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Nonlinear Models of Brazilian Sheep in Adjustment of Growth Curves

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ABSTRACT

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Growth curves of the Morada Nova sheep males and females were described using nonlinear models and the relationships between body weight and thoracic circumference were evaluated. Altogether 1516 repeated measures of body weight and thoracic circumference of the Morada Nova sheep (668 males and 848 females) taken since birth till 730 days of age were used. The Brody, Richards, von Bertalanffy, Gompertz, and Logistic models have been tested. The Fisher's test (F) was used to verify the differences ($P < 0.05$) in growth curves between males and females. The Gompertz model presented a significant difference ($P < 0.001$) for growth curve parameters between males (asymptotic weight (A) = 40.5 kg and maturing rate (k) = 0.0043 kg/day) and females (A = 36.44 kg and k = 0.0028 kg/day). The relationships between body weight and thoracic circumference presented R^2 above 0.7 and a high significance ($P < 0.0001$) for all categories, showing that the thoracic circumference may be a good indicator of body weight. In addition, a significant effect ($P < 0.05$) of the relationship between thoracic circumference and prediction of animal's body weight was verified using the models of linear, quadratic, and cubic regression. Among the models studied, the Gompertz model presented the best fit and biological interpretation. Furthermore, the Gompertz model indicated the need to separate animals by sex in order to properly meet nutritional requirements and determine adequate slaughter age. Thoracic circumference can be used to predict animal body weight with a high accuracy.

Keywords: body weight; Gompertz; growth rate; mature weight; thoracic circumference

In animal production systems, there is a constant search for the supply of animal protein that meets the requirements of the consumer market. In animal breeding programmes evaluating the growth curves, effect of sex, and animal category can lead to improvements in productive efficiency. Moreover, these assessments make it possible to define the optimal age at slaughter and consequently obtain a better quality of carcass and meat. The Morada Nova breed is an important genetic resource for sheep meat production in Brazil. This is a native breed of woolless sheep found principally in hot

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tropical semi-arid northeast Brazil and characterised by high fertility, small stature, good skin quality, hardiness, good maternal ability, and no reproductive seasonality.

Growth curves representing relationships between animal size and growth time can be adjusted by functions or nonlinear models, the most used being the models of Richards, Gompertz, Brody, Von Bertalanffy, and the Logistic model (Chalh and El Gazzah 2014; Lupi et al. 2015). With these models, it is possible to work with a set of information (data) such as weight at various ages. These in turn are quantified using biologically interpretable parameters, such as asymptotic weight (A) and maturing rate (k), which are usually required in animal breeding programs (Saghi et al. 2012; Crispim et al. 2015). Through the nonlinear functions, it is possible to consider the most appropriate models (Lupi et al. 2015) to select animals with higher growth rates, but not necessarily higher body weight.

In addition, growth curves can be used in animal production to (a) synthesise the parameters of nonlinear models, (b) evaluate responses of treatments over time, (c) analyse response interactions of subpopulations or treatments over time, and (d) identify the heaviest animals in a population at younger ages. Such information can be obtained by analysing parameters A (asymptotic weight) and k (maturing rate) of growth curves (Crispim et al. 2015). Also sex can influence the parameters of the growth curve and the body weight of the animals. On average, male lambs are heavier and gain more weight from birth to weaning than females. Carrijo et al. (1999) found that sex significantly influences all growth parameters. This significant influence may be due to sexual dimorphism (Lupi et al. 2015).

Animal body measures can be evaluated based also on the thoracic circumference. Although there have been discrepancies about which body measures should be used to predict weight, the accuracy of prediction based on thoracic circumference has been shown to be high (Khalil and Vaccaro 2002). Silva et al. (2006) reported that the thoracic circumference was efficient in estimating the body weight of Santa Ines sheep, being more efficient in females. Thus, the study of the relationship between the thoracic circumference and body weight in sheep can aid prediction of body parameters in the Morada Nova breed.

