AGRICULTURAL AND FOOD SCIENCE

Agricultural and Food Science (2024) 33: 201–211

https://doi.org/10.23986/afsci.145198

Statistical modelling of growth curve for longitudinal data on a feeding trial in goat breeds

Ihab Shaat[1,2], Alaa Alhamadani[1], Khalfan Al-Sharji[1], Rashid Al-Habsi[1], Talal Al-Sedeiri[1], Asila Al Naabi[2] and Asko Mäki-Tanila[3]

[1]Livestock Research Center, Directorate General for Agricultural and Livestock Research, Ministry of Agriculture, Fisheries and Water Resources, Oman

[2]Mawarid, Ministry of Higher Education, Research & Innovation, Oman

[3]Department of Agricultural Sciences, University of Helsinki, Finland

e-mail: ihab.m.shaat@gmail.com

The growth curve parameters were estimated extending a linear regression to higher degree polynomial with attempts to use also the biologically appealing Gombertz function. The data contained monthly weight records from weaning to the age of 14 months of kids in two Omani goat breeds Sahrawi and Jabbali used in a feeding trial assessing the effect of concentrate supplement (14% crude protein). The growth curve parameters were estimated within the fixed effects breed and feed concentrate level (2 or 3% of live body weight) with an extension to mixed models using animals as random effects. The parameters and model contrasting were performed with ML or REML as appropriate with relative comparison relying on AIC and significance testing of estimated parameters. The mixed model analyses were performed with publicly available R software package programs. The fixed effect cubic regression with linear random effect model fitted into the data. The higher level of concentrates improved the immediate post-weaning growth in the same way in the breeds while the subsequent growth curve differed with more pronounced weight increments in the Jabbali breed.

Key words: growth rate, concentrate feeding, polynomial regression, mixed model, Omani goats

Introduction

Goats are well adapted to the harsh environment and limited feed to produce high protein products, in the form of milk and meat for human consumption. The overall productivity for a meat producing herd is made of several traits, such as kids' birth weight, growth rate, slaughter weight, carcass yield and does' age at puberty, kidding interval and litter size (e.g. the review by Raheem et al. 2024). Herd management is paramount in deciding about breed, feed and nutrition and in mitigating stress and disease risks. In most subtropical and arid countries, the productivity of goats is below their potential with inefficiency at both the primary production and post-production system with slaughter and meat processing industry (Devendra 1999, Matossian de Pardos 2000). Although goats tolerate high temperatures and humidity of the tropics, they do have reproduction problems associated with nutritional deficiencies, which causes drawbacks in the overall productivity. In a grazing situation, animals should have access to lush or leafy forage or high pasture. In addition, goats should be supplemented with a concentrate feed when the grazed forage does not satisfy their nutritional requirements (Preston and Leng 1987).

Animals' response to different feeding options can be studied with small scale experiments. In the experiments it has been customary to express the growth performance as group means and variance between groups, without providing information on changes over time. When longitudinal data is available, a growth curve can be estimated. In a statistical analysis, the curve function could be estimated with allowance for fixed effects, such as feeding intensity, breed and sex, and for a random animal effect to explain more fully the variation and thereby improve the power of an analysis (e.g. Murphy et al. 2016). Biologically relevant growth curves usually have a sigmoidal shape, with a rapid early growth up to the inflection point (of the maximum rate), followed by deceleration until mature weight is reached, which is best described by a non-linear Gompertz function (Winsor 1932, Wilson 1977). An alternative and computationally simpler way is to use a pure mathematical approach and fit a linear polynomial regression function. Growth curves can be used for improving feeding strategies and meeting the nutrient requirements in the early growth of different breeds and individual animals. They would also allow producers to detect and respond to slower growth phases.

In Oman, goat meat is highly preferred by the local population, and goats are slaughtered regularly for social and religious occasions. The total local goat population is over two million (MAF 2013). The performance of local goat

Received 22 April 2024 / Accepted 20 October 2024
The Scientific Agricultural Society of Finland

breeds in Oman has not been adequately assessed under improved management systems. This study focusses on analyzing the possible immediate gain and the overall pattern in growth due to improved diet. The research has two primary objectives. The first goal is to implement the statistical methodology applicable to investigating post-weaning growth patterns across fixed effects. Secondly, the methodology is utilized in assessing the influence of high-level nutrition on the post-weaning growth in the local goat breeds.

Material and methods

Feeding trial

The data stems from a feeding trial carried out in 2015 in two main local Omani goat breeds (Jabbali and Sahrawi) at Rumais Research Station of the Livestock Research Center under the Ministry of Agriculture, Fisheries and Water Resources. Data were collected on 22 male kids over the experimental period after weaning from four to 14 months of age. Body weight was recorded weekly over the studied period.

The kids were fed Rhodes grass hay (*Chloris guyana*) *ad libitum* and pelleted commercial concentrate feed with the levels 2 or 3% of live weight. The concentrate mixture consisted of corn and barley grain, wheat bran, soybean meal, molasses, vitamins, major and trace minerals with on average 14% of crude protein, 2% crude fat and 9% crude fiber and 10.5 MJ kg^{-1} of metabolic energy. In the feeding trial, the animals were housed in semi-open pens and water was offered all the time by the automatic water supply.

Breed characterization

Local Jabbali and Sahrawi goat breeds have a promising performance in Oman. They are used mainly for meat production. The Jabbali breed is widely spread across the mountain ridge in the north. The breeders have made much improvement in this breed, and it is called Rahebi or Sawalem. The color varies from brown to light brown with a large head, curved nose, small ears and short tail. The breed is widely used for meat production and is raised under medium-input production system (Shaat and Al-Habsi 2016).

