for MP and that mechanisms in the model could be improved. The random bias was higher than 85% indicating the absence of nonsystematic errors and that he equation in the model fitted the data properly.

Figure 4 displays observed versus predicted values and the corresponding unity regression equation (i.e. observed = predicted). The model had the least bias in a narrow range and MP was underpredicted (Figure 4a), ML overpredicted (Figure 4b), MF underpredicted (Figure 4c) and CH_4 underestimated at lower values and overestimated at higher values (Figure 4d). The residual standard error for MP, ML, MF and energy in CH_4 was off by 19.83, 22.87, 49.63 and 11.77 kJ/kg $BW^{0.75}$ per day, respectively.

Analyses of residuals are shown in Figure 5. Results are consistent with the biases illustrated in Figure 4. Slopes of regression lines for residuals versus predicted were positive for MP energy pool (Figure 5a) and negative for ML, MF and CH_4 (Figures 5b, 5c and 5d). Thus, we observed underprediction when the amount of milk energy in protein increased, and overprediction for lactose, fat and CH_4.

External model evaluation

Data from 20 energy balance experiments (n = 77) were used for external evaluation of the model. Goodness of fit is shown in Table 8. The RMSPE value was higher than 20% indicating that some variation remained to be explained. Evaluation through CCC was in agreement with RMSPE as we showed previously. The CCC for CH_4 was not calculated because some literature experiments did not determine CH_4 emissions. Mean bias represents the accuracy of the model being around 0 for ML, but greater for others, hence, some disturbances were detected. The slope bias was around 0 for CH_4 (1.17%), but different from 0 for milk energy components, meaning lack of precision with the external data set. Random bias was 98.47% for CH_4 energy, 97.28% for MF energy, 97.11% for MP and 92.83% for MF. Therefore, random bias was higher than 85% indicating the absence of nonsystematic errors and that the equation in the model fitted the data appropriately.

Plots of observed versus predicted values in milk energy composition and CH_4 are shown in Figure 6. This figure includes 20 data sets from energy balance experiments form a literature review. Data points from the same experiment share the same color. Briefly, Figure 6a shows overestimation in MP at higher values, Figure 6b shows underestimation in ML at lower values. For MF we observed an overestimation (Figure 6c) at grater values and in CH_4 we observed underprediction for all studies (Figure 6d).

Analyses of residuals (regressing residuals against predicted values) are shown in Figure 7, and for an unbiased model the slope of residuals regressed on prediction must be 0. The slope was negative for MP, ML, MF and CH_4 (Figure 5a, 5b, 5c and 5d, respectively), being less accurate for extreme values.

Discussion

Comparable models

The model was conceptually based on two established models from indirect calorimetry data as previously was mentioned, Chwalibog et al. (1997a) and Fernández et al. (2020). The Chwalibog et al. (1997a) model was based on a combination of nitrogen and energy balance with indirect calorimetry which made possible empirical calculations to estimate protein, fat, energy retention and mobilization in the body. Besides, total heat production and net substrate oxidation, and energy transfer between protein, carbohydrate and fat at the whole-body level were calculated. The model evaluated growth and retention of energy and dynamic changes over time were not contemplated. Fernández et al. (2020) developed a dynamic model in lactating goats based on energy balance and indirect calorimetry, assessed daily variation in CH_4 emissions, milk and loss of heat when daily changes in DMI, lipid and fiber were taking place. However, neither oxidation of nutrients nor partitioning of energy into milk protein, lactose and fat were considered.

External simulation

We observed some variation among the 20 published studies that could be due to inherent differences associated with feeding system, diets, treatments, breed, and/or unique experimental conditions. Below we first discuss those published experiments with the poorest goodness of fit.

External milk protein simulation

The largest overprediction we observed was for MP (Figure 6a), due mainly to the studies of Silva et al. (2018), Molina-Alcaide et al. (2010) and Romero-Huelva et al. (2012). Silva et al., (2018) conducted two experiments with lactating Alpine goats studying the effects of restricted access to feeders. The diet used was formulated to be relatively high in quality so as to allow opportunity for a rapid rate of ingestion and acceptable performance with limited feeder access. Milk yield was determined and chemical composition was obtained with a MilkoScan 400 analyzer (Foss Electric, Hillerød, Denmark). Experiment 1 was run in mid to late lactation; the restricted feed access treatment had neither marked negative nor positive effects on feed intake and performance measures, reflecting considerable flexibility in feeding behavior. Only the 4-hour feeder access treatment reduced milk yield and the concentrations of milk protein, which the authors could not explain, thus, this lower milk protein obtained caused overprediction by the model.

The study of Molina-Alcaide et al. (2010) evaluated the effect of partial replacement of concentrate with two types of feed blocks on ruminal protozoa, nitrogen and energy balance, microbial N flow to the duodenum and milk performance. Granadina breed goats were hand-milked once a day and milk total solid determined by Kjeldahl for N (protein was obtained multiplied by 6.38). Romero-Huelva et al. (2012) replaced 35% of a cereal-based concentrate with feed-blocks containing waste tomato fruit or cucumber in lactating Granadina goats. Milk chemical analysis was conducted as reported by Molina-Alcaide et al. (2010). It could be possible that the different methods for measuring milk protein (Kjeldahl-N vs. MilkoScan FT120) was responsible for the observed model overprediction.

External milk lactose simulation

The underprediction observed in ML (Figure 6b) was mainly due to the study of Tovar-Luna et al. (2010b). Tovar-Luna et al. (2010b) studied the effect of stage of lactation and the level of feed intake in Alpine dairy goats. Energy balance in metabolic cages and indirect calorimetry were used and milk samples were analyzed for protein, lactose and fat in a MilkoScan 400 analyzer (Foss Electric, Hillerød, Denmark). Goats were fed ad libitum, but some after ad libitum consumption were restricted to near ME requirements for maintenance followed by 4-d of fasting. For other does, fasting was immediately following the ad libitum consumption. Thus, the underprediction observed was detected under feed restriction and fasting those likely induced physiological adaptations not considered in the present model.

External milk fat simulation

Based on visual inspection of MF (Figure 6c), the study of Silva et al. (2018) seems to be responsible for the overestimation observed. Silva et al. (2018) could not explain the low milk fat concentrations during the 4-h access to feeders in experiment 1 and during the 2-h access to feeders in experiment 2. The present model overpredicts milk fat, being greater in experiment 1 than 2, but Silva et al. (2018) reported unexpectedly low values.

External methane simulation

The model underestimates CH_4 emissions mainly in the studies of Molina-Alcaide et al. (2010), Ibáñez et al. (2016), Romero-Huelva et al. (2017), and Fernández et al. (2021b). Since Silva et al. (2018) did not report CH_4 this study was not used in the analysis. The study of Molina-Alcaide et al. (2010) did not conduct indirect calorimetry, thus, no heat production or oxidation of nutrients and CH_4 were available. The CH_4 production was estimated from Aguilera et al. (2001) as 10.32% of digestible energy. Therefore, the values were not comparable with the present model predictions.

In the study of Ibáñez et al. (2016) the CH_4 model prediction was lower than observed for all treatments. Murciano-Granadina goats at mid lactation were fed three alfalfa hay and concentrate-based mixed diets in which concentrate replaced barley grain with orange pulp or soy hulls. No differences in CH_4 emissions were observed among diets for observed and model prediction, but on average the model estimated 45 kJ/kg $BW^{0.75}$ lower emission than observed. The challenge in quantifying CH_4 in vivo is well known. Thus, the observed differences were likely due to the indirect calorimetry equipment used or the calibration of the equipment during the studies. Ibáñez et al. (2016) used the equipment described by Fernández et al. (2015) and the present study used an improved version of the system described by Fernández et al. (2019).

Romero-Huelva et al. (2017) using lactating Granadina goats replaced 47% of the concentrate (corn, wheat bran, sunflower meal and soy flour) with a mixture of fruit waste that included tomato, citrus pulp, brewer’s grain and yeast. The CH_4 was recorded and a gas analyzer used (ADG MGA3000, Spurling Works, Herts, UK). The study did not detail information regarding flowmeter and calibration factors used for measuring the gas exchange. An underestimation was only found for the control group. In the other groups (mixture of fruit) a reduction of CH_4 was observed and the model adjusted better. The presence of plant secondary compounds in by-products may promote less CH_4 production as Romero-Huelva et al. (2017) suggested.

Fernández et al. (2021b) studied the CH_4 emissions when forage to concentrate ratios changed during lactation. Murciano-Granadina goats were fed with mixed diets based on alfalfa and concentrate. One group was fed with the forage to concentrate ratio of 35:65 during the whole lactation and the present model predicted successfully the CH_4 emissions. The other group was fed with a ratio 35:65 in early lactation, 50:50 at mid lactation and 65:35 in late lactation. The worse estimation by the model was obtained when the ratio changed from 35:65 to 50:50 and to 65:35 (underestimation of 65 kJ/kg $BW^{0.75}$, on average). Hence, it seems that the model was useful for most of the studies tested, but the accuracy diminishes when there was a restriction in access to feed, fasting and changes in the forage to concentrate ratio. These factors could change tissue energy accretion, presumably with associated nutrient partitioning, and contribute to changes in milk composition. Clearly, those management aspects and the ensuing physiological changes were not contemplated in the present model.

Modelling predictions with existing energy balance studies

The 20 studies with indirect calorimetry facilities were conducted across Research Centers. Since most of these did not calculate macronutrient oxidation nor milk energy partitioning in fat, protein and lactose, the present data enhanced the value of the data by making predictions with the model.

We evaluated, with the present model, the study of Rapetti et al. (2005) conducted at Istituto di Zootecnia Generale, Università di Milano (Italy). These authors used indirect calorimetry and fed lactating Saanen goats with forage and forage-free diets (the qm was greater than 0.6 for all diets). Using data from the non-forage diet (qm = 0.65), the amount of energy in MP, ML and MF predicted was 67, 98 and 268 kJ/kg $BW^{0.75}$ (total energy of

434 kJ/kg $BW^{0.75}$ similar to the value observed; 444 kJ/kg $BW^{0.75}$), respectively. Due to the high qm value, enough ME energy was available from carbohydrate and the retention of energy was positive; the observed energy retention was 143 kJ/kg $BW^{0.75}$ and the predicted was 255 kJ/kg $BW^{0.75}$. Thus, the model could predict the energy transfer when positive energy balance was observed as follows. Since the diet was predominantly based in cereals, the oxidation of carbohydrates was higher than fat oxidation (58 vs 30%), the accretion of fat retention was positive (107 kJ/kg $BW^{0.75}$) favoring the energy transfer from the FA to RF pool (body fat deposition). The daily transfer of energy from the CA to FA pool was of 430 kJ/kg $BW^{0.75}$ indicating that carbohydrate that is not oxidized contributed to fat metabolism, either transferred to milk (lipogenesis and esterification) or oxidized. The predicted energy lost as CH_4 was 96 kJ/kg $BW^{0.75}$, 16 kJ/kg $BW^{0.75}$ lower than observed.

We have evaluated the study of Tovar-Luna et al. (2010a) conducted at the American Institute for Goat Research, Langston University (USA) using indirect calorimetry in Alpine dairy goats. Different dietary concentrate levels were used and we selected groups with higher and lower qm. A group of goats in early lactation fed 20% concentrate had a qm of 0.53, and the amount of energy transferred to MP, ML and MF was 92, 74 and 249 kJ/kg $BW^{0.75}$, respectively (observed values were 76, 104 and 157 kJ/kg $BW^{0.75}$, respectively). The model predicted storage of body energy as fat of 151 kJ/kg $BW^{0.75}$, and an energy wasted in CH_4 of 68 kJ/kg $BW^{0.75}$ (the observed value was 56 kJ/kg $BW^{0.75}$). The original study did not calculate the oxidation of nutrients and the present model estimated the oxidation of protein at approximately 17% with the oxidation of carbohydrate (37%) being lower than the oxidation of fat (46%). That is, greater oxidation of fat than carbohydrate took place, underscoring that we must evaluate the flux of energy from carbohydrate to fat and also lipid tissue mobilization.

The daily energy transfer from the protein pool to the carbohydrate pool was of 43 kJ/kg $BW^{0.75}$ (from PA to CA pool), and the transfer from the carbohydrate to the fat pool was 474 kJ/kg $BW^{0.75}$ (from CA to FA pool). The daily accretion of fat reserves was -33 kJ/kg $BW^{0.75}$, (difference between F_{FA_RF} and F_{RF_FA}) denoting that mobilization of fat reserves took place in order to support deposition of energy as milk fat. The group of goats fed 60% of concentrate in mid lactation had a qm of 0.62, and the energy transferred to MP, ML, MF and CH_4 was 112, 78, 212 and 68 kJ/kg $BW^{0.75}$ (close to the observed values 95, 125, 192 and 85 kJ/kg $BW^{0.75}$, respectively), respectively. Thus, total milk energy predicted was 402 kJ/kg $BW^{0.75}$ and the observed 412 kJ/kg $BW^{0.75}$. Due to the greater ME available with this diet, higher body fat retention than the diet with qm = 0.53 was observed (242 vs 151 kJ/kg $BW^{0.75}$ for qm diets of 0.62 and 0.53 respectively) and the oxidation of carbohydrate was higher, followed by fat and protein oxidation (46%, 33% and 21%, respectively). The accretion of fat reserves was positive (75 kJ/kg $BW^{0.75}$ and day), indicating accumulation of fat.

Although theorical daily simulation of gluconeogenesis was similar between diets (44 kJ/kg $BW^{0.75}$), lipogenesis was 52 kJ/kg $BW^{0.75}$ greater in the diet with a lower qm. The diet with 20% of concentrate had 60% of alfalfa hay and 43% of NDF while the 60% concentrate diet had 20% of alfalfa hay and 31% of NDF. According to Van Knegsel et al. (2007), a diet with 20% of concentrate should be considered mainly lipogenic because of the predominance of forage stimulates ruminal production of acetate and butyrate and the dietary fat provides fatty acids for uptake by tissues. In contrast, a diet with 60% of concentrate should be considered a glucogenic diet. Therefore, the group with a lower qm (20% of concentrate) was lipogenic, had greater oxidation of fat (13% greater), greater fat mobilization, greater lipogenesis, lower retention of fat reserves (151 kJ/kg $BW^{0.75}$ vs 242 kJ/kg $BW^{0.75}$) and 37 kJ/kg $BW^{0.75}$ more daily milk energy in the form of fat. In lactating ruminants fed isoenergetic diets, lipogenic nutrients can increase the partitioning of ME into milk (increasing milk fat yield), and consequently decrease partitioning of ME into body reserves (Van Knegsel et al., 2007).

Another center with indirect calorimetry facilities and studies in dairy goats is the Estación Experimental de Zaidin (CSIC), Granada (Spain). The study of Marcos et al. (2020) aimed to reduce feeding costs and diminish the negative environmental impact associated with agro-industrial by-product disposal by replacing 44% of cereal grains with a mixture of dried distillers' grains, citrus pulp and olive cake in the concentrate of lactating Murciano-Granadina goats. The diets were isoproteic and isoenergetic and fat was added to the diet (from 3 to 5%EE, respectively) to increase the energy content of the by-product diet. The qm was approximately 0.65 in both diets and the NDF was the same (21%).

