GROWTH CURVES THROUGH NON-LINEAR MODELS IN CREOLE LAMBS FROM THE MIXTECA REGION OF OAXACA, MEXICO †

[CURVAS DE CRECIMIENTO MEDIANTE MODELOS NO LINEALES EN BORREGOS CRIOLLOS DE LA MIXTECA OAXAQUEÑA, MÉXICO]

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SUMMARY

Background. Growth curves allow to predict the mature weight, the grow rate unto maturity, as well as the age and weight at inflexion point, to improve management on productive animals. **Objective**. To identify the best non-linear model (NLM), which best describe the growth curve of Creole sheep from the Mixteca region of Oaxaca, Mexico. **Material and methods**. The live weights of 720 sheep (438 females and 239 males) between 1 and 60 months of age were used. The NLM evaluated were: Logistic, Gompertz, Michaelis-Menten, Weibull and Mechanist. Analyzes were performed with SAS JMP software. The criteria used to select the best model were the corrected Akaike information criterion (AICc), Bayesian (BIC) and coefficient of determination (R^2). **Results.** For females, the Mechanist and Weibull models adjusted better de data (lowest AICc, BIC), but not being differences with the Michaelis-Menten and Gompertz. For males the lowest AICc, BIC and the highest R^2 (0.84) values were for the Logistic, Gompertz and Mechanist models. **Implications**. The knowledge of the parameters of the growth curves of the creole sheep of the Mixteca region could be used for taking better decisions on the management of this type of sheep. **Conclusion**. According to the models, the inflection point of the growth curves was reached at a young age and a lower body weight in females than in males; therefore, different models should be used to study the growth kinetics between sexes.
Key words: growth curves; model selection; growth rate; mature weight.

RESUMEN

Antecedentes. Las curvas de crecimiento permiten predecir el peso maduro y la rapidez de crecimiento a la madurez, así como, tasa de madurez, para mejorar el manejo en los animales domésticos, **Objetivo.** Identificar el mejor modelo no lineal (MNL) que describe la curva de crecimiento de ovinos criollos de la Mixteca oaxaqueña, México. **Materiales y métodos**. Se utilizaron 720 pesos vivos de borregos (438 hembras y 239 machos) entre 1 y 60 meses de edad. Los MNL evaluados fueron: Gompertz, Logístico, Michaelis-Menten, Weibull y Mecanicista. Los análisis se realizaron con el software JMP de SAS. Los criterios utilizados para seleccionar el mejor modelo fueron el criterio de información Akaike corregido (AICc), Bayesiano (BIC) y coeficiente de determinación (R^2). **Resultados**. Para las hembras, los modelos Mecanicista y Weinbul ajustaron mejor los datos (valores menores de AICc, BIC) para describir la curva de crecimiento en las hembras. Para los machos los valores más bajos de AICc, BIC correspondieron a los modelos Logístico, Gompertz y Mecanicista. **Implicaciones**. El conocimiento de los parámetros de las curvas de crecimiento

de los ovinos criollos de la Mixteca, podría servir para la toma de mejores decisiones en el manejo de este tipo de ovinos. **Conclusiones**. Según estos modelos, los puntos de inflexión de las curvas de crecimiento se alcanzaron a una edad más temprana y a un peso vivo inferior en hembras que en machos, por lo tanto, se deben utilizar diferentes modelos para estudiar la cinética de crecimiento entre sexos.

Palabras clave: curvas de crecimiento; selección de modelos; tasa de crecimiento; peso maduro.

INTRODUCTION

The productive performance in creole sheep from Oaxaca, Mexico, is not well known, particularly, the way they grow. The knowledge of the growth curve of sheep is important to develop management practices that could help management decisions and increase the animal and herd productivity. There are different types of nonlinear models to descriptive the growth pattern of animals. The identification of the best fit model for curve description is important to provides objective and precise information on the growth pattern of sheep and other domestic animals, information which can be used by breeders in making decisions related to production, management and genetic selection (Domínguez - Viveros *et al*., 2019). The most used non-linear models are the Logistic (Nelder, 1961) and Gompertz (Laird, 1965) models. Topal *et al*. (2004) reported that the Gompertz model was the most appropriate in Morkaraman sheep; while Parés-Casanova *et al*. (2015), in creole sheep from Chiapas, observed that, the model that best adjusted the data was the Logistic one. However, the growth curves of sheep, as happens with genetic parameters, could vary according to the region, management, feeding and genetic background of animals. Therefore, the best models for each breed and system of production must be identified.