Sahrawi breed, called desert breed, is found over plains and valleys all over the country. Black body with brown stripes around the neck and the belly characterizes it. The head is small and both sexes have horns. The legs are fine of medium length and the ears are of medium length. The breed is raised under a medium-input system and is widely used for both meat and milk production (Shaat and Al-Habsi 2016).

Herd management

The kids used for the experiment were born in February – March within six weeks, hence no season effect was included in the statistical model. The parents' mating period of 45 d was in September – October. Does were randomly divided into mating groups of 15–20 with each under a randomly assigned fertile buck. The bucks were selected on yearling weight, body conformation and birth type. Does were first joined with a buck at the age of about 18 m with their age at kidding varying from 2 to 6 years. The pedigree data was recorded. Full sib and half sib mating were avoided. The Sahrawi kids were sired by seven bucks and the Jabbali kids by five bucks. The average additive relationship amongst pairs of kids in the experiment was 0.034 in Sahrawi and 0.050 in Jabbali, with maximum value being 0.50 (full sibs of unrelated parents) in both breeds. In the statistical analyses the kids were assumed to be unrelated. The experimental groups were the following: Sahrawi had 5 kids at 2% concentrate level and 7 at 3% level, and Jabbali 4 and 6 kids, respectively. In the Jabbali breed, at the initial stage of the experiment two kids had been lost from the 2% level group. Kids were weaned at three months of age.

Studied traits

The traits considered were monthly weight records from the age of three months (weaning) up to the age of 14 months, also the birth weight data was used. Weights were adjusted by interpolating linearly over the weighing dates. Preweaning daily gain (*PREW*, g d^{-1}) was computed from weights at birth and weaning, post weaning daily gain (*PSTW,* g d^{-1}) was computed from the difference of weights at weaning and at six months of age. The daily gain (g d^{-1}) during the whole trial period was calculated from the difference between the weaning weight and the final weight at fourteen months of age. The growth curve analysis used the monthly records from weaning until the age of 14 months.

Statistical models with fixed effects

Single time point records

The data has a kid's dam's age. The first model investigated the influence of kid's dam's age on kids' weight. This is studied by analysing the variation in the preweaning daily gain (from birth to weaning) before the feeding trial. The statistical model is

$$PREW_{ijk} = \mu + breed_i + dam's\ age_j + e_{ijk} \qquad (1.1)$$

where μ refers to the overall level, *breed* to the fixed breed effect with two classes (i = 1, 2), *dam's age* is a fixed effect with classes 2, …, 6 years of age and *e* is a random residual effect accounting for the variation within the fixed effect classes with the subscript *k* running from 1 to the number of animals in the two breeds, i.e. 12 in Sahrawi and 10 in Jabbali. The residual effects are independent and identically distributed following a normal distribution, $N(\mathbf{0}, \boldsymbol{I}\sigma_e^2)$ where ***I*** is the identity matrix and σ_e^2 is the residual variance (i.e. the variance in the analysed trait not explained by the chosen fixed effects).

The study is focussed on the effect of breeds and increased feed concentrate level on the post-weaning growth until the age of six months. Both effects have two classes and were considered as fixed effects. The statistical model with these effects were

$$PSTW_{ijk} = \mu + breed_i + level_j + e_{ijk} \qquad (1.2)$$

$$PSTW_{ijk} = \mu + breed \times level_{ij} + e_{ijk} \qquad (1.3)$$

where μ refers to the overall level, *breed* is like in the model (1.1), *level* is the fixed concentrate level in the feed with two classes, either 2 or 3 % of the live body weight (respective index *k* = 2, 3), (*breed × level*) the interaction effect between the fixed effects and *e* refers to the random residual effect accounting for the variation within the fixed effect classes with the index *k* running from 1 to the number of observations (4, 5, 6 or 7) in the smallest group level. The properties of residual effects are similar to those of the model (1.1). The statistical models (1.2) and (1.3) were also used to analyse the variation in the daily gain over the period from weaning until the end of the experimental final weight at the age of 14 month.

Longitudinal data

Initially we compared polynomial regression models with linear, quadratic, and cubic curve on time with the aforementioned fixed effects except kid's dam's age. The mathematical formulations are the following: Let the analyzed record be the *weight* of a kid *k* in *breed i* with concentrate *level j* at month *t* for *i* = 1,2, *j* = 1,2, *k* = from 1 to the number of individuals in the respective class *ij* (4, 5, 6 or 7) and t = 3, …, 14). The statistical models

$$weight_{ijk} = \mu + breed \times level_{ij} + b_{1ij}\,t + e_{ijk} \qquad (2.1)$$

$$weight_{ijk} = \mu + breed \times level_{ij} + b_{1ij}\,t + b_{2ij}\,t^2 + e_{ijk} \qquad (2.2)$$

$$weight_{ijk} = \mu + breed \times level_{ij} + b_{1ij}\,t + b_{2ij}\,t^2 + b_{3ij}\,t^3 + e_{ijk} \qquad (2.3)$$

represent the slope of the linear, quadratic, and cubic terms (fixed coefficients) of the polynomial response of weight on the time variable (or age) with *t* running from 3 to 14 months. The random residual effect is assumed to have the distribution given earlier.