No negative effects on CH_4 emission and a greater milk fat and protein content was detected when the agro-industrial by-products were fed. The model predicted milk protein, lactose and fat with values of 3.5%, 4.1% and 4.9% for the control diet and the observed values were similar: 3.2%, 5.2% and 4.6%, respectively with exception of lactose. The quality composition of milk predicted with the diet with agro-industrial by-products was 2.9%, 3.7% and 4.6% of protein, lactose and fat, respectively and the observed values were 3.3%, 5.3% and 4.8%. Thus, values were similar with the exception of lactose that was greater again. Consequently, the diet with more fibrous by-product was expected to increase ruminal production of acetate and butyrate and reduce propionate, precursor of lactose in milk (Van Knegsel et al., 2007), but there was no difference between diets for lactose (5.2%, on average), although these differences were detected by the model (4.1% vs 3.7%, for control and by-product diet, respectively).

It is possible that the higher value of milk lactose observed was because Marcos et al. (2020) assessed it as the difference between the total solids and the sum of protein, fat and ash. Regarding milk fat, we expected greater estimated values with the by-product diet because, according to Van Knegsel et al. (2007), it was a lipogenic diet. However, the lack of difference in milk fat estimated by the model was likely due to the fact that diets were isoenergetic and Marcos et al. (2020) reported the same NDF value for both diets (20.7%) and the present model used NDF to adjust milk fat.

The CH_4 predicted and observed, for the control diet, was 22 and 26 g/d, respectively. The CH_4 predicted and observed with the by-product diet was the same (21 g/d) demonstrating that the model was not able to capture the changes in the diet because the higher fat was not accompanied by a rise in dietary fiber with the agro-industrial by-products. The model estimated the oxidation of macronutrients that was not calculated by Marcos et al. (2020). The oxidation of protein was low (15%, on average) due largely to the fact that protein is not the main source of energy for mammals and goats acquire more of the energy from oxidation of carbohydrate and fat. Again, due to greater qm (0.65 in both diets) and identical GEI and NDF, the oxidation of carbohydrate and fat was the same between diets; being greater the oxidation of carbohydrates (50%) than fat (35%). Therefore, this is a scenario where similar transfer of energy among protein, carbohydrate and fat pools between diets was observed, and enough energy was available to support milk fat and body fat deposition.

The last study considered in this discussion was one that replaced portions of cereal grain in the concentrate with orange leaves and rice straw in lactating Murciano-Granadina goats (Fernández et al., 2021a). This study was conducted at the Instituto de Ciencia y Tecnología Animal en la Universitat Politecnica de Valencia (Spain) that has indirect calorimetry facilities. Again, as most of the studies with dairy goats, the main objective was to reduce feeding costs by using horticultural byproducts. In this study the control diet had a qm = 0.61 and the byproduct diet a qm = 0.54. For the qm = 0.61, the predicted milk energy in MP, ML and MF was 119, 100 and 268 kJ/kg $BW^{0.75}$ (3.8%, 4.4% and 5.2%, respectively) and the observed values were similar 128, 105 and 286 kJ/kg $BW^{0.75}$ (4.1%, 4.6% and 5.5%). Therefore, the cheese extract for predicted and observed was close, 9.0% and 9.6%, respectively.

The CH_4 predicted (29 g/d) and observed value (30 g/d) was similar. For the lower qm (0.54) the predicted milk energy in MP, ML and MF were 122, 98 and 342 kJ/kg $BW^{0.75}$ (4.3%, 4.8% and 7.3%, respectively) and the observed values were 118, 97 and 303 kJ/kg $BW^{0.75}$ (4.2%, 4.7% and 6.5%). Therefore, the cheese extract for predicted and observed was again similar, 11.7% and 10.7%, respectively. The CH_4 predicted (28 g/d) and the observed value (27 g/d) was almost identical. Consequently, the present model had a good fit for milk energy partitioning and CH_4 emissions, and could forecast the changes in diet (reduction of cereal grain and increasing agro-industrial byproducts) increasing milk fat (2.1 points) and cheese extract (from 9% to 11.7%) and a slight reduction of CH_4 emissions (1 g/d).

With the scenario proposed in the study of Fernández et al. (2021a), the group of goats fed a diet with qm = 0.61 had greater oxidation of carbohydrate than fat (47% vs 35%), and in the group with a lower qm the oxidation of fat was higher than oxidation of carbohydrate (46% vs 37%). The model revealed a similar trend as in the study of Tovar-Luna et al. (2010a) with high and low qm; when the qm was high, the energy oxidized from carbohydrate was higher than from fat oxidation and when the qm was low and/or the proportion of fiber increased, less carbohydrate and more fat was oxidized (Van Knegsel et al., 2007; Derno et al., 2013).

We observed that the daily energy flux from the PA to the CA pool was 48 kJ/kg $BW^{0.75}$ and 56 kJ/kg $BW^{0.75}$ (for qm high and low respectively). Therefore, when the qm was lower, more energy from PA was transferred to CA to support energy demands indicating that PA could drive amino acids to body retention and MP, and the deaminated amino acids also could be used for other pathways such as gluconeogenesis (Chwalibog et al. 1997b; 2004). The flux of energy from the CA to the FA pool was 58 kJ/kg $BW^{0.75}$ lower for the diet with qm = 0.61 than the diet with qm = 0.54. Thus, when qm was lower a surplus of carbohydrate, which is not oxidized, contributed to fat metabolism being either oxidized or transferred to milk. The process of producing fat (i.e. triacylglycerol) encompasses lipogenesis and esterification of the fatty acids produced (e.g. palmitate) followed by storage in the body or secretion into milk (Chwalibog et al. 2004; Harvatine et al. 2009). The daily accretion of fat reserves was -28 kJ/kg $BW^{0.75}$ (difference between F_{FA_RF} and F_{RF_FA}) highlighting that in the diet with lower qm mobilization of fat reserves took place to support milk fat energy production.

The present model confirmed the hypothesis proposed by Van Knegsel et al. (2007) that energy partitioning between milk and body tissue can be altered by feeding isocaloric diets that differ in lipogenic and glucogenic nutrient content. When diets were isoenergetic, the model predicted that goats fed a mainly lipogenic diet (higher in forage and fat) tended to have higher milk fat compared with feeding the glucogenic diet. When diets were lower in energy, there was increased body fat mobilization and not always a higher milk fat output.

Model application in practice

In the Mediterranean countries goat milk production has traditionally been destined for cheese manufacture, the physicochemical characteristics and composition of raw milk being essential for successful development of the dairy goat industry and also for the marketing of the final products. In Spain, farmers are paid based on two components in the milk, protein and fat (cheese extract). The cheese extract is the main parameter for farmers because the price of milk depends on it (milk price per cheese extract was 0.0937€; consulted 06/23/22 at Lonja de Albacete, Castilla-La Mancha, www.oviespana.com). The simulation of the study of Tovar-Luna et al. (2010a) showed a cheese extract of 6.5% and 7.8% for a high and a low qm (0.62 and 0.53, respectively), and a milk price of 0.61€/L and 0.73€/L of milk produced, respectively for isoenergetic diets with 60% or 20% of concentrate. The model evaluation of Fernández et al. (2021a) showed greater cheese extract for the diet with agro-industrial by products (9.0% and 11.7%), and a price of 0.84€/L and 1.10€/L of milk produced for isoenergetic diets based on cereals or partial replacement of cereals, respectively.

Conclusions

The model has provided a dynamic description of energy use, which is a useful framework to test hypotheses of physiological regulation of energy use by dairy goats. It allowed to shift the focus towards a more efficient transfer of dietary energy into milk components. Clearly, this model must be improved to cover greater variations in dietary concentrate and forages, together with stage of lactation, evaluation of body reserves and the potential impact of climate change (e.g. heat stress).

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Conflict of interest statement

The authors have no conflict of interest to report

Literature Cited

Aguilera, J. F. 2001. Aportaciones al conocimiento de la nutrición energética de pequeños rumiantes, con particular referencia al ganado caprino. *Arch. Zootec.* 50:565–596.

Agricultural and Food Research Council (AFRC) 1993. *Energy and protein requirements of ruminants*. CAB International: Wallingford, UK.

Association of Official Analytical Chemists (AOAC) 2012. *Official Methods of Analysis*, 19th ed. AOAC International, Gaithersburg, MD, USA.

Bailey, K. E., C. M. Jones, and A. J. Heinrichs. 2005. Economic returns to Holstein and Jersey herds under multiple component pricing. *J. Dairy Sci.* 88:2269-2280.

Bethard, G. and S. Stokes. 1999. On-Farm tools for monitoring feeding and production. *Western Dairy Management Conference* 113-124.

Baumgard, L. H., R. J. Collier, and D. E. Bauman. 2017. A 100-year review: Regulation of nutrient partitioning to support lactation. *J. Dairy Sci.* 100:10353–10366.

Bibby, J. and H. Toutenburg. 1977. *Prediction and improved estimation in linear models*. John Wiley& Son, London, UK.

Brouwer, E. 1965. Report of sub-committee on constants and factors. In: Blaxter, K. L. editor. Proceeding of the *3th EAAP Symposium on Energy Metabolism*, pp. 441-443. Academic Press, London, UK.

Chwalibog, A., A. H. Tauson, and G. Thorbek. 1997a. Oxidation of nutrients in growing calves. In: McCracken, K. J., Unsworth E. F. and A. R. G. Wylie editors. Proceeding of the *14th EAAP Symposium on Energy and Protein Metabolism* (ed.), pp. 213-216. CAB International, London, UK.

Chwalibog, A., A. H. Tauson, and G. Thorbek. 1997b. Quantitative oxidation of nutrients in growing calves. *Ernährungswiss* 36:313-316.

Chwalibog, A., A. H. Tauson, and G. Thorbek. 2004. Energy metabolism and substrate oxidation in pigs during feeding, starvation and re-feeding. *J. Anim. Physiol. Anim. Nutr.* 88:101-112.

Criscioni, P., J. V. Martí, I. Pérez-Baena, J. L. Palomares, T. Larsen, and C. Fernández. 2016. Replacement of alfalfa (*Medicago sativa*) hay with maralfalfa (*Pennisetum sp.*) hay in diets of lactating dairy goats. *Anim. Feed Sci. Technol.* 219:1-12.

Criscioni, P. and C. Fernández. 2016. Effect of rice bran as a replacement for oat grain in energy and nitrogen balance, methane emissions, and milk performance of Murciano-Granadina goats. *J. Dairy Sci*. 99:280-290.

Derno, M., G. Nürnberg, P. Schön, A. Schwarm, M. R.ntgen, H. M. Hammon, C. C. Metges, R. M. Bruckmaier, and B. Kuhla. 2013. Short-term feed intake is regulated by macronutrients oxidation in lactating Holstein cows. *J. Dairy Sci.* 96:971–980.

Demeyer, D. I. 1992. Quantitative aspects of microbial metabolism in the rumen and hindgut. In: Jouany, J. P. editor. *Rumen microbial metabolism and ruminant digestion*. INRA Editions, Paris, 217-237.

European Union. 2003. *Protection of animals used for experimental purposes*. Council Directive 86/609/EEC of 24 November 1986, amended 16.9.2003. European Council, Brussels, Belgium.

Fahey, G. C., and L. L. Berger. 1988. *Carbohydrate nutrition of ruminants*. Pages 269–297 in The Ruminant Animal: Digestive Nutrition and Physiology. D. C. Church, ed. Prentice-Hall.

Food and Agriculture Organization (FAOSTAT) 2020. FAO Statistical data base Food and Agriculture Organization of the United Nations, Rome, Italy, available at: http://faostat.fao.org/ (Accessed Oct. 10 2021).

Fernández, C., M. C. López, and M. Lachica. 2015. Low cost open-circuit hood system for measuring gas exchange in small ruminants: from manual to automatic recording. *J. Agri. Sci.* 153:1302-1309.

Fernández, C., J. V. Martí, I. Pérez-Baena, J. L. Palomares, C. Ibáñez, and J. V. Segarra. 2018. Effect of lemon leaves on energy and CN balances, methane emission and milk performance in Murciano-Granadina dairy goats. *J. Anim. Sci.* 96:1508-1518.

Fernández, C., I. Pérez-Baena, J. V. Martí, J. L. Palomares, J. Jorro-Ripoll, and J. V. Segarra. 2019. Use of orange leaves as a replacement for alfalfa in energy and nitrogen partitioning, methane emissions and milk performance of Murciano-Granadinas goats. *Anim. Feed Sci. Technol.* 247:103-111.

Fernández, C., J. Gomis-Tena, A. Hernández, and J. Saiz. 2019. An open-circuit indirect calorimetry head hood system for measuring methane emission and energy metabolism in small ruminants. *Animals* 9:380; doi:10.3390/ani9060380

Fernández, C., I. Hernando, E. Moreno-Latorre, and J. J. Loor. 2020. Development of a Dynamic energy-partitioning model for enteric methane emissions and milk production in goats using energy data from indirect calorimetry studies. *Animal* 14:S2, s382-s395.

Fernández, C., T. Romero, J. V. Martí, V. J. Moya, I. Hernando and J. J. Loor. 2021a. Energy, nitrogen partitioning, and methane emissions in dairy goats differ when an isoenergetic and isoproteic diet contained orange leaves and rice straw residues. *J. Dairy Sci.* 104:7830-7844.

Fernández, C., A. Hernández, J. Gómis-Tena and J. J. Loor. 2021b. Changes in nutrient balance, methane emissions, physiologic biomarkers, and production performance in goats fed different forage to concentrate ratios during lactation. *J. Anim. Sci.* 99 (7):1-13

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

Grainger, C. and K. A. Beauchemin. 2011. Can enteric methane emissions from ruminants be lowered without lowering their production? *Anim. Feed Sci. Technol.* 166-167, 308-320.

Harvatine, K. J., Y. R. Boisclear, and D. E. Bauman. 2009. Recent advances in the regulation of milk fat synthesis. *Animal* 3:40-54.

Ibáñez, C., M. C. López, P. Criscioni, and C. Fernández. 2014. Effect of replacing dietary corn with beet pulp on energy partitioning, substrate oxidation and methane production in lactating dairy goats. *Anim. Prod. Sci.* 55:56-63.

Ibáñez, C., V. J. Moya, H. Arriaga, D. M. López, P. Merino and C. Fernández. 2015. Replacement of cereal with low starch by-products on nutrient utilization and methane emissions in dairy goats. *Open J. Anim. Sci.* 5:198-209.

Ibáñez, C., P. Criscioni, H. Arriaga, P. Merino, F. J. Espinós, and C. Fernández. 2016. Murciano-Granadina Goat Performance and Methane Emission after Replacing Barley Grain with Fibrous By-Products. *PLoS ONE* 11(3): e0151215

Institute Nationale Recherche Agronomique (INRA) 2018. *Feeding system for ruminants*. Wageningen Academic Publishers, Wageningen, the Netherlands.

International Panel on Climate Change (IPCC) 2014. *Fifth IPCC Assessment Report*. Cambridge University Press, Cambridge, UK.

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

Kebreab, E., J. France, R. E. Agnew, T. Yan, M. S. Dhanoa, J. Dijkstra, D. E. Beever and C. K. Reynolds. 2003. Alternatives to linear analysis of energy balance data from lactating dairy cows. *J. Dairy Sci.* 86:2904-2913.

Lin, L. I. K. 1989. A concordance correlation coefficient to evaluate reproducibility. *Biometrics* 45, 255-268.

Lonja de Albacete, Castilla-La Mancha, www.oviespana.com. Accessed July 1, 2022.

López, M. C., F. Estellés, V. J. Moya, and C. Fernández. 2014. Use of dry citrus pulp or soybean hulls as a replacement for corn and grain in energy and nitrogen partitioning, methane emissions and milk performance in lactating Murciano-Granadina goats. *J. Dairy Sci.* 97:7821-7832.

López, M. C. and C. Fernández. 2013. Energy partitioning and substrate oxidation by Murciano-Granadina goats during mid lactation fed soy hulls and corn gluten feed blend as a replacement for corn grain. *J. Dairy Sci.* 96:4542-4552.