Nonlinear models for adjusting growth curves and the ratio between the thoracic circumference and body weight have widely been used (Hossein-Zadeh 2015), but not in the Morada Nova breed. However, Hifzan et al. (2015) emphasised that there is no consensus about the most appropriate model to describe body growth in animals. The objectives of this study were to describe the growth curve of the Morada Nova sheep using nonlinear models, to analyse the growth difference between males and females and, in addition, to evaluate the relationship between the body weight and the thoracic circumference.

MATERIAL AND METHODS

Animals and data. Totally 1516 repeated measures of body weight and thoracic circumference of the Morada Nova sheep (668 males and 848 females), recorded since birth till 730 days of age, were used. The animals were housed in the Instituto de Zootecnia (IZ), Nova Odessa, Brazil. Data were collected within one year (October 2012–2013), with measurements taken every 15 days for animals up to 1 year of age and every 30 days for 1–2-year-old animals. The feeding system for all age categories was semi-intensive, with rotational grazing on Aruana grass (*Panicum maximum* cv. Aruana IZ-5) supplemented with corn silage and concentrate (0.2 kg per animal) containing 16% crude protein. Water and mineral salt were offered *ad libitum*. Females of approximately 12–14 months, weighing 28–30 kg, were referred to reproduction, and males were selected for breeding or slaughter.

Nonlinear models and selection criteria. The animals were divided into 26 age categories (Table 1) for growth curve studies using the nonlinear models of Brody, von Bertalanffy, Richards, Gompertz, and the Logistic model (Table 2). Parameters of the models were estimated by the modified Gauss–Newton method (Hartley 1961), using the procedure NLIN of SAS software (Statistical Analysis System, Version 9.1). With this procedure, a maximum of 1000 iterations for convergence criteria was established. Convergence occurred when $(SQR_{j-1} - SQR_j)/(SQR_j + 10^{-6})$ was smaller than 10^{-8}, which is the residual sum of squares in the j^{th} iteration (SQR_j).

To select the model best fitting the growth curve, the following criteria were used: mean squared error (MSE), coefficient of determination (R^2), mean absolute error (MAE) used by Marinho et

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al. (2013), and residual standard deviation (RSD) used by Chrobok et al. (2004). The RSD value indicates if the function underestimates (–) or overestimates (+) the body weight observed. In the case the value approaches zero, the model tested can be considered the best.

Application of the best model on sex effect. After selecting the models best fitting the growth curve, the influence of sex was verified using SAS software (Statistical Analysis System, Version 9.1). Two nonlinear models were considered.

The first model, complete, was as follows:

$$Y_1 = A_1 e^{-b_1 e^{(-k_1 t)}}$$

where:

Y_1 = trait observed

A_1 = asymptotic value of the trait

e = exponential function

b_1 = constant of integration without biological interpretation

k_1 = rate of maturity and indicated tissue growth rate

t = age (in days)

This model considered different sets (alternative hypothesis – Ha) of parameter estimates (A, k) in the function of sex to define the adjusted response by the best model.

The second was a reduced model that considered there were no differences (null hypothesis – H_0) between sexes:

$$Y = A e^{-b e^{(-kt)}}$$

Thus, the growth curve of the animals can be defined by a single set of parameter estimates (A, k, and M). Fisher's exact test (*F*) was used to

Table 1. Descriptive statistics for body weights in all categories in the Morada Nova sheep breed (1516 animals in total – 668 males and 848 females)