Random effect part in the statistical models

Improving the power of the analysis and fully using the information, we consider the individuals' random deviation from the fixed model estimates of regression coefficients. We can investigate whether the fit of data can be improved by adding a random intercept term to the baseline fixed effect model. Random effects represent individual effects as random deviations from the fixed effects, and they allow each animal within a breed – nutrition-level class to have its own curve with its own particular features. Random regression models were considered for linear, quadratic, and cubic mean response functions. As example, we consider the quadratic function

$$weight_{ijk} = \mu + breed \times level_{ij} + u_{0ijk} + (b_{1ij} + u_{1ijk})\, t + (b_{2ij} + u_{2ijk})\, t^2 + \, e_{ijk} \qquad (3)$$

where in addition to the aforementioned fixed effects, subscripts and random residual effect, there are random intercept u_0 and random 1st and 2nd order regression coefficients u_1 and u_2, respectively. The fixed part of the model is expressed as $\mu + breed \times level_{ij} + b_{1ij}\, t + b_{2ij}\, t^2$ and the random part of the model is expressed as $u_{0ijk} + u_{1ijk}\, t + u_{2ijk}\, t^2 + \, e_{ijk}$. For l (m) = 0, 1, 2 each $u_1 \sim N(\mathbf{0}, \boldsymbol{I}\sigma_e^2)$ and has covariance $\sigma_{lm(m \neq l)}$ with the other two.

We can also assess if the residuals within individuals display some autocorrelation possibly reflecting the degree to what extent the records close in time are more strongly related to each other than those far apart in age. It is further possible to see how the correlation is changed and possibly vanished when more parameters are included in the statistical models.

Solving the parameters and statistical testing of their significance

The estimates of fixed level classes have standard errors and t-tests for significance. ANOVA tables are computed for the fixed effects and F-values are computed as test statistics. The fixed effect models are solved with maximum likelihood (ML) (see Lindstrom and Bates 1988) and nested models are compared using likelihood ratio test (LRT) with the formula $-2\, log \frac{likelihood(null\ hypothesis\ model)}{likelihood(alternative\ model)}$ or extant vs. new model. Mixed model cases are solved using restricted ML (REML), and given the same fixed effects in the models, LRT can be computed using the restricted log-likelihood function. The significance of the –2 log-likelihood deviance is deduced from a chi-squared distribution using the degree of freedom equal to the number of parameter differences between the contrasted models. LRT statistic can be computed using REML log-likelihood but comparing it to the chi-square statistic is incorrect because the variance structures between contrasted models differ (cf. Meyer 2001). More general comparison between the mixed models relies under normality assumptions on minimized value of –log-likelihood. Further, Akaike's Information Criterion (AIC) was used in evaluating alternative model in terms of their fitting performance (Akaike 1973). The formula of AIC is $2 \times$ *number of parameters estimated* – log(*likelihood of parameter estimates*). The number of parameters refers to the fixed intercept and effects and the random intercept and effects and their covariances and the random residual effect. Lower values of the statistics imply preferred goodness of fit to the model to the data amongst the investigated models and a more accurate explanation of the variation. Adding more factors into the model penalizes the stat istic for overfit as AIC will increase by 2 for every additional parameter estimated.

Gombertz growth curve

Ideally the growth curve should be found out by using a biologically appealing non-linear Gompertz function (Winsor 1932). The function will imitate a sigmoidal (S shaped) curve, which for an individual's *i* weight measurement at age *t* can be expressed using the statistical model

$$weight_j = a_i \, \exp\{-b_i \; exp\{-c_i \, t_{ij}\}\} + e_{ij} \qquad (4)$$

where the three biologically interpretable parameters are *a* referring to the mature weight, *b* giving the ratio of mature weight to birth weight in log scale, and *c* representing the maturation rate as the ratio of maximum growth rate to mature weight (expressed as kg/time unit per mature weight) and *e* is the random residual. The parameters were estimated for all the individuals for possible further analyses (cf. Coyne et al. 2015).

Software

The actual mixed model analyses were performed with publicly available R software (R Core Team 2021) using *gls* procedure for fixed effect model with both ML and REML, *lme* procedure of the nlme package (https://cran.r-project.org/web/packages/nlme/nlme.pdf) for mixed models with REML. We estimated the Gompertz function parameters using R program *nls* (https://www.rdocumentation.org/packages/stats/versions/3.6.2/topics/nls) which exploits the Gauss-Newton method as a standard nonlinear least squares solver on the first- or second-order Taylor approximation of the nonlinear function.

Results

Single time point records

The average birth weight was 2.64 kg in Sahrawi and 3.27 kg in Jabbali. The average weaning weight in Sahrawi was 13.13 kg and 15.54 in Jabbali. Neither the breed nor the dam's age has an effect on the pre-weaning daily gain.

Table 1. Estimates of fixed effects breed (j for Jabbali and s for Sahrawi) and feed concentrate percentage (2 or 3% of live weight) on daily gain immediately after weaning and over the whole experimental period until the age of 14 months. The significance (*** *p*< 0.001, ** *p* < 0.01, * *p*< 0.05, ns non-significant) of the estimates is given by t test. Akaike's Information Content (AIC) provides a means for comparing the statistical models. The number of parameters in the model is represented by *k*.

fixed effects	post-weaning daily gain (g d^{-1})	daily gain (g d^{-1}) from weaning to month 14
intercept	66.50 (10.47) ***	75.25 (3.40) ***
breed × conc. %		
j2	–	–
j3	31.83 (13.52) *	18.58 (4.39) ***
s2	–3.10 (0.82) ns	–5.25 (4.55) ns
s3	14.64 (13.13) ns	5.32 (4.26) ns
	AIC = 201.86, *k* = 5	AIC = 152.34, *k* = 5
intercept	22.93 (24.26) ns	49.51 (8.13) ***
breed j	–	–
s	–11.45 (8.87) ns	–10.00 (2.97) **
conc. % 2	–	–
3	24.10 (8.99) *	14.19 (3.01) ***
	AIC = 200.57, *k* = 4	AIC = 152.47, *k* = 4

The main goal was to study the effect of the intensified nutrition applied after weaning until the age of 14 months on the daily gain during this period. The results in Table 1. can be summarized as follows: The daily gain over the first two months of the trial was showing the influence of the intensified nutrition, while there were no differences between the two breeds. Over the whole experimental period, both the concentrate level and breed had a significant effect. For choosing a statistical model, the AIC values in the two traits behave in a different way. For reaching a more parsimonious model, only the joint interaction effect of the two fixed effects was used.