In the literature, no studies were found that describe the growth of Creole sheep from the Mixteca region, even though Oaxaca has a considerable number of Creole sheep whose breeding has served as a livelihood for low-income rural families (Martínez-Peña *et al*., 2018). This type of information would contribute to generate information necessary to establish genetic rescue programs for Creole sheep in this region, which have demonstrated, for years, adaptation to the adverse ecological environment, where they develop. Therefore, the speed and way they growth is an aspect important to know, which would provide information on their productive performance and the possible use of genetic selection under local environmental conditions. The objective of this study was to find the best fitted growth curves using five non-linear models for female and male Creole sheep from the Mixteca region of Oaxaca, Mexico.

MATERIAL AND METHODS

Study location and animals

The study was carried out with 24 sheep producers from 17 municipalities of the Mixteca region of Oaxaca, Mexico. Four-hundredth eighty-one females and 239 Creole males from 1 to 60 months of age (n=720 weights) were used Age was declared by the farmers and corroborated by the teeth of the animals. The region is characterized by having altitudes of 1,200 to 2,300 meters above sea level, with mainly mountainous relief (81.6%). The climate varies between warm-semi-dry to temperate-humid, there are extremely dry parts, except during the summer rains (June to October) with annual rainfall ranging from 400 to 800 mm. Live weight was obtained by direct weighing of each animal with digital scales. The same person collected all weights and data. In the region the animals were kept under extensive systems, grazing during the day and closed at night.

Models and statistical analysis

The nonlinear models used to describe the growth of sheep were Logistic, Gompertz, Michaelis-Menten, Weibull and Mechanistic. The mathematical expressions that represent each of the prediction models and their parameters are shown in Table 1. To distinguish the adjustment capacity of each evaluated model, the most common criteria: corrected Akaike (AICc) and Bayesian (BIC) were used. Those two criteria combine maximum likelihood theory and theoretical and entropy information, considering the best model the one with the lowest value for AIC, BIC. In addition, the coefficient of determination (R^2) criteria (the highest the better) was also calculated. The age at the inflection point for the Gompertz and Logistic models was calculated as $\ln(b)/c$ and the weight at the inflection point as A/e and $A/2$, respectively. The analyses were performed with the maximum likelihood method of the statistical program JMP®, version 15.1.0 of SAS (2020).

In terms of the sum of squares of the error (SSE) and sum squares of the total (SST), the AIC, BIC and R^2 are calculated as:

$$AIC=n*\ln(SSE/n)+(2p+1)$$

BIC = n*ln(SSE/n) + p*ln(n)

R^2 = (SST-SSE)/SST;

Where n is the number of weights, ln is the natural log, and p the number of parameters in the model.

To test for model fit differences, the probability of choosing between two models was calculated as p = exp(-|AICc difference|/2)/(1+exp(-|AICc difference|/2); where p < 0.05, indicates a statistical difference between the two models being compared (Motulsky and Christopoulos, 2003). Both AIC and BIC introduce a penalty term for the number of parameters in the model.

RESULTS

Tables 2 and 3 show the selection criteria values to choose the best model (AICc, BIC and R^2) and measures of variation of the error. R^2 values were very similar for all models. Based on AICc and BIC criteria,

and the formula to detect differences between AICc values, the models that best described the data were the Mechanist, Weibull and Michaelis-Menten for females (Table 2), and Logistic, Gompertz and Mechanist for males (Table 3).

The estimated parameters, standard errors and 95% confidence intervals for the growth curves evaluated for both female and male creole sheep are shown in Tables 4 and 5, respectively. The estimates of the asymptotes (mature weight) for the Mechanist, Michaelis-Menten and Weibull models ranged from 28.14 to 32.15 kg for females. For males, the asymptotes for the best two models (Logistic, Gompertz and Mechanist) were 36.26, 35.25 and 38.49 kg. The growth rate for the Mechanist and Weibull models were 0.11 and 0.73 kg/month, for females and 0.14, and 0.22 kg/month for males. Because Gompertz and Logistic are two popular functions to describe a curve in animals. the age and weight at the inflection point were calculated and were different between sexes (Table 6).

Table 1. Mathematical description of the non-linear growth models for the evaluation of creole sheep from the Mixteca region of Oaxaca, Mexico.