Marcos, C. N., M. D. Carro, J. E. Fernández-Yepes, A. Haro, M. Romero-Huelva and E. Molina-Alcaide. 2020. Effects of agro-industrial by-products supplementation on dairy goat milk characteristics, nutrient utilization, ruminal fermentation and methane production. *J. Dairy Sci.* 103:1472-1483.

Molina-Alcaide, E., E. Y. Morales-Garcia, A. I. Martin-Garcia, H. Ben Salem, A. Nefzaoui, and M. R. Sanz-Sampelayo. 2010. Effects of partial replacement of concentrate with feed blocks on nutrient utilization, microbial N flow, and milk yield and composition in goats. *J. Dairy Sci.* 93:2076–2087.

Ørskov, E. R. and M. Ryle. 1998. Energy nutrition in ruminants. *Elsevier Science Publishers* Ltd. UK. pp149

Pirisi, A., A. Lauret, and J. P. Dubeuf. 2007. Basic and incentive payments for goat and sheep milk in relation to quality. *Small Rumin. Res.* 68:167–178.

R Core Team 2016. R: A language and environment for statistical computing. Version 1.1.447. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rapetti, L., L. Bava, A. Tamburini and G. M. Crovetto. 2005. Feeding behaviour, digestibility, energy balance and productive performance of lactating goats fed forage-based and forage-free diets. *Ital. J. Anim. Sci.* 4:71-83.

Romero-Huelva, M., E. Ramos-Morales, and E. Molina-Alcaide. 2012. Nutrient utilization, ruminal fermentation, microbial abundances, and milk yield and composition in dairy goats fed diets including tomato and cucumber waste fruits. *J. Dairy Sci.* 95:6015–6026.

Romero-Huelva, M., M. A. Ramírez-Fenosa, R. Planelles-González, P. García-Casado, and E. Molina-Alcaide. 2017. Can by-products replace conventional ingredients in concentrate of dairy goat diet? *J. Dairy Sci.* 100:4500–4512.

Stella Architect Professional software 2018. High Performance System Version 1.9.4. ISEE Systems Incorporation. Hanover, New Hampshire, USA.

Nhayandra, C. D., N. C. D. Silva, R. Puchala, T. A. Gipson, T. Sahlu, and A. L. Goetsch. 2018. Effects of restricted periods of feed access on feed intake, digestion, behavior, heat energy, and performance of Alpine goats. *J. Appl. Anim. Res.* 46:1, 994-1003

Tovar-Luna, I., R. Puchala, T. Sahlu, H. C. Freetly and A. L. Goetsch. 2010a. Effects of stage of lactation and dietary concentrate level on energy utilization by Alpine dairy goats. *J. Dairy Sci.* 93:4818-4828.

Tovar-Luna, I., R. Puchala, T. Sahlu, H. C. Freetly, and A. L. Goetsch. 2010b. Effects of stage of lactation and level of feed intake on energy utilization by Alpine dairy goats. *J. Dairy Sci.* 93:4829-4837.

US EPA (United States Environmental Protection Agency). 2021. Inventory of U.S. Greenhouse Gas Emissions and Sinks. Accessed July 1, 2022.

Van Knegsel, A. T. M., H. van den Brand, J. Dijkstra, W. M. van Straalen, M. J. Heetkamp, S. Tamminga, and B. Kemp. 2007. Dietary energy source in dairy cows in early lactation: energy partitioning and milk composition. *J. Dairy Sci.* 90:1467-1476.

Figure 1. Diagrammatic representation of the energy partitioning mathematical model in dairy goats (using Stella Architect software). See Table 2 for legend.

Figure 2. Observed versus predicted values of milk energy in protein (a), lactose (b) fat (c) and energy in methane (d) used for model development in dairy goats [kJ/kg $BW^{0.75}$ day; $BW^{0.75}$ = MBW]. The regression equations were as follow: milk protein energy Y = 28.27 + 0.76X (standard error = 13.36 and 0.11 for the intercept and slope respectively; residual standard error = 23.08; R^2 = 0.30); milk lactose energy Y = -2.34 + 1.01X (standard error = 14.88 and 0.15 for the intercept and slope respectively; residual standard error = 22.22; R^2 = 0.31); milk fat energy Y = -41.25 + 1.16X (standard error = 33.29 and 0.12 for the intercept and slope respectively; residual standard error = 43.84; R^2 = 0.44); methane Y = 24.08 + 0.75X (standard error = 7.52 and 0.08 for the intercept and slope respectively; residual standard error = 11.36; R^2 = 0.42).

Figure 3. Residuals plot of milk energy in protein (a), lactose (b) fat (c) and energy in methane (d) used for model development in dairy goats [kJ/kg $BW^{0.75}$ day; $BW^{0.75}$ = MBW].

Figure 4. Observed versus predicted values of milk energy in protein (a), lactose (b) fat (c) and energy in methane (d) used for model internal evaluation in dairy goats [kJ/kg

$BW^{0.75}$ day; $BW^{0.75}$ = MBW]. The regression equations were as follow: milk protein energy Y = -7.47 + 1.12X (standard error = 17.56 and 0.15 for the intercept and slope respectively; residual standard error = 19.83; R^2 = 0.51); milk lactose energy Y = 6.59 + 0.91X (standard error = 21.61 and 0.21 for the intercept and slope respectively; residual standard error = 22.87; R^2 = 0.26); milk fat energy Y = 23.37 + 0.94X (standard error = 50.70 and 0.19 for the intercept and slope respectively; residual standard error = 49.63; R^2 = 0.32); methane Y = 19.72 + 0.76X (standard error = 10.95 and 0.12 for the intercept and slope respectively; residual standard error = 11.77; R^2 = 0.43).

Figure 5. Residuals plot of milk energy in protein (a), lactose (b) fat (c) and energy in methane (d)used for model internal evaluation in dairy goats [kJ/kg $BW^{0.75}$ day; $BW^{0.75}$ = MBW].

Figure 6. Observed versus predicted values of milk energy in protein (a), lactose (b) fat (c) and energy in methane (d) used for model external evaluation in dairy goats [kJ/kg $BW^{0.75}$ day; $BW^{0.75}$ = MBW].

Figure 7. Residuals plot of milk energy in protein (a), lactose (b) fat (c) and energy in methane (d) used for model external evaluation in dairy goats [kJ/kg $BW^{0.75}$ day; $BW^{0.75}$ = MBW].

Table 1. Descriptive statistics of variables in the database used to develop the milk energy partitioning model and methane for dairy goats (n = 106 observations)

Lactating Dairy Goat fed Mixed Diet				
Variable[1]	Mean	Min.	Max.	SD
Diet Composition (%DM)				
DM	93.3	93.0	94.0	0.45
CP	18.2	17.1	19.5	0.15
EE	2.7	1.8	3.5	0.85
NDF	31.2	21.0	42.0	8.23
NFC	32.5	31.0	35.0	1.63
GE (MJ/kgDM)	17.2	16.8	17.6	0.21
qm	0.60	0.44	0.71	0.061
Apparent digestibility (%)				
CP	70	67	72	1.9
EE	67	53	76	8.3
Energy	67	54	79	5.2
Energy partitioning (kJ/kg $BW^{0.75}$ per day)				
GEI	2085	1496	2781	273.1
Protein intake	520	366	705	70.3
Carbohydrate intake	1439	1049	1894	198.3
Fat intake	127	68	220	40.7
Volatile fatty acids	855	597	1140	119.1
Methane	89	57	114	15.3
DE	1389	1007	1807	178.1
Protein absorbed	365	246	508	53.2

Carbohydrate absorbed	936	610	1275	161.7
Fat absorbed	88	36	168	36.4
MEI	1222	853	1628	170.1
HP	657	515	889	92.6
HPx	637	501	858	87.9
HPf	21	6	81	11.3
OXP	114	32	268	44.3
OXC	301	66	558	135.3
OXF	221	19	530	108.6
Protein retention	28	-498	174	84.7
Fat retention	66	-346	827	171.8
Retained energy	94	-390	529	171.9
Energy in milk protein	116	60	182	28.1
Energy in milk lactose	97	46	174	27.7
Energy in milk fat	258	128	395	79.6
Total energy in milk	471	274	684	91.2
Nitrogen balance (g/day)				
Urinary nitrogen	20	10	35	6.7
Retained nitrogen	3	-3	8	3.6
Goat characteristics				
DMI (g/day)	2146	1597	2503	210.1
Body weight (kg)	47	36	55	4.7
Milk yield (kg/day)	2.3	1.1	2.6	0.52

[1] CP = crude protein; EE = ether extract; GE = gross energy; qm = metabolizability; GEI = gross energy intake; DE = digestible energy; MEI = metabolizable energy intake; HP = heat production; HPx = heat production from oxidation; HPf = heat production from fermentation; OXP = protein oxidation; OXC = carbohydrate oxidation; OXF = fat oxidation; DMI = dry matter intake.

Table 2. Descriptive statistics of variables in the evaluation database used to evaluate the milk energy partitioning model and methane for dairy goats (n = 52 observations)

	Lactating Dairy Goat fed Mixed Diet			
Variable[1]	Mean	Min.	Max.	SD
Diet Composition (%DM)				
DM	93.2	93.0	94.0	0.40
CP	18.2	17.0	19.4	0.12
EE	2.6	1.8	4.0	0.91
NDF	30.0	21.0	43.0	8.36
NFC	33.0	31.0	35.2	1.75
GE (MJ/kgDM)	17.3	16.9	17.5	0.19
qm	0.60	0.49	0.70	0.050
Apparent digestibility (%)				
CP	69	66	72	1.9
EE	67	54	75	9.1
Energy	68	59	77	4.9

Energy partitioning (kJ/kg $BW^{0.75}$ per day)				
GEI	2054	1497	2651	263.8
Protein intake	511	367	656	67.8
Carbohydrate intake	1417	1060	1886	193.6
Fat intake	126	68	219	42.6
Volatile fatty acids	855	605	1241	126.1
Methane	86	57	113	15.4
DE	1386	1028	1959	187.2
Protein absorbed	357	246	459	51.3
Carbohydrate absorbed	941	628	1427	170.7
Fat absorbed	87	36	167	38.9
MEI	1222	864	1772	180.2
HP	636	517	892	94.4
HPx	617	503	861	89.7
HPf	19	3	45	9.2
OXP	107	22	227	45.9
OXC	289	59	529	127.9
OXF	221	76	552	93.3
Protein retention	33	-226	148	75.9
Fat retention	103	-299	366	151.4
Retained energy	136	-236	422	158.3
Energy in milk protein	118	65	193	29.2
Energy in milk lactose	98	41	188	29.2
Energy in milk fat	272	72	541	92.8
Total energy in milk	489	237	867	131.6
Nitrogen balance (g/day)				
Urinary nitrogen	14	13	15	2.9
Retained nitrogen	6	5	7	0.3

Goat characteristics				
DMI (g/day)	2119	1636	2408	210.0
Body weight (kg)	47	39	55	4.4
Milk yield (kg/day)	2.2	1.0	3.7	0.55

[1] CP = crude protein; EE = ether extract; GE = gross energy; qm = metabolizability; GEI = gross energy intake; DE = digestible energy; MEI = metabolizable energy intake; HP = heat production; HPx = heat production from oxidation; HPf = heat production from fermentation; OXP = protein oxidation; OXC = carbohydrate oxidation; OXF = fat oxidation; DMI = dry matter intake.

Table 3. Pools, fluxes and symbols used in the milk energy partitioning and methane for dairy goat model

Label	Description
Energy pools (kJ/kg $BW^{0.75}$)	
Q_GEI	Energy intake
Q_PI	Protein intake
Q_CI	Carbohydrate intake
Q_FI	Fat intake

Q_VFA	Volatile fatty acids
Q_CH_4	Methane
Q_PA	Protein assimilation
Q_CA	Carbohydrate assimilation
Q_FA	Fat assimilation
Q_RP	Protein retention
Q_FR	Fat retention
Q_MP	Milk protein
Q_ML	Milk lactose
Q_MF	Milk fat
Energy fluxes (kJ/kg $BW^{0.75}$ per hour)	
F_{GEI_PI}	energy intake from diet protein
F_{GEI_CI}	energy intake from diet carbohydrate
F_{GEI_FI}	energy intake from diet fat
F_{PI_feces}	energy lost in feces from protein intake
F_{PI_PA}	energy absorbed from protein
F_{CI_feces}	energy lost in feces from carbohydrate intake
F_{CI_CA}	energy absorbed from carbohydrates
F_{CI_VFA}	carbohydrate fermentation to volatile fatty acids
F_{FI_feces}	energy lost in feces from fat intake
F_{FI_FA}	energy absorbed from fat
F_{VFA_CA}	volatile fatty acids to carbohydrate absorbed pool
F_{VFA_FA}	volatile fatty acids to fat absorbed pool
F_{VFA_CH4}	methane production
F_{VFA_Hf}	heat of fermentation
F_{PA_RP}	protein retention
F_{PA_MP}	protein in milk
F_{PA_UEN}	nitrogen urine energy

F_{PA_OXP}	protein oxidation
F_{PA_CA}	gluconeogenesis
F_{CA_ML}	lactose in milk
$F_{CA\_UENfree}$	urine enegy nitrogen free
F_{CA_OXC}	carbohydrate oxidation
F_{CA_FA}	lipogenesis
F_{FA_MF}	fat in milk
F_{FA_RF}	fat retention
$F_{FA\_UENfree}$	urine energy nitrogen free
F_{FA_OXF}	fat oxidation
F_{RP_PA}	mobilization of protein
F_{RF_FA}	mobilization of fat
Fractional rates (/hour)	
k_{GEI_PI}	fractional rate of F_{GEI_PI}
k_{GEI_CI}	fractional rate of F_{GEI_CI}
k_{GEI_FI}	fractional rate of F_{GEI_FI}
k_{PI_feces}	fractional rate of F_{PI_feces}
k_{PI_PA}	fractional rate of F_{PI_PA}
k_{CI_feces}	fractional rate of F_{CI_feces}
k_{CI_CA}	fractional rate of F_{CI_CA}
k_{CI_VFA}	fractional rate of F_{CI_VFA}
k_{FI_feces}	fractional rate of F_{FI_feces}
k_{FI_FA}	fractional rate of F_{FI_FA}
k_{VFA_Hf}	fractional rate of F_{VFA_Hf}
k_{VFA_CA}	fractional rate of F_{VFA_CA}
k_{VFA_FA}	fractional rate of F_{VFA_FA}
k_{VFA_CH4}	fractional rate of F_{VFA_CH4}
k_{PA_RP}	fractional rate of F_{PA_RP}

k_{PA_UEN}	fractional rate of F_{PA_UEN}
k_{PA_OXP}	fractional rate of F_{PA_OXP}
k_{PA_CA}	fractional rate of F_{PA_CA}
k_{PA_MP}	fractional rate of F_{PA_MP}
$k_{CA\_UENfree}$	fractional rate of $F_{CA\_UENfree}$
k_{CA_OXC}	fractional rate of F_{CA_OXC}
k_{CA_FA}	fractional rate of F_{CA_FA}
k_{CA_ML}	fractional rate of F_{CA_ML}
$k_{FA\_UENfree}$	fractional rate of $F_{FA\_UENfree}$
k_{FA_OXF}	fractional rate of F_{FA_OXF}
k_{FA_MF}	fractional rate of F_{FA_MF}
k_{RP_PA}	fractional rate of F_{RP_PA}
k_{FA_RF}	fractional rate of F_{FA_RF}
k_{RF_FA}	fractional rate of F_{RF_FA}
Reference constants	
HP	heat production
HPx	heat production form oxidation of nutrients
Hf	heat of fermentation
OXP	oxidation of protein
OXC	oxidation of carbohydrates
OXF	oxidation of fat
Inputs	
BW (kg)	body weight
DMI (g/kg DM)	dry matter intake
GE (MJ/kg DM)	Dietary gross energy
CP (%DM)	Dietary crude protein
CPd	Apparent digestibility of protein
EE (%DM)	Dietary fat

