An Overview of Dairy Cattle Models for Predicting Milk Production

Their Evolution, Evaluation and Application for the Agricultural Model Intercomparison and Improvement Project (AgMIP) for Livestock

Working Paper No. 94

CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)

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Abstract

The contemporary concern about anthropogenic release of greenhouse gas (GHG) into the environment and the contribution of livestock to this phenomenon have sparked animal scientists' interest in predicting methane (CH_4) emissions by ruminants. Focusing on milk production, we address six basic nutrition models or feeding standards (mostly empirical systems) and five complex nutrition models (mostly mechanistic systems), describe their key characteristics, and highlight their similarities and differences. Four models were selected to predict milk production in lactating dairy cows, and the adequacy of their predictions was measured against the observed milk production from a database that was compiled from 37 published studies from six regions of the world, totalling 173 data points. We concluded that not all models were suitable for predicting predict milk production and that simpler systems might be more resilient to variations in studies and production conditions around the world. Improving the predictability of milk production by mathematical nutrition models is a prerequisite to further development of systems that can effectively and correctly estimate the contribution of ruminants to GHG emissions and their true share of the global warming event.

Keywords

Adequacy; Comparison; Modelling; Nutrition; Simulation; Testing.

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Contents

Acronyms

AFRC	Agricultural and Food Research Council
ANSJE	Amino Acid and Nitrogen Supply Jolly Estimator
APIM	Agricultural Production Systems Simulator
ARC	Agricultural Research Council
Cb	Model accuracy
CCC	Concordance correlation coefficient
CH_4	Methane
CHO	Carbohydrate
CNCPS	Cornell Net Carbohydrate and Protein System
CP	Crude protein
DairyMod	Australian Dairy Grazing Systems
DCP	Digestible crude protein
DIESE	Discrete Event Simulation Environment
DM	Dry matter
DMI	Dry matter intake
EE	Ether extract
FASSET	Farm Assessment Tool
FC	Fibre carbohydrate
FiM	Feed into Milk
FU	Feed unit
GE	Gross energy
GHG	Greenhouse gas
GPFARM	Great Plains Framework for Agricultural Resource
HPM	Hurley Pasture Model
IFSM	Integrated Farm System Model
iNDF	Indigestible neutral detergent fibre
INRA	Institut National de La Recherche Agronomique
IPCC	Intergovernmental Panel on Climate Change
kd	Fractional degradation rate
kp	Fractional passage rate
LRNS	Large Ruminant Nutrition System
MB	Mean bias
MCP	Microbial crude protein
ME	Metabolisable energy

MES	Model Evaluation System
MP	Metabolisable protein
MSEP	Mean square error of prediction
MY	Milk yield
NDF	Neutral detergent fibre
NE	Net energy
NFC	Nonfibre carbohydrate
NPN	Nonprotein nitrogen
NRC	National Research Council
OM	Organic matter
PAMELA	Protozoa and Acid Metabolism Estimator; a Lift to ANSJE
PaSim	Pasture Simulation
pdNDF	Potentially digestible neutral detergent fibre
RMSEP	Root of mean square error of prediction
SGS	Sustainable Grazing Systems
TDN	Total digestible nutrients
VFA	Volatile fatty acids
WFM	Whole Farm Model

Introduction

The Agricultural Model Intercomparison and Improvement Project (AgMIP[1]) is an international endeavour whose purpose is to bring together agricultural modelling communities with cutting-edge information technology to enhance models' predictions and to foster the development of the next generation of models for the agricultural sector. Rosenzweig et al. (2013) indicated the goals of AgMIP are to improve world food security (e.g., meat and milk) and to enhance adaptation capacity across different regions of the globe in light of climate change. Thus, the intercomparison of models' adequacy in predicting meat and milk production is an important step.

Recent estimates from the Intergovernmental Panel on Climate Change (IPCC) indicate that agriculture was responsible for 13.5% of the global anthropogenic greenhouse gas (GHG) emissions in 2004 (IPCC, 2007). Agricultural methane (CH_4) emissions, of which 33 to 39% is ruminant enteric CH_4, accounts for about 60% of the global anthropogenic CH_4 emissions (Moss et al., 2000). Consequently, about 2.7 to 3.2% of global anthropogenic GHG is due to CH_4 emissions from ruminant enteric fermentation. To identify potential strategies for mitigating CH_4 emissions to the environment, valid predictions of CH_4 emissions by ruminants (e.g., cattle, sheep, and goats) must be available in order to accurately represent their share of GHG emissions (Gerber et al., 2013; Hristov et al., 2013; Tedeschi et al., 2011; Tedeschi et al., 2003).

Several attempts have been made to predict CH_4 emissions by ruminants, from simple empirical relationship regressions (Axelsson, 1949; Blaxter and Clapperton, 1965; Kriss, 1930) to more robust empirical regressions using dietary nutrient intake and composition (Ellis et al., 2009; Ellis et al., 2007; Jentsch et al., 2007; Moe and Tyrrell, 1979; Moraes et al., 2014; Ramin and Huhtanen, 2012, 2013; Wilkerson et al., 1995; Yan et al., 2009) to more complex systems using biochemical pathways and anaerobic fermentation stoichiometry (Baldwin, 1995; Danfær et al., 2006a; Dijkstra et al., 1992; Gill et al., 1989; Mills et al., 2001; Pitt et al., 1996) and thermodynamics (Janssen, 2010; Kohn and Boston, 2000). Though empirical regressions may generally yield more accurate and precise estimates of animal responses than mechanistic models for practical applications (France et al., 2000), they may

[1] http://www.agmip.org

not be as useful as mechanistic/dynamic systems in understanding the mechanisms underlying CH_4 production and in providing opportunities to discover strategies for mitigating CH_4 emissions under different scenarios of production. Benchaar et al. (1998), however, found that mechanistic models provided greater precision and accuracy than empirical regressions and that mechanistic models could be calibrated through adjustment factors to yield even better predictions.

Several attributes of commercial ruminant production poses additional complications to developing comprehensive mathematical models. The first issue is methodological: the discrepancy between methods can bias model predictions. For example, the respiration chamber method measures total CH_4 (rumen and hindgut), whereas sulphur hexafluoride (SF_6) method determines rumen CH_4 only, which does not represent complete recovery of the ruminant animal's total CH_4 emission, though the difference can be as low as 4% or less for SF_6 (McGinn et al., 2006a). A revised methodology for the SF_6 tracer technique has been proposed (Deighton et al., 2014). The second issue is statistical: in addition to predictive errors of mathematical models, the observed data also contains sources of random, unknown errors. The scientific community does not entirely accept the use of meta-analytical techniques to overcome this issue because, when predicting CH_4 emission, one cannot remove the random errors associated with a random factor (e.g., studies) if its share of the total variance is considerable. The third issue is related to grazing ruminants: besides the inherent difficulties in modelling grazing ruminants (Teague et al., 2013), the techniques for measuring CH_4 emission in pasture conditions are challenging, even the use of open-path laser scanners to determine concentrations of CH_4 has produced contradictory or incomplete results (McGinn and Beauchemin, 2012; McGinn et al., 2006b; McGinn et al., 2011; Tomkins et al., 2011). Though mathematical nutrition models for ruminants can predict animal performance under different environmental conditions, it is not entirely clear which nutrition model can adequately predict animal production in different parts of the world.

Most intercomparisons of the adequacy of livestock mathematical models' predictions of animal response have been performed only as needed, and few have used guided and experimentally designed comparisons. Often, model evaluations are perceived as ways to promote the use of one system over another rather than highlight important gaps and limitations of scientific knowledge and how to address them. It is very common to find publications about models that have been "validated"; when in reality models cannot be validated in the sense of proving their correctness and utility for future predictions; they can simply be evaluated on an *ad hoc* basis (Tedeschi, 2006). For beef cattle, intercomparisons of livestock ruminant models for the performance of growing animals have been conducted (Arnold and Bennett, 1991a, b), but recent models for beef cattle have not been compared.

Others have made partial comparisons or critiques of specific elements of nutrition models (Alderman, 2001; Alderman et al., 2001a, b; Bannink et al., 1997; Dijkstra et al., 2008; Sauvant, 1996; Sundstøl, 1993; Tedeschi et al., 2013a), but there have been only limited comparisons about the models' ability to predict growth or milk yield (MY) in different parts of the world under distinct production scenarios (e.g., feedstuffs, breeds, management, and climatic factors). Furthermore, model comparisons for nutrient excretion and GHG emissions of modern livestock operations are lacking (Tedeschi et al., 2005b), mainly for regions of the world that produce large quantities of meat and milk to support the livelihood of humans.

The goal of this manuscript was to update and expand the discussion on the evolution and evaluation of models for milk production by Tedeschi et al. (2014). The first objective is to provide the evolution and a brief synopsis of important mathematical nutrition models that can be used to assess animal performance (i.e., milk production) or CH_4 emission of dairy cattle production systems in different parts of the world. The second objective is to a show preliminary comparison of a subset of these mathematical nutrition models on the adequacy of their predictions of MY. The third objective is to discuss the inclusion of ruminant nutrition models into modern whole farm models.

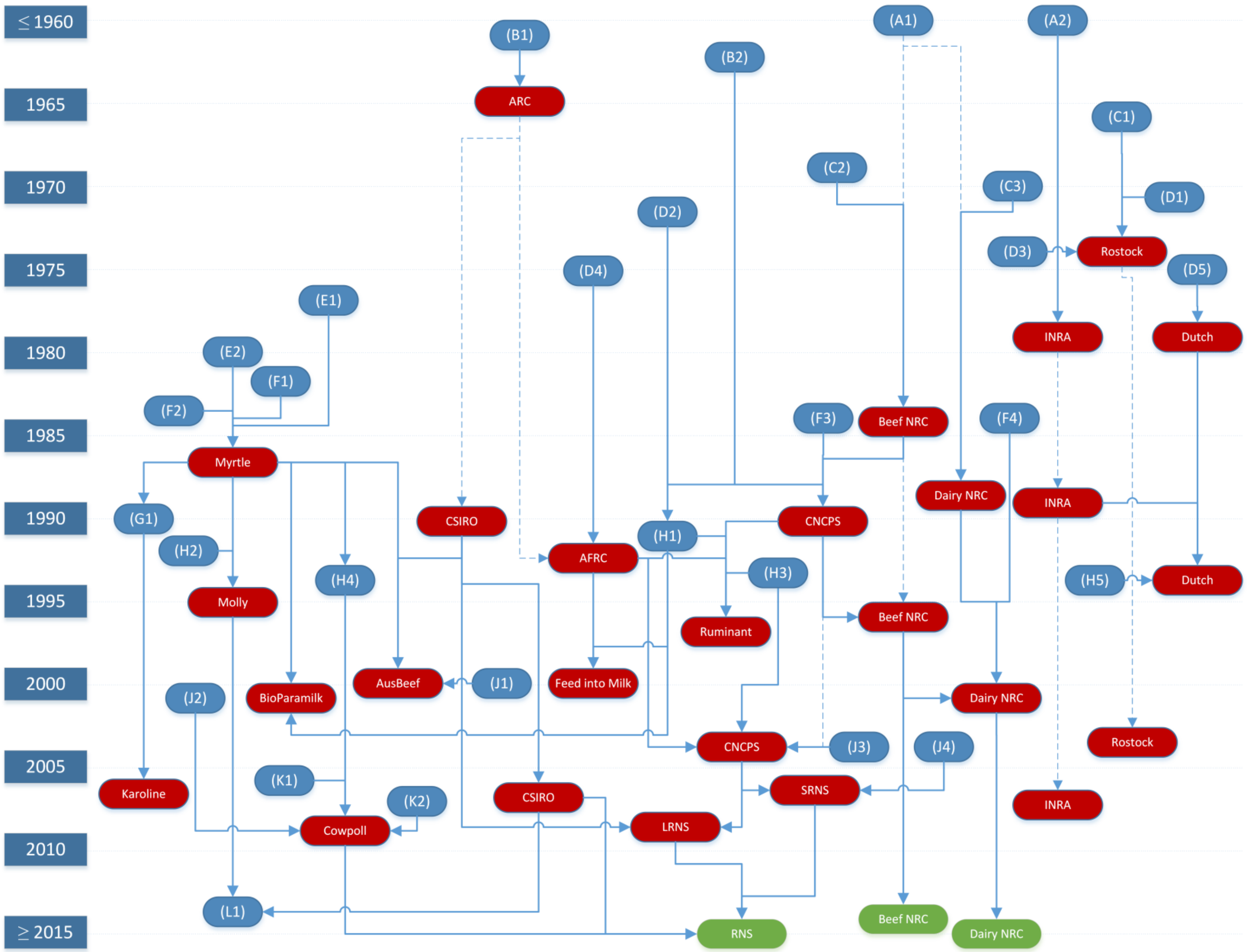
Evolution of Nutrition Models

Figure 1 shows the chronological evolution of relevant nutrition models and feeding standard systems that were developed to facilitate fundamental research as well as on-farm applications for evaluation and formulation of diets. The models described below are usually classified as empirical systems and they formed the conceptual basis for the development of more complex, modern mathematical nutrition models. Appendix 1 has detailed information about selected nutrition models provided by their developers.

Description of empirical nutrition models

The American model—National Research Council (NRC)

The NRC system is based on the work of the group within the United States Department of Agriculture (Beltsville, Maryland) studying dairy cattle by using respiration chambers (Moe et al., 1972; Moe and Tyrrell, 1974; Moe and Tyrrell, 1975; Moe et al., 1970; Moe et al., 1971; Tyrrell and Moe, 1975a; Tyrrell and Moe, 1975b; Tyrrell et al., 1970) and studies conducted at the University of California-Davis for growing and finishing cattle by using the comparative slaughter technique (Garrett et al., 1959; Lofgreen, 1965; Lofgreen and Garrett, 1968; Lofgreen et al., 1962). The first Recommended Nutrient Allowances for Dairy and Recommended Nutrient Allowances for Beef were published in 1945 (NRC, 1945a; 1945b).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Rostock
(D4)
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(E1)
INRA
Dutch
(E2)
(F1)
(F2)
(F3)
Beef NRC
(F4)
Myrtle
Dairy NRC
(G1)
CSIRO
CNCPS
INRA
(H1)
(H2)
AFRC
(H3)
(H4)
(H5)
Dutch
Molly
Beef NRC
Ruminant
(J1)
BioParamilk
AusBeef
Feed into Milk
Dairy NRC
(J2)
CNCPS
(J3)
(J4)
Rostock
Karoline
(K1)
SRNS
(K2)
CSIRO
INRA
Cowpoll
LRNS
(L1)
Beef NRC
RNS
Dairy NRC

Figure 1.Chronological evolution of mathematical nutrition models (red boxes) and key references (blue boxes). Year of publication or release is shown on the left. The green boxes represent models not yet released to the public. The solid line represents a direct relationship of influence, and the dashed line represents that at least one other version or edition was released in between the marks. References are: (A1) (NRC, 1945a; NRC, 1945b) (A2) Leroy (1954), (B1) (Blaxter, 1962), (B2) Van Soest (1963a) and Van Soest (1963b), (C1) Nehring et al. (1966), (C2) Lofgreen and Garrett (1968), (C3) Moe et al. (1970), (D1) Schiemann et al. (1971), (D2) Waldo et al. (1972), (D3) Hoffmann et al. (1974), (D4) Ministry of Agriculture, Fisheries and Food (1975), (D5) Van Es (1975), (E1) Baldwin et al. (1977), (E2) Baldwin et al. (1980), (F1) France et al. (1982), (F2) Gill et al. (1984), (F3) Fox and Black (1984), (F4) Conrad et al. (1984), (G1) Danfær (1990), (H1) Illius and Gordon (1991), (H2) France et al. (1992), (H3) Russell et al. (1992), Sniffen et al. (1992), and Fox et al. (1992), (H4) Dijkstra et al. (1992), Neal et al. (1992), and Dijkstra (1993), (H5) Tamminga et al. (1994), (J1) Nagorcka et al. (2000), (J2) Mills et al. (2001), (J3) Fox et al. (2004), (J4) Cannas et al. (2004), (K1) Bannink et al. (2006), (K2) Bannink et al. (2008), and (L1) Gregorini et al. (2013). RNS is the Ruminant Nutrition System. Adapted from Tedeschi et al. (2014).

The latest revision of the Nutrient Requirements for Dairy Cattle was released in 2001 (NRC, 2001). Nutrient Requirements for Beef Cattle was published in 1996 (NRC, 1996) and updated in 2000 (NRC, 2000).

The British model—Agricultural Research Council (ARC)

Van Es (1975) compared the feeding standard systems of dairy cows developed by the American (Beltsville), German (Rostock), Dutch (Wageningen), and British groups, and concluded that the starch equivalent system incorrectly evaluated feeds for dairy cows. Van Es (1975) proposed that the newly obtained information from energy balance trials with dairy cows should be used instead. The starch equivalent system assumed that the feeding values of feedstuffs for growing and finishing steers would rank the same when fed to lactating dairy cows. The first livestock system by the ARC was released in 1965 (ARC, 1965), and it was substantially revised in 1980 (ARC, 1980). The 1965 publication relied largely on data from non-lactating ruminants and used the factorial approach (Van Es, 1975). The ARC (1965) adopted the metabolisable energy (ME) feeding system developed by Blaxter (1962). Later, the metabolisable protein (MP) was introduced in the ARC (1980). Technical reports published in 1990 and 1991 by the Agricultural and Food Research Council (AFRC) further modified the ARC (1980). A revised publication in 1993 incorporated these modifications (AFRC, 1993). Agnew and Yan (2000) indicated that the main limitations of the ME system as adopted by the ARC and AFRC publications were the lack of calorimetric data obtained in the UK and the ancient data used to develop these systems. The MP system of the AFRC (1993) was based on basal endogenous nitrogen (N) losses at a maintenance level of intake, and there was no provision to adjust for cows consuming at production level. The Feed into Milk (FiM) project was developed to overcome these limitations, but it still uses the original concepts proposed in the 1960s. Agnew and Newbold (2002) provide a more detailed discussion about the evolution of the feeding systems in the UK.

The German model—Rostock Feed Evaluation System

Jentsch et al. (2003) and Chudy (2006) describe the evolution of the German feeding standards. Oskar Kellner's *Starch Value System* was the main ruminant feeding system until the twentieth century. It was based on Gustav Kühn's methods and the energy metabolism of adult oxen. Kurt Nehring validated the use of the starch value system to assign energy values to different feeds, using open-circuit respiration chambers at the Oskar Kellner Institut fur Tierernahrung of the Academy of Agricultural Science. This research site used four air-conditioned respiration chambers to study the fundamentals of energy metabolism and nutrient utilization in farm animals, to apply the results in feed evaluation, and to develop a complete feed evaluation system (Chudy, 2006). The publications by Nehring et al. (1966), Schiemann et al. (1971), and Hoffmann et al. (1974) formed the basis of the Rostock Feed Evaluation System. In 1971, the system was referred to as the "GDR Feed Evaluation

System," and seven editions were published until 1989. The most current edition (Beyer et al., 2003) was revised by Jentsch et al. (2003).

The French model—Institut National de la Recherche Agronomique (INRA)

In France, for a long time, the energy value of feeds and the energy requirements of ruminant animals were based on the feed unit (FU) system developed in 1954 by André M. Leroy (Leroy, 1954). In the 1970s, the INRA proposed a new system based on the same principles adopted by the Netherlands (Van Es, 1978) and Switzerland (Bickel and Landis, 1978), systems in which the net energy (NE) values of feeds were estimated from ME and from the partial efficiency of use of ME for maintenance, growth, and lactation. However, it differed in three aspects: the ME content of feeds was computed from gross energy (GE), the NE content of feeds was still expressed in FU equivalent, and the energy allowances for growing and finishing cattle of different breeds were determined using experiments conducted in France (Vermorel, 1978). These modifications were published by the INRA in its 1978 publication *Alimentation des Ruminants*. The INRA updated the French system in 1988 (INRA, 1988) and 1989 (INRA, 1989). The latest revised publication of the French system was released in 2007 (INRA, 2007).

