Mexican Creole chickens: effect of data collection periods on goodness-of-fit and parameter precision of growth models

Diego Zárate-Contreras,‡*, Fernando González-Cerón,† Juan M. Cuca-García,‡*, Arturo Pro-Martínez,‡*,1 Gustavo Ramírez-Valverde,‡*, Samuel E. Aggrey,† Omar Hernández-Mendo,‡* Jaime Gallegos-Sánchez,‡* and Eliseo Sosa-Montes†

*College of Postgraduates Campus Montecillo, Texcoco, State of Mexico CP 56230, Mexico; †Department of Animal Science, Chapingo Autonomous University, Texcoco, State of Mexico CP 56230, Mexico; and ‡Poultry Genetics and Biotechnology Laboratory, Department of Poultry Science and Institute of Bioinformatics, University of Georgia, Athens, GA 30602, USA

ABSTRACT The objective of this study was to estimate the good-of-fit and precision of parameters of the Gompertz-Laird, Logistic, Richards, and Von Bertalanffy growth models, using different data collection periods (DCP). Two hundred and sixty-two Mexican Creole chicks (116 females and 146 males), were individually weighed to form the following sets of data for each sex: DCP1 (weights recorded weekly from hatching to 63 d, and every 2 wk, from 63 to 133 d of age), DCP2 (weights recorded weekly from hatching to 133 d of age), DCP3 (weights recorded every third day, from hatching to 63 d, and every 14 d, from 63 to 133 d of age), and DCP4 (weights recorded every third day, from hatching to 63 d, and weekly, from 63 to 133 d of age). Data were analyzed using the NLIN procedure of SAS (Marquardt algorithm). For all growth models, the width of confidence interval (CI) of each parameter, was estimated ($\alpha = 0.05$). The adjusted coefficient of determination ($AR^2$), as well as the Akaike (AIC) and Bayesian information criteria (BIC) were used to select the best model. The higher the $AR^2$, and the lower the width of CI, as well as the AIC and BIC values, the better the model. The Gompertz-Laird model, more frequently showed the highest $AR^2$, and the lowest AIC and BIC values compared to the other models. Moreover, for all models, both sexes and all parameters, most confidence interval widths (all with the Gompertz-Laird model) were the lowest with DCP3 when compared to the other sets of data. In conclusion, the Gompertz-Laird model was the best provided that the chickens are weighed every third day from hatching until 63 d of age, and every 2 wk thereafter.

Key words: growth curves, Mexican Creole chickens, nonlinear models, confidence intervals, good-of-fit

INTRODUCTION

In poultry farming, the BW of birds is an economically important and heritable trait (Mata-Estrada et al., 2020), and can be improved by genetic selection (Osei-Amponsah et al., 2013). Changes in BW over time can be represented by growth curves (Aggrey, 2002; Naring et al. 2010), based on nonlinear models (Zhao et al., 2015; Adamaie et al., 2017; Mata-Estrada et al., 2020). According to Naring et al. (2017) the nonlinear model most used for growth curves of zootechnical interest are: Gompertz, Logistic, Richards, and Von Bertalanffy. Some parameters estimated therein are initial or hatching BW ($W_0$), specific initial rate ($L$), specific maturation rate ($K$), age of maximum growth ($t_0$), and asymptotic weight ($W_A$). For the estimation of parameters, BW of animals is recorded at different data collection periods (DCP), that is, at different frequencies and durations (Aggrey, 2002; Manjula et al., 2018; Faraji-Arough et al., 2019). Aggrey (2008) demonstrated with the Gompertz model, that the precision of initial growth rate, age of maximum growth, and asymptotic weight, is affected by the DCP. Aggrey (2002) and Mata-Estrada et al. (2020) used a DCP, in which the BW of chickens was obtained every third day from hatching to 54 d of age and subsequently, every 14 d until the age of 170 d. In contrast, Faraji-Arough et al. (2019), reported in native chickens evaluated up to 203 d of age, a DCP of 7 d, from hatching to 147 d of age; subsequently, data collection was carried out every 14 d. Other researchers used longer DCP, Manjula et al. (2018), established a DCP of 14 d from hatching to 140 d of age, while Osei-Amponsah et al. (2011, 2013, 2014) reported a similar DCP from hatching to 84 d of age, followed by every 28 d until 280 d of age. Although there is already data about growth modeling of Mexican Creole chickens (Mata-Estrada et al., 2020), data on the effect of DCP...
on the model goodness-of-fit and the precision of the estimated parameters remains scant. Confidence intervals (CI) provide the precision with which a parameter is estimated, the narrower the interval, the greater the precision is (Dagnino, 2014). Additionally, the adjusted coefficient of determination ($R^2_a$), as well as the Akaike (AIC) and Bayesian information criteria (BIC) are goodness-of-fit criteria used to select the best model. In this case, the higher the $R^2_a$, and the lower the AIC and BIC values, the better the fit of the model (Leeb and Pötscher, 2009). It is likely that the length and frequency of data collection period affects the precision of parameters and the fit of growth models. Therefore, in this study, the goodness-of-fit of the following nonlinear models, Gompertz-Laird, Logistic, Richards, and Von Bertalanffy and their respective parameter precision, were estimated. To achieve this objective, different data collection periods were used along the growth curve of Mexican Creole chickens.

