

RAFAEL MARZALL DO AMARAL

**DYNAMICS OF ANIMAL GROWTH AND MILK YIELD
USING ANIMAL AND DIET CHARACTERISTICS**

Thesis submitted to the Animal Science
Graduate Program of the Universidade Federal
de Viçosa in partial fulfillment of the
requirements for the degree of *Doctor Scientiae*.

VIÇOSA
MINAS GERAIS – BRAZIL
2018

**Ficha catalográfica preparada pela Biblioteca Central da Universidade
Federal de Viçosa - Câmpus Viçosa**

T

A485d
2018 Amaral, Rafael Marzall do, 1984-
Dynamics of animal growth and milk yield using animal
and diet characteristics / Rafael Marzall do Amaral. – Viçosa,
MG, 2018.
ix, 51 f. : il. ; 29 cm.

Texto em inglês.

Orientador: Marcelo Teixeira Rodrigues.

Tese (doutorado) - Universidade Federal de Viçosa.

Inclui bibliografia.

1. Ovelhas - Nutrição. 2. Ovelhas - Crescimento. 3. Leite -
Produção. 4. Dinâmica de sistemas. I. Universidade Federal de
Viçosa. Departamento de Zootecnia. Programa de
Pós-Graduação em Zootecnia. II. Título.





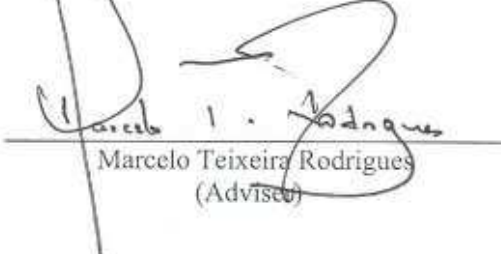
CDD 22. ed. 636.30852

RAFAEL MARZALL DO AMARAL

**DYNAMICS OF ANIMAL GROWTH AND MILK YIELD
USING ANIMAL AND DIET CHARACTERISTICS**

Thesis submitted to the Animal Science
Graduate Program of the Universidade Federal
de Viçosa in partial fulfillment of the
requirements for the degree of *Doctor Scientiae*.

APPROVED: June 20, 2018.

 Fernando de Paula Leonel	 Izabelle A. M. de Almeida Teixeira
 Iran Borges (Co-adviser)	 Ricardo Augusto Mendonça Vieira (Co-adviser)
 Marcelo Teixeira Rodrigues (Advisor)	

ACKNOWLEDGEMENTS

I would like to thank my mother, Hanelise Marzall, for her constant support and encouragement over the years, my sister, Carolina Marzall, for understanding my absence during all these years, and to my life mate, Tania Segura, for her fellowship and unconditional support during this process.

A special thanks to my adviser, Marcelo Teixeira Rodrigues, Ph.D. for his support, confidence, stimulus, and liberty to conduct my thesis.

Thanks to the Department of Animal Science at Universidade Federal de Viçosa and all professors that I had the pleasure to meet. I would like to acknowledge the professors Izabelle Auxiliadora M. de Almeida Teixeira, Fabyano Fonseca e Silva, Moysés Nascimento, and Ricardo Augusto M. Vieira for their availability to be part of the qualify committee.

BIOGRAPH

RAFAEL MARZALL DO AMARAL was born on November 19th, 1984 in Curitiba, PR, Brazil.

In 2003, he began the Animal Science undergraduate course at Universidade Estadual de Maringá in the state of Paraná, graduating in 2007.

In 2008, he entered the M. Sc. degree in Animal Science at the Universidade Estadual de Maringá; the concentration area was animal production, concluding the course in March 2010.

From 2011 to 2013 he was a part-time professor of a Veterinary Medicine undergraduate course at Centro Universitário Catarinense in Santa Catarina state.

In 2012 and 2013 he was a substitute professor of Animal Science, Agronomy, and Food Science Technology undergraduate courses at Universidade Federal de Santa Catarina in the Santa Catarina state.

In 2014, he began the D.Sc. degree program at Universidade Federal de Viçosa; the concentration area was Ruminant Nutrition and Production. He was initiated under professor Marcelo Teixeira Rodrigues, Ph.D. advice, and started to work with system dynamics modeling applied to animal production, concluding the doctoral process on June 20th, 2018.

SUMMARY

ABSTRACT.....	vi
RESUMO.....	viii
GENERAL INTRODUCTION.....	1
REFERENCES	3
ARTICLE 1 - A DYNAMIC TOOL TO DESCRIBE ANIMAL GROWTH AND ITS USE AS A DECISION SUPPORT SYSTEM	8
ABSTRACT.....	8
INTRODUCTION	8
METHODS	10
Model framework.....	10
Simulation procedure	14
Model evaluation as support decision tool.....	14
Model evaluation as a descriptive tool.....	16
RESULTS	16
Model results as decision support tool.....	16
Model results as a descriptive tool.....	19
DISCUSSION.....	24
CONCLUSIONS	27
REFERENCES	28
ARTICLE 2 – MODELLING MILK YIELD AND METHANE EMISSIONS IN A TROPICAL RUMINANT FORAGE-BASED SYSTEM USING ANIMAL AND DIET CHARACTERISTICS.....	33
ABSTRACT.....	33
INTRODUCTION	34
METHODS	35
Model framework.....	35
Dry matter intake and production model.....	35
Methane production from manure model	37
Methane production from enteric fermentation.....	38
Feed and energy efficiencies and emission intensity	38
Model inputs and simulations	38
Animal description	38
Feed description.....	38
RESULTS	39

Dry matter intake and production model	39
Methane production from manure model.....	40
Methane production from enteric fermentation	40
Fiber quality, feed and energy efficiencies, and emission intensity	41
DISCUSSION	42
Dry matter intake and production model	42
Methane production from manure model.....	43
Methane production from enteric fermentation	44
Fiber quality, feed and energy efficiencies, and emission intensity	45
CONCLUSIONS	47
REFERENCES	48

ABSTRACT

AMARAL, Rafael Marzall do, D.Sc., Universidade Federal de Viçosa, June, 2018.
Dynamics of animal growth and milk yield using animal and diet characteristics.
Adviser: Marcelo Teixeira Rodrigues. Co-advisers: Ricardo Augusto Mendonça Vieira and Iran Borges.

This thesis is composed by two studies that aim to simulate biological process of animal production using System Dynamics (SD) approach. The first study aimed to use SD and mechanistic equations from current nutritional systems to describe and simulate the energy and protein requirements, the composition of gain, growth rate, and body mass of feedlot lambs. The developed model was evaluated with a dataset of 564 individual measures of final body mass and diet energy concentration. The simulation provides a graphical and numerical description of the nutrient requirements, composition of gain, and estimates animal performance over time. The simulation of final body mass presents a root-mean-squared error of 3.11 kilograms (kg), which corresponds to 7.79% of observed final body mass and a R^2 of 0.89 indicating accuracy and precision, respectively. Based on empirical and conceptual equations proposed on scientific literature, the second study aimed to model the dry matter intake based on physiological energy demand and on physical limitation theory, the nutritional requirements, metabolizable energy intake, milk yield allowed, and methane production from enteric and manure fermentation as a function of fiber composition. By using the simulated information, the amount of each variable required per unit of fat corrected milk, the efficiency of feed and energy use, and the emission intensity were calculated. A simulation was conducted with chemical composition data of five maturity stages *Pennisetum purpureum* Schum. grass (61, 82, 103, 124 and 145 days after planting) as exclusive diet to a 450 kg double purpose cow with 20 kg·d⁻¹ of potential milk yield with 3.5% of fat. The dry matter intake was limited by rumen fill capacity to all grasses maturities and decreases as neutral detergent fiber composition increases with forage maturity, reducing metabolizable energy intake, fermentative substrate intake, and milk yield. Milk yield allowed was ranged from 9.407 to 4.568 kg d⁻¹ to younger and older forage, respectively. Methane production from enteric fermentation reduces with forage maturity, simulated values range from 103.8 and 74.5 g·day⁻¹, to younger and older forage, respectively. A reduction of feed efficiency of 9.25% was estimated from 61 to

82 days of growing grass, accounting the reduction of feed intake and the metabolizable energy concentration. Simulated methane production per unit of product presents a difference of 32.33% ranging between 11.0 and 16.3 grams per kilogram of product to 61 and 145 days of regrowth, respectively. The models can be used as a support decision and as learning tools to illustrate practical principles of animal nutrition, nutrient requirement relationships, body composition changes, understanding of standard body mass implications, feed intake regulation, tropical dairy cattle performance, feed and energy efficiencies, and methane emissions from enteric and manure fermentation as function of fiber composition.

RESUMO

AMARAL, Rafael Marzall do, D.Sc., Universidade Federal de Viçosa, junho de 2018. **Dinâmica do crescimento animal e da produção de leite usando características dos animais e das dietas.** Orientador: Marcelo Teixeira Rodrigues. Coorientadores: Ricardo Augusto Mendonça Vieira e Iran Borges.

Esta tese é composta por dois estudos que objetivam simular processos biológicos inerentes a produção animal utilizando a abordagem da dinâmica de sistemas (DS). O primeiro estudo teve como objetivo utilizar a DS e equações mecanicistas de sistemas nutricionais atuais para descrever e simular as exigências de energia e proteína, a composição do ganho, a taxa de crescimento e a massa corporal de cordeiros confinados. O modelo desenvolvido foi avaliado com um conjunto de dados composto por 564 mensurações individuais de massa corporal final e concentração energética na dieta. A simulação fornece uma descrição gráfica e numérica dos requerimentos nutricionais, composição do ganho e estima o desempenho dos animais ao longo do tempo. As predições da massa corporal final apresentam uma raiz de erro quadrático médio de 3,11 kg, o que corresponde a 7,79 % da massa corporal final observada e um R^2 de 0,89 indicando acurácia e precisão, respectivamente. O segundo estudo objetivou modelar, com base em equações empíricas e conceituais propostas na literatura científica, o consumo de matéria seca com base na demanda fisiológica de energia e na teoria da limitação física, as exigências nutricionais, a ingestão de energia metabolizável, a produção de leite possível e a produção de metano de origem entérica ou do esterco em função da composição da fibra. Com a informação simulada, calculou-se a quantidade de cada variável por unidade de produto, fornecendo as eficiências de uso de alimentos e energia, e as intensidades de emissão. Uma simulação foi conduzida com dados de composição química de cinco estádios de maturidade de uma gramínea, *Pennisetum purpureum* Schum., aos 61, 82, 103, 124 e 145 dias após o plantio, como dieta exclusiva para uma vaca de duplo propósito com 450 kg de massa corporal e um potencial de produção de 20 kg·d⁻¹, com 3,5% de gordura. O consumo de matéria seca foi limitado pelo enchimento ruminal em todos os estádios de maturidade da gramínea. O consumo foi diminuído conforme aumentava a concentração da fibra em detergente neutro com a maturidade da forragem, reduzindo o consumo de energia metabolizável, o consumo de substrato fermentável e a produção de leite. A produção de leite possível

foi de 9,407 a 4,568 kg·d⁻¹ para as gramíneas mais novas e mais velhas, respectivamente. A produção de metano a partir da fermentação entérica reduz com a maturidade da forragem, os valores simulados variaram entre 103,8 e 74,5 g·dia⁻¹, para as gramíneas com 61 e 145 dias de crescimento, respectivamente. Uma redução da eficiência alimentar de 9,25% foi estimada para a forragem 82 dias comparada a de 61 dias, representando a redução do consumo e da concentração de energia metabolizável do alimento. A produção simulada de metano entérico por unidade de produto apresentou uma diferença de 32,33%, variando entre 11,0 e 16,3 gramas por quilograma de produto, para 61 e 145 dias de rebrota, respectivamente. Os modelos podem ser usados como uma ferramentas para a tomada de decisões e para a aprendizagem, ilustrando princípios práticos de nutrição animal, determinação das exigências nutricionais, mudanças na composição corporal, compreensão das implicações da massa corporal padrão, regulação do consumo de alimentos, desempenho de animais leiteiros em condições tropicais e eficiências alimentar e energética, além das emissões de metano a partir da fermentação entérica e do esterco em função da composição da fibra.

GENERAL INTRODUCTION

On ruminant production research some terms like sustainability (Bocquier and González-García, 2010; Guedes Pinto et al., 2016; Herrero and Thornton, 2013), sustainable intensification (Rao et al., 2015; Silva et al., 2016; Tedeschi et al., 2015; Vanlauwe et al., 2014) and eco-efficiency (Basset-Mens et al., 2009; Keating et al., 2010; Rao et al., 2015) frequently appear. These three terms are related and used to describe general approaches that objectively develop social, economic, and environmental benefits. To achieve these goals and produce more food to meet the world's increasing demand, a careful attention must be paid in the process involved in all stages of animal production and the natural resources had to be efficiently used to reduce the waste of energy and nutrients during the production cycle and at same time contribute to mitigate (Gerber et al., 2013; Martin et al., 2009), stop (Smith et al., 2007) or revert (Conant, 2010; Stanley et al., 2018) the negative effects of animal production to the environment. In this context, a better comprehension and description of the process involved in the ruminant production are part of a solution.

In animal production systems the biological processes related to animal feed intake, nutrition, digestion, metabolism, determination of nutritional requirements, ruminal fermentation, and animal performance are complex dynamic systems. Complex, that in a simple definition is “consisting of many different and connected parts” (Oxford English Dictionary, 2017), can be better understood, in the animal production context, as a set of interdependent organs, microorganisms, chemical compounds, and electrical signals that are connected to make up the organism which is subjected to internal and external factors of the system. It is dynamic because the processes depend on time as well as on the feedback relations between system elements and systems, which in a simple definition are a set of interrelated and interdependent elements that compose a complex whole.

The knowledge about these processes and their organization is necessary to improve our capacity to understand and support management decisions of producers and animal scientists. With this information, it is possible to formulate more precise diets and adjust forage management practices to meet animal requirements in different production systems, estimate the food quality and quantity, and the time required to get the final product. Therefore, the resources must be used carefully and technically to improve animal performance and reducing the amount of feed, energy, and

environmental damage (i.e. fewer greenhouse gases and fewer pollutant emissions) by doing a better use of natural resource in an economical way.

The description of the growth of farm animals is usually carried through empirical studies, which adjust a series of non-linear regressions to the collected data and compare them, verifying the best fit (Araujo et al., 2015; Hojjati and Hossein-Zadeh, 2017). These studies are important to describe physiological events and understanding the stages of animal growth but they are of little practical use because the independent variable of these equations is the time, not using common productive variables as feed composition and environmental characteristics to describe animal growth. Current nutritional models like Cornell Net Carbohydrate and Protein System (CNCPS) and CNCPS based models, as the CNCPS-Sheep, the Small Ruminant Nutrition System (SRNS) and the Ruminant Nutrition System (RNS) establish dependent relations between feed compositions, environmental and animal description generating punctual estimates of animal performance. Therefore, the current tools that indicate the growth of the animals are not connected and do not allow a description of the integrated animal growth connecting elements of the nutritional models to a curve of body growth and tissue deposition.

Fiber from forage is the main diet component of tropical ruminant production systems. The effects of forage fiber composition on dry matter intake, ruminal degradation and passage rates, and animal performance are well described on scientific research, especially on temperate conditions (Jung and Allen, 1995; Mertens, 1997, 1987). The diet neutral detergent fiber content is one of the main predictors of dry matter intake in ruminants (Mertens, 1987) and both variables are considered the best predictors of animal performance (Oba and Allen, 1999) and enteric methane production (Niu et al., 2018). A tool that allows to dynamically estimate the dry matter intake, animal performance, and methane production from manure and ruminal fermentation based on the diet neutral detergent fiber concentration as a predictor, can be useful not only as a learning tool that helps to understand the existent relations between these variables, but also to demonstrate their effects on system efficiency at productive and environmental levels.

Dynamic modeling has been conducted in different areas of animal production like farm production and management policies (Guimarães et al., 2009), diet preference and selection (Gregorini et al., 2015), methane emission by livestock (Herrero et al., 2008), ruminal microbiology (Russell et al., 2009), cattle growth (Garcia et al., 2008;

Tedeschi et al., 2004), dairy cattle production and body reserves (Martin and Sauvant, 2007), dairy goats (Guimarães et al., 2009; Puillet et al., 2008) and as support decision systems, helping to improve the production system profitability and knowledge of systemic behavior (Tedeschi et al., 2011). The models have been used as predictive or descriptive elements as part of decision support systems and learning tools (Mertens, 1977). A complete description of the system dynamics elements, principles, and work can be found on Sterman (2000) and application examples can be founded on (Guimarães, 2007).

This thesis aims to use the system dynamics approach to simulate different biological process related to animal feed intake, nutrient requirements, milk production and animal growth, and sustainable intensification elements like energy efficiency, methane production from enteric and manure fermentation based on diets composition as descriptive inputs of modeling simulation. The following chapters present two independent studies that aim to: 1) describe and predict with a system dynamics approach the nutritional requirements, composition of gain and growth using SRNS equations; 2) modeling animal performance and methane emissions in a tropical ruminant forage-based system using fiber quality as a predictor.

REFERENCES

Araujo, R.P.; Vieira, R.A.M.; Rocha, N.S.; Abreu, M.L.C.; Glória, L.S.; Rohem Júnior, N.M.; Fernandes, A.M. Long-term growth of body, body parts and composition of gain of dairy goat wethers. **J. Agric. Sci.**, v. 153, p. 1321-1340, 2015. <https://doi.org/10.1017/S0021859615000532>.

Basset-Mens, C.; Ledgard, S.; Boyes, M. Eco-efficiency of intensification scenarios for milk production in New Zealand. **Ecol. Econ.**, v. 68, p. 1615-1625, 2009. <https://doi.org/10.1016/j.ecolecon.2007.11.017>.

Bocquier, F.; González-García, E. Sustainability of ruminant agriculture in the new context: Feeding strategies and features of animal adaptability into the necessary holistic approach. **Animal**, v. 4, p. 1258-1273, 2010. <https://doi.org/10.1017/S1751731110001023>.

Conant, R.T. **Challenges and opportunities for carbon sequestration in grassland systems**: a technical report on grassland management climate change mitigation. 2010. <https://doi.org/ISBN 978-92-5-106494-8>.

Garcia, F.; Sainz, R.D.; Agabriel, J.; Barioni, L.G.; Oltjen, J.W. Comparative analysis of two dynamic mechanistic models of beef cattle growth. **Anim. Feed Sci. Technol.**, v. 143, p. 220-241, 2008. <https://doi.org/10.1016/j.anifeedsci.2007.05.012>.