Model	Parameters	Model*
Logistic	a= Asymptote (Mature weight)	y = a/(1 + exp (- c (age – b)))
	b= Inflexion point	
	c= Growth rate	
Gompertz	a= Asymptote	y = a * exp (- exp(- c (age – b)))
	b= Inflexion point	
	c= Growth rate	
Weibull	a= Asymptote	y = a (1-exp(- (age/b)^c))
	b= Inflexion point	
	c= Growth rate	
Mechanist	a= Asymptote	y = a (1 – b* exp (-c * age))
	b= Scale	
	c= Growth rate	
Michaelis-Menten	A= Rate of maximum reaction	y = (A * age)/(B + age)
	B= Inverse affinity	

*Formulas provided by the JMP, SAS program.

Table 2. Selection criteria for the non-linear models used to describe the growth curve in female creole sheep from the Mixteca region of Oaxaca, Mexico.

Model	AICc	BIC	SSE	MSE	RMSE	R^2
Mechanist	2838.51a	2855.13	10121.77	21.17	4.60	0.71
Weibull	2839.48a	2856.10	10142.35	21.22	4.61	0.71
Michaelis-Menten	2842.35a	2854.83	10246.16	21.39	4.63	0.71
Gompertz	2843.75a	2860.37	10232.71	21.41	4.63	0.71
Logistic	2849.81b	2866.43	10362.39	21.68	4.66	0.70

AICc= Corrected Akaike Information Criterion; BIC= Bayesian information criterion; SSE= error sum of squares; MSE= mean squares error; RMSE= squares root of MSE; R^2= coefficient of determination. a,b literals different in the AICc column, indicates statistical difference at 95%, taken as reference the mechanist model.

Table 3. Selection criteria for the nonlinear models used to describe the growth curve of male creole sheep from the Mixteca region of Oaxaca, Mexico.

Model	AICc	BIC	SSE	MSE	RMSE	R^2
Logistic	1428.94a	1442.67	5341.34	22.63	4.76	0.84
Gompertz	1428.99a	1442.72	5342.41	22.64	4.76	0.84
Mechanist	1432.79a	1446.52	5428.03	23.00	4.79	0.84
Weibull	1440.62b	1454.35	5608.82	23.77	4.88	0.83
Michaelis-Menten	1445.58b	1455.91	5776.19	24.37	4.94	0.83

AICc= Corrected Akaike Information Criterion; BIC= Bayesian information criterion; SSE= sum of squares of the error; MSE= mean squares of the error; RMSE= squares root of MSE; R^2= coefficient of determination. a,b literals different in the AICc column, indicates statistical difference at 95%, taken as reference the logistic model..

Table 4. Estimated growth curve parameters for five nonlinear models fitted to describe the growth curve of female creole sheep from the Mixteca region of Oaxaca, Mexico.

Model	Parameters	Estimates	SE	95%CI	
Mechanist	Asymptote (Mature weight)	28.14	0.44	27.27	29.00
	Scale	0.87	0.03	0.82	0.92
	Growth rate	0.11	0.01	0.09	0.13
Weibull	Asymptote	29.38	0.91	27.59	31.17
	Inflexion point	8.17	0.84	6.54	9.81
	Growth rate	0.73	0.05	0.63	0.83
Michaelis-Menten	Maximum reaction rate	32.15	0.64	30.89	33.41
	Inverse affinity	5.69	0.47	4.76	6.61
Gompertz	Asymptote	27.51	0.35	26.82	28.20
	Inflexion point	3.08	0.28	2.53	3.62
	Growth rate	0.17	0.01	0.14	0.19
Logistic	Asymptote	27.16	0.31	26.55	27.77
	Inflexion point	5.54	0.29	4.96	6.12
	Growth rate	0.23	0.02	0.20	0.26

SE= Standard error ; 95%CI= 95% confidence interval.

Table 5. Estimated growth curve parameters for five nonlinear models fitted to describe the growth curve of male creole sheep from the Mixteca region of Oaxaca, Mexico.

Model	Parameter	Estimates	SE	95%CI	
Mechanist	Asymptote	38.49	1.30	35.94	41.04
	Scale	0.92	0.02	0.88	0.95
	Growth rate	0.08	0.01	0.07	0.09
Weibull	Asymptote	40.89	2.62	35.76	46.03
	Inflexion point	12.85	2.10	8.75	16.96
	Growth rate	0.79	0.06	0.68	0.90
Michaelis-Menten	Maximum reaction rate	46.57	1.82	43.01	50.14
	Inverse affinity	10.09	0.99	8.13	12.04
Gompertz	Asymptote	36.26	0.86	34.56	37.95
	Inflexion point	4.93	0.31	4.32	5.55
	Growth rate	0.14	0.01	0.13	0.16
Logistic	Asymptote	35.25	0.71	33.85	36.64
	Inflexion point	7.67	0.34	7.01	8.33

SE= Standard error; 95%CI= 95% confidence interval.