Category	Age (days)	*n*	M (kg)	SD (±)	Min	Max
1	0 (birth)	15	2.53	0.66	1.10	4.20
2	1–30	11	4.80	2.24	2.50	9.30
3	31–45	26	7.39	2.48	2.90	11.70
4	46–60	25	9.42	2.89	5.60	14.10
5	61–75	20	9.56	2.99	2.90	17.30
6	76–90	50	10.17	2.83	4.90	16.30
7	91–105	75	11.29	3.25	5.70	20.50
8	106–120	62	11.96	3.65	5.40	22.00
9	121–150	128	12.88	4.10	5.20	23.90
10	151–180	100	13.60	4.35	4.60	24.20
11	181–210	101	16.21	5.13	4.70	31.50
12	211–240	109	17.88	5.75	5.30	30.70
13	241–270	91	17.54	7.16	5.00	35.00
14	271–300	108	19.70	8.20	6.00	39.30
15	301–330	90	20.07	8.96	5.40	39.90
16	331–360	78	21.90	9.25	6.40	42.30
17	361–390	82	22.79	9.32	6.10	42.00
18	391–420	115	26.70	8.90	6.30	48.90
19	421–450	59	27.92	9.69	10.00	51.00
20	451–480	34	24.31	7.12	12.40	42.00
21	481–510	28	25.15	5.83	16.50	40.00
22	511–540	27	27.89	6.61	16.00	40.70
23	541–570	33	28.00	5.54	17.20	42.80
24	571–600	19	29.28	5.98	22.00	43.40
25	601–630	13	30.77	7.19	16.00	45.60
26	631–730	17	34.05	8.86	19.00	51.70

n = number of animals for categories, M = means of body weight for categories, SD = standard deviation, Min = minimum values, Max = maximum values

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Table 2. Parameters analysed for models applied in the Morada Nova sheep breed

Model	Equation
Brody	$y_t = A(1 + be^{-kt})$
von Bertalanffy	$y_t = A(1 + be^{-kt})^3$
Richards	$y_t = A(1 - be^{-kt})^m$
Logistic	$y_t = A(1 + be^{-kt})^{-m}$
Gompertz	$y_t = Ae^{-be\exp(-kt)}$

y_t = trait observed at age t (in days), A = asymptotic value of the trait by age t, b = constant of integration without biological interpretation as was established by the values of the trait at age zero tended to infinity, k = rate of maturity and indicated tissue growth rate until adult age, m = shape of the growth curve and, consequently, point of inflection at which the phase of deceleration started until the adult measure was reached

test the hypotheses referring to each model. To calculate the probability of the observed value of the *F* test, the PROBF function of SAS software (Version 9.1) was used. This function reflects the probability of *F* distribution, with numerator degrees of freedom equal to the difference between the degrees of freedom residues (reduced and complete models) and denominator degrees of freedom equal to the degrees of freedom residue (complete model). Furthermore, it allows calculating the significance of the growth difference between males and females.

Relationship between body weight in function of thoracic perimeter. To describe the relationship ($P < 0.05$) between thoracic circumference (TC) and body weight (BW) with linear, quadratic, and cubic regression models, the PROC GLMSELECT of SAS (Version 9.1) was applied. To verify if this association was significant ($P < 0.05$), the animals were divided into three distinct groups based on age (CAT1: lambs 0–138 days old, CAT2: wethers 91–184 days old, CAT3: adults 223–408 days old).

RESULTS AND DISCUSSION

Selection of the best model. Among the nonlinear models used, only the Richards model did not reach convergence (Table 3). Crispim et al. (2015) also observed this result when studying the five nonlinear models to describe growth curves in Brahman cattle. However, Hossein-Zadeh (2015) found that the Richards equation provided the best fit for the growth curve in Guilan sheep. However, considering the results found in the present study, the Richards model should not be chosen to demonstrate the growth curve in the Morada Nova sheep, due to curve adjustment and difficulties in reaching convergence, as pointed out also by Silva et al. (2012).

