

# A comparison of three nutritional models for estimating total metabolisable energy requirements for a ewe, beef breeding cow, lamb, and a calf/yearling in New Zealand's pasture-only system

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## HIGHLIGHTS

- Models may yield different ME requirement values, but the extent of variation matters.
- The AIM (MPI, 2022) model estimated a higher total ME for a ewe, cow, and calf/yearling relative to Nicol and Brookes (2017) and CSIRO (2007) models.
- Differences were mainly due to maintenance requirements estimates.
- Model estimates could yield different stocking rates, carrying capacities, and productivity for a given farm.
- Model estimates could also yield different greenhouse gas emissions profiles for the same farm.

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## ABSTRACT

In New Zealand (NZ), the metabolisable energy requirements (MER) of ruminants can be estimated using nutritional models from Nicol and Brookes (2017), CSIRO (2007), and NZ's Agricultural Inventory Model (AIM) of the Ministry for Primary Industries [MPI] (2022). The aim in this study was to calculate the total MER of a ewe, beef breeding cow, lamb, and a calf/yearling in a pasture-only system in NZ under the same assumptions to assess the extent and reasons for variations among the three commonly used nutritional models, and the implications for a given farm/s. The study utilised MER models from the three sources above using a factorial method. This method determines the MER for each physiological phase of an animal, to estimate total MER for each animal. The AIM (MPI 2022) model relative to Nicol and Brookes (2017), and CSIRO (2007) models respectively, estimated 13.4 % and 8.0 % higher MER for a ewe, 16.3 % and 16.6 % for a cow, 1.1 % and 2.0 % lower for a lamb, and 9.2 % and 9.2 % higher for a calf/yearling mainly due to a higher maintenance MER compared to the other models. This has implications for feed budgeting and stocking rates (SR) for a given farm, as the AIM (MPI 2022) model leads to a lower SR than the other two models for a given level of feed available. Energy balances and productivity could be negatively impacted if a model underestimates MER. This also yields different greenhouse gas (GHG) profiles, especially enteric methane, for a given farm and could potentially have financial consequences for farmers if an Emissions Trading Scheme was introduced. For consistency in ME estimates and GHG reporting, further research (feeding trials) is required to compare these model estimates to actual requirements of ruminants under NZ conditions. This could help identify the model that most accurately reflects MER for ruminants in the country.

## 1. Introduction

In New Zealand (NZ), metabolisable energy (ME) is the energy available from a given feed in Megajoules (MJ), after urinary, combustible gases (mainly methane (CH<sub>4</sub>)) and fecal energy loss, and for use by

animals for maintenance and production requirements (CSIRO, 2007; Nicol and Brookes, 2017). Therefore, ME is, used to describe/express the energy requirements of animals (CSIRO, 2007) in NZ. A factorial method (not factorial design) calculates the requirements for individual physiological processes i.e., maintenance, growth (live-weight changes),

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**Table 1**

Assumptions used to calculate ME requirements of a ewe, beef breeding cow, a lamb, and a calf/yearling.

Assumptions	Parameters
<b>General:</b>	
Terrain	1.5
Pasture mass/ green forage availability	3.5 t/ha
Feed Gross energy <sup>2</sup>	18.45 MJ
<b>Sheep and lamb:</b>	
Age	4 years
Lamb age	<1yr = 0.5, ≥1yr = 1
Ewe live weight	60 kg
Standard Reference Weight	65 kg
Lamb birth weight	6 kg
Gestation length	147 days
Lactation length <sup>A</sup>	91 days
Annual Milk yield <sup>A</sup>	103 kg (100 L)
Monthly milk yield proportions <sup>A</sup>	Sept – 0.164, Oct, 0.254, Nov – 0.246, Dec – 0.254, Jan – 0.082
Weaning weight	30 kg
Lamb targeted sale weight	50 kg
Age at target weight	182 days
<b>Beef breeding cow and calf/yearling:</b>	
Age	6 years
Calf/yearling age	<1yr = 0.5, ≥1 yr = 1
Cow live weight	600 kg
Standard Reference Weight	600 kg
Calf birth weight	35 kg
Gestation length <sup>A</sup>	281 days
Lactation length <sup>A</sup>	200 days
Annual Milk yield <sup>A</sup>	824 kg (800 L)
Monthly milk yield proportions <sup>A</sup>	For 6 Months–0.167 (0.143 for 7 months)
Weaning weight	220 kg
Heifer targeted mating weight	350 kg
Age at target weight	457 days

<sup>A</sup> Sourced from MPI (2022).

gestation, and lactation, and is used in determining the total energy requirements for an animal (Cannas, 2004; Nicol and Brookes, 2017).

MER requirement (MER) estimates for different classes of animals on a farm are important for feed budgeting (Webby and Bywater, 2017), and to ensure that the animal-productive performance requirements are met. In addition, MER estimates are important because enteric CH<sub>4</sub> emissions per head per day for cattle and sheep increase as dry matter intakes (DMI) increases (Hammond et al., 2014, 2013; Molano and Clark, 2008; Muetzel and Clark, 2015). Dry matter intake can be estimated from the MER of an animal (INRA, 2018).

For this reason, the estimation of enteric CH<sub>4</sub> emissions in the NZ national inventory of greenhouse gas (GHG) emissions, as recommended by the International Panel on Climate Change (IPCC), is based on MER estimates of all subclasses of animals within a production system (International Panel on Climate Change, 2019, 2006). The estimated total MER of ruminants are comprised of requirements for maintenance ( $ME_m$ ), growth (live-weight change) ( $ME_g$ ), gestation ( $ME_c$ ), lactation ( $ME_l$ ), and/or wool growth ( $ME_w$ ) in the case of sheep (CSIRO, 2007; Nicol and Brookes, 2017). These MER are used to calculate DMI using given ME concentration in feed (M/D). Since DMI drives CH<sub>4</sub> emissions, the accuracy of its estimation via MER estimates is crucial.

Several ruminant energy requirement calculation methods exist from which ME estimates for the various physiological stages of ruminants can be estimated, i.e., Agriculture and Food Research Council [AFRC] (1993), National Research Council [NRC] (1985, 1935), Agriculture Research Council [ARC] (1980), CSIRO (2007), among others. However, these energy requirement methods are not universal as some have been found to predict animals' requirements differently due to the assumptions made and the system used to develop them (Cannas, 2004; Cannas et al., 2010; Robinson et al., 1987). In NZ, there are two notable nutritional models - Nicol and Brookes (2017) and CSIRO (2007), from which

MER of common domesticated ruminants can be estimated especially, under pasture-based livestock systems. The Agricultural Inventory Model (AIM) (Ministry for Primary Industries, [MPI] 2022) is also another source used to calculate MER. However, an important point is how much variation exists among the MER estimates of these three nutritional models under the same sets of conditions or assumptions. This is especially important when MER drives DMI, and therefore, enteric CH<sub>4</sub> emissions, which may have financial implications for farmers in NZ if farmers have to pay for emissions under an Emission Trading Scheme (ETS) (Ministry for the Environment [MoE] 2022). To the authors' knowledge, there have not been any studies in NZ comparing these three nutritional model estimates for sheep and beef, the reasons for model variations, and the implications thereof for sheep and beef farms in NZ.

The aim in this study was to estimate the total MER of a ewe, beef breeding cow (cow), lamb, and a beef yearling using the factorial method, as described in the AIM, in a pasture-only system in NZ under the same set of assumptions, to assess the extent and reasons for variations among the three commonly used nutritional models, if any, and the implications for a given farm/s. The study utilised MER models from CSIRO (2007), Nicol and Brookes (2017), and the AIM (MPI, 2022) in this study.

## 2. Methods

### 2.1. Background

#### 2.1.1. New Zealand's pastoral system

New Zealand's climate supports robust pasture growth, which is essential for sheep and beef cattle production, as it constitutes over 95 % of their diet (Hodgson et al., 2005). Pasture production is seasonal and drives lamb and beef production, such that the timing of breeding is to ensure lambing and calving coincide with the increasing availability of pasture in spring (deNicolo et al., 2008). Sown pastures are predominantly a mix of perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) (Lambert et al., 2004). Pasture quality varies across seasons and regions, and ranges from 8 to 12 MJ ME per kg dry matter (Lambert and Litherland, 2000) with the highest values in spring and the lowest in summer. However, pasture quality of 10–10.5 MJ ME is often considered medium quality (Waghorn et al., 2017). Sheep and beef cattle are grazed extensively throughout the year in a rotational system. Grasslands can conveniently be categorized into three main farming groups based on their topography and elevation: high country, hill country, and flat to rolling terrain (Morris, 2013).