DISCUSSION

The coefficient of determination was not a good criterion to differentiate between statistical models; therefore, the AICc and BIC criteria were used here, to decide the best models. The Logistic and Gompertz growth curves of both sexes of the Mixteca creole sheep showed a typical sigmoid curve, whereas the other three models provided a linear and quadratic type of relationship (Figures 1 and 2). Commonly, differences are reported in weight and growth of males and females. In some studies, female and male sheep

show differences in weight at weaning, at one year, at maturity, and in the rate of growth (González-Garduño *et al*., 2002; Hinojosa-Cuellar *et al*., 2018; López-Carlos *et al*., 2021). Therefore, differences in the growth curves of both sexes are expected, as appreciated in Figures 1 and 2; as well as in the parameters estimated in the present study, as described by the five nonlinear models (Tables 4 and 5). Differences between different non-linear models for sheep by sex and in other species of domestic animals have been reported (Andrade-Souza *et al*., 2011; Parés-Casanova *et al.*, 2015). Likewise, it has been found that different models can better adjust the growth curves of females and males (Domínguez-Viveros *et al*., 2019). This could occur due to differences in the frequency and measurement intervals between sexes, as well as differences in handling and particularly in feeding. Briefly, the management and feeding of the Creole sheep, from the Mixteca region, used here, consisted of grazing natural pastures during the day with confinement at night. Breed and sex differences in body weights of sheep are common to be found under good feed conditions that when they are poorly fed.

Table 6. Age and weight at the inflection point of Creole sheep from the Mixteca region of Oaxaca, Mexico.

Model	Sex	AIP(Months)	WIP(Kg)
Gompertz	Male	11.39	24.19
	Female	6.61	15.81
Logistic	Male	9.26	20.67
	Female	7.44	16.50

AIP= Age (months) at inflexion point; WIP= body weight (kg) at inflexion point.

Scatter plots of the relationship between weight and age from 1 to 60 months, mean growth curve, and asymptotic (mature) weight are shown for each of the five non-linear models used to adjust the growth curves of the Mixteca creole sheep (females and males) from the Mixteca region of Oaxaca, Mexico (Figures 1 and 2). Logistic and Gompertz curves seems to represent a sigmoid typical curve than the other three models used, for both sexes.

The range of mature weight values, here estimated, for females was 27.16 to 29.38 kg and 35.25 to 40.89 kg for males. Here, the importance of choosing the best fitting data model. The mature weight here does not refer to the maximum weight that an animal reaches, but rather the average weight at maturity, free of seasonal variations (Brown *et al*., 1976). Andrade-Souza *et al*. (2011), using the Logistic model, observed similar results in Morada Nova Creole sheep in Brazil with values of mature weights of 26.01 and 26.82 kg for females and males, respectively. Parés-Casanova *et al*. (2015) obtained values of 31.01 and 40.04 kg for females and males, respectively, in creole sheep from Chiapas, with ages ranging from 3 to 156 months and finding that the Logistic model fitted the data better. Mendes *et al*. (2008) mention that not only the statistical aspect should be taken in the identification of the best growth curve model, but also that the estimated parameters have a biological interpretation. In medium-sized breeds such as Pelibuey and Blackbelly in Mexico, values of 35.9 and 33.1 kg were obtained with the Logistic model and 40.7 and 36.9 kg with the Gompertz model (Domínguez-Viveros *et al*., 2019).

