The Journal of Agricultural Science

cambridge.org/ags

Animal Research Paper

Cite this article: Brito Neto AdeS, Herbster CJL, Marcondes MI, Chagas JCC, Oliveira RL, Bezerra LR, da Silva LP, Pereira ES (2024). Using carcass information as a predictor variable of empty body weight, empty body weight gain and retained energy of hair sheep. *The Journal of Agricultural Science* **162**, 384–393. https://doi.org/10.1017/S0021859624000455

Received: 6 February 2024
Revised: 2 July 2024
Accepted: 8 July 2024

Keywords:
Carcass gain; energy; meta-analysis; prediction model; sheep

Corresponding author:
Elzania Sales Pereira;
Email: elzania@hotmail.com

Using carcass information as a predictor variable of empty body weight, empty body weight gain and retained energy of hair sheep

Antonio de Sousa Brito Neto[1], Caio Julio Lima Herbster[1], Marcos Inacio Marcondes[2], Juana Catarina Cariri Chagas[3], Ronaldo Lopes Oliveira[4], Leilson Rocha Bezerra[5], Luciano Pinheiro da Silva[1] and Elzania Sales Pereira[1]

[1]Department of Animal Science, Federal University of Ceara, Fortaleza, Ceara, Brazil; [2]Department of Animal Science, Washington State University, Pullman, WA, USA; [3]Departament of Applied Animal Science and Welfare, Swedish University of Agricultural Sciences, Umeå, Sweden; [4]School of Veterinary Medicine and Animal Science, Federal University of Bahia, Salvador, Bahia, Brazil and [5]Center of Health and Agricultural Technology, Federal University of Campina Grande, Patos, Paraiba, Brazil

Abstract

The objective was to develop equations to predict carcass weight (CW), use CW to predict empty body weight (EBW); and carcass gain (CG) to predict empty body weight gain (EBWG) and retained energy (RE) in hair sheep. To generate the prediction models, a data set was composed of individual measurements from 569 sheep encompassing intact males ($n = 416$), castrated males ($n = 51$), and females ($n = 102$). Validation analyses were performed by using the Model Evaluation System (MES). The prediction equations for CW, EBW, and EBWG were not influenced by sex class ($P > 0.05$), and the following equations were generated, respectively: CW (kg) = − 0.234 (±1.1358) + 0.485 (±0.0387) × FBW; EBW (kg) = 1.367 (±0.5472) + 1.681 (±0.0210) × CW and EBWG (kg) = 0.004 (±0.0026) + 1.679 (±0.0758) × CG. There was an effect of sex class on the intercept ($P = 0.0013$) of the relationship between RE and CG: RE (MJ/day) = 1.448 (±0.0657) × $EBW^{0.75}$ × $CG^{0.797\ (\pm 0.0399)}$; RE (MJ/day) = 1.522 (±0.0699) × $EBW^{0.75}$ × $CG^{0.797\ (\pm 0.0399)}$ and RE (MJ/day) = 1.827 (±0.0739) × $EBW^{0.75}$ × $CG^{0.797\ (\pm 0.0399)}$ for intact males, castrated males and females, respectively. This study highlights the importance of incorporating carcass information into EBW, EBWG, and RE predictions. Replacing empty body weight gain with carcass gain might be a suitable alternative to estimate the retained energy of hair sheep. In addition, the generated equations will provide support for meat production systems in carcass weight prediction.

Introduction

Hair sheep are commonly used in meat production systems in tropical regions (Araújo *et al.*, 2017) due to the perception that they are more resistant to harsh environments and heat tolerant (Costa *et al.*, 2013; McManus *et al.*, 2020) and therefore offer a valuable genetic resource. Studies of nutritional requirements are frequently compiled and generate representative and practical recommendations for animal feeding. This information and learning cycle strongly depend on the predictive capacity of mathematical equations (Tedeschi, 2023), which, through the relationship between variables, allow the estimation of parameters with biological meanings. Body weight adjustments represent an indispensable tool for estimating animal performance in feeding tests, nutritional requirement studies, and production systems (Herbster *et al.*, 2020).

Empty body weight (EBW) is a basic measurement for nutritional trials, as it accurately represents the mass of body tissues (BR-CORTE, 2023) and, therefore, the calculation of requirements is carried out based on EBW (Oliveira *et al.*, 2018). However, as the EBW is determined laboriously, we must seek estimation equations that can be easily applied in a practical scenario, facilitating the nutritionist's work in formulating diets. Within this scenario, information about the carcass can be associated with EBW, empty body weight gain (EBWG), and retained energy (RE) as it represents tissue deposition during the animal's growth.

Meyer *et al.* (1960) suggested the use of the term corrected carcass to evaluate the response of beef cattle to various treatments. This measure, which is essentially the carcass weight corrected to a standard caloric value, has the advantage of removing the effect of fill. Furthermore, with this variable a larger volume of data can be available, generated in non-experimental locations, such as commercial slaughterhouses (Benedeti *et al.*, 2021), which can provide new data sets for future estimates or validation of new equations.

The EBWG is a measure highly correlated with RE in the body and it is therefore useful in many models of energy requirements. The independent variables input in prediction models must be representative of the response variable, easy to obtain, and have a practical relationship with production systems. In this context, replacing EBWG with carcass gain (CG) in predicting RE is a viable alternative, considering that carcass weight (CW) contains a significant proportion of body energy retained in the form of protein and fat. Furthermore, CW is a measurement routinely performed on the slaughter line and is less susceptible to measurement errors. Equations for predicting CW, as well as the use of CG as a predictor variable, can be useful tools for the sheep meat production system, as well as animal feeding systems.

Our hypothesis is that CG can be used to predict the RE of hair sheep. Therefore, our objective was to develop equations to predict CW and use CW to predict EBW, and CG to predict EBWG and RE in hair sheep.

Materials and methods

Description of the data set

The data set used to generate the models was composed of individual measurements from 569 sheep derived from sixteen studies (Pereira, 2011; Costa *et al.*, 2013; Oliveira *et al.*, 2014; Pereira *et al.*, 2014, 2017, 2018a, 2018b; Rodrigues *et al.*, 2016; Gois *et al.*, 2017; Brito Neto, 2020; Mendes *et al.*, 2021; Silva *et al.*, 2021; Rocha, 2022; A. C. Rocha, unpublished data; A. S. Brito Neto, unpublished data; C. J. L. Herbster, unpublished data) with records of three sex classes: intact males ($n = 416$), castrated males ($n = 51$) and females ($n = 102$). The most representative hair sheep genotypes in the data set were: Santa Ines ($n = 192$); Morada Nova ($n = 121$), Brazilian Somali ($n = 47$), ½ Dorper × ½ Santa Ines ($n = 63$) and crossbred ($n = 146$). Within this data set, 429 records were originated from comparative slaughter (Pereira, 2011; Costa *et al.*, 2013; Oliveira *et al.*, 2014; Pereira *et al.*, 2014, 2017, 2018a; Rodrigues *et al.*, 2016; Mendes *et al.*, 2021; A. C. Rocha (unpublished data); A. S. Brito Neto (unpublished data); C. J. L. Herbster (unpublished data)). In these studies, 77 animals were slaughtered initially and named as reference or baseline group; 114 animals were fed at maintenance level, and 238 fed above maintenance. The remaining records ($n = 140$) were originated from feeding trials (Gois *et al.*, 2017; Pereira *et al.*, 2018b; Brito Neto, 2020; Silva *et al.*, 2021; Rocha, 2022), studies which did not use the comparative slaughter methodology, with animals fed above maintenance. Information on level of feeding for each study is described in the supplementary material (Table S1). The quantitative information body weight (BW), fasting body weight (FBW), CW, EBW, and RE were utilized to generate the models (Table 1).