Gerber, P.J.; Steinfeld, H.; Henderson, B.; Mottet, A.; Opio, C.; Dijkman, J.; Falculi, A.; Tempio, G. **Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities**, Food and Agriculture Organization of the United Nations. 2013. <https://doi.org/10.1016/j.anifeedsci.2011.04.074>.

Gregorini, P.; Villalba, J.J.; Provenza, F.D.; Beukes, P.C.; Forbes, J.M. Modelling preference and diet selection patterns by grazing ruminants: a development in a mechanistic model of a grazing dairy cow, MINDY. **Anim. Prod. Sci.**, v. 55, p. 360-375, 2015. <https://doi.org/10.1071/AN14472>.

Guedes Pinto, L.F.; Hajjar, R.; Newton, P.; Agrawal, A.; Adshead, D.; Bini, D.; Bogaerts, M.; Cirhigiri, L.; Maguire-Rajpaul, V.A.; González-Chaves, A.; Milder, J.; Pinho, P.; Robinson, I.; Rodkin, M.; Wollenberg, E. **Transitioning to more sustainable, low-emissions agriculture in Brazil lessons from certification and other projects for sustainable cattle and coffee in Brazil**. 2016. p. 1-7.

Guimarães, V.P. **Modelagem de uma unidade de produção para caprinos leiteiros utilizando a dinâmica de sistemas**. 2007. Tese (Doutorado) - Universidade Federal de Viçosa, Viçosa, MG.

Guimarães, V.P.; Tedeschi, L.O.; Rodrigues, M.T. Development of a mathematical model to study the impacts of production and management policies on the herd dynamics and profitability of dairy goats. **Agric. Syst.**, v. 101, p. 186-196, 2009. <https://doi.org/10.1016/j.agsy.2009.05.007>.

Herrero, M.; Thornton, P.K. Livestock and global change: emerging issues for sustainable food systems. **Proc. Natl. Acad. Sci.**, v. 110, p. 20878-20881, 2013. <https://doi.org/10.1073/pnas.1321844111>.

Herrero, M.; Thornton, P.K.; Kruska, R.; Reid, R.S. Systems dynamics and the spatial distribution of methane emissions from African domestic ruminants to 2030. **Agric. Ecosyst. Environ.**, v. 126, p. 122-137, 2008. <https://doi.org/10.1016/j.agee.2008.01.017>.

Hojjati, F.; Hossein-Zadeh, N. Comparison of non-linear growth models to describe the growth curve of Mehraban sheep. **J. Appl. Anim. Res.**, v. 2119, p. 1-6, 2017. <https://doi.org/10.1080/09712119.2017.1348949>.

Jung, H.G.; Allen, M.S. Characteristics of plant cell walls affecting intake and digestibility of forages by ruminants. **J. Anim. Sci.**, v. 73, p. 2774-2790, 1995. <https://doi.org/10.2527/1995.7392774x>.

Keating, B.A.; Carberry, P.S.; Bindraban, P.S.; Asseng, S.; Meinke, H.; Dixon, J. Eco-efficient agriculture: concepts, challenges, and opportunities. **Crop Sci.**, v. 50, p. S-109-S-119, 2010. <https://doi.org/10.2135/cropsci2009.10.0594>.

Martin, C.; Morgavi, D.P.; Doreau, M. Methane mitigation in ruminants: from microbe to the farm scale. **Animal**, v. 4, p. 351-365, 2009. <https://doi.org/10.1017/S1751731109990620>

Martin, O.; Sauvant, D. Dynamic model of the lactating dairy cow metabolism. **Animal**, v. 1, p. 1143-1166, 2007. <https://doi.org/10.1017/S1751731107000377>.

Mertens, D.R. Creating a system for meeting the fiber requirements of dairy cows. **J. Dairy Sci.**, v. 80, p. 1463-1481, 1997. [https://doi.org/10.3168/jds.S0022-0302\(97\)76075-2](https://doi.org/10.3168/jds.S0022-0302(97)76075-2).

Mertens, D.R. Predicting intake and digestibility using mathematical models of ruminal function. **J. Anim. Sci.**, v. 64, p. 1548-1558, 1987. <https://doi.org/10.2527/jas1987.6451548x>.

Mertens, D.R. Principles of modeling and simulation in teaching and research. **J. Dairy Sci.**, v. 60, p. 1176-1186, 1977. [https://doi.org/10.3168/jds.S0022-0302\(77\)84005-8](https://doi.org/10.3168/jds.S0022-0302(77)84005-8).

Niu, M.; Kebreab, E.; Hristov, A.N.; Oh, J.; Arndt, C.; Bannink, A.; Bayat, A.R.; Brito, A.F.; Boland, T.; Casper, D.; Crompton, L.A.; Dijkstra, J.; Eugène, M.A.; Garnsworthy, P.C.; Haque, M.N.; Hellwing, A.L.F.; Huhtanen, P.; Kreuzer, M.; Kuhla, B.; Lund, P.; Madsen, J.; Martin, C.; McClelland, S.C.; McGee, M.; Moate, P.J.; Muetzel, S.; Muñoz, C.; O’Kiely, P.; Peiren, N.; Reynolds, C.K.; Schwarm, A.; Shingfield, K.J.; Storlien, T.M.; Weisbjerg, M.R.; Yáñez-Ruiz, D.R.; Yu, Z. Prediction of enteric methane production, yield, and intensity in dairy cattle using an intercontinental database. **Glob. Chang. Biol.**, p. 0-2, 2018. <https://doi.org/10.1111/gcb.14094>

Oba, M.; Allen, M.S. Evaluation of the importance of the digestibility of neutral detergent fiber from forage: effects on dry matter intake and milk yield of dairy cows. **J. Dairy Sci.**, v. 82, p. 589-596, 1999. [https://doi.org/10.3168/jds.S0022-0302\(99\)75271-9](https://doi.org/10.3168/jds.S0022-0302(99)75271-9).

Oxford English Dictionary. **Oxford English Dictionary Online**. Oxford English Dict., 2017. <http://dictionary.oed.com>.

Puillet, L.; Martin, O.; Tichit, M.; Sauvant, D. Simple representation of physiological regulations in a model of lactating female: application to the dairy goat. **Animal**, v. 2, p. 235-246, 2008. <https://doi.org/10.1017/S1751731107001140>.

Rao, I.; Peters, M.; Castro, A.; Schultze-Kraft, R.; White, D.; Fisher, M.; Miles, J.; Lascano, C.; Blummel, M.; Bungenstab, D.; Tapasco, J.; Hyman, G.; Bolliger, A.; Paul, B.; Van Der Hoek, R.; Maass, B.; Tiemann, T.; Cuchillo, M.; Douxchamps, S.; Villanueva, C.; Rincón, Á.; Ayarza, M.; Rosenstock, T.; Subbarao, G.; Arango, J.; Cardoso, J.; Worthington, M.; Chirinda, N.; Notenbaert, A.; Jenet, A.; Schmidt, A.; Vivas, N.; Lefroy, R.; Fahrney, K.; Guimarães, E.; Tohme, J.; Cook, S.; Herrero, M.; Chacón, M.; Searchinger, T.; Rudel, T. **LivestockPlus - the sustainable intensification of forage-based agricultural systems to improve livelihoods and ecosystem services in the tropics.** *Trop. Grasslands - Forrajes Trop.*, v. 3, p. 59-82, 2015. [https://doi.org/10.17138/TGFT\(3\)59-82](https://doi.org/10.17138/TGFT(3)59-82).

Russell, J.B.; Muck, R.E.; Weimer, P.J. Quantitative analysis of cellulose degradation and growth of cellulolytic bacteria in the rumen. *FEMS Microbiol. Ecol.*, v. 67, p. 183-197, 2009. <https://doi.org/10.1111/j.1574-6941.2008.00633.x>.

Silva, R.O.; Barioni, L.G.; Hall, J.A.J.; Folegatti Matsuura, M.; Zanett Albertini, T.; Fernandes, F.A.; Moran, D. Increasing beef production could lower greenhouse gas emissions in Brazil if decoupled from deforestation. *Nat. Clim. Chang.*, v. 6, p. 493-497, 2016. <https://doi.org/10.1038/nclimate2916>.

Smith, P.; Cai, Z.; Gwary, D.; Janzen, H.; Kumar, P.; McCarl, B.; Ogle, S.; O'Mara, F.; Rice, C.; Scholes, B.; Sirotenko, O. **Agriculture in climate change 2007: mitigation.** Cambridge Univ. Press, 2007. p. 1-44, 2007. <https://doi.org/10.2753/JES1097-203X330403>.

Stanley, P.L.; Rowntree, J.E.; Beede, D.K.; DeLonge, M.S.; Hamm, M.W. Impacts of soil carbon sequestration on life cycle greenhouse gas emissions in Midwestern USA beef finishing systems. *Agric. Syst.*, v. 162, p. 249-258, 2018. <https://doi.org/10.1016/j.agsy.2018.02.003>.

Sterman, J.D. **Business dynamics: systems thinking and modeling for a complex world, management.** 2000. <https://doi.org/10.1057/palgrave.jors.2601336>.

Tedeschi, L.O.; Fox, D.G.; Guioy, P.J. A decision support system to improve individual cattle management. 1. A mechanistic, dynamic model for animal growth. *Agric. Syst.*, v. 79, p. 171-204, 2004. [https://doi.org/10.1016/S0308-521X\(03\)00070-2](https://doi.org/10.1016/S0308-521X(03)00070-2).

Tedeschi, L.O.; Muir, J.P.; Riley, D.G.; Fox, D.G. The role of ruminant animals in sustainable livestock intensification programs. *Int. J. Sustain. Dev. World Ecol.*, v. 22, p. 452-465, 2015. <https://doi.org/10.1080/13504509.2015.1075441>.

Tedeschi, L.O.; Nicholson, C.F.; Rich, E. Using system dynamics modelling approach to develop management tools for animal production with emphasis on small ruminants. *Small Rumin. Res.*, v. 98, p. 102-110, 2011. <https://doi.org/10.1016/j.smallrumres.2011.03.026>.

Vanlauwe, B.; Coyne, D.; Gockowski, J.; Hauser, S.; Huising, J.; Masso, C.; Nziguheba, G.; Schut, M.; Van Asten, P. Sustainable intensification and the African smallholder farmer. **Curr. Opin. Environ. Sustain.**, v. 8, p. 15-22, 2014. <https://doi.org/10.1016/j.cosust.2014.06.001>.

ARTICLE 1 - A DYNAMIC TOOL TO DESCRIBE ANIMAL GROWTH AND ITS USE AS A DECISION SUPPORT SYSTEM

R. M. Amaral

Departamento de Zootecnia, Universidade Federal de Viçosa, MG, Brazil

ABSTRACT

A dynamic model was developed based on a set of mechanistic equations from current nutritional systems to describe and simulate the energy and protein requirements, the composition of gain, growth rate, and body mass of feedlot lambs. The model inputs are initial body mass (kg), standard final mass (kg), age (days) and diet energy concentration ($\text{Mcal}\cdot\text{kg}^{-1}$). To evaluate the model as a descriptive tool, the main variables are presented in a graphic form describing their behaviors over time and their patterns compared to biological functions and scientific data. The model was evaluated as decision support tool with a dataset composed by 564 individual measures of final body mass and diet energy concentration. The simulation provides a graphical and numerical description of the nutrient requirements and composition of gain and it also estimates animal performance over time. The simulation of final body mass presents a root mean squared error of 3.11 kg, which corresponds to 7.79% of observed final body mass and a R^2 of 0.89 indicating accuracy and precision, respectively. The dynamic model can be used as a support decision tool to estimate final body mass, as well as the days on feed required to reach certain final mass with precision and accuracy; the model can also be used as a learning tool to illustrate practical principles of animal nutrition, nutrient requirement relationships, and body composition changes in addition to the understanding of standard body mass implications.

Keywords: energy efficiency, feedlot, growth curve, performance simulation

INTRODUCTION

Proper nutrient requirement determination and nutrition of farm animals is a basic statement of sustainable intensification. The adequate use of feed sources on adequate proportions allows to reduce the necessary time until slaughter, minimizing the amount of feed and water needed and the amount of manure and nutrients excreted as well as the amount of greenhouse gases emissions. These aspects must be

accompanied by a responsible social, economic, and environmental interaction that can still be profitable (Tedeschi et al., 2017).

The processes of nutrition, digestion, metabolism, and determination of nutritional requirements and animal growth are complex dynamic systems. They are complex because they are interdependent, being subjects to internal and external factors of the system and dynamic because the processes depend on time as well as on the feedback relations between their elements. They are also systems, which in a simple definition are a set of interrelated elements that compose a complex whole. The knowledge about these processes is necessary to support management decisions of producers and animal scientists. With this information it is possible to formulate more precise diets to meet animal requirements in different production systems, estimate the quality and quantity of food, and the time required to get the final product; therefore, the resources must be carefully and technically used to improve animal performance and reduce environmental damage (i.e. fewer greenhouse gases and fewer pollutant emissions) in an economical way.

Dynamic modelling has been conducted in different areas of animal production, like farm production and management policies (Guimarães et al., 2009), diet preference and selection (Gregorini et al., 2015), methane emission by livestock (Herrero et al., 2008), ruminal microbiology (Russell et al., 2009), dairy cattle production (Martin and Sauvant, 2007), and with cattle growth (Garcia et al., 2008; Tedeschi et al., 2004). The models have been used as predictive or descriptive elements as part of decision support systems and learning tools (Mertens, 1977).

Current nutritional models like Cornell Net Carbohydrate and Protein System (CNCPS) and CNCPS based models, the Small Ruminant Nutrition System (SRNS), and the Ruminant Nutrition System (RNS) establish dependent relations between feed compositions, level of intake, nutritional aspects, and animal performance. These models, with a mechanistic structure, establish these relations and give a significant contribution to their understanding with better descriptions of the different nutritional processes. All of these models are static; they support only punctual estimation related to the animal needs and their individual performances without a feedback or continuity on information flow.

The proposed dynamic model aims to integrate some equations of CNCPS-S, SRNS, and RNS models to obtain protein and energy requirements, body composition

of gain and animal growth, and accounting cyclical changes over time on feedlot lambs before weaned until their maturity, using animal and diet characteristics as input.

METHODS

Model framework

The model was constructed using the System Dynamics approach and part of the mechanistic equations proposed on CNCPS-S (Cannas et al., 2004), SRNS (Tedeschi et al., 2010), and RNS (Tedeschi and Fox, 2016) to describe the nutritional requirements, composition of gain, and the dynamic of growth over time. This model was constructed on a set of ordinary differential equations based on the causality relations between selected variables with the arrangement of the main components of dynamic simulation like stocks, flows, feedbacks, delays, and decision rules (Sterman, 2000).

All variables and equations involved are presented in Table 1 and Table 2, respectively.

The model diagram presents the established relationships between the variables and the feedback structure (Figure 1). Mathematically the flow into the stocks can be written as:

$$BM(t) = \int_{t_0}^t ADG_{(t_i)} ds + BM_{(t_0)}$$

$$\text{Total body fat}(t) = \int_{t_0}^t \text{fat in gain}_{(t_i)} ds + \text{Total body fat}_{(t_0)}$$

$$\text{Total body protein}(t) = \int_{t_0}^t \text{protein in gain}_{(t_i)} ds + \text{Total body protein}_{(t_0)}$$

The BM is body mass, ADG is average daily gain, t_0 is the initial time, and t_i is the time in i moment.

Table 1. Description of the units and abbreviations of variables used in the equations of model

Variable	Unity	Description
a_1	$\text{NE}_M \cdot \text{kg}^{0.75}$	Maintenance requirement
ADG	$\text{g} \cdot \text{day}^{-1}$	Average daily gain
AF	%	Proportion of empty body fat
Age	Days	Current age
AP	%	Proportion of empty body protein
BCS	1 to 5	Body condition score
BM	kg	Body mass
CP	$\text{g} \cdot \text{day}^{-1}$	Crude protein
DMI	$\text{kg} \cdot \text{day}^{-1}$	Dry matter intake
EBM	kg	Empty body mass
EVG	$\text{Mcal} \cdot \text{day}^{-1}$	Energy content of gain
k_G	*	Partial efficiency of ME to NE for growth
k_M	*	Partial efficiency of ME to NE for maintenance
L	*	Intake above maintenance
ME	$\text{Mcal} \cdot \text{kg}^{-1}$	Metabolizable energy
ME_G	$\text{Mcal} \cdot \text{day}^{-1}$	ME available for growth
MEI	$\text{Mcal} \cdot \text{day}^{-1}$	ME intake
ME_M	$\text{Mcal} \cdot \text{day}^{-1}$	ME requirement for maintenance
MP	$\text{g} \cdot \text{day}^{-1}$	Metabolizable protein
MP_M	$\text{g} \cdot \text{day}^{-1}$	MP for maintenance
NE_G	$\text{Mcal} \cdot \text{day}^{-1}$	Net energy available for growth
P	*	Degree of maturity
RE_{Fat}	$\text{Mcal} \cdot \text{day}^{-1}$	Retained energy from fat
RE_P	*	Proportion of retained energy as protein
RE_{prot}	$\text{Mcal} \cdot \text{day}^{-1}$	Retained energy from protein
S	*	Factor. 1 to female and castrated male and 1.15 to intact males
SBM	kg	Shrunk body mass
$\text{SBM}^{0.75}$	kg	Metabolic SBM
SFM	kg	Standard final mass
TE	Mcal	Total energy
TF	kg	Total body fat
TP	kg	Total body protein

Source: Cannas et al. (2004) and Tedeschi et al. (2010).

* = dimensionless.

Environmental conditions were not added as input because this information is not usually included on research papers, so we consider the animals in thermoneutral condition.

No nutritional model establishes the inflection point in the growth of the animals, nor the point at which the animals reach maturity. This is because these models commonly aim to describe animal growth in a short time period, without detailing the point where the variation in body mass is minimal, the body maturity. The first model developed attempts to generate an exponential positive curve and not the standard sigmoid pattern, verified at empirical growth studies, where multiple nonlinear models are tested with goats and sheep (Hojjati and Hossein-Zadeh, 2017; Hossein-Zadeh, 2015; Regadas Filho et al., 2014; Rocha et al., 2015). The sigmoid pattern can be obtained in dynamic models accounting the dependence of nonlinear interactions between positive and negative loops, where the positive loop initially promotes exponential growth up to a point where it loses its dominance for a negative loop and the system slowly tends to the equilibrium, in our case the body mass at maturity.

To verify the composition of gain, the variables, retained energy from fat (REfat), and retained energy from protein (REprot), were divided by the energy content of fat and protein, 9.4 and 5.7, respectively. This information generates the rates accfat and accprot that were used to accumulate in the stocks total body protein and total body fat the amount of nutrients retained during the simulation. An initial value was obtained from this simulation in regards to the fat and protein contents on the initial body mass from Cannas et al. (2004) equations.