Growth rate is related to maturation rate and mature weight, and it has been suggested that these variables are related to lifetime productivity in animals (Pala *et al*., 2005). On the other hand, a slow growth rate causes a low market weight, being this, one of the limiting factors in the profitability of production systems (Abegaz *et al*., 2010), mainly under extensive systems (Maldonado-Jáquez *et al*., 2021). In the present study, the growth rate was similar between males and females, although slightly higher in females, which implies the difference in the age inflection point between both sexes. Animals with higher growth rates, mature earlier than those with a low growth rate at a similar initial weight; therefore, animals with faster growth can be slaughtered at a younger age (Malhado *et al*., 2009). The literature indicates that as lambs age advance and/or nutritional conditions improve, the difference between the sexes increases (Bianchi, 2006). However, when feeding is restricted, the differences between sexes are not appreciable (Bianchi and Garibotto, 2002; Bianchi *et al*., 2003). According to Parés-Casanova *et al*. (2015), Chiapas sheep present a similar growth pattern for both sexes, although the overall increase in weight was greater for females; a result like that observed here. In that study, the authors observed a better fit (lower value of AICc) for males and females with the Logistic model. The estimates for mature weight, growth rate and inflection point for all the models in the present study were higher than the estimates in Creole sheep in Colombia (25.57 kg, 0.01 kg/month and 2.1, respectively) with the Gompertz model (Vergara *et al*., 2017). Model, which according to Sarmento *et al*. (2006), in Santa Ines breed, and Lambe et al. (2006), in Texel and Blackbelly breeds, offers more reliable results and the best adjustments to describe the live weight of sheep.
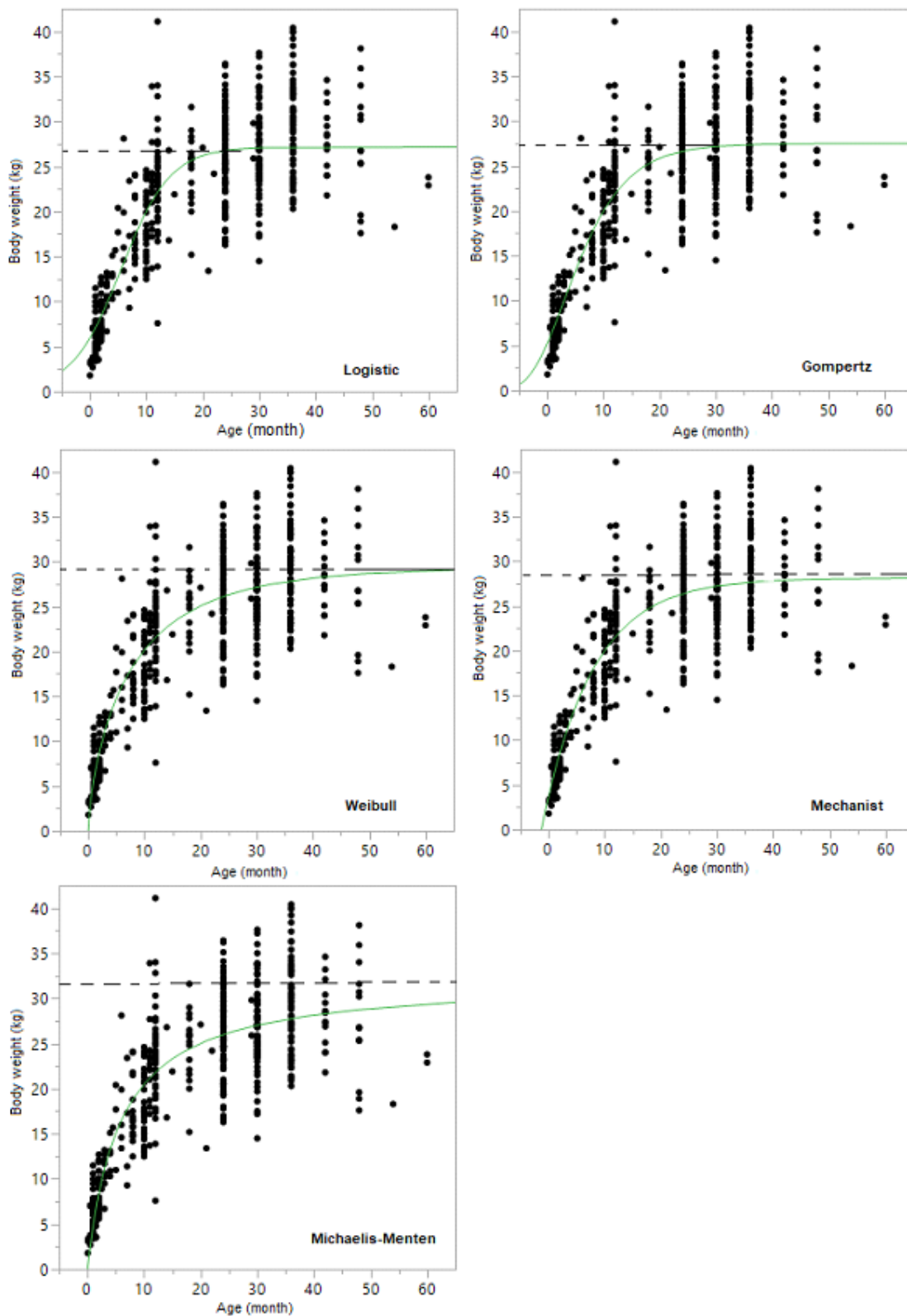
Figure 1. Growth curves of female creole sheep from the Mixteca region of Oaxaca, Mexico, adjusted by five non-linear functions. The dashed horizontal line corresponds to the estimated asymptotic (mature) body weight, and the black dots are observed weights.
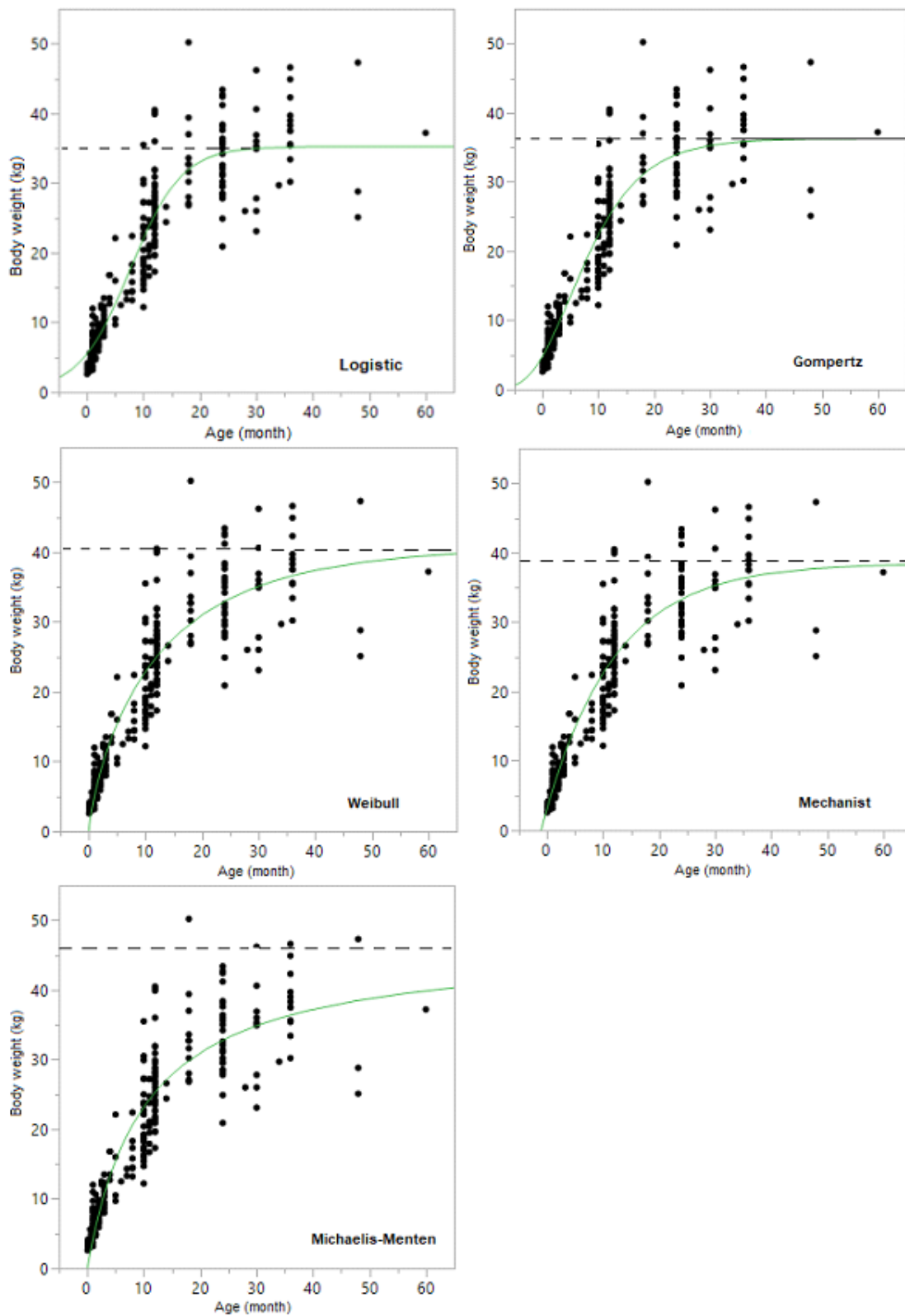
Figure 2. Growth curves of male creole sheep from the Mixteca region of Oaxaca, adjusted by five non-linear functions. The dashed horizontal line corresponds to the estimated asymptotic (mature) body weight, and the black dots are observed weights.