Slaughter procedures and chemical analyses

Slaughter procedures were similar in all studies. In summary, FBW was obtained before slaughter, after 18 h without feed and water. Slaughter was carried out by stunning with a captive bolt pistol, causing a cerebral concussion and severing of the jugular vein until the animals completely bled, followed by skinning and evisceration. The blood, internal organs, visceral fat, head, hooves, and skin were weighed, collected, and frozen. The gastrointestinal tract (GIT), bladder, and gallbladder were weighed full, emptied, washed, drained, and weighed empty. The EBW was obtained as the FBW minus the GIT, bladder, and gallbladder contents.

The carcasses were weighed, refrigerated at 4°C for 24 h, divided in half lengthwise, and then frozen. Subsequently, the non-carcass components, hides, and right half carcass samples were cut with a band saw and ground separately in an industrial meat grinder. After grinding and homogenization, samples were taken for chemical analysis. For determination of the body composition, the ground samples of the right half-carcasses, non-carcass parts, and hides were pre-dried at 55°C to constant weight and after this period, defatted by extraction with ether in a Soxhlet apparatus (AOAC, 1990; method number 920.39) for 12 h (Pereira *et al.*, 2017). Subsequently, the fat-free samples were ground in a ball mill and analysed for dry matter (AOAC, 1990; method 967.03) and crude protein content (AOAC, 1990; method 984.13).

Models and estimation of variables

To estimate the initial EBW and CW of the performance animals in the comparative slaughter studies, regression equations of the FBW against the BW, EBW against the FBW, and CW against the EBW were generated from the data baseline animals. Likewise, the initial body energy of the performance animals was estimated by regression equations of the body energy contents against the EBW from the data baseline animals (Herbster *et al.*, 2024).

The CG (kg/day) was obtained by the difference between the final and initial carcass weight, divided by the number of experimental days, within each study. The daily RE (MJ/day) was obtained by the difference between the final and initial body energy content (BEC). The BEC was obtained for each animal from the body content of protein and fat and their caloric equivalents (ARC, 1980) according to the following equation:

$$BEC = (5.6405 \times BPC) + (9.3929 \times BFC) \quad (1)$$

where BEC is the body energy content (MJ); BPC is body protein content (kg); and BFC is body fat content (kg).

The CW, EBW and EBWG were estimated through linear regressions using the following equations, respectively:

$$CW = \beta 0 + \beta 1 \times FBW \quad (2)$$

$$EBW = \beta 0 + \beta 1 \times CW \quad (3)$$

$$EBWG = \beta 0 + \beta 1 \times CG \quad (4)$$

where CW is the carcass weight (kg); FBW is fasting body weight (kg); EBW is the empty body weight (kg); EBWG is empty body weight gain; CG is the carcass gain; and $\beta 0$ and $\beta 1$ correspond to the intercept and slope of the linear regression, respectively.

To predict the RE, the model suggested by the NRC (1984) was used, which describes the relationship between the RE and the EBWG for a given EBW, being the EBWG variable replaced by the CG variable, as suggested by Benedeti *et al.* (2021):

$$RE = \beta 0 \times EBW^{0.75} \times CG^{\beta 1} \quad (5)$$

where RE is the retained energy (MJ/day); $EBW^{0.75}$ is metabolic empty body weight (kg); CG is carcass gain (kg/day); $\beta 0$ is the

https://doi.org/10.1017/S0021859624000455 Published online by Cambridge University Press

Table 1. Descriptive statistics of the variables used to generate the prediction models

Items	FBW (kg)	EBW (kg)	CW (kg)	EBWG (kg/day)	CG (kg/day)	RE (MJ/kg$^{0.75}$ EBW/day)
Sex class						
Intact males						
n	397	300	416	226	226	226
Average ± SD	28 ± 9.1	22 ± 8.9	13 ± 4.8	0.1 ± 0.07	0.05 ± 0.042	0.12 ± 0.095
Minimum	8.60	6.67	3.21	−0.147	−0.091	−0.197
Maximum	53.10	44.19	25.65	0.313	0.216	0.365
Castrated males						
n	34	51	51	39	39	39
Average ± SD	19 ± 5.2	16 ± 5.4	9 ± 3.0	0.05 ± 0.068	0.02 ± 0.043	0.1 ± 0.11
Minimum	11.60	7.67	3.45	−0.101	−0.076	−0.155
Maximum	29.5	29.33	14.85	0.171	0.082	0.303
Females						
n	84	102	102	87	87	87
Average ± SD	23 ± 7.9	18 ± 7.0	10 ± 4.3	0.06 ± 0.060	0.03 ± 0.037	0.1 ± 0.11
Minimum	11.66	8.17	3.88	−0.062	−0.056	−0.087
Maximum	40.00	35.27	21.65	0.235	0.096	0.391
Genotype						
Santa Ines						
n	192	180	192	130	130	130
Average ± SD	26 ± 10.0	21 ± 9.2	12 ± 5.4	0.09 ± 0.067	0.05 ± 0.042	0.13 ± 0.093
Minimum	10.08	7.76	3.54	−0.035	−0.029	−0.066
Maximum	53.10	44.19	25.65	0.313	0.216	0.332
Morada Nova						
n	121	109	121	86	86	86
Average ± SD	22 ± 8.2	18 ± 7.3	10 ± 4.4	0.07 ± 0.042	0.04 ± 0.025	0.11 ± 0.058
Minimum	8.60	6.67	3.21	0.00002	0.0002	−0.002
Maximum	45.60	40.05	23.65	0.164	0.098	0.217
Brazilian Somali						
n	47	47	47	39	39	39
Average ± SD	21 ± 6.3	18 ± 6.0	10 ± 3.3	0.09 ± 0.046	0.05 ± 0.023	0.17 ± 0.084
Minimum	10.24	7.96	4.02	0.0003	0.002	0.021
Maximum	34.96	31.18	17.76	0.183	0.092	0.357
½ Dorper × ½ Santa Ines						
n	63	63	63	54	54	54
Average ± SD	32 ± 8.5	27 ± 7.4	16 ± 4.4	0.08 ± 0.062	0.05 ± 0.037	0.13 ± 0.090
Minimum	13.50	9.72	5.00	−0.040	−0.025	−0.050
Maximum	49.30	41.66	24.65	0.209	0.126	0.309
Crossbred						
n	92	54	146	43	43	43
Average ± SD	31 ± 5.1	17 ± 6.3	12 ± 4.0	0.03 ± 0.102	0.00 ± 0.055	0.06 ± 0.17
Minimum	21.20	7.67	3.49	−0.147	−0.091	−0.197
Maximum	47.12	30.03	22.20	0.235	0.096	0.391