#### 2.1.2. The agricultural inventory model (AIM) and energy requirement estimation

New Zealand's detailed methodology for reporting agricultural greenhouse gases (GHG) uses metabolisable energy (ME) to estimate DMI for animals. For an animal, the total ME requirement is comprised of energy for maintenance, production, pregnancy, lactation, and activity (e.g., grazing and walking). The total daily ME is calculated by assessing the maintenance, production, pregnancy, and grazing components of ME, commonly referred to as the factorial method (Cannas, 2004; Nicol and Brookes, 2017), for an average animal for an average day, for a given month. Together with monthly pasture quality, it determines the total daily DMI of the average animal for a specific class for an average day in a given month. This is then applied to the general population of animals in that class for a day, a month, and a year. For mature breeding animals (i.e., ewes and beef cows), the model assumes that there are no live weight changes within a calendar year. Sheep and beef pasture quality is assumed to be the same for all regions, but it varies each month. For details, see the AIM of the Ministry for Primary Industries (2024).

## 2.2. Estimating metabolizable energy

Metabolisable energy (ME) is estimated for the various components of ME (i.e., maintenance, pregnancy, lactation, growth, and grazing) as described in the AIM using the relevant equations of the three nutritional models.

## 2.3. Estimating maintenance requirements

The daily maintenance energy ( $ME_m$ ) requirements (MJ ME) for the four classes of ruminants were estimated using Eqs. (1) to 2.3 with their respective assumptions from Table 1.<sup>1</sup>

$$ME_m = K S M \frac{0.28LW^{0.75} \exp^{-0.03A}}{k_m} + 0.1 ME_p + ME_{graze} \quad (\text{CSIRO 2007; MPI 2022}) \quad (1)$$

$$ME_{graze} = \frac{\left( (C * (0.9 - DMD) * (ME_m + ME_p - Z_1)) + 0.05 * \left( \frac{T}{GF+3} \right) * MD \right) * LW + 0.05 * \left( \frac{T}{GF+3} \right) * MD * LW}{k_m * MD - C * LW * (0.9 - DMD)} \quad (1.1)$$

$$ME_{graze} = (C * DMI * (0.9 - DMD) + 0.0026 * H) * LW / k_m \quad (\text{CSIRO 2007}) \quad (1.2)$$

$$ME_m = K S \frac{0.28LW^{0.75} \exp^{-0.03A}}{k_m} + ME_{graze} + ME_{move} + ME_{activity} \quad (\text{N \& B 2017}) \quad (2)$$

$$ME_{graze} = LW * ((C * DMI * (0.9 - DMD))) / k_m \quad (2.1)$$

$$ME_{move} = \left( 0.0026 * LW * Sl * \frac{\left( \frac{T * SR}{SD} \right)}{0.057 * PM + 0.16} \right) \quad (2.2)$$

$$ME_{activity} = LW * [(0.0026 * Hk_m) + (0.028 * Vk_m)] / k_m \quad (2.3)$$

Where  $K$  = species with a value of 1 for sheep and 1.2 – 1.4 for beef cattle,  $S$  = sex (1 for females and castrates, 1.15 entire males),  $M$  = 1 + (0.23\*proportion of milk in digestible energy from milk) or 1+(0.26 – 0.015\*week of life),  $LW$  = liveweight (kg),  $A$  = age (years),  $ME_p$  = ME for production (MJ),  $DMD$  = DM digestibility given as M/D/15.088 (Nicol and Brookes, 2017),  $Sl$  or  $T$  = the slope or terrain of the land being grazed = (1, 1.5 and 2 for flat, rolling and hilly respectively),  $SR$  = current stocking density = animals/ha,  $SD$  = maximum animals/ha = 40 (sheep) or 5 (cattle),  $PM$  or  $GF$  = pasture mass (t/ha),  $Hk_m$  = horizontal distance walked by the animal (km),  $Vk_m$  = vertical distance climbed (km) and  $k_m$  = the efficiency of utilization of ME for maintenance given by  $0.02 * MD + 0.5$  (CSIRO, 2007; Nicol and Brookes, 2017) or  $0.35 * (feed_{ME}/feed_{GE}) + 0.503$  (MPI, 2022) where  $feed_{ME}$  or  $M/D$  = ME content of feed/pasture and  $feed_{GE}$  = gross energy (18.45 MJ ME/kg DM),  $C$  = additional energy required for grazing, and  $Z_1$  = energy received from milk.

For a lamb and calf, the energy in milk from their dam consumed,

was accounted for so as not to inflate the requirement for grazing. It was assumed that the daily milk produced by the dam was all consumed by the lamb or calf. The MPI's adjustment factor (Eq. (3)) accounted for the energy in the milk supplied by the dam daily during lactation.

$$Z_1 = \frac{Y}{d_l * P_{lamb}} * \frac{\text{Milk energy}}{k_l} \quad (\text{MPI 2022}) \quad (3)$$

Where  $Z_1$  = the energy received from milk,  $Y$  = annual milk yield (kg or l),  $d_l$  = days of receiving milk,  $P_{lamb}$  is the lambing or calving percentage, and  $k_l$  = the efficiency of utilizing ME for lactation. The respective milk energy equations from the three models were substituted into Eq. (3) for these calculations. This ME ( $Z_1$ ) was deducted from the daily  $ME_m$  required by the lamb or calf, and the resulting non-negative  $ME_m$  was used to derive the DMI for estimating  $ME_{graze}$  for a lamb or calf. The total  $ME_m$  requirement for each class was the sum of the daily  $ME_m$  requirements for the period.

### 2.3.1. Sensitivity analysis

Pasture quality varies each month; therefore, in the current study, monthly pasture quality used in the AIM (MPI, 2022) model for sheep and beef was adopted. Hill country sheep and beef farms in NZ are comprised, an average, of a blend of flat (11 %), rolling (32 %), and steep (40 %) terrains, 3 % plantation forest, and 14 % native vegetation (Beef + Lamb New Zealand, 2020). A sensitivity analysis of the estimated  $ME_m$  for the subclasses was conducted by varying the pasture ME to 10.0, 11.0, 11.5, and 12.0 MJ ME and held constant throughout the year to assess its effect on the estimated  $ME_m$  by the nutritional models. The terrain,  $T$ , was varied to 1, and 2 from 1.5 to determine the impact of terrain on the estimated  $ME_m$  by the models.

## 2.4. Estimating gestational requirements

The daily gestational energy ( $ME_c$ ) requirement of a ewe was calculated with Eqs. (4) to 6, and that of a cow with Eqs. (7) to 9, respectively. The total  $ME_c$  requirements for a ewe and a cow were given by the sum of the daily  $ME_c$  requirements, respectively.

Ewe:

$$ME_c = 0.25 W_l \frac{0.07372E_t \exp^{-0.00643d}}{k_c} \quad (\text{MPI 2022}) \quad (4)$$

$$E_t = 10^{(3.322 - 4.979 * \exp^{-0.00643d})} \quad (4.1)$$

$$ME_c = \frac{11.46 * 0.00643 (\exp^{-0.00643d}) y}{k_c} \quad (\text{CSIRO 2007}) \quad (5)$$

<sup>1</sup> Nicol and Brookes (2017).

$$y = SBW \exp^{7.46 - 11.46 (\exp^{-0.00643d})} \quad (5.1)$$

$$ME_l = \frac{(0.328F + 0.0028d_{sm} + 2.2033) Y}{k_l} \quad (\text{MPI 2022}) \quad (10)$$

$$ME_c = \frac{(W_l/4) (\exp^{7.649 - 11.465 \exp^{-0.00643d}}) * (0.0737 \exp^{-0.00643d})}{k_c} \quad (\text{Nicol and Brookes 2017}) \quad (6)$$

Cow:

$$ME_c = 0.025 LW_c \frac{0.0201 E_t \exp^{-0.0000576d}}{k_c} \quad (\text{MPI 2022}) \quad (7)$$

$$E_t = 10^{(151.665 - 151.64 \exp^{-0.0000576d})} \quad (7.1)$$

$$ME_c = \frac{349.16 * 0.0000576 (\exp^{-0.0000576d}) y}{k_c} \quad (\text{CSIRO2007}) \quad (8)$$

$$y = SBW \exp^{349.22 - 349.16 (\exp^{-0.0000576d})} \quad (8.1)$$

$$Y = \frac{(Y_{sheepm} * mp_{month})}{d_{month}} \quad (10.1)$$

$$ME_l = \frac{(0.0328F + 0.0025 D + 2.2033) Y}{k_l} \quad (\text{CSIRO 2007}) \quad (11)$$

$$ME_l = \frac{1.1 * Y [(0.376 F\%) + (0.209 P\%) + 0.976]}{k_l} \quad (\text{Nicol and Brookes 2017}) \quad (12)$$

Cow:

$$ME_c = \frac{(LW_c/40) (\exp^{349.222 - 349.164 \exp^{-0.0000576d}}) * (0.0201 \exp^{-0.0000576d})}{k_c} \quad (\text{N \& B 2017}) \quad (9)$$

Where  $W_l$  or  $LW_c$  = the birth weight of the offspring (kg),  $SBW$  = scaled birth weight,  $d$  = days of gestation,  $y$  and  $E_t$  are the energy content of the gravid uterus and gravid foetus (MJ), respectively, and  $k_c$  = the efficiency of utilization of ME for gestation = 0.13 (MPI, 2022) or 0.133 (CSIRO, 2007; Nicol and Brookes, 2017).