The model was developed using the software Vensim PLE (Ventana Systems Inc., 2017). The simulation unit was “day” and it used a long-term horizon of 730 days (two years). The Euler integration method was used with a time step of 0.25 by day, which means that each simulated day the software ran four times (1/0.25) for integration.

The model file can be downloaded from:

https://1drv.ms/u/s!AmS9fSMhYD8Oh2CioCIC_bB3mvZR

The software Vensim PLE version can be downloaded from:

<http://vensim.com/free-download/>

Simulation procedure

1. Initial input data was: initial body mass (kg), standard final mass (kg), age (days), sex (1 or 1.15), and diet metabolizable energy concentration (Mcal kg⁻¹).
2. Sequentially, the model calculates the nutritional requirements for maintenance (Mcal EM day⁻¹) and estimates dry matter intake (kg day⁻¹) and then the metabolizable energy intake above maintenance (dimensionless) is calculated by giving the metabolizable energy available for growth (Mcal EM day⁻¹).
3. Based on the metabolizable energy available for growth and the degree of maturity the energy content of gain (Mcal day⁻¹) as the sum of the retained energy from protein (Mcal day⁻¹) and the retained energy from fat (Mcal day⁻¹) are estimated.
 - Based on retained energy from protein and fat the protein in gain (g day⁻¹) and the fat in gain (g day⁻¹) are calculated, which is accumulated on total body protein (kg) and total body fat (kg).
4. Based on the proportion of energy retained as protein, the k_G is calculated and multiplied by the metabolizable energy to gain, giving the net energy on gain.
5. The average daily gain is estimated with the net energy available to gain value, which is accounted to the initial body mass. This change is automatically computed to animal body mass closing the feedback loop and influencing the intake capacity and the nutritional requirements over time dynamically.

The feedback structure allows nutritional requirements to be changed as the animal gains or loses mass, according to the energy available in a given diet, describing different growth scenarios on the basis of hypothetical diets energy concentration and animal description.

Model evaluation as support decision tool

An analysis with a dataset of independent studies was conducted to evaluate the predicting ability of final body mass and the selection criteria was the following: initial and final body mass, dry matter intake, average daily gain, metabolizable energy or total digestible nutrients, breed or cross, gender, initial age, and feedlot time. The dataset reference, the number of observations, standard final mass, and genotype are described in Table 3. The dataset summary statistics were presented in Table 4.

The standard final mass (SFM) of the different breeds or crosses were based on the information available at “Breeds of Livestock” web page from Oklahoma State

University: <http://www.ansi.okstate.edu/breeds/sheep> and at Domestic Animal Genetic Resources Information System available at <http://dagris.info/> (Kemp et al., 2007).

Table 3. References, number of treatments, number of observations, standard final mass, and genotype of evaluation dataset

Reference	Treatments	Observations	SFM*(kg)	Genotype
Fimbres et al. (2002)	4	20	55	Pelibuey
Alves et al. (2003)	3	18	100	Santa Inês
Sheridan et al. (2003)	2	16	105	Mutton Merino
Haddad and Younis (2004)	2	14	80	Awassi
Ebrahimi et al. (2007)	3	54	81	Mehbraban
Kioumarsis et al. (2008)	6	36	35	Taleshi
Cunha et al. (2008)	4	24	100	Santa Inês
Pereira et al. (2008)	4	24	100	Santa Inês
Bensimon et al. (2011)	3	27	100	Santa Inês
Lopez-Carlos et al. (2011)	1	10	105	Dorper x Katadhin
Papi et al. (2011)	4	80	80	Chall
Azevedo et al. (2012)	4	24	100	Santa Inês
Costa et al. (2012)	5	45	100	Santa Inês
Jaborek et al. (2017)	3	72	119	Hampshire
Tadayon et al. (2017)	6	36	80	Chall
Sadri et al. (2017)	4	24	81	Mehbraban
Estrada-Angulo et al. (2018)	4	40	75	Pelibuey x Katahdin

*Standard Final Mass

Table 4. Dataset summary¹

Item	Mean	Standard deviation	Minimum	Maximum
Days on feed	68.85	18.99	35.00	105.00
Dietary ME (Mcal kg ⁻¹ of DM)	2.54	0.21	2.10	2.96
Initial body mass (kg)	25.85	5.90	18.05	39.10
Final body mass (kg)	39.94	8.87	29.15	61.70
Dry matter intake (kg day ⁻¹)	1.30	0.30	0.87	2.33
Average daily gain (kg day ⁻¹)	0.22	0.05	0.10	0.31

¹ Dataset comprised 17 studies with 62 treatments for a total of 564 individual measures in growing male lambs.

The statistical evaluation was assessed between simulated and observed values to final body mass. To evaluate the accuracy and precision of the model the mean bias [eq. 1]; mean square error (MSE) [eq. 2]; root mean square error (RMSE) [eq. 3]; coefficient of determination (R^2) [eq. 4]; and the MSE decomposition into mean bias

(U^M), systematic bias (U^S) and random error (U^C) (Sterman, 2000; Theil, 1979) [eq. 5 to eq. 7] were used.

$$[eq. 1] \quad MB = \frac{\sum_{i=1}^n (Y_i - f(X_1, \dots, X_p)_i)}{n}$$

$$[eq. 2] \quad MSE = \frac{\sum_{i=1}^n (Y_i - f(X_1, \dots, X_p)_i)^2}{n}$$

$$[eq. 3] \quad RMSE = \sqrt{MSE}$$

$$[eq. 4] \quad R^2 = \left(\frac{s_{f(X_1, \dots, X_p)Y}}{s_Y \times s_{f(X_1, \dots, X_p)}} \right)^2$$

$$[eq. 5] \quad U^M = (\bar{f}(X_1, \dots, X_p) - \bar{Y}) / MSE$$

$$[eq. 6] \quad U^S = (s_{f(X_1, \dots, X_p)} - s_Y) / MSE$$

$$[eq. 7] \quad U^C = (2(1 - r)s_{f(X_1, \dots, X_p)}s_Y) / MSE$$

Where: $f(X_1, \dots, X_p)_i$ is the i th simulated value; $\bar{f}(X_1, \dots, X_p)$ average simulated value; n sample size; $s_{f(X_1, \dots, X_p)Y}$ (Co)variance between Y and $f(X_1, \dots, X_p)_i$; $s_{f(X_1, \dots, X_p)}$ standard deviation for $f(X_1, \dots, X_p)_i$; s_Y is the standard deviation of the Y variable; \bar{Y} is the average simulated value; Y_i i th observed or measured value; r is the Pearson correlation coefficient.

Model evaluation as a descriptive tool

To evaluate the model as a descriptive tool, the main variables are presented in a graphic form to describe their behaviors over time and their patterns compared to biological functions and scientific data. The simulation was conducted using the data from Sheridan et al. (2003) as input; they worked with South African Mutton Merino lambs in feedlot receiving a high and a low energy diet, 2.89 and 2.36 Mcal ME kg^{-1} , respectively. The input data was standard final mass (105 kg), sex (intact male), initial age (90 days), and initial mass of 33.31 kg for lambs fed with a high energy diet and 32.13 kg for lambs fed with a low energy diet.

RESULTS

Model results as decision support tool

The dataset used to model the evaluation and the bias of the observed final body mass of the empirical studies in contrast to the final body mass simulated by the model simulation is showed in Table 5. The linear regression between observed and simulated

values to final body mass is presented in Figure 6. The model evaluation generates the following information:

1. mean bias (MB) was 0.656 kg;
2. the mean square error of prediction (MSE) was 9.68;
3. the root mean square error of prediction (RMSE) was 3.11 kg;
5. the coefficient of determination (R^2) of regression was 0.892 (Figure 3);
6. the mean bias (U^M), systematic bias (U^S), and random error (U^C) values were: 0.044, 0.024 and 0.93, respectively.

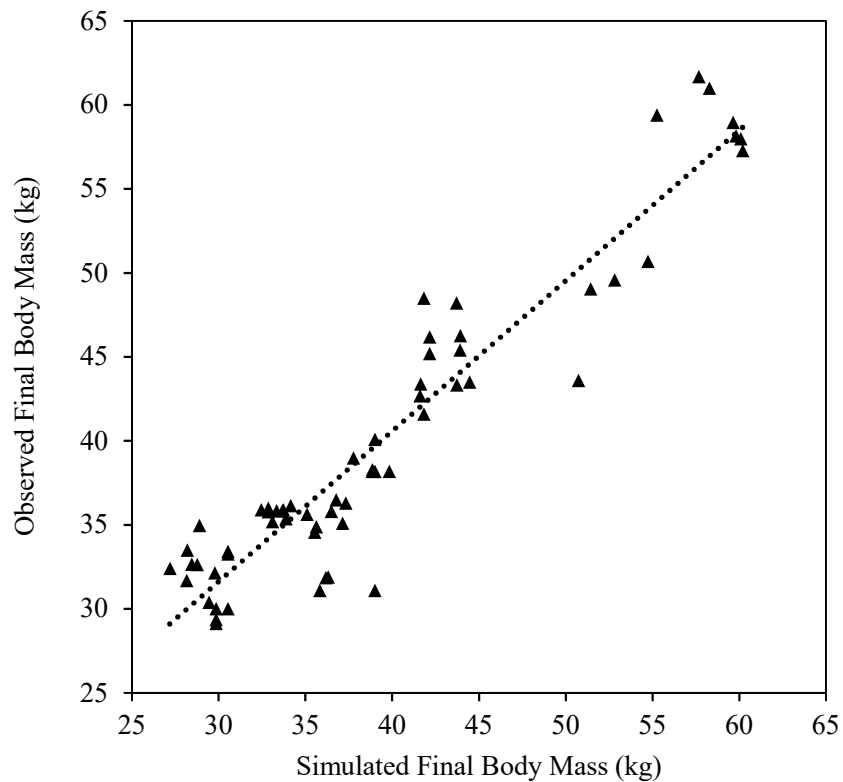


Figure 6. Regression of simulated against observed final body mass.

Table 5. Initial inputs, observed body mass data, simulated final body mass values, and bias of simulation

Reference	N	ME (Mcal·kg ⁻¹)	Days on feed	Observed Initial Mass (kg)	Observed Final Mass (kg)	Simulated Final Mass (kg)	Bias (O-P)
Fimbres et al. (2002)	5	2.96	60	23.90	39.00	37.75	1.25
Fimbres et al. (2002)	5	2.88	60	23.90	36.30	37.32	-1.02
Fimbres et al. (2002)	5	2.78	60	23.90	36.50	36.77	-0.27
Fimbres et al. (2002)	5	2.61	60	23.90	31.10	35.83	-4.73
Alves et al. (2003)	6	2.42	98	20.17	31.87	36.17	-4.30
Alves et al. (2003)	6	2.66	96	20.10	31.10	39.00	-7.90
Alves et al. (2003)	6	2.83	76	20.47	31.90	36.30	-4.40
Sheridan et al. (2003)	8	2.89	56	33.31	49.05	51.43	-2.38
Sheridan et al. (2003)	8	2.36	56	32.13	43.51	44.45	-0.94
Haddad and Younis (2004)	7	2.72	72	20.30	34.90	35.62	-0.72
Haddad and Younis (2004)	7	2.84	72	20.50	35.10	37.13	-2.03
Ebrahimi et al. (2007)	18	2.70	70	35.40	50.70	54.73	-4.03
Ebrahimi et al. (2007)	18	2.50	70	35.40	49.60	52.81	-3.21
Ebrahimi et al. (2007)	18	2.30	70	35.30	43.60	50.73	-7.13
Kioumars et al. (2008)	6	2.30	105	19.70	30.02	29.84	0.18
Kioumars et al. (2008)	6	2.30	105	19.70	29.15	29.84	-0.69
Kioumars et al. (2008)	6	2.30	105	19.70	29.38	29.84	-0.46
Kioumars et al. (2008)	6	2.50	105	19.70	30.02	30.52	-0.50
Kioumars et al. (2008)	6	2.50	105	19.70	33.44	30.52	2.92
Kioumars et al. (2008)	6	2.50	105	19.70	33.28	30.52	2.76
Cunha et al. (2008)	6	2.39	70	19.10	33.50	28.18	5.32
Cunha et al. (2008)	6	2.41	70	19.16	32.66	28.45	4.21
Cunha et al. (2008)	6	2.36	70	19.96	30.41	29.44	0.97
Cunha et al. (2008)	6	2.40	70	19.96	32.16	29.77	2.39
Pereira et al. (2008)	6	2.54	67	18.74	31.70	28.14	3.56
Pereira et al. (2008)	6	2.58	67	18.05	32.42	27.18	5.24
Pereira et al. (2008)	6	2.62	67	18.82	34.97	28.89	6.08
Pereira et al. (2008)	6	2.77	67	18.15	32.65	28.75	3.90
Bensimon et al. (2011)	7	2.64	44	26.07	34.57	35.53	-0.96
Bensimon et al. (2011)	10	2.61	43	26.19	35.65	35.08	0.57
Bensimon et al. (2011)	10	2.58	47	26.49	35.82	36.49	-0.67
Lopez-Carlos et al. (2011)	10	2.92	42	28.40	38.20	39.82	-1.62
Papi et al. (2011)	20	2.17	84	38.90	59.40	55.25	4.15
Papi et al. (2011)	20	2.38	84	39.10	61.70	57.66	4.04
Papi et al. (2011)	20	2.55	84	37.70	61.00	58.27	2.73
Papi et al. (2011)	20	2.71	84	38.00	58.00	60.09	-2.09
Azevedo et al. (2012)	6	2.39	60	23.55	35.86	33.67	2.19
Azevedo et al. (2012)	6	2.36	60	24.18	36.16	34.14	2.02
Azevedo et al. (2012)	6	2.33	60	23.65	35.85	33.33	2.52
Azevedo et al. (2012)	6	2.31	60	24.11	35.38	33.87	1.51
Costa et al. (2012)	9	2.30	35	26.60	35.90	32.44	3.46
Costa et al. (2012)	9	2.20	35	27.30	35.80	32.85	2.95
Costa et al. (2012)	9	2.20	35	28.00	35.90	33.71	2.19
Costa et al. (2012)	9	2.10	35	27.70	36.00	32.86	3.14
Costa et al. (2012)	9	2.10	35	27.90	35.20	33.10	2.10
Jaborek et al. (2016)	24	2.62	85	35.21	57.29	60.19	-2.90
Jaborek et al. (2016)	24	2.62	84	35.18	58.17	59.80	-1.63
Jaborek et al. (2016)	24	2.62	83	35.29	58.96	59.63	-0.67
Tadayon et al. (2017)	6	2.49	60	28.00	41.60	41.81	-0.21
Tadayon et al. (2017)	6	2.48	60	27.90	42.70	41.60	1.10
Tadayon et al. (2017)	6	2.50	60	28.20	45.20	42.15	3.05
Tadayon et al. (2017)	6	2.47	60	28.00	43.40	41.64	1.76
Tadayon et al. (2017)	6	2.50	60	28.20	46.20	42.15	4.05
Tadayon et al. (2017)	6	2.49	60	28.00	48.50	41.81	6.69
Sadri et al. (2018)	6	2.63	60	25.00	38.20	38.99	-0.79
Sadri et al. (2018)	6	2.63	60	24.90	38.20	38.85	-0.65
Sadri et al. (2018)	6	2.63	60	24.90	38.30	38.85	-0.55
Sadri et al. (2018)	6	2.63	60	25.00	40.10	38.99	1.11
Estrada-Angulo et al. (2018)	10	2.80	84	23.95	43.35	43.71	-0.36
Estrada-Angulo et al. (2018)	10	2.80	84	24.04	45.42	43.90	1.52
Estrada-Angulo et al. (2018)	10	2.80	84	24.05	46.27	43.92	2.35
Estrada-Angulo et al. (2018)	10	2.80	84	23.94	48.22	43.69	4.53

Model results as a descriptive tool

The dynamic application of SRNS model provides a description of the nutrient requirements, composition of gain, and estimates animal performance over time. The results of the descriptive evaluation are showed as follow. Metabolizable energy intake (MEI), metabolizable energy intake above maintenance factor (L), metabolizable energy required to maintenance (ME_m) and available to growth (ME_g), metabolizable protein required to maintenance (MP_m), and gain (MP_g) (Figure 2). Maturity degree, the energy content of gain (EVG), retained energy from protein (RE_{prot}) and from fat (Refat), partial efficiency of ME to NE for growth (k_G), and net energy to gain (NE_g) (Figure 3). Protein and fat retained as function of body mass (Figure 4) and dry matter intake (DMI), growth rate (ADG), and body mass (BM) change (Figure 5).

The metabolizable energy intake (MEI) pattern follow the changes on dry matter intake (Figure 5) and the difference between the diets' energy concentration, both low and high. MEI was 4.03 and 5.10 Mcal day⁻¹ for the first day of simulation and the fifty-sixth day in the low energy group and 5.07 and 6.85 Mcal day⁻¹ for the first and fifty-sixth day of simulation in the high energy group. The metabolizable energy intake above maintenance factor (L) accounts for energy consumed allowed to productive functions; the simulated values from the first day were 2.09 and 2.45 times the metabolizable energy required to maintain the low and high energy levels, respectively.

The metabolizable energy requirement (ME_m) and metabolizable protein requirement to maintenance (MP_m) had direct dependence on body mass (BM) following the same sigmoid pattern in their respective scales. The values of ME_m were 1.93, 2.45 and 4.17 Mcal day⁻¹ on the first, fifty-sixth, and 730 days, respectively on a low energy diet. The MP_m was 52.31, 65.77 and 95.29 g day⁻¹ on the first, fifty-sixth, and 730 days, respectively on a low energy diet.

The metabolizable energy available to growth (ME_g) was 2.10 and 3.00 Mcal day⁻¹ on the first day in low and high energy levels, respectively with the difference of 0.90 Mcal d⁻¹. This difference increased on the fifty-sixth day, where the values were 2.65 and 4.01 Mcal d⁻¹ and the difference was 1.36 Mcal day⁻¹.

Metabolizable protein required for growth (MP_g) had a distinct behavior as function of their dependency on the growth rate (ADG). On the first, fifty-sixth, and 730th days of simulation, the simulated requirement of MP_g was 54.21, 72.39, and 1.04 g day⁻¹ on high energy levels, respectively.