CW, carcass weight; CG, carcass gain; FBW, fasting body weight; EBW, empty body weight; EBWG, empty body weight gain; RE, retained energy; SD, standard deviation.

https://doi.org/10.1017/S0021859624000455 Published online by Cambridge University Press

Table 2. Summary of studies used to validate the generated equations

Study	*T*	*n*	Sex class	Genotype
Validation of CW and EBW[a]				
Cunha *et al.* (2008)	4	24	Intact male	Santa Ines
Dantas *et al.* (2008)	3	24	Castrated male	Santa Ines
Menezes *et al.* (2008)[b]	3	33	Intact male	Santa Ines
Medeiros *et al.* (2009)	4	32	Castrated male	Morada Nova
Xenofonte *et al.* (2009)	4	24	Intact male	Crossbred
Araújo Filho *et al.* (2010)	3	54	Intact male	Santa Ines/Morada Nova/½ Dorper × ½ Santa Ines
Pereira *et al.* (2010)	4	20	Intact male	Santa Ines
Vieira *et al.* (2010)	4	20	Intact male	Morada Nova
Costa *et al.* (2011)	4	20	Intact male	Morada Nova
Alvarenga (2013)	2	50	Intact male	Crossbred
Fernandes Júnior *et al.* (2013)	5	30	Intact male	Santa Ines
Souza *et al.* (2013)[b]	2	20	Intact male	½ Dorper × ½ Santa Ines/½ Dorper × ½ Somalis Brasileira
Bastos *et al.* (2015)[b]	5	25	Intact male	Santa Ines
Lima Júnior *et al.* (2015)	2	16	Intact male	Morada Nova
Queiroz *et al.* (2015)	3	24	Intact male	Santa Ines
Urbano *et al.* (2015)[c]	5	40	Intact male	Santa Ines
Silva *et al.* (2016)[b]	4	40	Intact male	Santa Ines
Oliveira *et al.* (2017)	4	32	Intact male	Santa Ines
Nascimento *et al.* (2018)	3	24	Intact male	½ Dorper × ½ Santa Ines
Validation of EBWG and RE[d]				
Nascimento Júnior (2010)	–	16	Castrated male	Dorper/Santa Ines
Silva *et al.* (2010)	–	16	Castrated male	Santa Ines
Regadas Filho *et al.* (2013)	–	15	Intact male	Santa Ines
C. J. L. Herbster (unpublished data)	–	16	Female	½ Dorper × ½ Santa Ines

CW, carcass weight; EBW, empty body weight; EBWG, empty body weight gain; *n*, in the number of observations in the study; RE, retained energy; *T*, is the number of treatments in the study.
[a]Compilation of means of treatments reported by independent publications.
[b]Study included only in the validation data set of the CW prediction equations.
[c]Study included only in the validation data set of the EBW prediction equations.
[d]Compilation of individual information originating from independent study data sets.

antilogarithm of the intercept of the linear regression of the logarithm of RE (MJ/kg$^{0.75}$ EBW/day) as a function of the logarithm of CG (kg/day); and $\beta 1$ corresponds to the slope of the regression.

To estimate EBWG and RE, only data from animals fed above the maintenance level were used, since the growth pattern of these animals differs from those feds at the maintenance level.

Statistical analysis

The parameters of the linear models were tested using the MIXED procedure of SAS (version 9.4, Inst. Inc., Cary, NC), and the significance level was set at 0.05. As the data set was composed of different studies, it was necessary to quantify the variance associated with the studies using the principles of meta-analysis, described by St-Pierre (2001). The random effect of the study was included and tested in the intercept and slope of all models, considering the possibility of covariance. The fixed effect of sex class on models' parameters was tested, and when the differences were significant, an equation was fitted for each sex class. Seventeen types of variance-covariance structures were tested, with the choice of structure for defining the most appropriate model based on Akaike's Information Criteria. Individual observations with Student residuals greater than 2.5 or below −2.5 were considered outliers (Pell, 2000; Tedeschi, 2006) and excluded from the data set. When Cook's distance was greater than 1.0, the study was considered an outlier and removed from the analysis (Cook and Weisberg, 1982).

Validation of equations

An independent validation framework was adopted, which consisted of searching for studies conducted with hair sheep raised in tropical conditions that had the same input information as the models generated to predict CW, EBW, EBWG and RE.

For CW and EBW we used values of mean of treatments, from published manuscripts, as described in Table 2 and 3. Although, for EBWG and RE we used raw (individual) values extracted from four independent studies.

Table 3. Characteristics of the data sets used to validate the generated equations

Items	Validation data sets		
	CW[a]	EBW[a]	EBWG and RE[b]
Study (*N*)	18	15	4
Means of treatments (*n*)	63	54	–
Animals (*n*)	512	434	63
Sex class (*n*)			
Intact males	456	378	15
Castrated males	56	56	32
Females	–	–	16
Genotype (*n*)			
Santa Ines	270	212	39
Morada Nova	106	106	–
Dorper	–	–	8
Crossbred	74	74	–
½ Dorper × ½ Santa Ines	52	42	16
½ Dorper × ½ Brazilian Somali	10	–	–
CW (kg)	7.66–21.90	7.66–21.90	–
FBW (kg)	18.64–44.88	–	–
EBW (kg)	–	14.38–39.36	–
EBWG (kg/day)	–	–	0.056–0.182
CG (kg/day)	–	–	0.043–0.104
RE (MJ/day)	–	–	0.492–3.182

CW, carcass weight; CG, carcass gain; FBW, fasting body weight; EBW, empty body weight; EBWG, empty body weight gain; RE, retained energy.
[a]Compilation of means of treatments reported by independent publications.
[b]Compilation of individual information originating from independent study data sets.

Model validation analyses were carried out using the Model Evaluation System (MES) software, version 3.1.13 (Tedeschi, 2006), and the significance established was 0.05. The predicted and observed values were compared using the following regression model:

$$Y = \beta 0 + \beta 1 \times X \tag{6}$$

where *Y* represents the observed values; *X* represents the predicted values; and $\beta 0$ and $\beta 1$ correspond to the intercept and slope of the regression, respectively. The regression was evaluated according to the following statistical hypotheses (Neter *et al.*, 1996): H_0: $\beta 0 = 0$ and $\beta 1 = 1$; H_a: rejection of H0. If the null hypothesis is not rejected, it is concluded that the tested equation estimates precisely and accurately. The coefficient of determination (R^2) was used as an indicator of precision, with values closer to 1 being better. The correlation and concordance coefficient (CCC) or reproducibility index, was used to evaluate the model in terms of prediction efficiency (Deyo *et al.*, 1991; Nickerson, 1997; Liao, 2003) and varies from −1 to +1, with values closer to +1 being better. The models' prediction errors were evaluated using the estimated mean squared error of prediction (MSEP; the closer to 0 the better), and its components (squared bias, SB; systematic bias, MaF; and random errors, MoF; Bibby and Toutenburg, 1977). The root mean square error of prediction (RMSEP) was used to evaluate model accuracy, and the lower the RMSEP, the better the model accuracy.