The Australian model—Commonwealth Scientific and Industrial Research Organization (CSIRO)

The first publication of feeding standards developed by the CSIRO was released in 1990 (CSIRO, 1990) and revised in 2007 (CSIRO, 2007). These standards are based on the UK feeding standards (AFRC, 1993; ARC, 1965; ARC, 1980). The CSIRO system (CSIRO, 1990) was the foundation of decision support systems for Australian conditions, named GrazPlan[2], which included models such as GrazFeed, GrassGro, and AusFarm (Donnelly et al., 2002; Donnelly et al., 1997; Freer et al., 1997; Salmon et al., 2004). Nagorcka et al. (2000) proposed a more mechanistic and dynamic rumen model that would have included variables other than substrate types and ruminal pH to improve the description and accountability of ruminal production of volatile fatty acids (VFA). This model was named AusBeef, and it is to be included in the GrazPlan suite of models.

The Dutch Feed Evaluation System

As described by Van Es (1978), the energy evaluation system used in the Netherlands was based on the work of Van Es (1975) with modifications to the calculation of the ME content of feeds, the maintenance requirement, and the use of FU equivalency, in which one lactation

[2] Available at http://www.grazplan.csiro.au

FU contained 1.65 Mcal of NE for lactation. Until 1991, the protein system was based on the digestible crude protein (DCP), and in 1994 the DVE/OEB, which is based on the MP concepts adopted by the INRA (1989), was proposed for inclusion in the Dutch protein system (Tamminga et al., 1994).

Description of mechanistic nutrition models

The models in the next group are usually classified as mechanistic because they contain conceptual and mechanistic elements in their logical structure. Some are intrinsically dynamic while others are static (i.e., time is not a continuous variable), but all of them are deterministic.

Molly

Molly[3] is a dynamic, mechanistic model based on biochemical reactions in animal metabolism (Baldwin, 1995). However, Molly was not the first mechanistic model; it came after Myrtle and Daisy (France, 2013), which were conceptualized based on the combination of extant models of rumen functions (Baldwin et al., 1977; France et al., 1982) and metabolism (Baldwin et al., 1980; Gill et al., 1984). The Myrtle's rumen model was developed to address the nutrient supply of North American diets and the metabolism model was designed to describe nutrient partitioning and energy balance of lactating cows (France, 2013). Myrtle and Daisy were described by Baldwin et al. (1987b), Baldwin et al. (1987c), and Baldwin et al. (1987a). Finally, after six years of improvements and modifications to the code (France, 2013), Baldwin (1995) released Molly. The present research programs in Australia (e.g., AusBeef; Nagorcka et al. (2000)) and in New Zealand are in many ways based on Baldwin's work (he spent two sabbatical leaves there with John Black and Bruce Robson), and Molly's successors are in active use there (John P. McNamara, personal communication). More recently, Hanigan et al. (2009) have updated Molly with sophisticated parameters fitting based on new datasets assembled over the last 20 years. Others other have challenged and improved the energy and adipose functions of Molly and integrated Molly with a model of reproductive processes (Boer et al., 2011) to create the first integrated model of nutritional and reproductive processes, known as Jenny (McNamara and Shields, 2013).

Cornell Net Carbohydrate and Protein System (CNCPS)

The most recent complete version of the CNCPS was published by Fox et al. (2003) and Fox et al. (2004). It includes both beef and dairy cattle with two levels of solution (L1 and L2).

[3] Available at http://www.vmtrc.ucdavis.edu/metabolic

Modifications have been made to L2 for the Cornell-Penn-Miner Institute (CPM) Dairy as described by Tedeschi et al. (2008), to CNCPS version 6.0 as described by Tylutki et al. (2008), and to subsequent CNCPS versions (Van Amburgh et al., 2010; Van Amburgh et al., 2013; Van Amburgh et al., 2009). The original description of the mechanistic ruminal fermentation submodel of the CNCPS was published in early 1990s (Fox et al., 1992; O'Connor et al., 1993; Russell et al., 1992; Sniffen et al., 1992), and additional modifications and new submodels have been developed since then (Lanzas et al., 2008; Lanzas et al., 2007a; Lanzas et al., 2007b; Seo et al., 2006; Tedeschi et al., 2002a; Tedeschi et al., 2008; Tedeschi et al., 2000a; Tedeschi et al., 2005a; Tedeschi et al., 2013b; Tedeschi et al., 2002b; Tedeschi et al., 2000b; Tedeschi et al., 2001; Tedeschi et al., 2006; Tylutki et al., 1994). Derivative models have been developed and deployed. CPM Dairy was developed for dairy cattle based on the computational engine of the CNCPS version 5.0 with additional features (Boston et al., 2000; Tedeschi et al., 2008) and Chalupa and Boston (2003) provide a historical perspective on the development of CPM Dairy. Similarly, the Large Ruminant Nutrition System[4] (LRNS) is based on the calculation logic of the CNCPS version 5.0. The AMTS.Cattle.Pro[5] is an implementation of the CNCPS version 6.1. Like the beef NRC (2000), the LRNS has two levels of solution: the L1 uses empirical equations to compute total digestible nutrients (TDN), ME, NE, and MP whereas L2 uses the fractionation of protein, fractional rates of ruminal degradation and ruminal passage, microbial crude protein (MCP) using the microbial growth submodel (Russell et al., 1992; Tedeschi et al., 2000b), and intestinal digestibility to compute MP. The MCP yield is predicted by two groups: those that grow slowly on fibre carbohydrates (FC) and those that grow more rapidly on nonfibre carbohydrates (NFC). Each feed carbohydrate (CHO) fraction (A is sugars, B1 is starch and pectins, B2 is available neutral detergent fibre (NDF), and C is unavailable fibre) and protein fraction (A is nonprotein N (NPN), B1 is soluble true, B2 is non-cell-wall, B3 is available cell wall, and C is unavailable cell wall) has its own fractional degradation rate (kd). Undegraded fractions flow out of the rumen with either the solid or the liquid passage rate (kp). CNCPS version 6.0 (Tylutki et al., 2008) expanded the CHO fractions were expanded to provide separate pools for organic and volatile fatty acids and soluble fibre, as documented by Lanzas et al. (2007a), and to provide new kp empirical equations developed by Seo et al. (2006). In CNCPS version 6.1 (Van Amburgh et al., 2010), peptides were shifted from the NPN to the soluble protein fraction that degrades with a reduced kd, and the liquid kp is used to predict the proportion of this fraction that passes undegraded from the rumen, as documented by Lanzas et al. (2008).

[4] Available at http://nutritionmodels.tamu.edu/lrns.html or http://nutritionmodels.com/lrns.html

[5] Available at https://www.agmodelsystems.com/AMTS/cattlepro.php

Ruminant

This model was first described by Herrero (1997) and the latest complete description presented in Herrero et al. (2013); it is largely based on the work of Illius and Gordon (1991), Sniffen et al. (1992) and AFRC (1993). It consists of a dynamic section that estimates intake and the supply of nutrients to the animal from the fermentation kinetics and passage of feed constituents (carbohydrate and protein) through the gastrointestinal tract and their subsequent excretion, whereas another section determines their nutrient requirements using well recognised principles. Feeds are described by four main constituents: ash, fat, carbohydrate, and protein. These are divided into soluble, insoluble but potentially degradable, and indigestible fractions. Carbohydrate fractions represent non-structural carbohydrates (solCHO), potentially digestible cell wall, and the indigestible residue. For concentrate feeds, the proportion of starch in the solCHO is also used. Starch and fat in forages are almost negligible, but they may be important fractions in grains. The protein fractions are the same as those estimated in the MP system (AFRC, 1993), with the difference that their representation in this model is dynamic. The pools of digested nutrients obtained from the model are used to calculate the supply of nutrients to the animals. The model takes as inputs the quantities of fermentable nutrients available in a particular time step and returns as outputs the products of fermentation. The inputs are fermentable carbohydrate separated into simple sugars, starch, and cell wall material; fermentable N separated into ammonia and protein; and lipid, each summed across the various feed constituents, together with the microbial pool size. The outputs are the quantities of new microbial matter, the individual VFA, CH_4, ammonia, and unfermented carbohydrates. It is assumed that there is only a single pool of microorganisms of fixed composition. The microbial maintenance requirement was set at 1.63 mM of ATP per gram of microbial dry matter (DM) per hour. The quantities of individual VFA and CH_4 produced are calculated according to the quantities of different substrates fermented. There is no fixed upper limit to the quantity of microbial matter produced; the lower limit is zero growth. If fermentable N supply limits the amount of fermentable carbohydrate that can be used, unfermented carbohydrate is returned to the appropriate rumen pool, thus reducing the effective rate of carbohydrate fermentation. The model is generic and can simulate animals of different bodyweights because of the incorporation of allometric rules for scaling passage rates. The model also includes explicit protein–energy interactions, feeding level effects on passage rates, and pH effects on cell wall degradation rates. These aspects are essential for predicting stoichiometry changes, the effect of different supplementation regimes, and the substitution effects of forages and concentrates. This model has been used in a number of systems analysis studies of feeding strategies for ruminants (Castelán-Ortega et al., 2003; Herrero et al., 1999), herd replacement decisions (Vargas et al., 2001), trade-offs in smallholder systems (Waithaka et al., 2006), greenhouse gas emissions an mitigation strategies in livestock systems (Bryan et al., 2013; Havlík et al., 2014; Herrero et al., 2013; Herrero et al., 2008; Thornton and Herrero, 2010).

Dutch Tier 3

The rumen fermentation models developed by Baldwin et al. (1977) and Black et al. (1981) had limitations. The model by Beever et al. (1981) was unable to predict duodenal flow of protein diets when low protein content were simulated, and the model by Baldwin et al. (1987c) could not describe fibre fermentation of high-concentrate diets. An attempt to modify these models and improve the predictions of VFA production in the rumen culminated in the development of another model that was described by Dijkstra et al. (1992) and evaluated by Neal et al. (1992), which led to the development of the *Amino Acid and Nitrogen Supply Jolly Estimator* (ANSJE) model (J. Dijkstra, personal communication). Subsequently, Mills et al. (2001) added an empirical representation of digestion occurring in the small intestine and a mechanistic representation of fermentation occurring in the hindgut. They also included the prediction of CH_4 production, including new coefficients for VFA formation that Bannink et al. (2006) obtained from data on lactating cows alone. After these modifications to the original ANSJE model, a computer interface was added, creating COWPOLL, a decision support tool for evaluating dairy cow diets for their pollution impact. Later, Bannink et al. (2008) developed a more mechanistic approach that made the formation of VFA in the rumen dependent on pH. Simultaneously, they developed a model describing the absorption of VFA across the rumen epithelium and metabolism of VFA therein. Concurrently to ANSJE, Dijkstra (1994) developed a rumen model with specific focus on the representation of the presence and activity of protozoa: *Protozoa and Acid Metabolism Estimator; a Lift to ANSJE* (PAMELA; J. Dijkstra, personal communication), but this version has not been incorporated into the COWPOLL fermentation model. PAMELA was evaluated by Dijkstra and Tamminga (1995). Since 2005, the model published by Mills et al. (2001), which included the VFA formation of Bannink et al. (2008) (which itself replaced that of Bannink et al. (2006)), has been used as a Tier 3 approach to estimating CH_4 emission in dairy cattle for the national inventory report in the Netherlands (Bannink et al., 2011). It is commonly called “Dutch Tier 3”. In recent years, further modifications have been made to the rumen and large intestine models, a mechanistic version has been developed for the small intestine submodel, and calculations on manure production and composition have been added. These modifications have not yet been made public (A. Bannink, personal communication).

Karoline

The dairy cow model Karoline, a dynamic and mechanistic model component of the Nordic feed evaluation system NorFor (Volden, 2011), allocates the feed CHO into eight fractions: forage indigestible NDF (iNDF), forage potentially digestible NDF (pdNDF), concentrate iNDF, concentrate pdNDF, starch, lactic acid, VFA (acetic, propionic, and butyric acids), and a heterogeneous remainder pool that is calculated by subtracting CHO, crude protein (CP), and ether extract (EE) from organic matter (OM), and that most likely contains water-soluble CHO, pectic substances, plant organic acids, and alcohols produced during the silage fermentation process (Danfær et al., 2006a). The feed CP is separated into six fractions: ammonia N, free amino acids, peptides, soluble true protein, insoluble protein, and potentially indigestible protein (Danfær et al., 2006a). The feed fat is converted to fatty acids from feed's EE by using different equations for forage and concentrate feedstuffs (Danfær et al., 2006a). Karoline allows the user to modify the ruminal kd for forage and concentrate pdNDF, starch, and insoluble true protein, but the other fractions are fixed. Danfær et al. (2006b) indicated that Karoline's prediction errors for some digestion variables were smaller than those obtained with the Molly model (Baldwin, 1995) as evaluated by Hanigan et al. (2013). Karoline adopted a two-pool ruminal kinetics with selective fibre retention for CHO and a three-pool ruminal kinetics with selective insoluble protein retention for protein as described by Danfær et al. (2006a) and schematized in Figure 2. A selective retention model is used to mathematically account for escapable and non-escapable pools in the rumen (Allen and Mertens, 1988; Mertens, 1989, 2005). The non-escapable pool can only be degraded (i.e., digested) or transferred to another pool, but it cannot escape the rumen, so it represents an intermediate step before escaping ruminal fermentation. There is some evidence that selective retention models more adequately mimic the ruminal kinetics of forage (Huhtanen et al., 2006; Mertens, 1993), concentrate (Mambrini, 1997; Wylie et al., 2000), and starch (Tothi et al., 2003), but the need to obtain an additional fractional rate of release from one pool to another has be taken into account. Karoline also contains a hindgut model that behaves similarly to the rumen model but is simpler. Karoline's prediction of CH_4 is based on pool size of fermentable substrates and anaerobic fermentation kinetics (Sveinbjörnsson et al., 2006).

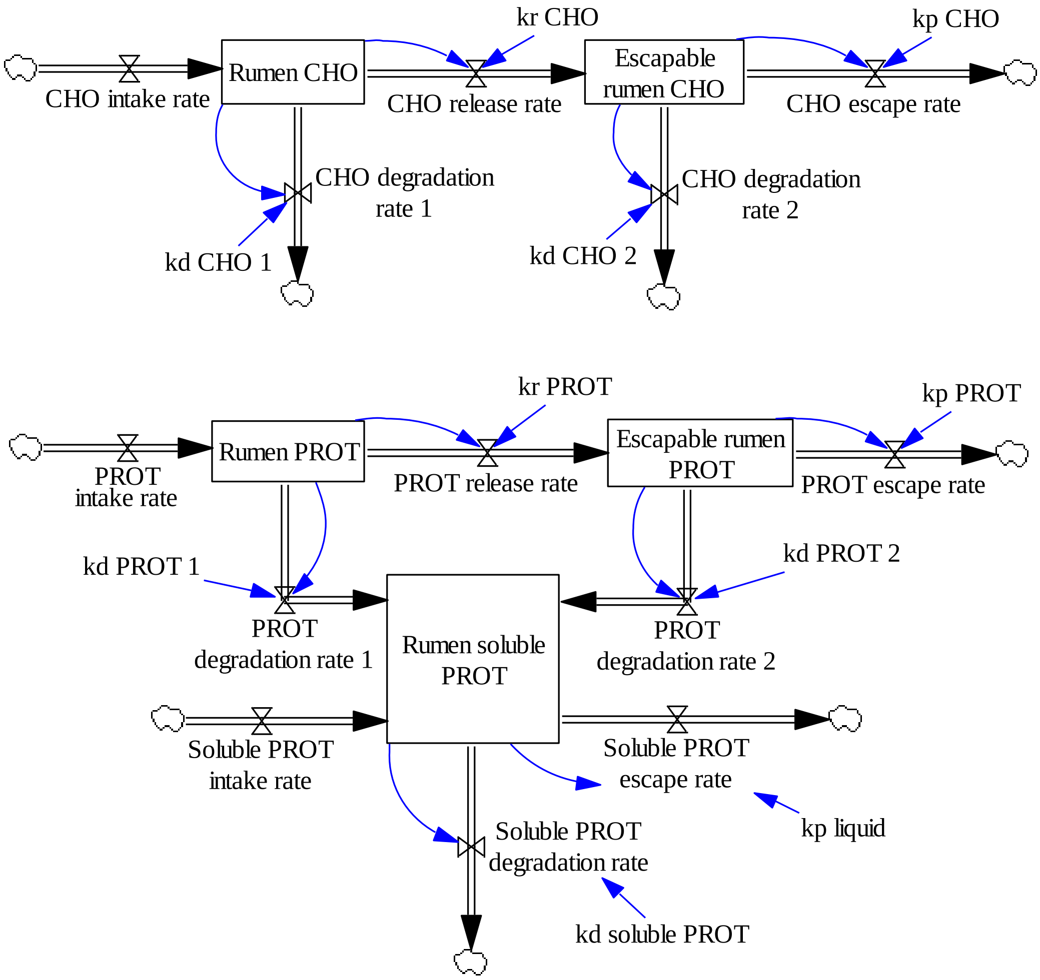


Figure 2. Illustration of the ruminal kinetics of carbohydrate and protein fractions based on the Karoline model. Boxes represent state, stock, or level variables (units); double-line arrows represent flows or rates (units/time); and single-line arrows represent variable causation and interrelationships. CHO is carbohydrate, kr is fractional release rate, kd is fractional degradation rate, kp is fractional passage rate, and PROT is protein. Adapted from Danfær et al. (2006a).

Intercomparison of Model Predictions for Milk Production

The models selected for this preliminary comparison were the LRNS version 1.0.30 (solutions L1 and L2), NRC[6] (2001) version 1.1.9, and Molly. Whenever available, the model-predicted MY was the least between the energy-allowable MY or the protein-allowable MY.

Description of the study database

A database was developed to compare the adequacy of selected nutrition models in predicting MY of dairy cows from six distinct regions around the world—Africa, Asia, Europe, Latin America, North America, and Oceania—based on their animal production characteristics: types of feeds (e.g., silage-based, pasture), feeding system (intensive versus extensive), type of cattle (e.g., Holstein-based, crossbreds), level of intensification, and animal management, among other factors. The database comprised of 50 scientific papers published in peer-reviewed journals from 1992 to 2014 (Abdullah et al., 2000; Alvarez et al., 2001; Assis et al., 2004; Auldist et al., 1999; Bargo et al., 2001; Chantaprasarn and Wanapat, 2008; Chen et al., 2008; Colmenero and Broderick, 2006; Danes et al., 2013; Dey and De, 2014; Erasmus et al., 2013; Erasmus et al., 1992; Erasmus et al., 1994; Erasmus et al., 1999; Erasmus et al., 2004; Fatahnia et al., 2008; Grainger et al., 2010; Greenwood et al., 2013; Guo et al., 2013; Heard et al., 2007; Heard et al., 2004; Irvine et al., 2011; Jesus et al., 2012; Kalscheur et al., 1999; Khezri et al., 2009; Kokkonen et al., 2000; Lehmann et al., 2007; Liu et al., 2008; Lunsin et al., 2012; McCormick et al., 2001a; McCormick et al., 2001b; Meeske et al., 2009; Moallem, 2009; Moharrery, 2010; Mosavi et al., 2012; Murphy, 1999; O'Mara et al., 1998; O’Mara et al., 2000; Oguz et al., 2006; Petit and Gagnon, 2011; Piamphon et al., 2009; Sanh et al., 2002; Suksombat and Chullanandana, 2008; Sun et al., 2009; Vafa et al., 2012; Valizadeh et al., 2010; Walker et al., 2010; Yalçın et al., 2011; Yan et al., 2011; Yarahmadi and Nirumand, 2012). The database contained 173 observations (19 for Africa, 45 for Asia, 16 for Europe, 12 for Latin America, 44 for North America, and 37 for Oceania) with the minimum information needed for simulation, such as animal and feedstuff characteristics, dry matter intake (**DMI**), and milk composition and production. Common feedstuff and animal databases were developed, and functions were created to import and export the data from one model to another using R (R Core Team, 2014).

[6] Available at https://nanp-nrsp-9.org/nrc-dairy-model

Description of the feedstuff information

The feedstuff database contained 173 records obtained from the studies. Missing information on needed dietary composition was obtained from the LRNS feed library, NRC (2000, 2001) feed libraries, American and Canadian tables of feed composition (NRC, 1982), and the Brazilian feedstuff composition repository[7]. The 10 most common feeds were finely ground dry corn, finely ground soybean meal, corn silage, barley grain, urea, wheat bran, beet pulp shreds, fishmeal, blood meal, and corn gluten. Table 1 summarizes the statistics of the main feed nutrients. Some specific mixes had to be created in order to maintain all ingredients used in the dataset.