Estimates of RSD obtained by the functions of Brody and von Bertalanffy (–15.897 ± 1.33 kg) were lower compared with the model of Gompertz

Table 3. Parameter estimate of the growth curve according to the models studied in the Morada Nova breed

Parameter	Model			
	von Bertalanffy	Brody	Gompertz	Logistic
A	51.21 ± 7.83	51.21 ± 7.83	37.24 ± 2.36	33.46 ± 1.42
b	0.90 ± 0.01	0.90 ± 0.01	1.77 ± 0.05	–
k	0.0004 ± 0.0001	0.001 ± 0.0003	0.003 ± 0.0003	0.005 ± 0.0004
M	–	–	–	3.71 ± 0.20
MSE	45.30	45.30	45.42	46.56
R^2	0.893	0.893	0.893	0.893
RSD	–15.897 ± 1.33	–15.897 ± 1.33	–16.618 ± 1.38	–17.128 ± 1.42
MAE	5.02	5.02	5.04	5.06
NI	8	8	6	7

A = asymptotic value of the trait by age t, b = constant of integration without biological interpretation as was established by the values of the trait at age zero tended to infinity, k = rate of maturity and indicated tissue growth rate until adult age, M = shape of the growth curve and, consequently, point of inflection at which the phase of deceleration started until the adult measure was reached, MSE= mean squared error, R^2 = determination coefficient, RSD = residual standard deviation, MAE = mean absolute error, NI = number of iterations

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(–16.618 ± 1.38 kg) and the Logistic model (–17.128 ± 1.42 kg). However, the asymptotic weight parameters were overestimated for the Brody (A = 51.21 ± 7.83) and the von Bertalanffy models (A = 51.21 ± 7.83) due to the observed mean weight (Category 26) equal to 34.05 kg (Table 1 and Figure 1); the same trend for the Brody model was observed by Hifzan et al. (2015). Forni et al. (2009) observed the goodness of fit using the Gompertz model. Also Lupi et al. (2015) reported higher values for the Logistic and Gompertz models (A = 36.8 and 46.14, respectively) if compared to the present study (Table 3). In this case, the Gompertz and Logistic models presented asymptotic weight (A) equal to 37.24 ± 2.36 kg and 33.46 ± 1.42 kg, respectively (Table 3), similar to the observed mean weight (Figure 1). In addition, Gompertz and Logistic functions (Table 3) showed smaller numbers of iterations (NI) to achieve convergence (NI = 6 and 7, respectively). Although it is not the most important criterion for the models assessment and selection, this observation is noteworthy due to saving time and computational memory.

The mean absolute error (MAE) presented similar values among models and the mean squared error (MSE) had lower values for the Gompertz (45.42), Brody (45.30), and von Bertalanffy (45.30) models (Table 3). However, better maturity rates showed the Brody (k = 0.001 ± 0.0003) and Gompertz models (k = 0.003 ± 0.0003). According to Marinho et al. (2013), animals with high k values present higher maturing rate than those with low k, even if these animals present similar body weight. It can be observed that in the animals assessed birth weight did not show large variations, but k parameters assumed greater variations. This result shows that there is a difference between the animals regarding relative maturing rates.

All models overestimated weight in the first categories (Figure 1), which can be explained by few data (n < 26) available on the population in the study (Table 1). However, comparing growth curves, the model that best approached the observed weight, including extremes (Categories 1 and 26), was that of Gompertz (Figure 1); this model was chosen also previously as the most adequate to estimate growth curves in goats (Hifzan et al. 2015) and sheep (Lupi et al. 2015). Lupi et al. (2015) reported that in the studies of growth curves, besides the models evaluation through statistical analysis, it is interesting to evaluate the results via biological interpretations. Therefore, the Gompertz model was chosen to adjust the growth curve of the Morada Nova breed based on the asymptotic weight values (A), good maturity rate, and principally high R^2 value, not denoting overestimation.

Sex effect. To evaluate differences of the growth curves adjusted between males and females, we considered the Gompertz and Logistic functions.

