Comparison of non-linear growth models to describe the growth curve of Mehraban sheep

Fatemeh Hojjati and Navid Ghavi Hossein-Zadeh

Department of Animal Science, Faculty of Agricultural Sciences, University of Guilan, Rasht, Iran

ABSTRACT

In order to describe the growth curves in Iranian Mehraban sheep, five non-linear mathematical equations (Brody, Negative exponential, Logistic, Gompertz and Von Bertalanffy) were used. The data set used in this study was obtained from the Agricultural Organization of Hamedan province and comprised 35,414 weight records of lambs which were collected from birth to 365 days of age during 1991–2011. Each model was fitted separately to body weight records of all lambs, male and female lambs and single and twin lambs using the NLIN and MODEL procedures in SAS. The models were tested for goodness of fit using adjusted coefficient of determination ($R^2_{adj}$), root mean square error (RMSE), Durbin–Watson statistic (DW), Akaike’s information criterion (AIC) and Bayesian information criterion (BIC). The Brody model provided the best fit of growth curve in all lambs, male and female lambs and single and twin lambs due to the lower values of AIC and BIC than other models. The Logistic model provided the worst fit of growth curve for all lambs, male and female lambs and single and twin lambs. Evaluation of different growth equations used in this study indicated the potential of the non-linear functions for fitting body weight records of Mehraban sheep.

1. Introduction

Throughout the drier regions of Africa, Middle East and Asia, sheep is a major livestock resource (Hamouda and Atti 2011). In 2007, the sheep population in Iran reached 25 million heads (Ghafouri-Kesbi 2013). This large population is mainly reared for meat production to provide a part of the protein requirements of a population of 75 million people (Ghafouri-Kesbi 2013). In Iran, the demand for meat products has increased in the last two decades and will continue to rise due to the high rate in population growth (Bathaei and Leroy 1998).

Mehraban sheep is one of the important Iranian sheep breeds. This breed of sheep originates from the western province of Iran known as Hamedan and is adapted to harsh and rocky environments. The Mehraban (approximately three million heads) is the predominant breed in this province, reared primarily for meat production (Yavarifard et al. 2016). Mehraban sheep is a fat-tailed carpet wool sheep with light brown, cream or grey colour, along with a dark face and neck (Yavarifard et al. 2016).

In recent decades, many breeding programmes targeting the growth performance have been planned and performed in most of the Iranian sheep breeds (Ghafouri-Kesbi 2013). Growth, which is defined as an increase in body size per unit time, is one of the most important characteristics of farm animals (Bathaei and Leroy 1998). Growth functions available for describing growth potential are the three-parameter models (Logistic, Brody, Gompertz and Von Bertalanffy) and the two-parameter model (Negative exponential), which summarize the most important growth characteristics. These non-linear models are more effective than linear models because growth has a sigmoid form (Tariq et al. 2013). Growth curves that relate animal weight to age help elucidate growth patterns. In particular, the use of non-linear models helps condense large volumes of information into a small set of parameters that can be interpreted biologically (da Silva et al. 2012). The association of parameters with productive and reproductive traits of the animal is an important tool for using in selection programmes (Fitzhugh 1976). Growth curve parameters provide potentially useful criteria for altering the relationship between body weight and age through selection (Mukasa-mugerwa and Lahlou-Kassi 1995; Abegaz et al. 2010), and an optimum growth curve can be obtained by selection for desired values of growth curve parameters (Bathaei & Leroy 1998; Abegaz et al. 2010). Growth curves provide several applications to animal production, such as (1) evaluation of the response to distinct treatments over time; (2) analysis of the interaction between subpopulations (or treatments) and time and (3) identification of heavier animals at younger ages within a population (Bathaei and Leroy 1996; Freitas 2005; Malhado et al. 2009). Therefore, the objective of this study was to compare the goodness of fit of non-linear functions (Von Bertalanffy, Logistic, Negative exponential, Gompertz and Brody) to provide a specific shape of the growth curve from birth to 365 days of age in Iranian fat-tailed Mehraban sheep.

