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CHARACTERIZATION OF GROWTH OF SOCORRO ISLAND MERINO LAMBS

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ABSTRACT

The aims of this study were to evaluate the effect of genetic and non-genetic factors on the growth of Socorro Island Merino lambs and to model their growth curve using nonlinear mathematical models. The weight of 41 Socorro Island Merino lambs was recorded at birth and at 45, 90, 135, 180, 225, 270, 315 and 365 days of life from May 2019 to September 2021. The effects on growth of sex, genotype, year of birth, and parity of the dam were analyzed. Four non-linear models (Brody, Logistic, Gompertz and von Bertalanffy) were fitted for determining the best model to describe growth curve. Birth weight and pre-weaning growth rate were not affected (P > 0.05) by any of the factors studied, while weaning weight was only significantly affected (P < 0.05) by sex. Year of birth significantly affected (P < 0.05) post-weaning growth rate and weight of the lamb from 270 days, while sex significantly affected (P < 0.05) weight at 315 days. The Gompertz and Brody models were the best fitted to describe growth curves of lambs. Purebred males showed a larger response to increasing levels of energy-protein supplementation, while they had greater mature weight and lower maturation rate compared to females and crossbred males. In conclusion, knowledge of growth and factors influencing growth pattern can help implement appropriate management strategies and make decisions aimed at the conservation of Socorro Island Merino lambs.

Keywords: Feral sheep, genotype, growth, non-linear models, parity, sex.

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INTRODUCTION

Socorro Island Merino sheep is a feral breed whose population is reduced to less than a hundred individuals, thus facing a very high risk of extinction (Fig. 1). The ancestors of this breed were introduced by Australian settlers in the year 1869 to the Revillagigedo Archipelago (18°49′17″N, 112°45′50″W), located at 720 km of the coast of Mexico, where they lived in feral conditions until eradicated in 2014 due to the severe ecological degradation of the Socorro Island (Izquierdo et al., 2005; Ortiz-Alcaraz et al., 2016).

In recent years, the conservation and sustainable use of animal genetic resources has become a global priority (FAO, 2007). The productive evaluation of breeds allows knowing parameters such as growth rate and weight at birth, weaning, and puberty, which provide essential information to implement rescue and genetic improvement programs (Atto, 2007).

Growth is considered one of the most important characteristics of farm animals and is defined as the increase in live weight per unit of time. Non-linear mathematical functions such as Brody, von Bertalanffy, Logistic and Gompertz have been used to define growth curves and provide a set of useful parameters to improve animal production, including contrasting different breeds, identifying and selecting superior and precocious animals, establishing feeding strategies, and determining optimal slaughter age, among others (Lupi et al., 2015). In addition, there are several genetic and non-genetic factors that can influence sheep growth, the most important being breed, sex, season or year of birth and ewe parity (Cuello-Estrada et al., 2019; Turkyilmaz and Esenbuga, 2019; García-Chávez et al., 2020).

Recent studies have analyzed the morphology (Hernandez et al., 2017) and physiology of Socorro Island Merino sheep (Arias et al., 2020; Prado et al., 2021). However, the growth characteristics and factors that affect this breed have not yet been determined. Therefore, the objectives of this study were to evaluate the effect of genetic and non-genetic factors on the growth of Socorro Island Merino lambs and to model their growth curve using nonlinear mathematical models.

MATERIALS AND METHODS

The study involved all Socorro Island Merino lambs (41 individuals) born from 2019 to 2021, 10 purebred females, 7 crossbred females, 9 purebred males and 15 crossbred males. The lambs were from a flock reared at the Faculty of Veterinary Medicine and Zootechnics of the University of Colima, located in Tecomán, Colima, Mexico. Crossbred lambs were the F_3 and F_4 generations from crossbreeding Socorro Island Merino sheep, with hair breeds such as Pelibuey, Blackbelly and Katahdin (87.5% Socorro Island Merino x 12.5% hair breeds and 93.75% Socorro Island Merino x

Fig. 1. Purebred Socorro Island Merino ewe lamb.

6.25% hair breeds). Weight records were obtained at birth and at 45, 90, 135, 180, 225, 270, 315 and 365 days of age.