Results

Sex class did not influence the intercept ($P = 0.831$) and slope ($P = 0.247$) of the linear regression of CW as a function of FBW. The lack of effect of sex class was also verified on the intercept ($P = 0.807$) and slope ($P = 0.251$) of the linear relationship between EBW and CW, and on the intercept ($P = 0.253$) and slope ($P = 0.250$) of the linear relationship between EBWG and CG. Therefore, general equations were adjusted to predict CW (Eqn (7)), EBW (Eqn (8)), and EBWG (Eqn (9)). For the CW and EBWG models, the variance-covariance structure selected was Antedependence and for the EBW model the variance-covariance structure selected was Autoregressive Heterogeneous.

$$\begin{aligned} CW &= -0.234\ (\pm 1.1358) + 0.485\ (\pm 0.0387) \times FBW \\ R^2 &= 0.983;\ MSE = 0.386;\ AIC = 1106.5 \end{aligned} \tag{7}$$

$$\begin{aligned} EBW &= 1.367\ (\pm 0.5472) + 1.681\ (\pm 0.0210) \times CW \\ R^2 &= 0.992;\ MSE = 0.569;\ AIC = 1075.7 \end{aligned} \tag{8}$$

$$\begin{aligned} EBWG &= 0.004\ (\pm 0.0026) + 1.679\ (\pm 0.0758) \times CG \\ R^2 &= 0.940;\ MSE = 0.0001;\ AIC = -1283 \end{aligned} \tag{9}$$

The validation analysis demonstrated that Eqns (7)–(9) can adequately predict CW, EBW and EBWG (Table 4), respectively, as the intercept was not different from 0 ($P > 0.05$) and the slope was not different from 1 ($P > 0.05$) in none of the three equations (Fig. 1), which presented R^2 of 0.912, 0.958 and 0.820, respectively. For Eqn (7), a CCC of 0.933 and MSEP of 0.859 were obtained; for Eqn (8), a CCC of 0.972 and MSEP of 1.101; and Eqn (9), CCC of 0.889 and MSEP of 0.0002.

There was a significant effect of sex class on the intercept ($P = 0.0013$) of the linear relationship between RE and CG. Therefore, Eqns (10)–(12) were adjusted for intact males, castrated males, and females, respectively. For the RE models, the variance-covariance structure selected was Toeplitz.

$$\text{Intact males:} RE = 1.448\ (\pm 0.0657) \times EBW^{0.75} \times CG^{0.797\ (\pm 0.0399)} \tag{10}$$

$$\text{Castrated males:} RE = 1.522 (\pm 0.0699) \times EBW^{0.75} \times CG^{0.797\ (\pm 0.0399)} \tag{11}$$

$$\begin{aligned} &\text{Females:} RE = 1.827\ (\pm 0.0739) \times EBW^{0.75} \times CG^{0.797\ (\pm 0.0399)} \\ &R^2 = 0.784;\ MSE = 0.005;\ AIC = -411.7 \end{aligned} \tag{12}$$

where RE is the retained energy (MJ/day); $EBW^{0.75}$ is metabolic empty body weight (kg); and CG is the carcass gain (kg/day).

https://doi.org/10.1017/S0021859624000455 Published online by Cambridge University Press

Table 4. Statistical validation of the relationship between predicted and observed values of carcass weight, empty body weight, empty body weight gain, and retained energy

	CW equation		EBW equation		EBWG equation		RE equations	
Items	Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted
Average (kg)	13.75	14.28	24.62	24.11	0.118	0.122	1.596	1.649
Standard deviation (kg)	2.59	2.43	4.52	4.39	0.031	0.027	0.573	0.497
Maximum (kg)	21.90	21.60	39.40	38.20	0.182	0.179	3.182	3.179
Minimum (kg)	7.70	8.80	14.40	14.20	0.056	0.077	0.492	0.828
R^2	–	0.912	–	0.958	–	0.820	–	0.600
CCC	–	0.933	–	0.972	–	0.889	–	0.763
Intercept								
Estimate	–	−0.737	–	0.332	–	−0.008	–	0.125
Standard deviation	–	0.585	–	0.715	–	0.008	–	0.161
P-value (H_0: $\beta_0 = 0$)	–	0.213	–	0.644	–	0.281	–	0.440
Slope								
Estimate	–	1.01	–	1.01	–	1.04	–	0.893
Standard deviation	–	0.040	–	0.029	–	0.062	–	0.093
P-value (H_0: $\beta_1 = 1$)	–	0.717	–	0.803	–	0.550	–	0.254
MSEP	–	0.859	–	1.10	–	0.00018	–	0.135
SB	–	0.277	–	0.259	–	0.00002	–	0.003
MaF	–	0.001	–	0.001	–	0.00000	–	0.003
MoF	–	0.581	–	0.840	–	0.00017	–	0.129
RMSEP	–	0.927	–	1.05	–	0.013	–	0.367

CW, carcass weight; EBW, empty body weight; EBWG, empty body weight gain; RE, retained energy; R^2, determination coefficient; CCC, correlation and concordance coefficient; MSEP, mean squared error of prediction; SB, square bias; MaF, systematic bias; MoF, random errors; RMSEP, root mean squared error of prediction.

The validation analysis of Eqns (10)–(12) showed that RE can be accurately estimated from CG (Table 4), as the intercept ($P = 0.440$) and slope ($P = 0.254$) were not different from 0 and 1, respectively (Fig. 1). In validating the RE prediction equations, an R^2 of 0.600, CCC of 0.763 and MSEP of 0.135 were observed.

Discussion

Several feeding systems use models to predict the performance and nutritional needs of ruminants based on information estimated based on EBW (Cannas *et al.*, 2004; Oliveira *et al.*, 2018; Herbster *et al.*, 2024). The EBW exactly represents the animal mass (Salazar-Cuytun *et al.*, 2022), and corresponds to the most precise measurement to express nutritional requirements (Owens *et al.*, 1995; Costa *et al.*, 2013). The empty BW has been estimated as a function of BW (ARC, 1980), FBW (Herbster *et al.*, 2020; Salazar-Cuytun *et al.*, 2022), and CW (Owens *et al.*, 1995). However, the difficulty of obtaining EBW has been reported (Owens *et al.*, 1995; Chay-Canul *et al.*, 2014; Herbster *et al.*, 2020; Benedeti *et al.*, 2021), due to the laborious procedures of evisceration, emptying of gastric compartments, washing, draining and weighing. Thus, it is necessary to evaluate alternative measures to predict this variable, since EBW cannot be used for much longer.

The CW was used to predict EBW in cattle (Garrett and Hinman, 1969; Fox *et al.*, 1976), due to the advantage of being a variable commonly measured in the slaughter line, in addition to representing the tissues accumulated during growth (Benedeti *et al.*, 2021). Chay-Canul *et al.* (2014) proposed an equation to predict EBW as a function of CW for Pelibuey sheep. However, for hair sheep, equations have not yet been generated from CW data, based on studies with different breeds and sex classes raised in tropical conditions. Much information related to BW, EBW, FBW and CW of hair sheep has been generated in recent years. Our study highlights the advantage of using CW or CG as variables to predict EBW, EBWG, and RE, because CW and/or CG are practical variables, due to the simplicity of quantifying and calculating.