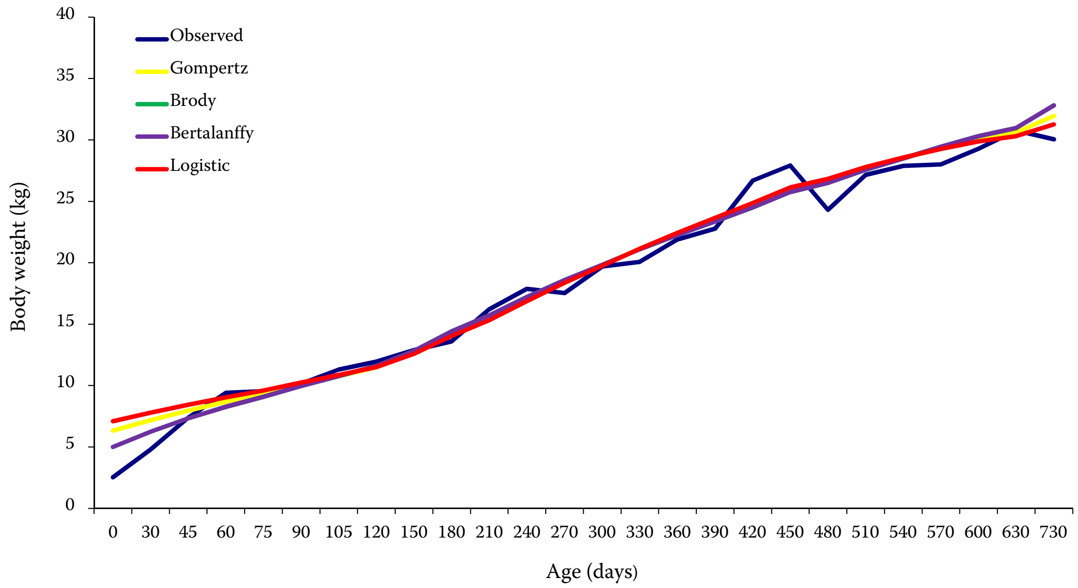

Figure 1. Body weight in the Morada Nova sheep breed estimated based on age obtained by the Gompertz, Brody, von Bertalanffy, and Logistic models, along with body weight observed

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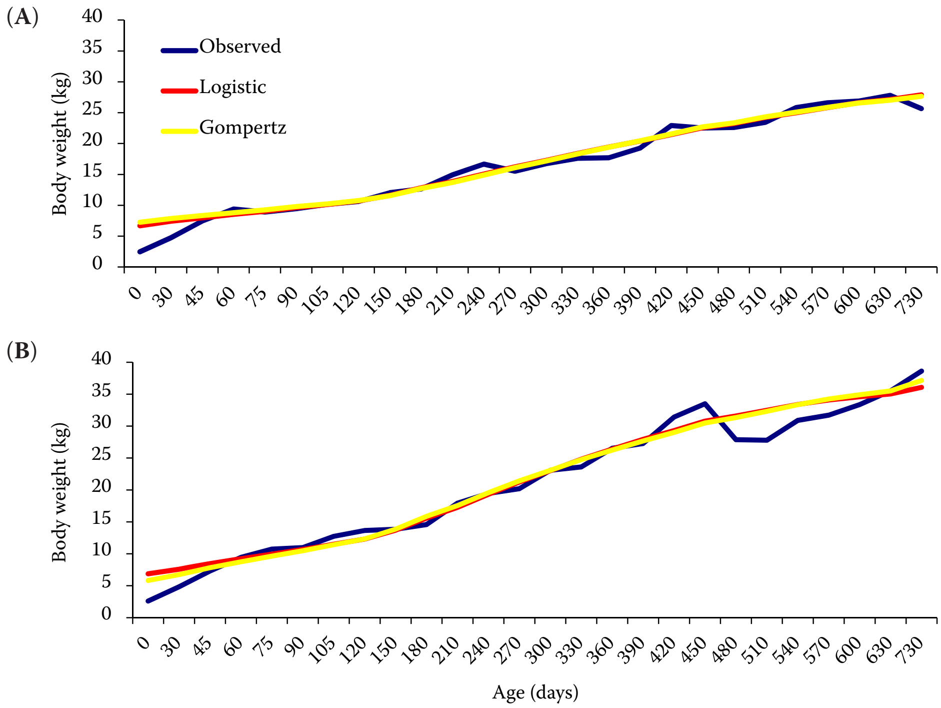