Lambs born in 2019 (n=18) remained housed with their mothers for the first 15 days of life; they grazed with their mothers for seven hours (from 07:30 to 14:30) on Tanzania grass (*Panicum maximum*) and African Star grass (*Cynodon nlemfuensis*) grasslands until weaning, which took place at 90 days of life. Twenty days before weaning, lambs were immunized against pneumonic and clostridial diseases, and dewormed with albendazole at a dose of 10 mg/kg body weight (BW). Vaccination and deworming were repeated every six and three months, respectively. Once weaned, lambs were housed in pens, and fed with chopped Tanzania grass and 300 g/d of a commercial concentrate (88.0% dry matter (DM), 15.0% crude protein (CP), 3.0% ether extract (EE), 57.0% nitrogen-free extracts (NFE), 7.0% crude fiber (CF), 6.0% ash), in an amount equivalent to 2.7% and 1.3% of live weight at the time of weaning and at a year of age, respectively.

Lambs born in 2020 (n=23) were also housed with their mothers the first 15 days of age. Then, they grazed with their mothers until weaning, being additionally creep-fed with a commercial concentrate containing 20.0% CP. From weaning to 180 days of age, lambs were fed with chopped Tanzania grass and a commercial concentrate (88.0% DM, 14.0% CP, 4.0% EE, 48.0% NFE, 10.0% CF, 12.0% ash), in an amount equivalent to 3.5% of LW. From 180 to 365 days, lambs fed the same concentrate *ad libitum*. Sanitary management was conducted as described above for lambs born in 2019.

Data were initially analyzed to examine the effect of genetic and non-genetic factors on live weight using a repeated-measures ANOVA with the model: $Y_{ijklm} = \mu + S_i + G_j + A_k + N_l + E_m + \varepsilon_{ijklmn}$, where, Y_{ijklmn} is the live weight, μ is the general mean, S is the fixed effect of ith sex (male, female), G is the fixed effect of jth genotype (purebred, crossbred), A is the fixed effect of kth year of birth (2019, 2020), N is the fixed effect of lth parity of the ewe (primiparous, multiparous), E is the fixed effect of mth age (0, 45, 90, 135, 180, 225, 270, 315,365 days) and ε_{ijklmn} is the random error.

Weight at birth was included in the model as a covariate for the analysis of weights at 45 and 90 days of age as well as the pre-weaning growth rate. For post-weaning growth rate and weights at 135, 180, 225, 270, 315, and 365-days of age, weaning weight was used as a covariate and the effect of ewe parity was removed from the model, since its influence on weight is related to the amount of milk produced during lactation, which ends at weaning. *Post hoc* comparisons were made using Tukey's test and results were considered significant when P < 0.05.

To describe the relation between live weight and age of lambs, four non-linear mathematical models were fitted to data: Brody: y_i = A*(1-B*exp(-k*t))+e_i; Gompertz: y_i = A*exp(-B*exp(-k*t))+e_i; Logistic: y_i = A/(1+B*exp(-k*t))+e_i; and Von Bertalanffy: y_i = A*(1−B*exp(−k*t))**3+e_i, where: y_i is weight in kg at age t; A is asymptotic weight; B is the integration constant; k is the maturation rate, m is the shape of the growth curve and e is the error. To select the best growth curve, the highest value of the coefficient of determination Pseudo R^2, the lowest value of the Akaike information criterion (AIC) and the lowest value of the root means square error (RMSE) were considered. Statistical analyses were performed using the SPSS v.15.0 program.

RESULTS

Genotype, year of birth or ewe parity did not affect (P > 0.05) pre-weaning growth rate or live weight of lambs from birth to weaning, while male lambs had a greater weaning weight (P < 0.05) than female lambs (Table 1).

Genotype did not affect (P > 0.05) post-weaning growth rate or live weight of lambs from 135 to 365 days of age. Lambs born in 2020 showed a greater (P < 0.05) postweaning growth rate and live weight from 270 days than those born in 2019, while males only had a greater weight (P < 0.05) than females at 315 days (Table 2).