The adjusted equation for predicting CW from FBW was not affected by sex class. Greater carcass yields were reported for females due to early fat deposition compared to males (Osório *et al.*, 1999). However, heavier carcasses are expected for intact males due to the greater potential for muscle growth (Hegarty *et al.*, 2006). The effect of sex on carcass weight and composition is well reported, but Prache *et al.* (2022) explained that this effect depends on age, which justifies obtaining a general equation for predicting CW. The Eqn (7) has been validated, which indicated that it adequately predicts the CW of hair sheep. The high values of R^2 (0.912) and CCC (0.933), and the low MSEP (0.859) verified in the validation indicate good reproducibility and precision of the proposed equation. Furthermore, the MSEP partitioning demonstrated low proportion of SB and MaF, which indicates a lower of prediction error associated with the model. Using Eqn. (7) and considering sheep with FBW of 10, 20, 30 and 40 kg,

https://doi.org/10.1017/S0021859624000455 Published online by Cambridge University Press

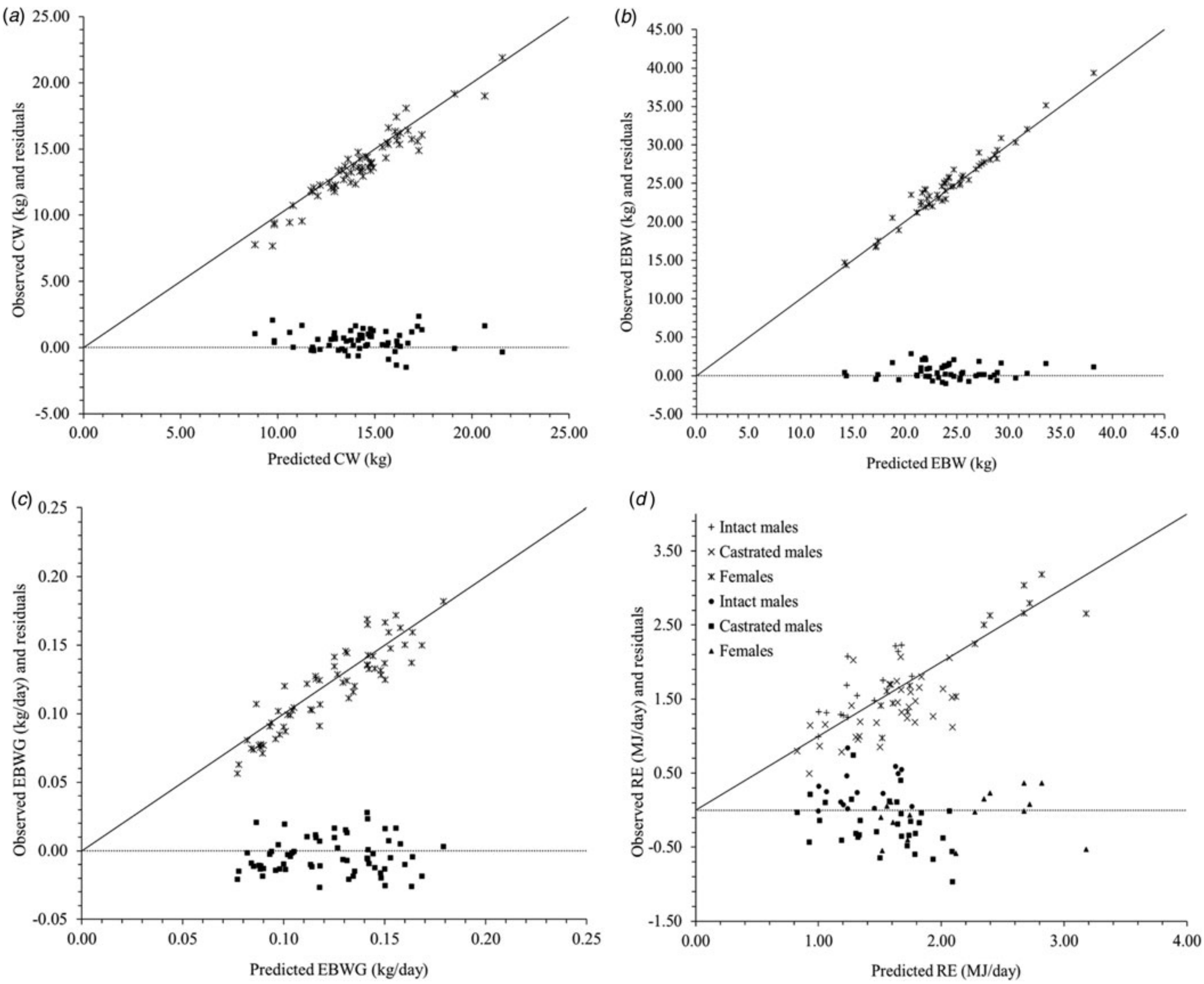

Figure 1. Relationships of observed and residual (observed – predicted) values with predicted values of carcass weight (CW; A), empty body weight (EBW; B), empty body weight gain (EBWG; C), and retained energy (RE; D). The points in the graphs originate from the validation data set, with the points in A and B corresponding to the compilation of treatment averages reported by independent publications; and in C and D, corresponding to individual information originating from independent studies data sets.

the CW is estimated at 4.62, 9.48, 14.34 and 19.20 kg, with a carcass yield equivalent to 46.2; 47.4; 47.8 and 48.0%, respectively. These values are consistent with the yields commonly found for hair sheep (Souza *et al.*, 2013; Queiroz *et al.*, 2015; Nascimento *et al.*, 2018), which range from 44 to 50%.

In our study, sex class did not affect the EBW estimate as a function of CW. This can be explained by the young age of the sheep in this study. In addition, greater differences in body composition generally occur closer to maturity, due to the effects of the hormone's testosterone and oestrogen, which modulate tissue deposition (Herbster *et al.*, 2023). The validation analysis demonstrated that the CW predictor variable adequately estimates EBW (Eqn (8); $R^2 = 0.958$). The CCC was close to 1 (0.972), which indicated good reproducibility, and the MSEP was 1.10, with 76% associated with the MoF, that is, error associated with random fluctuation of the data, which suggests that Eqn (8) has good predictive ability. For example, considering CW of sheep with 5, 10, 15 and 20 kg, we obtain a EBW of 9.77, 18.18, 26.59 and 34.99 kg, respectively.

The EBWG is generally predicted to be a function of ADG (Cannas *et al.*, 2004; Herbster *et al.*, 2024). For hair sheep, Herbster *et al.* (2020) proposed that the EBWG is equivalent to 91% of the ADG. The use of carcass information to predict EBW and EBWG is an interesting alternative since obtaining EBW is a laborious measure in the experimental trials. In addition, CG is composed only of retained tissues and can be calculated from a variable routinely measured in slaughterhouses. The accretion of carcass protein and fat as the sheep grows depends on adult BW which varies with genotype, sex class and birth weight (Prache *et al.*, 2022).

