Animal 17 (2023) 100835

Contents lists available at ScienceDirect

Animal
The international journal of animal biosciences

Review: Harnessing extant energy and protein requirement modeling for sustainable beef production

L.O. Tedeschi

Department of Animal Science, Texas A&M University, College Station, TX 77843-2471, United States

A R T I C L E I N F O

Article history:
Received 26 October 2022
Revised 13 January 2023
Accepted 17 January 2023
Available online 28 April 2023

Keywords:
Cattle
Development
Growth
Mathematics
Simulation

A B S T R A C T

Numerous mathematical nutrition models have been developed in the last sixty years to predict the dietary supply and requirement of farm animals' energy and protein. Although these models, usually developed by different groups, share similar concepts and data, their calculation routines (i.e., submodels) have rarely been combined into generalized models. This lack of mixing submodels is partly because different models have different attributes, including paradigms, structural decisions, inputs/outputs, and parameterization processes that could render them incompatible for merging. Another reason is that predictability might increase due to offsetting errors that cannot be thoroughly studied. Alternatively, combining concepts might be more accessible and safer than combining models' calculation routines because concepts can be incorporated into existing models without changing the modeling structure and calculation logic, though additional inputs might be needed. Instead of developing new models, improving the merging of extant models' concepts might curtail the time and effort needed to develop models capable of evaluating aspects of sustainability. Two areas of beef production research that are needed to ensure adequate diet formulation include accurate energy requirements of grazing animals (decrease methane emissions) and efficiency of energy use (reduce carcass waste and resource use) by growing cattle. A revised model for energy expenditure of grazing animals was proposed to incorporate the energy needed for physical activity, as the British feeding system recommended, and eating and rumination (**H_jE_{er}**) into the total energy requirement. Unfortunately, the proposed equation can only be solved iteratively through optimization because H_jE_{er} requires metabolizable energy (**ME**) intake. The other revised model expanded an existing model to estimate the partial efficiency of using ME for growth (**k_g**) from protein proportion in the retained energy by including an animal degree of maturity and average daily gain (**ADG**) as used in the Australian feeding system. The revised k_g model uses carcass composition, and it is less dependent on dietary ME content, but still requires an accurate assessment of the degree of maturity and ADG, which in turn depends on the k_g. Therefore, it needs to be solved iteratively or using one-step delayed continuous calculation (i.e., use the previous day's ADG to compute the current day's k_g). We believe that generalized models developed by merging different models' concepts might improve our understanding of the relationships of existing variables that were known for their importance but not included in extant models because of the lack of proper information or confidence at that time.

Implications

The development of mathematical animal models to assist sustainable development in agriculture-related businesses might benefit drastically by merging existing animal models, more specifically those related to nutrition, given the amount of available data already collected worldwide and many different well-throughout concepts. However, problems in merging existing models include different paradigms, structural decisions, and parameterization processes that could render the merging undertaking infeasible. Another reason is that the predictability of the merged model might increase due to offsetting errors that cannot be thoroughly studied, creating an invalid model. Combining concepts rather than calculation routines might be more achievable and promising.

Introduction

We live in a time where sustainability has dominated the conversation in every scientific field (Pretty, 1997), yet we barely

---

E-mail address: luis.tedeschi@tamu.edu

https://doi.org/10.1016/j.animal.2023.100835
1751-7311/

understand its prerequisites and full potential in animal science (Tedeschi et al., 2015). Sustainability comes in many shapes and forms, given the needs of each country or region. Producing enough food to prevent hunger and eradicate poverty might be a more pressing issue than *saving* the environment in some places, though both might need to walk side-by-side to be effective (Anonymous, 2022). The growing demand for sustainable agricultural production systems presents complex problems that are best analyzed using mathematical modeling to assist researchers in recommending solutions to policymakers. The notion of using mathematical modeling to assist sustainable development in agriculture-related businesses is not new (Sharma et al., 2006; Gouttenoire et al., 2011; Tedeschi, 2020; Vlontzos et al., 2021).

Several mathematical animal nutrition models have been developed in the last sixty years to predict the dietary supply and animal's requirements of energy, protein, and other nutrients (Tedeschi and Fox, 2020a). These mathematical models share similar purposes, ideas, concepts, and original data. Fig. 1 depicts the chronological development and evolution of nutrition (Tedeschi et al., 2014) and grazing models (Tedeschi et al., 2019) and their derivative work (Tedeschi, 2019a). The development of animal bioenergetics, energy partitioning and utilization, and protein metabolism in the early days have been nicely documented in the past by Brody (1945), Blaxter (1962), and Kleiber (1961), and many comprehensive reviews have been updated and expanded these traditional publications (Van Es, 1978; Moe, 1981; Garrett and Johnson, 1983; Johnson et al., 2003; Ferrell and Oltjen, 2008; Tedeschi, 2019a). Fig. 1 indicates that the development of nutrition models commenced in the mid-1960s and has since been refined and expanded vertically (i.e., released versions/editions) and horizontally (i.e., different models or schools of thoughts). These models have distinct objectives, depending on their intended development purpose, but in the end, the primary goal has usually been to improve their prediction accuracy and precision to increase the efficiency of animal production.

As Garrett and Johnson (1983) pointed out, "one of the goals of energy metabolism research with ruminants always has been the development of an accurate means for evaluating feedstuffs and stating animal requirements." Despite intrinsic relationships and dependencies among extant mathematical animal nutrition models, given their shared similarities, the supply prediction approaches have evolved further and independently of the requirement prediction approaches. For instance, the Cornell Net Carbohydrate and Protein System (**CNCPS**)-based model (Fox et al., 2004) developed by Tedeschi and Fox (2020a), Ruminant Nutrition System (**RNS**), has three levels of solution for predicting the supply of energy and nutrients but a single common calculation logic for predicting the energy and nutrient requirements. The overarching

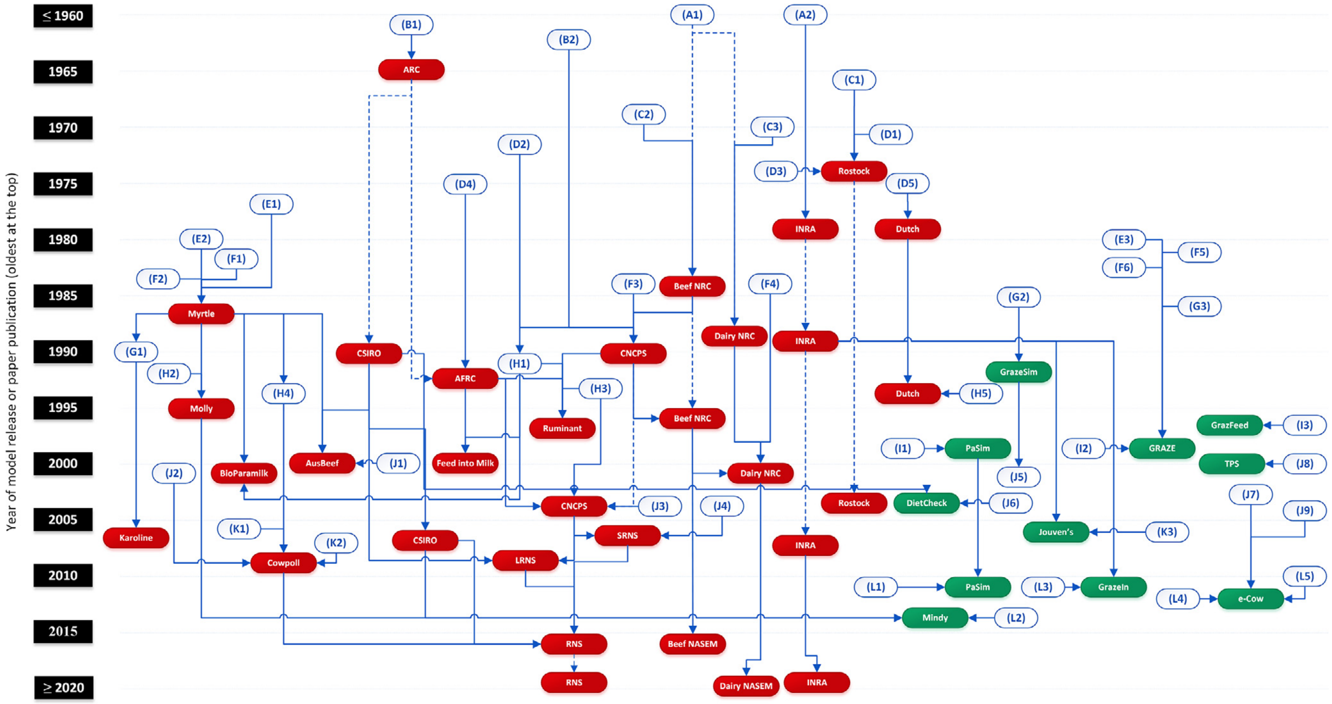

Fig. 1. Chronological evolution (older at the top to newer at the bottom) of key mathematical models whose primary goal lies within ruminant nutrition only (red squircles) or pasture/grazing ruminants (green squircles) domains. The approximate year of publication or release is shown on the left. The solid line represents a direct relationship of influence, and the dashed line represents that at least one other version or edition was released between the marks. The lack of lines connecting the same model does not imply that the model has been phased out. AFRC is Agricultural and Food Research Council; ARC is Agricultural Research Council; CNCPS is Cornell Net Carbohydrate and Protein System; LRNS is Large Ruminant Nutrition System; CSIRO is Commonwealth Scientific and Industrial Research Organisation; INRA is Institut National de la Recherche Agronomique; NASEM is the National Academies of Sciences, Engineering, and Medicine; NRC is National Research Council; RNS is Ruminant Nutrition System; SRNS is Small Ruminant Nutrition System; and TPS is Tropical Pasture Simulator. Key references (empty blue squircles) are: (A1) NRC (1945a and 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), (E3) Loewer et al. (1980), (F1) France et al. (1982), (F2) Gill et al. (1984), (F3) Fox and Black (1984), (F4) Conrad et al. (1984), (F5) Loewer et al. (1981), (F6) Loewer et al. (1983), (G1) Danfær (1990), (G2) Mertens et al. (1985, 1987), (G3) Bridges et al. (1986), (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), (I1) Riedo et al. (1998) based on the Hurley Pasture Model (Thornley, 1998), (I2) Loewer (1998), (I3) Freer et al. (1997), (J1) Nagorcka et al. (2000), (J2) Mills et al. (2001), (J3) Fox et al. (2004), (J4) Cannas et al. (2004) and Tedeschi et al. (2010), (J5) Vazquez and Smith (2001), (J6) Heard et al. (2004), (J7) Baudracco et al. (2010), (J8) Herrero et al. (2000a, 2000b), (J9) Vetharaniam et al. (2003), (K1) Bannink et al. (2006), (K2) Bannink et al. (2008), (K3) Jouven et al. (2006b and 2006a), (L1) Graux et al. (2011), (L2) Gregorini et al. (2013), (L3) Delagarde et al. (2011a, 2011b) and Faverdin et al. (2011), (L4) Baudracco et al. (2012), and (L5) Friggens et al. (2004). The figure was replicated with permission from Tedeschi (2019a).

goal of extant animal nutrition models was in line with agriculture's mode of action at that time: increasing productivity. In the last two decades, however, agriculture's mode of action has been transitioning to a more sustainable perspective (environmental, social, and economic), and animal production systems have been placed at the forefront of the debate (Tedeschi, 2022a). Therefore, mathematical nutrition models for sustainable animal agriculture might have to be re-engineered to accommodate current needs. It may include a complete overhauling of animal nutrition models to fit the *new* expectations, but it may also need to harness specific aspects of extant animal nutrition models and seamlessly combining them into an integrated platform to represent reality more accurately and precisely.

The relative contribution of beef cattle production to the climate change phenomenon differs among countries, varying from up to 4% (Dillon et al., 2021; Tedeschi, 2022a; Tedeschi and Beauchemin, 2023) in the US to 10% in Australia (Henry et al., 2012) to 21% in Brazil (Brazilian Ministry of Science, 2021), with a perception to represent 14.5% of human-induced greenhouse gas (**GHG**) emissions worldwide (Gerber et al., 2013). Such discrepancies in beef cattle contribution to the anthropogenic GHG among countries are primarily due to the relative sizes of their energy, industrial, and transportation sectors (thus, diluting more or less the beef cattle production contribution) but also due to (a) our inability to accurately quantify methane (CH_4) emissions given the hurdles to applying existing methodologies to diverse production systems and large-scale regions (Tedeschi et al., 2022) and (b) controversies regarding the calculations of the global warming potential of atmospheric CH_4 about its half-life and the time horizon used in climate change models (Cain et al., 2019; Lynch et al., 2020).

Nevertheless, the question remains, what are the advancements and limitations in predicting farm animals' energy and protein requirements, specifically growing ruminants, that could improve animal agriculture sustainability? The objective of this paper was to spark discussions of two critical areas in beef cattle production (energy requirements of grazing animals and efficiency of use of energy) to ensure adequate diet formulation by borrowing concepts used in different mathematical models. Tedeschi (2022b) presented and documented the preliminary analyses of this study.

Improving the prediction of energy requirements for grazing cattle

Grazing animals produce more methane per weight gain than confined animals (Pelletier et al., 2010). In part, the discrepancy arises because low-quality, high-fiber diets (e.g., forages) yield about four times more methane than high-quality, low-fiber diets (e.g., feedlot), respectively 0.23 vs 0.07 kg CH_4/animal/day (Harper et al., 1999). Furthermore, about 80% of total GHG emissions and 84% of methane emissions come from the cow-calf phase, whereas only 20 and 16%, respectively, come from the feedlot phase (Beauchemin et al., 2010). Therefore, accurately determining grazing animals' energy requirements is critical to ensure that strategic energy and protein supplementation is delivered to optimize animal growth and development (Tedeschi et al., 2019).