### 2.5. Estimating lactation requirements

The daily lactational energy ( $ME_l$ ) requirements were calculated with Eqs. (10) to 12 for a ewe and 13 to 15 for a cow. The total  $ME_l$  for a ewe,

$$ME_l = \frac{(0.376 F + 0.209 P + 0.948) Y}{k_l} \quad (\text{MPI 2022}) \quad (13)$$

$$Y = \frac{(N_m \times mp_{month})}{d_{month}} \quad (13.1)$$

$$ME_l = \frac{(0.0458 F + 1.222) Y}{k_l} \quad (\text{CSIRO 2007}) \quad (14)$$

$$ME_l = \frac{1.1 * Y [(0.376 F\%) + (0.209 P\%) + 0.976]}{k_l} \quad (\text{Nicol and Brookes 2017}) \quad (15)$$

and a cow were given as the sum of the daily  $ME_l$  for their respective lactation period, starting 1st September.

Ewe:

Where  $d_{sm}$  = the number of days producing milk,  $Y$  = daily milk yield (kg or litres in Eqs. (12) and 15),  $D$  = the day of lactation,  $F$  and  $P$  = fat and protein content of milk, respectively (%),  $Y_{sheepm}$  or  $N_m$  = annual

milk yield (kg or L) per sheep/cow,  $mp_{month}$  = month's proportion of total milk produced,  $d_{month}$  = the number of days in a given month,  $k_l$  = efficiency of utilization of ME for lactation =  $0.019 * MD + 0.42$  for sheep,  $0.35 * (feed_{ME} / feed_{GE}) + 0.42$  for cattle (MPI, 2022), or  $0.02 * MD + 0.4$  for all (CSIRO, 2007; Nicol and Brookes, 2017).

The AIM (MPI, 2022) model assumes an estimated annual milk yield of 100 litres (103 kg) per ewe for five months, and depending on the month, a certain fraction of the annual yield, which is constant for a given month for the lactation period (Table 1). It is worthwhile to note that this is, however, biologically incorrect as ewes have lactation curves (Beef + Lamb New Zealand, 2009; Cannas et al., 2002; Reynish, 2018) which varies weekly or fortnightly and peaks in the third to fourth week of lactation (Beef + Lamb New Zealand, 2009; Reynish, 2018). The AIM (MPI, 2022) model also assumes an annual milk yield of 800 litres (824 kg) per cow and that a fixed fraction of the annual yield is produced each month during the cow's lactation period. This is also biologically incorrect as beef cows also display lactation curves. These assumptions were applied, despite the limitations, to estimate  $ME_l$  requirement in all three models for a ewe, and cow.

### 2.6. Estimating growth requirements

It was assumed that a ewe or cow does not gain or lose weight. The daily energy requirement for  $ME_g$  of a lamb or calf was estimated using the respective equations from the three models (Eqs. (16) to 18):

$$ME_g = 0.92 * LWG \left( (6.7 + R) + \left( \frac{20.3 - R}{1 + \exp\left(-6 \left(\frac{LW}{SRW} - 0.4\right)\right)} \right) \right) / k_g \quad \text{(CSIRO 2007)} \quad (16)$$

$$R = \left( \frac{ME_l}{ME_m} \right) - 2 \quad (16.1)$$

$$ME_g = \frac{(6.7 + R) + \frac{20.3 - R}{1 + \exp\left(-6 \left(\frac{LW}{SRW} - 0.4\right)\right)}}{k_g} * LWG * 0.92 \quad \text{(MPI 2022)} \quad (17)$$

$$R = \left( \frac{0.92 * LWG}{4 * SRW^{0.75}} \right) - 1 \quad (17.1)$$

$$ME_g = 0.92 * LWG * \left( (6.7 + R) + \left( \frac{20.3 - R}{1 + \exp\left(-6 \left(\frac{LW}{SRW} - 0.4\right)\right)} \right) \right) / k_g \quad \text{(N & B 2017)} \quad (18)$$

$$R = \left( \frac{920 * LWG}{4 * SRW^{0.75}} \right) - 1 \quad (18.1)$$

Where  $LWG$  = live weight gain,  $LW$  = live weight (kg),  $SRW$  = standard reference weight,  $k_g$  = the efficiency of utilization of ME for growth =  $0.042 * MD + 0.006$ , and  $R$  is the rate of change in live weight (CSIRO,

**Table 2**

The calculated total maintenance requirements for: a 60 kg ewe and a 600 kg cow from pregnancy to weaning; a lamb weighing 6 kg at birth to a target weight of 50 kg at 182 days, and a calf weighing 35 kg at birth to a heifer mating weight of 350 kg at 457 days, using three ME requirement models.

Specie	Calculated Maintenance Requirement (MJ ME)			MPI %change relative to:	
	N&B (2017) A	CSIRO, 2007	MPI, 2022	N&B (2017) A	CSIRO, 2007
Ewe	3437	3329	3706	7.3	10.2
Cow	25,726	25,653	32,468	20.8	21.0
Lamb	1072	1352	1323	19.0	-2.2
Calf/ yearling	15,395	16,717	19,697	21.8	15.1

<sup>A</sup> Nicol and Brookes (2017).

2007; MPI, 2022),  $MEI$  = ME intake. A Gompertz curve from Hojjati and Hossein-Zadeh (2018) was adapted to mimic the growth pattern of the lamb and provided its daily growth rate (LWG).

$$LW_t = A * e^{(-B * e^{(-ct)})} \quad (19)$$

Where  $LW_t$  = live weight at time  $t$ ,  $A$  = asymptotic weight (64.5 kg),  $B$  is the proportion of the asymptotic mature weight to be gained after birth (2.4),  $c$  is a function of the ratio of maximum growth rate to mature

weight (0.0125). The growth of the calf/yearling was divided into pre-weaning and post-weaning phases. Firstly, calf birth weight = 35 kg, and weaning weight = 220 kg was estimated for 184 days, secondly, the weaning weight to first mating weight = 350 kg of the calf now yearling was calculated for an additional 273 days. Live weight gains in the two phases were different but assumed to be linear. The total  $ME_g$  requirement of the lamb or calf was calculated as the sum of the daily  $ME_g$  requirements for their respective growth period.

### 2.7. Estimating wool requirements

The daily MER for wool growth ( $ME_w$ ) was estimated for only a ewe and with Eq. (20) (a common equation among models), where  $fl$  is the greasy fleece weight (kg). The annual total  $ME_w$  requirement for the ewe was the sum of the daily requirements for the period.

$$ME_w = 0.13 * \left( \left( \frac{fl * 1000}{365} \right) - 6 \right) \quad \text{(CSIRO 2007; MPI 2022)} \quad (20)$$

### 2.8. Estimating total ME requirements

For a ewe and a cow, the daily total MER was calculated as the sum of

**Table 3**

The effect of changing pasture quality and terrain on the three models' calculated maintenance requirements of the considered animal subclasses and the % changes in the MPI (2022) estimates relative to the two models.

Pasture M/ D <sup>A</sup>	Calculated Maintenance Requirements (MJ ME)			MPI %change relative to:	
	N&B (2017) B	CSIRO (2007)	MPI (2022)	N&B (2017) B	CSIRO (2007)
<b>Ewe:</b>					
10.0	3475	3349	3769	7.8	11.1
10.5	3392	3302	3620	6.3	8.8
11.0	3315	3256	3490	5.0	6.7
11.5	3244	3211	3374	3.8	4.8
12.0	3178	3168	3270	2.8	3.1
<b>Cow:</b>					
10.0	26,008	25,839	33,007	21.2	21.7
10.5	25,306	25,473	31,576	19.9	19.3
11.0	24,665	25,118	30,333	18.7	17.2
11.5	24,076	24,772	29,240	17.7	15.3
12.0	23,533	24,436	28,270	16.8	13.6
<b>Lamb:</b>					
10.0	1063	1202	1298	18.1	7.4
10.5	1036	1179	1242	16.6	5.0
11.0	1011	1157	1193	15.3	3.0
11.5	988	1137	1150	14.1	1.2
12.0	967	1117	1112	13.1	(0.4)
<b>Calf/ Yearling:</b>					
10.0	15,614	16,909	20,096	22.3	15.9
10.5	15,297	16,637	19,515	21.6	14.7
11.0	15,002	16,376	18,993	21.0	13.8
11.5	14,726	16,124	18,519	20.5	12.9
12.0	14,467	15,881	18,086	20.0	12.2
<b>Terrain</b>					
<b>Ewe:</b>					
1.0	3320	3176	3571	7.0	11.1
1.5	3437	3329	3706	7.3	10.2
2.0	3554	3482	3841	7.5	9.3
<b>Cow:</b>					
1.0	24,544	24,124	31,089	21.1	22.4
1.5	25,726	25,653	32,468	20.8	21.0
2.0	26,908	27,183	33,847	20.5	19.7
<b>Lamb:</b>					
1.0	1044	1315	1291	19.2	-1.9
1.5	1072	1352	1323	19.0	-2.2
2.0	1100	1390	1355	18.8	-2.6
<b>Calf/ Yearling:</b>					
1.0	14,882	16,032	19,128	22.2	16.2
1.5	15,395	16,717	19,697	21.8	15.1
2.0	15,908	17,401	20,266	21.5	14.1

<sup>A</sup> ME concentration in pasture or quality.