In our study, the intercept of the RE prediction equation as a function of CG was influenced by sex class. The RE is equivalent to the heat of combustion of the protein and fat deposited in the gain (ARC, 1980). The composition of the gain is markedly affected by sex class (Pereira *et al.*, 2018a; Herbster *et al.*, 2024) so females have more fat in the gain and less protein than castrated males, which deposit more fat and less protein in the

https://doi.org/10.1017/S0021859624000455 Published online by Cambridge University Press

gain compared to intact males (Greenhalgh, 1986). The anabolic effect of testosterone in intact males reduces protein catabolism in muscles and intensifies the proliferation of satellite cells (Paulino *et al.*, 2009), which causes them to deposit more protein in the gain compared to castrated males. In this way, castrated males are deprived of the anabolic potential of protein synthesis and advance more quickly for maturity (Herbster *et al.*, 2024). Body fat is the item that varies the most, while fat-free dry mass is quite constant since the main change in body composition that occurs with animal growth and development is the increase in fat content and this mechanism represents the degree of maturity of the animal (NRC, 2007). Females' hair sheep initiate fat deposition more quickly when compared to males (Pereira *et al.*, 2018a), which is associated with preparation for reproductive activity (Wade and Schneider, 1992). Therefore, for the same EBW and CG, energy retention will be greater in females, lower in intact males and intermediate in castrated males. These physiological events clarify the effect of sex on the equations developed to predict RE.

The RE prediction equations (Eqns (10)–(12)) were validated and found to be accurate in prediction ability (CCC = 0.763; MSEP = 0.135). The MSEP decomposition demonstrated that 96% of the errors associated with the estimate are random (Mof), which highlights the precision of the generated equations. Considering a sheep with a EBW of 25 kg and CG of 0.100 kg, intact males, castrated males and females have RE estimated at 2.58, 2.71 and 3.26 MJ/day, respectively.

Conclusion

This study highlights the importance of incorporating carcass information into EBW, EBWG, and RE predictions. Replacing empty body weight gain with carcass gain might be a suitable alternative to estimate the retained energy of hair sheep. In addition, the generated equations will provide support for meat production systems in carcass weight prediction.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0021859624000455.

Acknowledgements. The authors thank the grants provided by Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq, Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – CAPES and Institutos Nacionais de Ciência e Tecnologia INCT- Ciência Animal and Cadeia Produtiva da Carne.

Authors' contributions. Conceptualization, EP; methodology, EP and MM; formal analysis, AB, CH, MM and JC; investigation, AB and CH; data curation, EP, MM, JC, RO, LB and LS; writing – original draft preparation, EP, AB and CH; review and editing, EP, AB, CH, RO, LB and LS; supervision, EP; project administration, EP. All authors have read and agreed to the published version of the manuscript.

Funding statement. This research received no specific grant from any funding agency, commercial or not-for-profit sectors.

Competing interests. None.

Ethical standards. Studies of C.J.L. Herbster (unpublished) and A.S Brito Neto (unpublished) were conducted according to the procedures established by the Comissão de Ética no Uso de Animais (CEUA) of the Federal University of Ceara (protocol 3381260719). The study of A.C. Rocha (unpublished) was conducted according to the procedures established by the Comitê de Ética no Uso de Animais de Produção (CEUAP) of the Federal University of Ceara (protocol 1502202201). For other studies, the approval of the ethics committee on animal use was not necessary for this study because the data were collected from previously published sources.

References

Agricultural Research Council (ARC) (1980) *The Nutrient Requirements of Ruminant Livestock*. Slough, UK: Commonwealth Agricultural Bureaux.

Alvarenga FAP (2013) Terminação de cordeiros sob pastejo com teores crescentes de proteína (MS thesis). Federal University of Lavras, Lavras, Minas Gerais, Brazil.

Araújo TL, Pereira ES, Mizubuti IY, Campos AC, Pereira MW, Heinzen EL, Magalhães HCR, Bezerra LR, Silva LP and Oliveira RL (2017) Effects of quantitative feed restriction and sex on carcass traits, meat quality and meat lipid profile of Morada Nova lambs. *Journal of Animal Science and Biotechnology* **8**, 1–12.

Araújo Filho JTD, Costa RG, Fraga AB, Sousa WHD, Cezar MF and Batista ASM (2010) Desempenho e composição da carcaça de cordeiros deslanados terminados em confinamento com diferentes dietas. *Revista Brasileira de Zootecnia* **39**, 363–371.

Association of Official Analytical Chemistry (AOAC) (1990) *Official Methods of Analysis*, 15th Edn. Washington, DC: AOAC.

Bastos MPV, Carvalho GGP, Pires AJV, Silva RR, Carvalho BMA, Brandão RKC and Maranhão CMA (2015) Impact of total substitution of corn for soybean hulls in diets for lambs. *Revista Brasileira de Zootecnia* **44**, 83–91.

Benedeti PDB, Valadares Filho SC, Chizzotti ML, Marcondes MI and Silva FAS (2021) Development of equations to predict carcass weight, empty body gain, and retained energy of Zebu beef cattle. *Animal: An International Journal of Animal Bioscience* **15**, 100028.

Bibby J and Toutenburg H (1977) *Prediction and Improved Estimation in Linear Models*, 1st Edn. Berlin: John Wiley & Sons.

BR-CORTE (2023) *Exigências Nutricionais de Zebuínos Puros e Cruzados*, 4th Edn. Visconde do Rio Branco, MG: Suprema Gráfica Ltda.

Brito Neto AS (2020) Avaliação bioeconômica do confinamento de borregos Santa Inês abatidos em diferentes pesos (MS thesis). Federal University of Ceará, Fortaleza, Ceará, Brazil.

Cannas A, Tedeschi LO, Fox DG, Pell AN and Van Soest PJ (2004) A mechanistic model for predicting the nutrient requirements and feed biological values for sheep. *Journal of Animal Science* **82**, 149–169.

Chay-Canul AJ, Espinoza-Hernandez JC, Ayala-Burgos AJ, Magaña-Monforte JG, Aguilar-Perez CF, Chizzotti ML, Tedeschi LO and Ku-Vera JC (2014) Relationship of empty body weight with shrunken body weight and carcass weights in adult Pelibuey ewes at different physiological states. *Small Ruminant Research* **117**, 10–14.

Cook RD and Weisberg S (1982) *Residuals and Influence in Regression*. New York, USA: Chapman and Hall.

Costa RG, Lima CAC, Medeiros AN, Lima GDC, Marques CAT and Santos ND (2011) Características de carcaça de cordeiros Morada Nova alimentados com diferentes níveis do fruto-refugo de melão em substituição ao milho moído na dieta. *Revista Brasileira de Zootecnia* **40**, 866–871.

Costa MRGF, Pereira ES, Silva AMA, Paulino PVR, Mizubuti IY, Pimentel PG, Pinto AP and Rocha Junior JN (2013) Body composition and net energy and protein requirements of Morada Nova lambs. *Small Ruminant Research* **114**, 206–213.

Cunha MGG, Carvalho FFR, Gonzaga Neto S and Cezar MF (2008) Características quantitativas de carcaça de ovinos Santa Inês confinados alimentados com rações contendo diferentes níveis de caroço de algodão integral. *Revista Brasileira de Zootecnia* **37**, 1112–1120.