EEd	Apparent digestibility of fat
MEI (kJ/kg $BW^{0.75}$ per day)	Metabolizable energy intake
qm	metabolisability

Table 4. Initial and final parameter estimation and standard deviation of optimized milk energy partitioning and methane dairy goat model parameters, other parameters and pools

Parameters[1]	Initial Values	Final Values	SD	CV (%)
k_{VFA_CH4}	0.142	0.110	0.0226	18
k_{PA_MP}	0.575	0.567	0.0057	1
k_{CA_ML}	0.073	0.075	0.0014	2
k_{FA_MF}	0.034	0.030	0.0028	9
Others Paremeters		Fractional rates (/hour)		
k_{GEI_PI}	0.25	F_{GEI_PI} / Q_GEI		mass action kinetics
k_{GEI_CI}	0.69	F_{GEI_CI} / Q_GEI		mass action kinetics
k_{GEI_FI}	0.06	F_{GEI_FI} / Q_GEI		mass action kinetics
k_{PI_feces}	0.30	F_{PI_feces} / Q_PI		mass action kinetics
k_{PI_PA}	0.70	F_{PI_PA} / Q_PI		mass action kinetics
k_{CI_feces}	0.05	F_{CI_feces} / Q_CI		mass action kinetics
k_{CI_CA}	0.36	F_{CI_CA} / Q_CI		mass action kinetics
k_{CI_VFA}	0.60	F_{CI_VFA} / Q_CI		mass action kinetics

k_{FI_feces}	0.31	F_{FI_feces} / Q_FI		mass action kinetics
k_{FI_FA}	0.69	F_{FI_FA} / Q_FI		mass action kinetics
k_{VFA_Hf}	0.02	F_{VFA_Hf} / Q_VFA		mass action kinetics
k_{VFA_CA}	0.35	F_{VFA_CA} / Q_VFA		mass action kinetics
k_{VFA_FA}	0.60	F_{VFA_FA} / Q_VFA		mass action kinetics
k_{PA_RP}	0.08	F_{PA_RP} / Q_PA		mass action kinetics
k_{PA_UEN}	0.06	F_{PA_UEN} / Q_PA		mass action kinetics
k_{PA_OXP}	0.58	F_{PA_OXP} / Q_PA		mass action kinetics
k_{PA_CA}	0.23	F_{PA_CA} / Q_PA	k computed for a qm=0.6	mass action kinetics
$k_{CA\_UENfree}$	0.03	$F_{CA\_UENfree}$ / Q_CA		mass action kinetics
k_{CA_OXC}	0.03	F_{CA_OXC} / Q_CA	k computed for a qm=0.6	mass action kinetics
k_{CA_FA}	0.53	F_{CA_FA} / Q_CA	k computed for a qm=0.6	mass action kinetics
$k_{FA\_UENfree}$	0.03	$F_{FA\_UENfree}$ / Q_FA		mass action kinetics
k_{FA_OXF}	0.03	F_{FA_OXF} / Q_FA	k computed for a qm=0.6	mass action kinetics
k_{FA_RF}	0.84	F_{FA_RF} / Q_FA		Kebreab et al. (2003)
k_{RP_PA}	0.001	F_{RP_PA} / Q_RP		mass action kinetics
k_{RF_FA}	0.66	F_{RF_FA} / Q_RF		Kebreab et al. (2003)

Pools (kJ/kg $BW^{0.75}$)	Pools (initial values)	Equations	
Q_GEI	2085	$(DMI \times GE_{diet})/BW^{0.75}$	
Q_PI	0	$[(DMI \times CP)/BW^{0.75}] \times 23.86$	
Q_CI	0	GEI - PI - FI	
Q_FI	0	$[(DMI \times EE)/BW^{0.75}] \times 39.76$	
Q_VFA	0	70% of MEI is supplied as VFA	Demeyer (1992)
Q_CH_4	0	observed from indirect calorimetry system	
Q_PA	0	$CI \times CP_{digestibility\ coefficient}$	
Q_CA	0	DE_{intake} - PA - FA	
Q_FA	0	$FI \times EE_{digestibility\ coefficient}$	
Q_RP	28	$[(N\ retained)/BW^{0.75}] \times 6.25 \times 23.86$	
Q_RF	66	RE - RP	
Q_MP	0	$[MY \times CP_{milk} \times 23.64]/BW^{0.75}$	
Q_ML	0	$[MY \times Lactose_{milk} \times 17.36]/BW^{0.75}$	
Q_MF	0	$[MY \times Fat_{milk} \times 39.33]/BW^{0.75}$	
Reference constants			

HP	657	$[16.18 \times O_2 + 5.02 \times CO_2 - 2.17 \times CH_4 - 5.99 \times N_{urine}]/BW^{0.75}$	Brouwer (1965)
HPx	637	$[16.18 \times O_2 + 5.02 \times CO_{2x} - 5.99 \times N_{urine}]/BW^{0.75}$	Brouwer (1965)
Hf	21	HP - HPx	
OXP	114	$6.25 \times N_{urine} \times 18.42$	Brouwer (1958); Chwalibog et al. (1997a)
OXC	301	$[(-2.968 \times O_2 + 4.174 \times CO_{2x} - 2.446 \times N_{urine}) \times 17.85]/BW^{0.75}$	Brouwer (1958); Chwalibog et al. (1997a)
OXF	221	$[(1.719 \times O_2 + 1.719 \times CO_{2x} - 1.963 \times N_{urine}) \times 39.76]/BW^{0.75}$	Brouwer (1958); Chwalibog et al. (1997a)
Inputs			
BW (kg)	47		observed (development database)
DMI (g/day)	2146		observed (development database)
GE (MJ/kg DM)	17.2		observed (development database)
CP (%DM)	18.2		observed (development database)
CPd (%)	70		observed (development database)
EE (%DM)	2.7		observed (development database)
EEd (%)	67		observed (development database)
MEI (kJ/kg $BW^{0.75}$ per day)	1222	MEI = GEI - Efeces - Eurine - E_{CH4}	
qm	0.60	MEI/GEI	AFRC (1993); INRA (2018)

[1] Parameters abbreviation is given in Table 2.

Table 5. Summary of the data used for model external evaluation (n = 77 average goats observations)

	Lactating Dairy Goat fed Mixed Diet			
Variable[1] (kJ/kg $BW^{0.75}$ per day)	Mean	Min.	Max.	SD
	Rapetti et al. (2005)			
Diet Composition (%DM)				
CP (%)	17.6	16.6	18.7	1.05
NDF (%)	32.0	30.2	34.2	2.04
EE (%)	2.3	1.8	2.9	0.55
GE (MJ/kgDM)	18.5	18.3	18.6	0.15
qm	0.62	0.60	0.65	0.027
Apparent digestibility (%)				
CP	68	64	72	4.1
EE	78	72	83	5.3
Energy partitioning				
GEI	1916	1877	1940	33.5
Energy in methane	106	97	112	7.8
MEI	1186	1140	1261	65.7
Enery in milk	430	424	436	5.6
Energy in milk protein	127	112	143	15.3
Energy in milk lactose	126	115	138	11.8
Energy in milk fat	208	190	232	21.2
Goat characteristics				
DMI (g/day)	2170	2054	2354	161.4

Body weight (kg)	53.9	53	55.4	1.27
Milk yield (kg/day)	3.3	3	3.7	0.35
Tovar-Luna et al. (2010a)				
Diet Composition (%DM)				
CP (%)	19.0	17.5	20.4	1.59
NDF (%)	37.2	31.3	43.1	6.46
EE (%)	-	-	-	-
GE (MJ/kgDM)	-	-	-	-
qm	0.55	0.45	0.62	0.068
Apparent digestibility (%)				
CP	68	61	74	5
EE	-	-	-	-
Energy partitioning				
GEI	1638	1486	1731	83.4
Energy in methane	69	50	91	16.3
MEI	905	753	1073	109.5
Enery in milk	316	171	407	86.9
Energy in milk protein	76	45	95	18.3
Energy in milk lactose	96	47	125	28.5
Energy in milk fat	156	86	203	44.2
Goat characteristics				
DMI (g/day)	1660	1460	1740	104.9
Body weight (kg)	51.9	49.1	54.1	1.93
Milk yield (kg/day)	2.3	1.2	2.9	0.65
Tovar-Luna et al. (2010b)				
Diet Composition (%DM)				
CP (%)	18.3	18.3	18.3	0.00
NDF (%)	33.4	33.4	33.4	0.00

EE (%)	-	-	-	-
GE (MJ/kgDM)	-	-	-	-
qm	0.65	0.59	0.69	0.039
Apparent digestibility (%)				
CP	75	70	79	3.8
EE	-	-	-	-
Energy partitioning				
GEI	1330	797	2025	588.2
Energy in methane	54	14	105	29.0
MEI	845	540	1231	326.9
Enery in milk	295	164	485	122.3
Energy in milk protein	71	41	112	27.8
Energy in milk lactose	86	32	162	49.7
Energy in milk fat	144	84	219	56.5
Goat characteristics				
DMI (g/day)	1338	770	1980	576.7
Body weight (kg)	49.8	44.9	55.2	4.05
Milk yield (kg/day)	2.0	0.8	3.6	1.06
Molina-Alcaide et al. (2010)				
Diet Composition (%DM)				
CP (%)	13.2	10.4	15.9	2.75
NDF (%)	16.9	12.7	21.4	4.35
EE (%)	0.3	0.3	0.4	0.07
GE (MJ/kgDM)	14.2	12.5	16.7	2.23
qm	0.58	0.57	0.59	0.012
Apparent digestibility (%)				
CP	71	69	72	1.4
EE	74	70	80	5.3

Energy partitioning				
GEI	1467	1370	1520	83.9
Energy in methane	104	95	111	8.2
MEI	848	781	899	60.5
Enery in milk	232	218	258	22.8
Energy in milk protein	57	46	75	15.8
Energy in milk lactose	62	49	87	21.7
Energy in milk fat	133	110	175	36.0
Goat characteristics				
DMI (g/day)	1358	1295	1405	56.6
Body weight (kg)	38.9	38.3	39.5	0.6
Milk yield (kg/day)	1.1	1.0	1.3	0.15
	Romero-Huelva et al. (2012)			
Diet Composition (%DM)				
CP (%)	15.9	14.9	17.0	1.01
NDF (%)	44.1	33.8	48.3	6.92
EE (%)	1.2	0.3	3.4	1.49
GE (MJ/kgDM)	16.4	15.6	18.2	1.23
qm	0.61	0.61	0.62	0.005
Apparent digestibility (%)				
CP	77	76	78	1.0
EE	76	73	80	3.1
Energy partitioning				
GEI	1823	1770	1930	72.7
Energy in methane	82	67	110	19.3
MEI	1115	1090	1180	43.6
Enery in milk	239	229	251	9.9
Energy in milk protein	54	49	62	5.7

Energy in milk lactose	63	49	80	13.1
Energy in milk fat	143	130	166	16.3
Goat characteristics				
DMI (g/day)	1572	1548	1631	39.5
Body weight (kg)	37	30.2	40.3	4.57
Milk yield (kg/day)	1.0	0.9	1.0	0.04
López and Fernández (2013)				
Diet Composition (%DM)				
CP (%)	18.7	18.6	18.8	0.14
NDF (%)	41.1	34.8	47.5	8.93
EE (%)	3.6	2.1	5.0	2.06
GE (MJ/kgDM)	19.1	18.8	19.4	0.45
qm	0.61	0.60	0.63	0.021
Apparent digestibility (%)				
CP	70	69	71	1.0
EE	75	66	84	12.4
Energy partitioning				
GEI	2356	2286	2427	100
Energy in methane	99	96	101	3.5
MEI	1444	1436	1453	11.7
Enery in milk	537	532	542	7.5
Energy in milk protein	124	121	127	4.5
Energy in milk lactose	106	103	110	4.9
Energy in milk fat	316	285	347	43.6
Goat characteristics				
DMI (g/day)	2070	2040	2100	42.4
Body weight (kg)	43.1	43.1	43.1	0.01
Milk yield (kg/day)	2.2	2.1	2.2	0.09

Ibáñez et al. (2014)				
Diet Composition (%DM)				
CP (%)	15.2	14.7	15.7	0.71
NDF (%)	33.2	30.7	35.7	3.54
EE (%)	2.3	1.9	2.7	0.57
GE (MJ/kgDM)	17.5	17.4	17.5	0.07
qm	0.68	0.65	0.71	0.036
Apparent digestibility (%)				
CP	76	76	77	0.6
EE	70	60	80	14.6
Energy partitioning				
GEI	1734	1595	1872	195.9
Energy in methane	77	61	92	21.9
MEI	1182	1044	1320	195.2
Enery in milk	285	277	292	10.6
Energy in milk protein	72	70	75	3.8
Energy in milk lactose	60	59	62	2.1
Energy in milk fat	139	125	152	19.6
Goat characteristics				
DMI (g/day)	1760	1630	1890	183.8
Body weight (kg)	47	46.8	47.1	0.21
Milk yield (kg/day)	1.3	1.3	1.4	0.04
López et al. (2014)				
Diet Composition (%DM)				
CP (%)	15.8	14.8	16.7	0.66
NDF (%)	39.7	30.1	59.0	16.67
EE (%)	2.3	2.0	2.7	0.24
GE (MJ/kgDM)	17.6	17.2	18.0	0.28

qm	0.69	0.65	0.72	0.026
Apparent digestibility (%)				
CP	70	65	75	3.6
EE	72	70	75	2.5
Energy partitioning				
GEI	1649	1629	1668	18.4
Energy in methane	107	84	118	14.0
MEI	1139	1079	1193	46.5
Enery in milk	400	364	445	37.7
Energy in milk protein	93	89	97	3.6
Energy in milk lactose	83	71	93	9.4
Energy in milk fat	238	206	274	32.7
Goat characteristics				
DMI (g/day)	1535	1508	1570	25.2
Body weight (kg)	41.7	41.4	42	0.22
Milk yield (kg/day)	1.7	1.5	1.9	0.19
	Ibáñez et al. (2015)			
Diet Composition (%DM)				
CP (%)	18.1	18	18.2	0.14
NDF (%)	43.6	40.6	46.5	4.17
EE (%)	4.8	4.3	5.3	0.71
GE (MJ/kgDM)	19.1	19.0	19.2	0.14
qm	0.61	0.61	0.62	0.008
Apparent digestibility (%)				
CP	77	76	78	1.4
EE	85	84	86	1.4
Energy partitioning				
GEI	2328	2286	2370	58.9

Energy in methane	95	95	95	0.0
MEI	1423	1411	1435	16.8
Enery in milk	536	530	542	8.4
Energy in milk protein	126	121	132	7.8
Energy in milk lactose	112	107	117	6.9
Energy in milk fat	319	309	330	14.6
Goat characteristics				
DMI (g/day)	2050	2030	2070	28.3
Body weight (kg)	43	43	43	0.0
Milk yield (kg/day)	2,3	2.2	2.4	0.14
	Criscioni et al. (2016)			
Diet Composition (%DM)				
CP (%)	16.1	15.8	16.4	0.42
NDF (%)	33.6	31.8	35.3	2.47
EE (%)	1.7	1.6	1.8	0.14
GE (MJ/kgDM)	17	17	17	0.0
qm	0.66	0.63	0.69	0.036
Apparent digestibility (%)				
CP	71	69	74	3.4
EE	61	58	65	4.7
Energy partitioning				
GEI	1650	1591	1709	83.4
Energy in methane	87	82	91	6.4
MEI	1089	1085	1092	4.9
Enery in milk	359	341	376	24.7
Energy in milk protein	100	98	102	2.5
Energy in milk lactose	79	77	82	3.3
Energy in milk fat	189	178	201	15.9