<sup>B</sup> Nicol and Brookes (2017).

the daily  $ME_m$ ,  $ME_c$ , and  $ME_l$  and  $ME_w$  (sheep) requirements. The annual  $ME_{total}$  requirement was calculated as the sum of the total  $ME_m$ ,  $ME_c$ ,  $ME_l$ , and  $ME_w$  (for sheep). The daily total MER for a lamb or a calf was calculated as the sum of the daily  $ME_m$ , and  $ME_g$  requirements. To account for the DMI of a lamb or beef yearling, the energy in milk obtained by the offspring from their dams during lactation,  $Z_1$  was deducted from the daily total MER of the lamb or beef yearling. The resulting ME, if not zero, (may be negative, but since energy is not drawn from the lamb or calf, it is assumed zero, especially in the early stages of life) is ME that needs to be met with pasture or any other feed to support the lamb's growth. The total MER ( $ME_{total}$ ) for a ewe and cow was given by Eqs. (21) and 22, respectively, while the total corrected MER ( $ME_{total}$ ) of a lamb and a beef yearling was given by Eq. (23).

$$Ewe ME_{total} = ME_m + ME_c + ME_l + ME_w \quad (21)$$

$$Cow ME_{total} = ME_m + ME_c + ME_l \quad (22)$$

$$Corrected ME_{total} = ME_m + ME_g - Z_1 \quad (23)$$

**Table 4**

The calculated gestational, lactational, and growth requirements for: a 60 kg ewe carrying a single lamb weighing 6 kg at birth over 147 days and weaning a 30 kg lamb over 91 days; a 600 kg beef breeding cow carrying a calf weighing 35 kg at birth over 281 days and weaning a 220 kg calf over 200 days; a lamb growing from 6 kg at birth to a target weight of 50 kg at 182 days; and a calf growing from 35 kg at birth to a heifer mating weight of 350 kg at 457 days, using three different ME requirement models.

Gestational:	Calculated Total Requirement (MJ ME)			MPI %change relative to:	
	N&B (2017) A	CSIRO, 2007	MPI, 2022	N&B (2017) A	CSIRO, 2007
Ewe	279	277	285	2.3	3.0
Cow	1870	1874	1869	0.0	-0.3
<b>Lactation:</b>					
Ewe	535	548	554	3.5	1.1
Cow	4842	4811	4427	-9.4	-8.7
<b>Growth:</b>					
Lamb	1916	1658	1633	-17.3	1.6
Calf/ yearling	11,067	9752	9449	-17.1	-3.2

<sup>A</sup> Nicol and Brookes (2017).

### 2.9. Data analysis

The MER were calculated in an Excel spreadsheet. Calculations were made for an average animal for an average day for a given month in the year, as described in the AIM (Ministry for Primary Industries, 2024). Percentages were, however, used to express how much the model estimates differed from each other.

## 3. Results

### 3.1. Estimated maintenance requirements

There were differences in the estimated total  $ME_m$  requirements for the animal classes considered (Table 2). The AIM (MPI, 2022) model predicted the highest daily  $ME_m$  requirement (9.9 MJ ME/d) for a ewe when it was non-pregnant and not lactating, followed by Nicol and Brookes (2017) (9.7 MJ ME/d), then CSIRO (2007) (9.0 MJ ME/d). The estimated annual total  $ME_m$  for a ewe also varied among the models and followed the same pattern as the daily  $ME_m$  requirement. The AIM (MPI, 2022) model predicted the highest annual  $ME_m$  requirement for a cow, followed by the Nicol and Brookes (2017), and the CSIRO (2007)

**Table 5**

The calculated total energy requirements for: a 60 kg ewe and a 600 kg cow from pregnancy to weaning; for a lamb weighing 6 kg at birth to a target weight of 50 kg at 182 days; and a calf weighing 35 kg at birth to a heifer mating weight of 350 kg at 457 days, using three ME requirement models.

Specie	Calculated Total ME Requirements (MJ ME)			MPI %change relative to:	
	N&B (2017) A	CSIRO, 2007	MPI, 2022	N&B (2017) A	CSIRO, 2007
Ewe	4250	4519	4910	13.4	8.0
Cow	32,438	32,339	38,764	16.3	16.6
Lamb	2988	3011	2956	-1.1	-1.9
Milk ME <sup>B</sup>	486	532	552		
Corrected ME <sup>C</sup>	2502	2479	2404	-4.1	-3.1
Calf/ yearling	26,462	26,469	29,147	9.2	9.2
Milk ME <sup>B</sup>	4401	4466	4425		
Corrected ME <sup>C</sup>	22,061	22,002	24,722	10.8	11.0

<sup>A</sup> Nicol and Brookes (2017).

<sup>B</sup> Milk energy.

<sup>C</sup> The ME to be met from pasture/feed.

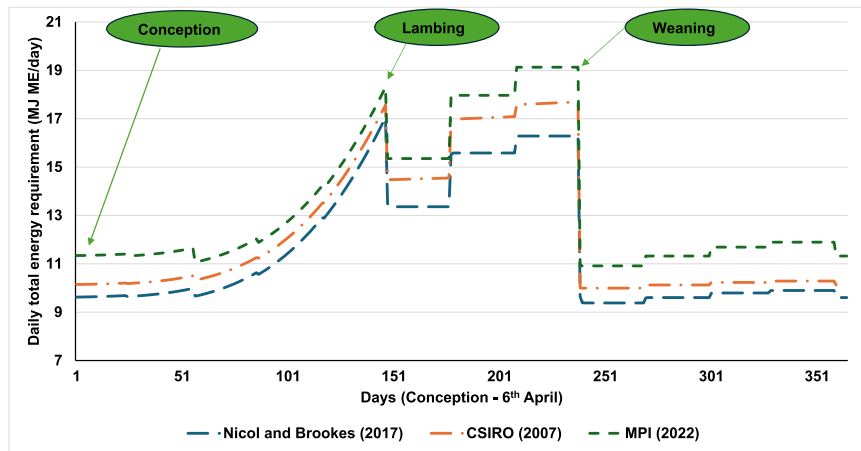


Fig. 1. A comparison of the calculated daily ME requirements (MER) for a pregnant ewe of 4 years old for a calendar year, that successfully rears its lamb using Nicol and Brookes (2017), CSIRO (2007), and MPI (2022) MER models.

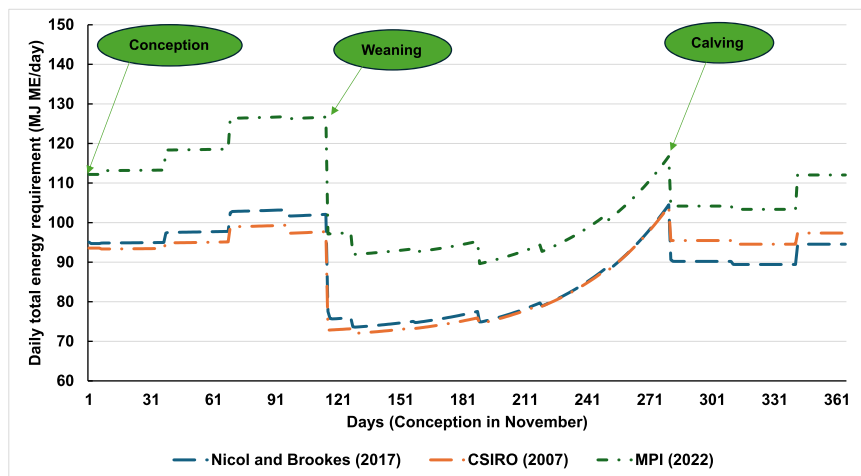


Fig. 2. A comparison of the calculated daily ME requirements (MER) for a pregnant beef breeding cow of 6 years for a calendar year, that successfully rears its calf using Nicol and Brookes (2017), CSIRO (2007), and MPI (2022) MER models.