Unfortunately, most recommendations for grazing animals' energy and protein requirements were grounded on those determined for confined animals. Partly because determining energy, protein, and other nutrients for grazing animals requires special equipment and methodology, making it more challenging, expensive, and laborious. Energy and protein requirements for confined animals have been extensively studied and disseminated for over 117 years (Kellner, 1905). Digestion trials have been implemented for a bit longer: since 1860 at the Weende Experiment Station at the University of Goettingen in Germany and since 1884 at the University of Wisconsin Agricultural Experiment State in the United States (Schneider and Flatt, 1975). For beef cattle, currently recommended energy and protein requirements stemmed from penfed animal studies using the comparative slaughter technique and the California Net Energy System methodology (Oltjen, 2019), though discrepancies might exist (Tedeschi et al., 2017; Tedeschi, 2019b).

Grazing animals have an additional energy requirement associated with grazing activity compared to confined animal requirements. It comprises the additional energy needed for body movements (i.e., locomotion) and forage browsing, selection, and prehension. The non-activity maintenance requirement of energy between grazing and confined growing or finishing animals might be identical on a metabolic weight basis as long as animals are at the same degree of maturity (i.e., same composition of gain) (Tedeschi and Fox, 2015). However, because the diet consumed by grazing animals (i.e., essentially forage) has a lower partial efficiency of energy use for growth ($\mathbf{k_g}$), grazing animals would require a greater DM intake (**DMI**) to achieve the same average daily gain (**ADG**). This fact becomes a significant limitation for grazing animals for two main reasons: (1) the distance traveled to reach maximum voluntary intake within a 24-h period (daily basis) may exceed the animal's locomotion or eating time capacities, worsening its energy balance; and (2) because DMI is also a function of rumen size (i.e., volume/space), low-quality forages, i.e., forage containing a higher proportion of fibrous material, may further restrict intake by triggering the negative effect of rumen fill on voluntary feed intake (Tedeschi and Fox, 2015; 2020a). Both reasons impede grazing animals from having the same ADG as confined animals. Although the energy cost of physical activities in cattle, sheep, and buffaloes has been extensively documented worldwide, a comprehensive physical activity calculation logic does not exist because the lack of information on the energy required for eating feed by the ruminant is considerably more significant for grazing animals than for confined animals (Tedeschi and Fox, 2015).

Assessing the nutritional value of the feeds consumed by the animal is an essential step in determining the animal's energy and protein requirements, and it is not a trivial task. Tedeschi and Fox (2015) and Tedeschi and Dias Batista (2021) discussed existing techniques to determine feedstuffs' nutritive value. Given our inability to definitively and accurately assess the consumption of digestible energy (**DE**) by grazing animals when a digestibility trial cannot be carried out, some have proposed the use of mathematical modeling or empirical predictions to predict DE or its equivalent, total digestible nutrients (**TDN**), given the chemical composition of the diet in addition to other factors (Tedeschi and Fox, 2020a; 2020b), especially for those under grazing conditions (Tedeschi et al., 2019; Woli et al., 2020). In part, the problem arises not only because the DE content is unknown with a high degree of certainty but because of inadequate predictions of feed intake and selection. Additional problems exist when converting DE to metabolizable energy (**ME**) (Galyean et al., 2016; Seo et al., 2021) for grazing animals given the highly variable contribution of energy loss via methane production. Thus, the question remains, can the intake of DE be accurately determined so energy partitioning can be estimated to assess animals' energy requirements under grazing or confined conditions?

Predicting energy expenditure for grazing cattle

In the United States, comprehensive discussions about energy and protein requirements, primarily based on confined animals (Tedeschi, 2019a), have been published by the National Research

Council (**NRC**) and National Academies of Sciences, Engineering, and Medicine (**NASEM**) for beef cattle from 1945 (NRC, 1945a) to 2016 (NASEM, 2016), for dairy cattle from 1945 (NRC, 1945b) to 2021 (NASEM, 2021), and for sheep and goats from 1945 (NRC, 1945c) to 2007 (NRC, 2007). Other countries and regions around the globe have followed suit and devised their own set of recommendations to meet their needs and production conditions. Few publications have meticulously addressed the grazing animal's energy expenditure (**EE**) as the Australian Nutrient Requirements of Domesticated Ruminants published by the Commonwealth Scientific and Industrial Research Organization (CSIRO, 1990; 2007).

The Agricultural Research Council (ARC, 1980) developed a factorial approach to estimate the EE (kcal/d) (Eq. (1)) associated with physical activities by assigning coefficients to the number of hours animals spent standing (h/day), the number of daily body changes (laying down and standing), and walking horizontal and ascent distances (km/day). Assuming the typical values for feedlot and continuous grazing of 12 and 18 h/d for standing, 6 daily position changes, 0 and 2 km/d for horizontal distance, and no vertical distance, the EE values for animals' physical activity with 300 kg of BW, usually assumed to be shrunk BW (NASEM, 2016), are 471.6 and 1 024.6 kcal/d. If the required net energy (**NE**) required for maintenance is assumed to be 70 kcal/kg$^{0.75}$ BW/d, these EE values for physical activity become an additional 9.35 and 20.3%, respectively. That means the daily required NE for maintenance becomes 1.0935 × (70 × BW$^{0.75}$) and 1.203 × (70 × BW$^{0.75}$) for animals under feedlot and continuous grazing conditions, respectively. Fox and Tylutki (1998) proposed to change the basal metabolic energy requirement from 77 kcal/kg$^{0.75}$ of BW, devised by Lofgreen and Garrett (1968), to 70 kcal/kg$^{0.75}$ of BW because of about 10% (i.e., 9.35%) needed for physical activity under typical feedlot conditions in the United States.

$$EE_{PA} = \begin{pmatrix} 0.1 \times Standing + 0.062 \times Position\ changes + \\ 0.621 \times Distance_{Flat} + 6.69 \times Distance_{Vertical} \end{pmatrix} \times FBW \tag{1}$$

where $Distance_{Flat}$ is the distance traveled by the animal on a horizontal, flat surface, km/d; $Distance_{Vertical}$ is the equivalent ascending distance traveled by the animal, km/d; EE_{PA} is energy expenditure for physical activity, kcal/d; *FBW* is full (unshrunk) BW, kg; *Position changes* is the number of standing and lying changes per day; and *Standing* is the number of hours standing, h.

Horizontal vs sloped vs vertical distances

In practice, an animal's locomotion is either on a leveled terrain (i.e., horizontal, flat) or a sloped terrain (i.e., inclined) with a gradient or an inclination angle; animals do not "walk vertically." The main limitation of measuring the EE for sloped terrains is that the inclination angle may differ between studies, making it challenging to compare the measured EE needed for sloped distances. Thus, the EE of vertical or ascent distance removes the inclination angle as it only assumes the differences in heights to estimate EE. Because cows climbing a ladder is unheard of, the EE for "walking vertically" has to be computed mathematically.

Fig. 2 shows the graphical relationships between these distances. An animal can go from point A to point B by walking the slopped distance from A → B, or walking horizontally from A → D and then "vertically" from D → B. Given the laws of thermodynamics of conservation of energy, as shown in Eq. (2), it is assumed that the amount of energy expended for s × $EE_{A\rightarrow B}$ is equal to the sum of the energy expended for h × $EE_{A\rightarrow D}$ plus v × $EE_{D\rightarrow B}$, assuming that the EE is expressed as energy per distance unit, and *s*, *h*, and *v* are distances.

$$EE_{A\rightarrow B} \times s = EE_{A\rightarrow D} \times h + EE_{D\rightarrow B} \times v \tag{2}$$

where *EE* is energy expenditure, Mcal/km.

The *h* and *v* (dashed red lines in Fig. 2) can be computed from the triangle A-B-D using trigonometric relationships, as shown in Eq. (3).

$$\begin{aligned} \cos(\alpha) &= h/s \therefore h = \cos(\alpha) \times s \\ \sin(\alpha) &= v/s \therefore v = \sin(\alpha) \times s \end{aligned} \tag{3}$$

Replacing *h* and *v* in Eq. (2) with those from Eq. (3), simplifying the equation, and re-arranging to estimate $EE_{D\rightarrow B}$, we obtain Eq. (4).

$$\begin{aligned} EE_{A\rightarrow B} \times s = EE_{A\rightarrow D} \times (\cos(\alpha) \times s) + EE_{D\rightarrow B} \times (\sin(\alpha) \times s) \therefore \\ EE_{D\rightarrow B} = (EE_{A\rightarrow B} - EE_{A\rightarrow D} \times \cos(\alpha)) / \sin(\alpha) \end{aligned} \tag{4}$$

where cos is the cosine function; *EE* is energy expenditure, Mcal/km; sin is the sine function; and α is the inclination angle, radians.

Because $EE_{A\rightarrow D}$ is the same as $EE_{A\rightarrow C}$ as they are expressed as energy per distance per kilogram of BW, we can substitute $EE_{A\rightarrow D}$ with $EE_{A\rightarrow C}$ to obtain the final mathematical formulation to compute $EE_{D\rightarrow B}$ with known measurements expressed as energy per distance, as shown in Eq. (5). Note that $EE_{D\rightarrow B}$ (i.e., uphill) might

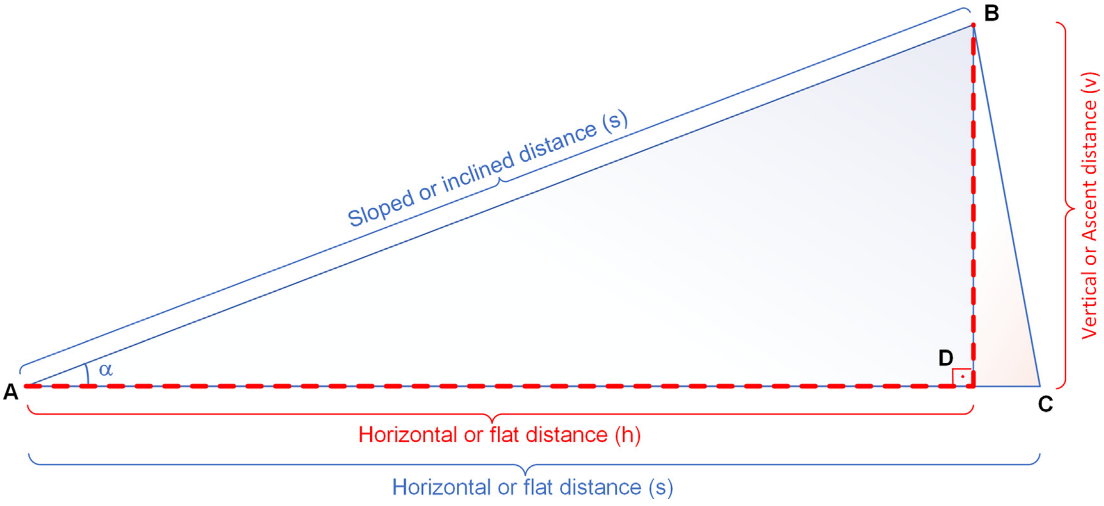

Fig. 2. Relationships among horizontal (h), sloped (s), and vertical (v) locomotion.

not be the same as $EE_{B\to D}$ (i.e., downhill) (Miwa et al., 2015; Mulvenna et al., 2022), given the EE required for maintaining equilibrium and stability to prevent falling (Hunter et al., 2010).

$$EE_{D\to B} = (EE_{A\to B} - EE_{A\to C} \times \cos(\alpha))/\sin(\alpha) \tag{5}$$

where cos is the cosine function; *EE* is energy expenditure, Mcal/km; sin is the sine function; and α is the inclination angle, radians.

Therefore, if an animal expends 0.62 kcal/km/kg of BW for walking on a horizontal path and 1.32 kcal/km/kg of BW for walking on a 6° sloped path, the "vertical walking" EE would be 6.73 kcal/km/kg of BW, calculated using Eq. (6).

$$EE_{D\to B} = (1.32 - 0.62 \times \cos(6 \times \pi/180))/\sin(6 \times \pi/180) \tag{6}$$

where cos is the cosine function; *EE* is energy expenditure, Mcal/km; sin is the sine function; and π is the Pi number.

For example, a 300-kg animal walking 2.5 km on a 6° sloped terrain would require 990 kcal (300 kg × 2.5 km × 1.32 kcal/km/kg). It is equivalent to a 300-kg animal walking 2.486 km horizontally ($\cos(6^\circ \times \pi/180)$) at 0.62 kcal/km/kg plus 0.261 km "vertically" ($\sin(6^\circ \times \pi/180)$) at 6.73 kcal/km/kg: 300 kg × 2.486 km × 0.62 kcal/km/kg + 300 kg × 0.261 km × 6.73 kcal/km/kg ≈ 990 kcal.

Revisiting the prediction of energy expenditure for grazing cattle

The CSIRO (2007) devised a different approach to compute the EE of grazing animals by adding an assessment of animals' DMI, grazing density (animals per ha), DM digestibility, and availability of the forage to the animals' physical activity (horizontal locomotion). While this is a more mechanistic approach to estimating grazing animals' EE, it requires additional information that might be neither available nor measurable. Novel methods and techniques to assess forage availability and quality (González et al., 2018) are promising, and their adoption in these situations might help our understanding of grazing animals' EE tremendously.

Table 1 has revised literature data published by Tedeschi and Fox (2020a), which was initially reported by Tedeschi (2001) and Tedeschi and Fox (2015), who provided a detailed description of the studies. The dataset summarizes EE for different grazing ruminant species, using different techniques from 18 studies, and a summary of Israeli studies for grazing Simmental × Hereford beef cows, using the heart rate technique and global positioning system from four studies. The average EE values for sloped (1.37, 1.33, and 1.32 kcal/kg/km) and vertical (6.59 and 6.69 kcal/kg/km) locomotions are nearly identical between the datasets (Table 1), but the EE for horizontal locomotion differs considerably from the values adopted by ARC (1980) and CSIRO (1990) by almost six times (0.11 vs 0.62 kcal/kg/km). The variation among different techniques assessing EE of grazing animals is high, partly because of the differences in feed quality, the amount used, and types of animals under different environments in each experiment. Thus, a direct comparison of the results is complicated.

Developing a holistic energy requirement for grazing animals

Besides the basal metabolism and physical activity for grazing animals, one could include the EE for chewing (i.e., eating and ruminating), given the digestibility of the diet. The idea would be similar to CSIRO's (2007) approach in which diet quality (i.e., digestibility) alters the EE of grazing animals. Tedeschi and Fox (2015) and Tedeschi and Fox (2020a) proposed a holistic approach to predict the increase in the NE required for maintenance due to physical activities, eating, and ruminating forages of different quality.