Table 1. Descriptive statistics of the feedstuff and dietary chemical compositions and animal characteristics

Items[1]	Median	Mean	SD[1]	Range		Quartiles	
				Min	Max	25%	75%
Diets							
DM, % as-fed	52.0	57.2	16.6	34.4	90.1	45.7	69.7
Fat, % DM	4.3	4.5	1.7	1.8	11.3	3.2	5.2
Ash, % DM	8.4	8.1	1.6	4.3	11.4	7.0	9.2
CP, % DM	18.0	18.2	2.8	10.1	25.5	16.3	20.2
Soluble CP, % CP	35.0	34.4	6.7	21.5	56.0	28.9	38.4
NPN, % CP	56.5	54.1	21.9	17.4	97.8	29.6	69.5
NDFIP, % CP	14.9	16.0	5.1	6.0	30.9	12.5	18.5
ADFIP, % CP	6.0	5.8	3.0	2.0	19.4	3.1	7.2
Starch, % NFC	70	67.5	14.8	27.2	93.7	59.0	78.9
NDF, % DM	35.8	34.9	5.8	22.2	46.8	30.3	38.7
Lignin, % NDF	8.5	8.3	2.5	3.6	13.4	6.3	11.0
Feedstuffs							
DM, % as-fed	90	79.7	26.9	11.3	100	86	97
Fat, % DM	2.6	6.8	18.3	0	100	0.2	3.9
Ash, % DM	7.5	24.8	37.0	0	100	4.0	13.3
CP, % DM	13.5	25.4	44.0	0	281	5.8	26.8
Soluble CP, % CP	21.0	26.4	24.9	0	100	4.0	40.0
NPN, % CP	55.0	46.4	40.1	0	100	0	89.0
NDFIP, % CP	8.0	11.9	13.5	0	75	0	18.0
ADFIP, % CP	2.0	3.9	5.5	0	65	0	6.4
Starch, % NFC	64.0	54.0	39.9	0	100	0	90.0

[7] Available at http://cqbal.agropecuaria.ws/webcqbal/index.php

Items[1]	Median	Mean	SD[1]	Range		Quartiles	
				Min	Max	25%	75%
NDF, % DM	15.1	21.4	20.3	0	78.9	0	37.8
Lignin, % NDF	4.3	6.0	6.4	0	30.7	0	10.4
Animals							
SBW, kg	567	555	66.4	345	660	522	598
DMI, kg/d	19.1	19.1	3.5	9.1	27.5	17.3	22.1
DIM, days	100	114	64.7	30	265	60	150
MY, kg/d	26.3	26.4	8.3	7.6	45	19.7	32.7
Milk fat, %	3.7	3.7	0.5	2.3	5.0	3.4	4.1
Milk protein, %	3.0	3.1	0.3	2.4	3.9	2.9	3.3

[1] DM = dry matter, CP = crude protein, NPN = nonprotein nitrogen, NDF = neutral detergent fibre, NDFIP = NDF insoluble protein, ADFIP = acid detergent fibre insoluble protein, NFC = non-fibre carbohydrate, SBW = shrunk body weight, DMI = DM intake, DIM = days in milk (i.e., days after calving), MY = milk yield, and SD = standard deviation.

Most of the values for kd of the protein and carbohydrate fractions, as well as for mineral and vitamin compositions, were from the LRNS feed library. The approach adopted by Hanigan et al. (2006) was used to obtain the nutrients and fractions needed by Molly, and the ME inputted was the ME predicted by the L1 solution of the LRNS. The feedstuff DMI was calculated as the dry matter (DM) percentage of each feedstuff multiplied by the observed DMI. The data was only used if it was possible to compute DMI for animals with *ad libitum* access to feeds.

Description of the animal information

All animal information provided in the studies was used as inputs. However, when relevant information such as mature body weight was not available from the studies, the LRNS default values for each breed were used. When no information was available for pregnancy days and days since calving, values such as less than 100 days and more than 60 days, respectively, were inputted to avoid conflict. Thus, significant pregnancy requirements and negative energy balance were not accounted for. For Molly, the udder cell parameter was estimated as suggested by Palliser et al. (2001) as $179.1 \times e^{0.053 \times MY}$, in which MY is mature daily peak milk yield (L/d). Not enough information was provided to account for the effect of body weight and body condition score changes on predicted MY (Tedeschi et al., 2006). Table 1 summarizes the statistics of the animal characteristics.

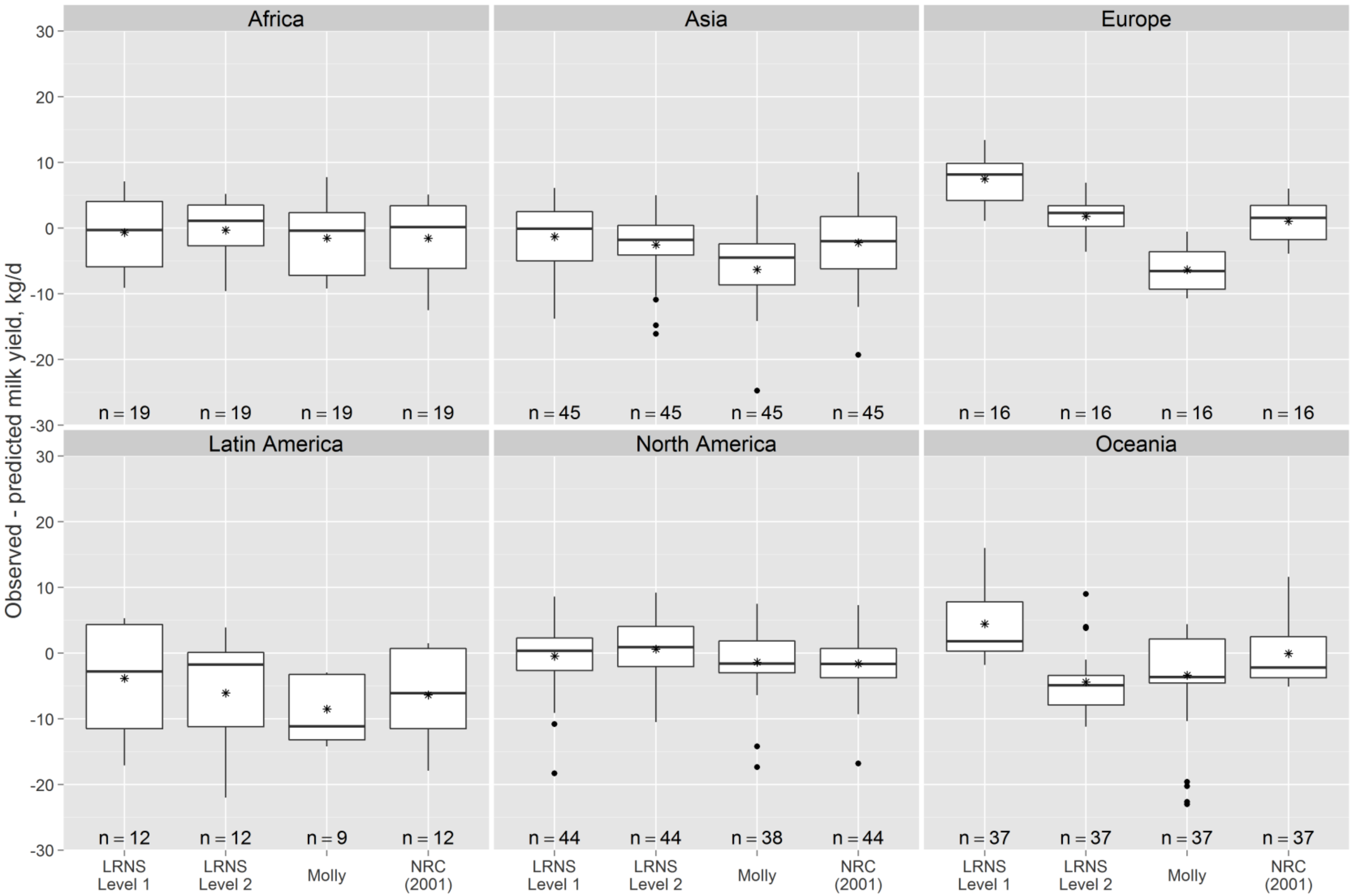
Assessment of model adequacy and regressions

The adequacy of the models was assessed by using the Model Evaluation System[8]. The models were compared on the following statistics were used: mean bias (MB); concordance correlation coefficient (CCC); model accuracy (Cb); model precision (r^2); mean square error of prediction (MSEP) and its decomposition into mean bias, systematic bias, and random errors; and MSEP square root (RMSEP) (Tedeschi, 2006). Statistical analyses were conducted with R version 3.1 (R Core Team, 2014) and graphics were generated with the *ggplot2* package (Wickham, 2009). Linear regressions used observed values as the dependent variable (Y-axis) and the predicted values as the independent variable (X-axis), and the ordinary least square linear regressions were obtained with the *lm* function (R Core Team, 2014). For random coefficient models, studies were assumed to be a random effect, and the parameter estimates were obtained with the generalized linear mixed-effects regressions using the *lme* function of the *nlme* package (Pinheiro et al., 2014). The variance components of the random coefficient models (i.e., random errors and study errors) were estimated using a diagonal positive-definite matrix constructor and only a random intercept parameter was fitted.

Results of the Model Intercomparison

Figure 3 has the boxplots of the residue of observed minus predicted MY for each model and region. Models had different MY residue distribution, and mean and median values across regions, but the MY residue for North America were the most consistent with the least variation. The MY residue for Latin American had the largest variations. Figure 4 depicts scatter plots between observed and predicted MY using the selected nutrition models. There was a disproportionate number of studies that had adequate information to execute the selected nutrition models. Quantitative information of feed nutrition models has long been lacking (Arnold and Bennett, 1991b; Sauvant, 1996), and the problem persists today. Most mechanistic models are detail-oriented systems that attempts to account for as many biological concepts and relational structures as possible. This poses a problem when evaluating these models: the needed information may not be available at all times for all production conditions. In fact, the levels of aggregation differs significantly among nutrition models for lactating ruminants (Sauvant, 1996). Model reduction techniques, such as the replacement of model variables with constants, might be an alternative for situations in which complex models have to be used with limited information (Crout et al., 2009). In fact, the simplest of the models selected for this study, LRNS L1, seemed to have the best graphical representation (i.e., less scatter around the Y = X line; Figure 4).

[8] Available at http://nutritionmodels.tamu.edu/mes.html or http://nutritionmodels.com/mes.html



Africa
Asia
Europe
Latin America
North America
Oceania
Observed - predicted milk yield, kg/d
30
20
10
0
-10
-20
-30
n = 19
n = 45
n = 16
n = 12
n = 9
n = 44
n = 38
n = 37
LRNS Level 1
LRNS Level 2
Molly
NRC (2001)

Figure 3. Boxplots of observed minus predicted milk yield (kg/d) for five models (Large Ruminant Nutrition System (LRNS) using solution levels 1 and 2, NRC (2001), and Molly) for six regions around the world (Africa, Asia, Europe, Latin America, North America, and Oceania). The box represents the first and third quartile, the whiskers (vertical lines) represent the minimum and maximum values, the horizontal line within the box represents the median, the asterisk represents the mean, and the solid dots represent outliers.

Each model has a distinct predictive behaviour, their direct comparison difficult and incomplete. This finding agrees with previous comparisons between CNCPS-based and Molly-based nutrition models (Kohn et al., 1994). These two models differ substantially in their modelling scope (i.e., applied versus biochemical) and logical structure (i.e., dynamic versus empirical)

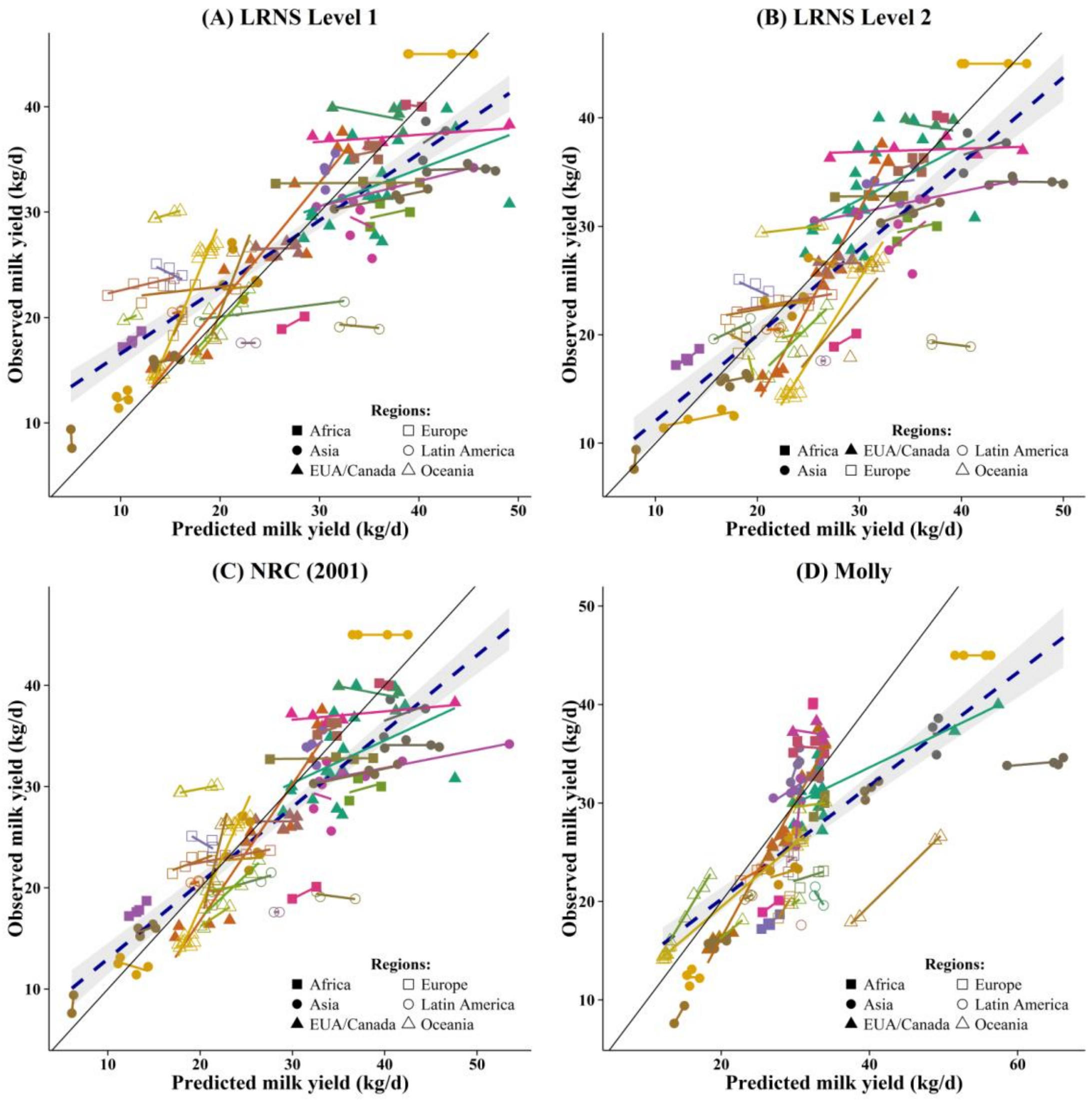


Figure 4. Relationship between observed milk yield (Y axis) and study-unadjusted predicted milk yield (X axis) by the Large Ruminant Nutrition System (LRNS) using solution levels 1 (A) and 2 (B), NRC (2001) (C), Molly (D), and Ruminant (E) for data collected from six regions around the world (Africa, ■; Asia, ●; North America, ▲; Europe, □, Latin America, ○; and Oceania, △). Studies are represented by different colours and linear trendlines. The dashed line represents the linear regression of all data points and the shaded area represents the 95% confidence interval of the linear regression. The solid diagonal line represents the Y = X line.

Table 2 lists the statistics of the models' adequacy in predicting MY. When study effect was not considered (i.e., data points within studies were assumed to be uncorrelated), MB varied from -4.06 (Molly) to 0.87 (LRNS L1) kg/d, and the RMSEP ranged from 5.6 (LRNS L2) to 8.07 (Molly) kg/d. These results suggest that, depending on the nutrition model used, a single-point prediction of MY might be between ±5.6 and ±8.07 kg/d different from the observed MY, but on average it can vary from -4.06 to 0.87 kg/d. Model precision (i.e., r2) was low to moderate and varied from 0.55 (Molly) to 0.69 (NRC, 2001). Although model accuracy (i.e., Cb) was high (> 0.88), the CCC was high for NRC (2001) (0.81), moderate for LRNS L2 (0.77) and LRNS L1 (0.79), and low for Molly (0.66) due to low model precision. The inadequacy of these models' predictions (i.e., MSEP) was mostly due to random errors for LRNS L1, LRNS L2, and NRC (2001), whereas MB was 25.4% of MSEP for Molly. These diagnostics are not that different from those reported by Tedeschi et al. (2008), who evaluated the CPM Dairy model with data on high-producing dairy cows. They found an r2 of 0.798, CCC of 0.89, Cb of 0.997, and RMSEP of 5.14 kg/d. Tylutki et al. (2008) evaluated CNCPS version 6.0 and reported improved statistics compared to ours (e.g., r2 > 0.847, CCC > 0.918, and RMSEP < 4.5 kg/d). Their evaluations indicated greater model accuracy and precision most likely because their dataset was more homogenous and their feedstuffs were standard and came with detailed physicochemical descriptions. For grass-based diets, Dijkstra et al. (2008) compared the dietary energy value predicted by the AFRC, FiM, the Dutch NE system, and a version of the Dutch Tier 3 model. They reported that the Dutch Tier 3 model (a mechanistic model) was more precise and accurate than the other three models (which, essentially, were empirical, static models). Others have found that empirical, static models can also predicted dietary energy values accurately (Kaustell et al., 1997).

For each graph in Figure 4, the inconsistency in the direction of the linear trendlines within studies suggests that the models were not accurate (and maybe not precise) within studies in predicting MY. Some study linear trendlines even have directions opposite to the Y = X line mark, indicating that as observed MY increased, models predicted less MY, or vice-versa. For other studies, a model predicted a change in MY, but observed MY was constant. In fact, most of the random variation (> 66%) was due to study effects (Table 2). This suggests that the lack of adequate inputs caused incomplete representation of the production scenarios, and that the models were unable to simulate the data because important variables were not part of the model or simply because the considerable variation within each study limited the predictability of MY. Other factors were likely not accounted for, such as inability to account for the impact of changes in body condition score on MY (Tedeschi et al., 2006). More complex models exist to predict such changes (Tedeschi et al., 2013b), but they would require even more specific inputs.

Table 2. Model adequacy statistics and variance component analysis of five models' predictions of milk yield[1]

Statistics	Milk yield not adjusted for study effect				Milk yield adjusted for study effect			
	LRNS		NRC	Molly	LRNS		NRC	Molly
	Level 1	Level 2	(2001)		Level 1	Level 2	(2001)	
N	173	173	173	164	173	173	173	164
Mean (kg/d)								
Predicted (X)	25.5	28.1	27.9	30.1	25.5	28.1	27.9	30.1
Observed (Y)	26.4	26.4	26.4	26.1	26.2	26.2	26.1	25.4
MB (kg/d)	0.87	-1.72	-1.49	-4.06	0.63	-1.88	-1.78	-4.75
r^2	0.68	0.63	0.69	0.55	0.85	0.84	0.84	0.93
CCC	0.79	0.77	0.81	0.66	0.85	0.86	0.86	0.77
Cb	0.96	0.98	0.98	0.88	0.92	0.94	0.94	0.80
MSEP								
Root (kg/d)	6.21	5.6	5.38	8.07	5.04	3.95	4.29	6.35
MB (%)	1.95	9.39	7.72	25.4	1.56	22.8	17.2	55.9
Slope (%)	40.8	9.36	18.1	29.9	69.1	32.9	42.8	36.2
Random (%)	57.3	81.3	74.2	44.7	29.3	44.3	39.9	7.87
Variances (kg^2/d^2)								
σ^2 (OLS)	22.3	25.9	21.7	29.5	7.53	6.98	7.44	3.21
$\sigma^2 + \sigma^2_{Study}$ (GLS)	27.9	27.8	27.2	37.9	—	—	—	—
σ^2_{Study} (GLS)	18.7	19.3	18.1	33.9	—	—	—	—
% of $\sigma^2 + \sigma^2_{Study}$	67.0	69.2	66.5	89.4	—	—	—	—

[1] MB = mean bias, CCC = concordance correlation coefficient, Cb = model adequacy, MSEP = mean square error of prediction, OLS = ordinary least squares (using linear models, LM), GLS = generalized least squares (using linear mixed-effects model, LME), LRNS = Large Ruminant Nutrition System, NRC = National Research Council.