models, which were very similar. The estimated annual total  $ME_m$  requirement of a lamb also showed that the CSIRO (2007) model yielded the highest, followed by the AIM (MPI, 2022) then the Nicol and Brookes

(2017) model estimates. The estimated total  $ME_m$  requirements of a calf/yearling showed that the AIM (MPI, 2022) model predicted the highest, followed by CSIRO (2007), then the Nicol and Brookes (2017)

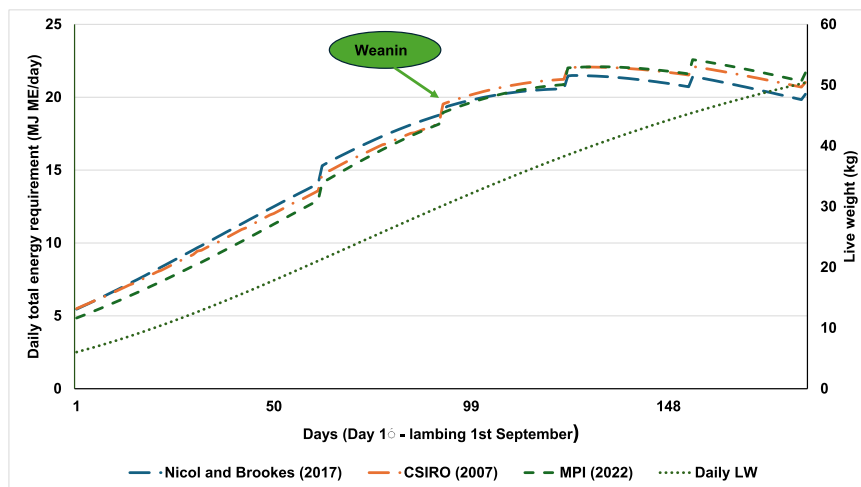


Fig. 3. A comparison of the calculated daily ME requirement (MER) of a lamb of 6 kg at birth, grown to a target weight of 50 kg using Nicol and Brookes (2017), CSIRO (2007), and MPI (2022) MER models.

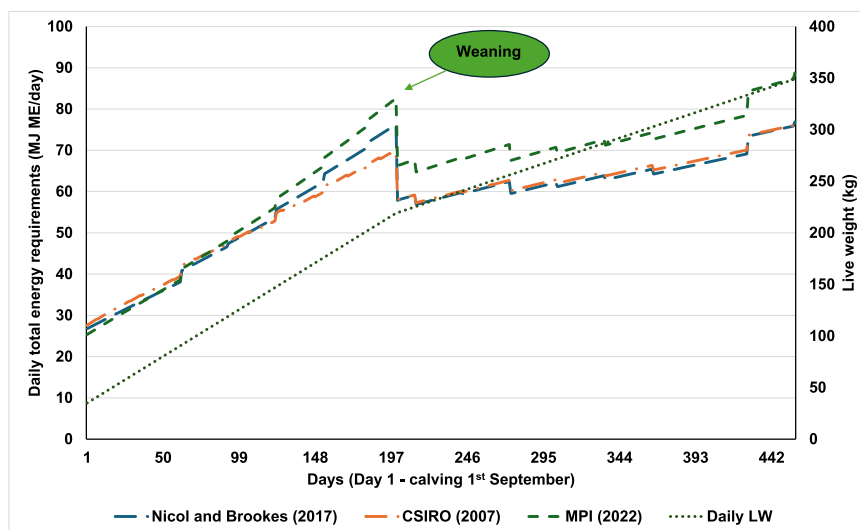


Fig. 4. A comparison of the calculated daily ME requirement (MER) of a calf/yearling of 35 kg at birth, grown to a mating weight of 350 kg using Nicol and Brookes (2017), CSIRO (2007), and MPI (2022) MER models.

model.

Also, using a gender value of 1.15, as used by AIM (MPI, 2022) model, instead of a value of 1.0 in both Nicol and Brookes (2017) and the CSIRO (2007) models resulted in a cow annual total  $ME_m$  requirement of approximately 28,739 MJ ME and 28,741 MJ ME, respectively, which was still lower than the AIM (MPI, 2022) model estimate. Substituting Nicol and Brookes (2017) cattle value of 1.3 with 1.4, as used in the AIM (MPI, 2022) model, resulted in an annual total  $ME_m$  requirement of approximately 30,515 MJ ME, which was approximately 6.0 % less than that of the AIM (MPI, 2022) model.

Sensitivity analysis with varying pasture quality revealed that despite the AIM (MPI, 2022) model generally, estimating a higher  $ME_m$  requirement for the subclasses, except for lamb, than the other two models, relative to the two models, these differences tend to decline to some extent with increasing pasture quality (Table 3). The same observations were made moving from flat to rolling/steep landscape. However, the effect of terrain on the observed differences between the AIM (MPI, 2022) model and the other two models were minimal (Table 3).

### 3.2. Estimated gestational requirements

There were some similarities and differences in the estimated annual total  $ME_c$  requirements for a ewe, and a cow (Table 4). The predicted total  $ME_c$  requirement for a ewe was similar for both Nicol and Brookes (2017) and CSIRO (2007) models, but slightly lower than the AIM (MPI, 2022) model. The average daily  $ME_c$  requirement for the week prior to lambing was the same at 7.3 MJ ME/d for both Nicol and Brookes (2017) and CSIRO (2007) models, while the AIM (MPI, 2022) model was 7.5 MJ ME/d. The estimated total  $ME_c$  requirement for a cow was similar for all three models.

### 3.3. Estimated lactational requirement

Variations in the estimated total  $ME_l$  requirement for a ewe were less than that of a cow (Table 4). The AIM (MPI, 2022) model estimated the highest  $ME_l$ , followed by CSIRO (2007), then the Nicol and Brookes (2017) model. The Nicol and Brookes (2017) model estimated the highest total  $ME_l$  for a cow, which was slightly higher than the CSIRO (2007) model but distinctly different from the AIM (MPI, 2022) model estimate.

### 3.4. Estimated growth requirements

The model estimates of the total  $ME_g$  varied and followed the same pattern for a lamb and a calf growing to a yearling (Table 4). The Nicol and Brookes (2017) model estimated the highest total  $ME_g$  requirement for a lamb, which was different from the estimates of the other two models. The CSIRO (2007) model estimate followed, but was slightly higher than the AIM (MPI, 2022) estimate. The estimated requirement of the calf/yearling also showed that the Nicol and Brookes (2017) model estimated the highest  $ME_g$  followed by CSIRO (2007) and the AIM (MPI, 2022) models. The variations in the beef yearling estimates were, however, distinct from each other.

### 3.5. Estimated wool requirements

The MER for wool was only calculated for a ewe. The daily and the annual total MER for wool growth ( $ME_w$ ) of a ewe were the same for CSIRO (2007) and the AIM (MPI, 2022) estimates. This was due to the use of the same equation for wool requirements. There was no estimate of  $ME_w$  for the Nicol and Brookes (2017) model.

### 3.6. Estimated total ME requirements

The calculated  $ME_{total}$  requirements for the various animal classes were different, and so were the corrected  $ME_{total}$  for both a lamb and calf/beef yearling (Table 5). The AIM (MPI, 2022) model estimated the highest  $ME_{total}$  for a ewe, followed by CSIRO (2007), then the Nicol and Brookes (2017) model, respectively. The variations among the models were quite significant, though not statistically proven. The estimated  $ME_{total}$  for a cow also showed that the MPI (2022) model was the highest, followed by Nicol and Brookes (2017), then the CSIRO (2007) model, respectively. The CSIRO (2007) model estimated the highest  $ME_{total}$  for a lamb, followed by the Nicol and Brookes (2017) model, which was slightly higher than the AIM (MPI, 2022) model estimate. The corrected  $ME_{total}$  showed a different pattern for a lamb, where the highest estimator was the Nicol and Brookes (2017), followed by CSIRO (2007), and then the AIM (MPI, 2022) models, due to the differences in milk energy estimates of the models. However, for a calf/yearling, the AIM (MPI, 2022) model estimated the highest  $ME_{total}$ , which was significantly (not statistically proven) different from the estimates of the other two models. The Nicol and Brookes (2017) and the CSIRO (2007) model estimates were similar. The corrected  $ME_{total}$  for the calf/yearling also followed the same pattern. Apart from the variations in the  $ME_{total}$  of the

models, the daily  $ME_{total}$  over the period also showed variations and some level of similarity for the different physiological stages of the ewe (Fig. 1), cow (Fig. 2), lamb (Fig. 3), and calf growing to a yearling (Fig. 4).