The prediction of EE for physical activities assumes an additive model; in other words, physical activity expenses plus the heat increment of feeding are added to basal metabolism ($\mathbf{H_eE}$) (White, 1993). The heat increment due to feed type in grazing systems may be incorrectly attributed to physical activity, and the EE attributed to physical activities may overlap the heat requirement for thermoregulation in cold conditions (T_c less than the lower critical temperature). Other factors, such as eating and ruminating, may also influence the EE of grazing animals, which depends on the biting size and rate. Di Marco et al. (1996) estimated the energy cost of eating was 1.84 kcal/$kg^{0.75}$/h for 59 bites/min (148 g DM/m^2 for ryegrass pasture) and 0.55 kcal/$kg^{0.75}$/h for 28 bites/min (228 g DM/m^2 for oat). Osuji (1974) had previously reported the value of 7.06 cal/kg/min for eating, which is approximately 1.89 kcal/$kg^{0.75}$/h for a 400-kg animal, nearly identical to the value of 59 bites/min measured by Di Marco et al. (1996).

A more holistic approach for partitioning the energy required (i.e., EE) of different behavior patterns of grazing animals is necessary to predict the maintenance energy needed to support physical activities and the animal's EE for eating and ruminating forages of different quality. The submodel developed by Tedeschi and Fox (2015) proposed to partition EE for eating (i.e., mastication and ingestion of fresh feed) and ruminating (i.e., chewing the cud). The NRC (1981) defined HE as the sum of heat for basal metabolism (i.e., H_eE); heat for muscular activity ($\mathbf{H_jE}$) required for standing, walking, grazing, drinking, and lying down; the heat of enzymatic digestion ($\mathbf{H_dE}$); the heat of fermentation as a result of ruminal

Table 1
Summary of additional energy expenditure (kcal/kg of BW) for diverse physical activities in ruminants.[1]

Items		Types of walked distances		
	Standing	Horizontal	Sloped	Vertical
	kcal/d/kg of BW	kcal/km/kg of BW		
Israeli's dataset[2]				
Average	2.59	0.11	1.37	–
SD	0.22	0.03	0.23	–
CV, %	8.4	28.1	16.9	–
Tedeschi's (2001) dataset[3]				
Average	–	0.11	1.33	6.59
SD	–	0.03	0.11	0.78
CV, %	–	29.3	16.2	11.9
ARC (1980)				
Average	2.39	0.62	1.32	6.69

[1] Revised from Tedeschi and Fox (2020a).

[2] References: Brosh et al. (2006), Aharoni et al. (2009), Brosh et al. (2010), Aharoni et al. (2013).

[3] References: Corbett et al. (1969), Ribeiro et al. (1977), Lawrence and Richards (1980), Havstad and Malechek (1982), Sanchez and Morris (1984), Thomas and Pearson (1986), Sahlu et al. (1988), Lawrence and Stibbards (1990), Nienaber et al. (1993), Méndez et al. (1996), Dijkman and Lawrence (1997), Fall et al. (1997), Prieto et al. (1997), Di Marco and Aello (1998), Herselman et al. (1998), Susenbeth et al. (1998).

microbial action (**$\mathbf{H_fE}$**); the heat associated with the metabolic processes of product formation from absorbed metabolites (**$\mathbf{H_rE}$**); thermal regulation (**$\mathbf{H_cE}$**), and waste formation and excretion (**$\mathbf{H_wE}$**). Heat increment (**$\mathbf{H_iE}$**) is the sum of H_dE, H_fE, H_rE, and H_wE. HE can be written as shown in Eq. (7) for an animal fed at maintenance.

$$HE = H_eE + H_jE + H_cE + H_iE \tag{7}$$

where H_cE is the heat for thermal regulation, Mcal/d; *HE* is heat production, Mcal/d; H_eE is the heat for basal metabolism, Mcal/d; H_iE is the heat increment, Mcal/d; and H_jE is the heat for muscular activity, Mcal/d.

For animals under no heat or cold stress, H_cE is assumed to be 0. Furthermore, for an animal fed at maintenance, retained energy (**RE**) is zero; thus, the HE is equal to ME intake (*MEI = HE + RE*). In the case of maintenance-level of intake, the MEI is the MEmr. We further subdivided heat for muscular activities (i.e., H_jE) into an animal's physical activity for locomotion or movement (**$\mathbf{H_jE_{pa}}$**) and eating and ruminating the digesta (**$\mathbf{H_jE_{er}}$**). After assuming these simplifications, Eq. (7) yields Eq. (8).

$$MEI = MEmr = H_eE + \left(H_jE_{pa} + H_jE_{er}\right) + H_iE \tag{8}$$

where H_eE is the heat for basal metabolism, Mcal/d; H_iE is the heat increment, Mcal/d; H_jE_{er} is the heat for eating and ruminating, Mcal/d; H_jE_{pa} is the heat for physical activities, Mcal/d; *MEI* is metabolizable energy intake, Mcal/d; and *MEmr* is ME required for maintenance, Mcal/d.

Susenbeth et al. (1997 and 1998) reported that EE for eating was 1.91 kcal/kg$^{0.75}$/h for 640-kg steers, with a literature review mean of 1.78 kcal/kg$^{0.75}$/h from a range of 0.7 to 2.7 kcal/kg$^{0.75}$/h (Susenbeth et al., 1997; 1998). These authors also reported that, on average, animals expended 0.52 kcal/kg$^{0.75}$/h on ruminating but that the EE for eating and ruminating varied with feed quality, from 0.19 Mcal/kg DM for high-quality forage to 0.57 Mcal/kg DM for wheat straw, representing 8 and 33% of MEI, respectively (Susenbeth et al., 1997; 1998). When we regressed the EE for eating and ruminating (Mcal/kg DM) on MEI (Mcal/d), using the data reported by Susenbeth et al. (1998), we obtained Eqs. (9) (power equation) and (10) (decay equation) to predict H_jE_{er}. For instance, a 300-kg animal eating 7 kg DM/d of a diet or 16.9 Mcal ME/d would have H_jE_{er} of 1.98 (Eq. (9)) Mcal ME/d, or about 11.7% of its energy required for maintenance. Alternatively, 2.15 Mcal ME/d is obtained with Eq. (10). Eq. (9) was adopted because it yielded a lower residual sum of squares than Eq. (10) (0.00048546 vs 0.00292620).

$$H_jE_{er} = \left(4.2557 \times MEI^{-0.95878}\right) \times DMI \tag{9}$$

$$H_jE_{er} = \left(0.95166 \times e^{-0.06705 \times MEI}\right) \times DMI \tag{10}$$

where *DMI* is DM intake, kg/d; *e* is the exponential function (i.e., *e* is the Napier's constant of 2.7182); H_jE_{er} is the heat for eating and ruminating, Mcal/d; and *MEI* is metabolizable energy intake, Mcal/d.

As shown in Eq. (11), the heat for basal metabolism (i.e., H_eE) is computed using the equation developed by Lofgreen and Garrett (1968) adjusted for the physical activity of pen-fed animals (Fox and Tylutki, 1998) and for the energy cost of eating and ruminating, using Eq. (9). The animals in the low level of feed intake used by Lofgreen and Garrett (1968) consumed about 3.3 kg DM/d and 8 Mcal ME/d. For these values, Eq. (9) yields H_jE_{er} of 1.9 Mcal/d. Consequently, H_eE (i.e., NEmr) adjusted for their animals' physical activity, eating, and ruminating EE is estimated as shown by Eq. (11). The H_jE_{pa} (i.e., $\mathrm{NEmr_{Act}}$) is computed with Eq. (1).

$$H_eE = NEmr_{Basal} = 0.07 \times SBW^{0.75} - 1.9 \tag{11}$$

where *HeE* is the heat for basal metabolism (i.e., $NEmr_{Basal}$), Mcal/d; and *SBW* is the shrunk BW, kg.

Although the energy cost associated with physical activity is included in the observed data of Lofgreen and Garrett (1968), the physical activity adjustment proposed by Fox and Tylutki (1998) might have introduced some degree of double accounting. The reason is that physical activity cost likely varies with feed intake, and extrapolating to zero feed intake might have already adjusted for some portion of it automatically.

When animals have been starved (i.e., energy intake is zero) for some time, yielding negligible amounts of energy from the digesta, the NEmr is equal to the fasting heat of production (i.e., H_eE or basal metabolism). However, when animals resume feeding (i.e., energy intake is greater than zero), the heat associated with obtaining feed (e.g., physical activity, eating, and ruminating) is added to the NEmr (NRC, 1981). The physical activity (**$\mathbf{H_jE_{pa}}$**) and eating and ruminating (**$\mathbf{H_jE_{er}}$**) heats are included in the NEmr as represented in Eqs. (12) and (13) when energy intake is greater than zero.

$$MEmr = NEmr + H_iE \tag{12}$$

$$NEmr = \begin{cases} H_eE & \text{Energy intake} = 0 \\ H_eE + H_jE_{pa} + H_jE_{er} & \text{Energy intake} > 0 \end{cases} \tag{13}$$

where H_eE is the heat for basal metabolism, Mcal/d; H_iE is the heat increment, Mcal/d; H_jE_{er} is the heat for eating and ruminating, Mcal/d; H_jE_{pa} is the heat for physical activities, Mcal/d; and *MEmr* is the metabolizable energy required for maintenance, Mcal/d.

Therefore, for an animal fed at maintenance (zero energy intake), the NEmr is equal to MEmr × k_m in which k_m is the partial efficiency of using ME to NE for maintenance. Consequently, replacing NEmr with MEmr × k_m in Eq. (12) and solving for H_iE shows that H_iE is MEmr×(1 – k_m). Then, substituting H_iE and NEmr (Eq. (13)) into Eq. (12) results in Eq. (14). Expanding Eq. (14) by replacing H_eE with Eq. (11), H_jE_{pa} with Eq. (1), and H_jE_{er} with Eq. (9) results in Eq. (15). Unfortunately, because H_jE_{er} requires MEI to be computed (i.e., MEmr for animals at maintenance), Eq. (15) can only be solved iteratively through optimization, highlighting the danger of adopting feedforward calculation only and ignoring feedback loops.

$$MEmr = H_eE + H_jE_{pa} + H_jE_{er} + MEmr \times (1 - k_m) \tag{14}$$

$$\begin{aligned} MEmr = {} & \left(0.07 \times SBW^{0.75} - 1.9\right) \\ & + \frac{\left(\begin{array}{l} 0.1 \times Standing + 0.062 \times PositionChanges + \\ 0.621 \times Distance_{Flat} + 6.69 \times Distance_{Vertical} \end{array}\right) \times FBW}{1000} \\ & + \left(4.2557 \times MEI^{-0.95878}\right) \times DMI + MEmr \times (1 - k_m) \end{aligned} \tag{15}$$

where $Distance_{Flat}$ is the distance traveled by the animal on a horizontal, flat surface, km/d; $Distance_{Vertical}$ is the equivalent ascending distance traveled by the animal, km/d; *DMI* is DM intake, kg/d; *FBW* is full (unshrunk) BW, kg; H_eE is the heat for basal metabolism, Mcal/d; H_iE is the heat increment, Mcal/d; H_jE_{er} is the heat for eating and ruminating, Mcal/d; H_jE_{pa} is the heat for physical activities, Mcal/d; k_m is the partial efficiency of the use of metabolizable energy for maintenance, Mcal/Mcal; *MEI* is metabolizable energy intake, Mcal/d; *MEmr* is the metabolizable energy required for maintenance, Mcal/d; *Position changes* is the number of standing and lying changes per day; *SBW* is shrunk BW, kg; and *Standing* is the number of hours standing, h.

An inconsistency that arises from the factorial approach to determine HE, as shown in Eq. (7), is that the partial efficiency of using ME to NE for maintenance (i.e., k_m) is only valid to estimate

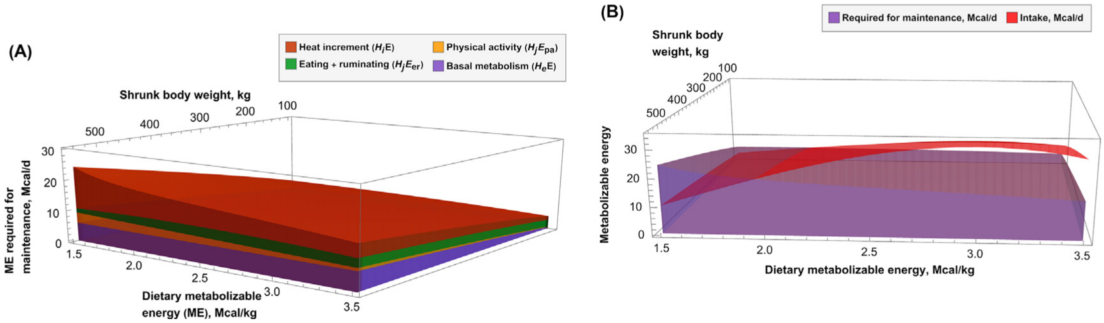

Fig. 3. (A) Metabolizable energy (ME) required for basal metabolism (H_eE), physical activity (H_jE_{pa}), eating and ruminating (H_jE_{er}), and heat increment (H_iE) of grazing cattle for different shrunk BWs and dietary ME contents calculated using Eq. (15). See Supplementary Video S1. (B) Total ME required for maintenance (purple) and predicted ME intake. See Supplementary Video S2. Based on Tedeschi and Fox (2020a).

the ME_{mr} from fasting heat production (H_eE or basal metabolism at zero energy intake). The reason is that $ME_{mr} = k_m \times H_eE$, as shown in Eqs. (12) and (13) (Garrett, 1980b). If all HE components are measured and summed up, using k_m will eventually result in double accounting. In that case, k_m needs to be "increased" to consider the HE included in estimating NE_{mr}; in other words, k_m needs to account for a smaller portion of the unaccounted HE.