Figure 2. Body weight in the Morada Nova sheep breed estimated based on age obtained through the Logistic and Gompertz models, and body weight observed in females (**A**) and males (**B**)

The Logistic model also presented the asymptotic weight predicted (A) close to the observed, but lower than the Gompertz model (Table 3). Observing the growth curves of the two models (Figure 2), the Gompertz model suited better and therefore it was chosen to adjust the estimated curve in relation to observed weights of males and females. By the Gompertz model (Figure 3), sex had a significant effect ($P < 0.001$) on asymptotic weight (A) and maturing rate (k). In this comparison, males showed higher values of A (40.95 kg/day) and k (0.0043 kg/day) parameters than females (A = 36.44 kg/day and k = 0.0028 kg/day). Amaral et al. (2011) emphasised the importance of these parameters to determine the ideal moment to slaughter, with maximum muscle deposition and minimum fat, satisfying the requirements of the final consumer. These authors indicated the importance of determining the condition and speed at which a breed reaches its maturity to achieve better carcass and meat qualities.

The A and k parameters provide information important for the animal selection process. McManus et al. (2003) also observed differences in A and k

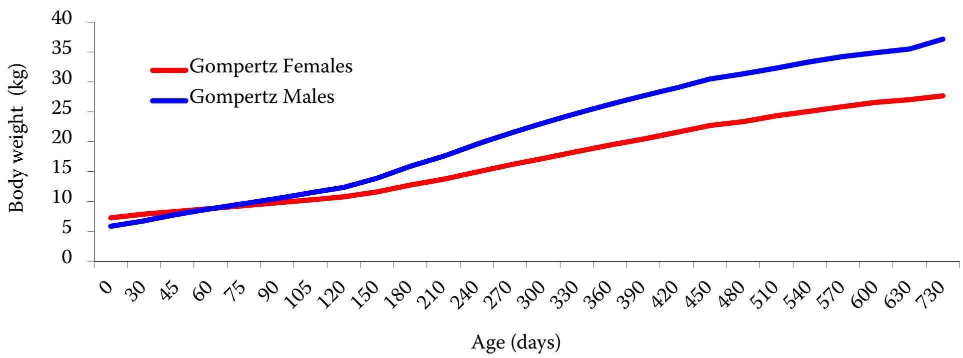

Figure 3. Body weight in the Morada Nova sheep breed estimated based on age, obtained by the Gompertz model in females and males

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Table 4. Age category and coefficient of determination for the linear regression, quadratic, and cubic models using measurements of body weight and thoracic circumference in the Morada Nova sheep breed

	Regression model								
	linear			quadratic			cubic		
	R^2 (%)	*P*	CV	R^2 (%)	*P*	CV	R^2 (%)	*P*	CV
CAT1	0.81	< 0.0001	16.58	0.86	< 0.0001	14.49	0.86	–	14.50
CAT2	0.89	< 0.0001	13.81	0.90	< 0.0001	12.77	0.90	–	12.77
CAT3	0.73	< 0.0001	12.29	0.76	< 0.0001	11.79	0.76	–	11.88

CAT1 = lambs 0–138 days old, CAT2 = wethers 91–184 days old, CAT3 = adults 223–408 days old, CV = coefficient of variation (in %), *P* = probability (%)

parameters of the curve when sexes were compared. Estimates of the asymptotic weight (A) of males and females, from birth to the post-maturity age, behaved similarly to those found in literature (Hifzan et al. 2015; Hossein-Zadeh et al. 2015; Lupi et al. 2015). The difference observed in body weight between males and females can be explained by sexual dimorphism caused by testicular steroids and their metabolites, modifying growth processes of males from prenatal development to maturity (Ford and Klindt 1989). However, Lupi et al. (2015) reported that growth rate estimated for females was higher than for males, indicating more growth precocity of females in relation to males. Based on the outcomes of this study as well as other literature results, categorising animals by sex (males and females) would be interesting so as to set the feeding management and slaughter age for each category, appropriately.