The plots of Figure 1. demonstrate a breed difference in the overall level for weight and growth rate. There is also variation among individual animals within breeds for both the starting weight and growth rate. Hence, when we analyze the data, the statistical testing should have at least breed as a fixed effect and consider possible breed-specific influence of concentrate feeding (or breed - concentrate level interaction). Further, including a random animal effect in a statistical model may reduce residual variation and thereby improve the probability of finding even a small difference due to the experimental concentrate feeding or other factors.

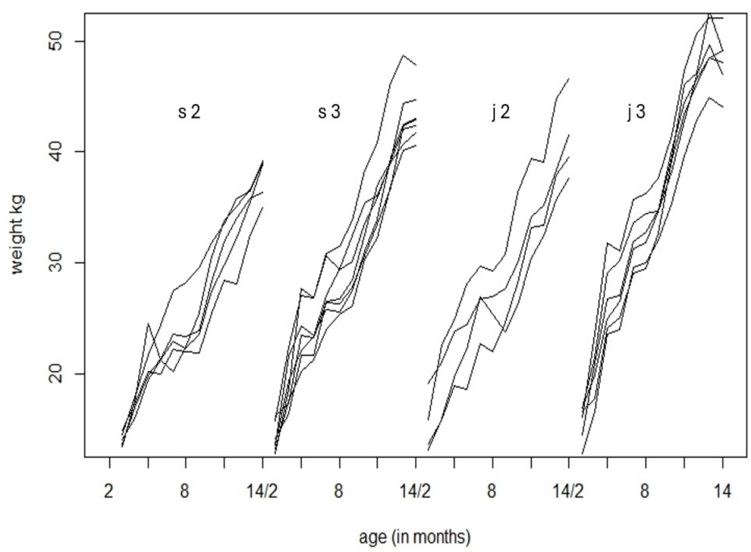

Fig.1. The individual growth curves of Sahrawi (s) and Jabbali (j) goats from weaning (month 3) to month 14 represented by monthly weight (kg) records at the feeding level of 2% (2) or 3% (3) concentrates of the live body weight.

Fixed polynomial regression

The data over the experimental time span of 12 months was studied with statistical models involving breed and concentrate level. The growth pattern was statistically modelled (models 2.1–2.3) using polynomial regression. When the parameters were solved (instead of least squares approach) with ML, it was possible to test if the (ML based) log-likelihood of the model with increased complexity deviates significantly from the log-likelihood of the existing model.

Initially, the simple linear regression on age was applied and step by step complexity was added by including 2nd and 3rd order term. At each step, log-likelihood ratios (deviances) between models were computed to aid decisions about including new fixed effect terms. The aim was to fit the most parsimonious model with testing whether a more complex model improves the fit beyond the existing terms in the model. To use models 2.1–2.3 in the tests, it is required that the estimation techniques used in the baseline model match those used in subsequent models. Doing so ensures contrasting of deviance terms.

The linear regression coefficient is highly significant in model (2.1). Adding a 2nd order term into the polynomial does not improve the fit of the model (2.2 vs 2.1), showed by the non-significant LRT, while the cubic function model (2.3) yields a significant deviance when compared to the linear regression model (2.1). Indicated by AIC and LRT values (Table 2) for the linear, quadratic and cubic curve function, the analyses give much support for the linear and cubic models. The 1st and 3rd order coefficients are positive, while the 2nd order coefficients are negative (and non-significant in the quadratic curve function). The estimate for the intercept in the cubic function is not significant.

Table 2. Fixed model polynomial regression analysis of goat kids' weight (kg) on age (months from birth) using the statistical models 2.1, 2.2 and 2.3. The subscripts of the 1st, 2nd and 3rd order intra-class regression coefficients refer as j for Jabbali and s for Sahrawi breed and as 2 and 3 for the respective concentrate percentage of the live weight. The (maximum) likelihood of the fit of the model into the data is given by log-L. AIC stands for Akaike's Information Criterion. The comparison of the statistical models (referring linear, quadratic and cubic curve function) is based on likelihood ratio test (LRT) and AIC. The number of parameters in the model is represented by *k*.

polynomial regression coefficient	linear	quadratic curve	cubic curve
intercept	8.86 (0.46) ***	8.53 (1.09) ***	2.83(6.14) ns
$b_{1\,j2}$	2.26 (0.063) ***	2.38 (0.33) ***	5.65(1.19) ***
$b_{1\,j3}$	3.03 (0.059) ***	3.25 (0.31) ***	4.95(1.19) ***
$b_{1\,s2}$	2.01 (0.061) ***	2.06 (0.32) ***	4.99(1.17) ***
$b_{1\,s3}$	2.49 (0.057) ***	2.51 (0.31) ***	5.17(1.15) ***
$b_{2\,j2}$		–0.007(0.022) ns	–0.500(0.17) **
$b_{2\,j3}$		–0.016(0.020) ns	–0.157(0.16) ns
$b_{2\,s2}$		–0.001(0.021) ns	–0.417(0.16) **
$b_{2\,s3}$		–0.001(0.019) ns	–0.353(0.16) *
$b_{3\,j2}$			0.021(0.007) **
$b_{3\,j3}$			0.003(0.007) ns
$b_{3\,s2}$			0.017(0.007) *
$b_{3\,s3}$			0.014(0.006) *
	log-L = –644.22	log-L = –643.60	log-L = –636.32
	AIC = 1300.44	AIC = 1307.20	AIC = 1300.64
	k = 6	*k* = 10	*k* = 14
		LRT(linear vs quadratic) = 7.19 with *p*= 0.126	LRT(linear vs cubic) = 15.81 with *p*= 0.045
			LRT(quadratic vs cubic) = 14.56 with *p*= 0.006

Standard error is in brackets after the estimate values. Significance levels of t test are *** $p< 0.001$, **$p< 0.01$, *$p< 0.05$ and ns for non-significant estimate.