Fig. 3A depicts the total daily ME required for a grazing animal, partitioned into EE for basal metabolism, physical activity, eating and ruminating, and heat increment, assuming dietary ME (1.5–3.5 Mcal/kg) and SBW (100–550 kg). The horizontal and vertical distances were assumed to vary (1 500–0 meters per day and 500–0 meters per day, respectively) for low- to high-quality dietary ME (1.5–3.5 Mcal/kg, respectively). The variable horizontal and vertical distances were used to mimic animals grazing farther on low-quality forages to meet their energy requirements for maintenance compared to those on high-quality forages (e.g., rotational grazing systems or confinement conditions). The number of hours standing was 12 h/d, and the number of body position changes was 6 times/d regardless of the diet ME and animal SBW. The proportion of MEI (i.e., MEmr) lost as heat (i.e., heat increment) was identical among animals of different SBW because the k_m was computed from dietary ME, which was identical for all animals. The heat increment (H_iE) was greater for heavier than lighter animals, but the proportion of MEI that was expended for eating and ruminating was greater for lighter than heavier animals as it was a function of dietary ME. The EE for eating and ruminating was greater for low-quality forage than grain-based finishing diets (Fig. 3A). The proportion of physical activity (i.e., movement or locomotion) was similar, ranging between 7 and 14%. As expected, animals expended more energy on low-quality forage than on high-quality forage (Fig. 3A). The EE for physical activity varied from 0.16 to 0.61 Mcal/d for the 100-kg animal and 0.90 to 3.35 Mcal/d for the 550-kg animal. Animals consuming diets containing less than approximately 1.9 Mcal ME/kg are predicted not to meet their energy requirements as their MEI is below the ME required for maintenance (Fig. 3B), and they would likely lose weight and eventually succumb if dietary ME remains low. The 1.9 Mcal ME/kg DM is approximately 53% TDN, confirming the minimum threshold of forage digestibility, suggested by Van Soest (1994; Figures 7.8 and 7.9), of approximately 50% to support cattle at maintenance.

As shown in Fig. 3A, the EE for physical activity (H_jE_{pa}) and chewing (H_jE_{er}) accounts for nearly all the differences between confined and grazing ruminants, and yet, our incomplete understanding of these components has delayed the development of a more definitive solution. In part, data collection of plant and animal interaction (forage selection, grazing behavior, pasture growth/regrowth, pasture quality, nutrient digestion and absorption, volatile fatty acids production and profile, and energy requirement) remains a critical bottleneck for adequate knowledge of forage intake by ruminants (Tedeschi et al., 2019). Most of the data on EE for ruminants crested in the early 1960s toward the mid-1980s, boosted by many open-circuit, indirect calorimetry apparatuses and methods, but none could be decisively deemed ideal, and the development and improvement of methodologies declined. More recently, with the advancement of global positioning systems (**GPS**) and heart rate monitoring systems, researchers have been able to track grazing animals and estimate their EE (Brosh, 2007). The adoption of these instruments to determine grazing animals' EE was likely motivated by the desire to identify efficient animals through the residual feed intake (**RFI**) technique (Asher et al., 2018).

As new technologies and methodologies become available, modeling the energy requirement of grazing and confined animals will likely close the gap between model-predicted and observed performance as more factors are considered in the predictive models. Nonetheless, caution should be exercised to avoid double accounting or offsetting errors in calculating EE that could elicit false improvements in predictability.

Improving the predictability of the efficiency of the energy use for growing cattle

The second bottleneck in ensuring adequate diet formulation is the accurate determination of the efficiency of ME use for growth. There is no shortage of growth model development, but perhaps combining the quintessence of extant growth models to improve the predictability of the gain composition is warranted. Once the gain composition is known, the energy and protein requirements are straightforward calculations. The RE and ADG have been the heartbeat of many theoretical growth models (Lofgreen and Garrett, 1968; Garrett, 1980a; Loewer et al., 1983; Fox and Black, 1984; NRC, 1984; 2000; Fox et al., 1992), including stochastic models (Parks, 1973). Some growth models used ADG and specific characteristics of animal growth (Keele et al., 1992; Williams et al., 1992; Williams and Jenkins, 1998; Kilpatrick and Steen, 1999) and combined mechanistic or dynamic modeling to predict body composition (Hoch and Agabriel, 2004a; 2004b), or used DNA (deoxyribonucleic acid) accretion curves and protein-to-DNA ratio (Oltjen et al., 1986b; Bywater et al., 1988; Di Marco et al., 1989; Oltjen et al., 2000). Primary biochemistry pathways associated with the development and growth of different tissues (e.g., viscera, muscle, and adipose) have been developed for sheep (Oddy et al., 1997; Oddy et al., 2019). Most mechanistic and dynamic conceptual growth models are based on metabolic processes (Gill, 1984; France et al., 1987; Gill et al., 1989; Gill, 1996), but such models rely heavily on the principle that substrate availability and saturation enzyme kinetics control the distribution of nutrients in body tissues (Baldwin, 1995).

Some growth models rely on empirical concepts and some elements of teleonomic behavior (Tedeschi and Fox, 2020a). Others possess some elements of mechanistic modeling, and very few or none adopted stochastic components (i.e., probabilistic theory). Because of the different modeling approaches to predict energy and protein requirements among existing growth models and their different variables, some critical limitations arise when comparing existing growth models. For instance, Arnold and Bennett (1991a and 1991b) compared four growth models developed in the early to mid-1980s: Roman L. Hruska US Meat Animal Research Center (Notter et al., 1979a; Notter et al., 1979b; 1979c), Texas A&M University (Sanders and Cartwright, 1979a; 1979b; Oltjen et al., 1986a), BEEFS156 (Loewer et al., 1983; Loewer et al., 1987), and UCDavis (Oltjen et al., 1986a; Oltjen et al., 1986b). They reported that two problems caused these models to yield inconsistent results: the definition of mature BW is different among growth models and different predictions of DMI. When these two variables were assigned independently within each model, the models simulated the animal's BW successfully but failed to predict body composition. Similarly, Garcia et al. (2008) compared the growth model developed by Institut National de la Recherche Agronomique (Hoch and Agabriel, 2004a; 2004b) and UCDavis (Oltjen et al., 1986a; Oltjen et al., 1986b), and reported that both models, developed with entirely different concepts and equations, could produce similar predictions of body composition (protein accretion), but they behaved differently under distinct growth trajectories. These evaluations reinforced the hypothesis that each model has to be evaluated within the purpose of its development, and intrinsic errors may offset each other within each model. Therefore, model comparisons should be carried out under various production conditions to accommodate each model's assumptions and purposes. Consequently, a generalized growth model is still needed.

Such limitations may hinder the predictability of growth models when different production conditions exist other than those established conditions in which the models were developed or calibrated (Tedeschi, 2022b). They may also prevent incorporating different modeling concepts from one model to another. For instance, for growing cattle, the partial efficiency of energy use for growth (i.e., k_g) in the American systems (e.g., NRC, NASEM, CNCPS, and RNS) is frequently computed based on an empirical (cubic) equation that estimates the NE for growth (**NEg,** Mcal/kg) based on the dietary concentration of the ME (Mcal/kg). Similarly, in the British and Australian systems (e.g., ARC, Agricultural and Food Research Council—**AFRC**, and CSIRO), the k_g also exclusively depends on dietary energy through the metabolizability of the diet (**M/D**), though a linear equation is applied. In addition to the diet characteristics, more specifically its digestibility, CSIRO (2007) proposed adjusting k_g for the legume proportion relative to grass.

Predicting the partial efficiency of the use of energy for growth

Although the dietary ME is related to the dietary contents of carbohydrates, fat, and protein and their digestibility, the efficiency to which energy is deposited in the tissue depends on the tissue gain composition (Reid et al., 1980; Tedeschi et al., 2004). Growth models rarely acknowledge this fact and still use dietary characteristics to estimate k_g and NEg; thus, incorrectly rendering k_g independent of carcass composition. If the protein proportion of RE is known, k_g can be estimated using Eq. (16), and assuming fat and protein deposition efficiencies of 75 and 20%, respectively, it yields Eq. (17) (Tedeschi, 2001; Williams and Jenkins, 2003; Tedeschi et al., 2004).

$$k_g = k_F \times k_P / (k_P + RE_P \times (k_F - k_P)) \tag{16}$$

$$k_g = 3/(4 + 11 \times RE_P) \tag{17}$$

where k_F is the efficiency of fat deposition, Mcal/Mcal; k_g is the partial efficiency of converting metabolizable energy into net energy for growth; k_P is the efficiency of protein deposition, Mcal/Mcal; and RE_P is the proportion of protein in the retained energy.

The impact of growth rate on the deposition efficiencies of fat and protein

These deposition efficiencies are not fixed, however, Cannas et al. (2006) and Tedeschi et al. (2010) reported values of 68 and 27% for fat and protein, respectively, for growing sheep, and Chizzotti et al. (2008) reported different deposition efficiencies of fat (79%) and protein (34%) for Nellore and Nellore × *Bos taurus*. Marcondes et al. (2013) empirically derived a non-linear relationship between k_g and the proportion of RE as protein (**RE_P**), and when solving their empirical equation, the deposition efficiencies for fat and protein are 60.7 and 21.2%, respectively. These studies suggest that deposition efficiencies of fat vary from 60.7 to 79% and of protein vary from 21.1 to 34%. Perhaps the most exciting finding elucidated by Marcondes et al. (2013) was that fat and protein deposition efficiencies are not constant; they increase linearly with ADG (Eq. (18) had r^2 of 0.916 and Eq. (19) had r^2 of 0.951). Their values suggested that fat and protein deposition efficiencies increased by about 1.84 and 1.76% for each 100 g/d increase in ADG, respectively. Interestingly, based on Eqs. (18) and (19), fat and protein deposition efficiencies are 69.1 and 19.8%, respectively, when ADG (i.e., empty weight gain, **EWG**) is zero. These values are close to their respective values reported above, suggesting these efficiencies are only valid when ADG approximates zero: body composition of low-gaining animals might be better estimated than high-gaining animals.

$$k_F = 0.1836 \times EWG + 0.691 \tag{18}$$

$$k_P = 0.1764 \times EWG + 0.198 \tag{19}$$

where *EWG* is empty weight gain, kg/d; k_F is the efficiency of fat deposition, Mcal/Mcal; and k_P is the efficiency of protein deposition, Mcal/Mcal.

Combining Eq. (16) with EWG-dependent fat (k_F) and protein (k_P) deposition efficiencies (Eqs. (18) and (19)) yields Eq. (20), which has the shape shown in Fig. 3A without restricting the maximum k_g to 79%.

$$k_g = \frac{19.0025 + EWG(21.9785 + 4.4982 \times EWG)}{27.5 + 24.5 \times EWG + RE_P(68.4722 + EWG)} \tag{20}$$

where *EWG* is empty weight gain, kg/d; k_g is the partial efficiency of converting metabolizable energy into net energy for growth; and RE_P is the proportion of protein in the retained energy.

Fig. 3A shows that the k_g decreases exponentially with the protein proportion in the RE and increases linearly with EWG. The direct correlation between EWG and k_g was expected because the rate of fat deposition increases as EWG increases (Owens et al., 1995), and the fat deposition efficiency is greater than protein, as discussed above. The protein requirement for growing animals can be theoretically estimated from RE and ADG (Tedeschi, 2019b); thus, improving RE (and ADG) predictions will improve the computation of protein needs.

The impact of maturity stage rate on the deposition efficiencies of fat and protein

The rate of fat accretion also increases with maturity (Owens et al., 1995; Tedeschi, 2019b), assuming empty body fat as a proxy for maturity. Thus, one would expect that k_g should also increase with maturity. Nevertheless, which variable (EWG or maturity) impacts kg the most is unknown. The British and Australian systems (e.g., ARC, AFRC, CSIRO) developed non-linear equations to compute the proportion of protein and fat in the gain as animals mature. That means these feeding systems assumed correctly that the animals' maturity stage could be used to adjust changes in body composition, i.e., fat content increases with maturity. These feeding systems adopted the logistic (sigmoidal) function to estimate fat or protein content in the gain for large lean breeds (Charolais, Chianina, Blonde d'Aquitane, Limousin, Maine Anjou, and Simmental) and other breeds, including crossbreds.

Therefore, combining such information (fat and protein in the gain with partial efficiency of energy use for growth) is interesting to enhance our ability to estimate the carcass composition of growing animals more accurately. Such enhancements would allow us to estimate better their requirements of energy and protein (and other nutrients), aiming to produce more resilient and sustainable production systems (i.e., less use of the resource, lower environmental pollution via an excess of nutrients, betterment of the quality of the animal product, fewer emissions of greenhouse gas due to precise nutrition and days on feed to achieve profitability).

Eqs. (21) and (22) developed by CSIRO (2007) are used to predict fat and protein retained energy in the empty body gain, using the coefficients for non-large, lean animal breeds. These equations use the intake level above maintenance (L) and degree of maturity (Z), assuming that protein contains 5.7 Mcal/kg and fat contains 9.4 Mcal/kg to compute RE. Eq. (23) combined Eq. (17) with Eqs. (21) and (22).

$$E_F = 0.94 \times \left((43 + 28 \times (L - 2)) + \frac{601 - 28 \times (L - 2)}{1 + e^{(-6 \times (Z - 0.4))}} \right) \qquad (21)$$

$$E_P = 0.57 \times \left((212 + 4 \times (L - 2)) + \frac{140 - 120 \times (L - 2)}{1 + e^{(-6 \times (Z - 0.4))}} \right) \qquad (22)$$

$$k_g = \frac{3}{4 + 11 \times (E_P/(E_P + E_F))} \qquad (23)$$

where E_F is the retained energy as fat, Mcal/d; E_P is the retained energy as protein, Mcal/d; k_g is the partial efficiency of converting metabolizable energy into net energy for growth; L is the level of intake above maintenance, dimensionless; and Z is the degree of maturity, dimensionless.

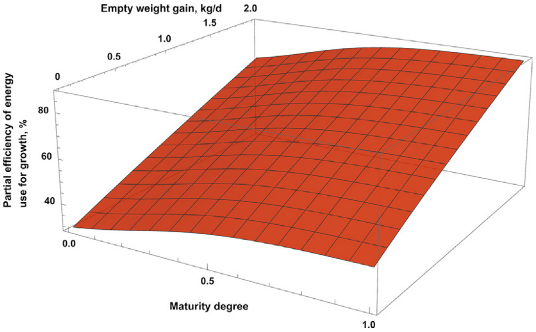

Fig. 5. Relationship between empty weight gain (kg/d) and degree of maturity on the partial efficiency of energy use for growth in cattle, assuming intake level of 2.5. See Supplementary Video S5.