Goat characteristics				
DMI (g/day)	1700	1600	1800	141.4
Body weight (kg)	45.8	45.6	45.9	0.21
Milk yield (kg/day)	1.7	1.7	1.8	0.08
Criscioni and Fernández (2016)				
Diet Composition (%DM)				
CP (%)	15.7	15.3	16.1	0.57
NDF (%)	25	22.8	27.2	3.11
EE (%)	7.9	4.1	11.7	5.37
GE (MJ/kgDM)	18.7	17.9	19.4	1.06
qm	0.68	0.66	0.71	0.034
Apparent digestibility (%)				
CP	72	71	73	0.9
EE	74	67	80	8.9
Energy partitioning				
GEI	1833	1777	1889	79.2
Energy in methane	84	73	95	15.6
MEI	1254	1248	1259	7.8
Enery in milk	508	491	524	23.3
Energy in milk protein	119	117	121	2.4
Energy in milk lactose	104	99	108	7.0
Energy in milk fat	297	266	328	44
Goat characteristics				
DMI (g/day)	1720	1610	1830	155.6
Body weight (kg)	46.1	45.8	46.4	0.42
Milk yield (kg/day)	2.2	2.1	2.2	0.07
Ibáñez et al. (2016)				
Diet Composition (%DM)				

CP (%)	13.2	11.9	14.0	0.80
NDF (%)	42.5	31.4	54.6	8.23
EE (%)	2.7	1.1	4.8	1.34
GE (MJ/kgDM)	17.8	16.9	18.0	0.48
qm	0.62	0.58	0.65	0.027
Apparent digestibility (%)				
CP	61	56	66	3,5
EE	61	34	74	16
Energy partitioning				
GEI	2174	2056	2296	87.9
Energy in methane	138	130	146	6.1
MEI	1352	1311	1412	47.2
Enery in milk	516	475	572	37.3
Energy in milk protein	116	106	130	8.9
Energy in milk lactose	104	93	115	8.6
Energy in milk fat	308	289	333	19.4
Goat characteristics				
DMI (g/day)	2020	2000	2100	44.7
Body weight (kg)	42.1	41.6	42.4	0.31
Milk yield (kg/day)	2.2	1.9	2.4	0.19
Romero-Huelva et al. (2017)				
Diet Composition (%DM)				
CP (%)	17.7	17.4	18.0	0.42
NDF (%)	28.4	26.9	29.9	2.12
EE (%)	3.3	3.1	3.6	0.31
GE (MJ/kgDM)	16.6	15.8	17.3	1.06
qm	0.67	0.65	0.68	0.026
Apparent digestibility (%)				

CP	80	79.0	81.0	1.3
EE	-	-	-	-
Energy partitioning				
GEI	1440	1360	1520	113.1
Energy in methane	105	86	123	26.2
MEI	957	930	984	38.2
Enery in milk	-	-	-	-
Energy in milk protein	83	82	83	0.8
Energy in milk lactose	77	73	81	5.1
Energy in milk fat	202	195	210	10.3
Goat characteristics				
DMI (g/day)	1525	1512	1537	17.7
Body weight (kg)	44.5	43.3	45.7	1.70
Milk yield (kg/day)	1.3	1.3	1.3	0.02
	Silva et al. (2018)			
Diet Composition (%DM)				
CP (%)	16.6	16.6	16.6	0.0
NDF (%)	40.6	40.6	40.6	0.0
EE (%)	-	-	-	-
GE (MJ/kgDM)	20.6	20.6	20.6	0.0
qm	0.58	0.53	0.65	0.033
Apparent digestibility (%)				
CP	81	79	83	1.8
EE	-	-	-	-
Energy partitioning				
GEI	2109	1906	2662	191.6
Energy in methane	-	-	-	-
MEI	1210	1054	1417	75.9

Enery in milk	300	194	446	80.9
Energy in milk protein	71	48	96	15.8
Energy in milk lactose	83	53	116	23.1
Energy in milk fat	160	99	251	46.1
Goat characteristics				
DMI (g/day)	2111	1874	2695	218.6
Body weight (kg)	56.5	54.3	59.9	1.79
Milk yield (kg/day)	2.3	1.6	3.2	0.62
	Fernández et al. (2018)			
Diet Composition (%DM)				
CP (%)	16.5	16.0	17.0	0.71
NDF (%)	26	21	31	7.1
EE (%)	2.5	2.0	3.0	0.71
GE (MJ/kgDM)	16.5	16.0	17.0	0.71
qm	0.6	0.6	0.7	0.046
Apparent digestibility (%)				
CP	70	66	73	5.0
EE	70	68	73	3.3
Energy partitioning				
GEI	1588	1462	1713	177.5
Energy in methane	55	47	63	11.3
MEI	998	970	1025	38.9
Enery in milk	347	336	358	15.6
Energy in milk protein	99	93	106	9.0
Energy in milk lactose	83	83	84	0.7
Energy in milk fat	203	198	209	7.4
Goat characteristics				
DMI (g/day)	1600	1500	1700	141.4

Body weight (kg)	44.1	41.5	46.7	3.68
Milk yield (kg/day)	1.3	0.8	1.7	0.64
Fernández et al. (2019)				
Diet Composition (%DM)				
CP (%)	16.0	14.7	17.3	1.84
NDF (%)	29.0	26.2	31.5	3.70
EE (%)	2.2	2.0	2.3	0.21
GE (MJ/kgDM)	16.5	16.0	17.0	0.71
qm	0.65	0.58	0.72	0.092
Apparent digestibility (%)				
CP	69	67	72	4.0
EE	63	57	70	9.6
Energy partitioning				
GEI	1477	1334	1620	202.2
Energy in methane	50	41	59	12.7
MEI	951	947	954	4.9
Enery in milk	291	281	301	14.1
Energy in milk protein	74	74	75	1.0
Energy in milk lactose	62	62	62	0.4
Energy in milk fat	167	159	175	10.9
Goat characteristics				
DMI (g/day)	1525	1360	1690	233.3
Body weight (kg)	43.3	42.5	44.1	1.13
Milk yield (kg/day)	1.29	1.25	1.33	0.06
Marcos et al. (2020)				
Diet Composition (%DM)				
CP (%)	16.7	16.0	17.4	0.99
NDF (%)	20.7	20.5	20.8	0.21

EE (%)	3.8	2.8	4.7	1.33
GE (MJ/kgDM)				
qm	0.65	0.65	0.66	0.008
Apparent digestibility (%)				
CP	61	46	75	20.7
EE				
Energy partitioning				
GEI	1730	1730	1730	0.0
Energy in methane	76	67	85	12.7
MEI	1130	1120	1140	14.1
Enery in milk	411	393	428	24.7
Energy in milk protein	90	85	94	5.9
Energy in milk lactose	107	103	111	5.7
Energy in milk fat	216	205	227	15.6
Goat characteristics				
DMI (g/day)	1614	1591	1637	32.5
Body weight (kg)	45.3	44.8	45.8	0.71
Milk yield (kg/day)	2.0	2.0	2.1	0.11
	Romero et al. (2020)			
Diet Composition (%DM)				
CP (%)	18	18	18	0.0
NDF (%)	38	34	42	5.6
EE (%)	3	2	4	1.4
GE (MJ/kgDM)	16.5	16.0	17.0	0.71
qm	0.59	0.56	0.62	0.037
Apparent digestibility (%)				
CP	69	67	72	3.1
EE	65	53	76	16.3

Energy partitioning				
GEI	1926	1913	1939	18.38
Energy in methane	85	75	95	14.1
MEI	1138	1095	1180	60.1
Enery in milk	423	402	444	29.7
Energy in milk protein	122	116	128	8.8
Energy in milk lactose	100	97	103	4.3
Energy in milk fat	300	270	330	42.0
Goat characteristics				
DMI (g/day)	2020	2000	2040	28.3
Body weight (kg)	47.4	47.3	47.4	0.07
Milk yield (kg/day)	2.3	2.2	2.4	0.11
	Fernández et al. (2021a)			
Diet Composition (%DM)				
CP (%)	18	18	18	0.0
NDF (%)	38.5	35.0	42.0	4.95
EE (%)	2.3	1.8	2.8	0.71
GE (MJ/kgDM)	16.5	16.0	17.0	0.71
qm	0.57	0.54	0.61	0.056
Apparent digestibility (%)				
CP	71	70	72	1.2
EE	69	67	71	4.1
Energy partitioning				
GEI	2203	2189	2217	19.8
Energy in methane	92	88	96	5.7
MEI	1266	1187	1345	111.7
Enery in milk	461	446	476	21.2
Energy in milk protein	123	118	128	7.2

Energy in milk lactose	101	97	105	6.1
Energy in milk fat	294	286	303	12.4
Goat characteristics				
DMI (g/day)	2230	2200	2260	42.4
Body weight (kg)	45.4	45.0	45.7	0.49
Milk yield (kg/day)	2.2	2.1	2.3	0.18
	Fernández et al. (2021b)			
Diet Composition (%DM)				
CP (%)	16	16	16	0.0
NDF (%)	32.5	30.0	40.0	4.18
EE (%)	2	2	2	0.0
GE (MJ/kgDM)	16.8	16.0	17.0	0.41
qm	0.59	0.52	0.65	0.055
Apparent digestibility (%)				
CP	69	66	72	2.2
EE	52	42	61	6.9
Energy partitioning				
GEI	1671	1216	1906	259.3
Energy in methane	110	90	126	11.9
MEI	994	629	1196	215.9
Enery in milk	376	222	485	98.7
Energy in milk protein	107	78	150	29.2
Energy in milk lactose	98	67	146	34.3
Energy in milk fat	223	155	326	76.1
Goat characteristics				
DMI (g/day)	1683	1280	1860	219.1
Body weight (kg)	44.6	42.3	47.3	2.04
Milk yield (kg/day)	2.0	1.5	3.0	0.67

[1] CP = crude protein; EE = ether extract; GE = gross energy; qm = metabolizability; GEI = gross energy intake; MEI = metabolizable energy intake; DMI = dry matter intake.

Table 6. Milk energy partitioning dairy goat model using performance data from the developmental dataset (n=106): prediction errors and decomposition associated with prediction of the outputs (kJ/kg $BW^{0.75}$ per day)

Variable	Observed mean	Predicted mean	RMSPE[1], %	Mean bias, %	Slope bias, %	Random bias, %	CCC[2]
Milk protein energy	116	115	19.4	0.15	3.11	96.75	0.514
Milk lactose energy	97	97	22.3	0.57	0.00	99.43	0.464
Milk fat energy	258	257	16.8	0.00	1.01	98.99	0.574
Methane energy	89	88	13.2	0.01	9.6	90.39	0.643

[1] RMSPE = root mean square prediction error as a percentage of observed mean.

[2] CCC = Concordance Correlation Coefficient.

Table 7. Milk energy partitioning dairy goat model using performance data from the evaluation dataset (n=52): prediction errors and decomposition associated with prediction of outputs (kJ/kg $BW^{0.75}$ per day)

Variable	Observed mean	Predicted mean	RMSPE[1], %	Mean bias, %	Slope bias, %	Random bias, %	CCC[2]
Milk protein energy	118	113	18.5	0.19	10.46	89.35	0.623
Milk lactose energy	98	96	22.9	0.05	0.84	99.11	0.464
Milk fat energy	271	259	19.2	0.02	2.54	97.44	0.489
Methane energy	86	87	13.7	0.39	5.90	93.71	0.646

[1] RMSPE = root mean square prediction error as a percentage of observed mean.

[2] CCC = Concordance Correlation Coefficient.

Table 8. Milk energy partitioning in dairy goat model using literature data from the external evaluation (n=77): prediction errors and decomposition associated with prediction of outputs (kJ/kg $BW^{0.75}$ per day)

Variable	Observed mean	Predicted mean	RMSPE[1], %	Mean bias, %	Slope bias, %	Random bias, %	CCC[2]
Milk protein energy	88	100	26.50	0.41	2.48	97.11	0.425
Milk lactose energy	89	88	26.51	0.02	2.70	97.28	0.430
Milk fat energy	201	194	30.44	0.12	7.05	92.83	0.345

Methane energy	90	92	35.04	0.36	1.17	98.47	-

[1] RMSPE = root mean square prediction error as a percentage of observed mean.

[2] CCC = Concordance Correlation Coefficient.

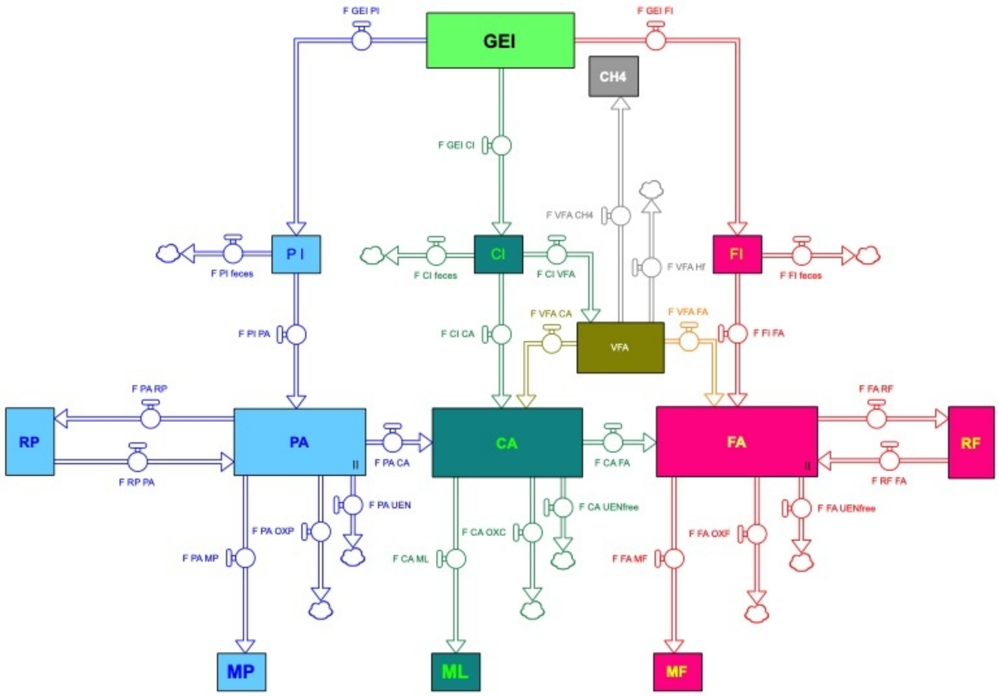

Figure 1. Diagrammatic representation of the energy partitioning mathematical model in dairy goats (using Stella Architect software). See Table 2 for legend.