#### 4. Discussion

The results revealed that variation existed among the models in the MER estimation for the various physiological stages, based on the assumptions used. The discussion of the results is in three aspects, firstly, the differences, secondly, the reasons, and lastly, the potential implications of the differences observed. The AIM (MPI, 2022) model estimates are used as the basis in this discussion, as the NZ national GHG inventory report is based on this model.

The results show that the Nicol and Brookes (2017), and the CSIRO (2007) model estimates of  $ME_m$  for the ewe, cow, lamb, and beef yearling were less than the AIM (MPI, 2022) estimates by 7.3 % and 10.2 % for a ewe, approximately 21.0 % and 21.0 % for a cow, 19.0 % less and -2.2 % more for a lamb, and 21.8 % and 15.1 % for a beef yearling, respectively. The variations in the estimated  $ME_m$  of the models were due in part to the coefficient/efficiency of conversion of net energy (NE) to  $ME_m$  ( $k_m$ ), (i.e.,  $0.02 \cdot M/D + 0.5$  for CSIRO (2007) and Nicol and Brookes (2017), and  $0.35 \cdot (feed_{ME}/feed_{GE}) + 0.503$ , MPI (2022)) used in daily estimation. This finding is similar to the findings by Cannas (2004) and Cannas et al. (2010). They compared the estimated energy requirements of mature ewe, and dairy cattle using different feeding systems' energy requirement models and found that the systems used different  $k_m$  values to convert NE to  $ME_m$ . The similarity between the  $k_m$  value of the Nicol and Brookes (2017) model, (which in part is based on the CSIRO (2007) model), and the CSIRO (2007) model itself, is the use of the  $k_m$  value proposed by the NRC (1935), a USA system which is different from the AIM (MPI, 2022) adoption, which is from the ARC (1980), which is a UK system. The USA system's  $k_m$  value was derived from extrapolated fasting heat production (National Research Council, 1985, 1935) while the UK system's  $k_m$  value was based on fasting heat production (ARC, 1980). The CSIRO (2007) model assumes that the cost of chewing and ruminating is accounted for by the adjustment of the  $k_m$  value while the Nicol and Brookes (2017) model, accounts for ME associated with these activities separately. AgResearch (2016) noted these differences with the  $ME_m$  model by Nicol and Brookes (2007), which is identical to the Nicol and Brookes (2017) version and suggested that the authors should correct the model for potential double counting, since chewing and ruminating are accounted for in the  $k_m$  value.

Besides these generic differences in the models, other parameters accounted for the differences such as  $C$ , the additional energy required for eating that grazing animals require, was different between models (i.e., 0.05 for AIM (MPI, 2022), and 0.02 in the Nicol and Brookes, 2017, and CSIRO, 2007) for a ewe or lamb. In the cow and calf/beef yearling model,  $C = 0.006$  for AIM (MPI, 2022) and 0.0025 for both Nicol and Brookes (2017) and CSIRO (2007). Specific to a cow or calf/beef yearling, other parameters were also different based on: breed, whether *Bos indicus* 1.2 or *Bos taurus* 1.4 for CSIRO (2007) and AIM (MPI, 2022), and 1.3 for Nicol and Brookes (2017); and gender, 1.15 entire males, 1.0 females and castrates for both Nicol and Brookes (2017), and CSIRO (2007), and 1.15 females and castrates for AIM (MPI, 2022). Specific to a lamb or calf is the accounting for the elevated fasting heat production  $M$  for a suckled animal compared to a weaned animal (CSIRO, 2007) by the CSIRO (2007) model. This increased the basal  $ME_m$  requirement from day one of lactation but its effect on basal  $ME_m$  decreases as the lamb or calf aged.

These various elements, together, accounted for the differences in the model estimates, especially the MPI (2022) model, which have implications for a farmer/farm manager and whole farm system modelling considering that the AIM (MPI, 2022) generalizes this to the broader population of the specific animal subclass. Because a number, divided by a smaller number, yields a higher value, and so does multiplying it by a

bigger number. The sensitivity analysis revealed that the difference in  $ME_m$  estimates between the AIM (MPI, 2022) model, and the other two models tend to decline during spring and early summer when pasture quality is high and increases during periods of low pasture quality. The effect of terrain on the differences was minimal compared to pasture quality. The variability in model estimates, however, observed with changing pasture quality and terrain, did not change the ranking of the models in their estimates

The results also showed that the Nicol and Brookes (2017), and CSIRO (2007) model estimates of  $ME_c$  were in the range of 2.3 – 3.0 % lower than the AIM (MPI, 2022) model for a ewe, but <1 % more than the AIM (MPI, 2022) model for a cow. This shows a marginal difference among the models in the estimate of  $ME_c$ , despite a slight inherent difference in the model estimates. The slight difference in the  $ME_c$  requirement estimates was due to the different  $k_c$  values of gestation used (i.e., 0.133 for both Nicol and Brookes, 2017, and CSIRO, 2007, and 0.13 for MPI, 2022). Cannas (2004) corroborates this finding that feeding systems that use almost the same  $k_c$ , lead to results that vary very little, regardless of the method used. The similar estimated  $ME_c$  requirement across the models for a ewe and a cow respectively, was also due to all the models estimating the energy content of the gravid uterus based on the scaled birth weight and the day of gestation. This implies that the use of any of the models to estimate  $ME_c$  for either a ewe or cow will result in a similar energy requirement.

Relative to the AIM (MPI, 2022) model, the results showed that Nicol and Brookes (2017), and CSIRO (2007) models estimated 3.5 % and 1.1 % less total  $ME_l$  for a ewe, and 9.4 % and 8.7 % more  $ME_l$  for a cow, respectively. The variations in the models were mainly due to the different milk energy equations and the predictors used. For example, the Nicol and Brookes (2017) estimates  $ME_l$  using milk fat, protein content, and daily milk yield, while adjusting the results by 10 % to account for the lactating udder. The CSIRO (2007) model estimates  $ME_l$ , based on a daily milk yield, milk fat content, and the day of lactation, while the AIM (MPI, 2022) model uses the milk fat content, the daily milk yield, and the total days of lactation. Cannas (2004) also established that most feeding systems used different equations due to either fat content and days of lactation or fat content alone, as predictors to estimate milk energy.

Relative to the AIM (MPI, 2022) model, the Nicol and Brookes (2017), and CSIRO (2007) models estimated 17.3 % and 1.6 % more  $ME_g$  for a lamb, and 17.1 % and 3.2 % more  $ME_g$  for a calf, respectively. Nicol and Brookes (2017) model increased the  $ME_g$  requirement by 10 % to account for the energy required to support the development of muscle and fat cells, hence its high  $ME_g$  estimate for both lamb and calf.

The  $ME_{total}$  requirement estimates of the models revealed that Nicol and Brookes (2017), and CSIRO (2007) models, respectively, estimated  $ME_{total}$  13.4 % and 8.0 % less for a ewe, while approximately 16.0 % and 17.0 % less for a cow. Further, they estimated 1.1 % and 1.9 % less  $ME_{total}$  for a lamb, and approximately 9.0 % and 9.0 % less  $ME_{total}$  for a calf/beef yearling. Nicol and Brookes (2017) model estimated the lowest  $ME_{total}$  requirement for a ewe because their model assumed that the daily  $ME_w$  requirement for wool growth was negligible and thus, they did not account for it. However, even if the annual  $ME_w$  requirement were calculated and included in Nicol and Brookes (2017) estimates, using  $ME_w$  equation, overall, their model would still be less than the AIM (MPI, 2022) model estimate, but slightly higher than the CSIRO (2007) model estimates. Accounting for milk energy in lamb, and calf/yearling requirements showed varied patterns due to differences in the models' estimate of milk energy. The corrected  $ME_{total}$  for a lamb was highest for Nicol and Brookes (2017) model followed by CSIRO (2007) and then the AIM (MPI, 2022) model. For a calf/yearling, the AIM (MPI, 2022) model was highest, while Nicol and Brookes (2017) and the CSIRO (2007) models were similar. The net effect was that the AIM (MPI, 2022) model generally estimates a higher  $ME_{total}$  for a ewe, cow, and calf/yearling, ranging from 8.0 – 17.0 % of its estimates than the other models. This is mainly due to its higher estimates of  $ME_m$  than the other two models.

The implications of these findings on stocking rates (SR), animal performance, and also GHG emissions on New Zealand farms, since they are the commonly used nutritional models, are covered in the following sections.