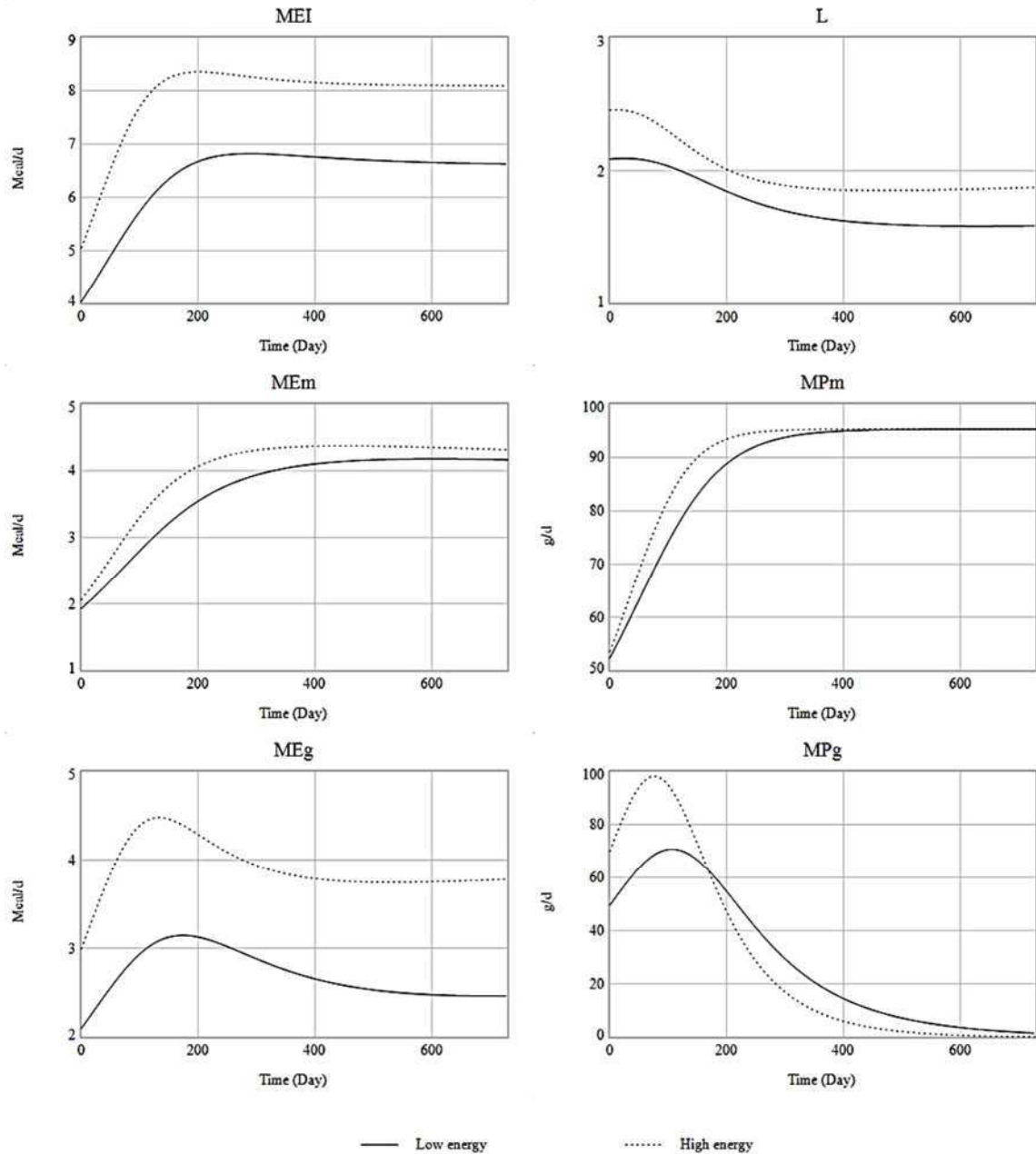


Figure 2. Metabolizable energy intake (MEI), metabolizable energy intake above maintenance factor (L), metabolizable energy and protein requirements to maintenance (ME_m and MP_m), and metabolizable energy available and protein required to growth (ME_g and MP_g) simulated with the input data from Sheridan et al. (2003). The solid line represents lambs fed low energy diet (2.36 Mcal ME kg⁻¹) and the dotted line represents the lambs fed high energy diets (2.89 Mcal ME kg⁻¹).

Figure 3 presents the simulated patterns of the maturity degree, the energy content of gain (EVG), the energy retained as protein (RE_{prot}) and as fat (RE_{fat}), the partial efficiency of metabolizable energy to net energy (k_G), and the net energy evaluable to gain (NE_g) as a function of time.

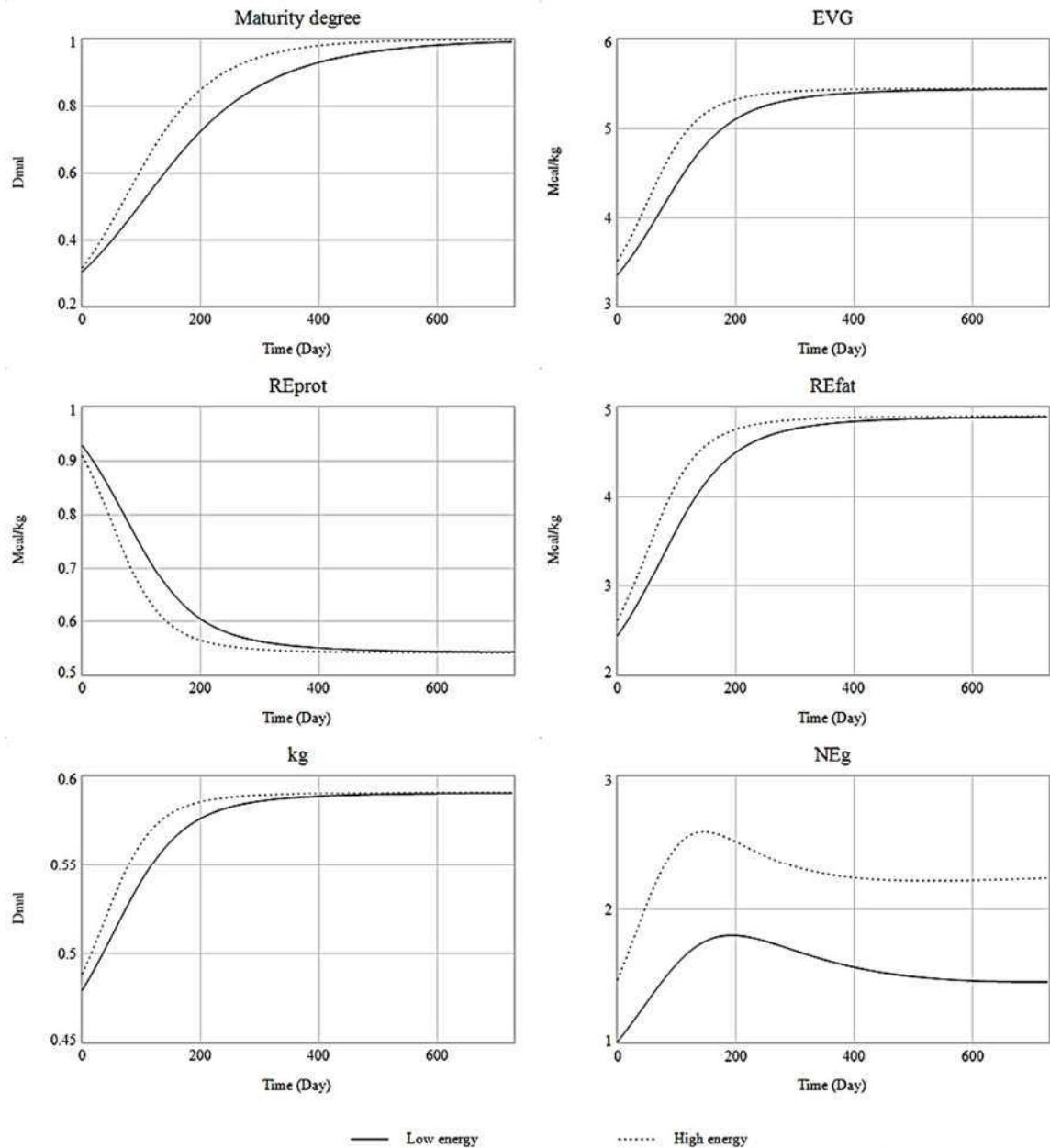


Figure 3. Maturity degree, energy content of gain (EVG), energy retained as protein (REprot), energy retained as fat (REfat), partial efficiency of metabolizable energy to net energy (k_G), and net energy evaluable to gain (NEg) simulated with the input data from Sheridan et al. (2003). The solid line represents lambs fed low energy diet ($2.36 \text{ Mcal ME kg}^{-1}$) and the dotted line represents the lambs fed high energy diets ($2.89 \text{ Mcal ME kg}^{-1}$).

A sigmoid curve describes the maturity degree (P) variable. As the simulation starts (day 0) the P value is 0.306 and 0.317 on lambs with 32.13 and 33.31 kg, respectively, and reaches 0.99 and 0.99 on the 730 days, almost reaching the standard final mass (1).

The energy content of gain (EVG) ranges between 3.36 and 3.52 Mcal kg⁻¹ on day zero and between 3.96 and 4.34 Mcal kg⁻¹ on the fifty-sixth day of simulation on low and high energy diets, describing both a sigmoid pattern.

The retained energy from protein (REprot) and from fat (REfat) displays an inverse behavior over time. REprot assumes on the first day of simulations 0.908 and 0.929 Mcal kg⁻¹ on low and high energy diets, respectively. The REprot reduces to 0.75 and 0.82 Mcal kg⁻¹ on the fifty-sixth day of simulation. REfat increases over time, being 2.44 and 2.62 Mcal kg⁻¹ on the first day of simulations on low and high energy diets, respectively, and 3.13 and 3.59 Mcal kg⁻¹ on the fifty-sixth day of simulation on low and high energy diets, respectively.

The k_G in these examples range between 0.479 to 0.513 in animals between 32.13 kg to 43.51 kg during the fifty-six days that were fed with the low energy content diet (2.36 Mcal ME kg⁻¹), and between 0.488 and 0.538 in animals between 33.31 kg to 51.43 kg during the fifty-six days that were fed with the high energy content diet (2.89 Mcal ME kg⁻¹).

Net energy available to gain (NEg) follows the pattern of MEg multiplied by k_G assuming the values of 1.00 and 1.47 Mcal day⁻¹ on the first day and 1.37 and 2.16 Mcal day⁻¹ on the fifty-sixth day on low and high energy levels, respectively.

Figure 4 presents the total body protein and total body fat as function of body mass (BM) simulated on fifty-six days and 730 days on animals fed high energy diets.

The total body protein started at 5.08 kg and the total body fat at 7.55 kg based on initial estimative. The total body protein reached 7.59 kg and 13.42 kg on the fifty-sixth and 730th days respectively, showing an exponential behavior that tends to stabilize at standard final mass and maturity. The total body fat reached 13.48 kg and 39.31 kg on the fifty-sixth and 730th days, respectively, showing an exponential behavior that tends to increase.

Figure 5 presents the simulated patterns of the dry matter intake (DMI), growth rate (ADG), and body mass (BM).

Dry matter intake behavior is closely related to the BM, expressing an ascending growth and reaching a top of intake on the 263rd and 183rd days of simulation on low and high energy diets. DMI started with 1.70 and 1.75 kg day⁻¹ in the animals with initial BM of (32.13 and 33.31 kg) and reached 2.80 kg day⁻¹ on both after 730 days of following the diet. It corresponds to 5.29% and 5.25 % of BM at the beginning and 2.66 % of BM at the end of simulation.

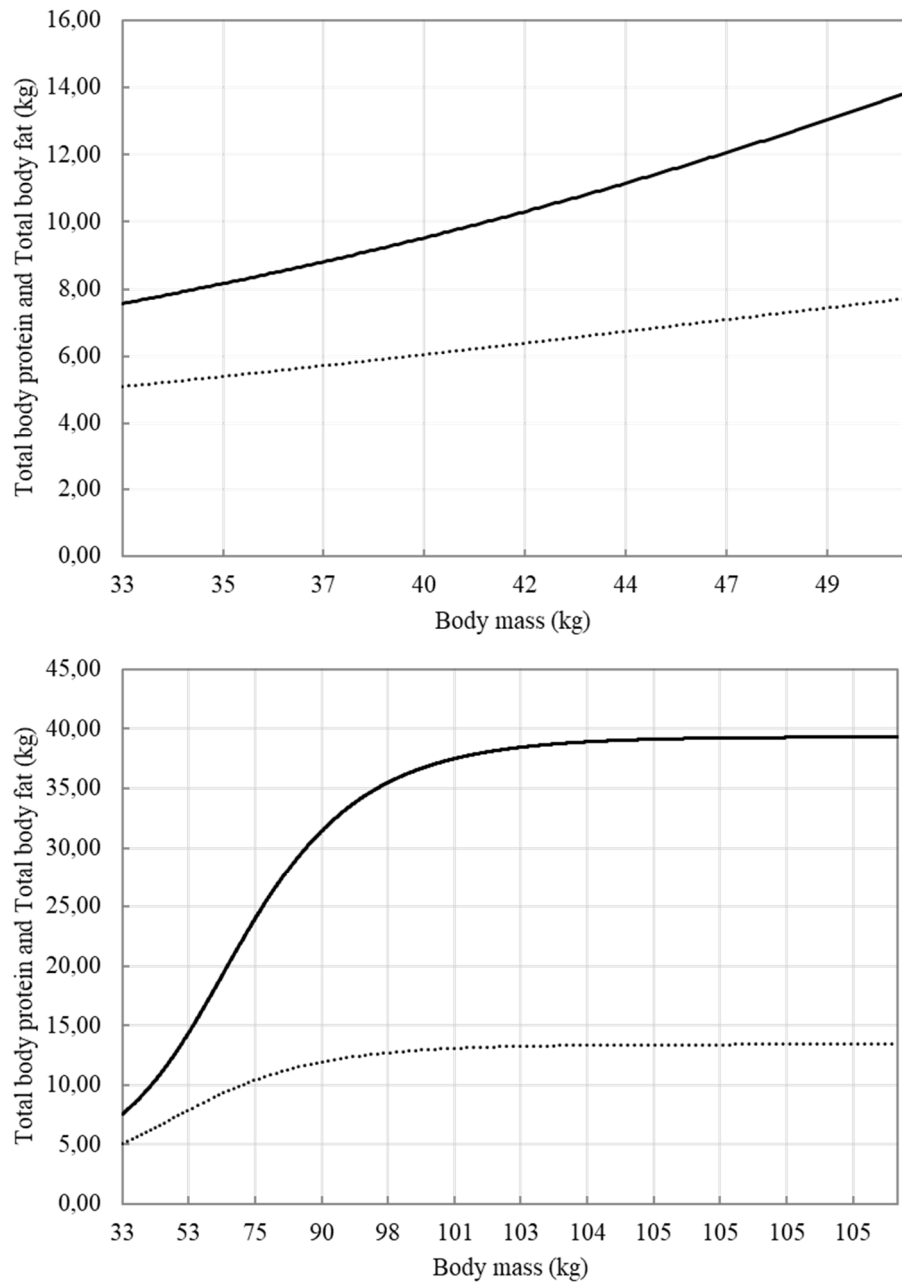


Figure 4. Total body protein (dotted line) and total body fat (solid line) in kilograms as function of body mass simulated to high energy diet on lambs, during 56 days (above) and 730 days (below).

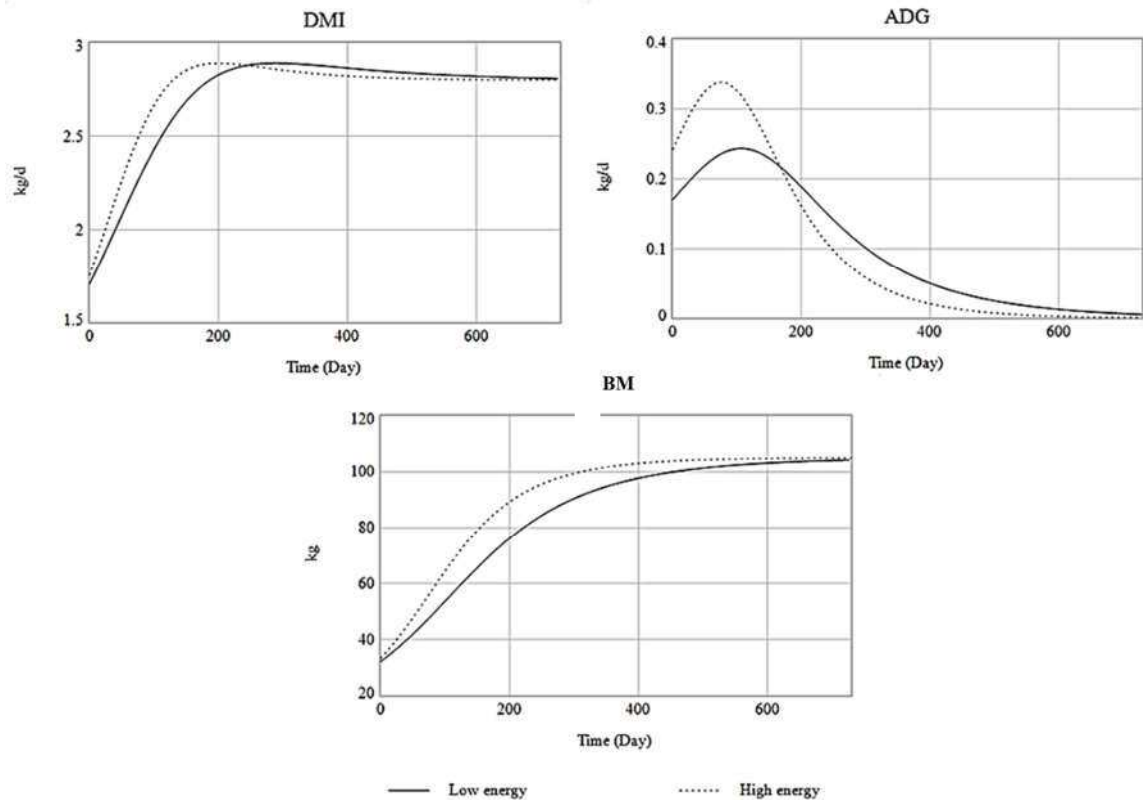


Figure 5. Dry matter intake (DMI), growth rate (ADG). and body mass (BM) simulated with the input data from Sheridan et al. (2003). The solid line represents lambs fed low energy diet ($2.36 \text{ Mcal ME kg}^{-1}$) and the dotted line represents the lambs fed high energy diets ($2.89 \text{ Mcal ME kg}^{-1}$).

The growth rate (ADG) showed an expressive development in the animals fed with high energy feed versus low energy feed. The values verified from the growth rate simulation range from zero grams when the animal reaches the standard body mass to 0.277 and $0.341 \text{ kg day}^{-1}$ as the maximum values on low and high energy diets, respectively.