Fig. 4B depicts the predicted retained energy as fat and protein, and k_g for the degree of maturity (BW basis) varying from 0 (born) to 1 (mature) and intake above maintenance varying from 2 to 4. As the degree of maturity increases, the proportion of fat and protein in the gain increases and decreases, respectively, as expected, given the shape of the non-linear logistic curve adopted by the CSIRO (2007). The k_g also increased from approximately 0.30 to 0.58 as maturity increased. The k_g values are within acceptable limits (Reid et al., 1980). However, Fig. 4B provides additional information regarding the interactions between the degree of maturity and level of feed intake above maintenance.

When we combined Eqs. (18) and (19) (growth rate effect) with Eqs. (21) and (22) (maturity stage effect) to estimate k_g (Eq. (16)), it became evident that k_g increases faster with increases in EWG (same degree of maturity) than with increases in the degree of maturity (same growth rate). Furthermore, k_g seems to increase slowly as the degree of maturity increases for animals above 50% maturity compared to those animals below 50% maturity (Fig. 5).

Combining different mathematical models

Combining submodels (i.e., model routines) obtained from distinct mathematical models, usually developed by different groups, might improve our intuition and understanding of the relationships of existing variables that were known for their importance but not included in the original models because of the lack of proper information or confidence during the development phase. The first mistake occurred by not including an essential variable in the model whose only infeasible value was zero (Tedeschi,

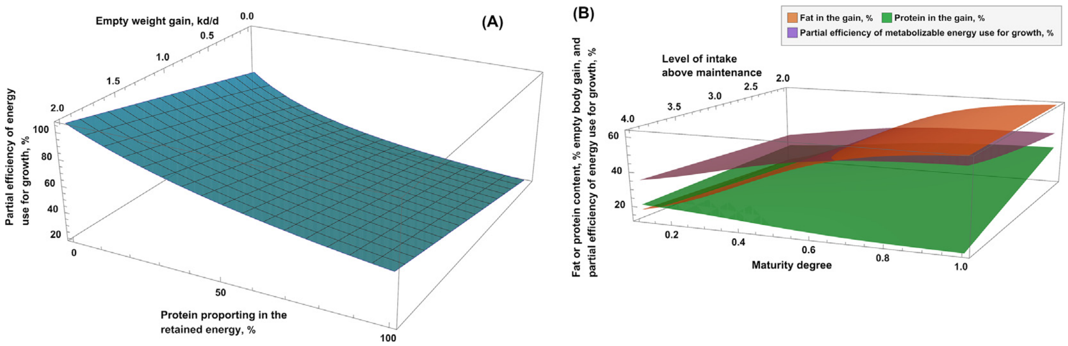

Fig. 4. (A) Relationship between empty weight gain (kg/d) and protein proportion in the retained energy on the partial efficiency of energy use for growth in cattle. Adapted from Tedeschi (2019b). See Supplementary Video S3. (B) Relationship between fat (orange plane) or protein (green plane) content in the empty body gain (g/100 g) and the partial efficiency of use of metabolizable energy for growth (×100) (purple plane) vs degree of maturity. See Supplementary Video S4. Replicated with permission from Tedeschi (2022b).

2023). The second mistake might happen when submodels are combined without judicious planning and evaluation. In this case, it might backfire because the *revised* model may improve the predictability; however, for the wrong reasons (e.g., offsetting errors, ill-conditioned or biased dataset)—hence no new knowledge is obtained. For instance, under specific conditions, model A overpredicts a variable of interest, whereas model B underpredicts it. Combining these models' calculation routines (i.e., submodels) may not improve the predictability because the submodels would yield different responses when changing the universe of acceptable inputs (i.e., inputs expected by a given submodel), thus, twisting or worsening the outcome by introducing systematic or slope biases. Different models have different attributes, such as paradigms (Tedeschi, 2019a, 2023), structural decisions, inputs/outputs, programming language and notation, and parameterization processes that could render them incompatible for merging into a functional model. Combining partial information from several models into a single one is known as *model merging*, and several factors make model merging a complex mission (Brunet et al., 2006), if not impractical in some situations. For instance, the many mathematical models developed recently to understand the COVID-19 pandemic are examples of such anomalies in model merging (James et al., 2021). Model merging is not to be confused with model integration, which combines different models into a whole-system approach (Ascough et al., 2019).

On the other hand, combining concepts and ideas is usually safer than combining models' routines. The two examples discussed above (EE of grazing animals and efficiency of energy use for growth) combined existing knowledge, concepts, and ideas to develop generalized or holistic predictive functional models. Although no former evaluation was conducted (lack of appropriate data), the goal was to discuss integrating existing information on these topics. Nonetheless, specific and global evaluations are necessary to establish confidence in the *revised* models.

Ensemble models

Another field in data analytics that has received greater attention lately is the development of ensemble models. Ensemble modeling is often adopted for artificial intelligence (e.g., machine learning) models to increase prediction accuracy, and it combines the outputs of unrelated models developed using different methods or algorithms but with similar scopes and purposes. Ensemble techniques include bagging (e.g., random forest, bootstrapping, decision trees), boosting (e.g., gradient boosting, adaptive boosting), stacking, and blending (Kyriakides and Margaritis, 2019). The prediction errors are expected to decrease when an ensemble approach is utilized despite contradicting the principle that the simplest solution is often the best (Elder, 2018). In the case of ensemble modeling, models (or submodels) per se are not combined or merged; their outputs are exploited. Examples of ensemble modeling exist for the impact of climate-related issues on crop (corn, wheat, soybean, and rice) yield (Jägermeyr et al., 2021), detection and management of emergent disease by integrating outputs from multiple models (Webb et al., 2017), and classification of cattle behavior (grazing, ruminating, resting, walking) using different machine learning techniques (Dutta et al., 2015) to list a few.

Summary

Because of our constant search for ways to increase the resilience and sustainability of livestock production systems, especially beef cattle production, combining different modeling concepts and ideas might help solve existing problems or limitations of modern feeding systems and meet our needs. The examples described above showed ways to expand our knowledge, concepts, and ideas by merging extant submodels in developing generalized or holistic predictive functional models. The EE of grazing animals can incorporate the energy needed for physical activity, eating, and rumination into the energy requirement for basal metabolism. The partial efficiency of using metabolizable energy for growth could be improved by including carcass composition rather than diet characteristics alone, and the interaction between the degree of maturity and average daily gain affects the partial efficiency differently. The proposed approaches might improve our assessment of the energy requirements of growing cattle, but before implementing them into other models, they still require further evaluation to refine the inconsistencies discussed.

Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.animal.2023.100835.

Ethics approval

Not applicable.

Data and model availability statement

Data or models were not deposited in an official repository. No new data were created.

Author ORCIDs

L.O. Tedeschi: https://orcid.org/0000-0003-1883-4911.

Author contributions

L.O. Tedeschi is the sole author.

Declaration of interest

The author has no perceived conflicts of interest to declare.

Acknowledgements

A preliminary version of this document was published by Tedeschi (2022b).

Financial support statement

The author acknowledges partial support of the Texas A&M University Chancellor's Enhancing Development and Generating Excellence in Scholarship (EDGES) Fellowship and the United States Department of Agriculture - National Institute of Food and Agriculture (USDA-NIFA) Hatch Fund (09123): *Development of Mathematical Nutrition Models to Assist with Smart Farming and Sustainable Production.*

Transparency Declaration

This article is part of a supplement entitled “Present and future challenges in energy and protein metabolism and their implication in animal nutrition” supported by the 2022 EAAP International Symposium on Energy and Protein Metabolism and Nutrition (ISEP).

References

National Academies of Sciences, Engineering, and Medicine, 2016. Nutrient Requirements of Beef Cattle, 8th. National Academy Press, Washington, DC, USA. doi: 10.17226/19014.

National Academies of Sciences, Engineering, and Medicine, 2021. Nutrient Requirements of Dairy Cattle, 8th. National Academy Press, Washington, DC, USA. doi: 10.17226/25806.

Agricultural Research Council, 1980. The Nutrient Requirements of Ruminant Livestock. Agricultural Research Council. The Gresham Press, London, UK.

Aharoni, Y., Henkin, Z., Ezra, A., Dolev, A., Shabtay, A., Orlov, A., Yehuda, Y., Brosh, A., 2009. Grazing behavior and energy costs of activity: A comparison between two types of cattle. Journal of Animal Science 87, 2719–2731. https://doi.org/10.2527/jas.2008-1505.

Aharoni, Y., Dolev, A., Henkin, Z., Yehuda, Y., Ezra, A., Ungar, E.D., Shabtay, A., Brosh, A., 2013. Foraging behavior of two cattle breeds, a whole-year study: I. Heat production, activity, and energy costs. Journal of Animal Science 91, 1381–1390. https://doi.org/10.2527/jas.2012-5400.

Anonymous, 2022. A truly sustainable future. Nature Sustainability 5, 281. https://doi.org/10.1038/s41893-022-00892-x.

Arnold, R.N., Bennett, G.L., 1991a. Evaluation of four simulation models of cattle growth and body composition: Part I – Comparison and characterization of the models. Agricultural Systems 35, 401–432. https://doi.org/10.1016/0308-521X(91)90117-S.

Arnold, R.N., Bennett, G.L., 1991b. Evaluation of four simulation models of cattle growth and body composition: Part II – Simulation and comparison with experimental growth data. Agricultural Systems 36, 17–41. https://doi.org/10.1016/0308-521X(91)90106-K.

Ascough, J.C., Ahuja, L.R., McMaster, G.S., Ma, L., Andales, A.A., 2019. Agriculture models. In Encyclopedia of Ecology (Second Edition) (ed. Fath, B.), Elsevier, Oxford, UK, pp. 1–10. doi: 10.1016/B978-0-12-409548-9.11173-X.

Asher, A., Shabtay, A., Cohen-Zinder, M., Aharoni, Y., Miron, J., Agmon, R., Halachmi, I., Orlov, A., Haim, A., Tedeschi, L.O., Carstens, G.E., Johnson, K.A., Brosh, A., 2018. Consistency of feed efficiency ranking and mechanisms associated with inter-animal variation among growing calves. Journal of Animal Science 96, 990–1009. https://doi.org/10.1093/jas/skx045.

Baldwin, R.L., 1995. Modeling Ruminant Digestion and Metabolism. Chapman & Hall, New York, NY, USA.

Baldwin, R.L., Koong, L.J., Ulyatt, M.J., 1977. A dynamic model of ruminant digestion for evaluation of factors affecting nutritive value. Agricultural Systems 2, 255–288. https://doi.org/10.1016/0308-521X(77)90020-8.

Baldwin, R.L., Smith, N.E., Taylor, J., Sharp, M., 1980. Manipulating metabolic parameters to improve growth rate and milk secretion. Journal of Animal Science 51, 1416–1428. https://doi.org/10.2527/jas1981.5161416x.

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 rumen of lactating cows. Journal of Theoretical Biology 238, 36–51. https://doi.org/10.1016/j.jtbi.2005.05.026.

Bannink, A., France, J., Lopez, S., Gerrits, W.J.J., Kebreab, E., Tamminga, S., Dijkstra, J., 2008. Modelling the implications of feeding strategy on rumen fermentation and functioning of the rumen wall. Animal Feed Science and Technology 143, 3–26. https://doi.org/10.1016/j.anifeedsci.2007.05.002.

Baudracco, J., López-Villalobos, N., Holmes, C.W., Macdonald, K.A., 2010. Prediction of herbage dry matter intake for dairy cows grazing ryegrass-based pastures. Proceedings of the New Zealand Society of Animal Production, June 2010, Palmerston North, New Zealand, pp. 80–85.

Baudracco, J., Lopez-Villalobos, N., Holmes, C.W., Comeron, E.A., Macdonald, K.A., Barry, T.N., Friggens, N.C., 2012. e-Cow: an animal model that predicts herbage intake, milk yield and live weight change in dairy cows grazing temperate pastures, with and without supplementary feeding. Animal 6, 980–993. https://doi.org/10.1017/S1751731111002370.

Beauchemin, K.A., Henry Janzen, H., Little, S.M., McAllister, T.A., McGinn, S.M., 2010. Life cycle assessment of greenhouse gas emissions from beef production in western Canada: A case study. Agricultural Systems 103, 371–379. https://doi.org/10.1016/j.agsy.2010.03.008.

Blaxter, K.L., 1962. The Energy Metabolism of Ruminants. Hutchinson, London, UK.

Brazilian Ministry of Science, Technology and Innovations, Secretariat for Research and Scientific Training, 2021. Fourth National Communication of Brazil to the United Nations Framework Convention on Climate Change/Secretariat for Research and Scientific Training.Brasilia, Brazil. Available at: https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/sirene/publicacoes/comunicacoes-nacionais-do-brasil-a-unfccc/arquivos/4comunicacao/executive_summary-_4nc_brazil_web.pdf. Accessed on: January 13, 2023.

Bridges, T.C., Turner, L.W., Smith, E.M., Stahly, T.S., Loewer Jr., O.J., 1986. A mathematical procedure for estimating animal growth and body composition. Transactions of the ASAE 29, 1342–1347. https://doi.org/10.13031/2013.30320.

Brody, S., 1945. Bioenergetics and Growth; With Special Reference to the Efficiency Complex in Domestic Animals. Reinhold Publishing Corporation, New York, NY, USA.

Brosh, A., 2007. Heart rate measurements as an index of energy expenditure and energy balance in ruminants: A review. Journal of Animal Science 85, 1213–1227.

Brosh, A., Henkin, Z., Ungar, E.D., Dolev, A., Orlov, A., Yehuda, Y., Aharoni, Y., 2006. Energy cost of cows' grazing activity: Use of the heart rate method and the Global Positioning System for direct field estimation. Journal of Animal Science 84, 1951–1967. https://doi.org/10.2527/jas.2005-315.

Brosh, A., Henkin, Z., Ungar, E.D., Dolev, A., Shabtay, A., Orlov, A., Yehuda, Y., Aharoni, Y., 2010. Energy cost of activities and locomotion of grazing cows: A repeated study in larger plots. Journal of Animal Science 88, 315–323. https://doi.org/10.2527/jas.2009-2108.