Fixed and random effects

When the fixed effect models were augmented by the random effects of individual animals, the parameters in statistical models (e.g. model 3) were solved by REML. Therefore, the log-L values differed from the fixed effect model solutions done with ML. Now the comparison of the models with LRT values were based on REML based log-L values and thereby possible only across mixed models with the same fixed effects. The use of AIC allows more general assessment for the mixed models than LRT.

The (REML) log-L values deviated significantly in all three regression cases from the respective fixed effect model, when a random intercept was added, and further when also a random 1st order regression coefficient was in the model (Table 3). The power of the analyses was higher and consequently the significant vlues of the regression coefficients were now more common, in particular of the 2nd order ones. For example, the intercept estimate of the cubic regression with mixed model reached in a statistical test a *p* value above 0.10.

Table 3. Mixed model polynomial regression analysis of goat kids' weight (kg) on age (months from birth) (cf. the statistical model 3). The indices of the 1st, 2nd and 3rd order intra-class regression coefficients refer as j for Jabbali and s for Sahrawi breed and as 2 and 3 for the respective concentrate percentage of the live weight. The (REML) likelihood of the fit of the model into the data is given by log-L. AIC stands for Akaike's Information Content. The comparison of the statistical models (referring linear, quadratic and cubic curve function) is based on likelihood ratio test (LRT) and AIC. The number of parameters in the model is represented by *k*.

fixed part	linear	quadratic curve	cubic curve
log-L	–653.51	–656.44	–675.43
AIC	1319.02	1350.89	1378.86
k	6	10	14
added random u_0			
log-L	–588.87	–599.10	–604.36
AIC	1191.74	1220.20	1238.73
LRT(fixed/mixed)	129.28***	132.69***	142.13***
k	7	11	15
added random $u_0 + u_1 t$			
log-L	–583.86	–594.61	–598.55
AIC	1185.73	1215.22	1231.11
LRT(fixed/mixed)	139.29***	141.67***	153.75***
LRT(comp.mixed)	10.01**	8.97*	11.62**
k	9	13	17
fixed effects			
intercept	8.87(0.46)***	8.53 (0.85)***	2.83 (1.73) °
$b_{1\,j2}$	2.22(0.11)***	2.16 (0.30)***	5.65(0.84)***
$b_{1\,j3}$	3.04(0.09)***	3.49 (0.26)***	4.92(0.79)***
$b_{1\,s2}$	2.01(0.09)***	1.94 (0.28)***	4.97(0.81)***
$b_{1\,s3}$	2.51(0.08)***	2.51 (0.25)***	5.21(0.78)***
$b_{2\,j2}$		0.005 (0.02) ns	–0.50(0.12)***
$b_{2\,j3}$		–0.031 (0.02) *	–0.15(0.11) ns
$b_{2\,s2}$		–0.006 (0.02) ns	–0.41(0.11)***
$b_{2\,s3}$		0.001 (0.01) ns	–0.36(0.10)***
$b_{3\,j2}$			0.021(0.005)***
$b_{3\,j3}$			0.003(0.004)ns
$b_{3\,s2}$			0.017(0.005)*
$b_{3\,s3}$			0.014(0.004)**

Standard error is in brackets after the estimate value. Significance levels of t test are *** $p< 0.001$, ** $p< 0.01$, * $p< 0.05$ and ° $p< 0.10$ and ns for non-significant estimate.

When the random intercept was added to a fixed model with linear, quadratic and cubic curve, the autocorrelation of the residual was 0.568. 0.563 and 0.622, respectively. After the extension of the models with a random slope, such correlation could longer be found. There was no support for any higher complexity of the random part in the model beyond intercept and 1st order regression coefficient as the additional 2nd order polynomial term in the random part did not change the log-L value of the models (results not shown).

The cubic curve model (2.3) can be used in interpreting the intensified feeding in the two breeds. The results are best appreciated from the curves in Figure 2. The higher concentrate level in the Jabbali breed yielded practically speaking (high) linear response over the experiment period with the 2[nd] and 3[rd] order coefficients being non-significant in analysing the model for the cubic curve (see also Table 3). The lower concentrate percentage in the feed with respect to live body weight led to the same high growth rate only towards the end of this period. In the Sahrawi breed the growth rate was lower and there was a noticeable difference in the trait between the applied concentrate levels.