The body mass is the accumulation of ADG over initial body mass, presenting the sigmoid pattern with the clear difference between animals fed with high energy diets.

DISCUSSION

The model usefulness is interpreted below. The R^2 was relatively high, indicating precision. The variation of RMSE accounts for just 7.79% of observed mean on the final body mass and on the MSE decomposition and the unexplained variation (U^C) accounts for 93%, which means that the model estimates well the mean and the

tendency, both indicating accuracy. The statistical assessment of the quality of simulation on the body mass, at the end of experimental period of dataset studies, shows precision and accuracy; thus, it indicates that the model can be used as a predictor of the animal growth.

The model provides an overtime graphical and numeric description of all variables involved, simulating different processes and behaviors of interrelated variables. This graphical presentation and the easy handling changes in inputs can be useful as a learning tool, hence it is possible to prove any range of standard final mass, initial mass, and diets' energy concentration and instantly visualize the nonlinear interactions and results.

In both diets used as descriptive purpose, the energy is above maintenance (L), allowing the growth. It is visible that the factor reduces as the energy requirements of maintenance and the energy content of gain increase (Figure 5) and the gap between low and high levels of feed energy is discernible. In this model the growth stops when the maturity mass reaches the imposed maturity degree, 105 kg in this example, which means that an over feeding situation before reaching the maturity mass cannot be accounted by the model. In both diets, the animals are still receiving more energy than the necessary to their maintenance.

The verified values to MEm and MPm are higher on lambs fed with high energy diets, that is a result of cyclical changes on body mass, where high energy fed animals had high body mass, which is used to account MEm and MPm. The metabolizable energy available to gain (MEg), that is accounted by the difference between metabolizable energy intake and metabolizable energy to maintenance, displays the difference between low and high levels of energy diets. It is lower at the beginning of simulation when the body mass is closed and it later changes following the body mass change until they almost reach the asymptote, being closed to standard final mass.

The metabolizable protein required to gain (MPg) is a direct function of average daily gain (ADG) (Figure 4). When the usual bell-shaped curve of ADG is plotted over time (Brand et al., 2017) the animal reaches standard final mass and the MPg tends to zero. The diet with high energy content require more MPg and less energetic diets require less MPg to support the estimated body mass change.

The maturity degree or relative size (P) is used by Australian (CSIRO, 2007; SCA, 1990), and Australian based systems to predict the protein, fat, and energy content of gain on cattle and sheep, as well to predict the potential dry matter intake. The

verified differences between P values imply directly on composition of gain, reflecting on the higher energy content of gain, the diminution of energy retained from protein, and the increase of energy retained from fat in the animal fed with a high energy diet. According to Corbett and Freer (2003) it is expected that in young or less developed animals the proportion of retained protein is greater than in older or better developed animals.

The equation to compute the partial efficiency of ME to NE (k_G) is one differential of the SRNS model because the current models use empirical relationships as linear (CSIRO, 2007) or nonlinear model (NRC, 2007) and the SRNS equation works in a mechanistically way, using the proportion of energy retained as protein as a factor. The application of the equations proposed by the current models, $k_G = 0.043 ME$ (MJ $kg^{-1}DM$) (CSIRO, 2007) and $k_G = [(1.42 \times ME - 0.174 \times ME^2 + 0.0122 \times ME^3) - 1.65] / ME$ (Mcal $kg^{-1} DM$) (NRC, 2007) give energy concentration 0.425 and 0.378 values of k_G to partial efficiency of ME to NE, respectively. Xu et al. (2015), found a k_G of 0,419 ($\pm 0,021$) in lambs between 20,3 to 35 kg and Deng et al. (2012) found a k_G of 0.46 (± 0.038) in lambs between 35 and 50 kg. Both researchers compare the empirical estimates with the NRC (2007) and CSIRO (2007) and found underestimated k_G values for both systems.

The dry matter intake was highly influenced by the body mass and diet energy concentration, thus as the animals increased their body mass, they also increased the dry matter intake. Hence, this causal relationship generates that pattern, with a substantial increase at the beginning and a stabilization when the standard final mass was reached. The feed intake per unit of mass is predicted to be greater when the animal is young in comparison with mature animals, when the potential intake declines with increasing body condition at an advanced age (Corbett and Freer, 2003).

The bell-shaped curve, commonly observed in the growth rate (ADG) when nonlinear functions are adjusted to empirical data (Brand et al., 2017; Malhado et al., 2009; Souza et al., 2013). The highest point of the curve is related to the inflection point of sigmoid pattern of growth curve. On the original research, the average daily gain reported 0.203 and 0.281 g on low and high energy levels, respectively (Sheridan et al., 2003). An interesting point of the simulation occurs on the 166th day on feed, according to the simulation, after this point the animal that received less energetic feed had a higher growth rate than the animal that received high energy feed; at this point the body mass was 70.27 and 82.99 kg on low and high energy levels, respectively. It can be

explained by the composition of gain. At this point, the animal that was fed high energy concentration feed was closer to reach its maturity mass, and the adipose tissue deposition is theoretically higher than the muscle tissue deposition. One gram of protein has an energy content of about 5.7 kilocalories and one gram of fat has an energy content of about 9.4 kilocalories, so as animals grow in their advanced stages of maturity, they become less efficient in terms of body mass gain per unit of food eaten (Warriss, 2000).

According to Brody and Lardy (1946), animal growth is a transitory state in which feedback mechanisms (positive and negative, mediated by nutrients, hormones, and other signals) and the assimilation, transport, storage or mobilization of nutrients combined, induce temporal delays that plotted against time and resemble a growing sigmoid pattern. The body mass presents the sigmoid pattern that represents the accumulation of the growth rate as a stock. The inflection point occurs at the sixty-fifth and ninetieth days on feed on high and low energy levels, respectively. The final body mass simulated at the fifty-sixth day on feed was 51,43 kg and 44,45 kg on high and low energy levels, respectively and the empirically observed data was 49,05 kg and 43,51 kg (Sheridan et al., 2003) on the same day, , showing a slight overestimation of simulated data.

CONCLUSIONS

The dynamic application of the SRNS model provides a tool to simulate, analyze, and understand nutritional requirements, composition of gain, and lamb growth in feedlot systems. The model simulates the final body mass in a consistent manner, presenting both precision and accuracy. Changes on nutritional requirements and composition of gain over time was consistent with physiological and nutritional interactions knowledge, which was corroborated with the original reports.

The dynamic model can be used as a support decision tool to estimate final body mass and the days on feed required to reach certain final body mass, according to different energy levels in a given scenario. Moreover, the model can be used as a learning tool to illustrate practical principles of animal nutrition, nutrient requirement relationships, and body composition changes, in addition to the understanding of standard body mass implications, where is possible to simulate a wide range of breeds (standard body mass), initial mass, and diet energy concentration, understanding the dynamic interactions between variables and getting performance simulations.

REFERENCES

Alves, K.S.; Fernando, F.; Carvalho, R. de; Sherlânea, A.; Vêras, C.; Andrade, M.F. de; Costa, R.G.; Maria, Â.; Batista, V.; Medeiros, N. de; José, R.; Maior, D.S.; Karla, D.; Andrade, B. de. Níveis de energia em dietas para ovinos Santa Inês : Desempenho 1 dietary levels of energy for Santa Inês sheep: performance. **Rev. Bras. Zootec.**, p. 1937-1944, 2003.

Azevedo, R.A.; Rufino, L.M. de A.; dos Santos, A.C.R.; da Silva, L.P.; Bonfá, H.C.; Duarte, E.R.; Geraseev, L.C. Desempenho de cordeiros alimentados com inclusão de torta de macaúba na dieta. **Pesqui. Agropecu. Bras.**, v. 47, p. 1663-1668, 2012. <https://doi.org/10.1590/S0100-204X2012001100014>.

Bensimon, A.M.G.; Moraes, G.V. de; Mataveli, M.; Macedo, F.A.F. de; Carneiro, T.C.; Rossi, R.M. Performance and carcass characteristics of lambs fed on diets supplemented with glycerin from biodiesel production. **Rev. Bras. Zootec.**, v. 40, p. 2211-2219, 2011. <https://doi.org/10.1590/S1516-35982011001000022>.

Brand, T.S.S.; Van Der Westhuizen, E.J.J.; Van Der Merwe, D.A.A.; Hoffman, L.C.C. Effect of days in feedlot on growth performance and carcass characteristics of Merino, South African Mutton Merino and Dorper lambs. **S. Afr. J. Anim. Sci.**, v. 47, p. 26-33, 2017. <https://doi.org/10.4314/sajas.v47i1.5>.

Brody, S.; Lardy, H.A. Bioenergetics and growth. **J. Phys. Chem.**, v. 50, p. 168-169, 1946. <https://doi.org/10.1021/j150446a008>.

Cannas, A.; Tedeschi, L.O.; Fox, D.G.; Pell, A.N.; Van Soest, P.J. A mechanistic model for predicting the nutrient requirements and feed biological values for sheep. **J. Anim. Sci.**, v. 82, p. 149-169, 2004.

Corbett, J.L.; Freer, M. Past and present definitions of the energy and protein requirements of ruminants. **Asian-Australasian J. Anim. Sci.**, v. 16, p. 609-624, 2003. <https://doi.org/10.5713/ajas.2003.609>.

Costa, R.G.; Treviño, I.H.; De Medeiros, G.R.; Medeiros, A.N.; Pinto, T.F.; De Oliveira, R.L. Effects of replacing corn with cactus pear (*Opuntia ficus indica* Mill) on the performance of Santa Inês lambs. **Small Rumin. Res.**, v. 102, p. 13-17, 2012. <https://doi.org/10.1016/j.smallrumres.2011.09.012>.

CSIRO PUBLISHING. **Nutrient requirements of domesticated ruminants.** 2007.

Cunha, M.G.G.; Carvalho, F.F.R.; Vêras, A.S.C.; Batista, A.M.V. Desempenho e digestibilidade aparente em ovinos confinados alimentados com dietas contendo níveis crescentes de caroço de algodão integral. **Rev. Bras. Zootec. J. Anim. Sci.**, v. 37, p. 1103-1111, 2008.

Deng, K.D.; Diao, Q.Y.; Jiang, C.G.; Tu, Y.; Zhang, N.F.; Liu, J.; Ma, T.; Zhao, Y.G.; Xu, G.S. Energy requirements for maintenance and growth of Dorper crossbred ram lambs. **Livest. Sci.**, v. 150, p. 102-110, 2012. <https://doi.org/10.1016/j.livsci.2012.08.006>.

Ebrahimi, R.; Ahmadi, H.R.; Zamiri, M.J.; Rowghani, E. Effect of energy and protein levels on feedlot performance and carcass characteristics of mehraban ram lambs. **Pakistan J. Biol. Sci.**, v. 10, p. 1679-1684, 2007.

Estrada-Angulo, A.; Castro-Pérez, B.I.; Urías-Estrada, J.D.; Ríos-Rincón, F.G.; Arteaga-Wences, Y.J.; Barreras, A.; López-Soto, M.A.; Plascencia, A.; Zinn, R.A. Influence of protein level on growth performance, dietary energetics and carcass characteristics of Pelibuey × Katahdin lambs finished with isocaloric diets. **Small Rumin. Res.**, v. 160, p. 59-64, 2018. <https://doi.org/10.1016/j.smallrumres.2018.01.012>.

Fimbres, H.; Hernández-Vidal, G.; Picón-Rubio, J.F.; Kawas, J.R.; Lu, C.D. Productive performance and carcass characteristics of lambs fed finishing ration containing various forage levels. **Small Rumin. Res.**, v. 43, p. 283-288, 2002. [https://doi.org/10.1016/S0921-4488\(02\)00014-7](https://doi.org/10.1016/S0921-4488(02)00014-7).

Garcia, F.; Sainz, R.D.; Agabriel, J.; Barioni, L.G.; Oltjen, J.W. Comparative analysis of two dynamic mechanistic models of beef cattle growth. **Anim. Feed Sci. Technol.**, v. 143, p. 220-241, 2008. <https://doi.org/10.1016/j.anifeedsci.2007.05.012>.

Gregorini, P.; Villalba, J.J.; Provenza, F.D.; Beukes, P.C.; Forbes, J.M. Modelling preference and diet selection patterns by grazing ruminants: a development in a mechanistic model of a grazing dairy cow, MINDY. **Anim. Prod. Sci.**, v. 55, p. 360-375, 2015. <https://doi.org/10.1071/AN14472>.

Guimarães, V.P.; Tedeschi, L.O.; Rodrigues, M.T. Development of a mathematical model to study the impacts of production and management policies on the herd dynamics and profitability of dairy goats. **Agric. Syst.**, v. 101, p. 186-196, 2009. <https://doi.org/10.1016/j.agsy.2009.05.007>.

Haddad, S.G.; Younis, H.M. The effect of adding ruminally protected fat in fattening diets on nutrient intake, digestibility and growth performance of Awassi lambs. **Anim. Feed Sci. Technol.**, v. 113, p. 61-69, 2004. <https://doi.org/10.1016/j.anifeedsci.2003.10.015>.

Herrero, M.; Thornton, P.K.; Kruska, R.; Reid, R.S. Systems dynamics and the spatial distribution of methane emissions from African domestic ruminants to 2030. **Agric. Ecosyst. Environ.**, v. 126, p. 122-137, 2008. <https://doi.org/10.1016/j.agee.2008.01.017>.

Hojjati, F.; Hossein-Zadeh, N. Comparison of non-linear growth models to describe the growth curve of Mehraban sheep. **J. Appl. Anim. Res.**, v. 2119, p. 1-6, 2017. <https://doi.org/10.1080/09712119.2017.1348949>.

Hossein-Zadeh, N.G. Modeling the growth curve of Iranian Shall sheep using non-linear growth models. **Small Rumin. Res.**, v. 130, p. 60-66, 2015. <https://doi.org/10.1016/j.smallrumres.2015.07.014>.

Jaborek, J.R.; Zerby, H.N.; Moeller, S.J.; Fluharty, F.L. Effect of energy source and level, and sex on growth, performance, and carcass characteristics of lambs. **Small Rumin. Res.**, v. 151, p. 117-123, 2017. <https://doi.org/10.1016/j.smallrumres.2017.04.009>.

Kemp, S.; Mamo, Y.; Asrat, B.; Dessie, T. Domestic animal genetic resources information system. **Addis Ababa, Ethiop. Int. Livest. Res. Inst.**, 2007. <http://dagris.info/>.

Kioumarsji, H.; Khorshidi, K.J.; Zahedifar, M.; Seidavi, A.R.; Mirhosseini, S.Z.; Taherzadeh, M.R. The effect of dietary energy and protein level on performance, efficiency and carcass characteristics of taleshi lambs. **Asian J. Anim. Vet. Adv.**, v. 3, p. 307-313, 2008. <https://doi.org/10.3923/ajava.2008.307.313>.

Lin, L.I.K. A concordance correlation coefficient to evaluate reproducibility. **Biometrics**, v. 45, p. 255, 1989. <https://doi.org/10.2307/2532051>.

Lopez-Carlos, M.A.; Ramirez, R.G.; Aguilera-Soto, J.I.; Plascencia, A.; Rodriguez, H.; Arechiga, C.F.; Rincon, R.M.; Medina-Flores, C.A.; Gutierrez-Bañuelos, H. Effect of two beta adrenergic agonists and feeding duration on feedlot performance and carcass characteristics of finishing lambs. **Livest. Sci.**, v. 138, p. 251-258, 2011. <https://doi.org/10.1016/j.livsci.2010.12.020>.

Malhado, C.H.M.; Carneiro, P.L.S.; Affonso, P.R.A.M.; Souza, A.A.O.; Sarmiento, J.L.R. Growth curves in Dorper sheep crossed with the local Brazilian breeds, Morada Nova, Rabo Largo, and Santa Ines. **Small Rumin. Res.**, v. 84, p. 16-21, 2009. <https://doi.org/10.1016/j.smallrumres.2009.04.006>.

Martin, O.; Sauvant, D. Dynamic model of the lactating dairy cow metabolism. **Animal**, v. 1, p. 1143-1166, 2007. <https://doi.org/10.1017/S1751731107000377>.

Mertens, D.R. Principles of modeling and simulation in teaching and research. **J. Dairy Sci.**, v. 60, p. 1176-1186, 1977. [https://doi.org/10.3168/jds.S0022-0302\(77\)84005-8](https://doi.org/10.3168/jds.S0022-0302(77)84005-8).

NRC. **Nutrient requirements of small ruminants: sheep, goats, cervids, and new world camelids.** National Academies Press, Washington, D.C., 2007. <https://doi.org/10.17226/11654>.

Papi, N.; Mostafa-Tehrani, A.; Amanlou, H.; Memarian, M. Effects of dietary forage-to-concentrate ratios on performance and carcass characteristics of growing fat-tailed lambs. **Anim. Feed Sci. Technol.**, v. 163, p. 93-98, 2011. <https://doi.org/10.1016/j.anifeedsci.2010.10.010>.

Pereira, M.S.; Ribeiro, E.L.D.A.; Mizubuti, I.Y.; Da Rocha, M.A.; Kuraoka, J.T.; Nakaghi, E.Y.O. Consumo de nutrientes e desempenho de cordeiros em confinamento alimentados com dietas com polpa citrica moída prensada em substituição silagem de milho. **Rev. Bras. Zootec.**, v. 37, p. 134-139, 2008. <https://doi.org/10.1590/S1516-35982008000100020>.

Regadas Filho, J.G.L.; Tedeschi, L.O.; Rodrigues, M.T.; Brito, L.F.; Oliveira, T.S. Comparison of growth curves of two genotypes of dairy goats using nonlinear mixed models. **J. Agric. Sci.**, v. 152, p. 829-842, 2014. <https://doi.org/10.1017/S0021859613000798>.

Rocha, N.S.; Vieira, R.A.M.; Abreu, M.L.C.; Araujo, R.P.; Glória, L.S.; Tamy, W.P.; Camisa Nova, C.H.P.; Fernandes, A.M. Traditional and biphasic nonlinear models to describe the growth of goat kids of specialized dairy breeds. **Small Rumin. Res.**, v. 123, p. 35-46, 2015. <https://doi.org/10.1016/j.smallrumres.2014.11.002>.

Russell, J.B.; Muck, R.E.; Weimer, P.J. Quantitative analysis of cellulose degradation and growth of cellulolytic bacteria in the rumen. **FEMS Microbiol. Ecol.**, v. 67, p. 183-197, 2009. <https://doi.org/10.1111/j.1574-6941.2008.00633.x>.

