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

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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) $\times$ FBW; EBW (kg) $= 1.367$ (±0.5472) $+ 1.681$ (±0.0210) $\times$ CW and EBWG (kg) $= 0.004$ (±0.0026) $+ 1.679$ (±0.0758) $\times$ 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) $\times$ EBW$^{0.75}$ $\times$ CG$^{0.797\ (\pm0.0399)}$; RE (MJ/day) $= 1.522$ (±0.0699) $\times$ EBW$^{0.75}$ $\times$ CG$^{0.797\ (\pm0.0399)}$ and RE (MJ/day) $= 1.827$ (±0.0739) $\times$ EBW$^{0.75}$ $\times$ CG$^{0.797\ (\pm0.0399)}$ 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:

$$CW = \beta0 + \beta1 \times FBW \quad (2)$$

$$EBW = \beta0 + \beta1 \times CW \quad (3)$$

$$EBWG = \beta0 + \beta1 \times CG \quad (4)$$

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 $\beta0$ and $\beta1$ 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):

$$RE = \beta0 \times EBW^{0.75} \times CG^{\beta1} \quad (5)$$

where RE is the retained energy (MJ/day); $EBW^{0.75}$ is metabolic empty body weight (kg); CG is carcass gain (kg/day); $\beta0$ is the

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.

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	CW[a]	EBW[a]	EBWG and RE[b]
		Validation data sets	
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.

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

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

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

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.

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

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

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

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).

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

Items	CW equation		EBW equation		EBWG equation		RE equations	
	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,
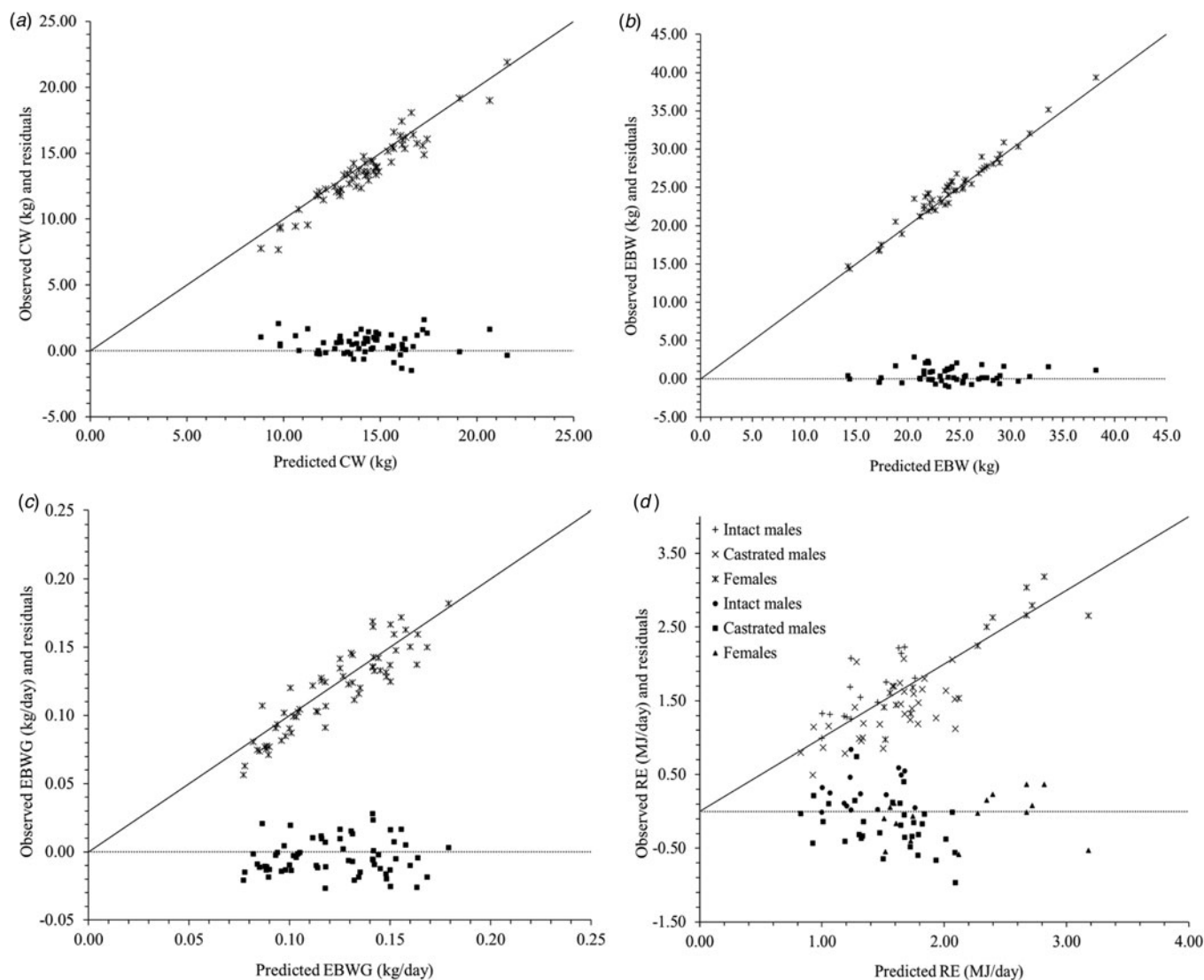
Figure 1. Relationships of observed and residual (observed – predicted) values with predicted values of carcass weight (CW; A), empty body weight (EBW; B), empty body weight gain (EBWG; C), and retained energy (RE; D). The points in the graphs originate from the validation data set, with the points in 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

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.

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