CONTACT Navid Ghavi Hossein-Zadeh navid.hosseinzadeh@gmail.com; nhosseinzadeh@guilan.ac.ir

Department of Animal Science, Faculty of Agricultural Sciences, University of Guilan, Rasht 41635-1314, Iran

© 2017 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
2. Materials and methods

The data set used in this study was obtained from the Agricultural Organization of Hamedan province and comprised body weights from 44 flocks between 1991 and 2011. Mehraban ewes were exposed to rams at about 18 months of age. There was a controlled mating system and each mating group including 10–15 ewes was set aside to a ram. Rams were selected at 1 year of age from some purebred flocks and were assigned to local flocks under supervision of the Breeding Station of Mehraban Sheep. The mating period was from the end of September to the end of October. Lambing was commenced in March. During the lambing season, the ewes were indoors and carefully managed. After lambing, the ewes and their lamb(s) were placed in separate pens and kept there for a few days, depending on the number of lambs born and the ewe’s rearing ability. Then a flock composed of suckling lambs and their dams was formed. During the suckling period, lambs were kept indoors and additionally fed with hay grass. Ewes were kept in the flock up to 7 years of age. Ewes usually give birth to lambs three times every 2 years. All lambs were weighed and ear tagged within 12 h after the birth. The lambs were weaned at around 90 days of age. Flocks were grazing during the daytime and housed at night (Yavarifard et al. 2016). The average of birth weight was 4.1 and 3.8 for males and females, respectively. Mature weight in males was 65–75 kg. The annual wool production in the female and males lambs was 1.5 and 1.8–2 kg, respectively. Lactation length and milk yield per lactation were 3.5 months and 55–75 kg, respectively. Also, twinning rate was 8–13%. This breed has high litter size, productivity and survival rate from birth to weaning (Khalidari 2008). Sheep have ad libitum access to Alfalfa hay, and received up to 0.5 kg/day concentrates (approximately 16% protein and 72% total digestible nutrients) composed of 58% barley, 25% dried sugar beet pulp, 15% wheat bran, 1% bone meal and 1% common salt (Bathaei and Leroy 1998).

The initial data set contained 35,414 body weight records from 26,690 animals. The data were screened several times and defective and out of range records were deleted. The final data set consisted of 7960 body weight records related to 1592 animals and additionally fed with hay grass. Ewes were kept in the flock up to 7 years of age. Ewes usually give birth to lambs three times every 2 years. All lambs were weighed and ear tagged within 12 h after the birth. The lambs were weaned at around 90 days of age. Flocks were grazing during the daytime and housed at night (Yavarifard et al. 2016). The average of birth weight was 4.1 and 3.8 for males and females, respectively. Mature weight in males was 65–75 kg. The annual wool production in the female and males lambs was 1.5 and 1.8–2 kg, respectively. Lactation length and milk yield per lactation were 3.5 months and 55–75 kg, respectively. Also, twinning rate was 8–13%. This breed has high litter size, productivity and survival rate from birth to weaning (Khalidari 2008). Sheep have ad libitum access to Alfalfa hay, and received up to 0.5 kg/day concentrates (approximately 16% protein and 72% total digestible nutrients) composed of 58% barley, 25% dried sugar beet pulp, 15% wheat bran, 1% bone meal and 1% common salt (Bathaei and Leroy 1998).

The initial data set contained 35,414 body weight records from 26,690 animals. The data were screened several times and defective and out of range records were deleted. The final data set consisted of 7960 body weight records related to 1592 animals, including 844 males and 748 females born between January 2001 and December 2011. Number of single and twin lambs were 1168 and 424, respectively. Animal weights were measured from 26,690 animals. The data were screened several times and defective and out of range records were deleted. The final data set consisted of 7960 body weight records related to 1592 animals. Mature weight in males was 65–75 kg, respectively.