Sadri, K.; Rouzbehan, Y.; Fazaeli, H.; Rezaei, J. Influence of dietary feeding different levels of mixed potato-wheat straw silage on the diet digestibility and the performance of growing lambs. **Small Rumin. Res.**, v. 159, p. 84-89, 2017. <https://doi.org/10.1016/j.smallrumres.2017.11.002>.

SCA. **Feeding Standards for Australian livestock**. Standing Comm. Agric. Ruminants Subcomm. CSIRO Publ., 1990. 266 p.

Sheridan, R.; Ferreira, A.V.; Hoffman, L.C. Production efficiency of South African Mutton Merino lambs and Boer goat kids receiving either a low or a high energy feedlot diet. **Small Rumin. Res.**, v. 50, p. 75-82, 2003. [https://doi.org/10.1016/S0921-4488\(03\)00109-3](https://doi.org/10.1016/S0921-4488(03)00109-3).

Souza, L.A.; Carneiro, P.L.S.; Malhado, C.H.M.; Silva, F.F.; Silveira, F.G. da. Traditional and alternative nonlinear models for estimating the growth of Morada Nova sheep. **Rev. Bras. Zootec.**, v. 42, p. 651-655, 2013. <https://doi.org/10.1590/S1516-35982013000900007>.

Sterman, J.D. **Business dynamics: systems thinking and modeling for a complex world, management**. 2000. <https://doi.org/10.1057/palgrave.jors.2601336>.

Tadayon, Z.; Rouzbehan, Y.; Rezaei, J. Effects of feeding different levels of dried orange pulp and recycled poultry bedding on the performance of fattening lambs1. **J. Anim. Sci.**, v. 95, p. 1751-1765, 2017. <https://doi.org/10.2527/jas2016.0889>.

Tedeschi, L.O.; Cannas, A.; Fox, D.G. A nutrition mathematical model to account for dietary supply and requirements of energy and nutrients for domesticated small ruminants: The development and evaluation of the Small Ruminant Nutrition System. **Small Rumin. Res.**, v. 89, p. 174-184, 2010. <https://doi.org/10.1016/j.smallrumres.2009.12.041>.

Tedeschi, L.O.; Fonseca, M.A.; Muir, J.P.; Poppi, D.P.; Carstens, E.; Angerer, J.P.; Fox, D.G. Invited review: a glimpse of the future in animal nutrition science . 2 . Current and future solutions. **Revista Brasileira de Zootecnia**, 2017

Tedeschi, L.O.; Fox, D.G. **The ruminant nutrition system**: an applied model for predicting nutrient requirements and feed utilization in ruminants. Acton, MA: XanEdu, 2016.

Tedeschi, L.O.; Fox, D.G.; Guiroy, P.J. A decision support system to improve individual cattle management. 1. A mechanistic, dynamic model for animal growth. **Agric. Syst.**, v. 79, p. 171-204, 2004. [https://doi.org/10.1016/S0308-521X\(03\)00070-2](https://doi.org/10.1016/S0308-521X(03)00070-2).

Theil, H. The measurement of inequality by components of income. **Econ. Lett.**, v. 2, p. 197-199, 1979. [https://doi.org/10.1016/0165-1765\(79\)90173-3](https://doi.org/10.1016/0165-1765(79)90173-3).

Ventana Systems Inc. Vensim® PLE Software. 2017.

Warriss, P.D. **Meat science** : an introductory text. CABI Publ., 2000. p. 234-239.

Xu, G.S.; Ma, T.; Ji, S.K.; Deng, K.D.; Tu, Y.; Jiang, C.G.; Diao, Q.Y. Energy requirements for maintenance and growth of early-weaned Dorper crossbred male lambs. **Livest. Sci.**, v. 177, p. 71-78, 2015. <https://doi.org/10.1016/j.livsci.2015.04.006>.

ARTICLE 2 – MODELLING MILK YIELD AND METHANE EMISSIONS IN A TROPICAL RUMINANT FORAGE-BASED SYSTEM USING ANIMAL AND DIET CHARACTERISTICS

R. M. Amaral

Departamento de Zootecnia, Universidade Federal de Viçosa, MG, Brazil

ABSTRACT

A dynamic model was developed based on a set of empirical and conceptual equations proposed on scientific literature to describe and predict the dry matter intake based on physiological energy demand and on physical limitation theory. The variables metabolizable energy intake, milk production allowed, volatile solids, biodegradable volatile solids and methane production from enteric, and manure fermentation were estimated by simulation based on forage composition and dry matter intake. The amounts of each variable required per unit of fat corrected milk was calculated by means of this information, giving the efficiencies of feed and energy use and the emission intensities. The model inputs are body mass, potential milk yield, milk fat concentration, diet neutral detergent fiber, crude protein, and ash. A simulation was conducted with chemical composition data of five maturity stages *Pennisetum purpureum* Schum. grass (61, 82, 103, 124 and 145 days after planting) as exclusive diet to a 450 kg double purpose cow with 20 kg d⁻¹ of potential milk production and 3.5 % of milk fat concentration. Simulated values of dry matter intake based on physiological energy demand were not reached, being limited by rumen fill capacity. Dry matter intake based on rumen fill capacity decreases as NDF concentration increases with forage maturity, reducing metabolizable energy intake, fermentative substrate intake, and milk yield. Milk yield allowed ranges from 9.407 to 4.568 kg d⁻¹ in younger and older forage, respectively. Methane production from manure fermentation increases with grass maturity and methane production from enteric fermentation reduces with forage maturity. Simulated values range from 3.0 and 3.4 g day⁻¹ (10.60 %) to 103.8 and 74.5 g-day⁻¹ (28.22%) of methane from manure and enteric fermentation, respectively. A reduction of feed efficiency of 9.25% was estimated from 61 to 82 days of growth grass, accounting the reduction of feed intake and the metabolizable energy concentration. Simulated methane production per unit of product present a difference of 32.33% ranging between 11.0 and 16.3 grams per kilogram of product to 61 and 145

days of regrowth, respectively. The model can be used as learning tool to illustrate practical principles of feed intake regulation, animal performance, feed and energy efficiencies, and methane emissions from enteric and manure fermentation as function of fiber composition.

Keywords: energy efficiency, methane production, neutral detergent fiber, performance simulation

INTRODUCTION

Forage fiber plays an important and complex role on different aspects of ruminant production systems. In tropical countries, the fiber from grasses is the major animal diet compound, being the energetic source for maintenance and production on forage-based systems. The forage fiber composition, structure, and processing had implications in many aspects of ruminant feeding and nutrition such as feed intake, ruminal degradation and passage rates, profile of ruminal gases production, manure production, and consequently the conversion of forage to human useful products. During the different stages of growth, the fiber structure and composition of grasses varies. As maturity increases, the fiber fraction (neutral detergent fiber) and lignin increase, which reduces the dry matter digestibility, implying a reduction of dry matter intake (Jung and Allen, 1995), fermentable material, and consequently the amount of energy allowed to maintenance and production. These changes on fiber composition are highly related to feed efficiency (Wilkinson, 2011), animal performance (Warner et al., 2016), and enteric methane production (Niu et al., 2018).

The premises of sustainable intensification in agriculture state that it is necessary to increase food production and, at same time, it is required to reduce the environmental damage (Garnett et al., 2013). Improving the efficiency of ruminant production systems has been proven as the main strategy to increase animal production and at same time reduce the environmental impact (Bocquier and González-García, 2010; Gerber et al., 2013; Silva et al., 2016). It is possible in tropical ruminant production systems by increasing system efficiency through the improvement of quantity, quality, and grazing efficiency of produced forage, which are related to feed efficiency, animal production, and reduction of greenhouse gases emissions per unit of animal product (Hristov et al., 2013; Stanley et al., 2018). Ruminant production has a strong relationship between productivity and emission intensity. The emission intensity decreases as yield increases, which means that improvements on feed quantity and quality (i.e., fiber digestibility) by

grazing management as well as feed conservation practices, can be useful to increase animal performance, reduce greenhouse gases emission intensity, and increases soil carbon sequestration (Stanley et al., 2018). Based on these premises, an adequate use of natural resources through the increase of systems efficiency with the use of improved and adapted grasses to different purposes and areas and a carefully grazing or cut management that allows the animals to consume the forages when they have an adequate balance between biomass production and quality must be emphasized.

The aim of this work is to model, based on scientific literature equations, the effects of different grass compositions, specifically fiber composition related to management practices like grazing system or regrowth time of tropical grasses and their implications on different process related to intensification and sustainability of ruminant production systems.

METHODS

Model framework

The model was structured on a set of equations based on the causality relationships between the available variables of each model with the arrangement of the main components of dynamic simulation: stocks, flows, feedback, delays, and decision rules (Sterman, 2000). The model was built using the software Vensim PLE (Ventana Systems Inc., 2017). The simulation unit was “day”. The Euler integration method was used with a time step of 0.25 per day, which means that each simulated day the software ran four times for integration. The model construction is based on scientific literature organized to generate dynamic relationships, allow feedback structures, and dynamic simulations based on user inputs. Acronyms, functions, unities, and equations used for the model development are presented on Table 1 and variables relationships are presented on Figure 1.

Dry matter intake and production model

A model to describe dry matter intake was developed using Mertens (1987) conceptual equations. The equations take into account the two main regulator constrains of ruminants feed intake: (1) the regulation of intake by physiological energy demand to meet its energy requirement and (2) the physical limitation theory of intake regulation by the rumen fill capacity (Mertens, 1987). The nutrient requirements of dairy cows was generated using NRC (2001) equations. The model estimates DMI based on

physiological energy demand and on rumen fill capacity, returning to the lowest value (DMI S) using a decision rule, nutrient requirements for maintenance and milk production (MEm, MEI), metabolizable energy intake (MEI), and production allowed by MEI (PA) (Table 1).

Table 1. List of acronyms, variables, and their determination used in the models

Acronym	Variable	Determination
Ash diet	Ash content of diet (g kg ⁻¹)	User
BM	Body Mass (kg)	User
CH ₄ _e	Methane enteric production (kcal 100 kcal of feed ⁻¹)	$1.3 + 0.112 \times DMD + L \times (2.37 - 0.05 \times DMD)$
CH ₄ _e energy	Methane enteric production as energy (kcal day ⁻¹)	$CH_4 \times GEI$
CH ₄ _e grams	Methane enteric production as mass (g day ⁻¹)	$CH_4 \text{ litre} \times 0.7157$
CH ₄ _e kg	Methane enteric production as mass (kg year ⁻¹)	$CH_4 \text{ grams} \div 1000$
CH ₄ _e liter	Methane enteric production as volume (L day ⁻¹)	$CH_4 \text{ energy} \div 9.44$
CH ₄ _e yield	Methane production divide by DMI (g kg ⁻¹)	$CH_4 \text{ grams} \div DMI$
CH ₄ _m	Methane production from manure (g day ⁻¹)	$VS \times 0.13 \times 0.0067$
CH ₄ _e intensity	Methane production divide by PA (g kg ⁻¹)	$CH_4 \text{ grams} \div PA$
CO ₂ -e	CO ₂ equivalent	$CH_4 \text{ kg} \times 34$
CP diet	Crude protein content of diet (g kg ⁻¹)	User
DMD	Apparent dry matter digestibility (%)	User or $61.15 + 1.04 \times CP \text{ diet} \times 100 - 0.26 \times NDF \text{ diet} \times 100$
DMI PED	DMI of Physiological energy demand (kg day ⁻¹)	$ME \div ME \text{ diet}$
DMI RFC	DMI based on Rumen fill capacity (kg DMI day ⁻¹)	$RFC \div NDF \text{ diet}$
DMI S	DMI Simulated, returns minimum value (kg day ⁻¹)	$MIN(DMI \text{ RFC}, DMI \text{ PED})$
dVS	Biodegradable volatile solids (kg day ⁻¹)	$-1.017 + 0.0221 \times OMI + 0.029 \times NDF - 0.023 \times CP$
FC	Milk fat content (g kg ⁻¹)	User
FIM	Feed intake to maintenance	$MEm \div ME \text{ diet}$
GEI	Gross energy intake (kcal day ⁻¹)	$MEI \text{ intake} \div 0.82 \times 10$
L	Level of feeding as multiple of maintenance level	$DMI \text{ S} \div FIM$
ME diet	Metabolizable energy of diet (Mcal kg ⁻¹)	$((83.79 - 0.4171 \times NDF \text{ diet} \times 100) \times 0.04409) \times 1.01 - 0.45$
MEg	Metabolizable energy to gain (Mcal kg ⁻¹)	$19.8 \times g \text{ of } ADG \times 0.239 \div 1000$
MEI	Metabolizable energy intake (Mcal day ⁻¹)	$DMI \text{ S} \times ME \text{ diet}$
MEI	Metabolizable energy lactation (Mcal kg ⁻¹)	$NEI \div 0.703 + 0.19$
MEI POT	MEI to reach POT (Mcal)	$MEI \times POT$
MEm	Metabolizable energy maintenance (Mcal kg ⁻¹)	$0.077 \times BM^{0.75}$
MEt	Total metabolizable energy demand (Mcal kg ⁻¹)	$MEm + MEI$
NDF diet	Neutral detergent fiber content of diet (g kg ⁻¹)	User
NEI	Net energy for lactation (Mcal kg ⁻¹)	$(0.36 + 0.0969 \times FC)$
PA	Milk production allowed by MEI (kg day ⁻¹)	$(MEI \text{ intake} - MEm) \div MEI$
POT	Potential of production (kg day ⁻¹)	User
RFC	Rumen fill capacity (kg day ⁻¹)	$BM \times 0.011$
RFC	Rumen fill capacity (kg of NDF day ⁻¹)	$BM \times 0.012$
VS	Volatile solids (kg day ⁻¹)	$1.201 + 0.402 \times OMI + 0.036 \times NDF - 0.024 \times CP$

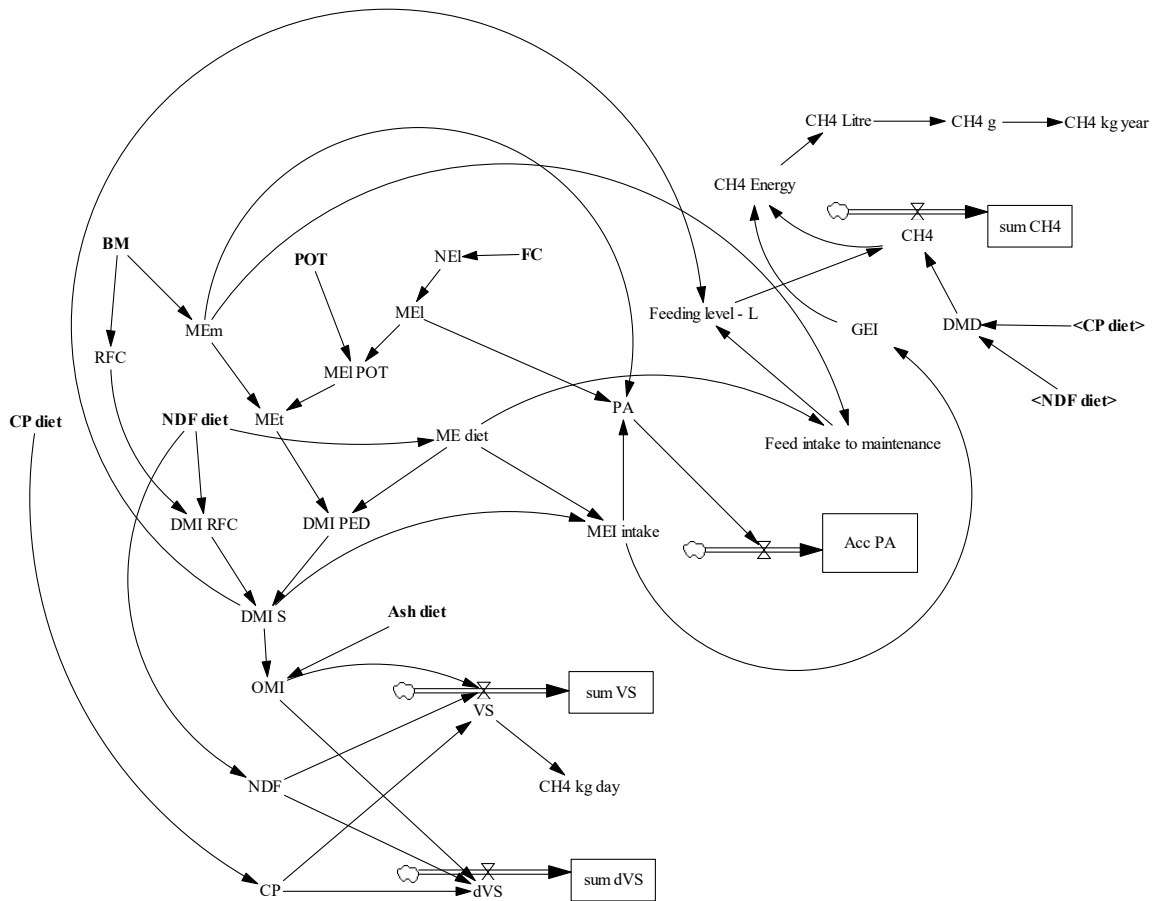


Figure 1. Variables relationship, bolded words and acronyms are user inputs and unbolded words and acronyms are constants, equations, and results.

Methane production from manure model

This model uses the empirical equations proposed by Appuhamy et al. (2018) to account the volatile solids (VS) and biodegradable volatile solids (dVS) produced in kilograms daily (Table 1). VS and dVS are fractions of organic matter present on livestock manure that are potentially fermentable and can originate methane. The equations are based on organic matter intake (OMI), dietary neutral detergent fiber (NDF), and dietary crude protein (CP) of feed. Methane production was estimated by the coefficient $B_o(T) = 0.13 \text{ m}^3 \text{ CH}_4 \text{ kg}^{-1}$ of VS excreted in Latin America (Zeeman and Gerbens, 1996) and then converted to grams (1L of $\text{CH}_4 = 0.670 \text{ g}$). The purpose is to account daily an accumulated amount of VS, dVS and CH_4 from manure produced as function of forage maturity and their fiber quality. Previous *dry matter intake model* is used to estimate DMI S and consequently the organic matter fraction.

Methane production from enteric fermentation

This model uses the equation proposed by Blaxter and Clapperton (1965), which use the dry matter digestibility (DMD) and the level of intake above the maintenance (L) as predictor variables. The study estimates methane production as kcal per each 100 kcal of feed consumed, then it is converted to litre (9.44 kcal of CH₄ = 1L) to grams (1L of CH₄ = 0.670 g) and then to CO₂ equivalent (CO₂-eq) using their global warming potential (CH₄ = 34). Previous *dry matter intake model* is used to estimate DMI S, nutrient requirements, feeding level above maintenance, and dry matter digestibility based on forage composition.