Brunet, G., Chechik, M., Easterbrook, S., Nejati, S., Niu, N., Sabetzadeh, M., 2006. A manifesto for model merging. Book of abstracts of the Proceedings of the 2006 international workshop on Global integrated model management, Shanghai, China, pp. 5–12. doi: 10.1145/1138304.1138307.

Bywater, A.C., Oltjen, J.W., Baldwin, R.L., St-Pierre, N.R., 1988. Modelling animal growth. Mathematics and Computers in Simulation 30, 165–174. https://doi.org/10.1016/0378-4754(88)90120-6.

Cain, M., Lynch, J., Allen, M.R., Fuglestvedt, J.S., Frame, D.J., Macey, A.H., 2019. Improved calculation of warming-equivalent emissions for short-lived climate pollutants. npj Climate and Atmospheric Science 2, 29. https://doi.org/10.1038/s41612-019-0086-4.

Cannas, A., Tedeschi, L.O., Fox, D.G., Pell, A.N., Van Soest, P.J., 2004. A mechanistic model for predicting the nutrient requirements and feed biological values for sheep. Journal of Animal Science 82, 149–169. https://doi.org/10.2527/2004.821149x.

Cannas, A., Tedeschi, L.O., Atzori, A.S., Fox, D.G., 2006. Prediction of energy requirements for growing sheep with the Cornell Net Carbohydrate and Protein System. In: Dijkstra, J. (Ed.), Nutrient Digestion and Utilization in Farm Animals. Modelling Approaches. CABI Publishing, Cambridge, MA, USA, pp. 99–113.

Chizzotti, M.L., Tedeschi, L.O., Valadares Filho, S.C., 2008. A meta-analysis of energy and protein requirements for maintenance and growth of Nellore cattle. Journal of Animal Science 86, 1588–1597. https://doi.org/10.2527/jas.2007-0309.

Commonwealth Scientific and Industrial Research Organization, 1990. Feeding Standards for Australian Livestock. Ruminants. Commonwealth Scientific and Industrial Research Organization, Melbourne, Australia.

Commonwealth Scientific and Industrial Research Organization, 2007. Nutrient Requirements of Domesticated Ruminants. Commonwealth Scientific and Industrial Research Organization, Collingwood, VIC, Australia.

Conrad, H.R., Weiss, W.P., Odwongo, W.O., Shockey, W.L., 1984. Estimating net energy lactation from components of cell solubles and cell walls. Journal of Dairy Science 67, 427–436. https://doi.org/10.3168/jds.S0022-0302(84)81320-X.

Corbett, J.L., Leng, R.A., Young, B.A., 1969. Measurements of energy expenditure by grazing sheep and the amount of energy supplied by volatile fatty acids produced in the rumen. Proceedings of the 4th Energy Metabolism of Farm Animals, September 1967, Warsaw, Poland, pp. 177–186.

Danfær, A., 1990. A Dynamic Model of Nutrient Digestion and Metabolism in Lactating Dairy Cows PhD. National Institute of Animal Science, Foulum, Denmark.

Delagarde, R., Faverdin, P., Baratte, C., Peyraud, J.L., 2011a. GrazeIn: a model of herbage intake and milk production for grazing dairy cows. 2. Prediction of intake under rotational and continuously stocked grazing management. Grass and Forage Science 66, 45–60. https://doi.org/10.1111/j.1365-2494.2010.00769.x.

Delagarde, R., Valk, H., Mayne, C.S., Rook, A.J., Gonzalez-Rodriguez, A., Baratte, C., Faverdin, P., Peyraud, J.L., 2011b. GrazeIn: a model of herbage intake and milk production for grazing dairy cows. 3. Simulations and external validation of the model. Grass and Forage Science 66, 61–77. https://doi.org/10.1111/j.1365-2494.2010.00770.x.

Di Marco, O.N., Aello, M.S., 1998. Energy cost of cattle walking on the level and on a gradient. Journal of Range Management 51, 9–13. https://doi.org/10.2307/4003556.

Di Marco, O.N., Baldwin, R.L., Calvert, C.C., 1989. Simulation of DNA, protein and fat accretion in growing steers. Agricultural Systems 29, 21–34. https://doi.org/10.1016/0308-521X(89)90068-1.

Di Marco, O.N., Aello, M.S., Méndez, D.G., 1996. Energy expenditure of cattle grazing on pastures of low and high availability. Animal Science 63, 45–50. https://doi.org/10.1017/S1357729800028277.

Dijkman, J.T., Lawrence, P.R., 1997. The energy expenditure of cattle and buffaloes walking and working in different soil conditions. Journal of Agricultural Science 128, 95–103. https://doi.org/10.1017/S0021859696003929.

Dijkstra, J., 1993. Mathematical Modelling and Integration of Rumen Fermentation Processes PhD. University of Wageningen, Wageningen, The Netherlands.

Dijkstra, J., Neal, H.D.S.C., Beever, D.E., France, J., 1992. Simulation of nutrient digestion, absorption and outflow in the rumen: Model description. Journal of Nutrition 122, 2239–2256. https://doi.org/10.1093/jn/122.11.2239.

Dillon, J.A., Stackhouse-Lawson, K.R., Thoma, G.J., Gunter, S.A., Rotz, C.A., Kebreab, E., Riley, D.G., Tedeschi, L.O., Villalba, J., Mitloehner, F., Hristov, A.N., Archibeque, S. L., Ritten, J.P., Mueller, N.D., 2021. Current state of enteric methane and the carbon footprint of beef and dairy cattle in the United States. Animal Frontiers 11, 57–68. https://doi.org/10.1093/af/vfab043.

Dutta, R., Smith, D., Rawnsley, R., Bishop-Hurley, G., Hills, J., Timms, G., Henry, D., 2015. Dynamic cattle behavioural classification using supervised ensemble classifiers. Computers and Electronics in Agriculture 111, 18–28. https://doi.org/10.1016/j.compag.2014.12.002.

Elder, J., 2018. The apparent paradox of complexity in ensemble modeling. In Handbook of Statistical Analysis and Data Mining Applications (ed. Nisbet, R., Miner, G. and Yale, K.), Academic Press, Boston, MA, USA, pp. 705–718. doi: 10.1016/B978-0-12-416632-5.00016-5.

Fall, A., Pearson, R.A., Lawrence, P.R., 1997. Nutrition of draught oxen in semi-arid west Africa. 1. Energy expenditure on oxen working on soils of different consistencies. Animal Science 64, 209–215. https://doi.org/10.1017/S1357729800015757.

Faverdin, P., Baratte, C., Delagarde, R., Peyraud, J.L., 2011. GrazeIn: a model of herbage intake and milk production for grazing dairy cows. 1. Prediction of intake capacity, voluntary intake and milk production during lactation. Grass and Forage Science 66, 29–44. https://doi.org/10.1111/j.1365-2494.2010.00776.x.

Ferrell, C.L., Oltjen, J.W., 2008. ASAS CENTENNIAL PAPER: Net energy systems for beef cattle–Concepts, application, and future models. Journal of Animal Science 86, 2779–2794. https://doi.org/10.2527/jas.2008-0954.

Fox, D.G., Black, J.R., 1984. A system for predicting body composition and performance of growing cattle. Journal of Animal Science 58, 725–739. https://doi.org/10.2527/jas1984.583725x.

Fox, D.G., Sniffen, C.J., O'Connor, J.D., Russell, J.B., Van Soest, P.J., 1992. A net carbohydrate and protein system for evaluating cattle diets: III. Cattle requirements and diet adequacy. Journal of Animal Science 70, 3578–3596. https://doi.org/10.2527/1992.70113578x.

Fox, D.G., Tedeschi, L.O., Tylutki, T.P., Russell, J.B., Van Amburgh, M.E., Chase, L.E., Pell, A.N., Overton, T.R., 2004. The Cornell Net Carbohydrate and Protein System model for evaluating herd nutrition and nutrient excretion. Animal Feed Science and Technology 112, 29–78. https://doi.org/10.1016/j.anifeedsci.2003.10.006.

Fox, D.G., Tylutki, T.P., 1998. Accounting for the effects of environment on the nutrient requirements of dairy cattle. Journal of Dairy Science 81, 3085–3095. https://doi.org/10.3168/jds.S0022-0302(98)75873-4.

France, J., Thornley, J.H.M., Beever, D.E., 1982. A mathematical model of the rumen. Journal of Agricultural Science 99, 343–353. https://doi.org/10.1017/S0021859600030124.

France, J., Gill, M., Thornley, J.H.M., England, P., 1987. A model of nutrient utilization and body composition in beef cattle. Animal Production 44, 371–385. https://doi.org/10.1017/S0003356100012307P.

France, J., Thornley, J.H.M., Baldwin, R.L., Crist, K.A., 1992. On solving stiff equations with reference to simulating ruminant metabolism. Journal of Theoretical Biology 156, 525–539. https://doi.org/10.1016/S0022-5193(05)80642-3.

Freer, M., Moore, A.D., Donnelly, J.R., 1997. GRAZPLAN: Decision support systems for Australian grazing enterprises-II. The animal biology model for feed intake, production and reproduction and the GrazFeed DSS. Agricultural Systems 54, 77–126. https://doi.org/10.1016/S0308-521X(96)00045-5.

Friggens, N.C., Ingvartsen, K.L., Emmans, G.C., 2004. Prediction of body lipid change in pregnancy and lactation. Journal of Dairy Science 87, 988–1000. https://doi.org/10.3168/jds.S0022-0302(04)73244-0.

Galyean, M.L., Cole, N.A., Tedeschi, L.O., Branine, M.E., 2016. BOARD-INVITED REVIEW: Efficiency of converting digestible energy to metabolizable energy and reevaluation of the California Net Energy System maintenance requirements and equations for predicting dietary net energy values for beef cattle. Journal of Animal Science 94, 1329–1341. https://doi.org/10.2527/jas.2015-0223.

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.

Garrett, W.N., 1980a. Energy utilization by growing cattle as determined in 72 comparative slaughter experiments. In: Proceedings of the 8th Symposium on Energy Metabolism of Farm Animals, September 1979, Cambridge, UK, pp. 3–7.

Garrett, W.N., 1980b. Factors influencing energetic efficiency of beef production. Journal of Animal Science 51, 1434–1440.

Garrett, W.N., Johnson, D.E., 1983. Nutritional energetics of ruminants. Journal of Animal Science 57, 478–497. https://doi.org/10.2527/animalsci1983.57Supplement_2478x.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling climate change through livestock - A global assessment of emissions and mitigation opportunities.Rome, Italy. Available at: http://www.fao.org/docrep/018/i3437e/i3437e.pdf. Accessed on: Aug 17, 2022.

Gill, M., 1984. Modelling the partition of nutrients for growth. In: Proceedings of the 2nd Modelling Ruminant Digestion and Metabolism, no date, Davis, CA, USA, pp. 75–79.

Gill, M., 1996. Modelling nutrient supply and utilization by ruminants. In: Garnsworthy, P.C., Cole, D.J.A. (Eds.), Recent Developments in Ruminant Nutrition, 3. Nottingham University Press, Nottingham, UK, pp. 23–34.

Gill, M., Thornley, J.H.M., Black, J.L., Oldham, J.D., Beever, D.E., 1984. Simulation of the metabolism of absorbed energy-yielding nutrients in young sheep. British Journal of Nutrition 52, 621–649. https://doi.org/10.1079/BJN19840129.

Gill, M., Beever, D.E., France, J., 1989. Biochemical bases needed for the mathematical representation of whole animal metabolism. Nutrition Research Reviews 2, 181–200. https://doi.org/10.1079/NRR19890014.

González, L.A., Kyriazakis, I., Tedeschi, L.O., 2018. Review: Precision nutrition of ruminants: approaches, challenges and potential gains. Animal 12, S246–S261. https://doi.org/10.1017/S1751731118002288.

Gouttenoire, L., Cournut, S., Ingrand, S., 2011. Modelling as a tool to redesign livestock farming systems: a literature review. Animal 5, 1957–1971. https://doi.org/10.1017/S175173111100111X.

Graux, A.I., Gaurut, M., Agabriel, J., Baumont, R., Delagarde, R., Delaby, L., Soussana, J. F., 2011. Development of the Pasture Simulation Model for assessing livestock production under climate change. Agriculture, Ecosystems & Environment 144, 69–91. https://doi.org/10.1016/j.agee.2011.07.001.

Gregorini, P., Beukes, P.C., Hanigan, M.D., Waghorn, G.C., Muetzel, S., McNamara, J.P., 2013. Comparison of updates to the Molly cow model to predict methane production from dairy cows fed pasture. Journal of Dairy Science 96, 5046–5052. https://doi.org/10.3168/jds.2012-6288.

Harper, L.A., Denmead, O.T., Freney, J.R., Byers, F.M., 1999. Direct measurements of methane emissions from grazing and feedlot cattle. Journal of Animal Science 77, 1392–1401.

Havstad, K.M., Malechek, J.C., 1982. Energy expenditure by heifers grazing crested wheatgrass of diminishing availability. Journal of Range Management 35, 447–450.

Heard, J.W., Cohen, D.C., Doyle, P.T., Wales, W.J., Stockdale, C.R., 2004. Diet check - a tactical decision support tool for feeding decisions with grazing dairy cows. Animal Feed Science and Technology 112, 177–194. https://doi.org/10.1016/j.anifeedsci.2003.10.012.

Henry, B., Charmley, E., Eckard, R.J., Gaughan, J.B., Hegarty, R.S., 2012. Livestock production in a changing climate: adaptation and mitigation research in Australia. Crop and Pasture Science 63, 191–202. https://doi.org/10.1071/CP11169.

Herrero, M., Fawcett, R.H., Dent, J.B., 2000a. Modelling the growth and utilisation of kikuyu grass (Pennisetum clandestinum) under grazing. 2. Model validation and analysis of management practices. Agricultural Systems 65, 99–111. https://doi.org/10.1016/S0308-521X(00)00029-9.