The mathematical forms of non-linear growth functions are as follows:

\[ y = A \left(1 - Be^{-Kt}\right), \]  
(1)

\[ y = A - \left(Ae^{-Kt}\right), \]  
(2)

\[ y = \frac{A}{1 + Be^{-Kt}}, \]  
(3)

\[ y = Ae^{Be^{-Kt}}, \]  
(4)

\[ y = A \left(1 - Be^{-Kt}\right)^3, \]  
(5)

where \( y \) represents body weight at age \( t \) (day), \( A \) represents asymptotic weight, which is interpreted as mature weight, and \( B \) indicates the proportion of the asymptotic mature weight to be gained after birth, established by the initial values of \( W \) (weight) and \( t \). \( K \) is a function of the ratio of maximum growth rate to mature weight, normally referred to as maturing rate. Large \( K \) values indicate early maturing animals and vice versa.

Each model was fitted separately to body weight records of all lambs, males and female lambs and singles and twin lambs using the NLIN and MODEL procedures in SAS (2002) and the parameters were estimated. The NLIN procedure produces least squares or weighted least squares estimates of the parameters of a non-linear model. When non-linear functions were fitted, the Gauss–Newton method was used as the iteration method. The models were tested for goodness of fit (quality of prediction) using adjusted coefficient of determination \((R^2_{adj})\), residual standard deviation or root mean square error \((\text{RMSE})\), Durbin–Watson statistic \((\text{DW})\), Akaike’s information criterion \((\text{AIC})\) and Bayesian information criterion \((\text{BIC})\).

\[ R^2_{adj} = 1 - \frac{\left[n - 1\right]}{\left[n - p\right]} \left[1 - R^2\right], \]  
(6)

where \( R^2 \) is the multiple coefficient of determination \((R^2 = 1 - \frac{\text{RSS}}{\text{TSS}})\), \( \text{TSS} \) is total sum of squares, \( \text{RSS} \) is residual sum of squares, \( n \) is the number of observations (data points) and \( p \) is the number of parameters in the equation. The \( R^2 \) lies always between 0 and 1, and the fit of a model is satisfactory if \( R^2 \) is close to unity.

\[ \text{RMSE} = \sqrt{\frac{\text{RSS}}{n - p - 1}}, \]  
(7)

where \( \text{RSS} \) is residual sum of squares, \( n \) is the number of observations (data points) and \( p \) is the number of parameters in the equation. \( \text{RMSE} \) value is one of the most important criteria to compare the suitability of used growth curve models. Therefore, the best model is the one with the lowest \( \text{RMSE} \).

\[ \text{DW} = \frac{\sum_{t=1}^{n} \left(e_t - e_{t-1}\right)^2}{\sum_{t=1}^{n} e_t^2}, \]  
(8)

where \( e_t \) is the residual at time \( t \) and \( e_{t-1} \) is residual at time \( t - 1 \).

\[ \text{AIC} = n \times \ln \left(\text{RSS}\right) + 2p. \]  
(9)

A smaller numerical value of \( \text{AIC} \) indicates a better fit when comparing models.
BIC combines maximum likelihood (data fitting) and choice of model by penalizing the (log) maximum likelihood with a term related to model complexity as follows:

\[ BIC = n \ln \left( \frac{RSS}{n} \right) + pln(n) \] (10)

A smaller numerical value of BIC indicates a better fit when comparing models.

3. Results

Parameter estimates for different growth models in Mehraban sheep are presented in Table 1. Also, goodness-of-fit statistics for comparing different models are reported in Table 2. The \( R^2_{adj} \) range was from 0.98 to 0.99, and Brody equation provided the greatest \( R^2_{adj} \) value for all lambs, males, females, singles and twins, and the Logistic model provided the lowest values of \( R^2_{adj} \) for males, females, singles, twins and all lambs. Also, the Brody function had the lowest values of DW for males and females, singles and twins and all lambs. In general, DW values indicated non-autocorrelation between the residuals. The Brody equation provided the lowest values of RMSE, AIC and BIC for males, females, singles and twins and all lambs. The Logistic model provided the worst fit of growth. For males, females, singles, twins and all lambs, the least asymptotic weight was for Logistic equation (Table 1). For all lambs, the greatest value of A parameter was for the Brody model (66.90) and the lowest was for the Logistic model (51.30). Also, the greatest value of B parameter was for the Logistic model (7.03) and the lowest was for Von Bertalanffy (0.58). In addition, the greatest value of \( K \) parameter was observed in the Logistic model (0.0157) and the lowest was for Brody equation (0.0039). The negative correlation of −0.96 to −0.98 between A and \( K \) parameters were obtained based on the best model for all lambs, male and female lambs and singles and twins. Predicted body weights (kg) as a function of age (days) obtained with different growth models for all lambs, males and female lamb and single and twin lambs are presented in Figures 1–5. The growth curves obtained were typically sigmoid.