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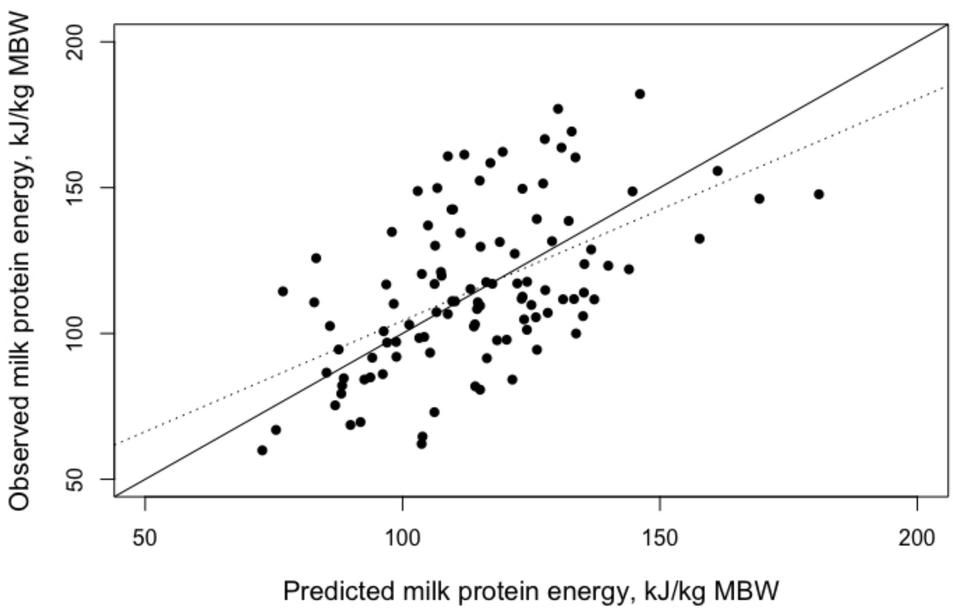
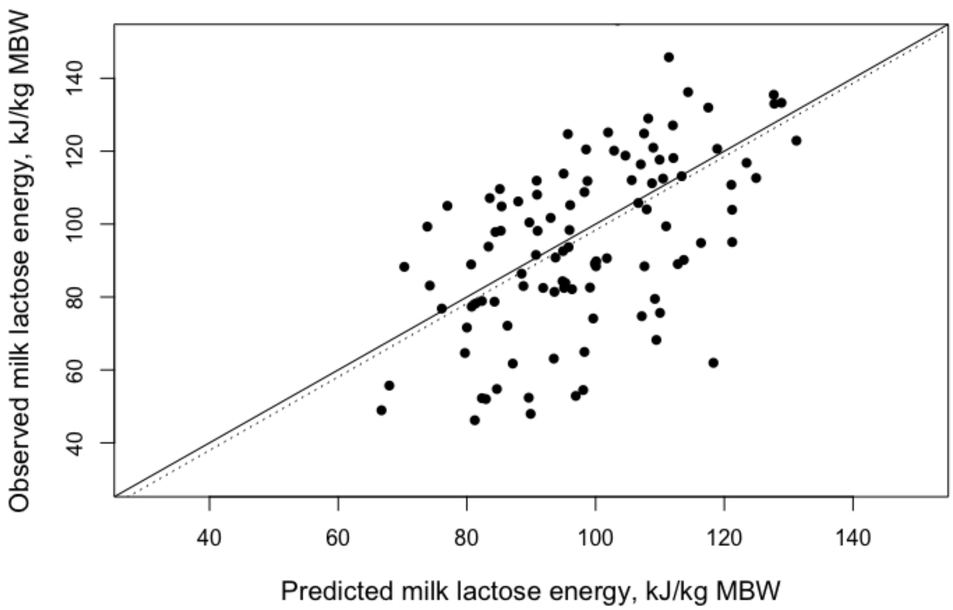


Figure 2. Observed versus predicted values of milk energy in protein (a), lactose (b) fat (c) and energy in methane (d) used for model development in dairy goats [kJ/kg BW0.75 day; BW0.75 = MBW]. The regression equations were as follow: milk protein energy Y = 28.27 + 0.76X (standard error = 13.36 and 0.11 for the intercept and slope respectively; residual standard error = 23.08; R2 = 0.30); milk lactose energy Y = -2.34 + 1.01X (standard error = 14.88 and 0.15 for the intercept and slope respectively; residual standard error = 22.22; R2 = 0.31); milk fat energy Y = -41.25 + 1.16X (standard error = 33.29 and 0.12 for the intercept and slope respectively; residual standard error = 43.84; R2 = 0.44); methane Y = 24.08 + 0.75X (standard error = 7.52 and 0.08 for the intercept and slope respectively; residual standard error = 11.36; R2 = 0.42).

252x181mm (72 x 72 DPI)



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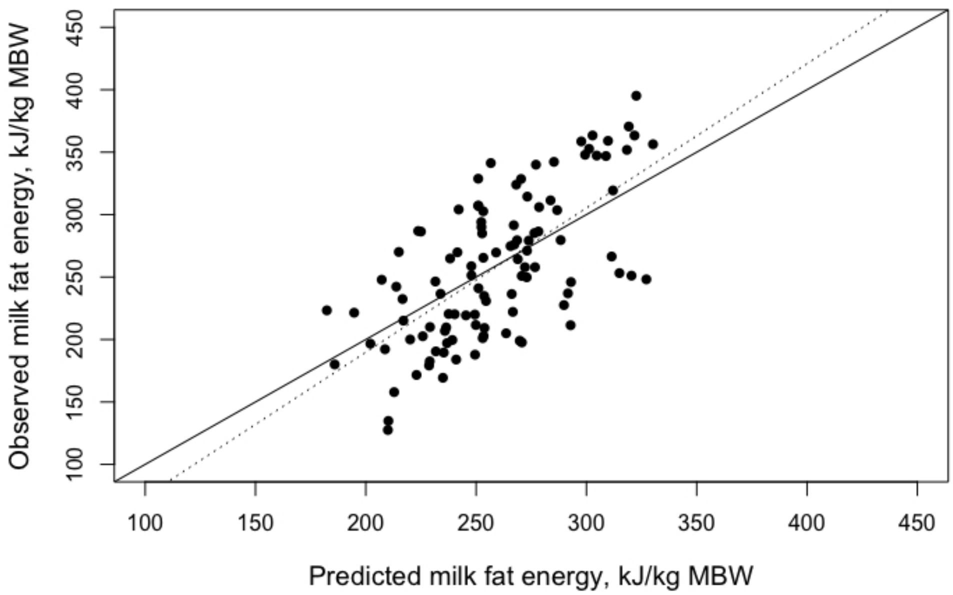

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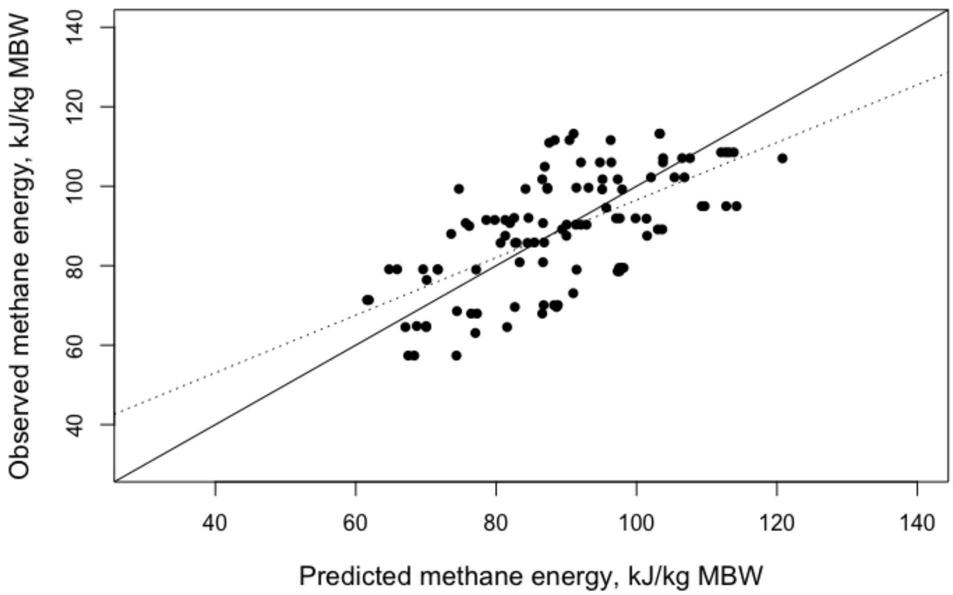

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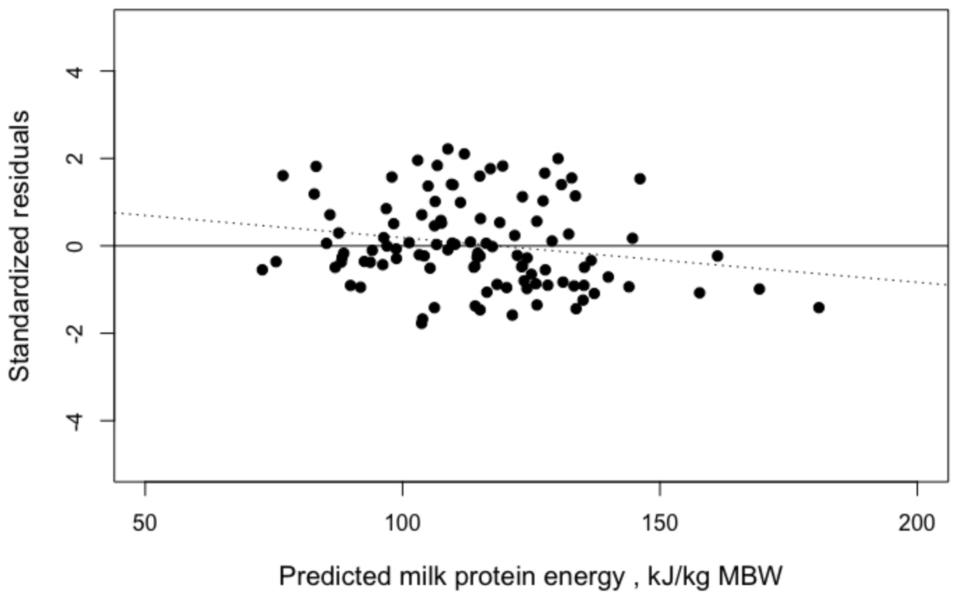
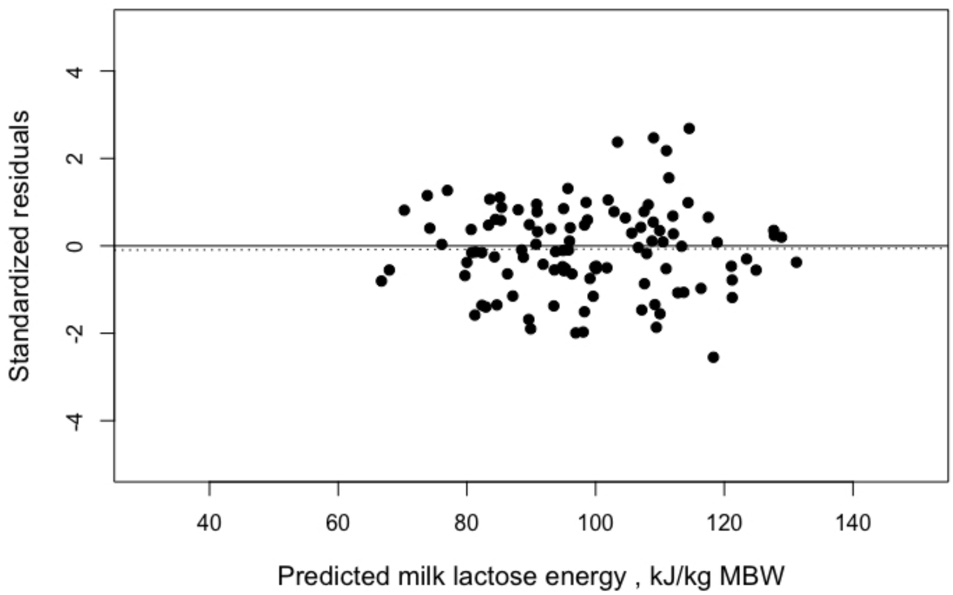


Figure 3. Residuals plot of milk energy in protein (a), lactose (b) fat (c) and energy in methane (d) used for model development in dairy goats [kJ/kg BW0.75 day; BW0.75 = MBW].

252x181mm (72 x 72 DPI)



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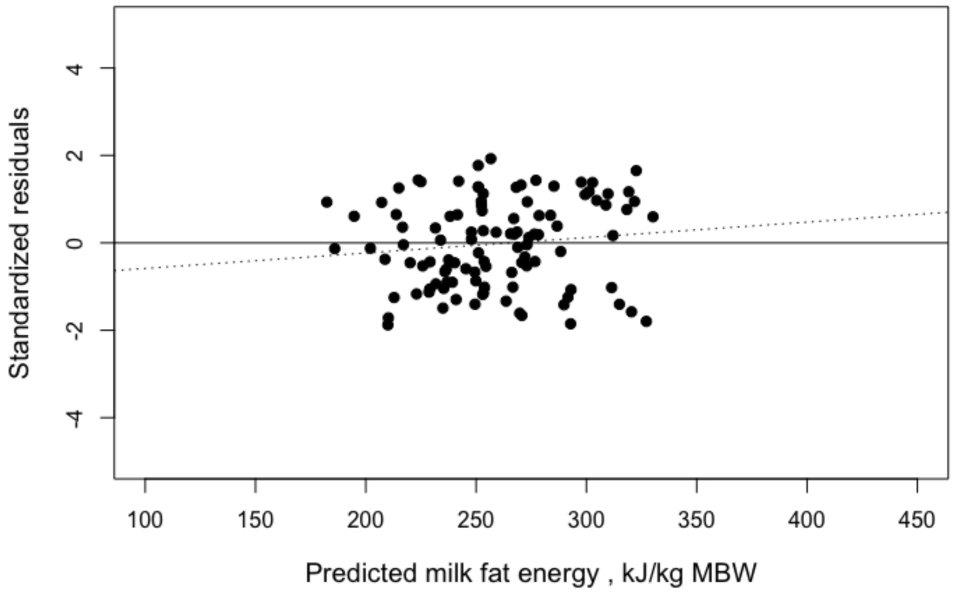

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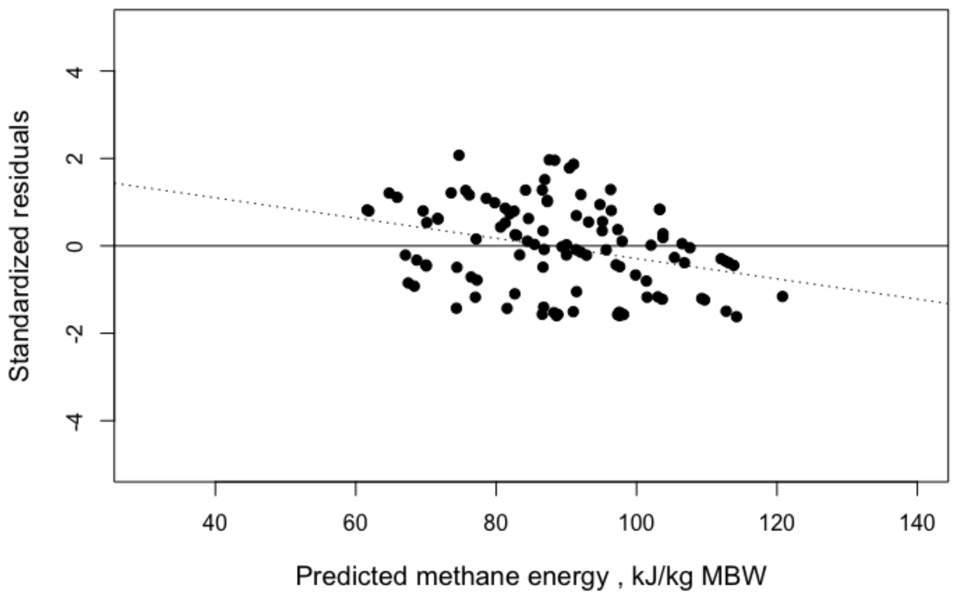