The variations observed in fit statistic criteria among all the nonlinear models evaluated were marginal. For lambs born in 2019, the Brody model showed the best goodness of fit criteria with the highest value for Pseudo R^2 and the lowest values for AIC and RMSE for all lambs, particularly for purebred and crossbred males and females (Table 3). For all lambs born in 2020, all 4 models showed the same Pseudo R^2 value, while the Gompertz model had the lowest value for AIC and the second lowest value for RMSE. Specifically, the Brody model showed the best fit for purebred and crossbred females, while Gompertz model did for purebred males (Table 4). In general, for both years, the Brody model showed the highest value for parameter A and the lowest value for parameter k; conversely, the Logistic growth model showed the lowest value for parameter A and the highest value for parameters B and k (Table 3 and Table 4).

According to all the models evaluated, for lambs born in 2019, purebred males showed the highest value for parameter A and the lowest value for parameter k, while crossbred females

Table 1. Effect of sex, genotype, year of birth and parity on preweaning weight (kg) and preweaning growth rate (g) of Socorro Island Merino lambs.

Factor	N	Age (days) 0	45	90	Preweaning growth rate
Overall	41	2.74 ± 0.22	8.42 ± 0.22	10.86 ± 0.22	90.39 ± 3.11
Sex					
Female	17	2.75 ± 0.31^{C}	8.26 ± 0.31^{B}	10.23 ± 0.30$^{A\ b}$	83.32 ± 5.09^{b}
Male	24	2.73 ± 0.30^{C}	8.56 ± 0.30^{B}	11.50 ± 0.30$^{A\ a}$	97.46 ± 4.92^{a}
Genotype					
Purebred	19	2.75 ± 0.32^{C}	8.52 ± 0.32^{B}	10.95 ± 0.31^{A}	91.30 ± 5.39
Crossbred	22	2.72 ± 0.28^{C}	8.31 ± 0.28^{B}	10.72 ± 0.27^{A}	89.49 ± 4.53
Parity					
Primiparous	11	2.75 ± 0.39^{C}	8.32 ± 0.39^{B}	11.36 ± 0.39^{A}	95.92 ± 6.62
Multiparous	30	2.72 ± 0.24^{C}	8.51 ± 0.24^{B}	10.37 ± 0.24^{A}	84.86 ± 3.96
Year of birth					
2019	18	2.61 ± 0.10^{C}	8.21 ± 0.24^{B}	10.21 ± 0.27^{A}	89.24 ± 4.75
2020	23	2.62 ± 0.13^{C}	8.17 ± 0.31^{B}	10.70 ± 0.32^{A}	91.54 ± 5.19

$^{A, B, C}$ Least squares means ± standard error followed by different capital letters in the same row are statistically different at $P < 0.05$.
$^{a, b}$ Least squares means ± standard error followed by different lowercase letters in the same column are statistically different at $P < 0.05$

had the lowest value for parameter A and the highest value for the parameter k (Table 3). For lambs born in 2020, purebred males showed the highest value for parameter A and, along with crossbred males, the lowest value for parameter k, whereas purebred females recorded the lowest value for parameter A and the highest value for parameter k (Table 4).

The growth pattern of lambs born in both years was similar from birth to 135 days, showing the highest growth rate during the first 45 days of life. After that, the lambs born in 2019 experienced weight loss up to 180 days, followed by a sustained growth rate up to 365 days of age. In the case of lambs born in 2020, they continued with the same growth trend until 180 days, followed by a significant increase in growth rate until 365 days. It is possible to observe that the Brody model, which showed the best fit for lambs born in 2019, underestimates observed weight at late ages, while the Gompertz model underestimates observed weight in lambs born in 2020 at early ages but overestimates it at late ages (Fig. 2A).

As seen in Figure 2B, the growth of lambs was almost similar from birth to 90 days (weaning), followed by a decrease in the growth rate of purebred and crossbred females and purebred males born in 2019. Crossbred males born in 2019 showed a similar growth rate to that observed in purebred females up to 225 days but then decreased, showing weight values equal to those of crossbred females. Purebred males born in 2020 had the highest weight from weaning to 365 days of age (Fig. 2B).