When the observed MY was adjusted for the random effects of studies (Table 2) using the random coefficient models with variance components for intercept and slope, as expected, the model precision increased (> 0.84), CCC increased (> 0.77), and RMSEP decreased (< ±6.35 kg/d). These statistics are more similar to those reported by Tedeschi et al. (2008), who also had previously adjusted MY for the random effects of studies.

Whole-Farm Modelling

The animal module of process-based whole-farm models that is used to estimate the flow of elements (e.g., C, N, and P) has posed an enduring model development challenge mainly for those systems that deal with grazing conditions. This challenge is caused by the intrinsic problem of estimating the amount and quality of the forage consumed by the animal. Several whole-farm simulation models have been developed and their animal modules differ considerably. Examples of whole-farm models include Agricultural Production Systems Simulator (APIM[9]) (Moore et al., 2007), Australian Dairy Grazing Systems (DairyMod) (Johnson et al., 2008) and Sustainable Grazing Systems (SGS) (Johnson et al., 2003) (both collectively referred to as AgMod[10]), DairyNZ Whole Farm Model, Discrete Event Simulation Environment (DIESE) (Martin-Clouaire and Clouaire, 2009), EcoMod (Johnson et al., 2008), Farm Assessment Tool (FASSET[11]) (Berntsen et al., 2003), Great Plains Framework for Agricultural Resource Management (GPFARM) (Andales et al., 2003), GRAZPLAN (Donnelly et al., 1997; Moore et al., 1997), Hurley Pasture Model (HPM), Integrated Farm System Model (IFSM[12]) (Rotz et al., 2005; Rotz et al., 1999), LINCFARM, Pasture Simulation (PaSim[13]) (Graux et al., 2011), PROGRASS, and Whole Farm Model (WFM) among many other systems. Bryant and Snow (2008) reviewed nine pastoral simulation models (APSIM, EcoMod, FASSET, GRAZPLAN, GPFARM, HPM, IFSM, LINCFARM, and WFM) and concluded that there was a need to include pests and diseases on pasture production as well as improved animal performance predictions, including a more mechanistic model for voluntary feed intake and ruminal fermentation processes. More

[9] Available at http://www.apsim.info/

[10] Available at http://www.imj.com.au/consultancy/index.html

[11] Available at http://www.fasset.dk/

[12] Available at http://www.ars.usda.gov/SP2UserFiles/Place/19020000/ifsmreference.pdf

[13] Available at https://www1.clermont.inra.fr/urep/modeles/pasim.htm

recently, Snow et al. (2014) provided a brief summary of six of these models (APSIM, AgMod, DIESE, FASSET, GRAZPLAN, and IFSM) and compared their different approaches to model forage mixtures in the paddocks, animal-forage interactions, N transfers by the animal in the paddocks, management of the whole farm, and future prospects. They also provided ideas and solutions for the imminent limitations of these six models. Del Prado et al. (2013) indicated that whole-farm models are the appropriate scale for mitigating GHG emissions because the farm represents the unit at which management decisions are made. They analysed different approaches for modelling GHG. Most of these reviews discussed the strengths and drawbacks of whole-farm models, but there is a lack of model intercomparison under different production systems.

Based on our intercomparison of ruminant nutrition models and the complexity of whole-farm models, our recommendation is that simple models such as the level 1 solution of the LRNS are used with whole-farm models to predict GHG emissions. More complex nutrition models can be implemented into whole-farm models if additional needed information is available and the complexity of the model does not impede or bias the interpretation of the simulations.

Conclusion/recommendations

In the first part of this manuscript, we highlighted that though mathematical nutrition models share similar assumptions and calculations, they have different conceptual and structural foundations inherent to their intended purposes. A direct comparison among these models was further complicated by the different models requiring unique inputs that are very often not available, and the low reliability of the inputs prevents an unbiased assessment of the models' predictions. Very few studies have collected the necessary information to run more mechanistic systems, and users have to rely on standard information to simulate MY using many models. Study effect was a critical source of variation that limited our ability to conclusively evaluate the models' applicability under different scenarios of production around the world. Only after study variation was removed from the database did the adequacy of the models' predictions of milk production improve, but deficiencies still existed. Based on these analyses, we conclude that not all models are suitable for predicting milk production and that simpler systems might be more resilient to variations in studies and production conditions around the world. Improving the predictability of milk production by mathematical nutrition models is a prerequisite to further development of systems that can effectively and correctly estimate the contribution of ruminants to GHG emissions and their true share of the global warming event.

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Yan, R., R. Zhang, X. Zhang, C. Jiang, J.-g. Han, and Y.-j. Zhang. 2011. Changes in milk production and metabolic parameters by feeding lactating cows based on different ratios of corn silage: Alfalfa hay with addition of extruded soybeans. Asian Australasian J. Anim. Sci. 24:800-8009.

Yan, T., M. G. Porter, and C. S. Mayne. 2009. Prediction of methane emission from beef cattle using data measured in indirect open-circuit respiration calorimeters. Animal. 3:1455-1462.

Yarahmadi, H. M., and H. Nirumand. 2012. The influence of feeding plant oils on milk production and fatty acid content. African Journal of Agricultural Research. 7:426-432.

Ruminant Nutrition Models

Model: AusBeef

Active: ☒ Yes, ☐ No

About the software:

Questions	Responses
Development information:	
Developed by	Barry Nagorcka
Year of first developed	2000
Year of last modification	2003
Current version (major, minor, revision)	Major
Country developed	Australia
Used in which countries?	Australia
Has the model been independently evaluated?	Yes
Retail and support information:	
Marketed by (name)	CSIRO
Phone	+61 7 3214 2929
Website	
Currency and price	Licensing arrangements as requested
Format (downloadable, CD, DVD)	
How often are updates available?	
Maintenance cost (annual, monthly)	
Supported by (technical/customer support)	Technical advice available from staff
Form of support (email, phone, face-to-face)	eMail

About the model usability: (1=very simple/easy ... 5 = very difficult)

Level of technical/nutritional knowledge required:
○1/None ○2/Low ◉3/Intermediate ○4/High ○5/Advanced

Ability/readiness of the software/model to be used for climate change simulation:
○1/None ○2/Low ○3/Intermediate ◉4/High ○5/Advanced

Ability/readiness of the software/model to be used for sustainability/long-term simulation:
○1/None ○2/Low ○3/Intermediate ◉4/High ○5/Advanced

Ability/readiness of the software/model to be used for Life Cycle Analysis:
○1/None ◉2/Low ○3/Intermediate ○4/High ○5/Advanced

Ability/readiness of the software/model to be used as Object-Oriented Module (integration):
○1/None ○2/Low ◉3/Intermediate ○4/High ○5/Advanced

Ability/readiness of the software/model to be used for greenhouse gas (methane) production:
○1/None ○2/Low ○3/Intermediate ○4/High ◉5/Advanced

Ability/readiness of the software/model to be used for nutrient excretion (e.g., N, P):
○1/None ○2/Low ○3/Intermediate ○4/High ◉5/Advanced

About the model characteristics:

Is the model based on a previous model or publications? Which? Modelling Nutrient Utilization in Farm Animals(2000) Ch3 nagorcka et al.

What is the programming language of the model and the software? VisSim

What is the nature of the model: ☐ deterministic or ☐ stochastic, ☐ empirical or ☒mechanistic, ☐ static or ☐ dynamic, ☐ continuous or ☐ discrete, ☐ homo-spatial or ☐ hetero-spatial, others

Recommended for use by: ☐ farmers/producers, ☒ nutritionists/consultants, ☐ veterinarians, ☒ research/scientists, ☒ teaching/student, ☐ extension/outreach, ☐ others.

What are the objectives/purposes of the model? ____

AusBeef makes predictions about the performance of feedlot cattle using basic information about the stock and feeds they are offered. Its goal is to assist lot managers and nutritionists in the formulation of rations and the development of feeding strategies that improve animal performance, lead to a desired lean/fat ratio, reduce feed costs, and reduce effluent production.

Specific description of the model (animal species, physiological stages, rumen/ intestinal/metabolism submodels, levels of solution, lactation, growth, pregnancy, maintenance, body reserves, energy/protein calculation):____ __________

AusBeef predicts the performance of cattle. A diagram of the model components is pasted in later in this document.

How is feed intake predicted? ____

Voluntary feed intake based on feedback from levels of metabolites predicted in blood.

What are the input requirements (characterization) for animal, feeds, environment, others _________

1. Describe the feedlot
2. Describe the cattle
3. Describe the rations
4. Describe the pens (housing)
5. Describe the feeding strategy
6. Describe sales markets
7. Select report options
8. Run Simulation

____

Please provide more detailed information about the model engine and functions, user interface (graphical, command, oriented), and specify key input parameters and outputs. For example, it is important to know if the model predicts methane and how, manure output (urine + feces, or separate), mineral and vitamin requirements, animal species and types, etc.

User interface is a series of tabulated sheets
Input tabs
Feedlot (Simulation title and feedlot operational costs if required)
Cattle (Breed, Sex, frame score, age, condition score, live weight, number of animals, economic values if required)
Rations (Select from extensive database. Specific regional information on many feedgrains from different regions of Australia. Also Forages, Silages, Protein sources, Fats and oils, non-protein nitrogen, By products, mineral supplements, animal derived products, user defined feeds(not in database)) (Subtabs specify mix composition, chemical properties of ingredient, volatile chemicals, amino acid composition,fatty acid composition, physical properties (flaked etc), minerals)
Pen (Floor area, Climate; temperature, humidity, wind speed, mud depth, shaded area)
Feeding strategy (Time of feeding each defined ration, Feeding method (daily event, ad libitum etc))
Markets (Economic values required if simulation to be costed)

Outputs
Table summarizing body composition at end of simulation
Table summarizing animal performance for each feeding period
Table and chart showing feed consumed each day
Table and chart showing animal body composition (live weight, caracase weuight, lean protein, viscera protein and body fat)
Growth rates of each body component
Conversion efficviency
Digestion rates
Absorption rates
Amino acid limitations
Rumen state (pH, size of microbial populations, concentrations of VFAs)
Effluents (Nitrogen and Methane)

Please provide references pertinent to the development, evaluation, or application of the model.

Reference provided above is the only formal reference.
Other documentation resides within CSIRO

Ruminant Nutrition Models

Model: Biopara-Milk

Active: ☒ Yes, ☐ No

About the software:

Questions	Responses
Development information:	
Developed by	DR N. S. Jessop Bioparametrics Ltd.
Year of first developed	2006
Year of last modification	2013
Current version (major, minor, revision)	2.69
Country developed	United Kingdom
Used in which countries?	UK, Eire, Poland
Has the model been independently evaluated?	Yes
Retail and support information:	
Marketed by (name)	Biopara-Milk
Phone	+44 131 667-6433
Website	http://www.bioparametrics.com
Currency and price	Annual license £500 with training and user group membership
Format (downloadable, CD, DVD)	Downloadable
How often are updates available?	Quarterly
Maintenance cost (annual, monthly)	Annual £2000
Supported by (technical/customer support)	Technical and user support
Form of support (email, phone, face-to-face)	Email, phone, and face to face

About the model usability: (1=very simple/easy ... 5 = very difficult)

Level of technical/nutritional knowledge required:
○ 1/None ● 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for climate change simulation:
○ 1/None ● 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for sustainability/long-term simulation:
○ 1/None ○ 2/Low ● 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for Life Cycle Analysis:
○ 1/None ○ 2/Low ● 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used as Object-Oriented Module (integration):
○ 1/None ● 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for greenhouse gas (methane) production:
● 1/None ○ 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for nutrient excretion (e.g., N, P):
○ 1/None ● 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

About the model characteristics:

Is the model based on a previous model or publications? Which? Digestion in Ruminants

What is the programming language of the model and the software? Delphi

What is the nature of the model: ☐ deterministic or ☐ stochastic, ☐ empirical or ☒mechanistic,

____

Recommended for use by: ☒ farmers/producers, ☒ nutritionists/consultants, ☐ veterinarians, ☒ research/scientists, ☒ teaching/student, ☐ extension/outreach, ☐ others.

What are the objectives/purposes of the model? ____

Feeding ruminants correctly to maximise microbial yield and use of home grown forage reducing purchased feed to that necessary to balance carbohydrate and protein supply for cost effective milk and meat production through better rumen management

Specific description of the model (animal species, physiological stages, rumen/ intestinal/metabolism submodels, levels of solution, lactation, growth, pregnancy, maintenance, body reserves, energy/protein calculation):____ __________

The model takes ingredients proffered over the day in sequence and calculates attainable milk yield after satisfying higher priority nutrient demands under the rumen volume constraint. How much can be eaten is facilitated by 5 passage rates (liquid, small and large forage, small and large concentrate) and a maximum of 7 fermentation rates applicable to nutrient components of each ingredient. Over 24 hours from ingested ingredients and their component fermentation rates, pH flux is predicted from complex rumen dynamics. The pH and the balance between carbohydrate and protein influence how much is fermented and the balance between new microbial matter and VFA's produced. Over a day, absorbed from the gut is a proportion of rumen microbes and VFA's produced and that which escapes into the small intestine (glucose and starch from escaped sugars, starch and microbial matter, amino acids from escaped protein and from microbial matter, fats from microbial matter and escaped fats and that produced in the hind-gut (VFAs).

Nutrient supply is then used to predict milk yield and/ or body weight change (separated for protein and lipid).

The models can be scaled for all ruminant species. Commercial use is mainly in dairy and beef cattle. Whilst fairly close agreement can be reached on energy and protein requirements for all functions nutrient supply depends on ability to manage the rumen environment. It is necessary to model microbial populations and their response to pH flux independently of the host animal.

How is feed intake predicted? ____

Through mechanistic simulation of degradation and passage so refill is a consequence

What are the input requirements (characterization) for animal, feeds, environment, others _________

Animals lactating: mature body weight, condition score, lactation potential, milk composition, cohort (heifers, 2nd lactation or 3+), week of lactation.
Animals growing: current weight, condition score, sex and mature size of animal.
Feeds: a library of ingredients fully analysed. Forages: Bioparametric analysis reports contain all of the data including degradation rates and necessary lag times.
The current models assume a thermo-neutral environment but can be adapted for heat stress and cold thermogenesis.

____

Please provide more detailed information about the model engine and functions, user interface (graphical, command, oriented), and specify key input parameters and outputs. For example, it is important to know if the model predicts methane and how, manure output (urine + feces, or separate), mineral and vitamin requirements, animal species and types, etc.

More detailed info:
Biopara-Milk runs as an exe file under Windows.
Biopara-Milk was developed from basic principles of rumen function, bacterial growth, feed digestion and passage rates, and animal physiology (maintenance, growth, lactation, pregnancy, and body reserves).
It is a simulation model that has a time-step of six minutes 10 per hour, and is run for 20 days per a one day output. Every simulated day, the outputs are checked and if necessary, the rumen fill is adjusted up (there is a maximum) or down for the next simulated day. A steady state is reached by 20 days in less than half a second.
Methane is produced from stoichiometries of microbial fermentation along with differing patterns of VFAs. There are five groups of microbe, each with a specific role. Each group represents the actions of many microbial species.
Rumen pH is predicted by continuous monitoring of the levels of bicarbonate and protons within the rumen. Bicarbonate is produced from saliva (rest, eating and ruminating) as well as additions in the diet. Protons are produced from fermentation producing or addition of acids. VFA and lactic acids are removed by absorption. Bicarbonate and protons are subject to liquid and solid flow.

Rumen pH affects the maintenance requirement of all groups of microbes. The cellulolytic ones are most affected so that reductions in pH cause an increase in the maintenance requirement of the microbes. Therefore their growth rate decreases.
The Well Cow bolus (intra-ruminal pH bolus) has been used to validate the method that Biopara-Milk uses to predict pH.

The ruminal carbohydrate to protein ratio can influence ruminal fermentation. If there is not enough protein to carbohydrate, the rate of fermentation of carbohydrate drops. Reduced fermentation causes material to remain longer in the rumen reducing dry matter intake.

Please provide references pertinent to the development, evaluation, or application of the model.

Commercial evaluation is provided through matching intake and performance characteristics on farm.

References:
Emmans, G.C. (1997). A Method to Predict the Food Intake of Domestic Animals from Birth to Maturity as a Function of Time. J Theor Biol 186, 189 – 199

Friggens N. C., Ingvartsen K. L., and Emmans, G. C. (2004). Prediction of Body Lipid Change in Pregnancy and Lactation. J. Dairy Sci. 87, 988 – 1000

Gordon, I J. and Illius, A. W. (1996). The nutritional ecology of African ruminants: a reinterpretation. Ecology 65, 18-28

Dijkstra, J., Ellis, J. L., Kebreab, E., Strathe, A. B., López, S., France, J., Bannink, A. (2012). Ruminal pH regulation and nutritional consequences of low pH. Animal Feed Science and Technology 172, 22– 33

Mertens, D. R. and Ely, L. O. (1979). A dynamic model of fiber digestion and passage in the ruminant for evaluating forage quality. J Anim Sci 49, 1088 – 1095

Jessop, N. S. and Herrero, M. (1996). Influence of soluble components on parameter estimation using the in vitro gas production technique. Anim. Sci. 62, 626-627

Rymer, C. and Givens, D. I. (1998). The effect of fibre quality on cow health and performance. Milk Development Council, a review Project number 98/R1/10

Ruminant Nutrition Models

Model: Dairy Gas Emission Model (DairyGEM) Active: ✔ Yes, No

About the software:

Questions	Responses
Development information:	
Developed by	C. Alan Rotz et al.
Year of first developed	Some of the original work began around 1980
Year of last modification	2010
Current version (major, minor, revision)	Version 2.6
Country developed	USA
Used in which countries?	Many countries, primarily US, Canada and northern Europe
Has the model been independently evaluated?	Only by other users
Retail and support information:	
Marketed by (name)	USDA / Agricultural Research Service
Phone	814-865-2049
Website	http://www.ars.usda.gov/Main/docs.htm?docid=2269
Currency and price	No charge
Format (downloadable, CD, DVD)	Internet download
How often are updates available?	Annually
Maintenance cost (annual, monthly)	None
Supported by (technical/customer support)	Support is limited; email, phone and face to face
Form of support (email, phone, face-to-face)	

About the model usability: (1=very simple/easy … 5 = very difficult)

Level of technical/nutritional knowledge required:
○ 1/None ○ 2/Low ● 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for climate change simulation:
○ 1/None ○ 2/Low ○ 3/Intermediate ● 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for sustainability/long-term simulation:
○ 1/None ○ 2/Low ○ 3/Intermediate ○ 4/High ● 5/Advanced

Ability/readiness of the software/model to be used for Life Cycle Analysis:
○ 1/None ○ 2/Low ○ 3/Intermediate ○ 4/High ● 5/Advanced

Ability/readiness of the software/model to be used as Object-Oriented Module (integration):
○ 1/None ○ 2/Low ● 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for greenhouse gas (methane) production:
○ 1/None ○ 2/Low ○ 3/Intermediate ○ 4/High ● 5/Advanced

Ability/readiness of the software/model to be used for nutrient excretion (e.g., N, P):
○ 1/None ○ 2/Low ○ 3/Intermediate ○ 4/High ● 5/Advanced

About the model characteristics:

Is the model based on a previous model or publications? Which? Earliest version was called DairyGHG

What is the programming language of the model and the software? Fortran and C++

What is the nature of the model: × deterministic or stochastic, empirical or × mechanistic,

____

Recommended for use by: farmers/producers, × nutritionists/consultants, veterinarians, × research/scientists, × teaching/student, × extension/outreach, others.

What are the objectives/purposes of the model? ____

Primarily an educational tool for evaluating air emissions and environmental footprints of dairy production systems.

Specific description of the model (animal species, physiological stages, rumen/ intestinal/metabolism submodels, levels of solution, lactation, growth, pregnancy, maintenance, body reserves, energy/protein calculation):____ __________

Dairy cattle; whole herd including heifers and dry cows; nutrient requirements are based upon NRC and CNCPS; an LP is used to determine optimal diets for each animal group based upon their requirements and available feeds.