Herrero, M., Fawcett, R.H., Silveira, V., Busqué, J., Bernués, A., Dent, J.B., 2000b. Modelling the growth and utilisation of kikuyu grass (Pennisetum clandestinum) under grazing. 1. Model definition and parameterisation. Agricultural Systems 65, 73–97. https://doi.org/10.1016/S0308-521X(00)00028-7.

Herselman, M.J., Sahlu, T., Hart, S.P., Goetsh, A.L., 1998. Energy expenditure by dry and lactating Alpine does estimated by entry rate of carbon dioxide. Journal of Dairy Science 81, 2469–2474.

Hoch, T., Agabriel, J., 2004a. A mechanistic dynamic model to estimate beef cattle growth and body composition: 1. Model description. Agricultural Systems 81, 1–15. https://doi.org/10.1016/j.agsy.2003.08.005.

Hoch, T., Agabriel, J., 2004b. A mechanistic dynamic model to estimate beef cattle growth and body composition: 2. Model evaluation. Agricultural Systems 81, 17–35. https://doi.org/10.1016/j.agsy.2003.08.006.

Hoffmann, L., Schiemann, R., Jentsch, W., Henseler, G., 1974. Die verwertung der futterenergie für die milchproduktion. Archiv für Tierernaehrung 24, 245–261. https://doi.org/10.1080/17450397409423145.

Hunter, L.C., Hendrix, E.C., Dean, J.C., 2010. The cost of walking downhill: Is the preferred gait energetically optimal? Journal of Biomechanics 43, 1910–1915. https://doi.org/10.1016/j.jbiomech.2010.03.030.

Illius, A.W., Gordon, I.J., 1991. Prediction of intake and digestion in ruminants by a model of rumen kinetics integrating animal size and plant characteristics. Journal of Agricultural Science 116, 145–157. https://doi.org/10.1017/S0021859600076255.

Jägermeyr, J., Müller, C., Ruane, A.C., Elliott, J., Balkovic, J., Castillo, O., Faye, B., Foster, I., Folberth, C., Franke, J.A., Fuchs, K., Guarin, J.R., Heinke, J., Hoogenboom, G., Iizumi, T., Jain, A.K., Kelly, D., Khabarov, N., Lange, S., Lin, T.-S., Liu, W., Mialyk, O., Minoli, S., Moyer, E.J., Okada, M., Phillips, M., Porter, C., Rabin, S.S., Scheer, C., Schneider, J.M., Schyns, J.F., Skalsky, R., Smerald, A., Stella, T., Stephens, H., Webber, H., Zabel, F., Rosenzweig, C., 2021. Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. Nature Food 2, 873–885. https://doi.org/10.1038/s43016-021-00400-y.

James, L.P., Salomon, J.A., Buckee, C.O., Menzies, N.A., 2021. The use and misuse of mathematical modeling for infectious disease policymaking: Lessons for the covid-19 pandemic. Medical Decision Making 41, 379–385. https://doi.org/10.1177/0272989X21990391.

Johnson, D.E., Ferrell, C.L., Jenkins, T.G., 2003. The history of energetic efficiency research: Where have we been and where are we going? Journal of Animal Science 81, E27–E38. https://doi.org/10.2527/2003.8113_suppl_1E27x.

Jouven, M., Carrère, P., Baumont, R., 2006a. Model predicting dynamics of biomass, structure and digestibility of herbage in managed permanent pastures. 1. Model description. Grass and Forage Science 61, 112–124. https://doi.org/10.1111/j.1365-2494.2006.00515.x.

Jouven, M., Carrère, P., Baumont, R., 2006b. Model predicting dynamics of biomass, structure and digestibility of herbage in managed permanent pastures. 2 Model evaluation. Grass and Forage Science 61, 125–133. https://doi.org/10.1111/j.1365-2494.2006.00517.x.

Keele, J.W., Williams, C.B., Bennett, G.L., 1992. A computer model to predict the effects of level of nutrition on composition of empty body gain in beef cattle. I. Theory and development. Journal of Animal Science 70, 841–857. https://doi.org/10.2527/1992.703841x.

Kellner, O.J., 1905. Die Ernährung der landwirtschaftlichen Nutztiere: Lehrbuch auf der Grundlage physiologischer Forschung und praktischer Erfahrung. Parey, Berlin, Germany.

Kilpatrick, D.J., Steen, R.W.J., 1999. A predictive model for beef cattle growth and carcass composition. Agricultural Systems 61, 95–107. https://doi.org/10.1016/S0308-521X(99)00040-2.

Kleiber, M., 1961. The Fire of Life: An Introduction to Animal Energetics. John Wiley & Sons Inc, New York, NY, USA.

Kyriakides, G., Margaritis, K.G., 2019. Hands-on ensemble learning with python: Build highly optimized ensemble machine learning models using Scikit-Learn and Keras. Packt Publishing, Limited, Birmingham, UK.

Lawrence, P.R., Richards, J.I., 1980. The energy cost of walking in some tropical draught animals. Animal Production 30, 455. https://doi.org/10.1017/S0003356100039118.

Lawrence, P.R., Stibbards, R.J., 1990. The energy costs of walking, carrying and pulling loads on flat surfaces by Brahman cattle and swamp buffalo. Animal Production 50, 29–39. https://doi.org/10.1017/S000335610000444X.

Leroy, A.M., 1954. Utilization de l'energie des aliments par les animaux. Annales de Zootechnie 3, 337–372.

Loewer Jr., O.J., 1998. GRAZE: A beef-forage model of selective grazing. In: Peart, R. M., Curry, R.B. (Eds.), Agricultural Systems Modeling and Simulation. Marcel Dekker Inc, New York, NY, pp. 301–417.

Loewer Jr., O.J., Smith, E.M., Benock, G., Gay, N., Bridges, T., Wells, L., 1980. Dynamic simulation of animal growth and reproduction. Transactions of the ASAE 23, 131–138. https://doi.org/10.13031/2013.34539.

Loewer Jr., O.J., Smith, E.M., Benock, G., Bridges, T.C., Wells, L., Gay, N., Burgess, S., Springate, L., Debertin, D., 1981. A simulation model for assessing alternate strategies for beef production with land, energy and economic constraints. Transactions of the ASAE 24, 164–173. https://doi.org/10.13031/2013.34218.

Loewer, O.J., Smith, E.M., Taul, K.L., Turner, L.W., Gay, N., 1983. A body composition model for predicting beef animal growth. Agricultural Systems 10, 245–256. https://doi.org/10.1016/0308-521X(83)90047-1.

Loewer, O.J., Turner, L.W., Gay, N., Muntifering, R., Brown, C.J., 1987. Using the concept of physiological age to predict the efficiency of growth in beef animals. Agricultural Systems 24, 269–289. https://doi.org/10.1016/0308-521X(87)90027-8.

Lofgreen, G.P., Garrett, W.N., 1968. A system for expressing net energy requirements and feed values for growing and finishing beef cattle. Journal of Animal Science 27, 793–806. https://doi.org/10.2527/jas1968.273793x.

Lynch, J., Cain, M., Pierrehumbert, R., Allen, M., 2020. Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. Environmental Research Letters 15. 044023. https://doi.org/10.1088/1748-9326/ab6d7e.

Marcondes, M.I., Tedeschi, L.O., Valadares Filho, S.C., Gionbelli, M.P., 2013. Predicting efficiency of use of metabolizable energy to net energy for gain and maintenance of Nellore cattle. Journal of Animal Science 91, 4887–4898. https://doi.org/10.2527/jas.2011-4051.

Méndez, D.G., Di Marco, O.N., Corva, P.M., 1996. Energy expenditure of cattle walking on a flat terrain. Animal Science 63, 39–44. https://doi.org/10.1017/S1357729800028265.

Mertens, D.R., 1987. Predicting intake and digestibility using mathematical models of ruminal function. Journal of Animal Science 64, 1548–1558. https://doi.org/10.2527/jas1987.6451548x.

Mertens, D.R., 1985. Factors influencing feed intake in lactating cows: From theory to application using neutral detergent fiber. Proceedings of the Georgia Nutrition Conference for the Feed Industry, 13–15 February 1985, Atlanta, GA, USA, pp. 1–18.

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. Journal of Animal Science 79, 1584–1597. https://doi.org/10.2527/2001.7961584x.

Ministry of Agriculture, Fisheries and Food, 1975. Energy allowances and feeding systems for ruminants. Ministry of Agriculture Fisheries and Food, London, UK.

Miwa, M., Oishi, K., Nakagawa, Y., Maeno, H., Anzai, H., Kumagai, H., Okano, K., Tobioka, H., Hirooka, H., 2015. Application of overall dynamic body acceleration as a proxy for estimating the energy expenditure of grazing farm animals: Relationship with heart rate. PLoS One 10, e0128042.

Moe, P.W., 1981. Energy metabolism of dairy cattle. Journal of Dairy Science 64, 1120–1139. https://doi.org/10.3168/jds.S0022-0302(81)82692-6.

Moe, P.W., Tyrrell, H.F., Flatt, W.P., 1970. Partial efficiency of energy use for maintenance, lactation, body gain and gestation in the dairy cow. Proceedings of the 5th Energy Metabolism of Farm Animals, September 1970, Vitznau, Switzerland, pp. 65–68.

Mulvenna, C.C., Marks, N.J., Wilson, R.P., Halsey, L.G., Scantlebury, D.M., 2022. Can metrics of acceleration provide accurate estimates of energy costs of locomotion on uneven terrain? Using domestic sheep (*Ovis aries*) as an example. Animal Biotelemetry 10, 8. https://doi.org/10.1186/s40317-022-00281-3.

Nagorcka, B.N., Gordon, G.L.R., Dynes, R.A., 2000. Towards a more accurate representation of fermentation in mathematical models of the rumen. In: McNamara, J.P., France, J., Beever, D.E. (Eds.), Modelling Nutrient Utilization in Farm Animals. CABI Publishing, New York, NY, USA, pp. 37–48.

National Research Council, 1945a. Recommended Nutrient Allowances for Beef Cattle. National Academy Press, Washington, DC, USA.

National Research Council, 1945b. Recommended Nutrient Allowances for Dairy Cattle. National Academy Press, Washington, DC, USA.

National Research Council, 1945c. Recommended Nutrient Allowances for Sheep. National Academy Press, Washington, DC, USA.

National Research Council, 1981. Nutritional Energetics of Domestic Animals and Glossary of Energy Terms. Natl. Acad. Press, Washington, DC, USA. doi: 10.17226/1670.

National Research Council, 1984. Nutrient Requirements of Beef Cattle, 6th. National Academy Press, Washington, DC, USA. doi: 10.17226/19398.

National Research Council, 2000. Nutrient Requirements of Beef Cattle, updated 7th. National Academy Press, Washington, DC, USA. doi: 10.17226/9791.

National Research Council, 2007. Nutrient Requirements of Small Ruminants: Sheep, Goats, Cervids, and New World Camelids, 7th. National Academy Press, Washington, DC, USA. doi: 10.17226/11654.

Neal, H.D.S.C., Dijkstra, J., Margaret, G., 1992. Simulation of nutrient digestion, absorption and outflow in the rumen: model evaluation. Journal of Nutrition 122, 2257–2272. https://doi.org/10.1093/jn/122.11.2257.

Nehring, K., Schiemann, R., Hoffmann, L., 1966. Vorschlag eines neuen systems der energetischen bewertung des futters auf der grundlage der nettoenergie-fett. Sitzungsberichte Deutschen Akademie der Landwirtschaftswissenschaften, Berlin, Germany, pp. 19–30.

Nienaber, J.A., Eisemann, J.H., Yen, J.T., Hunington, G.B., 1993. Technical note: Comparison of techniques for measurement of oxygen uptake by cattle. Journal of Animal Science 71, 2756–2759.

Notter, D.R., Sanders, J.O., Dickerson, G.E., Smith, G.M., Cartwright, T.C., 1979a. Simulated efficiency of beef production for a Midwestern cow-calf-feedlot management system. I. Milk production. Journal of Animal Science 49, 70–82.

Notter, D.R., Sanders, J.O., Dickerson, G.E., Smith, G.M., Cartwright, T.C., 1979b. Simulated efficiency of beef production for a Midwestern cow-calf-feedlot management system. II. Mature body size. Journal of Animal Science 49, 83–91.

Notter, D.R., Sanders, J.O., Dickerson, G.E., Smith, G.M., Cartwright, T.C., 1979c. Simulated efficiency of beef production for a Midwestern cow-calf-feedlot management system. III. Crossbreeding systems. Journal of Animal Science 49, 92–102.

Oddy, V.H., Ball, A.J., Pleasants, A.B., 1997. Understanding body composition and efficiency in ruminants: a non-linear approach. Recent Advances in Animal Nutrition in Australia 11, 209–222.

Oddy, V.H., Dougherty, H.C., Oltjen, J.W., 2019. Integration of energy and protein transactions in the body to build new tools for predicting performance and body composition of ruminants. Animal Production Science 59, 1970–1979. https://doi.org/10.1071/AN19229.

Oltjen, J.W., 2019. How did Lofgreen and Garrett do the math? Translational Animal Science 3, 1011–1017. https://doi.org/10.1093/tas/txz072.

Oltjen, J.W., Bywater, A.C., Baldwin, R.L., 1986a. Evaluation of a model of beef cattle growth and composition. Journal of Animal Science 62, 98–108. https://doi.org/10.2527/jas1986.62198x.

Oltjen, J.W., Bywater, A.C., Baldwin, R.L., Garrett, W.N., 1986b. Development of a dynamic model of beef cattle growth and composition. Journal of Animal Science 62, 86–97. https://doi.org/10.2527/jas1986.62186x.

Oltjen, J.W., Pleasants, A.B., Soboleva, T.K., Oddy, V.H., 2000. Second-generation dynamic cattle growth and composition models. In Modelling Nutrient Utilization in Farm Animals (ed. McNamara, J.P., France, J. and Beever, D.E.), CABI Publishing, New York, NY, USA, pp. 197–209.

Osuji, P.O., 1974. The physiology of eating and the energy expenditure of the ruminant at pasture. Journal of Range Management 23, 437–443. https://doi.org/10.2307/3896717.

Owens, F.N., Gill, D.R., Secrist, D.S., Coleman, S.W., 1995. Review of some aspects of growth and development of feedlot cattle. Journal of Animal Science 73, 3152–3172. https://doi.org/10.2527/1995.73103152x.