4. Discussion

In this study, only a suitable model was selected for growth curve. The Brody model provided the best fit of growth curve in females and males, singles and twins and all lambs due to the lower values of RMSE, AIC and BIC than other models. For this reason, Brody function is the best among a number of mathematical models compared. Similar to this study, Bathaei and Leroy (1996) evaluated the growth curve in Iranian fat-tailed Mehraban sheep using Brody function because of interpretation simplicity and ease of estimation. Similar to the current study, Akbas et al. (1999) studied the fitting performance of the Brody, Negative exponential, Gompertz, Logistic and Von Bertalanffy models to data on weight–age of Kývýrcý and Daglýc male lambs and found that the Brody model was the best equation for describing the growth of lambs. Ghavi Hossein-Zadeh (2015) compared the Brody, Logistic, Gompertz, Richards, Negative exponential and Von Bertalanffy models to describe the growth curve in Shall lambs and found that the Richards model was the best equation for describing the growth in males, females and all lambs. Tariq et al. (2013) selected the Morgan–Mercer–Flodin model as the best-fitted equation for growth curve in Mengali sheep breed of Balochistan. Similar to the results of this study, Gbangboche et al. (2008) selected the Brody model as the best function to fit the growth curve of African Dwarf sheep. Freitas (2005) reported that Logistic, Von Bertalanffy and Brody functions were more versatile to fit growth curves in sheep. Lambe et al. (2006) selected the Richards and Gompertz models for their accuracy of fit among for competing models (Gompertz, Logistic, Richards and the exponential model). Topal et al. (2004) reported that the Gompertz and Von Bertalanffy models showed the best fit in Morkaraman and Awassi lambs. Malhado et al. (2009) reported that both Gompertz and Logistic functions presented the best fit of growth curve in a crossbreed of Dorper sheep with the local Brazilian breeds, Morada Nova, Rabo Largo and Santa Inés. Sarmento et al. (2006) observed that the Gompertz function presented the best adjustment when compared to the other models in studies of growth curves of Santa Inés sheep flocks in the state of Paraíba.
Brazil. Goliomytis et al. (2006) reported the excellent fit of the Richards function to the weight–age data of Karagouniko sheep. Alizadeh’s (2015) study on Moghani sheep indicated that the Gompertz model was the best fitted for growth curve among the Brody, Gompertz and Logistic models. Bahreini Behzadi et al. (2010) concluded that the von Bertalanffy and Logistic models were the best for the prediction of Baluchi sheep growth with the high accuracy and low error. Also, in study on Mvrkaraman and Kyvyrsk sheep, the Gompertz model was the best fitted for growth curve (Eyduran et al. 2008).

Parameter $A$ is an estimate of asymptotic weight, which can be interpreted as mature or adult weight. Greater estimate of $A$ parameter in the models fitted in this study may indicate that animals are heavy as adults and may be considered slow growth, as these sheep require more time to reach maturity compared to other breeds. The definition of an optimum adult weight is controversial, because it depends on the species, breed, selection method, management system and environmental conditions (Malhado et al. 2009). Contrary to the current results, da Silva et al. (2012) reported high asymptotic weight estimates in Santa Inês sheep. Malhado et al. (2008) obtained a values ranging from 29.14 to 32.16 kg in Texel × Santa Inês crossed sheep and Malhado et al. (2009) reported values of 29.35–32.41 in the fit of different growth functions for local Brazilian breeds, Morada Nova, Rabo Largo and Santa Inês sheep. Animals with high $K$ values show a precocious maturity compared to those with lower $K$ values and similar initial weight. The parameter $K$, which represents the maturation rate, is another important feature to be considered, since it indicates the growth speed to reach the asymptotic weight. In this study, female and twin lambs generally obtained higher values of $K$ compared to other groups.