DISCUSSION

Several studies have indicated that male lambs are heavier than females at birth (Yilmaz et al., 2018; Turkyilmaz and Esenbuga, 2019; García-Chávez et al., 2020; Bangar et al., 2021; López-Carlos et al., 2021). However, the results obtained in the present study revealed that sex had no effect on birth weight, which agrees with the findings reported by Rashad et al. (2017), Catalan et al. (2018) and Baa et al. (2020). Haqq et al. (1994) indicate that the presence of a Y-chromosome and the products of SRY gene activation explain the effects of sex on fetal growth. However, Gardner et al. (2007) mention that maternal environment (maternal body composition prior to pregnancy and maternal nutrition during late gestation) has the largest influence on birth weight. In accordance with Yilmaz et al. (2018) and Baa et al. (2020), no difference was found between birth weight of lambs born from primiparous or multiparous ewes. On the contrary, other authors have mentioned that birth weight of lambs born from multiparous ewes is greater than that of lambs born to primiparous females (Catalán et al., 2018; Lamesegn et al., 2018; García-Chávez

Table 2. Effect of sex, genotype, and year of birth on postweaning weight (kg) and postweaning growth rate (g) of Socorro lambs

Factor	N	Age (days)						Postweaning growth rate
		135	180	225	270	315	365	
Overall	41	12.58 ± 0.64	13.08 ± 0.65	17.29 ± 0.65	21.31 ± 0.65	23.16 ± 0.65	25.68 ± 0.66	54.38 ± 3.00
Sex								
Female	17	12.83 ± 1.01^{C}	13.33 ± 1.04^{C}	16.64 ± 1.01^{BC}	19.52 ± 1.01^{AB}	$20.70 \pm 1.01^{AB\,b}$	23.76 ± 1.01^{A}	48.15 ± 4.78
Male	24	12.34 ± 0.83^{D}	12.82 ± 0.85^{D}	17.93 ± 0.88^{C}	23.09 ± 0.88^{B}	$25.62 \pm 0.89^{AB\,a}$	27.59 ± 0.90^{A}	60.61 ± 4.24
Genotype								
Purebred	19	12.38 ± 0.89^{D}	12.54 ± 0.94^{D}	17.22 ± 0.94^{C}	21.31 ± 0.94^{B}	23.09 ± 0.94^{AB}	25.53 ± 0.94^{A}	54.04 ± 4.33
Crossbred	22	12.79 ± 0.90^{D}	13.61 ± 0.91^{D}	17.35 ± 0.91^{C}	21.30 ± 0.91^{B}	23.23 ± 0.92^{AB}	25.81 ± 0.94^{A}	54.72 ± 4.30
Year of birth								
2019	18	12.62 ± 0.94^{C}	11.92 ± 0.94^{C}	$15.12 \pm 0.97B^{C}$	$17.74 \pm 0.97^{AB\,b\,b}$ $0.97^{AB,b}$	$20.27 \pm 0.97^{A\,b}$	$21.31 \pm 0.97^{A\,b}$	38.49 ± 4.44^{b}
2020	23	12.55 ± 0.88^{D}	14.23 ± 0.93^{D}	19.45 ± 0.89^{C}	$24.87 \pm 0.88^{B\,a}$	$26.05 \pm 0.90^{AB\,a}$	$30.03 \pm 0.92^{A\,a}$	70.27 ± 4.23^{a}

$^{A, B, C, D}$ Least squares means ± standard error followed by different capital letters in the same row are statistically different at $P < 0.05$.
$^{a, b}$ Least squares means ± standard error followed by different lowercase letters in the same column are statistically different at $P < 0.05$.

et al., 2020). This is attributable to a competition for available nutrients between the fetus and the ewe, which has not reached its adult size and continues to grow during gestation. The results of the present study coincide with the findings of Mellado et al. (2016), who indicate that crossing Katahdin ewes with Charolais, Hampshire or Texel rams does not affect birth weight. In contrast, Abate et al. (2020) have indicated that birth weight of crossbred lambs was greater than that of purebred lambs, while Turkyilmaz and Esenbuga (2019) found that crossbreeding Turkish indigenous Morkaraman ewes with Romanov rams negatively affected birth weight

Table 3. Estimated parameters and goodness of fit statistics of the fitted models for lambs born in 2019.