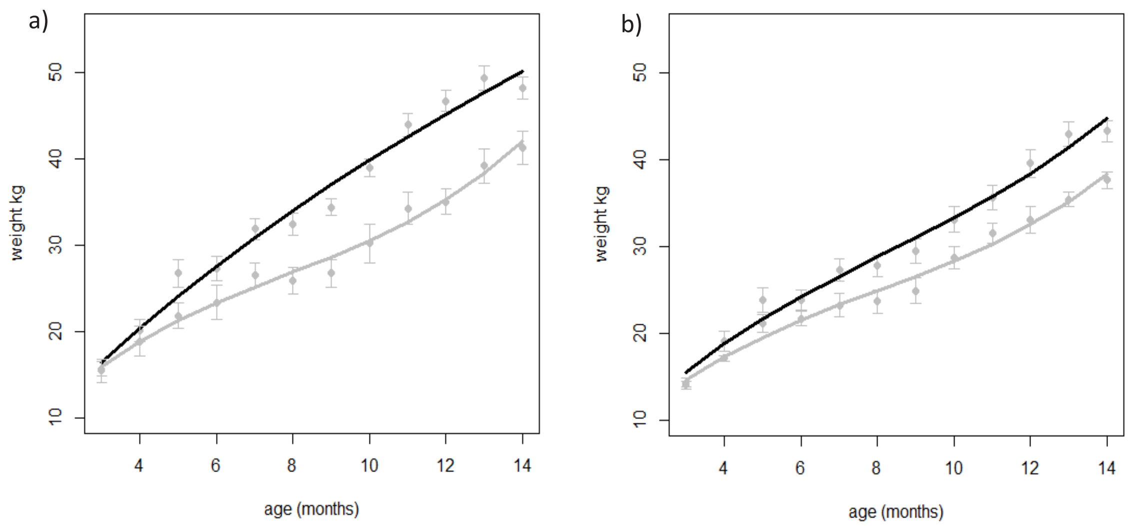

Fig. 2. The growth curve (from month 3 to month 14) estimated with a mixed model made of a 3[rd] order fixed effect regression model and linear random effect regression for Jabbali (a) and Sahrawi (b) goats at different levels (black 3% and grey 2% of body weight) of concentrate feeding. The individual points are given with the whiskers indicating one residual standard deviation for monthly records when the variation amongst animals is removed.

Gompertz growth curves

We estimated the Gompertz function parameters using R package program *nls*. There were three individuals/feeding levels (individuals 30231 and 30233 of Sahrawi breed at feeding level 2 and individual 30302 of Jabbali breed at feeding level 2) with no convergence in the iterative estimation. Most of the remaining animals had estimated mature weights highly above the biologically feasible level. Figure 3 represent the Gompertz curve predicted growth pattern for the three individuals with an estimated mature weight in the range 44–52 kg.

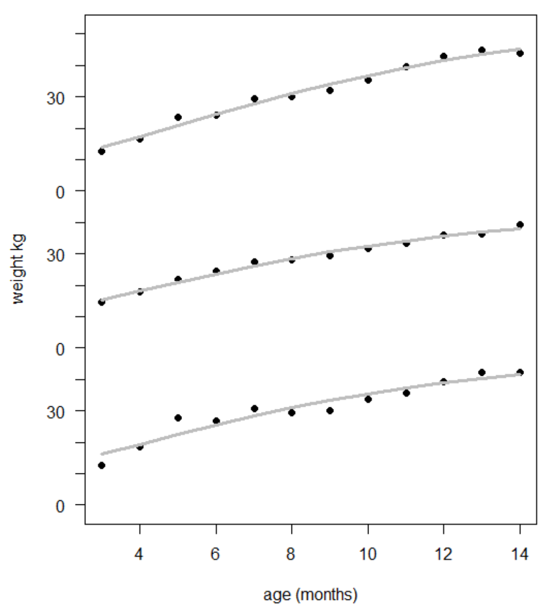

Fig. 3. Gompertz function growth curves (starting from bottom) for Sahrawi individual 30209 at feeding level 3%, Sahrawi 30228 at feeding level 2% and Jabbali individual 30290 at feeding level 3%.

Discussion

Under the concentrate feeding, Sahrawi and Jabbali goat breeds were different in growth rate and 14-month (marketing) weight with Jabbali being higher in these two traits. The increasing effect of concentrate level on the immediate post-weaning growth was the same in the breeds. The overall growth patterns were different in the two breeds in the experimental period from weaning to the age of 14 months. The higher concentrate level yielded a faster growth in Jabbali than in Sahrawi.

Statistical analyses

The analysis on the overall growth pattern was based on using a mathematical model of a polynomial regression of weights on age. The estimation of fixed breed and nutrition had a higher power when an individual animal as random effect in the model removed autocorrelation in the records of animals, explained the observed variation better and reduced the residual variation. This improved the possibility of detecting fixed effects causing tiny differences and providing better picture on the growth patterns.

The comparison of nested fixed and random effect models was possible with ML and REML, respectively. The goal is to find the most parsimonious model, which in growth modelling is the linear one. Next, one would test whether a quadratic function explains the change pattern better, and then contrast the quadratic model to a cubic one, and so on, until the new parameters are no longer significant. Growth data hardly support models beyond a cubic model. In terms of tests of significance, the model contrasting with mixed models is appropriate when the two models have the same fixed effects. More general comparison of the models is possible with AIC. At the end, one should find out the significance of each particular growth term by examining the parameter estimate, standard error, and t value associated with the term (cf. Bliese and Ployhart 2002).

The attempt to use the biologically attractive Gompertz function in the statistical analysis produced feasible results only for very few animals. This was most likely because the experiment setting lasted until month 14, still far from the maturation around month 18 (MAF 2014). Also, the use of non-linear modelling may benefit from more data while the modified nutrition may be perturbing the growth from its normal pattern. Furthermore, the weights in the analysed interval did not have the birth weight needed for accurate estimation of the b parameter in the Gompertz function. Consequently, the observed weights did not show the sigmoid curve typical to the Gompertz growth function.

Practical considerations

The variation in body weight offers opportunity for breed improvement through selection (see Mahgoub et al. 2005a). Results of local Omani goat breeds at the research stations (MAF 2015) showed that weight daily gains of growing kids during post-weaning period were low (45–55 g/day/kid). As a part of supporting the current breeding programs for small ruminants, a series of experiments have been planned to evaluate the response of local small ruminant breeds to high-level of nutrition after weaning. The present study is a part of these experiments.