### Table 1. Parameter estimates (standard errors in parentheses) for the different growth models in Mehraban sheep.

| Item                 | Parameter | Brody          | Negative exponential | Logistic | Gompertz | Von Bertalanffy |
|----------------------|-----------|----------------|----------------------|----------|----------|-----------------|
|                      |           | $A$            | $B$                  | $K$      | $A$      | $B$             | $K$             | $A$          | $B$       | $K$       | $A$          | $B$        | $K$          | $A$          | $B$        | $K$          | $A$          | $B$        | $K$          | $A$          | $B$        | $K$          | $A$          | $B$        | $K$          | $A$          | $B$        | $K$          |
| All lambs            |           | 66.90 (0.5098) | 62.83 (0.3713)       | 51.30 (1.1382) | 54.05 (1.840) | 56.14 (2.240) |
| Male lambs           |           | 0.0039 (0.000059) | 0.0046 (0.000054)   | 0.0157 (0.000143) | 0.0099 (0.000096) | 0.0079 (0.000081) |
|                      |           | 68.50 (0.7113) | 64.00 (0.5117)       | 51.95 (1.870)  | 54.84 (2.502)  | 57.04 (3.059)  |
|                      |           | 0.0038 (0.000076) | 0.0045 (0.000071)   | 0.0155 (0.000185) | 0.0098 (0.000124) | 0.0078 (0.000105) |
|                      |           | 65.18 (0.7257) | 61.54 (0.5365)       | 50.57 (2.037)  | 53.17 (2.695)  | 55.14 (3.265)  |
| Female lambs         |           | 0.05 (0.00252) | –                    | 7.08 (1.741)   | 2.45 (0.0310)  | 0.58 (0.0052)  |
|                      |           | 0.0040 (0.000091) | 0.0047 (0.000083)   | 0.0160 (0.000222) | 0.0102 (0.000149) | 0.0081 (0.000125) |
|                      |           | 67.41 (0.6319) | 62.92 (0.4486)       | 51.46 (1.672)  | 54.26 (2.248)  | 56.39 (2.749)  |
| Single lambs         |           | 0.0038 (0.000071) | 0.0046 (0.000065)   | 0.0155 (0.000167) | 0.0098 (0.000113) | 0.0078 (0.000096) |
|                      |           | 65.66 (0.8390) | 62.62 (0.6511)       | 50.87 (2.422)  | 53.51 (3.141)  | 55.49 (3.781)  |
| Twin lambs           |           | 0.10 (0.00301) | –                    | 7.59 (2.397)   | 2.54 (0.0407)  | 0.60 (0.00670) |
|                      |           | 0.0082 (0.000150) | 0.0104 (0.000181)   | 0.0164 (0.000278) | 0.0046 (0.000096) | 0.0040 (0.000105) |

Notes: $A$ is the predicted asymptotic weight at maturity (kg), $B$ is the proportional difference between $A$ and birth weight (kg) and $K$ is the rate of maturing.

### Table 2. Comparing goodness of fit for different growth curves in Mehraban sheep.

| Item           | Statistics | Brody | Negative exponential | Logistic | Gompertz | Von Bertalanffy |
|----------------|------------|-------|----------------------|----------|----------|-----------------|
|                |            | $R^2_A$ | DW                   | $R^2_A$  | DW       | $R^2_A$  | DW       | $R^2_A$  | DW       | $R^2_A$  | DW       |
| All lambs      |            | 0.9839 | 1.1773               | 1.2485   | 5.0677   | 4.9036   | 4.6899   |
| Male lambs     |            | 4.6571 | 4.765                | 5.0677   | 9.7337   | 9.6812   | 9.6104   |
| Female lambs   |            | 95992  | 96357                | 97337    | 25860    | 25328    | 24627    |
| Single lambs   |            | 24515  | 24879                | 25860    | 25328    | 25328    | 24627    |
| Twin lambs     |            | 0.9824 | 0.9816               | 0.9794   | 0.9808   | 0.9822   | 0.9822   |