Parks, J.R., 1973. A stochastic model of animal growth. Journal of Theoretical Biology 42, 505–518. https://doi.org/10.1016/0022-5193(73)90243-9.

Pelletier, N., Pirog, R., Rasmussen, R., 2010. Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. Agricultural Systems 103, 380–389. https://doi.org/10.1016/j.agsy.2010.03.009.

Pretty, J., 1997. The sustainable intensification of agriculture. Natural Resources Forum 21, 247–256. https://doi.org/10.1111/j.1477-8947.1997.tb00699.x.

Prieto, C., Lachica, M., Bermúdez, F.F., Aguilera, J.F., 1997. The application of the labelled ^{13}C-bicarbonate method for estimating energy expenditure in goats. Proceedings of the 14th Energy Metabolism of Farm Animals, 14–20 September 1997, Newcastle, UK, pp. 185–188.

Reid, J.T., White, O.D., Anrique, R.G., Fortin, A., 1980. Nutritional energetics of livestock: some present boundaries of knowledge and future research needs. Journal of Animal Science 51, 1393–1415. https://doi.org/10.2527/jas1981.5161393x.

Ribeiro, J.M.C.R., Brockway, J.M., Webster, A.J.F., 1977. A note on the energy cost of walking in cattle. Animal Production 25, 107–110. https://doi.org/10.1017/S0003356100039118.

Riedo, M., Grub, A., Rosset, M., Fuhrer, J., 1998. A pasture simulation model for dry matter production, and fluxes of carbon, nitrogen, water and energy. Ecological Modelling 105, 141–183. https://doi.org/10.1016/S0304-3800(97)00110-5.

Russell, J.B., O'Connor, J.D., Fox, D.G., Van Soest, P.J., Sniffen, C.J., 1992. A net carbohydrate and protein system for evaluating cattle diets: I. Ruminal fermentation. Journal of Animal Science 70, 3551–3561. https://doi.org/10.2527/1992.70113551x.

Sahlu, T., Jung, H.G., Nienaber, J.A., Morris, J.G., 1988. Developing and validation of a prediction equation estimating heat production by carbon dioxide entry rate technique. Journal of Animal Science 66, 2036–2043.

Sanchez, M.D., Morris, J.G., 1984. Energy expenditure of beef cattle grazing annual grassland. Canadian Journal of Animal Science 64, 332–334.

Sanders, J.O., Cartwright, T.C., 1979a. A general cattle production systems model. I: Structure of the model. Agricultural Systems 3, 217–227.

Sanders, J.O., Cartwright, T.C., 1979b. A general cattle production systems model. Part 2 – Procedures used for simulating animal performance. Agricultural Systems 4, 289–309.

Schiemann, R., Nehring, K., Hoffmann, L., Jentsch, W., Chudy, A., 1971. Energetische Futterbewertung und Energienormen: Dokumentation der wissenschaftlichen Grundlagen eines neuen energetischen Futterbewertungssystems. Deutscher Landwirtschaftsverlag, Berlin, Germany.

Schneider, B.H., Flatt, W.P., 1975. The Evaluation of Feed through Digestibility Experiments. The University of Georgia Press, Athens, GA, USA.

Seo, S., Kang, K., Jeon, S., Lee, M., Jeong, S., Tedeschi, L., 2021. Development of a model to predict dietary metabolizable energy from digestible energy in beef cattle. Journal of Animal Science 99, 1–9. https://doi.org/10.1093/jas/skab182.

Sharma, T., Carmichael, J., Klinkenberg, B., 2006. Integrated modeling for exploring sustainable agriculture futures. Futures 38, 93–113. https://doi.org/10.1016/j.futures.2005.04.006.

Sniffen, C.J., O'Connor, J.D., Van Soest, P.J., Fox, D.G., Russell, J.B., 1992. A net carbohydrate and protein system for evaluating cattle diets: II. Carbohydrate and protein availability. Journal of Animal Science 70, 3562–3577. https://doi.org/10.2527/1992.70113562x.

Susenbeth, A., Mayer, R., Köhler, B., Neumann, O., 1997. Heat production associated with eating in cattle. Proceedings of the 14th Energy Metabolism of Farm Animals, 14–20 September 1997, Newcastle, UK, pp. 279–282.

Susenbeth, A., Mayer, R., Köhler, B., Neumann, O., 1998. Energy requirement for eating in cattle. Journal of Animal Science 76, 2701–2705. https://doi.org/10.2527/1998.76102701x.

Tamminga, S., Van Straalen, W.M., Subnel, A.P.J., Meijer, R.G.M., Steg, A., Wever, C.J. G., Blok, M.C., 1994. The Dutch protein evaluation system: The DVE/OEB-system. Livestock Production Science 40, 139–155. https://doi.org/10.1016/0301-6226(94)90043-4.

Tedeschi, L.O., 2019a. ASN-ASAS SYMPOSIUM: FUTURE OF DATA ANALYTICS IN NUTRITION: Mathematical modeling in ruminant nutrition: approaches and paradigms, extant models, and thoughts for upcoming predictive analytics. Journal of Animal Science 97, 1321–1944. https://doi.org/10.1093/jas/skz092.

Tedeschi, L.O., 2019b. Relationships of retained energy and retained protein that influence the determination of cattle requirements of energy and protein using the California Net Energy System. Translational Animal Science 3, 1029–1039. https://doi.org/10.1093/tas/txy120.

Tedeschi, L.O., 2020. Modelling a sustainable future for livestock production. Scientia 2020, 88–91. https://doi.org/10.33548/SCIENTIA523.

Tedeschi, L.O., 2023. Review: The prevailing mathematical modelling classifications and paradigms to support the advancement of sustainable animal production. Animal. 100813. https://doi.org/10.1016/j.animal.2023.100813.

Tedeschi, L.O., Beauchemin, K.A., 2023. GALYEAN APPRECIATION CLUB REVIEW: A holistic perspective of the societal relevance of beef production and its impacts on climate change. Journal of Animal Science 101, 1–19. https://doi.org/10.1093/jas/skad024.

Tedeschi, L.O., Dias Batista, L.F., 2021. Precision determination of energy and protein requirements of grazing and feedlot animals. Virtual meeting of the fifth Animal Nutrition Conference of Canada (ANCC) under the theme 'Feeding the Future: Precision Nutrition for Tomorrow's Animal', 10–14 May 2021, pp. 177–204.

Tedeschi, L.O., Fox, D.G., 2015. Energy and nutrient requirements of grazing and confined growing beef cattle: Refining the assessment of energy expenditure for grazing animals. In Proceedings of the X NESPRO Meeting & II International Symposium on Beef Cattle Production Systems (ed. Pereira, G.R., de Oliveira, T.E. and Barcellos, J.O.J.). Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brazil, pp. 21–56.

Tedeschi, L.O., Fox, D.G., 2020a. The Ruminant Nutrition System: Volume I - An Applied Model for Predicting Nutrient Requirements and Feed Utilization in Ruminants, 3rd. XanEdu, Ann Arbor, MI, USA.

Tedeschi, L.O., Fox, D.G., 2020b. The Ruminant Nutrition System: Volume II – Tables of Equations and Coding. XanEdu, Ann Arbor, MI, USA.

Tedeschi, L.O., Fox, D.G., Guiroy, P.J., 2004. A decision support system to improve individual cattle management. 1. A mechanistic, dynamic model for animal growth. Agricultural Systems 79, 171–204. https://doi.org/10.1016/S0308-521X(03)00070-2.

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

Tedeschi, L.O., Cavalcanti, L.F.L., Fonseca, M.A., Herrero, M., Thornton, P.K., 2014. The evolution and evaluation of dairy cattle models for predicting milk production: an agricultural model intercomparison and improvement project (AgMIP) for livestock. Animal Production Science 54, 2052–2067. https://doi.org/10.1071/AN14620.

Tedeschi, L.O., Muir, J.P., Riley, D.G., Fox, D.G., 2015. The role of ruminant animals in sustainable livestock intensification programs. International Journal of Sustainable Development & World Ecology 22, 452–465. https://doi.org/10.1080/13504509.2015.1075441.

Tedeschi, L.O., Galyean, M.L., Hales, K.E., 2017. Recent advances in estimating protein and energy requirements of ruminants. Animal Production Science 57, 2237–2249. https://doi.org/10.1071/AN17341.

Tedeschi, L.O., Molle, G., Menendez, H.M., Cannas, A., Fonseca, M.A., 2019. The assessment of supplementation requirements of grazing ruminants using nutrition models. Translational Animal Science 3, 811–828. https://doi.org/10.1093/tas/txy140.

Tedeschi, L.O., Abdalla, A.L., Álvarez, C., Anuga, S.W., Arango, J., Beauchemin, K.A., Becquet, P., Berndt, A., Burns, R., De Camillis, C., Chará, J., Echazarreta, J.M., Hassouna, M., Kenny, D., Mathot, M., Mauricio, R.M., McClelland, S.C., Niu, M., Onyango, A.A., Parajuli, R., Pereira, L.G.R., del Prado, A., Tieri, M.P., Uwizeye, A., Kebreab, . Quantification of methane emitted by ruminants: A review of methods. Journal of Animal Science 100, 1–22. https://doi.org/10.1093/jas/skac197.

Tedeschi, L.O., 2001. Development and Evaluation of Models for the Cornell Net Carbohydrate and Protein System: 1. Feed Libraries, 2. Ruminal Nitrogen and Branched-Chain Volatile Fatty Acid Deficiencies, 3. Diet Optimization, 4. Energy Requirement for Maintenance and Growth. PhD thesis, Cornell University, Ithaca, NY, USA.

Tedeschi, L.O., 2022a. A holistic perspective of the societal relevance of beef production and its impacts on climate change. Retrieved on 12 January 2023 from https://zenodo.org/record/6078225.

Tedeschi, L.O., 2022b. K7 Energy and protein requirements of farm animals: Harnessing extant modeling approaches for sustainable animal production. Animal – Science Proceedings 13, 239-240. doi: 10.1016/j.anscip.2022.07.009.

Thomas, C.K., Pearson, R.A., 1986. Effects of ambient temperature and head cooling on energy expenditure, food intake and heat tolerance of Brahman and Brahman x Friesian cattle working on treadmills. Animal Production 43, 83–90. https://doi.org/10.1017/S0003356100018353.

Thornley, J.H.M., 1998. Grassland Dynamics: An Ecosystem Simulation Model. CAB International, Wallingford, UK.

Van Es, A.J.H., 1975. Feed evaluation for dairy cows. Livestock Production Science 2, 95–107. https://doi.org/10.1016/0301-6226(75)90029-9.

Van Es, A.J.H., 1978. Feed evaluation for ruminants. I. The systems in use from May 1977-onwards in The Netherlands. Livestock Production Science 5, 331–345. https://doi.org/10.1016/0301-6226(78)90029-5.

Van Soest, P.J., 1963a. Use of detergents in analysis of fibrous feeds. I. Preparation of fiber residues of low nitrogen content. Journal of the Association of Official Analytical Chemists International 46, 825–829. https://doi.org/10.1093/jaoac/46.5.825.

Van Soest, P.J., 1963b. Use of detergents in analysis of fibrous feeds. II. A rapid method for the determination of fiber and lignin. Journal of the Association of Official Analytical Chemists International 46, 829–835. https://doi.org/10.1093/jaoac/46.5.829.

Van Soest, P.J., 1994. Nutritional Ecology of the Ruminant. Comstock Publishing Associates, Ithaca, NY, USA.

Vazquez, O.P., Smith, T.R., 2001. Evaluation of alternative algorithms used to simulate pasture intake in grazing dairy cows. Journal of Dairy Science 84, 860–872. https://doi.org/10.3168/jds.S0022-0302(01)74544-4.

Vetharaniam, I., Davis, S.R., Upsdell, M., Kolver, E.S., Pleasants, A.B., 2003. Modeling the effect of energy status on mammary gland growth and lactation. Journal of Dairy Science 86, 3148–3156. https://doi.org/10.3168/jds.S0022-0302(03)73916-2.

Vlontzos, G., Ampatzidis, Y., Manos, B., Pardalos, P.M., 2021. Modeling for Sustainable Management in Agriculture, Food and the Environment. CRC Press, Boca Raton, FL, USA. doi: 10.1201/9780429197529.

Waldo, D.R., Smith, L.W., Cox, E.L., 1972. Model of cellulose disappearance from the rumen. Journal of Dairy Science 55, 125–129. https://doi.org/10.3168/jds.S0022-0302(72)85442-0.

Webb, C.T., Ferrari, M., Lindström, T., Carpenter, T., Dürr, S., Garner, G., Jewell, C., Stevenson, M., Ward, M.P., Werkman, M., Backer, J., Tildesley, M., 2017. Ensemble modelling and structured decision-making to support Emergency Disease Management. Preventive Veterinary Medicine 138, 124–133. https://doi.org/10.1016/j.prevetmed.2017.01.003.

White, R.G., 1993. Energy expenditure of ruminants on pasture. Proceedings of the VII World Conference on Animal Production, 28 June–2 July 1993, Edmonton, Canada, pp. 475–498.

Williams, C.B., Jenkins, T.G., 1998. A computer model to predict composition of empty body weight changes in cattle at all stages of maturity. Journal of Animal Science 76, 980–987. https://doi.org/10.2527/1998.764980x.

Williams, C.B., Jenkins, T.G., 2003. A dynamic model of metabolizable energy utilization in growing and mature cattle. II. Metabolizable energy utilization for gain. Journal of Animal Science 81, 1382–1389. https://doi.org/10.2527/2003.8161382x.

Williams, C.B., Keele, J.W., Bennett, G.L., 1992. A computer model to predict the effects of level of nutrition on composition of empty body gain in beef cattle. II. Evaluation of the model. Journal of Animal Science 70, 858–866. https://doi.org/10.2527/1992.703858x.

Woli, P., Rouquette Jr., F.M., Long, C.R., Tedeschi, L.O., Scaglia, G., 2020. Modification of the summative equation to estimate daily total digestible nutrients for bermudagrass pasture. Journal of Animal Science 98, 1–9. https://doi.org/10.1093/jas/skaa354.