How is feed intake predicted? ____

A function of NDF and NDF digestibility based upon work of Dave Mertens and Mike Allen

What are the input requirements (characterization) for animal, feeds, environment, others _________

Important input parameters include available feeds and their nutrient contents, animal breed characteristics, housing facilities, and manure handling methods.

____

Please provide more detailed information about the model engine and functions, user interface (graphical, command, oriented), and specify key input parameters and outputs. For example, it is important to know if the model predicts methane and how, manure output (urine + feces, or separate), mineral and vitamin requirements, animal species and types, etc.

DairyGEM consists of the animal and manure handling components of the IFSM model. This provides a simpler tool, primarily for educational purposes. There are fewer input requirements and more graphical output compared to IFSM. The model is used to study air emissions and environmental (carbon, energy and water) footprints of dairy production systems.

Feed allocation and animal responses are related to the nutrient contents of available feeds and the nutrient requirements of the animal groups making up the herd. The quantity and nutrient contents of the manure produced are a function of the feeds consumed and herd characteristics. Nutrient flows are tracked through the farm to predict air emissions and carbon, energy and water footprints for the milk produced. Carbon dioxide, methane, and nitrous oxide emissions are tracked from feed, animal, and manure sources and sinks to predict net greenhouse gas emission. Other important emissions include ammonia and hydrogen sulfide. Fifteen year simulations provide longterm average annual emissions and footprints.

Please provide references pertinent to the development, evaluation, or application of the model.

1. Chianese, D.S., C.A. Rotz and T.L. Richard. Simulation of carbon dioxide emissions from dairy farms to assess greenhouse gas reduction strategies. Trans. ASABE 52(4):1301-1312. 2009.
2. Chianese, D.S., C.A. Rotz and T.L. Richard. Simulation of methane emissions from dairy farms to assess greenhouse gas reduction strategies. Trans. ASABE 52(4):1313-1323. 2009.
3. Chianese, D.S., C.A. Rotz and T.L. Richard. Simulation of nitrous oxide emissions from dairy farms to assess greenhouse gas reduction strategies. Trans. ASABE 52(4):1325-1335. 2009.
4. Montes, F., A. Rotz, and H. Chaoui. 2009. Process modeling of ammonia volatilization from ammonium solution and manure surfaces. Trans. ASABE 52(5):1707-1719.
5. Rotz, C.A., F. Montes and D.S. Chianese. 2010. The carbon footprint of dairy production systems through partial life cycle assessment. J. Dairy Sci. 93(3):1266-1282.
6. Rotz, C.A., D.S. Chianese, F. Montes, and S.D. Hafner. 2012. Dairy Gas Emissions Model: Reference Manual. University Park, PA: USDA Agricultural Research Service. Available at: http://www.ars.usda.gov/Main/docs.htm?docid=21345.

Ruminant Nutrition Models

Model: Dutch Tier 3 for Enteric Methane in Cows Active: ☒ Yes, ☐ No

About the software:

Questions	Responses
Development information:	
Developed by	Jan Dijkstra, Jim France, Jonathan Mills, Andre Bannink
Year of first developed	1992
Year of last modification	2008
Current version (major, minor, revision)	Major
Country developed	NL, UK
Used in which countries?	NL, UK, CA, US
Has the model been independently evaluated?	Yes, but mostly by model developers themselves
Retail and support information:	
Marketed by (name)	NA, interface currently built trough
Phone	NA (Andre Bannink)
Website	NA
Currency and price	NA
Format (downloadable, CD, DVD)	NA yet
How often are updates available?	NA
Maintenance cost (annual, monthly)	NA
Supported by (technical/customer support)	NA
Form of support (email, phone, face-to-face)	NA yet

About the model usability: (1=very simple/easy ... 5 = very difficult)

Level of technical/nutritional knowledge required:
○ 1/None ○ 2/Low ● 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for climate change simulation:
○ 1/None ○ 2/Low ○ 3/Intermediate ● 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for sustainability/long-term simulation:
○ 1/None ○ 2/Low ○ 3/Intermediate ● 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for Life Cycle Analysis:
○ 1/None ○ 2/Low ○ 3/Intermediate ● 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used as Object-Oriented Module (integration):
○ 1/None ○ 2/Low ○ 3/Intermediate ● 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for greenhouse gas (methane) production:
○ 1/None ● 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for nutrient excretion (e.g., N, P):
○ 1/None ● 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

About the model characteristics:

Is the model based on a previous model or publications? Which? Dijkstra, Mills, Bannink

What is the programming language of the model and the software? ACSL

What is the nature of the model: ☒ deterministic or ☐ stochastic, ☐ empirical or ☒mechanistic, Multicompartment digestive tract ruminant

____

Recommended for use by: ☐ farmers/producers, ☒ nutritionists/consultants, ☐ veterinarians, ☒ research/scientists, ☒ teaching/student, ☒ extension/outreach, ☒ others policy makers, inventories

What are the objectives/purposes of the model? ____

The aim of the model is to predict the response of dairy cows to nutritional strategies in terms of enteric fermentation and intestinal digestion, nutrients absorbed, milk production based on most limiting nutrient or energy, excretion with urine and feces, and methane emission.

Specific description of the model (animal species, physiological stages, rumen/ intestinal/metabolism submodels, levels of solution, lactation, growth, pregnancy, maintenance, body reserves, energy/protein calculation):____ __________

The model represents the mechanisms of microbial activity and substrate fermentation in the rumen and hindgut of lactating cows. Predicted microbial fermentation is hence an outcome of concentration of fermentable material and the concentration of micro-organisms present.

Other aspects (intestinal digestion, metabolism, milk production, excretion) are described by empirical equations comparable to energy and protein evaluation systems.

The current Tier 3 only rumen and hindgut submodels are included. The newest model version includes an adapted rumen and hindgut submodel, as well as an intestinal submodel.

How is feed intake predicted? ____

Not predicted, but a model input

What are the input requirements (characterization) for animal, feeds, environment, others _________

Characterisation of feed intake and feed composition. Feed composition to be calculated from dietary ingredients with known chemical composition (soluble carbohydrates, starch, NDF, CP, ammonia, fat, ash, VF A) and intrinsic (in situ) degradation characteristics (soluble/washable, potentially degradable and undegradable fraction, fractional degradation rate degradable fraction for starch, NDF and CP).

Facultatively, empirical equations for rumen passage rate (solids, fluid) and volume (fluid), and diurnal pH dynamics can be given as an input. This particularly holds when the model is applied to other species such as beef(e.g. correction VFA for effect of monensin).

Please provide more detailed information about the model engine and functions, user interface (graphical, command, oriented), and specify key input parameters and outputs. For example, it is important to know if the model predicts methane and how, manure output (urine + feces, or separate), mineral and vitamin requirements, animal species and types, etc.

The user interface is the ACSL platform at the moment.

The model engine is a representation of the mechanisms of fermentation processes, including pool sizes for various substrates, three classes of micro-organisms (amylolytic bacteria, fibrolytic bacteria and protozoa) and intraruminal recycling (microbial death and predation), and urea recycling from blood, and including absorptive processes for VF A and ammonia.

The model is standard used for dairy cattle. Beef or dry cows seems possible as well though.

The model requires feed intake and feed composition and degradation characteristics as an input. It predicts methane emission from rumen and hindgut, VF A molar proportions and hydrogen balance, and the Ym factor for methane emission. Also, excreta composition and volume can be predicted (not used with the application as Tier 3 though) with a characterisation of compounds in urine and feces.

Please provide references pertinent to the development, evaluation, or application of the model.

Development:
Bannink A, Van Schijndel MW, Dijkstra J, 2011. A model of enteric fermentation in dairy cows to estimate methane emission for the Dutch National Inventory Report using the IPCC Tier 3 approach. Animal Feed Science and Technology 166-167,603-618.

Bannink, A., France, J., Lopez, S., Gerrits, W.J.J., Kebreab, E., Tamminga, S., Dijkstra, J., 2008. Modelling the implication of feeding strategy on rumen fermentation and functioning of the mmen wall. Anim. Feed Sci. Technol. 143, 3-26.

Bannink, A., Kogut, J., Dijkstra, J., France, J., Kebreab, E., Van Vuuren, A.M., Tamminga, S., 2006. Estimation of the stoichiometry of volatile fatty acid production in the mmen of lactating dairy cows. J. Theor. Biol. 238, 36-51.

Dijkstra, J., Neal, H.D., St., C., Beever, D.E., France, J., 1992. Simulation of nutrient digestion, absorption and outflow in the rumen: model description. J. Nutr. 122, 2239-2256.

Mills, J.A.N., Dijkstra, J., Bannink, A., Cammell, S.B., Kebreab, E., France, J., 2001. A mechanistic model of whole-tract digestion and methanogenesis in the lactating dairy cow: model development, evaluation, and application. J. Anim. Sci. 79, 1584-1597.

Evaluation:
Alemu, A. W., J. Dijkstra, A. Bannink, J. France, and E. Kebreab. 2011. Rumen stoichiometric models and their contribution and challenges in predicting enteric methane production. Anirn. Feed Sci. Technol. 166--167:761-778.

Ellis JL, Dijkstra J, Bannink A, Parsons AJ, Rasmussen S, Edwards GR, Kebreab E, France J: The effect of high-sugar grass on predicted nitrogen excretion and milk yield simulated using a dynamic model. Journal ofDairy Science 2011, 94:3105-3118.

Ellis, J.L., J. Dijkstra, J. France, A. J. Parsons, G. R. Edwards, S. Rasmussen, E. Kebreab, A. Bannink, 2012. Effect of high-sugar grasses on methane emissions simulated using a dynamic model Journal of Dairy Science 95 :272-285.

Morvay, Y., A. Bannink, J. France, E. Kebreab, and J. Dijkstra, 2011. Evaluation of models to predict the stoichiometry of volatile fatty acid profiles in rumen fluid oflactating Holstein cows. J. Dairy Sci. 94 :3063-3080

Application:
Bannink A, Van Schijndel MW, Dijkstra J: A model of enteric fermentation in dairy cows to estimate methane emission for the Dutch National Inventory Report using the IPCC Tier 3 approach. Animal Feed Science and Technology 2011, 166-167:603-618.

Bannink A, Smits MCJ, Kebreab E, Mills JAN, Ellis JL, K1op A, France J, Dijkstra J, 2010. Simulating the effects of grassland management and grass ensiling on methane emission from lactating cows. Journal of Agricultural Science 148:55-72.

J Dijkstra, O. Oenerna and A Bannink. 2011. Dietary strategies to reducing N excretion from cattle: implications for methane emissions. Current Opinion in Environmental Sustainability 2011,3:414--422.

Dijkstra J, Kebreab E, Mills JAN, Pellikaan WF, Lopez S, Bannink A, France J. 2007. From nutrient requirement to animal response: predicting the profile of nutrients available for absorption in dairy cattle. Animal1:99-111.

Ellis JL, Dijkstra J, Bannink A, Parsons AJ, Rasmussen S, Edwards GR, Kebreab E, France J: The effect of high-sugar grass on predicted nitrogen excretion and milk yield simulated using a dynamic model. Journal of Dairy Science 2011, 94:3105-3118.

Ruminant Nutrition Models

Model: Integrated Farm System Model (IFSM) Active: ✔ Yes, No

About the software:

Questions	Responses
Development information:	
Developed by	C. Alan Rotz et al.
Year of first developed	Some of the original work began around 1980
Year of last modification	2012
Current version (major, minor, revision)	Version 3.6
Country developed	USA
Used in which countries?	Many countries, primarily US, Canada and northern Europe
Has the model been independently evaluated?	Not sure what this implies, been evaluated by many
Retail and support information:	
Marketed by (name)	USDA / Agricultural Research Service
Phone	814-865-2049
Website	http://www.ars.usda.gov/Main/docs.htm?docid=2269
Currency and price	No charge
Format (downloadable, CD, DVD)	Internet download
How often are updates available?	Annually
Maintenance cost (annual, monthly)	None
Supported by (technical/customer support)	Support is limited; email, phone and face to face
Form of support (email, phone, face-to-face)	

About the model usability: (1=very simple/easy ... 5 = very difficult)

Level of technical/nutritional knowledge required:
○ 1/None ○ 2/Low ● 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for climate change simulation:
○ 1/None ○ 2/Low ○ 3/Intermediate ● 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for sustainability/long-term simulation:
○ 1/None ○ 2/Low ○ 3/Intermediate ○ 4/High ● 5/Advanced

Ability/readiness of the software/model to be used for Life Cycle Analysis:
○ 1/None ○ 2/Low ○ 3/Intermediate ○ 4/High ● 5/Advanced

Ability/readiness of the software/model to be used as Object-Oriented Module (integration):
○ 1/None ○ 2/Low ● 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for greenhouse gas (methane) production:
○ 1/None ○ 2/Low ○ 3/Intermediate ○ 4/High ● 5/Advanced

Ability/readiness of the software/model to be used for nutrient excretion (e.g., N, P):
○ 1/None ○ 2/Low ○ 3/Intermediate ○ 4/High ● 5/Advanced

About the model characteristics:

Is the model based on a previous model or publications? Which? Originally known as DAFOSYM

What is the programming language of the model and the software? Fortran and C++

What is the nature of the model: × deterministic or stochastic, empirical or × mechanistic,

____

Recommended for use by: farmers/producers, × nutritionists/consultants, veterinarians, × research/scientists, × teaching/student, × extension/outreach, others

What are the objectives/purposes of the model? ______________________________

Primarily a research tool for evaluating the environmental impact and economic sustainability of crop, dairy and beef production systems.

Specific description of the model (animal species, physiological stages, rumen/ intestinal/metabolism submodels, levels of solution, lactation, growth, pregnancy, maintenance, body reserves, energy/protein calculation):______________________________

Dairy and beef cattle; whole herd including heifers and dry cows; nutrient requirements are based upon NRC and CNCPS; an LP is used to determine optimal diets for each animal group based upon their requirements and available feeds.

How is feed intake predicted? ______________________________

A function of NDF and NDF digestibility based upon work of Dave Mertens and Mike Allen

What are the input requirements (characterization) for animal, feeds, environment, others _________

Important input include all aspects of the farm system (crops, machinery, tillage and harvest information, animals, manure handling, etc.). Important animal/feed parameters include animal breed characteristics and nutritive contents of purchased feeds. The model predicts the nutritive content of farm produced feeds.

____

Please provide more detailed information about the model engine and functions, user interface (graphical, command, oriented), and specify key input parameters and outputs. For example, it is important to know if the model predicts methane and how, manure output (urine + feces, or separate), mineral and vitamin requirements, animal species and types, etc.

Crop production, feed use, and the return of manure nutrients back to the land are simulated for many years of weather on a crop, beef, or dairy farm. Growth and development of crops are predicted for each day based upon soil water and N availability, ambient temperature, and solar radiation. Simulated tillage, planting, harvest, storage, and feeding operations predict resource use, timeliness of operations, crop losses, and nutritive quality of feeds as influenced by weather. Feed allocation and animal responses are related to the nutrient contents of available feeds and the nutrient requirements of the animal groups making up the herd. The quantity and nutrient contents of the manure produced are a function of the feeds consumed and herd characteristics.

Nutrient flows are tracked through the farm to predict nutrient losses to the environment and potential accumulation in the soil. Environmental losses include denitrification and leaching losses of N from the soil, erosion of sediment across the farm boundaries, and the runoff of sediment-bound and dissolved phosphorus. Carbon dioxide, methane, and nitrous oxide emissions are tracked from crop, animal, and manure sources and sinks to predict net greenhouse gas emission. Whole-farm mass balances of nitrogen, phosphorus, potassium, and carbon are determined as the sum of nutrient imports in feed, fertilizer, deposition, and legume fixation minus the nutrient exports in milk, excess feed, animals, manure, and losses leaving the farm.

Simulated performance is used to determine production costs, incomes, and economic return for each year of weather. A whole-farm budget includes fixed and variable production costs. All important production costs are subtracted from the total income received for milk, animal, and feed sales to determine a net return to management. By comparing simulation results, differences among production systems are determined, including annual resource use, production efficiency, environmental impacts, production costs, and farm profit. Simulations are conducted over a 25 year sample of recent historical weather, so the resulting distribution of annual predictions represents the effects of varying weather. The model can also be used to simulate farm systems over projected future climate scenarios to assist the adaptation of farms to climate change.

Please provide references pertinent to the development, evaluation, or application of the model.

Major publications since 2005:

1. Rotz, C.A., D.R. Buckmaster, and J.W. Comerford. A beef herd model for simulating feed intake, animal performance, and manure excretion in farm systems. J. Anim. Sci. 83:231-242. 2005.
2. Rotz, C.A., D.L. Zartman and K.L. Crandall. Economic and environmental feasibility of a perennial cow dairy farm. J. Dairy Sci. 88:3009-3019. 2005.
3. Rotz, C.A. and T.M. Harrigan. Predicting suitable days for field operations in a whole farm simulation. Applied Eng. Agric. 21(4):563-571. 2005.
4. Rotz, C.A. and J. Oenema. Predicting management effects on ammonia emissions from dairy and beef farms. Trans. ASAE 49(4):1139-1149. 2006.
5. Rotz, C.A., J. Oenema, and H. van Keulen. Whole farm management to reduce nitrogen losses from dairy farms: a simulation study. Applied Eng. Agric. 22(5):773-784. 2006.
6. Corson, M.S., C.A. Rotz, and R.H. Skinner. Evaluating warm-season grass production in temperate-region pastures: a simulation approach. Agric. Systems 93 (1-3): 252-268. 2007.
7. Crosson, P., C.A. Rotz and M.A. Sanderson. Conversion from corn to grassland provides economic and environmental benefits to a Maryland beef farm. Online. Forage and Grazinglands doi:10.1094/FG-2007-0119-01-RS. 2007.
8. Crosson, P., C.A. Rotz, P. O'Kiely, F.P. O'Mara, M. Wallace, R.P.O. Schulte. Modeling the nitrogen and phosphorus inputs and outputs of financially optimal Irish beef production systems. Applied Eng. Agric. 23(3):369-377. 2007.
9. Ghebremichael, L.T., P.E. Cerosaletti, T.L. Veith, C.A. Rotz., J.M. Hamlett, and W.J. Gburek. Economic and phosphorus-related effects of precision feeding and forage management at a farm scale. J. Dairy Sci. 90:3700-3715. 2007.
10. Sedorovich, D.M., C.A. Rotz, P.A. Vadas, and R.D. Harmel. Simulating management effects on phosphorus loss from farming systems. Trans. ASAE 50(4):1443-1453. 2007.
11. Rotz, C.A., G.H. Kamphuis, H.D. Karsten and R.D. Weaver. Organic dairy production systems in Pennsylvania: a case study evaluation. J Dairy Sci. 90:3961-3979. 2007.
12. Corson, M.S., C.A. Rotz, R.H. Skinner, M.A. Sanderson. Adaptation and evaluation of the integrated farm system model to simulate temperate multiple-species pastures. Agric. Systems 94(2):502-508. 2007.
13. García, A.M., T.L. Veith, P.J.A. Kleinman, C.A. Rotz, and L.S. Saporito. Assessing manure management strategies through small-plot research and whole-farm modeling. J. Soil Water Conserv. 63(4): 204-211. 2008.
14. Chianese, D.S., C.A. Rotz, and T.L. Richard. Whole-farm greenhouse gas emissions: a review with application to a Pennsylvania dairy farm. Appl. Eng. Agric. 25(3):431-442. 2009.
15. Chianese, D.S., C.A. Rotz and T.L. Richard. Simulation of carbon dioxide emissions from dairy farms to assess greenhouse gas reduction strategies. Trans. ASABE 52(4):1301-1312. 2009.
16. Chianese, D.S., C.A. Rotz and T.L. Richard. Simulation of methane emissions from dairy farms to assess greenhouse gas reduction strategies. Trans. ASABE 52(4):1313-1323. 2009.
17. Chianese, D.S., C.A. Rotz and T.L. Richard. Simulation of nitrous oxide emissions from dairy farms to assess greenhouse gas reduction strategies. Trans. ASABE 52(4):1325-1335. 2009.
18. Rotz, C.A., K.J. Soder, R.H. Skinner, C.J. Dell, P.J. Kleinman, J.P. Schmidt, and R.B. Bryant. 2009. Grazing can reduce the environmental impact of dairy production systems. Online. Forage and Grazinglands doi:10.1094/FG-2009-0916-01-RS.
19. Ghebremichael, L.T., T.L. Veith, P.E. Cerosaletti, D.R. Dewing, and C.A. Rotz. 2009. Exploring economically and environmentally viable northeastern dairy farm strategies for coping with rising corn grain prices. J. Dairy Science 92:4086-4099.
20. Montes, F., A. Rotz, and H. Chaoui. 2009. Process modeling of ammonia volatilization from ammonium solution and manure surfaces. Trans. ASABE 52(5):1707-1719.
21. Rotz, C.A., F. Montes and D.S. Chianese. 2010. The carbon footprint of dairy production systems through partial life cycle assessment. J. Dairy Sci. 93(3):1266-1282.
22. Deak, A., M.H. Hall, M.A. Sanderson, A. Rotz, and M. Corson. 2010. Whole farm evaluation of forage mixtures and grazing strategies. Agron. J. 102:1201-1209.
23. Rotz, C.A., P.J.A. Kleinman, C.J. Dell, T.L. Veith, and D.B. Beegle. 2011. Environmental and economic comparisons of manure application methods in farming systems. J Environ. Quality 40:438-448.
24. Belflower, J.B., J.K. Bernard, D.K. Gattie, D.W. Hancock, L.M. Risse, C.A. Rotz. 2012. A case study of the potential environmental impacts of different dairy production systems in Georgia. Agric. Systems 108:84-93.
25. Stackhouse-Lawson, K.R., C. A. Rotz, J. W. Oltjen, and F. M. Mitloehner. 2012. Carbon footprint and ammonia emissions of California beef production systems. J. Anim. Sci. 90:4641-4655.
26. Stackhouse-Lawson, K.R., C.A. Rotz, J.W. Oltjen, and F.M. Mitloehner. 2012. Growth-promoting technologies decrease the carbon footprint, ammonia emissions, and costs of California beef production systems. J. Anim. Sci. 90:4656-4665.
27. Rotz, C.A., M.S. Corson, D.S. Chianese, F. Montes, S.D. Hafner, and C.U. Coiner. 2012. Integrated Farm System Model: Reference Manual. University Park, PA: USDA Agricultural Research Service. Available at: http://www.ars.usda.gov/Main/docs.htm?docid=8519.