Notes: $R^2_A$, adjusted coefficient of determination; RMSE, root mean square error; DW, Durbin–Watson; AIC, Akaike information criterion; BIC: Bayesian information criterion.
showed higher values for this parameter than male and single lambs indicating higher maturity rates (they reached mature weight earlier). The greater values of $K$ parameter for female lambs in this study indicated higher maturity rates. Therefore, animals with higher $K$ values achieved asymptotic weight early. Bathaei and Leroy (1996) estimated much higher $K$ values for body weight than the current study, for male and female Mehraban sheep, when applying the Brody growth model, over a 48-month period. This difference could be attributed to the time unit they used, month instead of day as in the present study, and the different growth function used (Goliomytis et al. 2006). Ghavi Hossein-Zadeh (2015) reported greater $K$ values in males, females and all lambs of Shall sheep compared to the present study. The most important biologically correlation for a growth curve is between $A$ and $K$ parameters. The negative correlation between these parameters in the current study implies that the earliest animals are less likely to exhibit high adult weight (da Silva et al. 2012). Also, sigmoid patterns of growth curves were obtained by other studies similar to present study (Goliomytis et al. 2006; Malhado et al. 2009; da Silva et al. 2012; Ghavi Hossein-Zadeh 2015).

The shape of the growth curve showed that male and single lambs were heavier than female and twin lambs, respectively. The higher weight of males than females has been described by hormonal and physiological differences between sexes which is in agreement with the results of Gbangboche et al. (2008) in Dwarf sheep in West Africa. The lower weight of twins was similarly reported (Armbruster et al. 1991; Abassa et al. 1992; Yapi-Gnaore et al. 1997) and in this case, the limited capacity of dams to provide more nourishment for the development of multiple foetuses and more milk for new born lambs could explain their low performance.

5. Conclusion

The five non-linear functions investigated in the present study were adequate in describing the growth pattern in Mehraban sheep. The Brody model provided the best fit of growth curve in all lambs, male and female lambs and single and twin lambs due to the lower values of AIC and BIC than other models. The results of this study can help planning farm management strategies and decision-making regarding the culling of poor producers and selecting the highly productive animals just by considering their growth curve.

Acknowledgements

The authors would like to acknowledge the Agricultural organization of Hamedan province for providing the data used in this study.

Disclosure statement

No potential conflict of interest was reported by the author.

ORCID

Navid Ghavi Hossein-Zadeh http://orcid.org/0000-0001-9458-5860

References

Abassa KP, Pessinaba J, Adeshola-Ishola A. 1992. Croissance pre-sevrage des agneaux Djallonke au Centre de Kolokope (Togo). Revue de levage et de Me decine Ve te rinaire des Pays Tropicaux. 45:49–54.
Abegaz S, Van Wyk JB, Olivier JJ. 2010. Estimation of genetic and phenotypic parameters of growth curve and their relationship with early growth and productivity in Horro sheep. Arch Tierz. 53(1):85–94.
Akbas Y, Taskyn T, Demiroren E. 1999. Comparison of several models to fit the growth curves of Kivircik and Daglic male lambs. Turkish J Vet Anim Sci. 23(Suppl 3):537–544.
Alizadeh H. 2015. Estimation of genetic parameters of growth curve characteristics in Moghani sheep [MSc thesis]. Rasht: Guilan University, Agriculture College. Persian.
Armbruster T, Peters KJ, Metz T. 1991. Sheep production in the humid zone of West Africa. Ill. Mortality and productivity of sheep in improved production systems in Co ted’Ivoire. J Anim Breed Genet. 108:210–219.

Bahreini Behzadi MR, Aslaminejad AA, Ebrahimzadeh M. 2010. Evaluation of different nonlinear growth models for prediction of Baluchi sheep growth. Fourth Iranian Congress of Animal Science; Karaj, Iran [In Persian].

Bathaei SS, Leroy PL. 1996. Growth and mature weight of Mehraban Iranian fat-tailed sheep. Small Rumin Res. 22:155–162.

Bathaei SS, Leroy PL. 1998. Genetic and phenotypic aspects of the growth curve characteristics in Mehraban Iranian fat-tailed sheep. Small Rumin Res. 29:261–269.