The age and weight at the inflexion point of the Creole sheep from the Mixteca region were only estimated for the Gompertz and Logistic models, because they are the most used models in the literature and for comparison purposes. In Pelibuey and Blackbelly sheep, the age and weight at the inflection point with the Logistic and Gompertz models were 63 and 83 days, and 13 to 18 kg of live weight, respectively (Domínguez-Viveros *et al.*, 2019). Compared with the results obtained here, the weight at the turning point was reached in Creole females between 6 and 7 months of age. In males, the age at the inflection point varied from 9 to 11 months with weights between 20 and 25 kg; a result that agrees with those reported by Bianchi (2006), Malhado *et al.* (2009) and Abegaz *et al.* (2010) regarding the comparative development of animals under ideal conditions and those under extensive schemes.

CONCLUSIONS

The nonlinear models used in this study showed that there was a different growth pattern between males and females, suggesting the use different models to study the growth kinetics between sexes. The differences, given the pattern of the curve and the growth indicators, express a low genetic potential for growth, which may be favorable under the conditions and production systems in the Mixteca region of Oaxaca, Mexico. In addition, the information from this research could help producers and specialists for better feeding systems and for breeding and conservation programs.

Conflict of interest. The authors declare that there is no conflict of interest.

Compliance with ethical standards. Do not apply.

Data Availability. Data are available upon request with the first author (avalos.raul@inifap.gob.mx)

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REFERENCES

Abegaz, S., Van Wyk, J.B. and Olivier, J.J., 2010. Estimation of genetic and phenotypic parameters of growth curve and their relationship with early growth and productivity in Horro sheep. *Archives of Animal Breeding,* 53, pp. 85-94. DOI: https://doi.org/10.5194/aab-53-85-2010

Andrade-Souza, de L., Souza-Carneiro, P.L., Mendes-Malhado, C.H., Samuel Rezende-Paiva, S., Novais-Caires, D. and Ferreira-Barreto, D.L., 2011. Curvas de crescimento em ovinos da raça morada nova criados no estado da Bahia. *Revista Brasileira de Zootecnia*, 40 (8), pp. 1700-1705.
DOI: https://doi.org/10.1590/S1516-35982011000800011

Bianchi, G. and Garibotto, G., 2002. Influencia del sexo y del largo de lactancia sobre características de crecimiento, composición de la canal y calidad de carne de corderos. Montevideo, Uruguay. *Producción Ovina,* 15, pp. 71-92.

Bianchi, G., Garibotto, G. and Bentancur, O., 2003. Efecto del sexo y del largo de lactación sobre el desempeño de corderos Corriedale pesados. III Congreso Latinoamericano de Especialistas en Pequeños Rumiantes y Camélidos Sudamericanos. 7-9 de mayo 2003. Viña del Mar, Chile. Asociación Latinoamericana de Especialistas en Pequeños Rumiantes y Camélidos sudamericanos (ALE-PRYCS), Santiago, Chile. pp.7-9.

Bianchi, G., 2006. Alternativas tecnológicas para la producción de carne ovina de calidad en sistemas pastoriles. Montevideo, Uruguy. Editorial Hemisferio Sur.

Brown, J.E., Fitzhugh Junior, H.A. and Cartwright, T.C.A. A., 1976. Comparison of nonlinear models for describing weight-age relationships in cattle. *Journal of Animal Science,* 42(4), pp. 810-818. DOI: https://doi.org/10.2527/jas1976.424810x

Domínguez-Viveros, J., Canul-Santos., E., Rodríguez-Almeida, F.A., Burrola-Barraza, M.A., Ortega-Gutiérrez, J.A. and Castillo-Rangel, F., 2019. Definición de curvas de crecimiento con modelos no lineales en borregas de siete razas con registro de pureza en México. *Revista Mexicana de Ciencias Pecuarias,* 10(3), pp. 664-675. DOI: https://doi.org/10.22319/rmcp.v10i3.4804

Gónzalez-Garduño R., Torres-Hernández, G. and Castillo-Álvarez, M., 2002. Crecimiento de corderos Blackbelly entre el nacimiento y el peso final en el trópico húmedo de México. *Veterinaria México,* 33(4), pp. 443-453. URL: https://www.redalyc.org/pdf/423/42333408.pdf

Hinojosa-Cuéllar, J.A., Oliva-Hernández, J., Torres-Hernández, G., Segura-Correa, J.C. and González- Garduño, R., 2018. Crecimiento pre y posdestete de corderos Pelibuey en clima cálido húmedo. *Nova Scientia,* 10(20), pp. 328-351. DOI: https://doi.org/10.21640/ns.v10i20.1335

Laird, A.K. 1965. Dynamics of relative growth. *Growth,* 29, pp. 249–263.