Post-weaning daily gain estimates obtained in the present study were comparable to those found by Mahgoub et al. (2005b) who worked on other Omani goat breed (Jabal Akhdar) and fed *ad libitum* a concentrate diet being 88–95 g d^{-1} for post-weaning daily gain. However, some authors stated that average daily gain decreased with increasing age (Fehr et al. 1976, Dhanda et al. 1999a). Growth rate obtained in the present study was comparable to those reported by Aregheore (2001), Dhanda et al. (1999b), Gibb et al. (1993) and Potchoiba et al. (1990).

Moreover, Kumaravel and Kumaran (2016) worked on Indian goats to study the effects of supplementary concentrate feeding on performance of goats and concluded that the supplementation of concentrate feed produces positive impact on growth performance of kids.

There are previous studies on the breed differences in Omani goats. Mahgoub et al. (2005a) worked on two local Omani goat breeds to study the performance of goats fed on various diets stated that, Batinah goat breed grew faster and reached higher body weight than Dhofari breed. Other studies revealed breed effects on daily live weight gain of Omani goats (El Hag and El Shargi 1996, Mahgoub and Lu 1998) as well as for other goat breeds (Gibb et al. 1993, Dhanda et al. 1999a).

The daily gain for both breeds studied increased when kids were fed a high level of nutrition. These findings are comparable to these reported by Ferdous et al. (2011) who worked on Black Bengal goat and concluded that concentrate supplementation and high protein diet are essential to fulfill the nutrient requirements and to increase the average live weight gain per day in kids. Moreover, Bhuiyan et al. (1996) reported that the higher level of concentrate supplement increased daily live weight gain of kids.

The results obtained in the present study indicated that daily gain after weaning could be improved by intensifying the feeding system according to the animal requirements. These results agree with those found by Bhuiyan et al. (1996) who suggested that higher level of concentrate supplementation increased daily live weight gain of kids. Similarly, Sharma and Ogra (1990) stated that supplementation of concentrate feed significantly ($p< 0.05$) improved growth rate and total DM intake of kids. Moreover, Paul et al. (1990) found that goats given a supplementation of concentrates were heavier from four to six months of age than goats that were only allowed to browse. Sultana et al. (2012) studied the effects of concentrate supplementation on growth of Black Bengal goats and concluded that concentrate supplementation increased live weight gain of kids. However, Tiwari et al. (1983) suggested a better growth rate could be achieved by maintaining kids in smaller groups and under better feeding and management conditions.

Conclusions

The variation in weaning weight was higher in the Jabbali breed than in the Sahrawi breed. The concentrate feeding started after weaning increased the growth in both breeds. The higher level of concentrates lifted the immediate post-weaning growth in the same way in the two breeds. The analysis on the subsequent growth was based on regressing the monthly weights on respective age point. Considering animal as random effect in the model would explain the observed variation better and reduce the residual variation thereby providing a detailed picture on the growth curves. The growth curve parameters affected by the concentrate feeding were different in the two breeds with more pronounced increments in the Jabbali breed.

Acknowledgements

The authors thank the sheep and goat experimentation staff at Livestock Research Center in Rumais, Ministry of Agriculture, Fisheries and Water Resources of Oman for their help during this work. We would sincerely like to thank Subject Editor in revealing to us the main message in the study and, in particular, Referee A, who has been better than us in expressing the formula subtleties and the statistical choreography of what we have had in our mind.

References

Akaike, H. 1973. Information theory as an extension of maximum likelihood principle. In: Petrov, B.N. and Csaki, F. (eds.). Second International Symposium on Information Theory. Akademiai Kiado, Budapest. p. 267–281.

Aregheore, E.M. 2001. Growth rate, apparent nutrient digestibility, and some blood metabolites of Gwembe Valley goats on rations based on crop residues in the hot dry season in Zambia. Tropical Animal Health and Production 33: 331–340. https://doi.org/10.1023/A:1010592104189

Bhuiyan, R., Baruah, K.K. & Das, P.C. 1996. Growth Response and Carcass Characteristics of Crossbred Kids Fed Ration Having Different Concentrate to Roughage Rations. Indian Journal of Animal Nutrition 13: 167–169.

Bliese, P.D. & Ployhart, R.E. 2002. Growth modeling using random coefficient models: Model building, testing, and illustration. Organizational Research Methods 5: 362–387. https://doi.org/10.1177/109442802237116

Coyne, J.M., Berry, D.P., Mäntysaari, E.A., Juga, J. & McHugh, N. 2015. Comparison of fixed effects and mixed model growth functions in modelling and predicting live weight in pigs. Livestock Science 177: 8–14. https://doi.org/10.1016/j.livsci.2015.03.031

Devendra, C. 1999. Goats: Challenges for Increased Productivity and Improved Livelihoods. Outlook on Agriculture 28: 215–226 https://doi.org/10.1177/003072709902800404

Dhanda, J.S., Taylor, D.G., McCosker, J.E. & Murray, P.J. 1999a. The influence of goat genotype on the production of Capretto and Chevon carcasses. 1. Growth and carcass characteristics. Meat Science 52: 355–361. https://doi.org/10.1016/S0309-1740(99)00016-9

Dhanda, J.S., Taylor, D.G., Murray, P.J. & McCosker, J.E. 1999b. The influence of goat genotype on the production of Capretto and Chevon carcasses. 2. Meat quality. Meat Science 52: 363–367. https://doi.org/10.1016/S0309-1740(99)00015-7

El Hag, M.G. & El Shargi, K.M. 1996. Feedlot performance and carcass characteristics of local (Dhofari) and exotic (Cashmere) goats fed on a high-fiber by-products diet supplemented with fish sardine. Asian-Australian Journal of Animal Science 9: 389–396. https://doi.org/10.5713/ajas.1996.389

Fehr, P.M., Sauvant, D., Delage, L., Dumont, B.L. & Ray, G. 1976. Effect of feeding methods and age of slaughter on growth performances and carcass characteristics of entire young male goats. Livestock Production Science 3: 183–194. https://doi.org/10.1016/0301-6226(76)90035-X