Burnham KP, Anderson DR. 2002. Model selection and multimodel inference: a practical–theoretic approach. 2nd ed. Berlin: Springer-Verlag.

da Silva LSA, Fraga AB, da Silva FDL, Guimarães Beelen PM, de Oliveira Silva RM, Tonhati H, Barros CDC. 2012. Growth curve in Santa Inês sheep. Small Rumin Res. 105:182–185.

Eyduran E, Kucuk M, Karakus K, Ozdemir T. 2008. New approaches to determination of the best nonlinear function describing growth at early phases of Kivrck and Morkaraman breeds. J Anim Vet Adv. 7(7):799–804.

Fitzhugh Jr HA. 1976. Analysis of growth curves and strategies for altering their shape. J Anim Sci. 42:1036–1051.

Freitas AR. 2005. Curvas de crescimento na produç ão animal. R Bras Zootec. 34:786–795.

Gbangocho AB, Giele-Kakai R, Salifou S, Albuquerque LG, Leroy P. 2008. Comparison of non-linear growth models to describe the growth curve in West African sheep. Animal. 2:1003–1012.

Ghafoori-Kesbi F. 2013. (Co)variance components and genetic parameters for growth rate and Kleiber ratio in fat-tailed Mehraban sheep. Arch Tierz. 56:55:564–572.

Ghavi Hossein-Zadeh N. 2014. Comparison of non-linear models to describe the lactation curves of milk yield and composition in Iranian Holsteins. J Agr Sci. 152:309–324.

Ghavi Hossein-Zadeh N. 2015. Modeling the growth curve of Iranian Shall sheep using non-linear growth models. Small Rumin Res. 130:60–66.

Goliomytis M, Orfanos S, Panopoulos E, Roudakis E. 2006. Growth curves for body weight and carcass components, and carcass composition of the Karagouniko sheep, from birth to 720 d of age. Small Rumin Res. 66:222–229.

Hamoudaa MB, Atti N. 2011. Comparison of growth curves of lamb fat tail measurements and their relationship with body weight in Babarine sheep. Small Rumin Res. 95:120–127.

Khaladari M. 2008. Sheep and goat husbandry, 3rd ed. Tehran: Sid Publications, pp. 30–78. Persian.

Lambe NR, Navajas EA, Simm G, Bünger L. 2006. A genetic investigation of various growth models to describe growth of lambs of two contrasting breeds. J Anim Sci. 84:2642–2654.

Malhado CHM, Carneiro PLS, Souza AAO Jr, Sarmento JLR. 2009. Growth curves in Dorper sheep crossed with the local Brazilian breeds, Morada Nova, Rabo Largo, and Santa Inês. Small Rumin Res. 84:16–21.

Malhado CHM, Carneiro PLS, Santos PF, Azevedo DMMR, Souza JC, Affonso PRAM. 2008. Curva de crescimento emovinos mestiç os Santa Inês×Texel criados no Sudoeste do Estado da Bahia. Rev Bras Saúde Prod An. 9:210–218.

Mukasa-Mugerwa E, Lahlou-Kassi A. 1995. Reproductive performance and productivity of Menz sheep in the Ethiopian highlands. Small Rumin Res. 17:167–177.

Sarmento JLR, Regazzi AJ, Sousa WH, Torres RA, Breda FC, Menezes GRO. 2006. Estudo da curva de crescimento de ovinos santa Inês. R Bras Zootec. 35(2):435–442.

SAS. 2002. SAS user`s guide v. 9.1: statistics. Cary (NC): SAS Institute, Inc.

Topal M, Ozdemir M, Aksakal V, Yildiz N, Dogru U. 2004. Determination of the best nonlinear function in order to estimate growth in Morkaraman and Awassi lambs. Small Rumin Res. 55:229–232.

Yapi-Gnaore CV, Oya A, Rege JEO, Dagno B. 1997. Analysis of an open nucleus breeding programme for Djallonke sheep in the Ivory Coast. I. Examination of non-genetics factors. Anim Sci. 64:291–300.

Yavarifard R, Ghavi Hossein-Zadeh N, Shadparvar AA. 2016. Estimation of genetic parameters for reproductive traits in Mehraban sheep. Czech J Anim Sci. 60(6):281–288.