Ruminant Nutrition Models

Model: INRAtion

Active: ☒ Yes, ☐ No

About the software:

Questions	Responses
Development information:	
Developed by	INRA PHASE division
Year of first developed	1991
Year of last modification	2010
Current version (major, minor, revision)	4.07
Country developed	France
Used in which countries?	Pologne, Irlande,
Has the model been independently evaluated?	yes?
Retail and support information:	
Marketed by (name)	Educagri (Dijon France)
Phone	
Website	www.inration.educagri.fr
Currency and price	450€
Format (downloadable, CD, DVD)	downloadable CD
How often are updates available?	if necessary
Maintenance cost (annual, monthly)	no
Supported by (technical/customer support)	no
Form of support (email, phone, face-to-face)	no

About the model usability: (1=very simple/easy … 5 = very difficult)

Level of technical/nutritional knowledge required:
○ 1/None ○ 2/Low ◉ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for climate change simulation:
○ 1/None ○ 2/Low ◉ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for sustainability/long-term simulation:
○ 1/None ◉ 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for Life Cycle Analysis:
○ 1/None ◉ 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used as Object-Oriented Module (integration):
○ 1/None ○ 2/Low ○ 3/Intermediate ◉ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for greenhouse gas (methane) production:
○ 1/None ◉ 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for nutrient excretion (e.g., N, P):
○ 1/None ○ 2/Low ○ 3/Intermediate ◉ 4/High ○ 5/Advanced

About the model characteristics:

Is the model based on a previous model or publications? Which? INRA books "nutrition of ruminants"

What is the programming language of the model and the software? Turbo Pascal Delphi/ Windew

What is the nature of the model: ☒ deterministic or ☐ stochastic, ☒ empirical or ☒mechanistic, ☒ static or ☐ dynamic, ☐ continuous or ☐ discrete, ☐ homo-spatial or ☐ hetero-spatial, others Not only one model but several

Recommended for use by: ☐ farmers/producers, ☒ nutritionists/consultants, ☐ veterinarians, ☐ research/scientists, ☒ teaching/student, ☒ extension/outreach, ☐ others

What are the objectives/purposes of the model? ____

INRAtion is a software which calculate daily diets for all french types of ruminants from a list of feedstuffs forages concentrates and animal characteristics

Specific description of the model (animal species, physiological stages, rumen/ intestinal/metabolism submodels, levels of solution, lactation, growth, pregnancy, maintenance, body reserves, energy/protein calculation):____

animal type : Dairy and beef cattle , Ewes, Goats
Young : growing or finishing
Animal characteristics : breed age, sex LW BCS
Animal Physiological stage (pregnant, lactation dry) date of calving ...

Feedstuffs characteristics (forage concentrate Net energy (UFL, UFV) Proteins digestibles in the intestine (PDI E/ PDI N)

Inside keeping / pasturing

Diet Calculation by of intake / energy / protein requirements

How is feed intake predicted? ____

By INRA fill unit system (including models of sustitution between forages ans concentrates

What are the input requirements (characterization) for animal, feeds, environment, others _________

Inputs : description of feedstuffs (age type chemical analysis) from the INRA tables or from user table . (need to use the INRA systems)
description of animals and the expected performance (or no performance at all)

Please provide more detailed information about the model engine and functions, user interface (graphical, command, oriented), and specify key input parameters and outputs. For example, it is important to know if the model predicts methane and how, manure output (urine + feces, or separate), mineral and vitamin requirements, animal species and types, etc.

Model engines are described in the INRA book. (in french and spanish).

No possibility to get directly methane in the available version
but availability of Nitrogen outputs or retained,
Calculated requirement in Phosphorus and calcium. Very simple prediction of oligo vitamin requirements.

Please provide references pertinent to the development, evaluation, or application of the model.

INRAtion :
Educagri éditions
26 bd Docteur Petitjean
BP 87999
21079 Dijon cedex
France

Alimentation des bovins, ovins et caprins. Besoins des animaux Valeurs des aliments
Tables INRA 2007 Quae Ed., 78026 Versailles, France)

Alimentation des ruminants 2007– INRA Productions Animales., N° 20, (4 articles).

Ruminant Nutrition Models

Model: Karoline

Active: ☒ Yes, ☐ No

About the software:

Questions	Responses
Development information:	
Developed by	Nordic scientists
Year of first developed	1998
Year of last modification	2004 (2013 Pekka Huhtanen)
Current version (major, minor, revision)	KarolineI
Country developed	Nordic
Used in which countries?	Sweden and Finland - on a research basis
Has the model been independently evaluated?	Yes
Retail and support information:	
Marketed by (name)	None
Phone	
Website	
Currency and price	
Format (downloadable, CD, DVD)	
How often are updates available?	
Maintenance cost (annual, monthly)	
Supported by (technical/customer support)	
Form of support (email, phone, face-to-face)	

About the model usability: (1=very simple/easy ... 5 = very difficult)

Level of technical/nutritional knowledge required:
○ 1/None ○ 2/Low ○ 3/Intermediate ● 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for climate change simulation:
○ 1/None ● 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for sustainability/long-term simulation:
○ 1/None ● 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for Life Cycle Analysis:
● 1/None ○ 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used as Object-Oriented Module (integration):
○ 1/None ● 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for greenhouse gas (methane) production:
○ 1/None ○ 2/Low ○ 3/Intermediate ○ 4/High ● 5/Advanced

Ability/readiness of the software/model to be used for nutrient excretion (e.g., N, P):
○ 1/None ○ 2/Low ○ 3/Intermediate ● 4/High ○ 5/Advanced

About the model characteristics:

Is the model based on a previous model or publications? Which? No

What is the programming language of the model and the software? Powersim

What is the nature of the model: ☒ deterministic or ☐ stochastic, ☒ empirical or ☒mechanistic,

____

Recommended for use by: ☐ farmers/producers, ☐ nutritionists/consultants, ☐ veterinarians, ☒ research/scientists, ☒ teaching/student, ☐ extension/outreach, ☐ others

What are the objectives/purposes of the model? ____

Formerly: evaluate and formulate diets for advisory purposes
Presently: research and teaching

Specific description of the model (animal species, physiological stages, rumen/ intestinal/metabolism submodels, levels of solution, lactation, growth, pregnancy, maintenance, body reserves, energy/protein calculation):____ __________

The lactating cow divided into a large number of sub-models. See references below for more details.

How is feed intake predicted? ____

Not presently predicted. However, the intake responses to changes in diet composition can be taken into account in ration formulation (Huhtanen et al., 2007, 2008)

What are the input requirements (characterization) for animal, feeds, environment, others _________

Feed composition: 23 variables including fermentation rates for insoluble CP, starch and potentially digestible NDF. NDF is separated into iNDF and pdNDF (forage and concentrate separately due to different passage kinetics). Silage fermentation parameters (lactic acid, VFA, ammonia). Intake of feeds, cow BW, week of lactation and some country specific information on milk payments

____

Please provide more detailed information about the model engine and functions, user interface (graphical, command, oriented), and specify key input parameters and outputs. For example, it is important to know if the model predicts methane and how, manure output (urine + feces, or separate), mineral and vitamin requirements, animal species and types, etc.

The model itself is graphical with easy access to parameter manipulation. It is dynamically linked to Excel. In Excel, you make all input adjustments with respect to cow and feed variables. Feeds are selected from menu and amounts are entered. Excel also collects output of all variables specified by the user and they can also be logged.

All flows of feed components into the cow and in all segments of the GI tract and into manure can be accumulated in the output as well as fermentation end-products (including gases), metabolic fluxes, milk components, urinary and energy output, etc, etc. Mineral elements, individual amino acids and vitamins are not implemented.

Please provide references pertinent to the development, evaluation, or application of the model.

Danfær, A., P. Huhtanen, P. Udén, J. Sveinbjörnsson, and H. Volden. 2006. The Nordic Dairy Cow Model, Karoline - Description. Pages 383-406 in Nutrient Digestion and Utilization in Farm Animals: Modeling Approaches. E. Kebreab, J. Dijkstra, A. Bannink, W. J. J. Gerrits and J. France, ed. CABI Publishing, Cambridge, MA.

Danfær, A., P. Huhtanen, P. Udén, J. Sveinbjörnsson, and H. Volden. 2006. The Nordic Dairy Cow Model, Karoline - Evaluation. Pages 407-415 in Nutrient Digestion and Utilization in Farm Animals: Modeling Approaches. E. Kebreab, J. Dijkstra, A. Bannink, W. J. J. Gerrits and J. France, ed. CABI Publishing, Cambridge, MA.

Sveinbjörnsson, J., P. Huhtanen, and P. Udén. 2006. The Nordic Dairy Cow Model, Karoline - Development of Volatile Fatty Acid Sub-Model. Pages 1-14 in Nutrient Digestion and Utilization in Farm Animals: Modeling Approaches. E. Kebreab, J. Dijkstra, A. Bannink, W. J. J. Gerrits and J. France, ed. CABI Publishing, Cambridge, MA.

Huhtanen, P., M. Rinne, and J. Nousiainen. 2007. Evaluation of the factors affecting silage intake of dairy cows: a revision of the relative silage dry-matter intake index. Animal. 1:758-770.

Huhtanen, P., M. Rinne, and J. Nousiainen. 2008. Evaluation of concentrate factors affecting silage intake of dairy cows: a development of the relative total diet intake index. Animal. 2:942-953.

P. Huhtanen and M. Ramin. 2013. Evaluation of the Nordic dairy cow model Karoline in predicting methane production. Acta Agric Scand. (In Press)

Ruminant Nutrition Models

Model: Large Ruminant Nutrition System (LRNS) Active: ☒ Yes, ☐ No

About the software:

Questions	Responses
Development information:	
Developed by	L.O. Tedeschi and D. G. Fox
Year of first developed	2009
Year of last modification	2013
Current version (major, minor, revision)	1.0.24
Country developed	USA
Used in which countries?	USA, Canada, Mexico, Brazil, Europe, South Africa, Vietnam, Australia
Has the model been independently evaluated?	Yes
Retail and support information:	
Marketed by (name)	Texas A&M University under license from Cornell University
Phone	979-845-5065
Website	http://nutritionmodels.tamu.edu/lrns.html
Currency and price	US$ 400 (commercial), US$ 200 (faculty), or free (students)
Format (downloadable, CD, DVD)	Downloadable
How often are updates available?	As needed, usually 2x per year
Maintenance cost (annual, monthly)	None
Supported by (technical/customer support)	Limited technical support
Form of support (email, phone, face-to-face)	Email

About the model usability: (1=very simple/easy … 5 = very difficult)

Level of technical/nutritional knowledge required:
○ 1/None ○ 2/Low ○ 3/Intermediate ○ 4/High ● 5/Advanced

Ability/readiness of the software/model to be used for climate change simulation:
○ 1/None ○ 2/Low ● 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for sustainability/long-term simulation:
○ 1/None ○ 2/Low ○ 3/Intermediate ● 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for Life Cycle Analysis:
○ 1/None ● 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used as Object-Oriented Module (integration):
● 1/None ○ 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for greenhouse gas (methane) production:
○ 1/None ● 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for nutrient excretion (e.g., N, P):
○ 1/None ○ 2/Low ○ 3/Intermediate ○ 4/High ● 5/Advanced

About the model characteristics:

Is the model based on a previous model or publications? Which? CNCPS by Fox et al. (2004)

What is the programming language of the model and the software? MS Visual Basic 6.0

What is the nature of the model: ☒ deterministic or ☐ stochastic, ☒ empirical or ☐mechanistic,

____

Recommended for use by: ☐ farmers/producers, ☒ nutritionists/consultants, ☒ veterinarians, ☒ research/scientists, ☒ teaching/student, ☒ extension/outreach, ☐ others

What are the objectives/purposes of the model? ____

LRNS is an applied nutrition model and it can be used for diet evaluation and diet formulation/balancing for different types of animal breeds under different scenarios of production. It is based on the Cornell Net Carbohydrate and Protein System version 5.0.

Specific description of the model (animal species, physiological stages, rumen/ intestinal/metabolism submodels, levels of solution, lactation, growth, pregnancy, maintenance, body reserves, energy/protein calculation):____

The LRNS is a computer program that estimates beef and dairy cattle requirements and nutrient supply under specific conditions of animal type, environment (climatic factors), management, and physicochemical composition of available feeds. The LRNS was developed from basic principles of rumen function, bacterial growth, feed digestion and passage rates, and animal physiology (maintenance, growth, lactation, pregnancy, and body reserves). The ruminal fermentation dynamics are computed based on the fractional rate of fermentation and passage, assuming steady state condition, and bacteria growth. Adjustments are made for diets that does not meet ruminal N requirements by the bacteria. Intestinal digestion is computed using digestibility coefficients.

How is feed intake predicted? ____

LRNS uses empirical equations, but users are encouraged to enter observed intake whenever available.

What are the input requirements (characterization) for animal, feeds, environment, others _________

The inputs for animal are breed, body weight, body weight at a given body composition, age, physical activity, body condition score, milk production and composition, and calf birth weight. The inputs for environment are previous and current temperature and relative humidity, hide thickness, hours of sunlight, and wind speed. The inputs for feed are crude protein, ether extract, ash (micro and macro minerals), neutral detergent fiber, lignin, soluble protein, protein bound to neutral and acid detergent fibers, physically effective neutral detergent fiber, and fractional rates of ruminal degradation.

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Please provide more detailed information about the model engine and functions, user interface (graphical, command, oriented), and specify key input parameters and outputs. For example, it is important to know if the model predicts methane and how, manure output (urine + feces, or separate), mineral and vitamin requirements, animal species and types, etc.

REQUIREMENT: Maintenance requirements in the LRNS are determined by accounting for breed, physiological state, activity, urea excretion, heat or cold stress and environmental acclimatization effects. In growing cattle, the net energy for maintenance (NEm) of each breed (kcal/kg metabolic shrunk body weight) is adjusted using a 1–9 body condition scale (BCS). Heat and cold stresses are also computed by the LRNS based on the effective temperature index. Growth requirements for energy and protein include adjustments for effects of body weight, rate of body weight gain, chemical composition of gain, and mature weight. A size scaling system based on the ratio of current to mature weight is used to predict the composition of gain. Shrunk body weight is adjusted to a weight equivalent to that of a standard reference animal at the same stage of growth. Pregnancy requirements and BW gain are computed from growth of the gravid uterus based on expected calf birth weight and day of gestation. Lactation energy and protein requirements are calculated from actual milk production and components. For beef cattle, the lactation curve is predicted based on peak milk.

SUPPLY: The LRNS has two levels of solution to accommodate the needs of different types of users. Level 1 is intended for conditions where feeds cannot be well characterized. Level 1 computes total digestible nutrients (TDN) and metabolizable protein (MP) values with empirical equations. Level 2 is intended for users who have advanced information on feed composition and dry matter intake (DMI) and an understanding of how to use the level 2 rumen model. Level 2 mechanistically computes ruminally available TDN and MP from fractional digestion and passage rates, assuming steady state condition: Kd/(Kd+Kp). Feed not digested in the rumen will pass undegraded to the intestines where it may or may not undergo further digestion. The LRNS characterizes each feedstuff by its carbohydrate and protein fractions. The fraction pool sizes of carbohydrate and protein fractions needed to predict rumen fermentation and escape are computed and default chemical composition values are provided in the feed library. Carbohydrates are defined as fiber carbohydrates (FC) or non-fiber carbohydrates (NFC). The FC is equal to the neutral detergent fiber (NDF) and NFC is total DM minus NDF (adjusted for neutral detergent insoluble protein, NDIP), crude protein (CP), fat, and ash. Carbohydrates are further categorized into A, B1, B2 and C fractions. The CHO A fraction is a very rapidly fermented, water soluble, pool that is largely composed of sugars, although it also contains organic acids and short oligosaccharides. The CHO B1 fraction, with a slower Kd than CHO A, is primarily starch and pectin. The CHO B2 pool is composed of available NDF. The CHO C pool is an indigestible fraction, and it is computed as NDF×Lignin×2.4 (% of dry matter). The assumption that the CHO A fraction is largely sugar is an oversimplification, and does not account for the fact that forages and silages can have a significant amount of organic acids. Organic acids are not utilized as efficiently for microbial growth as sugars. Microbial growth from the organic acid fraction of CHO A of silages in the feed library is reduced by 50% to adjust this overestimation of microbial growth. Protein fractions (as a percentage of CP) are described using a scheme similar to that used for carbohydrates. Protein fraction A (PROT A) of CP is NPN that enters the ruminal ammonia pool directly. PROT B1 is true protein that has a rapid Kd and is nearly completely degraded in the rumen. The PROT C fraction is acid detergent insoluble protein (ADIP) and is assumed to be unavailable. The PROT B3 or slowly degraded protein fraction is determined by subtracting the value determined for ADIP from the value determined for neutral detergent insoluble protein (NDIP). The PROT B2 fraction, which is partly degraded in the rumen, is then estimated as the difference between CP and the sum of soluble + B3 + C where the soluble protein equals A + B1. Intestinal digestibility of CHO A and B1 is 100%, CHO B2 is 20%, and the amino acid intestinal digestibility is assumed to be 100% for B1 and B2, and 80% for B3 protein fractions.

Please provide references pertinent to the development, evaluation, or application of the model.

DEVELOPMENT:

Fox, D. G., L. O. Tedeschi, T. P. Tylutki, J. B. Russell, M. E. Van Amburgh, L. E. Chase, A. N. Pell, and T. R. Overton. 2004. The Cornell Net Carbohydrate and Protein System model for evaluating herd nutrition and nutrient excretion. Anim. Feed Sci. Technol. 112:29-78.

Russell, J. B., J. D. O'Connor, D. G. Fox, P. J. Van Soest, and C. J. Sniffen. 1992. A net carbohydrate and protein system for evaluating cattle diets: I. Ruminal fermentation. J. Anim. Sci. 70:3551-3561.

Sniffen, C. J., J. D. O'Connor, P. J. Van Soest, D. G. Fox, and J. B. Russell. 1992. A net carbohydrate and protein system for evaluating cattle diets: II. Carbohydrate and protein availability. J. Anim. Sci. 70:3562-3577.