Lambe, N.R., Navajas, E.A., Simm, G. and Bünger, L.A., 2006. Genetic investigation of various growth models to describe growth of lamb of two contrasting breeds. *Journal of Animal Science,* 84(10), pp. 2642-2654. DOI: https://doi.org/10.2527/jas.2006-041

López-Carlos, M., Fernández-Mier, R., Aréchiga-Flores, C., Hernández-Briano, P., Medina-Flores, C. and Ramírez-Chéquer, J., 2021. Crecimiento de corderos de pelo en el altiplano semiárido de Zacatecas durante el invierno. *Abanico Veterinario,* 11, pp. e102. DOI: https://doi.org/10.21929/abavet2021.4

Maldonado-Jáquez, J.A., Castañeda-Bustos, V.J., Granados-Rivera, L.D., Salinas-González, H., Pastor-López, F.J. and Torres-Hernández, G., 2021. Curva de crecimiento y tasas de crecimiento absoluto y relativo de cabritos locales en el norte de México. *Tropical and Subtropical Agroecosystems,* 24(2), pp. 1 – 11. URL: https://www.revista.ccba.uady.mx/ojs/index.php/TSA/article/download/3515/1621

Malhado, C., Carneiro, P., Affonso, P., Souza, A. and Sarmento, J., 2009. Growth curves in Dorper sheep crossed with the local Brazilian breeds, Morada Nova, Rabo Largo, and Santa Inês. *Small Ruminant Research,* 84(1-3), pp. 16-21. DOI: https://doi.org/10.1016/j.smallrumres.2009.04.006

Martínez-Peña, M., Villagómez-Cortés, J.A. and Mora-Brito, A.H., 2018. Rentabilidad del sistema de producción ovina en el bajo Mixe, Oaxaca, México. Agrociencia, 52, pp. 107-122. URL: https://agrociencia-colpos.mx/index.php/agrociencia/article/view/1743/1743

Mendes, P. N., Muniz, J. A., Silva, F. F. and Mazzini, A.R.D.A., 2008. Modelo logístico difásico no estudo do crescimento de fêmeas da raça Hereford. *Ciência Rural,* 38(7), pp. 1984-1990. DOI: https://doi.org/10.1590/S0103-84782008000700029

Motulsky, H. and Christopoulos, A., 2003. Fitting Models to Biological Data using Linear and Nonlinear Regression. A practical guide to curve fitting. Graph Pad Software Inc. San Diego, California.

Nelder, J.A., 1961. The fitting of a generalization of the logistic curve. B*iometrics,* 17, pp. 89–110. DOI: https://doi.org/10.2307/2527498

Pala, A., Savas, T., Uğur, F. and Daş, G., 2005. Growth curves of Turkish Saanen goats' kids grouped for weight and body mass index. *Archives of Animal Breeding,* 48(2), pp. 185-193. DOI: https://doi.org/10.5194/aab-48-185-2005

Parés-Casanova, P.M, Caballero, M. and Perezgrovas, R., 2015. Comparación de modelos no lineales para describir curvas de crecimiento según sexo en el Borrego Chiapas. *Revista de Investigación Veterinaria del Perú,* 26(3), pp. 389-394. DOI: http://dx.doi.org/10.15381/rivep.v26i3.11170

Sarmento, J.L.R., Regazzi, A.J., Sousa, W.H.D., Torres, R.D.A., Breda, F.C. and Menezes, G.R.D.O., 2006. Estudo da curva de crescimento de ovinos Santa Inês. *Revista Brasileira de Zootecnia,* 35(2), pp. 435-442. DOI: http://doi.org/10.1590/S1516-35982006000200014

SAS. 2020. Discovering JMP version 15.1.0 Cary, NC: SAS Institute Inc.

Topal, M., Ozdemir, M., Aksakal, V., Yildiz, N. and Dogru, U., 2004. Determination of the best nonlinear function in order to estimate growth in Morkaraman and Awassi lambs. *Small Ruminant Research,* 55, pp. 229–232. DOI: https://doi.org/10.1016/j.smallrumres.2004.01.007

Vergara, G.O., Medina, R.H., Robles, S.C., Simanca, S.J. and Bustamante, Y.M., 2017. Determinación de la curva de crecimiento en ovinos criollos de pelo, mediante la utilización del modelo Gompertz, en el trópico bajo colombiano. *Revista U.D.C.A Actualidad & Divulgación Científica,* 20(2), pp. 385-391. DOI: https://doi.org/10.31910/rudca.v20.n2.2017.396