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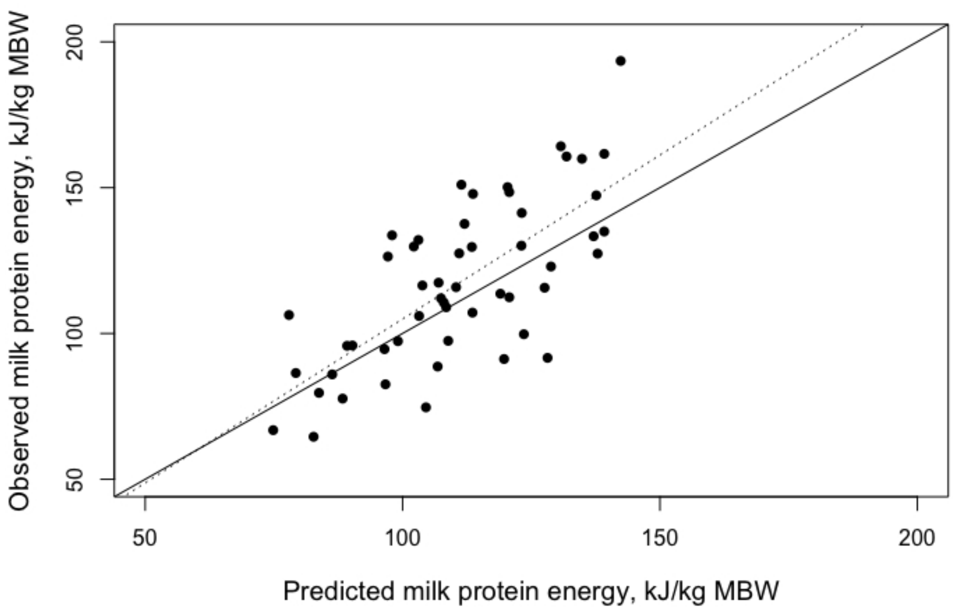

Figure 4. Observed versus predicted values of milk energy in protein (a), lactose (b) fat (c) and energy in methane (d) used for model internal evaluation in dairy goats [kJ/kg BW0.75 day; BW0.75 = MBW]. The regression equations were as follow: milk protein energy Y = -7.47 + 1.12X (standard error = 17.56 and 0.15 for the intercept and slope respectively; residual standard error = 19.83; R2 = 0.51); milk lactose energy Y = 6.59 + 0.91X (standard error = 21.61 and 0.21 for the intercept and slope respectively; residual standard error = 22.87; R2 = 0.26); milk fat energy Y = 23.37 + 0.94X (standard error = 50.70 and 0.19 for the intercept and slope respectively; residual standard error = 49.63; R2 = 0.32); methane Y = 19.72 + 0.76X (standard error = 10.95 and 0.12 for the intercept and slope respectively; residual standard error = 11.77; R2 = 0.43).

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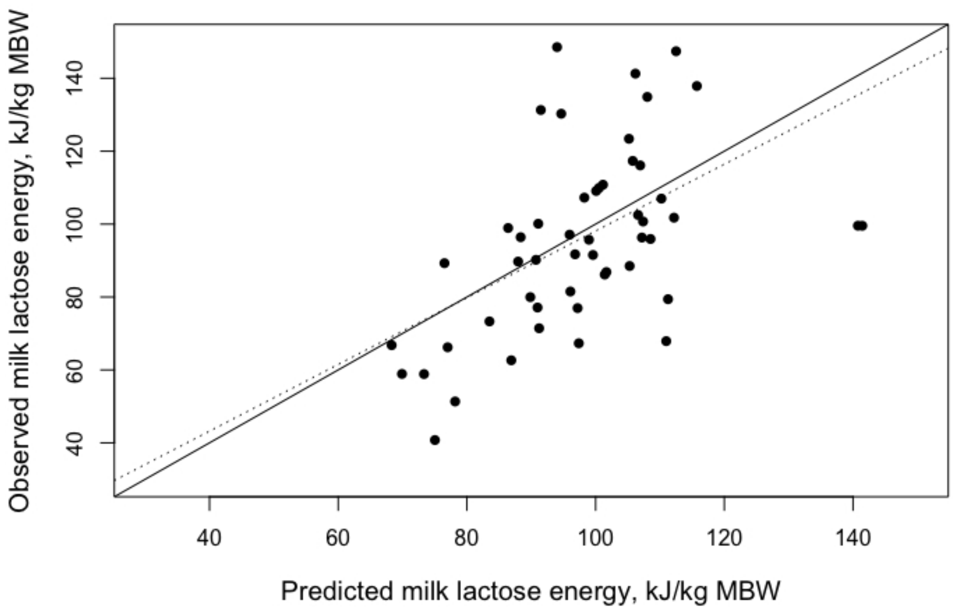

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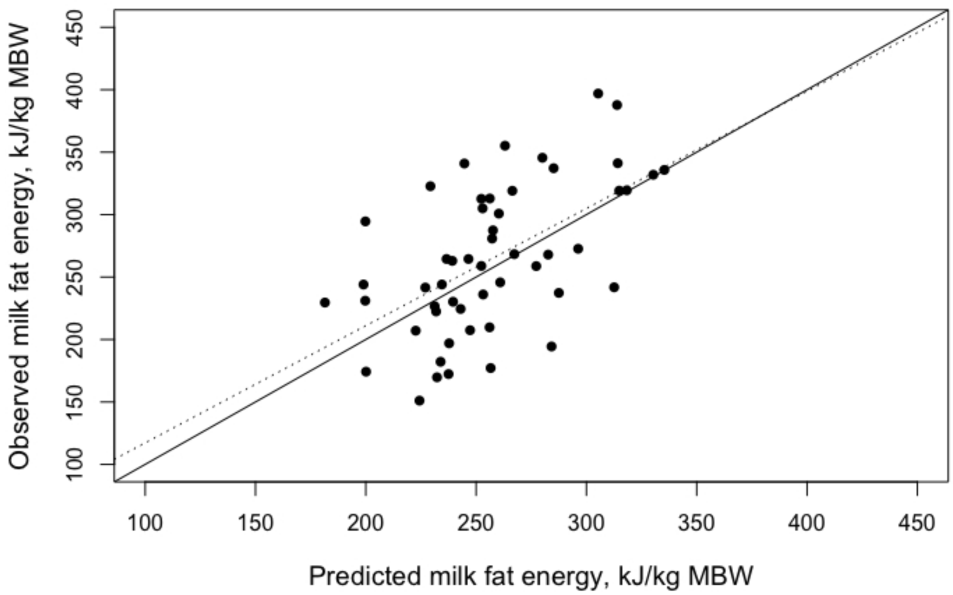

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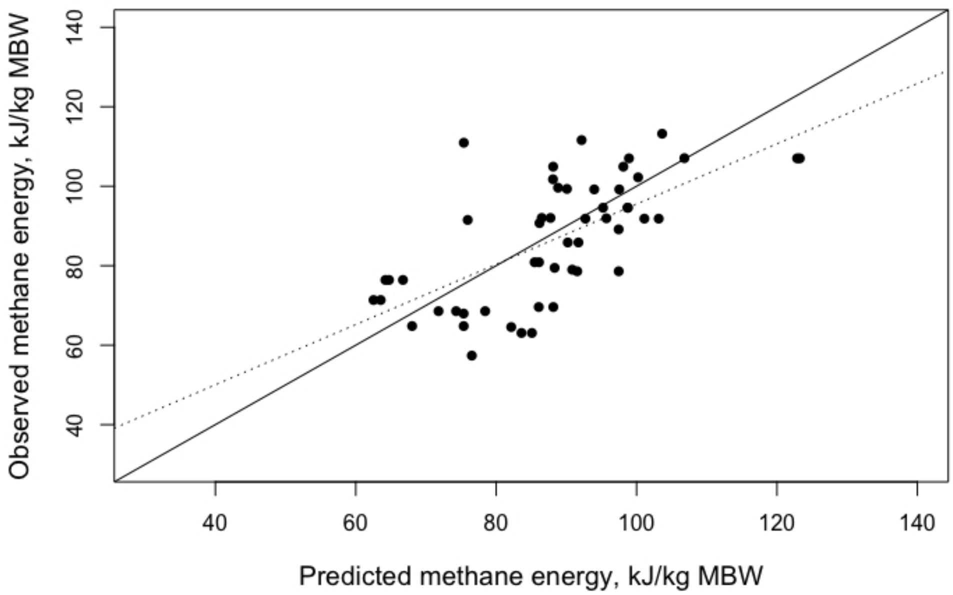

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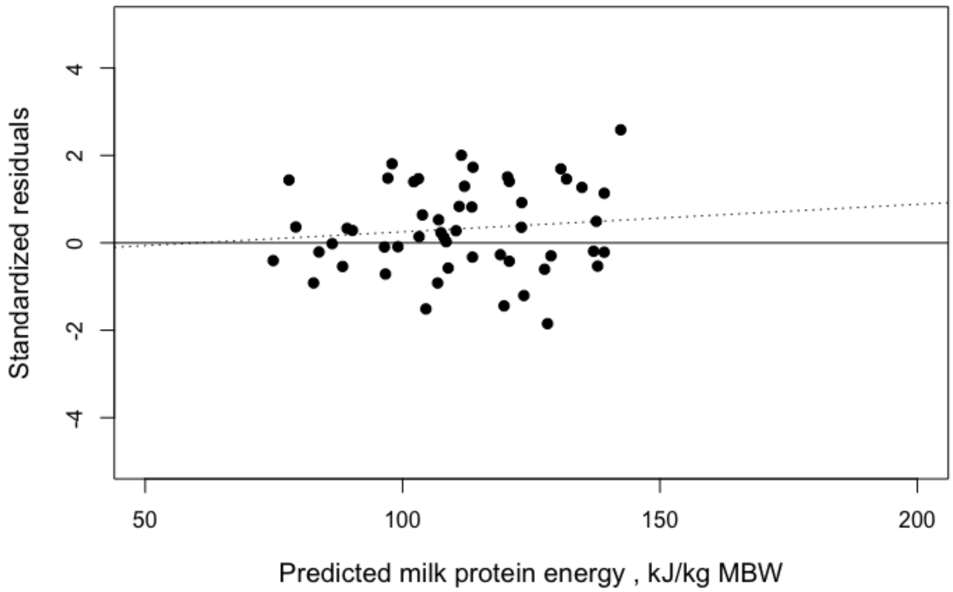
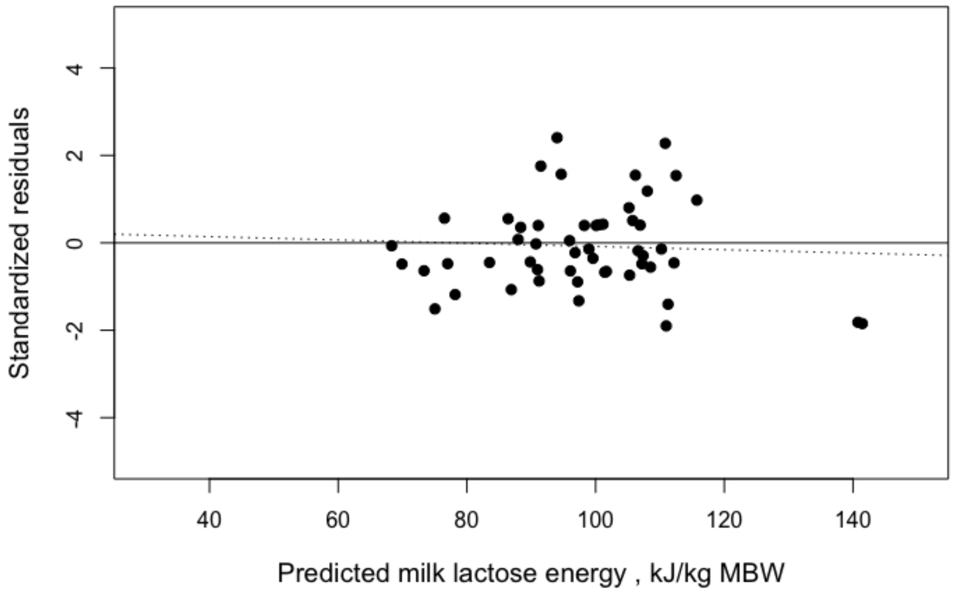


Figure 5. Residuals plot of milk energy in protein (a), lactose (b) fat (c) and energy in methane (d)used for model internal evaluation in dairy goats [kJ/kg BW0.75 day; BW0.75 = MBW].

252x181mm (72 x 72 DPI)



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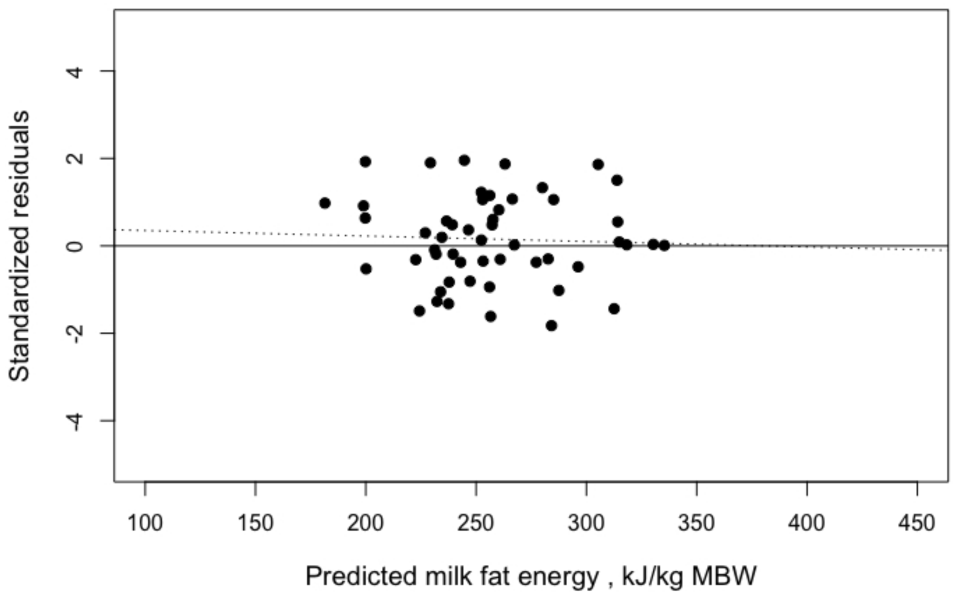

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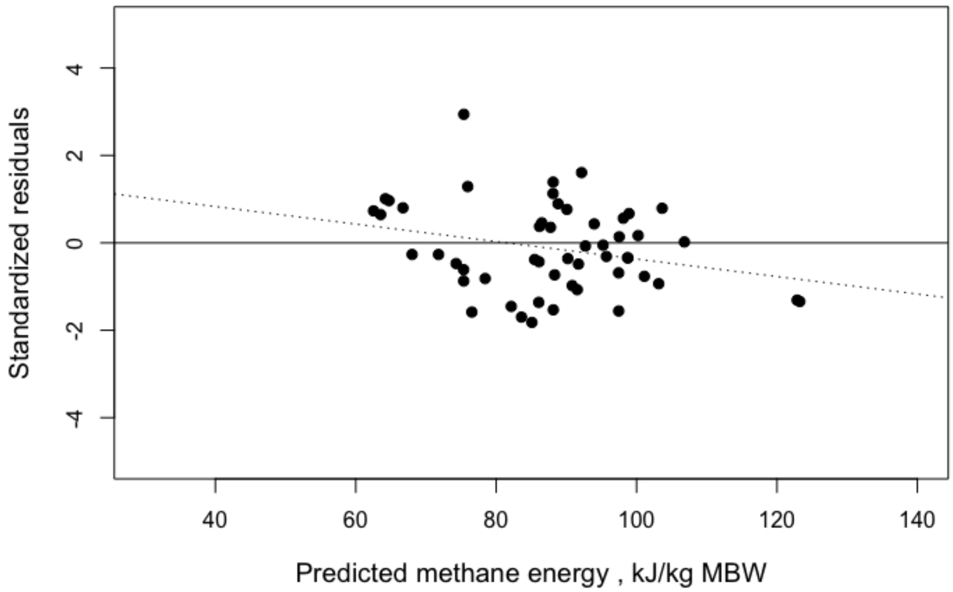