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Pitt, R. E., J. S. Van Kessel, D. G. Fox, A. N. Pell, M. C. Barry, and P. J. Van Soest. 1996. Prediction of ruminal volatile fatty acids and pH within the net carbohydrate and protein system. J. Anim. Sci. 74:226-244.

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EVALUATION:

Alderman, G. 2001. A critique of the Cornell Net Carbohydrate and Protein System with emphasis on dairy cattle. 1. The rumen model. J. Anim. Feed Sci. 10:1-24.

Alderman, G., J. France, and E. Kebreab. 2001. A critique of the Cornell Net Carbohydrate and Protein System with emphasis on dairy cattle. 2. The post-rumen digestion model. J. Anim. Feed Sci. 10:203-221.

Alderman, G., J. France, and E. Kebreab. 2001. A critique of the Cornell Net Carbohydrate and Protein System with emphasis on dairy cattle. 3. The requirements model. J. Anim. Feed Sci. 10:361-383.

Molina, D. O., I. Matamoros, Z. Almeida, L. O. Tedeschi, and A. N. Pell. 2004. Evaluation of the dry matter intake predictions of the Cornell Net Carbohydrate and Protein System with Holstein and dual-purpose lactating cattle in the tropics. Anim. Feed Sci. Technol. 114:261-278.

Morenz, M. J. F., J. F. Coelho da Silva, L. J. M. Aroeira, F. Deresz, H. M. Vásquez, F. C. F. Lopes, D. S. C. Paciullo, and L. O. Tedeschi. 2012. Evaluation of the Cornell Net Carbohydrate and Protein System model on the prediction of dry matter intake and milk production of grazing crossbred cows. Revista Brasileira de Zootecnia. 41:398-506.

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Ruminant Nutrition Models

Model: Mecsic

Active: ☒ Yes, ☐ No

About the software:

Questions	Responses
Development information:	
Developed by	INRA / Arvalis/ Institut de l'Elevage (France)
Year of first developed	2004 ///2012
Year of last modification	
Current version (major, minor, revision)	Version 1
Country developed	France
Used in which countries?	
Has the model been independently evaluated?	yes
Retail and support information:	
Marketed by (name)	Arvalis. Software named "JB-Box" available in september 2013
Phone	
Website	in progress!
Currency and price	not decided
Format (downloadable, CD, DVD)	
How often are updates available?	
Maintenance cost (annual, monthly)	
Supported by (technical/customer support)	
Form of support (email, phone, face-to-face)	

About the model usability: (1=very simple/easy ... 5 = very difficult)

Level of technical/nutritional knowledge required:
○ 1/None ◉ 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for climate change simulation:
○ 1/None ◉ 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for sustainability/long-term simulation:
○ 1/None ◉ 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for Life Cycle Analysis:
○ 1/None ◉ 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used as Object-Oriented Module (integration):
○ 1/None ○ 2/Low ○ 3/Intermediate ◉ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for greenhouse gas (methane) production:
○ 1/None ◉ 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for nutrient excretion (e.g., N, P):
○ 1/None ○ 2/Low ◉ 3/Intermediate ○ 4/High ○ 5/Advanced

About the model characteristics:

Is the model based on a previous model or publications? Which? Hoch Agabriel 2004 (Mecsic model)

What is the programming language of the model and the software? model : turbo pascal; software ?

What is the nature of the model: ☒ deterministic or ☐ stochastic, ☐ empirical or ☒mechanistic, ☐ static or ☒ dynamic, ☒ continuous or ☐ discrete, ☐ homo-spatial or ☐ hetero-spatial, others

Recommended for use by: ☒ farmers/producers, ☒ nutritionists/consultants, ☐ veterinarians, ☐ research/scientists, ☒ teaching/student, ☒ extension/outreach, ☐ others

What are the objectives/purposes of the model? ____

simulation of beef bulls body composition and growth during the finishing period

Specific description of the model (animal species, physiological stages, rumen/ intestinal/metabolism submodels, levels of solution, lactation, growth, pregnancy, maintenance, body reserves, energy/protein calculation):____ __________

Young bulls (dairy or beef) between 6 and 24 month old
Finishing period
simulation of daily growth daily ADG composition , LW EBW carcass weight, carcass composition total muscle and fat, weight of 3 muscles of interest.

How is feed intake predicted? ____

Model of intake from characteristics of animal and characteristic of feedstuffs (chemical analysis)

What are the input requirements (characterization) for animal, feeds, environment, others _________

animal : breed age, initial LW, initial BCS
feedstuffs : types (forages concentrates), chemical analysis, time of distribution (in days)

Please provide more detailed information about the model engine and functions, user interface (graphical, command, oriented), and specify key input parameters and outputs. For example, it is important to know if the model predicts methane and how, manure output (urine + feces, or separate), mineral and vitamin requirements, animal species and types, etc.

input model linked with a growth model (Mecsic (4 compartments and 28 parameters))
working with daily MEnergy available /day.

Prediction of growth and carcass composition and quality.

User interface will be graphical : first full version july 2013.

Please provide references pertinent to the development, evaluation, or application of the model.

Hoch T., Agabriel J., 2004. A mechanistic dynamic model to estimate beef cattle growth and body composition : 1. Model description. Agricultural Systems, 81, 1-15.

Hoch T., Agabriel J., 2004. A mechanistic dynamic model to estimate beef cattle growth and body composition : 2. Model description. Agricultural Systems. 81, 17-35

Garcia F., Sainz R.D., Agabriel J., Barioni L.G., Oltjen J.W., 2008.Comparative analysis of two dynamic mechanistic models of beef cattle growth. Animal Feed Science and Technology, 143, 220-241.

229. Ferard A., Bastien D., Cabon G., Micol D. Agabriel J., Garcia-Launay F. 2012 BEEFBOX, un simulateur dynamique des performances de croissance et d'abattage de jeunes bovins selon le régime d'engraissement Renc. Rech. Ruminants, 2012, 19 317-320. (reference free available in French (summary in english) on the website www.journees3R.fr bottom of page : texte en ligne)

Ruminant Nutrition Models

Model: Molly

Active: ☒ Yes, ☐ No

About the software:

Questions	Responses
Development information:	
Developed by	R.L. Baldwin
Year of first developed	1978
Year of last modification	2012
Current version (major, minor, revision)	Various versions exist
Country developed	USA
Used in which countries?	USA, Australia, NZ
Has the model been independently evaluated?	Yes
Retail and support information:	
Marketed by (name)	Molly
Phone	
Website	
Currency and price	Free
Format (downloadable, CD, DVD)	http://www.vmtrc.ucdavis.edu/metabolic
How often are updates available?	Yearly
Maintenance cost (annual, monthly)	Variable
Supported by (technical/customer support)	none
Form of support (email, phone, face-to-face)	none

About the model usability: (1=very simple/easy … 5 = very difficult)

Level of technical/nutritional knowledge required:
○ 1/None ○ 2/Low ○ 3/Intermediate ● 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for climate change simulation:
○ 1/None ○ 2/Low ● 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for sustainability/long-term simulation:
○ 1/None ○ 2/Low ● 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for Life Cycle Analysis:
● 1/None ○ 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used as Object-Oriented Module (integration):
● 1/None ○ 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for greenhouse gas (methane) production:
○ 1/None ○ 2/Low ○ 3/Intermediate ○ 4/High ● 5/Advanced

Ability/readiness of the software/model to be used for nutrient excretion (e.g., N, P):
○ 1/None ○ 2/Low ○ 3/Intermediate ● 4/High ○ 5/Advanced

About the model characteristics:

Is the model based on a previous model or publications? Which? Baldwin's (1995) book

What is the programming language of the model and the software? ACSL

What is the nature of the model: ☒ deterministic or ☐ stochastic, ☐ empirical or ☒mechanistic,

____

Recommended for use by: ☐ farmers/producers, ☐ nutritionists/consultants, ☐ veterinarians, ☒ research/scientists, ☒ teaching/student, ☐ extension/outreach, ☐ others

What are the objectives/purposes of the model? ____

to evaluate concepts and data concerning the underlying metabolic processes which dictate productive efficiency in dairy cattle.

Specific description of the model (animal species, physiological stages, rumen/ intestinal/metabolism submodels, levels of solution, lactation, growth, pregnancy, maintenance, body reserves, energy/protein calculation):____ __________

Animal Species - Beef and Dairy Cattle
Physiological Stage - lactating, dry
Submodels - mostly rumen but also includes post rumen nutrient metabolism
Level of solution - deterministic
Lactation - predicts for the whole lactation period
Growth - similar model (Davis Growth Model) does growth
Pregnancy - included
Maintenance & Body reserves - it is mechanistic so it is included in the model

How is feed intake predicted? ____

Feed intake is an input in the model

What are the input requirements (characterization) for animal, feeds, environment, others _________

Animal: BW, BCS, physiological state
Feed: dietary starch, NDF, ADF, lignin, ash, ether extract, CP, acetate, lactate, butyrate.
Feed protein: soluble, ruminally undegraded, NPN, and urea in CP equivalents
Feed CHO: soluble and ruminally undegraded starch (% of starch), ruminally undegraded ADF
Environment: latitude and day of the year.

____

Please provide more detailed information about the model engine and functions, user interface (graphical, command, oriented), and specify key input parameters and outputs. For example, it is important to know if the model predicts methane and how, manure output (urine + feces, or separate), mineral and vitamin requirements, animal species and types, etc.

The model has a visual basic user interface and in the background runs in ACSL (advanced continuous simulation language). It is fairly easy to enter inputs (if you know the diet) and also easy to get outputs.

The model bridges gap between basic knowledge of cow digestion and metabolism, and animal performance. Absorption is simple (straight percentages) but metabolism is fairly detailed and it connects nutrient, intake, metabolism and milk production in a mechanistic way. Molly has limited capability for predicting reproduction, health, management and environment (temperature etc). For reproduction there are some specific equations that deals with when the animal is pregnant. For genetics there is only one parameter (udder cells) - it sets the genetic potential to produce milk.

Molly has about 15 state variable such as Amino acids, glucose, acetate, fatty acids, adipose triglycerides, body protein, plasma urea nitrogen, visceral protein, ammonia, large particles, small particles, microbes, Rumen VFAs.

Feed inputs required are Dry matter intake, soluble ash, cellulose, hemicellulose, soluble, insoluble protein (you can also use only crude protein), soluble carbohydrates, starch, lipid

You can run for the whole lactation, dry her off and then restart again. Or you can do within day simulations as well (not used often).

Outputs include milk production (and composition), methane emissions, fecal excretion (of different nutrients) and pregnancy (depending on physiological state).

Please provide references pertinent to the development, evaluation, or application of the model.

The model has been modified so many different ways and there are a multiple copies of the model. Dr. Mark Hanigan has done some modifications to enzyme kinetics, particularly on the N metabolism. Dr. John McNamara has added some equations on reproduction.

References

Baldwin, R. L., J. France, D. E. Beever, M. Gill, and J. H. Thornley. 1987a. Metabolism of the lactating cow. III. Properties of mechanistic models suitable for evaluation of energetic relationships and factors involved in the partition of nutrients. J. Dairy Res. 54:133-145.

Baldwin, R. L., J. France, and M. Gill. 1987b. Metabolism of the lactating cow. I. Animal elements of a mechanistic model. J. Dairy Res. 54:77-105.

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Baldwin, R. L. 1995. Modeling ruminant digestion and metabolism. Chapman and Hall, London, UK.

Gregorini, P., P. C. Beukes, M. D. Hanigan, G. Waghorn, S. Muetzel, and J. P. McNamara. 2013. Comparison of updates to the Molly cow model to predict methane production from dairy cows fed pasture. J. Dairy Sci. 96:5046-5052.

Hanigan, M. D., H. G. Bateman, J. G. Fadel, J. P. McNamara, and N. E. Smith. 2006. An ingredient-based input scheme for Molly. Pages 328-348 in Nutrient Digestion and Utilization in Farm Animals: A Modelling Approach. E. Kebreab, J. Dijkstra, A. Bannink, W. Gerrits, and J. France, ed. CAB International, Walingford, UK.

Hanigan, M. D., H. G. Bateman, J. G. Fadel, and J. P. McNamara. 2006. Metabolic Models of Ruminant Metabolism: Recent Improvements and Current Status. J. Dairy Sci. 89: E52-64E.

Hanigan, M. D., A. G. Rius, E. S. Kolver, and C. C. Palliser. 2007. A redefinition of the representation of mammary cells and enzyme activities in a lactating dairy cow model. J. Dairy Sci. 90:3816-3830.

Hanigan, M. D., C. C. Palliser, and P. Gregorini. 2009. Altering the representation of hormones and adding consideration of gestational metabolism in a metabolic cow model reduced prediction errors. J. Dairy Sci. 92:5043-5056.

Hanigan, M. D., J. A. D. R. N. Appuhamy, and P. Gregorini. 2013. Revised digestive parameter estimates for the Molly cow model. J. Dairy Sci. 96:3867-3885.

McNamara, J. P., 2010. Integrating transcriptomic regulation into models of nutrient metabolism in agricultural animals. Pp 27-37 in Energy and Protein Metabolism and Nutrition, EAAP Pub. No. 127, Wageningen Academic Press, G. Matteo Crovetto, Ed. Plenary lecture at ISEP meetings, Parma, Italy, Sept. 2010.

McNamara, J. P. 2012. Integrating nutritional, genetic and reproductive management in early lactation dairy cattle. J. Animal Sci. 90:1846-1854.

Ruminant Nutrition Models

Model: NorFor

Active: ☒ Yes, ☐ No

About the software:

Questions	Responses
Development information:	
Developed by	Volden and collaborators
Year of first developed	2003-2009
Year of last modification	The model and tools (on-line & off line) are updated twice per year
Current version (major, minor, revision)	1.75
Country developed	Denmark, Sweden, Norway and Iceland
Used in which countries?	Denmark, Sweden, Norway and Iceland
Has the model been independently evaluated?	Yes, EAAP publication no 130, 2011 (Ed: Harald Volden)
Retail and support information:	
Marketed by (name)	Dairy Mgt .System (Denmark); IndividRam (Sweden); Optifor (Norway/Iceland)
Phone	0045-30921725
Website	norfor.info
Currency and price	150-1200 euro/year
Format (downloadable, CD, DVD)	On-line (downloadable in DK, NO & Ice – off-line in Sweden)
How often are updates available?	Updates, free of charge, twice per year
Maintenance cost (annual, monthly)	
Supported by (technical/customer support)	Hotline – technical & biological (free of charge/part of yearly subscription)
Form of support (email, phone, face-to-face)	

About the model usability: (1=very simple/easy … 5 = very difficult)

Level of technical/nutritional knowledge required:
○ 1/None ● **2/Low** ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for climate change simulation:
○ 1/None ○ 2/Low ● **3/Intermediate** ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for sustainability/long-term simulation:
○ 1/None ○ 2/Low ○ 3/Intermediate ● **4/High** ○ 5/Advanced

Ability/readiness of the software/model to be used for Life Cycle Analysis:
○ 1/None ● **2/Low** ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used as Object-Oriented Module (integration):
● **1/None** ○ 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for greenhouse gas (methane) production:
● **1/None** ○ 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for nutrient excretion (e.g., N, P):
● **1/None** ○ 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

About the model characteristics:

Is the model based on a previous model or publications? Which? Yes. See references

What is the programming language of the model and the software?

What is the nature of the model: ☒ deterministic or ☐ stochastic, ☐ empirical or ☒mechanistic,

____

Recommended for use by: ☒ farmers/producers, ☒ nutritionists/consultants, ☐ veterinarians, ☒ research/scientists, ☒ teaching/student, ☐ extension/outreach, ☐ others Feed companies

What are the objectives/purposes of the model? ____

NorFor is used for dairy cows, dairy heifers and dairy bulls and beef young stock

Specific description of the model (animal species, physiological stages, rumen/ intestinal/metabolism submodels, levels of solution, lactation, growth, pregnancy, maintenance, body reserves, energy/protein calculation):____ __________

See detailed information below.

How is feed intake predicted? ____

Feed intake: each feedstuff has a Fill value (dependent on NDF & OMD) and the cow has a Capacity (dependent on DIM, BW, & ECM)

What are the input requirements (characterization) for animal, feeds, environment, others _________

NorFor can estimate N, P & K in feces and urine (relatively simple equations)
NorFor can estimate methane (relatively simple equations)

____

Please provide more detailed information about the model engine and functions, user interface (graphical, command, oriented), and specify key input parameters and outputs. For example, it is important to know if the model predicts methane and how, manure output (urine + feces, or separate), mineral and vitamin requirements, animal species and types, etc.

Scientific basis for "parts" of NorFor is partly inspired/based on other models:
+ A Norwegian digestion model (Volden, 2001)
+ A Dutch net energy system (Van Es, 1978)
+ A modified Danish DMI-system (Kristensen, 1997)
+ A Danish structure value system (Nørgaard, 2009)
+ A modified French system for growth (INRA, 1989)
+ Lots of data from Nordic universities for development and testing of NorFor
+ Min & Vit requirements are from Nordic recommendations and NRC (2001)

The NorFor model can be divided into five parts:
1) an input section that describes animal and feed characteristics
2) a module that simulates processes in the digestive tract and the intermediary metabolism, termed the feed ration calculator, FRC
3) a module that predicts feed intake
4) a module that predicts the physical structure of the diet
5) an output section that describes nutrient supply, nutrient balances and production response

Energy is calculated as net energy for lactation and both ECM and protein yields are predicted. Interactions between animal characteristics, feeding level and feed composition are taken into account when calculating nutrient supply. This implicates that energy and protein values for individual feeds are not constant or additive.

With the NorFor model feed rations are formulated by a non-linear economical optimization. This means that NorFor finds the cheapest combination of feed ingredients that meets the nutritional requirements. It is possible to optimize from 84 nutritional variables in NorFor, but the default setting in the national clients are eight nutritional constraints.

The NorFor model makes it possible to better predict the "true" feeding value of a ration, which results in a more efficient feed utilization with economic as well as environmental advantages.

Development is underway for dairy calves and beef cows.

Hvelplund, T. and Madsen, J. 1990. A study of the quantitative nitrogen metabolism in the gastro-intestinal tract, and the resultant new protein evaluation system for ruminants. The AAT-PBV system. The Royal Vetenarian and Agricultural University, Copenhagen, Denmark.

INRA – Institut National de la Recherche Agronomique. 1989. Ruminant nutrition: Recommended allowances and feed tables. John Libbey and Co Ltd, London. 389 pp.

Kristensen, V.F. 1995. Forudsigelsen af foderoptagelsen hos malkekøer. Intern rapport nr 61. Statens Husdyrbrugsforsøg. 28 pp.

Nørgaard, P., E. Nadeau, and A. Randby. 2010. A new Nordic structure evaluation system for diets fed to dairy cows. In: Modelling nutrient digestion and utilization in farm animals. Eds: D. Sauvant, J. McNamara and J. France. Wageningen Academic Publishers.

Van Es, A.J.H. 1978. Feed evaluation for ruminants. I. The system in use from May 1978 onwards in the Netherlands. Livestock Prod. Sci. 5:331-345.

Volden. H. 2001. Utvikling av et mekanistisk system for vurdering av fôr til drøvtyggere, AAT-modellen. I: Fôropptak og fôrmiddelvurdering hos drøvtyggere. Fagseminar 18.-19. september 2001. 30 pp.

Please provide references pertinent to the development, evaluation, or application of the model.

Volden, H. 2011. NorFor - The Nordic Feed Evaluation System. Wageningen Academic Publishers, Wageningen, The Netherlands.