Models can potentially under or overestimate the energy and invariably feed requirements of ruminants. However, the extent of these variations among a set of models commonly used in a country matter. Underestimation may lead to a higher SR, and overestimation a lower SR per hectare, than required when feed budgeting. Further, incorrect estimation of SR can result in either a feed deficit or excess through feed supply not meeting demand. Research conducted under Australian conditions has shown that stocking rates that are 30 % below or above the optimal level can result in losses of approximately \$AUD 50 per hectare (Young et al., 2022). Even though, close to 60 % of NZ farmers do not formally conduct feed budgeting (Gray et al., 2003), they instead depend on their intuition, which is informed by the current and previous experiences (Webby and Bywater, 2017) to match feed demand and supply. Feed budgeting challenges farmers and or farm managers to match the animal feed requirements to the feed supply to determine current and future balances between them (Monteath, 1973). Stocking rates too high or too low have consequences for pasture growth and quality in a grazing system. Relatively high SR increases grazing pressure, leading to pasture deterioration, and a relatively low SR means that pasture growth may not be controlled to improve pasture quality, impacting animal performance (Webby and Bywater, 2017). High SR has been reported to reduce animal intake slightly (Chen et al., 2010) and fecundity in sheep (Mishra et al., 2001). A study using experimental data from cattle found a linear relationship between SR and gain per animal in the range of 0.18 – 2.0 times the optimum SR (Jones and Sandland, 1974). They, however, cautioned that negative animal gain arises when SR exceeds twice the optimum. Combined, these indicate that when a model incorrectly estimates MER, leading to an incorrect SR, it can negatively impact animal performance, in one way or the other. For example, the  $ME_{total}$  difference between the AIM (MPI, 2022) estimate and Nicol and Brookes (2017), and CSIRO (2007) estimates translate to approximately 63 kg and 37 kg of DM difference annually for a ewe, and approximately 600 kg for a cow, assuming pasture ME is 10.5 MJ ME which is medium quality pasture in New Zealand (Waghorn et al., 2017). The difference in cow estimates is equivalent to one stock unit (SU), given that traditionally in NZ one SU is equivalent to one 55 kg breeding ewe weaning a lamb and consuming approximately 550 kg of DM annually (Reynish, 2018). This also potentially means that the estimated requirements for nine (9) ewes in the AIM (MPI, 2022) model per these calculations, would match the requirements for approximately 10 ewes in the Nicol and Brookes (2017) model.

At the moment, it is unclear which of these models are right or wrong without conducting a feeding trial to ascertain which reflects the NZ situation appropriately. The findings indicate that, at least for mature ewes and beef cows on the same farm with similar pasture conditions, the model estimates will produce different results. Irrespective, underestimating MER could result in a negative energy balance (NEB) of the ruminant (NRC, 1981) when the animals are fed incorrectly based on the use of a model. A NEB affects animal health, Body Condition Score (BSC), reproductive and lactation performance, and weight gain (Kenyon et al., 2014, 2004; Kenyon and Webby, 2017; Morris, 2017; Morris and Kenyon, 2004; Wang et al., 2024). This suggests that a farmer may unintentionally underfeed animals due to an excessively high SR if guided by a model that underestimates the MER for the different classes of animals on the farm.

On a per-animal basis, the differences in the MER estimates could also impact GHG production, especially enteric CH<sub>4</sub>. Since the three models estimated different  $ME_{total}$  requirements, estimated DMI, and invariably enteric CH<sub>4</sub> outputs will be different also on an individual animal basis if GHG estimates are based on DMI. However, it could be that a high-estimate energy model would result in a lower estimated SR, and vice versa, on a given farm, so the difference in the estimated DMI or

enteric CH<sub>4</sub> output, may net out on a whole farm basis when that farm has a maximum feed availability. However, it does appear that the industry (Beef + Lamb, NZ) relies on Nicol and Brookes (2007, 2017) model estimates to determine SR, as well as, advise farmers on intake requirements on sheep and beef farms (See Beef + Lamb New Zealand, 2018) while the national inventory report bases its estimates on the AIM (MPI, 2022) model. With a proposed NZ Emissions Trading Scheme (ETS) (Ministry for the Environment, 2022) which is most likely to be based on the AIM (MPI, 2022) model estimates, the apparent total farm GHG may be higher than if calculated using the Nicol and Brookes (2017) or CSIRO (2007) models, when calculations are done based on numbers and type of animals present, rather than total feed available.

## 5. Conclusions

The study found that compared to the AIM (MPI, 2022) model, both Nicol and Brookes (2017) and the CSIRO (2007) models generally, estimated less  $ME_{total}$  requirements for a ewe, beef breeding cow, lamb, and calf/yearling, despite the similarity in the estimates of some of the individual physiological requirements. The differences in the coefficient of conversion of NE to ME for maintenance ( $k_m$ ) and some other parameters accounted for the higher  $ME_m$  requirement estimates of the AIM (MPI, 2022) model. Variations in pasture quality throughout the year changed the relative estimated values, but not the ranking of the models. These differences potentially hold implications for the stocking rate and carrying capacities of farms, individual ruminant energy balance and productive performance, and the estimated farm GHG output. This is especially the case if these models are used interchangeably. To ensure consistency in MER estimation, farm management decisions, and GHG reporting by farmers/industry (Beef and Lamb, NZ) and the AIM (MPI, 2022) model, further research (i.e., feeding trial), is needed to compare these model estimates with the actual requirements of selected ruminants under NZ conditions. This will help identify the model that most accurately reflects MER for ruminants in the country and that should be utilised for all feeding requirement calculations and the implications of those calculations.

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## CRedit authorship contribution statement

**Joseph A. Adjabui:** Writing – original draft, Conceptualization, Validation, Writing – review & editing, Formal analysis. **Patrick H.C. Morel:** Supervision, Writing – review & editing, Conceptualization, Validation. **Stephen T. Morris:** Writing – review & editing, Conceptualization, Validation, Supervision. **Paul R. Kenyon:** Validation, Supervision, Writing – review & editing, Conceptualization. **Peter R. Tozer:** Supervision, Writing – review & editing, Conceptualization, Validation.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## References