		Brody	Gompertz	Logisticvon	Bertalanffy
All lambs	A	33.008 ± 8.865	25.979 ± 3.565	23.864 ± 2.418	27.282 ± 4.359
	B	0.876 ± 0.028	0.517 ± 0.072	1.245 ± 0.123	0.446 ± 0.025
	K	0.002 ± 0.001	0.005 ± 0.001	0.008 ± 0.001	0.004 ± 0.001
	AIC	416.45	420.03	423.01	419.52
	Pseudo R^2	0.69	0.69	0.68	0.69
	MSE	12.60	12.94	13.18	12.84
Purebred female	A	31.954 ± 11.276	24.492 ± 4.195	22.275 ± 2.740	25.866 ± 5.225
	B	0.880 ± 0.036	0.530 ± 0.088	1.273 ± 0.151	0.450 ± 0.032
	K	0.002 ± 0.001	0.005 ± 0.001	0.009 ± 0.002	0.004 ± 0.001
	AIC	102.81	105.39	107.30	104.85
	Pseudo R^2	0.83	0.82	0.81	0.82
	MSE	5.63	5.93	6.14	5.84
Crossbred female	A	20.236 ± 4.875	18.506 ± 2.956	17.925 ± 2.392	18.872 ± 3.324
	B	0.808 ± 0.069	0.346 ± 0.192	0.948 ± 0.315	0.389 ± 0.060
	K	0.005 ± 0.003	0.008 ± 0.004	0.011 ± 0.004	0.007 ± 0.003
	AIC	95.64	96.76	97.62	96.28
	Pseudo R^2	0.63	0.62	0.61	0.62
	MSE	12.06	12.39	12.69	12.28
Purebred male	A	613.317 ± 21682.08	51.865 ± 86.579	35.146 ± 33.060	68.82 ± 167.656
	B	0.992 ± 0.291	0.799 ± 0.675	1.606 ± 0.962	0.570 ± 0.323
	K	0.00006 ± 0.002	0.002 ± 0.003	0.005 ± 0.003	0.001 ± 0.003
	AIC	56.65	57.89	58.10	56.98
	Pseudo R^2	0.74	0.74	0.73	0.74
	MSE	7.58	7.72	7.78	7.68
Crossbred male	A	40.383 ± 14.492	30.824 ± 5.17	28.195 ± 3.350	32.508 ± 6.479
	B	0.899 ± 0.033	0.596 ± 0.102	1.390 ± 0.187	0.473 ± 0.036
	K	0.002 ± 0.001	0.006 ± 0.002	0.010 ± 0.002	0.005 ± 0.002
	AIC	116.28	117.93	119.12	117.52
	Pseudo R^2	0.81	0.81	0.80	0.81
	MSE	11.60	12.06	12.38	11.92

A: asymptotic or mature weight; B: integration constant related to initial animal weight; K: maturation rate; M, inflection parameter, that is, the moment when the concavity change occurs; AIC: Akaike's information criterion; Pseudo R^2: non-linear determinative coefficient; RMSE: root means square error.

of crossbred lambs, also indicating that climate and management-nutritional conditions of a particular region make local purebred lambs more suitable than crossbred individuals.

Several authors have reported that weaning weight of male lambs is greater than that of females (Lamesegn et al., 2018; García-Chávez et al., 2020; López-Carlos et al., 2021). This occurs because male lambs begin to secrete testosterone after birth, a steroidal hormone important in growth due to its anabolic effects and stimulation of growth hormone (O'Shaughnessy, 2015). In contrast, other studies (Rashad et al., 2017; Turkyilmaz and Esenbuga, 2019; Baa et al., 2020) have indicated that sex does not affect weight at weaning because the hormonal effect of testosterone to promote greater growth is significant up to 70 days after birth (ARC, 1980). Furthermore, Lamesegn et al. (2018) and García-Chávez et al. (2020) reported that lambs born to multiparous ewes show greater weaning weight than those born to primiparous ewes, which can be attributed to the fact that as the ewe reaches its maximum body development, and thus milk production as well as the expression of maternal ability increase. On the contrary, coinciding with the results of the present study, Rashad et al. (2017) and Baa et al. (2020) found that weaning weight of lambs born from primiparous ewes was similar to that of multiparous ewes. Regarding the effect of genotype, Abate et al. (2020) reported that crossbred lambs have a higher weaning

Table 4. Estimated parameters and goodness of fit statistics of the fitted models for lambs born in 2020.