Feed and energy efficiencies and emission intensity

The information generated on previous models was interpreted in relation to the estimated animal performance (PA) in kilograms of fat corrected milk per day, establishing the follow variables: DMI S, MEI, VS, dVS, CH₄ m, CO₂-eq m, CH₄ e and CO₂-eq e per kg of PA. These relations allow to understand the effects of forage quality in terms of feed and energy efficiency and emission intensity of methane emission; they also allow to compare simulated to empirical studies data.

Model inputs and simulations

Animal description

Model inputs to generate cow nutrient requirement are body mass (BM) (kg), potential milk production (POT) (kg d⁻¹), and milk fat content (FC) (%). Based on this information, the model estimates the nutritional requirements of energy to maintenance based on NRC (2001) equations. The simulation presented was performed to a dual propose cow with 450 kg of BM, 20 kg of POT and milk FC of 3.5 %, which describes common cattle in Latin American conditions, being within the parameters described by Reynoso-Campos et al. (2004).

Feed description

The simulation was carried considering exclusive forage-based diet. Model inputs to feed description are neutral detergent fiber (NDF) (g kg⁻¹ of DM), crude protein (CP) (g kg⁻¹ of DM), and ash (g kg⁻¹ of DM). Based on this information, energetic values and dry matter digestibility (DMD) (% of DM) were estimated from Cappelle et al. (2001) and Barton et al. (1976) equations for tropical grasses,

respectively. The feed chemical composition used as input to simulations comes from Vieira et al. (1997) data. They cut the C4 *Pennisetum purpureum* Schum. grass at five maturity stages, 61, 82, 103, 124 and 145 days after planting, the NDF composition was 583, 619, 689, 697 and 734 g kg⁻¹, CP values were 160, 133, 88, 76 and 68 g kg⁻¹, ash values were 132, 75, 57, 51, and 37 g kg⁻¹ to 61, 82, 103, 124 and 145 days after planting.

RESULTS

Dry matter intake and production model

DMI based on physiological energy demand (DMI PED) increases as nutritional quality reduces with time (Table 2). The simulated values of DMI PED were not reached, being limited by rumen fill capacity to all forage maturity stages. DMI based on rumen fill capacity (DMI RFC) decreases as NDF concentration increases with forage maturity. Based on the model decision rule, the value used for the calculations was the lowest (DMI S). The reduction of DMI S because of the increase fiber concentration and reduction of metabolizable energy led to reduce the metabolizable energy intake (MEI) and daily milk yield allowed (PA) with grass maturity.

Table 2. Dry matter intake based on physiologic demand and ruminal fill capacity, metabolizable energy intake, and production allowed as function of cutting age

Cutting age	DMI PED (kg·d ⁻¹)	DMI RFC (kg·d ⁻¹)	DMI S (kg·d ⁻¹)	ME (Mcal·kg ⁻¹)	MEI (Mcal·d ⁻¹)	PA (kg·d ⁻¹)
61 days	14.951	8.491	8.491	2.198	18.666	9.407
82 days	15.420	7.997	7.997	2.131	17.045	8.039
103 days	16.421	7.184	7.184	2.001	14.379	5.788
124 days	16.544	7.102	7.102	1.987	14.109	5.560
145 days	16.993	6.744	6.744	1.918	12.934	4.568

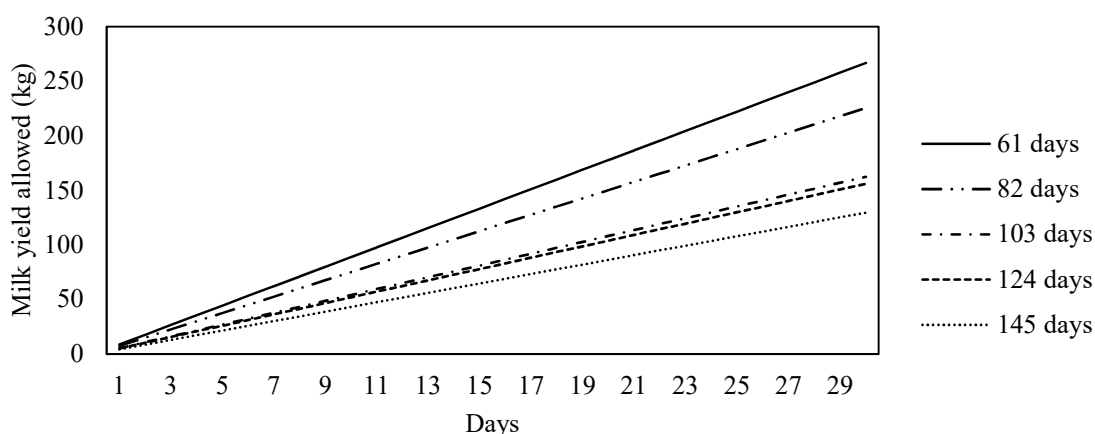


Figure 2. Estimated milk yield allowed (kg) simulated for 30 days as function of grass cutting age.

Methane production from manure model

As forage indigestible fractions increase with time, the amounts of volatile solids and biodegradable volatile solids increase, reaching higher values on 145-day grass (Table 3). Potentially methanogenic fractions of manure were 10.62 % and 57.41 % higher on 145-day grass in comparison to 61-day forage to VS and dVS, respectively. CH₄ estimates from manure was 10.60 % lower for 61-day than 145-day forage, despite the higher DMI estimated to sixty-one-day simulation.

Table 3. Volatile solids, biodegradable volatile solids, and CH₄ m simulated to 1 and 365 days as function of cutting age

Cutting age	VS ^a (kg·d ⁻¹)	dVS ^b (kg·d ⁻¹)	CH ₄ m (g·d ⁻¹)	CH ₄ m (kg·365 d ⁻¹)
61 days	3.476	0.468	3.0	1.105
82 days	3.682	0.636	3.2	1.170
103 days	3.792	0.928	3.3	1.205
124 days	3.835	0.978	3.3	1.219
145 days	3.889	1.099	3.4	1.236

^aVS is Volatile solids. ^bdVS is biodegradable volatile solids.

Methane production from enteric fermentation

Estimates of dry matter digestibility and level of intake above maintenance, generated on previous *dry matter intake and production model*, change as diet NDF concentration increases with the time. In response to these variables and the diminution of dry matter intake, the amount of fermentative material intake is reduced and as a consequence less CH₄ from enteric fermentation is produced in oldest forages. The

values of sixty-one-day forage were 3.56% lower in comparison to 145-day forage, whose values were kcal of CH_{4 e} per each 100 kcal of feed. Enteric methane (CH_{4 e}) per kilogram of DMI S is reduced in 9.65% in oldest forage in comparison to sixty-one-day forage.

Table 4. Estimated dry matter digestibility (DMD), level of intake above maintenance (L), enteric methane in kcal per each 100 kcal of feed (CH_{4 e}), enteric methane in grams per cow per day (CH_{4 e g}) and per kg of dry matter intake (CH_{4 e kg DMI}) as function of cutting age

Cutting age	DMD (%)	L (factor)	CH _{4 e} (kcal, 100 kcal ⁻¹)	CH _{4 e g} (g, d ⁻¹)	CH _{4 e kg DMI} (g, kg DMI S ⁻¹)
61 days	62.63	2.481	6.425	103.8	12.2
82 days	58.89	2.266	6.594	97.3	12.2
103 days	52.39	1.911	6.690	83.3	11.6
124 days	50.93	1.875	6.673	81.5	11.5
145 days	49.14	1.719	6.654	74.5	11.0

Fiber quality, feed and energy efficiencies, and emission intensity

Dry matter intake, metabolizable energy intake, volatile solids, biodegradable volatile solids, and CH₄ and CO₂ – eq values from enteric and manure fermentation are presented as ratio of production allowed (PA) described on *dry matter intake model* as function of different grass maturity stages (Table 5).

Table 5. Feed and energy efficiencies and emission intensity per unit of production as function of cutting age

Item	Cutting age				
	61 days	82 days	103 days	124 days	145 days
DMI PA (kg, kg PA ⁻¹)	0.903	0.995	1.241	1.277	1.476
MEI PA (Mcal, kg PA ⁻¹)	1.984	2.120	2.484	2.538	2.831
VS PA(kg, kg PA ⁻¹)	0.370	0.458	0.655	0.690	0.851
dVS PA(kg, kg PA ⁻¹)	0.050	0.079	0.160	0.176	0.241
CH _{4 m} PA (g, kg PA ⁻¹)	0.3	0.4	0.5	0.6	0.7
CO ₂ –eq _m PA (g, kg PA ⁻¹)	10.9	13.6	19.6	20.4	25.2
CH _{4 e} PA (g, kg PA ⁻¹)	11.0	12.1	14.4	14.6	16.3
CO ₂ – eq _e PA (g, kg PA ⁻¹)	375.2	411.4	489.2	498.3	554.4

Dry matter intake per unit of product was 57.28 % higher on 145-day forage in comparison to sixty-one-day forage. Metabolizable energy intake required per unit of product was 29.92 % higher on 145-day forage in comparison to sixty-one -day forage. Volatile solids and biodegradable volatile solids were 56.52 and 79.25 %, respectively higher on 145-day forage than on sixty-one-day forage. CH₄ and CO₂-eq values from manure fermentation increase as forage quality reduces. CH₄ from enteric fermentation by unit of product was 32.33 % higher on 145-day forage in comparison to sixty-one - day forage.

DISCUSSION

Dry matter intake and production model

The dry matter intake simulated was limited by reticulorumen physical constrains; the maximum value was 8.491 kg d⁻¹ on sixty-one days of forage growth, which is reduced in 20.57% on the older 145 days of forage growth. To reach the proposed potential milk production of 20 kg d⁻¹ with 3.5 % of fat content, the DMI PED of sixty-one days forage must be 43.21 % higher than the DMI RFC estimates, which corresponds to 6.46 kg of DMI in one day, being not possible to reach in an exclusive tropical grass-fed diet. The limit of DMI based on reticulorumen fill is a normal effect verified on ruminant forage-based diets, which is more pronounced on tropical (C4) grasses. According to Archimède et al. (2018), studying the effects of C3 and C4 grasses on feed intake of sheep verified lower dry matter intake of C4 grasses of both qualities in comparison to C3 grasses, giving the higher NDF and ADF concentrations that are common in C4 grasses. The changes on composition as function of grass maturity is also reported by Warner et al. (2016), who verified in three maturity stages of grass regrowth (28, 41, and 62 days) a reduction of 11 % DMI with advancing grass maturity. Rumen fill capacity is a result of a dynamic process, which is related to passage and digestion rates of feed that occur in ruminoreticulum. As NDF concentration and the grade of lignification increase, more time is required to degrade this material until they leave ruminoreticulum space. Thus, it does not allow the ingestion of more food, which is one of the main limitations of animal production in tropics.

Tropical grasses such as *Pennisetum purpureum* Schum. and *Panicum maximum* (Syn. *Megathyrsus maximum*) have a tall-tufted growth habit, high potential growth rate and biomass yield (Batistoti et al., 2012; Da Silva et al., 2015). Moreover, they have

positive aspects such as supporting high stock rates and allow fast rotation cycles (until 15 days of regrowth time), which potentiate the area carrying capacity. However, a negative aspect related to these grasses is their difficult handling, where the rapid growth and the growth habit imply fast stem lignification and quality reduction, which leads the producers to lose the control of the height or age for the cut or grazing, often providing low quality feed to their animals. For instance, Mutimura et al. (2018) studied Napier grass (*Pennisetum purpureum*) as exclusive diet in Rwanda and found a DMI of 8.3 kg d⁻¹ and a mean daily milk production of 5.4 liters per day. Muinga et al. (1995), in Kenya, also found that crossbred cow fed exclusively with *Pennisetum purpureum* (4 to 6 weeks regrowth) has an intake of 75 g, kg M^{0.75} ⁻¹, which corresponds to a 450 kg animal 7.327 kg d⁻¹ of DMI, and the value ranges between 8.491 and 6.744 kg d⁻¹ of simulated data.

As reflection of changes on forage quality, the systems efficiency is impaired. The reduction of DMI as function of forage maturity is accomplished by a reduction of forage quality, taking a multiplicative effect on metabolizable energy intake. These effects allow the simulation energy to produce 14.54 % less milk in 21 days of growth (61 to 82-days of regrowth). Voltolini et al. (2010) studied the effect of two grazing intervals, 19,4 days based on 95% of light interception and 26 days as fixed, on *Pennisetum purpureum* in rotational grazing system of dairy cows receiving concentrate feed. He found important effects of these variables on just 6.6 days of difference. The authors found 17.65 and 14.88 kg d⁻¹ of fat corrected milk (3.5 %) mean per cow, and a production of 114 and 75 kg d⁻¹ per hectare on 19.4 days and 26 days of grazing intervals, respectively (Voltolini et al., 2010).

Methane production from manure model

Volatile solids, biodegradable volatile solids, and methane production from manure increases as forage quality reduces, despite the increase of organic matter intake. The dry matter digestibility, estimated through an equation, presents a reduction of 13.49 % from young to older grass maturities. These effects are related to the increase of undegradable fraction of forage with the forage maturity, implying a reduction of system efficiency by the loss of energy and nutrients on manure. Hence, the best the feed utilization is, the least nutrients are excreted and the least energy is loosed; these aspects are directly related to feed efficiency.

According to IPCC 2006 Guidelines for National Greenhouse Gas Inventories (Dong et al., 2006), the emission factor utilized in Tier 1 for dairy cattle manure management on Latin America condition, which almost all manure is managed as a solid on pastures and ranges, is 1 and 2 kg CH₄ head⁻¹ year⁻¹ in temperate and tropical zones, respectively. The current study's estimation had an average mean of 1.187 kg CH₄ head⁻¹ year⁻¹. It must be accounted that when the manure is deposited on pastures and rangelands or handled to make compost in a solid way, the tendency is to decompose under more aerobic conditions, producing less CH₄ than in a liquid form as lagoons, ponds, tanks, or bio digester (Dong et al., 2006).

Methane production from enteric fermentation

Simulated daily enteric CH₄ production ranges from 103.8 to 74.5 g d⁻¹ per cow for sixty-one to 145-day grass, respectively, accounting a difference of 28.24% (Table 4). As cell wall increases (NDF), the neutral detergent soluble fraction and the dry matter intake decrease, generating a multiplicative reduction of fermentative substrate and consequently reducing the enteric CH₄ production. The same behavior was discussed by Primavesi et al. (2004), who evaluated enteric methane production in tropical dairy cattle on Brazilian conditions and concluded that low quality forages had reduced feed intake, and as a consequence the CH₄ emission rate was reduced. Also, Warner et al. (2016), evaluated methane production on dairy cows as function of grass maturity and found smaller daily enteric CH₄ production with advancing grass maturity (28, 41, and 62 days of regrowth grass silage), accounting less 6% in older grasses. The authors justified their results by the reduction of feed digestibility.

The enteric CH₄ production estimates in g per kg of DMI was reduced with forage maturity. Archimède et al. (2018), found less enteric CH₄ production in low quality (91 days of regrowth) C4 forage (13.8 g kg DMI⁻¹) in comparison to high quality (36 days of regrowth) C4 forage (20.1 g kg DMI⁻¹). These values are close to those simulated, which range between 12.2 and 11.0 g kg DMI⁻¹ on sixty-one and 145 days of growth, respectively. Therefore, an inverse effect was verified by Warner et al. (2016), who found higher enteric CH₄ production per kg of DMI on 62 days in comparison to 28 days of regrowth of C3 grass silage, giving 24.6 and 21.7 g kg DMI⁻¹, respectively.

As discussed by original equation authors (Blaxter and Clapperton, 1965) and reinforced by Johnson and Johnson (1995) and Clark (2013), the main variables that affect the methane production are the diet digestibility and feeding level. At a

maintenance level of feeding (L), methane production increases with the dry matter digestibility (DMD) as function of increased energy allowed to fermentation. Hence, as the feeding level increases with high digestibility diets, the amount of methane produced per unit of feed consumed is reduced.

Between many possible strategies to mitigate enteric methane emission from ruminant animals like archaea inhibitors and ionophores, plant active compounds, inclusion of concentrate, the increase of forage digestibility and digestible forage intake were the mainly recommended methane mitigation strategies (Clark, 2013; Hristov et al., 2013; Knapp et al., 2014; Martin et al., 2009). It can be explained because, despite the knowledge about the inclusion of concentrates on ruminants diets and their effect on reduction of enteric methane produced and the emission intensities (Clark, 2013; Knapp et al., 2014) it is not necessarily a sustainable solution in economic aspects to small producers in developing countries (Ritzema et al., 2017). Even on developed countries, the supplementation of animals in forage-based systems especially on cow-calf or growing phase with the purpose of mitigation GHGs impacts can be considered a difficult obstacle to overcome (Clark, 2013).

Fiber quality, feed and energy efficiencies, and emission intensity

Improvements of feeding efficiency, which means to get more animal output with the same input or get same animal output with the less feed (Wilkinson, 2011), had important economic, social and environmental effects. On simulated data, the dry matter required per kilogram of product ranges from 0.903 to 0.995 kg d⁻¹, on sixty-one to eighty-two days of growth, respectively, which corresponds to 9.25 % more feed per unit of milk and implies an improper and less efficient use of resources. Figure 2 presents simulated values of time, DMI, and MEI required to produce 100 kg of fat corrected milk. It shows the clear inefficiency, being required more time, feed, and energy to same production as time of regrowth increases. Rao et al. (2015) described that improvements on systems efficiency can be achieved with improved forages and proper forage management, where high quality feed can contribute to produce more meat and milk.