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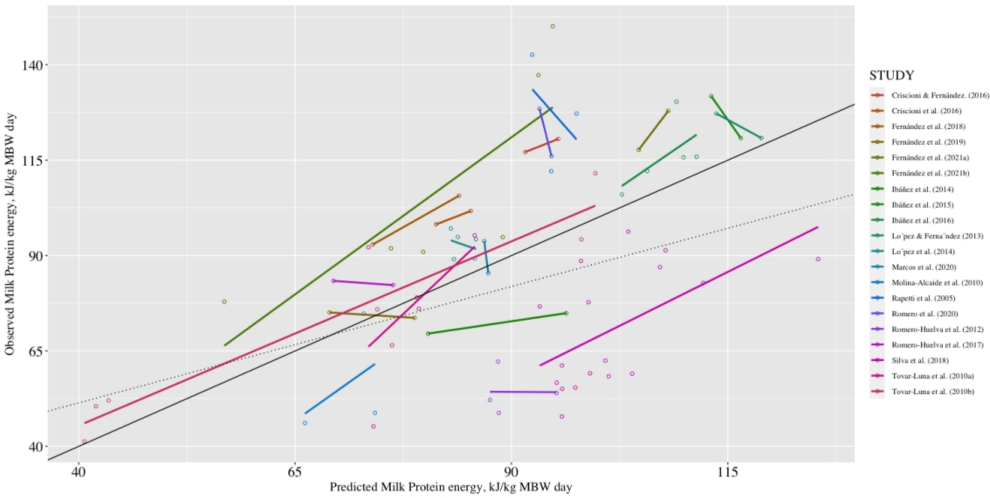

Figure 6. Observed versus predicted values of milk energy in protein (a), lactose (b) fat (c) and energy in methane (d) used for model external evaluation in dairy goats [kJ/kg BW0.75 day; BW0.75 = MBW].

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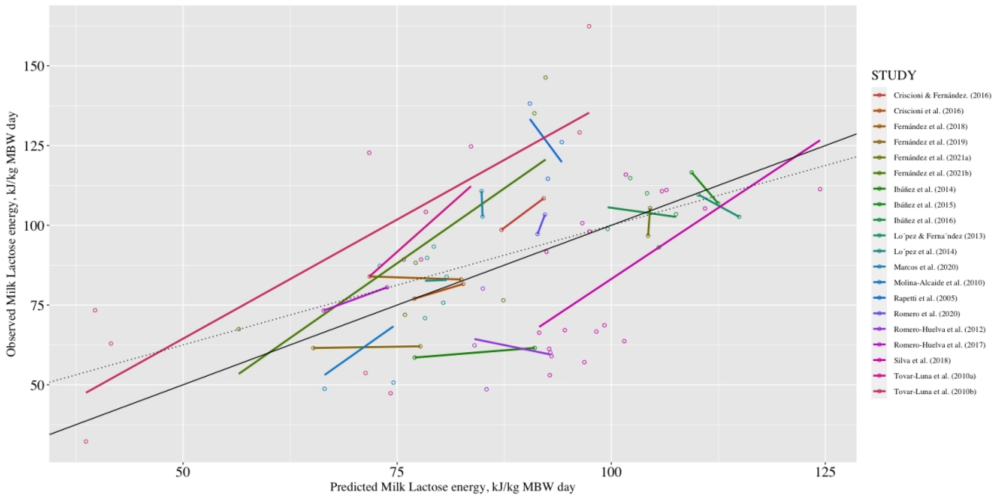

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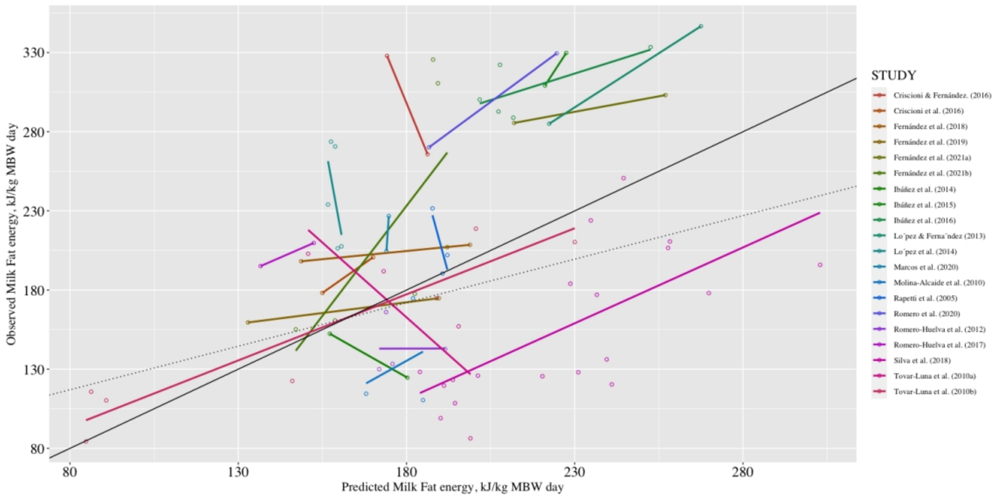

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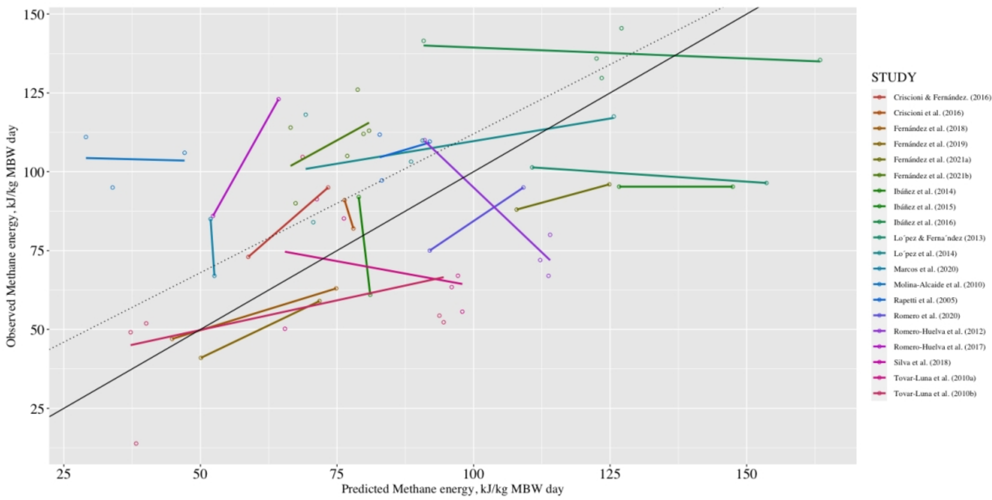

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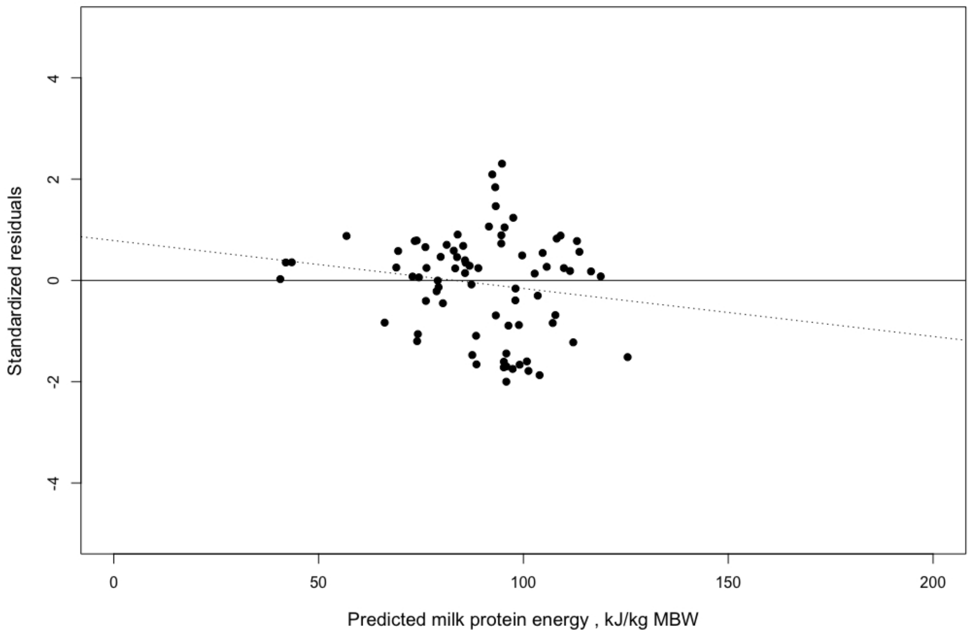
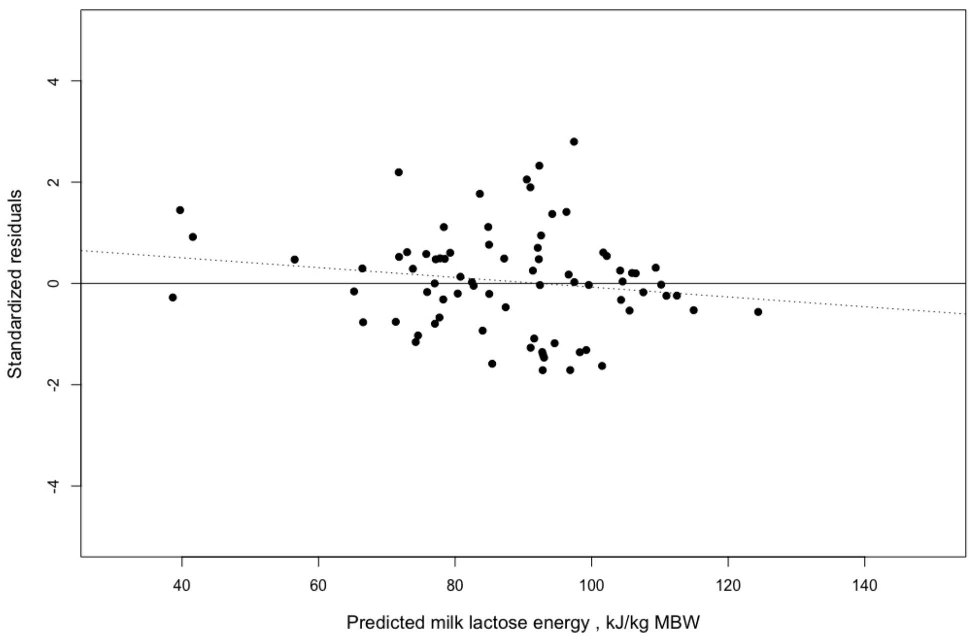


Figure 7. Residuals plot of milk energy in protein (a), lactose (b) fat (c) and energy in methane (d) used for model external evaluation in dairy goats [kJ/kg BW0.75 day; BW0.75 = MBW].

363x261mm (72 x 72 DPI)



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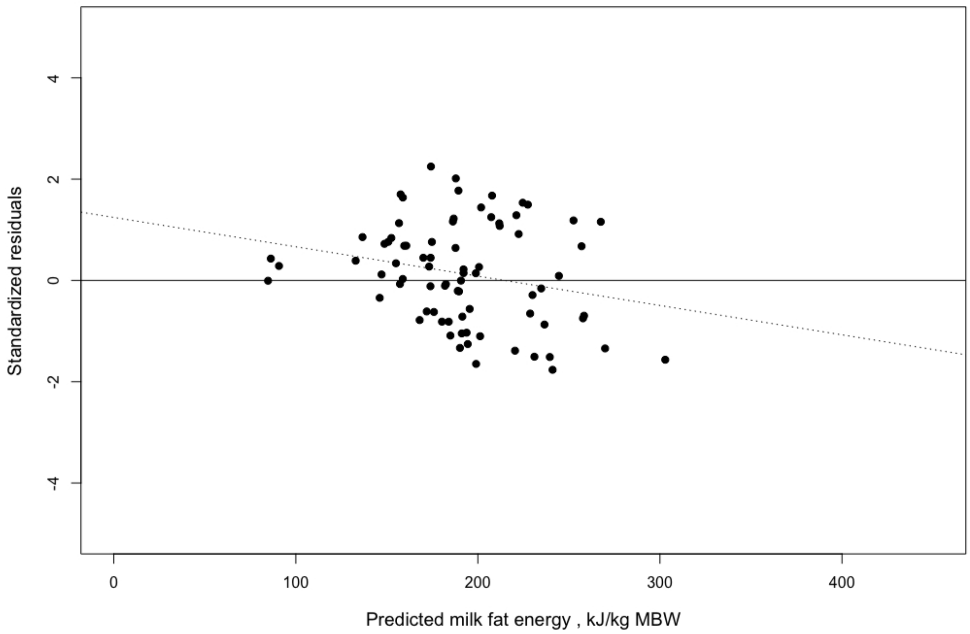

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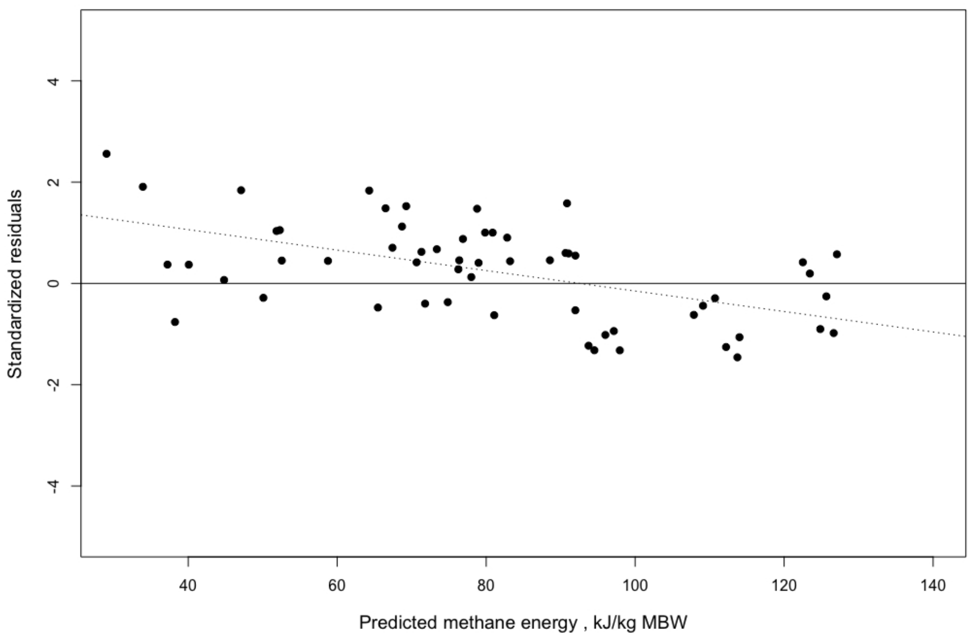

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