		Brody	Gompertz	Logistic	von Bertalanffy
All lambs	A	3122.000 ± 0.001	58.393 ± 16.342	40.035 ± 5.128	81.573 ± 38.016
	B	0.999 ± 0.034	0.939 ± 0.080	1.971 ± 0.115	0.624 ± 0.046
	K	0.00002 ± 0.001	0.004 ± 0.001	0.009 ± 0.001	0.002 ± 0.001
	AIC	643.20	642.19	642.74	642.70
	Pseudo R^2	0.77	0.77	0.77	0.77
	MSE	23.08	23.06	23.12	23.02
Purebred female	A	79.000 ± 106.688	34.508 ± 10.085	29.001 ± 5.234	38.792 ± 14.773
	B	0.956 ± 0.052	0.734 ± 0.108	1.621 ± 0.194	0.528 ± 0.045
	K	0.001 ± 0.002	0.005 ± 0.002	0.009 ± 0.002	0.004 ± 0.002
	AIC	79.44	81.27	82.40	80.58
	Pseudo R^2	0.86	0.86	0.85	0.86
	MSE	8.15	8.54	8.82	8.42
Crossbred female	A	1002.271 ± 31078.63	39.970 ± 20.024	30.660 ± 7.966	48.877 ± 35.870
	B	0.997 ± 0.104	0.829 ± 0.159	1.784 ± 0.262	0.571 ± 0.078
	K	0.00006 ± 0.002	0.004 ± 0.002	0.009 ± 0.003	0.003 ± 0.002
	AIC	72.97	74.05	74.33	73.28
	Pseudo R^2	0.82	0.82	0.82	0.82
	MSE	11.95	12.14	12.27	12.08
Purebred male	A	5715.293 ± 386386.07	75.854 ± 35.529	46.976 ± 9.010	123.515 ± 109.432
	B	1.000 ± 0.033	1.039 ± 0.119	2.155 ± 0.164	0.673 ± 0.078
	K	0.00002 ± 0.001	0.004 ± 0.001	0.009 ± 0.002	0.002 ± 0.001
	AIC	156.07	153.89	154.00	154.09
	Pseudo R^2	0.87	0.88	0.88	0.88
	MSE	16.10	15.54	15.58	15.53
Crossbred male	A	3589.057 ± 195612.92	59.117 ± 24.447	40.991 ± 7.622	81.858 ± 56.629
	B	0.999 ± 0.053	0.941 ± 0.117	1.997 ± 0.179	0.622 ± 0.068
	K	0.00002 ± 0.001	0.004 ± 0.002	0.009 ± 0.002	0.002 ± 0.001
	AIC	297.01	295.67	295.19	296.34
	Pseudo R^2	0.75	0.76	0.76	0.76
	MSE	28.36	28.11	27.95	28.14

A: asymptotic or mature weight; B: integration constant related to initial animal weight; K: maturation rate; M, inflection parameter, that is, the moment when the concavity change occurs; AIC: Akaike's information criterion; Pseudo R^2: non-linear determinative coefficient; RMSE: root means square error.

weight than purebred lambs. However, studies conducted by Koritiaki et al. (2013) and Mellado et al. (2016) have reported that lamb genotype does not affect weaning weight, which is in agreement with our results. The authors also mention that weaning weight is strongly affected by the maternal environment, and thus the good maternal ability that characterizes some breeds exerts a greater influence on this productive parameter than genotype.