Ruminant Nutrition Models

Model: RUMINANT

Active: ☒ Yes, ☐ No

About the software:

Questions	Responses
Development information:	
Developed by	Mario Herrero, Neil Jessop and Roy Fawcett
Year of first developed	1997
Year of last modification	2002
Current version (major, minor, revision)	3
Country developed	UK and Kenya
Used in which countries?	Mexico, Brazil, Costa Rica, Bolivia, Spain, throughout Africa, for global analyses
Has the model been independently evaluated?	Yes
Retail and support information:	
Marketed by (name)	Mario Herrero
Phone	+61 477 764 244
Website	
Currency and price	Free
Format (downloadable, CD, DVD)	Downloadable
How often are updates available?	As needed
Maintenance cost (annual, monthly)	None
Supported by (technical/customer support)	Limited technical support
Form of support (email, phone, face-to-face)	Email

About the model usability: (1=very simple/easy … 5 = very difficult)

Level of technical/nutritional knowledge required:
○ 1/None ○ 2/Low ○ 3/Intermediate ● 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for climate change simulation:
○ 1/None ○ 2/Low ● 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for sustainability/long-term simulation:
○ 1/None ○ 2/Low ○ 3/Intermediate ● 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for Life Cycle Analysis:
○ 1/None ○ 2/Low ○ 3/Intermediate ● 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used as Object-Oriented Module (integration):
○ 1/None ○ 2/Low ○ 3/Intermediate ● 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for greenhouse gas (methane) production:
○ 1/None ○ 2/Low ○ 3/Intermediate ● 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for nutrient excretion (e.g., N, P):
○ 1/None ○ 2/Low ● 3/Intermediate ○ 4/High ○ 5/Advanced

About the model characteristics:

Is the model based on a previous model or publications? Which? Illius and Gordon (1991), AFRC (1993) CNCPS (1992)

What is the programming language of the model and the software? C++

What is the nature of the model: ☒ deterministic or ☐ stochastic, ☒ empirical or ☐mechanistic,

____

Recommended for use by: ☐ farmers/producers, ☒ nutritionists/consultants, ☒ veterinarians, ☒ research/scientists, ☒ teaching/student, ☒ extension/outreach, ☐ others

What are the objectives/purposes of the model? ____

Specific description of the model (animal species, physiological stages, rumen/ intestinal/metabolism submodels, levels of solution, lactation, growth, pregnancy, maintenance, body reserves, energy/protein calculation):____ __________

See details below.

How is feed intake predicted? ____

The model estimates intake of the basal feed endogenously from physical fill constraints and degradation and passage rates

What are the input requirements (characterization) for animal, feeds, environment, others _________

The inputs for animal are breed, body weight, body weight at a given body composition, age, physical activity, body condition score, milk production and composition. The inputs for feed are crude protein, ether extract, ash (micro and macro minerals), neutral detergent fiber, soluble carbohydrate, lignin, soluble protein, insoluble but degradable protein, and fractional rates of ruminal degradation.

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Please provide more detailed information about the model engine and functions, user interface (graphical, command, oriented), and specify key input parameters and outputs. For example, it is important to know if the model predicts methane and how, manure output (urine + feces, or separate), mineral and vitamin requirements, animal species and types, etc.

The model consists of a dynamic section that estimates intake and the supply of nutrients to the animal from knowledge of the fermentation kinetics and passage of feed constituents (carbohydrate and protein) through the gastrointestinal tract and their subsequent excretion, whereas another section determines their nutrient requirements using well-recognized principles (8). Feeds are described by four main constituents: ash, fat, carbohydrate, and protein. These are divided into soluble, insoluble but potentially degradable, and indigestible fractions (9, 8). For the ith feedstuff, the carbohydrate fractions represent nonstructural carbohydrates (solCHOi), potentially digestible cell wall, and the indigestible residue. For concentrate feeds, the proportion of starch in the solCHOi is also required (7). Starch and fat in forages are almost negligible (10), but they may be important fractions in grains (11, 12). The protein fractions described here are the same as those estimated in the metabolizable protein (MP) system proposed by AFRC (8), with the difference that their representation in this model is dynamic. For example, the pools of soluble protein, degradable protein, and undegraded protein represent the terms quickly and slowly degraded crude protein and undegraded crude protein of the AFRC MP system (8), respectively. These are obtained using in vitro (i.e., gas production or in vitro digestibilities) or in situ methods (dacron bags). Exceptions to this rule are silages, which additionally require knowledge of organic acids and ammonia concentrations, and feeds with high concentrations of starch, for which this information is necessary. The pools of digested nutrients obtained from the model are used to calculate the supply of nutrients, namely metabolizable energy and protein, to the animals. The model takes as inputs the quantities of fermentable nutrients available in a particular time step and returns as outputs the products of fermentation. The inputs are (i) fermentable carbohydrate separated into simple sugars, starch, and cell wall material; (ii) fermentable nitrogen separated into ammonia and protein; and (iii) lipid, each summed across the various feed constituents, together with the microbial pool size. The outputs are the quantities of new microbial matter, the individual volatile fatty acids (VFAs) acetate, propionate, and butyrate, methane (CH4), ammonia, and unfermented carbohydrates. It is assumed that there is only a single pool of microorganisms of fixed composition (13). The microbial maintenance requirement was set at 1.63 mmoles ATP per gram of microbial dry matter (DM) per hour(14). The quantities of individual VFAs and CH4 produced are calculated according to the quantities of different substrates fermented using the stoichiometries of Black et al. (13). Microbial growth is thus dependant on both fermentable nitrogen (either as protein or ammonia) and fermentable carbohydrate supply. There is no fixed upper limit to the quantity of microbial matter produced; the lower limit is zero growth. If fermentable nitrogen supply limits the amount of fermentable carbohydrate that can be used, unfermented carbohydrate is returned to the appropriate rumen pool, thus reducing the effective rate of carbohydrate fermentation. The model is generic and can simulate animals of different body weights because of the incorporation of allometric rules for scaling passage rates. The model also includes explicit protein–energy interactions, feeding level effects on passage rates, and pH effects on cell wall degradation rates. These aspects are essential for predicting stoichiometry changes, the effect of different supplementation regimes, and the substitution effects of forages and concentrates. Validations have been carried out for more than 80 tropical and temperate diets and the results (i.e., intake residuals ± 5 g/kg body weight^0.75) suggest that the model has the required accuracy not only as a research tool but also for providing decision support at the farm level. Among its many uses, the model has been previously used for estimating CH4 emission factors of tropical livestock (15).

Please provide references pertinent to the development, evaluation, or application of the model.

DEVELOPMENT:

Herrero, M. 1997. Modelling dairy grazing systems: an integrated approach. Phd Thesis University of Edinburgh, Edinburgh, Scotland (first description of the model)

Herrero M, Fawcett RH, Jessop NS (2002) Predicting Intake and Nutrient Supply of Tropical and Temperate Diets for Ruminants Using a Simple Dynamic Model of Digestion. Bioparametrics Ruminant Nutrition Reference Laboratories Monograph (Institute of Ecology and Resource Management, University of Edinburgh, UK).

EVALUATION and APPLICATION:

Herrero, M., Fawcett, R.H. and Dent, J.B. 1999. Bio-economic evaluation of dairy farm management scenarios using integrated simulation and multiple-criteria models. Agricultural Systems 62: 149-168.

Vargas, B., Herrero, M. and van Arendonk, J.A.M. 2001. Interactions between optimal culling and insemination policies and feeding strategies in dairy herds. Livestock Production Science 69, 17-31.

Vargas, B., Groen, A., Herrero, M. and van Arendonk, J.A.M. 2002. Economic values for production and functional traits in Holstein cattle of Costa Rica. Livestock Production Science 75, 101-116.

Castelan-Ortega, O., Fawcett, R.H., Arriaga, C. and Herrero, M. 2003. A decision support system for smallholder campesino maize-cattle production systems of the Toluca Valley in Central Mexico. 1. Integrating biological and socio-economic models into a holistic system. Agricultural Systems 75, 1-21.

Castelan-Ortega, O., Fawcett, R.H., Arriaga, C. and Herrero, M. 2003. A decision support system for smallholder campesino maize-cattle production systems of the Toluca Valley in Central Mexico. 2. Emulating the farming system. Agricultural Systems 75, 23-46.

Waithaka, MM., Thornton, PK., Shepherd, KD. and Herrero, M. 2007. Bio-economic evaluation of farmers' perceptions of sustainable farms in Western Kenya. Agricultural Systems 90, 243-271.

González-Estrada, E. , Rodriguez, L. C., Walen, V. K. ,Naab, J. B. , Jawoo K., Jones, J. W. , Herrero, M., and Thornton, P.K. 2008. Carbon sequestration and farm income in West Africa: Identifying best management practices for smallholder agricultural systems in northern Ghana, Ecological Economics 67, 492-502.

Herrero, M., Thornton, P.K., Kruska, R. and Reid, R.S. 2008. Systems dynamics and the spatial distribution of methane emissions from African domestic ruminants to 2030. Agriculture, Ecosystems & Environment 126, 122-137.

Zingore, S. Gonzalez-Estrada, E., Delve, R.J., Herrero, M. Dimes, J and Giller K , 2009. An integrated evaluation of strategies for enhancing productivity and profitability of resource-constrained smallholder farms in Zimbabwe. Agricultural Systems 101, 57–68.

van Breugel, P., Herrero, M., van de Steeg, J., Peden, D. 2010. Livestock water use and productivity in the Nile Basin. Ecosystems 13, 205-221.

Thornton P K and Herrero, M 2010. The potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics. PNAS 107, 19667-19672.

Bryan, E., Ringler, C., Okoba, B., Koo, J., Herrero, M. and Silvestri, S. 2012. Can agriculture support climate change adaptation, greenhouse gas mitigation and rural livelihoods? Insights from Kenya. Climatic Change, 118: 151-165.

Havlík, P. et al. (2013) Crop productivity and the global livestock sector: Implications for land use change and greenhouse gas emissions. Am J Agric Econ 95, 442-448.

Hávlik, P. Herrero, M., Valin, H., Obersteiner, M., Schmid, E., Rufino, M., Mosnier, A., Bötcher, H., Frank, S., Fritz, S., Fuss, S., Kraxner, F., Notenbaert, A and Thornton, P.K.. 2013. The role of livestock systems transition in the future food production and climate change mitigation. PNAS (submitted)

Herrero, M., Hávlik, P., Notenbaert, A., Rufino, M., Thornton, P., Obersteiner, M., Blümmel, M., Duncan, A., Wright, I. 2013. Global livestock systems: biomass use, production, feed efficiency, and GHG emissions. PNAS (submitted)

Searchinger, T., Notenbaert, A., Herrero, M., Thornton, P., Estes, L., Rubenstein, D., Beringer, T. 2012. Trade-offs in the uses of Africa's woodlands and wetter savannas. PNAS (submitted)

Heinke, J., Lannerstad, M., Hoff, H., Müller, C., Herrero, M., Hávlik, P., Gerten, D., Peden, D., Notenbaert, A., Rockström, J. 2013. Current patterns of global water consumption by livestock. PNAS (submitted)

Lotze-Campen, H., Weindl, I., Popp, A., Müller, C., Schmitz, C., Rolinski, S., Havlik, P., Herrero, M. 2013. Climate change impacts and the costs of adaptation in global livestock production systems. PNAS (submitted).

Ruminant Nutrition Models

Model: Small Ruminant Nutrition System

Active: ☒ Yes, ☐ No

About the software:

Questions	Responses
Development information:	
Developed by	Vajesh Durbal
Year of first developed	2000 (as Cornell Net Carbohydrate and Protein System for Sheep)
Year of last modification	2012
Current version (major, minor, revision)	1.9.4468
Country developed	USA
Used in which countries?	Worldwide
Has the model been independently evaluated?	Yes
Retail and support information:	
Marketed by (name)	Texas A&M University under license from Cornell University
Phone	+1-979-845-5065
Website	http://nutritionmodels.tamu.edu/srns.html
Currency and price	US$ 300 (commercial), US$ 150 (faculty), or free (students)
Format (downloadable, CD, DVD)	Downloadable
How often are updates available?	As needed, no plans to update it
Maintenance cost (annual, monthly)	None
Supported by (technical/customer support)	Limited technical support
Form of support (email, phone, face-to-face)	Email

About the model usability: (1=very simple/easy ... 5 = very difficult)

Level of technical/nutritional knowledge required:
○ 1/None ○ 2/Low ● 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for climate change simulation:
○ 1/None ● 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for sustainability/long-term simulation:
○ 1/None ● 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for Life Cycle Analysis:
○ 1/None ● 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used as Object-Oriented Module (integration):
● 1/None ○ 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for greenhouse gas (methane) production:
○ 1/None ● 2/Low ○ 3/Intermediate ○ 4/High ○ 5/Advanced

Ability/readiness of the software/model to be used for nutrient excretion (e.g., N, P):
○ 1/None ○ 2/Low ● 3/Intermediate ○ 4/High ○ 5/Advanced

About the model characteristics:

Is the model based on a previous model or publications? Which? CNCPS for Sheep

What is the programming language of the model and the software? MS Visual Studio 2010

What is the nature of the model: ☒ deterministic or ☐ stochastic, ☒ empirical or ☐mechanistic,

___

Recommended for use by: ☐ farmers/producers, ☐ nutritionists/consultants, ☒ veterinarians, ☐ research/scientists, ☒ teaching/student, ☒ extension/outreach, ☒ others

What are the objectives/purposes of the model? ___

Evaluate sheep and goat diets, by estimating nutrient supply, animal requirements and whole animal and rumen nutrient balance.

Specific description of the model (animal species, physiological stages, rumen/ intestinal/metabolism submodels, levels of solution, lactation, growth, pregnancy, maintenance, body reserves, energy/protein calculation): ___

Sheep and goats (dairy, meat, wool, indigenous) in all physiological stages. It includes a rumen submodel based on the CNCPS for cattle approach, modified in the equations to predict feed and liquid passage rate. Does not include metabolism submodels. Only one level of solution (equivalent of level 2 of the CNCPS). It predicts energy, protein Ca and P requirements for all functions: maintenance, cold stress, growth, wool production, milk production, pregnancy, body reserves (energy, fat, and protein).

How is feed intake predicted? ___

Empirical equations for various animal categories mostly based on requirements (no filling effects considered)

What are the input requirements (characterization) for animal, feeds, environment, others ___

Inputs for animals: species, category, age, current BW, mature BW, wool depth, clean wool production, current temperature, previous temperature,wind speed, rainfall, horizontal distance walked, vertical distance walked, BCS, days pregnant, lamb or kid birth weight, milk yield, milk fat content, and milk protein content.

Feeds: amounts, cost, standard feed composition, CNCPS protein and CHO fractions, peNDF, degradation rates, CHO, protein, fat and ash intestinal digestibility, Ca, and P.

___

Please provide more detailed information about the model engine and functions, user interface (graphical, command, oriented), and specify key input parameters and outputs. For example, it is important to know if the model predicts methane and how, manure output (urine + feces, or separate), mineral and vitamin requirements, animal species and types, etc.

Inputs: see above

Outputs:
a) rumen N and peptide balance, rumen pH, whole animal energy, MP, Ca and P supply, requirements and balance; cold stress costs; days to gain or lose 1 BCS; milk from reserves; MP from feed and of bacterial origin, cost of urea excretion;

b) in growing animals only: composition (fat, protein, water+ minerals) of the gain, average daily gain

c) feces amount and composition. No information provided on urinary N excretion and methane production;

Animal species: sheep and goats of all categories (growing, mature, lactating, pregnant, dry, adult males)

Please provide references pertinent to the development, evaluation, or application of the model.

Cannas A., Fox D.G., Tedeschi L.O., Pell A.N., Van Soest P.J. 2003. A mechanistic model to predict nutrient requirements and feed biological values for sheep in each unique production situation. Book of Abstracts of the 54th Annual meeting of the European Association of Animal Production, 31 August - 3 September 2003, Rome, Italy, 346. (Abstr.)

Cannas, A., Tedeschi L. O., Fox D. G., Pell A. N., Van Soest P. J.. 2003. Evaluation of the CNCPS sheep model for predicting nutrient requirements and feed biological values on farms. In: Word Conference on Animal Production, 9., Porto Alegre, Brasil. WAAP, 17. (Abstr.)

Cannas A., Tedeschi L.O., Fox D.G., Pell A.N., Van Soest P.J. 2004. A mechanistic model to predict nutrient requirements and feed biological values for sheep. Journal of Animal Science, 82, 149-169.

Cannas A., Tedeschi L.O., Fox D.G. 2006. Small Ruminant Nutrition System: a computer model to develop feeding programs for sheep and goats. Journal of Dairy Science, 89 (Suppl. 1), 376. (Abstr.)

Cannas A., Tedeschi L.O., Atzori A.S., Fox D.G., 2006. Prediction of energy requirement for growing sheep with the Cornell Net Carbohydrate and Protein System. In: Kebreab E., Dijkstra J., Bannink A., Gerrits W.J.J., France J. (Eds.), Nutrient digestion and utilization in farm animals: modelling approaches. CAB International, Wallingford, UK, pp. 99-113.

Cannas A., Tedeschi L.O., Atzori A.S., Fox D.G. 2007. Estimativa do ganho de peso de cabritos utilizando o modelo Small Ruminant Nutrition System. In: 44th Annual Meeting of the Brazilian Society of Animal Science, 24-27 July 2007, Jaboticabal, SP, Brazil. Anais SBZ, 2007a. 1-3. (CD-ROM)

Cannas A., Tedeschi L.O., Atzori A.S., Fox D.G. 2007. The Small Ruminant Nutrition System: development and evaluation of a goat submodel. Italian Journal of Animal Science, 6 (Suppl. 1), 609-611.

Cannas A., Tedeschi L.O., Fox D.G. 2007. Prediction of the metabolizable energy intake and energy balance of goats with the Small Ruminant Nutrition System model. In: Ortigues-Marty I. (ed). Energy and protein metabolism and nutrition. EAAP publication No. 124, 569-570.

Cannas A., Tedeschi L.O., Fox D.G. 2007. The small ruminant nutrition system: development of a goat submodel. Journal of Dairy Science, 90 (Suppl. 1), 505. (Abstr.)

Cannas A., Erasmus L. J., Van Niekerk W., Coertze R., Linsky A. 2008. Evaluation of the predictions of the Small Ruminant Nutrition System on the Dorper and South African Mutton Merino. Proceedings of the World Congress of Animal Science. Cape Town, South Africa. (Abstr.).

Cannas A., Tedeschi, L.O., Atzori A.S., Fox D.G. 2008. The Small Ruminant Nutrition System (SRNS) model for prediction of energy and protein requirements of goats and sheep. Journal of Dairy Science, 91, E-Suppl. 1, 187. (Abstr.) (Invited talk)

Cannas A., Tedeschi, L.O., Atzori A.S., Fox D.G. 2008. The Small Ruminant Nutrition System, a nutrition model to account for dietary supply and requirements of nutrients for sheep and goats. Book of abstracts of the 59th EAAP meeting. 24-27 August 2008, Vilnius, Lithuania, 230. (Abstr.)

Tedeschi L.O., Cannas A., Fox D.G. 2008. 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. Revista Brasileira de Zootecnia, 37, suplemento especial, 178-190. (Invited paper)

Cannas A., Tedeschi L.O., Atzori A.S., Fox D.G., 2010. The development and evaluation of the Small Ruminant Nutrition System In: J. Dijkstra, (Ed), Modeling Nutrient Utilization in Farm Animals, CABI Publishing, Cambridge, MA, 263-272.

Gentil R.S., Susin I., Cannas A., Pires A.V.,. Mendes C.Q, Ferreira E.M., Rodrigues G.H., Atzori A.S., Tedeschi L.O., 2010. Prediction of rumen pH and digestibility of diets containing soybean hulls fed to ram lambs by the Small Ruminant Nutrition System. Journal of Dairy Science, 93, E-Suppl. 1, 730.

Oltjen, J.W., A. Cannas, A., A.S. Atzori, L.O. Tedeschi, R.D. Sainz and D.G. Fox. 2010. Integration of the Small Ruminant Nutrition System and of the UC Davis sheep growth model for improved predictions. In: G.M. Crovetto (Ed.) Energy and Protein Metabolism and Nutrition European Assoc. for Anim. Prod. Publ. No. 127, pp. 553-554.

Tedeschi, L.O., Cannas, A., Fox D.G. 2010. A nutrition mathematical model to account for dietary supply and requirements of energy and other nutrients for domesticated small ruminants: The development and evaluation of the Small Ruminant Nutrition System. Small Ruminant Research, 89, 174–184.

Independent evaluations:

NRC (2007). Nutrient requirements of small ruminants. Sheep, goats, cervids and New World camelids. The National Academies Press, Washington D.C., US.

Duarte-Vera F., Sandoval-Castro C, Srmiento-Farnco L 2009. Empleo del modelo SRNS para predecir la ganancia de peso en ovinos machos Pelibuey en crecimiento. Arch. Zootec. 58 (224): 671-681.

Galvani D. B., Pires C. C., Kozloski G. V. and. Wommer T. P. 2008. Energy requirements of Texel crossbred lambs. J. Anim. Sci. 86:3480-3490.

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