Ferdous, M.R., Khan, M.J., Rashid, M.A. & Kamruzzaman, M. 2011. Effect of different levels of concentrate supplementation on the performance of Black Bengal goat. Bang. Journal of Animal Science 40: 40–45. https://doi.org/10.3329/bjas.v40i1-2.10789

Gibb M.J., Cook, J.E. & Treacher, T.T. 1993. Performance of British Saanen, Boer X British Saanen and Anglo-Nubian castrated male kids from 8 weeks to slaughter at 28, 33 or 38 kg live weight. Animal Production 57: 263–271. https://doi.org/10.1017/S0003356100006875

Kumaravel, V. & Kumaran, S. 2016. Effects of supplementary concentrate feeding on performance of goats. International Journal of Applied and Pure Science and Agriculture 2: 81–84.

Lindstrom, M.J. & Bates, D.M. 1988 Newton-Raphson and EM Algorithms for Linear Mixed Effects Models for Repeated-Measures Data. Journal of the American Statistical Association 83: 1014–1022. https://doi.org/10.1080/01621459.1988.10478693

MAF 2013. Agriculture Census, Ministry of Agriculture and Fisheries, Oman.

MAF 2014. Agriculture and Livestock Research Annual Report, Directorate General of Agriculture and Livestock Research, Ministry of Agriculture and Fisheries, Sultanate of Oman.

MAF 2015. Agriculture and Livestock Research Annual Report, Directorate General of Agriculture and Livestock Research, Ministry of Agriculture and Fisheries, Sultanate of Oman.

Mahgoub, O., Lu, C.D., Hameed, M.S., Richie, A., Al-Halhali, A.S. & Annamalai, A. 2005a. Performance of Omani goats fed diets containing various metabolizable energy densities Small R.minant Research 58: 175–180. https://doi.org/10.1016/j.smallrumres.2004.09.008

Mahgoub, O., Kadim, I.T., Al-Saqry, N.M. & Al-Busaidi, R.M. 2005b. Potential of Omani Jebel Akhdar goat for meat production under feedlot conditions. Small Ruminant Research 56: 223–230. https://doi.org/10.1016/j.smallrumres.2004.06.005

Mahgoub, O. & Lu, C.D. 1998. Growth body composition and carcass tissue distribution in goats of large and small sizes. Small Ruminant Research 27: 267–278. https://doi.org/10.1016/S0921-4488(97)00055-2

Matossian de Pardo, C. 2000. Market studies and good quality products are the key to successful projects. Seventh International Conference on Goats; 14th May; France. p. 15–21.

Meyer, K. 2001. Estimates of direct and maternal covariance functions for growth of Australian beef calves from birth to weaning. Genetics Selection Evolution 33: 487–514. https://doi.org/10.1051/gse:2001129

Murphy, T.W., Thomas, D.L. & Montgomery, T.L. 2016. Linear and nonlinear mixed model analyses of growth performance of commercial U.S. dairy buck kids. Small Ruminant Research. Small Ruminant Research 136: 151–155. https://doi.org/10.1016/j.smallrumres.2016.01.012

Paul, S., Sahu, B.B., Singh, D. & Rawat, P.S. 1990. Effect of season of birth, weaning age and concentrate supplementation on growth and chevon production. Indian Journal of Animal Production and Management 6: 182–186.

Potchoiba, M.J., Lu, C.D., Pinkerton, F. & Sahlu, T. 1990. Effects of all-milk diet on weight gain, organ development, carcass characteristics and tissue composition, including fatty acid and cholesterol contents of growing male goats. Small Ruminant Research 3: 583–592. https://doi.org/10.1016/0921-4488(90)90053-9

Preston, T.R. & Leng, R.A. 1987. Matching Ruminant Production Systems with Available Resources in the Tropics and Subtropics. Penambul Books, Armidale. 259 p.

R Core Team 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Raheem, K.A., Basiru, A., Raji. L-.O. & Odetokun, I.A. 2024. Productive performance of goat. Trends in Clinical Diseases, Production and Management of Goats 1: 163–177. https://doi.org/10.1016/B978-0-443-23696-9.00001-8

Shaat, I. & Al-Habsi, R. 2016. Current status of animal genetic resources in Oman. Journal of Agricultural Science and Food Technology 2: 139–146.

Sharma, K. & Ogra, J.L. 1990 Growth Rate and Feed Conversion Efficiency of Barbari Kids Fed Khejri Prospis cineria Leaves with Different Level of Concentrate. Indian Veterinary Journal 67: 252–254.

Sultana, M.J., Khan, M., Hassan, R. & Khondoker, M.A.M.Y. 2012. Effects of concentrate supplementation on growth, reproduction and milk yield of Black Bengal goats Caprahircus Department of Animal Nutrition, Bangladesh Agricultural University, Mymensingh-2202, Bangladesh. The Bangladesh Veterinarian 291: 7–16. https://doi.org/10.3329/bvet.v29i1.11884

Tiwari, S.B., Saini, A.L. & Bhat, P.N. 1983. Management of Barbari goats. Annual Report, Central Institute for Research on Goats, Makhdoom, Mathura, India. p. 72–75.

Wilson, B.J. 1977. Growth curves: Their analysis and use. In: Boorman, K.N. & and Wilson, B.J. (eds.). Growth and Poultry Meat Production. British Poultry Science Ltd., Edinburgh, UK. p. 89–115.

Winsor, C.P. 1932. The Gompertz curve as a growth curve. Proceedings of the National Academy of Sciences of the United States of America 18: 1–8. https://doi.org/10.1073/pnas.18.1.1