Dantas AF, Pereira Filho JM, Silva AMA, Santos EM, Sousa BB and Cézar MF (2008) Características da carcaça de ovinos Santa Inês terminados em pastejo e submetidos a diferentes níveis de suplementação. *Ciência e Agrotecnologia* **32**, 1280–1286.

Deyo RA, Diehr P and Patrick DL (1991) Reproducibility and responsiveness of health status measures: statistics and strategies for evaluation. *Controlled Clinical Trials* **12**, 142S–1158.

Fernandes Júnior F, Ribeiro ELA, Mizubuti IY, Silva LDF, Barbosa MAAF, Prado OPP, Pereira ES, Pimentel PG and Constantino C (2013) Características de carcaça e qualidade da carne de cordeiros Santa Inês alimentados com torta de girassol em substituição ao farelo de algodão. *Semina: Ciências Agrárias* **34**, 3999–4014.

Fox DG, Dockerty TR, Johnson RR and Preston RL (1976) Relationship of empty body weight to carcass weight in beef cattle. *Journal of Animal Science* **43**, 566–568.

Garrett WN and Hinman N (1969) Re-evaluation of the relationship between carcass density and body composition of beef steers. *Journal of Animal Science* **28**, 1–5.

Gois GC, Santos EM, Sousa WH, Ramos JPF, Azevedo PS, Oliveira JS, Pereira GA and Perazzo AF (2017) Qualidade da carne de ovinos terminados em confinamento com dietas com silagens de diferentes cultivares de sorgo. *Arquivo Brasileiro de Medicina Veterinária e Zootecnia* **69**, 1653–1659.

Greenhalgh JFD (1986) Recent studies on the body composition of ruminants. *Proceedings of the Nutrition Society* **45**, 119–130.

Hegarty RS, Warner RD and Pethick DW (2006) Genetic and nutritional regulation of lamb growth and muscle characteristics. *Australian Journal of Agricultural Research* **57**, 721–730.

Herbster CJL, Silva LP, Marcondes MI, Garcia IFF, Oliveira RL, Cabral LS, Souza JG and Pereira ES (2020) Weight adjustment equation for hair sheep raised in warm conditions. *Animal: An International Journal of Animal Bioscience* **14**, 1718–1723.

Herbster CJL, Abreu MLC, Brito Neto AS, Mendes MS, Silva LP, Marcondes MI, Mazza PHS, Cabral LS, Bezerra LR, Oliveira RL and Pereira ES (2023) Macromineral requirements for maintenance and growth in male and female hair sheep. *Frontiers in Veterinary Science* **10**, 1032429.

Herbster CJL, Oliveira AP, Brito Neto AS, Justino ES, Teixeira IAMA, Azevedo JAG, Santos SA, Silva LP, Marcondes MI, Oliveira RL, Bezerra LR and Pereira ES (2024) Understanding the effect of sex on energy requirements of hair sheep. *Animal: An International Journal of Animal Bioscience* **18**, 101071.

Liao JJZ (2003) An improved concordance correlation coefficient. *Pharmaceutical Statistics* **2**, 253–261.

Lima Júnior DM, Carvalho FFR, Batista ÂMV, Ferreira BF and Ribeiro MN (2015) Componentes do peso corporal de ovinos morada nova alimentados com feno de maniçoba ou feno de Tifton. *Revista Caatinga* **28**, 239–246.

McManus CM, Faria DA, Lucci CM, Louvandini H, Pereira SA and Paiva SR (2020) Heat stress effects on sheep: are hair sheep more heat resistant? *Theriogenology* **155**, 157–167.

Medeiros GR, Carvalho FFR, Batista ÂMV, Dutra Júnior WM, Santos GRA and Andrade DKB (2009) Efeito dos níveis de concentrado sobre as características de carcaça de ovinos Morada Nova em confinamento. *Revista Brasileira de Zootecnia* **38**, 718–727.

Mendes MS, Souza JG, Herbster CJL, Brito Neto AS, Silva LP, Rodrigues JPP, Marcondes MI, Oliveira RL, Bezerra LR and Pereira ES (2021) Maintenance and growth requirements in male Dorper × Santa Ines lambs. *Frontiers in Veterinary Science* **8**, 574.

Menezes LFO, Louvandini H, Martha Júnior GB, McManus C, Garcia JAS and Murata LS (2008) Características de carcaça, componentes não-carcaça e composição tecidual e química da 12ª costela de cordeiros Santa Inês terminados em pasto com três gramíneas no período seco. *Revista Brasileira de Zootecnia* **37**, 1286–1292.

Meyer JH, Lofgreen GP and Gareett WN (1960) A proposed method for removing sources of error in beef cattle feeding experiments. *Journal of Animal Science* **19**, 1123–1131.

Nascimento UFS, Santos GRA, Azevedo CS, Macedo FAF, Gonçalves TR, Bomfim LELM, Farias JS and Santos ADF (2018) Performance and carcass characteristics of lambs ½ Dorper +½ Santa Inês, slaughtered with different thicknesses of subcutaneous fat. *Revista Brasileira de Saúde e Produção Animal* **19**, 125–135.

Nascimento Junior NG (2010) Desempenho, características de carcaça e exigências nutricionais de proteína e energia para ganho de cordeiros Santa Inês e ½ Dorper x ½ Santa Inês em pastejo na região semiárida (PhD thesis). Federal University of Campina Grande, Paraíba, Brazil (2010).

National Research Council (NRC) (1984) *Nutrient Requirements of Beef Cattle*, 6th Edn. Washington, DC, USA: National Academies Press.

National Research Council (NRC) (2007) *Nutrient Requirements of Small Ruminants: Sheep, Goats, Cervids and New World Camelids*. Washington, DC, USA: National Academies Press.

Neter J, Kutner MH, Nachtsheim CJ and Wasserman W (1996) *Applied Linear Statistical Models*, 4th Edn. Boston: McGraw-Hill Publishing Company.

Nickerson CA (1997) A note on "A concordance correlation coefficient to evaluate reproducibility". *Biometrics* **53**, 1503–1507.

Oliveira AP, Pereira ES, Pinto AP, Silva ADA, Carneiro MDS, Mizubuti IY, Ribeiro ELA, Campos ACN and Gadelha CRF (2014) Estimates of nutritional requirements and use of Small Ruminant Nutrition System model for hair sheep in semiarid conditions. *Semina: Ciências Agrárias* **35**, 1985–1997.

Oliveira JPF, Ferreira MA, Freitas APD, Urbano SA and Silva ÁEM (2017) Características de carcaça de ovinos Santa Inês alimentados com mazoferm substituindo o farelo de soja. *Revista Ciência Agronômica* **48**, 708–715.

Oliveira AP, Pereira ES, Biffani S, Medeiros AN, Silva AMA, Oliveira RL and Marcondes MI (2018) Meta-analysis of the energy and protein requirements of hair sheep raised in the tropical region of Brazil. *Journal of Animal Physiology and Animal Nutrition* **102**, e52–e60.

Osório MTM, Sierra I, Sañudo C and Osório JC (1999) The influence of breed, sex and weight/age on carcass yield in lambs. *Ciência Rural* **29**, 139–142.