Male lambs had higher weight than females only at 315 days of age. This coincides with Amare et al. (2018), who found no weight difference between male and female Wollo Highland lambs at 6, 9 and 12 months of age. In addition, Amare et al. (2018) and Abate et al. (2020) indicate that crossbreeding significantly increased post-weaning weight of lambs. In this sense, our results agree with the findings of Koritiaki et al. (2013), who concluded that there is no difference in the post-weaning weight of purebred and crossbred Santa Ines lambs. The crossbreed lambs studied here belonged to an F_3 and F_4 generations and, although crossbreeding lambs offer two advantages over purebreds, heterosis and breed complementarity (Leymaster, 2002), the highest level of individual heterosis is always observed in the F_1 generation and decreases in subsequent generations (Simm, 2000).

Year of birth did not affect birth weight and although lambs born in 2020 were creep fed during lactation, their weaning weight and pre-

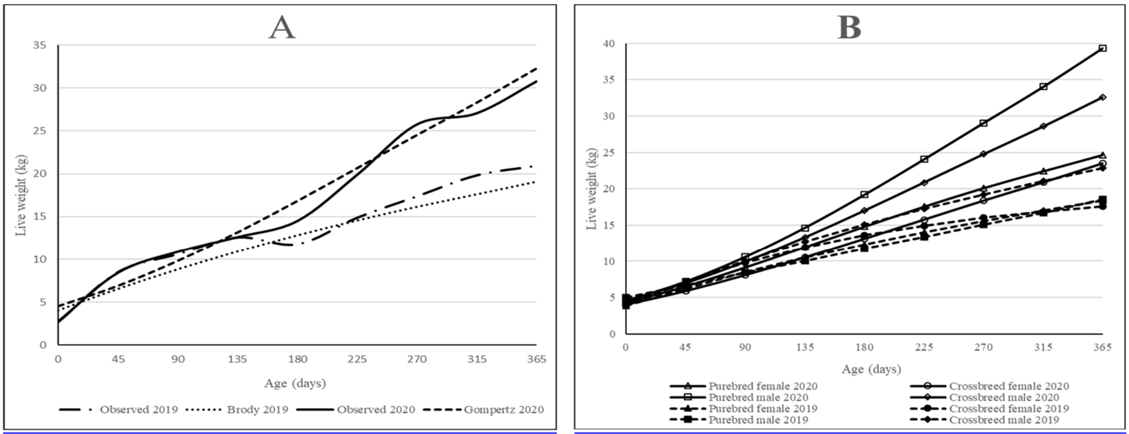

Fig. 2. Live weight observed and predicted by the best fitted nonlinear models for all lambs (A). Growth curves of Socorro Island Merino lambs according with their sex and genotype, with weight predicted by the Brody (2019) and Gompertz (2020) models (B).

weaning growth rate were similar to those born in 2019. This contrasts with the assertions of Cézar and Sousa (2003), who indicate that creep feeding is a worldwide nutritional practice that may increase growth rate of lambs up to 20%. According to Galvani et al. (2014), improving ewe nutrition seems to be more efficient than providing an additional source of solid food to lambs. Post-weaning growth rate and live weight from 270 days were affected by year of birth, being higher in those born in 2020 because of the greater inclusion of concentrate in their diet. On the other hand, the growth reduction suffered by lambs born in 2019 (from 135 to 180 days), was due to an outbreak of hepatic photosensitization resulting from the ingestion of *Brachiaria* grass when supplied by a management error in substitution of Tanzania grass (Macedo et al., 2022).

Given that the differences between fit statistic criteria were marginal, all the evaluated models are suitable for describing growth of Socorro Island Merino lambs, being Brody and Gompertz the models that best described growth of lambs born in 2019 and 2020, respectively. Recent studies conducted by Ali et al. (2020), Bangar et al. (2021), Iqbal et al. (2021) and Sharif et al. (2021) determined that the Brody model was the best nonlinear model for describing growth curve in Kajli, Harnali, Harnai and Lohi sheep, respectively. The Gompertz model was also found appropriate for describing growth curve of Thalli (Waheed et al., 2016), Rahmani (Rashad et al., 2017) and Morada Nova sheep (Paro de Paz et al., 2018). The Brody model provided the highest and the lowest estimates for parameters A and k, respectively, whilst the logistic model provided the lowest and the highest estimates of parametesr A and k, respectively, which agrees with the findings of several previous studies (Ali et al., 2020; Bangar et al., 2021; Iqbal et al., 2021; Sharif et al., 2021).