- AgResearch, 2016. Assessment of the OVERSEER metabolisable energy requirements model. Accessed on 29TH October 2024 from. [https://assets.ctfassets.net/bo1h2c9cbxaf/1Tr5agQ07Dy6XGjn8OqD5H/fcd46d7888cd4f57b519a4fd71a48ed4/Metabolic\\_Energy\\_Requirements\\_Review.pdf](https://assets.ctfassets.net/bo1h2c9cbxaf/1Tr5agQ07Dy6XGjn8OqD5H/fcd46d7888cd4f57b519a4fd71a48ed4/Metabolic_Energy_Requirements_Review.pdf).
- Agricultural Research Council, 1980. The Nutrient Requirements of Ruminant Livestock. Commonwealth Agricultural Bureaux, Farnham Royal.
- Agriculture and Food Research Council, 1993. Energy and Protein Requirements of Ruminants: an Advisory manual Prepared by the AFRC Technical Committee On Response to Nutrients. CAB International, Wallingford, UK.
- Beef + Lamb New Zealand, 2020. Fact sheet; hill country sheep and beef farms. Accessed on 1st November 2024 from. <https://beeflambnz.com/knowledge-hub/PDF/hill-country-sheep-and-beef-farms.pdf>.
- Beef + Lamb New Zealand, 2018. A guide to feed planning for sheep farmers. Accessed on 1st November 2024 from. <https://beeflambnz.com/knowledge-hub/PDF/guide-feed-planning-sheep-farmers.pdf>.
- Beef + Lamb New Zealand, 2009. Fact Sheet: lactation, lamb growth and the lamb weaning decision. Accessed on 1st November 2024 from. <https://beeflambnz.com/sites/default/files/factsheets/pdfs/fact-sheet-94-lactation-lamb-growth-and-the-weaning-decision.pdf>.
- Cannas, A., 2004. Energy and Protein requirements, in: Dairy Sheep Nutrition. CABI Publishing, Wallingford UK, pp. 31–49.
- Cannas, A., Atzori, A.S., Teixeira, I.A.M.A., Sainz, R.D., Oltjen, J.W., 2010. The energetic cost of maintenance in ruminants: from classical to new concepts and prediction systems. Energy and Protein Metabolism and Nutrition. Wageningen Academic, pp. 531–542.
- Cannas, A., Nudda, A., Pulina, G., 2002. Nutritional strategies to improve lactation persistency in dairy ewes. In: Proceedings of the 8th Great Lakes Dairy Sheep Symposium.
- Chen, X.J., Hou, F.J., Matthew, C., He, X.Z., 2010. Stocking rate effects on metabolizable energy intake and grazing behaviour of Tan sheep in steppe grassland on the Loess Plateau of Northwest China. J. Agric. Sci. 148, 709–721. <https://doi.org/10.1017/S0021859610000511>.
- CSIRO, 2007. Nutrient Requirements of Domesticated Ruminants. CSIRO publishing, Collingwood, Vic., Australia.
- deNicolò, G., Morris, S.T., Kenyon, P.R., Morel, P.C.H., 2008. A comparison of two lamb production systems in New Zealand. N. Z. J. Agric. Res. 51, 365–375. <https://doi.org/10.1080/00288230809510467>.
- Gray, D.I., Parker, W.J., Kemp, E.A., Kemp, P.D., Brookes, I.M., Horne, D., Kenyon, P.R., Matthew, C., Reid, S.T.M.J.I., Valentine, I., 2003. Feed planning-alternative approaches used by farmers. In: Proceedings of the New Zealand Grassland Association, pp. 211–217.
- Hammond, K.J., Burke, J.L., Koolaard, J.P., Muetzel, S., Pinares-Patiño, C.S., Waghorn, G.C., 2013. Effects of feed intake on enteric methane emissions from sheep fed fresh white clover (*Trifolium repens*) and perennial ryegrass (*Lolium perenne*) forages. Anim. Feed. Sci. Technol. 179, 121–132. <https://doi.org/10.1016/j.anifeedsci.2012.11.004>.
- Hammond, K.J., Pacheco, D., Burke, J.L., Koolaard, J.P., Muetzel, S., Waghorn, G.C., 2014. The effects of fresh forages and feed intake level on digesta kinetics and enteric methane emissions from sheep. Anim. Feed. Sci. Technol. 193, 32–43. <https://doi.org/10.1016/j.anifeedsci.2014.04.005>.
- Hodgson, J., Cameron, K., Clark, D., Condron, L., Fraser, T., Hedley, M., Holmes, C., Kemp, P., Lucas, R., Moot, D., 2005. New Zealand's pastoral industries: efficient use of grassland resources. Grassl.: Dev. Oppor. Perspect. 181–205.
- Hojjati, F., Hossein-Zadeh, N.G., 2018. Comparison of non-linear growth models to describe the growth curve of Mehraban sheep. J. Appl. Anim. Res. 46, 499–504. <https://doi.org/10.1080/09712119.2017.1348949>.
- INRA, 2018. INRA Feeding System For Ruminants. Wageningen Academic Publishers, The Netherlands. <https://doi.org/10.3920/978-90-8686-292-4>.
- International Panel on Climate Change, 2019. Emissions from livestock and manure management. In: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Accessed from. [https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4\\_Volume4/19R\\_V4\\_Ch10\\_Livestock.pdf](https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch10_Livestock.pdf).
- International Panel on Climate Change, 2006. Emissions from livestock and manure management. In: 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme. Accessed from. [https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4\\_Volume4/V4\\_10\\_Ch10\\_Livestock.pdf](https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf).
- Jones, R.J., Sandland, R.L., 1974. The relation between animal gain and stocking rate: derivation of the relation from the results of grazing trials. J. Agric. Sci. 83, 335–342. <https://doi.org/10.1017/S0021859600052035>.
- Kenyon, P.R., Maloney, S.K., Blache, D., 2014. Review of sheep body condition score in relation to production characteristics. N. Z. J. Agric. Res. 57, 38–64. <https://doi.org/10.1080/00288233.2013.857698>.
- Kenyon, P.R., Morel, P.C.H., Morris, S.T., 2004. The effect of individual liveweight and condition scores of ewes at mating on reproductive and scanning performance. N. Z. Vet. J. 52, 230–235. <https://doi.org/10.1080/00480169.2004.36433>.
- Kenyon, P.R., Webby, R.W., 2017. Pastures and supplements in sheep production systems. In: Rattray, P.V., Brookes, I.M., Nicol, A.M. (Eds.), Pasture and Supplements for Grazing Animals. New Zealand Society of Animal Production, Hamilton, New Zealand, pp. 259–277.
- Lambert, M.G., Clark, D.A., Litherland, A.J., 2004. Advances in pasture management for animal productivity and health. N. Z. Vet. J. 52, 311–319. <https://doi.org/10.1080/00480169.2004.36447>.
- Lambert, M.G., Litherland, A.J., 2000. A practitioner's guide to pasture quality. In: Proceedings of the New Zealand Grassland Association, pp. 111–115.
- Ministry for Primary Industries, 2024. Methodology for calculation of New Zealand's agricultural greenhouse gas emissions. Accessed on 23RD October 2024 from. <https://www.mpi.govt.nz/dmsdocument/13906-detailed-methodologies-for-agricultural-greenhouse-gas-emission-calculation>.
- Ministry for Primary Industries, 2022. Methodology for calculation of New Zealand's agricultural greenhouse gas emissions. Accessed on 1st May 2023 from. <http://www.mpi.govt.nz/news-and-resources/publications/>.
- Ministry for the Environment, 2022. Towards a productive, sustainable and inclusive economy: new Zealand's First Reduction Plan. Accessed on 23rd August 2023 from. <https://environment.govt.nz/publications/aotearoa-new-zealands-first-emissions-reduction-plan/agriculture/>.
- Mishra, C., Prins, H.H.T., Van Wieren, S.E., 2001. Overstocking in the trans-Himalayan rangelands of India. Environ. Conserv. 28, 279–283. <https://doi.org/10.1017/S0376892901000297>.
- Molano, G., Clark, H., 2008. The effect of level of intake and forage quality on methane production by sheep. Aust. J. Exp. Agric. 48, 219–222. <https://doi.org/10.1071/EA07253>.
- Monteath, M.A., 1973. Feed budgeting: an aid to profitable management. In: Proceedings of the New Zealand Grassland Association, pp. 135–141.
- Morris, S.T., 2017. Pastures and supplements in beef production systems. In: Rattray, P.V., Brookes, I.M., Nicol, A.M. (Eds.), Pasture and Supplements for Grazing Animals. New Zealand Society of Animal Production, Hamilton, New Zealand, pp. 247–259.
- Morris, S.T., 2013. Sheep and beef cattle production systems. Ecosyst. v. NZ 79–84.
- Morris, S.T., Kenyon, P.R., 2004. The effect of litter size and sward height on ewe and lamb performance. N. Z. J. Agric. Res. 47, 275–286. <https://doi.org/10.1080/00288233.2004.9513596>.
- Muetzel, S., Clark, H., 2015. Methane emissions from sheep fed fresh pasture. N. Z. J. Agric. Res. 58, 472–489. <https://doi.org/10.1080/00288233.2015.1090460>.
- National Research Council, 1985. Nutrient Requirements of Sheep. National Academy Press, Washington, DC, USA. ).
- National Research Council, 1981. Nutritional Energetics of Domestic Animals and Glossary of Energy Terms. The National Academies Press, Washington, DC.
- National Research Council, 1935. Report of the conference on energy metabolism. In: National Research Council Committee on Animal Nutrition, Washington, DC, State College Pennsylvania.
- Nicol, A.M.& Brookes, I.M., 2007. The metabolisable energy requirements of grazing livestock. In: Rattray, P.V., Brooks, I.M., Nicol, A.M. (Eds.), Pasture and Supplements for Grazing Animals. New Zealand Society of Animal Production, Hamilton, New Zealand, pp. 151–172.
- Nicol, A.M.& Brookes, I.M., 2017. The metabolisable energy requirements of grazing livestock. Eds.. In: Rattray, P.V., Brooks, I.M., Nicol, A.M. (Eds.), Pasture and Supplements for Grazing Animals. New Zealand Society of Animal Production, Hamilton, New Zealand, pp. 151–172.
- Reynish, R., 2018. Farm Technical Manual. Faculty of Agribusiness & Commerce, Lincoln University.
- Robinson, J.J., Haresign, W., Cole, D.J.A., 1987. Energy and protein requirements of the ewe. Recent Dev. Rumin. Nutr. 2, 365–382.
- Waghorn, G.C., Burke, J.L., Kolver, E.S., 2017. Principles of feeding values. In: Rattray, P.V., Brooks, I.M., Nicol, A.M. (Eds.), Pasture and Supplements for Grazing Animals.
- Wang, Z., Chen, P., Liang, Y., Wang, F., Zhang, Y., 2024. Negative energy balance affects perinatal ewe performance, rumen morphology, rumen flora structure, and placental function. J. Anim. Physiol. Anim. Nutr. (Berl). <https://doi.org/10.1111/jpn.14009n/a>.
- Webby, R.W., Bywater, A.C., 2017. Principles of feed planning and management. In: Rattray, P.V., Brookes, I.M., Nicol, A. (Eds.), Pasture and Supplements for Grazing Animals. New Zealand Society of Animal Production, Hamilton, New Zealand, pp. 189–224.
- Young, M., Vercoe, P.E., Kingwell, R.S., 2022. Optimal sheep stocking rates for broad-acre farm businesses in Western Australia: a review. Anim. Prod. Sci. 62, 803–817. <https://doi.org/10.1071/AN21462>.