Owens FN, Gill DR, Secrist DS and Coleman SW (1995) Review of some aspects of growth and development of feedlot cattle. *Journal of Animal Science* **73**, 3152–3172.

Paulino PVR, Valadares Filho SDC, Detmann E, Valadares RFD, Fonseca MA and Marcondes MI (2009) Deposição de tecidos e componentes químicos corporais em bovinos Nelore de diferentes classes sexuais. *Revista Brasileira de Zootecnia* **38**, 2516–2524.

Pell RJ (2000) Multiple outlier detection for multivariate calibration using robust statistical techniques. *Chemometrics and Intelligent Laboratory Systems* **52**, 87–104.

Pereira GM (2011) Exigências de proteína e energia de carneiros Santa Inês na região semiárida brasileira (MS thesis). Federal University of Campina Grande, Patos, Paraíba, Brazil.

Pereira ES, Fontenele RM, Silva AMA, Oliveira RL, Ferreira MRG, Mizubuti IY, Carneiro MSS and Campos ACN (2014) Body composition and net energy requirements of Brazilian Somali lambs. *Italian Journal of Animal Science* **13**, 3583.

Pereira ES, Lima FWR, Marcondes MI, Rodrigues JPP, Campos ACN, Silva LP, Bezerra LR, Pereira MWF and Oliveira RL (2017) Energy and protein requirements of Santa Ines lambs, a breed of hair sheep. *Animal: An International Journal of Animal Bioscience* **11**, 2165–2174.

Pereira ES, Pimentel PG, Fontenele RM, Medeiros AN, Regadas Filho JGL and Villarroel ABS (2010) Características e rendimentos de carcaça e de cortes em ovinos Santa Inês, alimentados com diferentes concentrações de energia metabolizável. *Acta Scientiarum. Animal Sciences* **32**, 431–437.

Pereira ES, Pereira MWF, Marcondes MI, Medeiros AN, Oliveira RL, Silva LP, Mizubuti IY, Campos ACN, Heinzen EL, Veras ASC, Bezerra LR and Araújo TLAC (2018a) Maintenance and growth requirements in male and female hair lambs. *Small Ruminant Research* **159**, 75–83.

Pereira GA, Oliveira JS, Santos EM, Carvalho GGP, Araújo GGL, Sousa WH, Homem Neto SP and Cartaxo FQ (2018b) Substitution of soybean meal for urea in diets based on deferred buffelgrass hay for feedlot sheep. *Revista Brasileira de Zootecnia* **47**, e20170035.

Prache S, Schreurs N and Guillier L (2022) Factors affecting sheep carcass and meat quality attributes. *Animal: An International Journal of Animal Bioscience* **16**, 100330.

Queiroz LO, Santos GRA, Macêdo FAF, Mora NHAP, Torres MG, Santana TEZ and Macêdo FG (2015) Características quantitativas da carcaça de cordeiros Santa Inês, abatidos com diferentes espessuras de gordura subcutânea. *Revista Brasileira de Saúde e Produção Animal* **16**, 712–722.

Regadas Filho JGL, Pereira ES, Pimentel PG, Villarroel ABS, Medeiros AN and Fontenele RM (2013) Body composition and net energy requirements for Santa Ines lambs. *Small Ruminant Research* **109**, 107–112.

Rocha AC (2022) Farelo de mamona industrialmente destoxificado como fonte proteica na dieta de ovinos (MS thesis). Federal University of Ceará, Fortaleza, Ceará, Brazil.

Rodrigues RTS, Chizzotti ML, Martins SR, Silva IF, Queiroz MAÁ, Silva TS, Busato KC and Silva AMA (2016) Energy and protein requirements of non-descript breed hair lambs of different sex classes in the semiarid region of Brazil. *Tropical Animal Health and Production* **48**, 87–94.

Salazar-Cuytun EDR, Pool-Yanez GE, Portillo-Salgado R, Antonio-Molina G, Garcia-Herrera RA, Camacho-Perez E, Zaragoza-Vera CV, Vargas-Bello-Pérez E and Chay-Canul AJ (2022) Evaluation of models to estimate empty body weight in hair sheep raised in a feedlot system. *Tropical and Subtropical Agroecosystems* **25**, 1–7.

Silva AMA, Santos EMD, Pereira Filho JM, Bakke OA, Gonzaga Neto S and Costa RGD (2010) Body composition and nutritional requirements of protein and energy for body weight gain of lambs browsing in a tropical semiarid region. *Revista Brasileira de Zootecnia* **39**, 210–216.

Silva RVMM, Carvalho GGP, Pires AJV, Pereira MLA, Pereira L, Campos FS, Perazzo AF, Araújo MLGML, Nascimento CO, Santos AS, Tosto MSL, Rufino LMA and Carvalho BMA (2016) Cottonseed cake in substitution of soybean meal in diets for finishing lambs. *Small Ruminant Research* **137**, 183–188.

Silva KB, Oliveira JS, Santos EM, Ramos JPF, Cartaxo FQ, Givisiez PEN, Souza AFN, Cruz GFL, Cézar Neto JM, Alves JP, Ferreira DJ, Lima AGVO and Zanine AM (2021) Cactus pear as roughage source feeding confined lambs: performance, carcass characteristics, and economic analysis. *Agronomy* **11**, 625.

Souza DA, Selaive-Villarroel AB, Pereira ES, Osório JCS and Teixeira A (2013) Growth performance, feed efficiency and carcass characteristics of lambs produced from Dorper sheep crossed with Santa Inês or Brazilian Somali sheep. *Small Ruminant Research* **114**, 51–55.

St-Pierre NR (2001) Invited review: integrating quantitative findings from multiple studies using mixed model methodology. *Journal of Dairy Science* **84**, 741–755.

Tedeschi LO (2006) Assessment of the adequacy of mathematical models. *Agricultural Systems* **89**, 225–247.

Tedeschi LO (2023) Harnessing extant energy and protein requirements modelling for sustainable beef production. *Animal: An International Journal of Animal Bioscience* **17**, 100835.

Urbano SA, Ferreira MA, Véras RML, Azevedo PS, Santos Filho HB, Vasconcelos GA and Oliveira JPF (2015) Características de carcaça e composição tecidual de ovinos Santa Inês alimentados com manipueira. *Revista Brasileira de Ciências Agrárias* **10**, 466–472.

Vieira MMM, Cândido MJD, Bomfim MAD, Severino LS, Zapata JFF, Beserra LT, Meneses AJG and Fernandes JPB (2010) Características da carcaça e dos componentes não-carcaça em ovinos alimentados com rações à base de farelo de mamona. *Revista Brasileira de Saúde e Produção Animal* **11**, 140–149.

Wade GN and Schneider JE (1992) Metabolic fuels and reproduction in female mammals. *Neuroscience & Biobehavioral Reviews* **16**, 235–272.

Xenofonte ARB, Carvalho FFR, Batista ÂMV and Medeiros GR (2009) Características de carcaça de ovinos em crescimento alimentados com rações contendo farelo de babaçu. *Revista Brasileira de Zootecnia* **38**, 392–398.