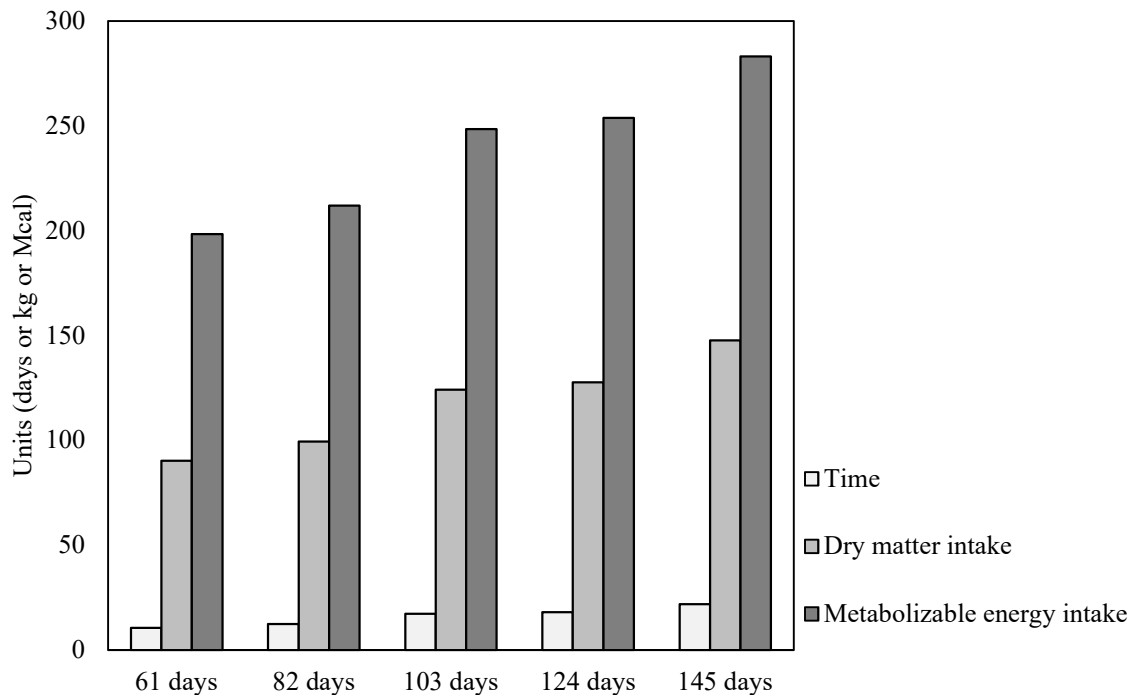


Figure 2. Time (days), dry matter intake (kg), and metabolizable energy intake (Mcal) required to produce 100 kg of fat corrected milk as function of forage maturity.

The variables simulated to manure, VS, and dVS divided by production allowed present increasing values as forage maturity increases. Methane production from manure was 2.3 times higher in oldest forage in comparison to the younger in the simulation.

When the enteric CH₄ values are divided by production allowed (PA), the emission intensity assumes values that range between 11.0 and 16.3 g kg⁻¹ of PA (Figure 3), which implies a substantial reduction of emission intensity. Working with an intercontinental data bank to estimate enteric CH₄ emissions of dairy cattle, Niu et al. (2018) summarized as minimum and maximum values of enteric CH₄ 79 and 729 g d⁻¹ per cow and 3 and 36 g kg⁻¹ per corrected milk production; these ranges include our simulated results. The estimated data behavior is supported by Clark (2013), who explained that changes on forage quality may not decrease absolute CH₄ emissions per unit of feed ingested, but the increase forage digestibility had influence on emissions intensity; hence increasing the quality should result in greater productivity at equivalent levels of intake and CH₄ emissions.

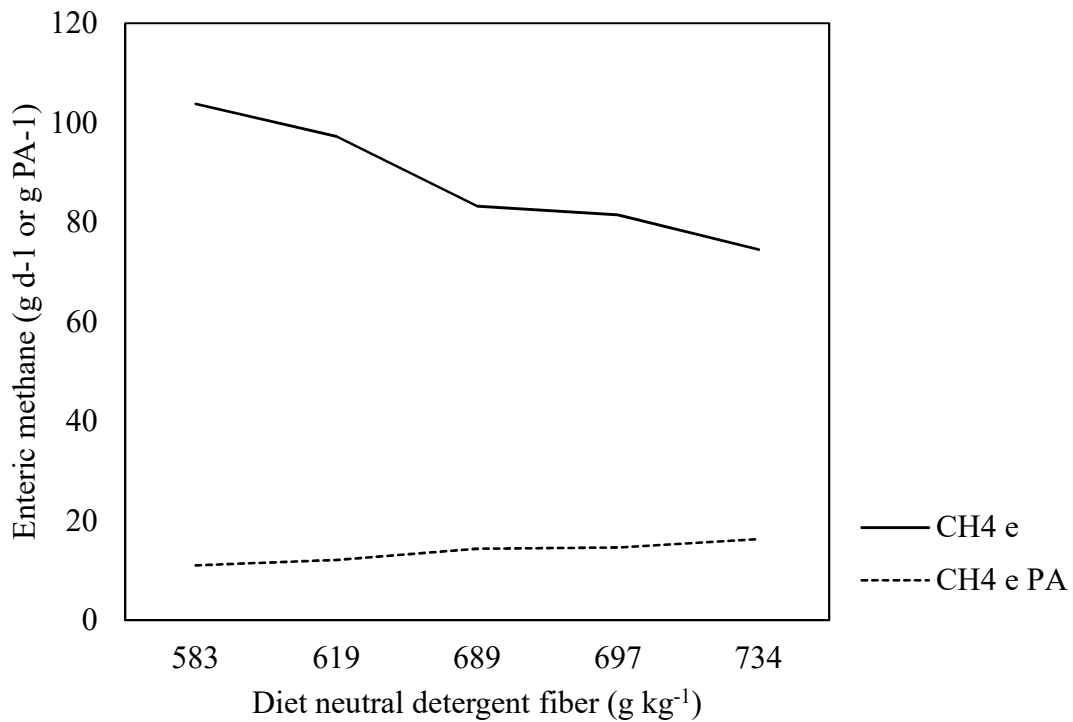


Figure 3. Methane production from enteric fermentation (g d⁻¹) and methane production from enteric fermentation divided by production allowed (g PA⁻¹) as function of neutral detergent fiber content (g kg⁻¹).

CONCLUSIONS

Simulated data of dry matter intake, milk yield, and CH₄ production of ruminant tropical forage-based systems are consistent to empirical data from scientific literature.

The simulation results suggest that small changes on forage fiber composition, as function of maturity, generate impacts on systems efficiency and CH₄ production. Methane enteric emission per kg of milk is negatively affected by forage quality on exclusively forage-based systems. Careful handling of tropical forages, in order to keep a good quality, must be emphasized as a low cost solution to improve feed intake and efficiency on the use of natural resources.

The model can be used as a learning tool to illustrate practical principles of feed intake regulation, animal performance and methane emissions from enteric, and manure fermentation as function of forage quality.

REFERENCES

- Appuhamy, J.A.D.R.N.; Moraes, L.E.; Wagner-Riddle, C.; Casper, D.P.; Kebreab, E. Predicting manure volatile solid output of lactating dairy cows. **J. Dairy Sci.**, v. 101, p. 820-829, 2018. <https://doi.org/10.3168/jds.2017-12813>.
- Archimède, H.; Rira, M.; Eugène, M.; Fleury, J.; Lastel, M.L.; Periacarpin, F.; Silou-Etienne, T.; Morgavi, D.P.; Doreau, M. Intake, total-tract digestibility and methane emissions of Texel and Blackbelly sheep fed C4 and C3 grasses tested simultaneously in a temperate and a tropical area. **J. Clean. Prod.**, v. 185, p. 455-463, 2018. <https://doi.org/10.1016/j.jclepro.2018.03.059>.
- Barton II, F.E.; Amos, H.E.; Burdick, D.; Wilson, R.L. Relationship of chemical analysis to in vitro digestibility for selected tropical and temperate grasses. **J. Anim. Sci.**, v. 43, p. 504-512, 1976.
- Batistoti, C.; Lempp, B.; Jank, L.; Morais, M. das G.; Cubas, A.C.; Gomes, R.A.; Ferreira, M.V.B. Correlations among anatomical, morphological, chemical and agronomic characteristics of leaf blades in *Panicum maximum* genotypes. **Anim. Feed Sci. Technol.**, v. 171, p. 173-180, 2012. <https://doi.org/10.1016/j.anifeedsci.2011.11.008>.
- Blaxter, K.L.; Clapperton, J.L. Prediction of the amount of methane produced by ruminants. **Br. J. Nutr.**, v. 19, p. 511, 1965. <https://doi.org/10.1079/BJN19650046>.
- Bocquier, F.; González-García, E. Sustainability of ruminant agriculture in the new context: Feeding strategies and features of animal adaptability into the necessary holistic approach. **Animal**, v. 4, p. 1258-1273, 2010. <https://doi.org/10.1017/S1751731110001023>.
- Cappelle, E.R.; Valadares Filho, S. de C.; Silva, J.F.C. da; Cecon, P.R. Estimativas do valor energético a partir de características químicas e bromatológicas dos alimentos. **Rev. Bras. Zootec.**, v. 30, p. 1837-1856, 2001. <https://doi.org/10.1590/S1516-35982001000700022>.
- Clark, H. Nutritional and host effects on methanogenesis in the grazing ruminant. **Animal**, v. 7, p. 41-48, 2013. <https://doi.org/10.1017/S1751731112001875>.
- Da Silva, S.; Sbrissia, A.; Pereira, L. ecophysiology of c4 forage grasses - understanding plant growth for optimising their use and management. **Agriculture**, v. 5, p. 598-625, 2015. <https://doi.org/10.3390/agriculture5030598>.
- Dong, H.; Mangino, J.; McAllister, T.A.; Hatfield, J.L.; Johnson, D.E.; Lassey, K.R.; Aparecida de Lima, M.; Romanovskaya, F.A. Emissions from livestock and manure management. **IPCC Guidelines Natl. Greenh. Gas Invent. Agric. For. Other L. Use**, v. 4, p. 10.1-10.89, 2006.

Garnett, T.; Appleby, M.C.; Balmford, A.; Bateman, I.J.; Benton, T.G.; Bloomer, P.; Burlingame, B.; Dawkins, M.; Dolan, L.; Fraser, D.; Herrero, M.; Hoffmann, I.; Smith, P.; Thornton, P.K.; Toulmin, C.; Vermeulen, S.J.; Godfray, H.C.J. Sustainable intensification in agriculture: premises and policies. **Science**, v. 80, n. 341, p. 33-34, 2013. <https://doi.org/10.1126/science.1234485>.

Gerber, P.J.; Steinfeld, H.; Henderson, B.; Mottet, A.; Opio, C.; Dijkman, J.; Falculli, A.; Tempio, G. **Tackling climate change through livestock**: a global assessment of emissions and mitigation opportunities, Food and Agriculture Organization of the United Nations. 2013. <https://doi.org/10.1016/j.anifeedsci.2011.04.074>.

Hristov, A.N.; Oh, J.; Firkins, J.L.; Dijkstra, J.; Kebreab, E.; Waghorn, G.; Makkar, H.P.S.; Adesogan, A.T.; Yang, W.; Lee, C.; Gerber, P.J.; Henderson, B.; Tricarico, J.M. Special topics: mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. **J. Anim. Sci.**, v. 91, p. 5045-5069, 2013. <https://doi.org/10.2527/jas2013-6583>.

Jung, H.G.; Allen, M.S. Characteristics of plant cell walls affecting intake and digestibility of forages by ruminants. **J. Anim. Sci.**, v. 73, p. 2774-2790, 1995. <https://doi.org/10.2527/1995.7392774x>.

Knapp, J.R.; Laur, G.L.; Vadas, P.A.; Weiss, W.P.; Tricarico, J.M. Invited review: Enteric methane in dairy cattle production: quantifying the opportunities and impact of reducing emissions. **J. Dairy Sci.**, v. 97, p. 3231-3261, 2014. <https://doi.org/10.3168/jds.2013-7234>.

Martin, C.; Morgavi, D.P.; Doreau, M. Methane mitigation in ruminants: from microbe to the farm scale. **Animal**, v. 4, p. 351-365, 2009. <https://doi.org/10.1017/S1751731109990620>.

Mertens, D.R. Predicting intake and digestibility using mathematical models of ruminal function. **J. Anim. Sci.**, v. 64, p. 1548-1558, 1987. <https://doi.org/10.2527/jas1987.6451548x>.

Muinga, R.W.; Topps, J.H.; Rooke, J.A.; Thorpe, W. The effect of supplementation with *Leucaena leucocephala* and maize bran on voluntary food intake, digestibility, live weight and milk yield of *Bos indicus* × *Bos taurus* dairy cows and rumen fermentation in steers offered *Pennisetum purpureum* ad libitum in. **Anim. Sci.**, v. 60, p. 13-23, 1995. <https://doi.org/10.1017/S1357729800008080>.

Mutimura, M.; Ebong, C.; Rao, I.M.; Nsahlai, I.V. Effects of supplementation of *Brachiaria brizantha* cv. Piatá and Napier grass with *Desmodium distortum* on feed intake, digesta kinetics and milk production in crossbred dairy cows. **Anim. Nutr.**, v. 1-5, 2018. <https://doi.org/10.1016/j.aninu.2018.01.006>.

Niu, M.; Kebreab, E.; Hristov, A.N.; Oh, J.; Arndt, C.; Bannink, A.; Bayat, A.R.; Brito, A.F.; Boland, T.; Casper, D.; Crompton, L.A.; Dijkstra, J.; Eugène, M.A.; Garnsworthy, P.C.; Haque, M.N.; Hellwing, A.L.F.; Huhtanen, P.; Kreuzer, M.; Kuhla, B.; Lund, P.; Madsen, J.; Martin, C.; McClelland, S.C.; McGee, M.; Moate, P.J.; Muetzel, S.; Muñoz, C.; O’Kiely, P.; Peiren, N.; Reynolds, C.K.; Schwarm, A.; Shingfield, K.J.; Storlien, T.M.; Weisbjerg, M.R.; Yáñez-Ruiz, D.R.; Yu, Z. Prediction of enteric methane production, yield, and intensity in dairy cattle using an intercontinental database. **Glob. Chang. Biol.**, p. 0-2, 2018. <https://doi.org/10.1111/gcb.14094>.

NRC. **Requirements of dairy cattle**. 7.ed. National Research Council Board on Agriculture and Natural Resources Committee on Animal Nutrition Subcommittee on Dairy Cattle Nutrition, 2001. <https://doi.org/10.1016/j.bbamcr.2011.06.003>.

Primavesi, O.; Shiraishi Frighetto, R.T.; Pedreira, M.D.S.; De Lima, M.A.; Berchielli, T.T.; Barbosa, P.F. Metano entérico de bovinos leiteiros em condições tropicais brasileiras. **Pesqui. Agropecu. Bras.**, v. 39, p. 277-283, 2004. <https://doi.org/10.1590/S0100-204X2004000300011>.

Rao, I.; Peters, M.; Castro, A.; Schultze-Kraft, R.; White, D.; Fisher, M.; Miles, J.; Lascano, C.; Blummel, M.; Bungenstab, D.; Tapasco, J.; Hyman, G.; Bolliger, A.; Paul, B.; Van Der Hoek, R.; Maass, B.; Tiemann, T.; Cuchillo, M.; Douxchamps, S.; Villanueva, C.; Rincón, Á.; Ayarza, M.; Rosenstock, T.; Subbarao, G.; Arango, J.; Cardoso, J.; Worthington, M.; Chirinda, N.; Notenbaert, A.; Jenet, A.; Schmidt, A.; Vivas, N.; Lefroy, R.; Fahrney, K.; Guimarães, E.; Tohme, J.; Cook, S.; Herrero, M.; Chacón, M.; Searchinger, T.; Rudel, T. LivestockPlus - the sustainable intensification of forage-based agricultural systems to improve livelihoods and ecosystem services in the tropics. **Trop. Grasslands - Forrajes Trop.**, v. 3, p. 59-82, 2015. [https://doi.org/10.17138/TGFT\(3\)59-82](https://doi.org/10.17138/TGFT(3)59-82).

Reynoso-Campos, O.; Fox, D.G.; Blake, R.W.; Barry, M.C.; Tedeschi, L.O.; Nicholson, C.F.; Kaiser, H.M.; Oltenacu, P.A. Predicting nutritional requirements and lactation performance of dual-purpose cows using a dynamic model. **Agric. Syst.**, v. 80, p. 67-83, 2004. <https://doi.org/10.1016/j.agry.2003.06.003>.

Ritzema, R.S.; Frelat, R.; Douxchamps, S.; Silvestri, S.; Rufino, M.C.; Herrero, M.; Giller, K.E.; López-Ridaura, S.; Teufel, N.; Paul, B.K.; Van Wijk, M.T. Is production intensification likely to make farm households food-adequate? A simple food availability analysis across smallholder farming systems from East and West Africa. **Food Secur.**, v. 9, p. 115-131, 2017. <https://doi.org/10.1007/s12571-016-0638-y>.

Silva, R.O.; Barioni, L.G.; Hall, J.A.J.; Folegatti Matsuura, M.; Zanett Albertini, T.; Fernandes, F.A.; Moran, D. Increasing beef production could lower greenhouse gas emissions in Brazil if decoupled from deforestation. **Nat. Clim. Chang.**, v. 6, p. 493-497, 2016. <https://doi.org/10.1038/nclimate2916>.

Stanley, P.L.; Rowntree, J.E.; Beede, D.K.; DeLonge, M.S.; Hamm, M.W. Impacts of soil carbon sequestration on life cycle greenhouse gas emissions in Midwestern USA beef finishing systems. **Agric. Syst.**, v. 162, p. 249-258, 2018. <https://doi.org/10.1016/j.agsy.2018.02.003>.

Sterman, J.D. **Systems thinking and modeling for a complex world**. 2000.

Vieira, R.A.M.; Pereira, J.; Malafaia, P.A.M.; de Queiroz, A.C. The influence of elephant-grass (*Pennisetum purpureum* Schum., Mineiro variety) growth on the nutrient kinetics in the rumen. **Anim. Feed Sci. Technol.**, v. 67, p. 151-161, 1997. [https://doi.org/10.1016/S0377-8401\(96\)01130-3](https://doi.org/10.1016/S0377-8401(96)01130-3).

Voltolini, T.V.; Santos, F.A.P.; Martinez, J.C.; Imaizumi, H.; Clarindo, R.L.; Penati, M.A. Produção e composição do leite de vacas mantidas em pastagens de capim-elefante submetidas a duas frequências de pastejo. **Rev. Bras. Zootec.**, v. 39, p. 121-127, 2010. <https://doi.org/10.1590/S1516-35982010000100016>.

Warner, D.; Hatew, B.; Podesta, S.C.; Klop, G.; Van Gastelen, S.; Van Laar, H.; Dijkstra, J.; Bannink, A. Effects of nitrogen fertilisation rate and maturity of grass silage on methane emission by lactating dairy cows. **Animal**, v. 10, p. 34-43, 2016. <https://doi.org/10.1017/S1751731115001640>.

Wilkinson, J.M. Re-defining efficiency of feed use by livestock. **Animal**, v. 5, p. 1014-1022, 2011. <https://doi.org/10.1017/S175173111100005X>.

Zeeman, G.; Gerbens, S. CH₄ emissions from animal manure. **Work. Pap. Support IPCC Good Pract. Guid. Uncertain. Manag. Natl. Greenh. gas Invent.**, p. 339-348, 1996.