Relationship between body weight and thoracic circumference. In the study involving the estimation of body weight (BW), the use of quadratic and cubic regression models would not be viable, because the intent has been to simplify the field measurements (Table 4). Therefore, using the measures presenting high correlation with BW, like the thoracic circumference (TC), is recommended (Table 4). Thus, in the present case, only the use of the TC measurement could predict the body weight of the Morada Nova breed because of a significant association ($P < 0.0001$) detected for all categories with linear and quadratic models. Another important outcome observed in relation of estimates between BW and TC, in addition to the significant association ($P < 0.0001$) reported previously, was that all coefficients of determination (R^2) were above 0.70 (Table 4). The small

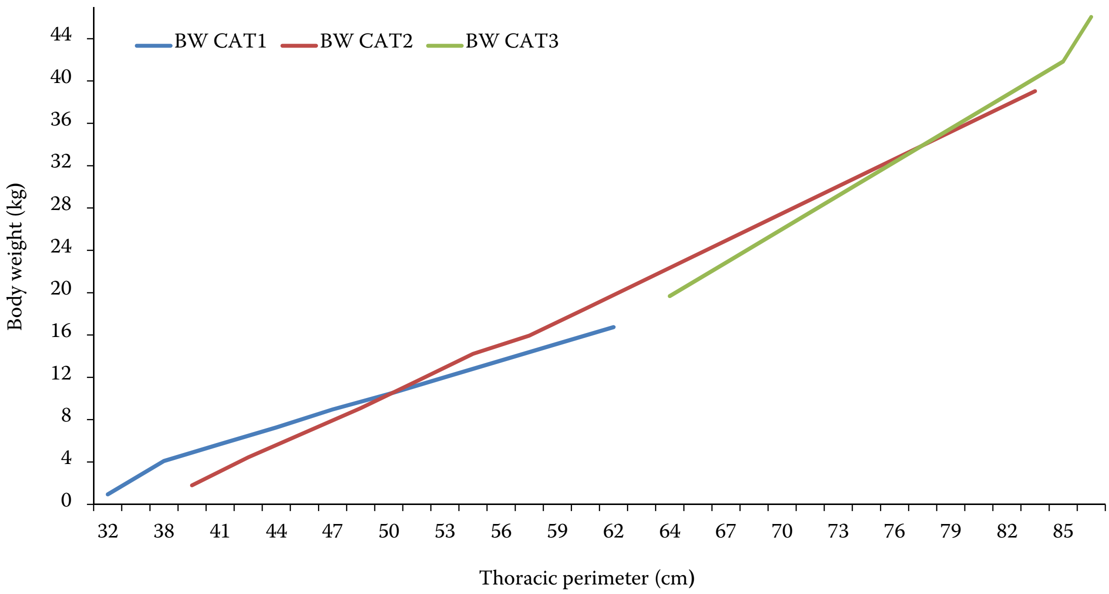

Figure 4. Relationship between body weight (BW) and thoracic circumference in the Morada Nova sheep breed
CAT1 = lambs 0–138 days old, CAT2 = wethers 91–184 days old, CAT3 = adults 223–408 days old

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difference observed in the R^2 estimates between regressions (linear, quadratic, cubic) justifies the only use of linear regression to estimate BW in relation to TC within the different animal categories.

Estimates between TC and BW of the Morada Nova breed were 32–62 cm with 0.94–16.75 kg for CAT1, 40–84 cm with 1.80–39.04 kg for CAT2, and 64–89 cm with 19.67–46.06 kg for CAT3, respectively (Figure 4). Based on these results (Figure 4) and on the regression analyses (Table 4), animal selection for greater body weight can be based on the thoracic circumference.

CONCLUSION

The Gompertz model, along with biological interpretations, could assist in interpreting the processes of growth and maturity rate of animals. In addition, it may be indicated to separate the animals based on sex and age to properly meet the nutritional requirements and determine adequate slaughter age, principally due to the influence of sexual dimorphism on growth. The thoracic circumference can be used to estimate body weight of animals with a high accuracy.

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