As observed in various sheep breeds, sex had a significant influence on all growth curve parameters with males showing a higher value for parameter A, indicating that their adult weight is greater than that of females (Ali et al., 2020; Bangar et al., 2021; Iqbal et al., 2021; Sharif et al., 2021). Parameter B is an integrated constant associated with early live weight and has a limited biological importance (Sharif et al., 2021). Regarding parameter k, a slightly higher value was observed in females, which indicates that females have a higher growth rate than males. Accordingly, they reach their adult weight, puberty and sexual maturity at an earlier age (Ali et al. (2020); Bangar et al. (2021); Iqbal et al (2021); Sharif et al., 2021). As observed in various breeds of feral sheep, this growth pattern probably allows ewe lambs to breed with heavier dominant adult males rather than young subordinate males (Ritchot et al., 2021).

The relation between parameters A and k is the most important biological relationship in a growth curve. A negative correlation between these parameters indicates that later maturing animals tend to grow into animals with greater mature weights, which occurred particularly with purebred male lambs in the present study. This can be seen in the parameters of the growth curve of purebred male lambs obtained utilizing all four models and, particularly in those obtained using the Brody model. It is important to note that although the Brody function constructs mathematical models that allow predicting live weight of Socorro Island Merino lambs with acceptable accuracy, its parameters are biologically inaccurate.

As seen in Figure 2A, the highest growth rate of lambs born in both years occurred from birth to 45 days (126 g/d), which coincides with a high availability of maternal milk. Notwithstanding that Socorro Island Merino is a small breed with low growth potential and that adult weights of males and females do not exceed 50 and 30 kg, respectively (Hernandez et al., 2017), there was a positive productive response to increasing levels of energy and protein of the diet once lambs were weaned. The highest post-weaning growth rate (118 g/d), only comparable to that observed during the first 45 days of life, was observed from 180 to 270 days in lambs born in 2020, stage in which they were fed *ad libitum* with a concentrate feed. In addition, the greatest productive response to improvement in diet quality was observed in purebred male lambs (Figure 2B), and not in crossbred male lambs as might be expected. Similarly, Canton et al. (2009) observed improved growth of meat lambs by increasing energy levels of the diet, without a positive effect of heterosis on weight gain. According to Khattab et al. (2021), heterosis estimates for F_1 are positive and increase with increasing age, declining in the F_2 generation to half of that in the F_1.

According to the recent literature, some breeds such as Santa Inés and Bonga show a productive behavior such as that observed Socorro Island Merino lambs, characterized by having a pre-weaning growth rate greater than the post-weaning growth rate (Koritiaki et al., 2013; Abate et al., 2020), although it should be noted that there are a large number of breeds that show an inverse behavior (Rosov and Gootwine, 2013; Amare et al., 2018; López-Carlos et al., 2021). In addition, productive parameters of Socorro Island Merino lambs were significantly lower than those shown by breeds specialized in meat production and their crosses, such as Merinolandschaf, Île-de-France, Charollais, Suffolk, Texel, Dorper, Katahdin, Pelibuey and Blackbelly (Schiller et al., 2015; Mellado et al., 2016; López-Carlos et al., 2021).

CONCLUSIONS

The growth of Socorro Island Merino lambs was not influenced by genotype of the lamb or parity of the ewe, while males had greater weight than females only at 90 and 315 days. Of all four nonlinear models evaluated, the Gompertz and Brody models were the best fitted to describe growth curve of Socorro Island Merino lambs. Although the Brody function constructs mathematical models that allow predicting the weight of lambs with acceptable accuracy, some of its parameters are biologically inaccurate. Purebred males showed a higher response to increasing levels of energy-protein supplementation, had greater mature weight and lower maturation rate compared to females and crossbred males. Knowledge of growth and factors influencing growth pattern can help implement appropriate management strategies and make decisions aimed at the conservation of this breed.

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