**MATERIALS AND METHODS**

All animal experiments were performed in accordance with the guide for care and use of experimental animals approved by the General Academic Council of the Colegio de Postgraduos (COLOPOS, 2016). This study was conducted at the experimental chicken house of the Colegio de Postgraduos, Campus Montecillo, located in Texcoco, State of Mexico, at 19° 27’ 47” north latitude, 98° 54’ 27” west longitude and 2,247 m altitude. A total of 30 hens and 30 roosters, Mexican Creole breeders, from an experimental population with pedigree, were used under random mating to produce 286 chicks (Mata-Estrada et al., 2020). The breeding was carried out by artificial insemination with 1:1 sex ratio. The chicks obtained were fed a corn-soybean non pelleted diet containing 21.5% CP and 2,900 kcal ME/kg, during the entire experimental period. Feed and water were offered ad libitum. From hatching to 42 d of age, the birds were housed in electric brooders with 5 levels; each level with 2 spaces of 0.4 m × 1.2 m (0.48 m²), and 10 birds per space for each sex (0.048 m² per bird). Thereafter, birds were housed in pens of 1 m × 1.5 m (1.5 m²), and 10 birds per pen per sex (0.15 m² per bird). Wood shavings of about 20 mm size, were used as bedding material. Birds were kept under natural light program. At hatching, chicks were kept at a temperature of 32°C, which decreased by 1°C per week until reaching 26°C. The temperature control in electric brooders was implemented with a thermostat that controlled the operation of electrical resistances. The temperature in the poultry house was regulated by adjusting side curtains. The experimental chicks were identity by sex and weighed individually. From hatching to 63 d of age, the birds were weighed individually every third day and seventh day. Subsequently, the individual weight records were obtained weekly until 133 d of age (Table 1). Hereafter, four sets with different DCP were formed: DCP$_1$ (weights recorded weekly from hatching to 63 d, and every 2 wk, from 63 to 133 d of age), DCP$_2$ (weights recorded weekly from hatching to 133 d of age), DCP$_3$ (weights recorded every third day, from hatching to 63 d, and every 14 d, from 63 to 133 d of age), and DCP$_4$ (weights recorded every third day, from hatching to 63 d, and weekly, from 63 to 133 d of age).

**Growth Models**

From each set of data, the parameters of the following nonlinear growth models were estimated: Gompertz-Laird, Logistic, Richards, and Von Bertalanffy. The following goodness-of-fit criteria were also estimated for the models: $AR^2$, AIC, and BIC.

**Gompertz-Laird Model**

The following model describes the Gompertz-Laird growth curve:

$$W_t = W_0 \exp [(L/K)(1 - \exp(-Kt))]$$

where $W_t$ is the BW of the chickens at time $t$; $W_0$ is the initial BW (hatching weight, g), $\exp$ is the exponential function ($\exp(1) = e^1 = 2.71828183$), $L$ is the specific initial growth rate [(g d$^{-1}$) g$^{-1}$=d$^{-1}$], $K$ is the specific maturation growth rate [(g d$^{-1}$) g$^{-1}$=d$^{-1}$] (Laird et al., 1965; Aggrey, 2002). Age at maximum growth or at the inflexion point ($t_i$, d) and asymptotic weight ($W_A$, g) were estimated as follows:

$$t_i = \left(\frac{1}{K}\right) \ln \left(\frac{L}{K}\right) \quad \text{and} \quad W_A = W_0 \exp \left(\frac{L}{K}\right)$$

**Logistic Model**

The following equation describes the logistic growth model:

$$W_t = W_A / [1 + \exp(-K(t - t_i))]$$

where $W_t$ is the BW at time $t$, $W_A$ is the asymptotic weight or weight at maturity, $K$ is the specific maximum growth rate [(g d$^{-1}$) g$^{-1}$=d$^{-1}$], $t_i$ is the age at the inflexion point (Robertson, 1923; Aggrey, 2002).

**Richards Model**

The following equation describes the Richards growth model:

$$W_t = W_A \left[1 - (1 - m)\exp\left[-K(t - t_i)/m^{m/(1-m)}\right]\right]^{1/(1-m)}$$

where $W_t$ is the BW of the chickens at time $t$, $W_A$ is the asymptotic weight or mature weight, $K$ is the specific growth rate at $t_i$, with respect $W_A$ [(g d$^{-1}$) g$^{-1}$=d$^{-1}$], $t_i$ is the age at the maximum growth rate or at the inflexion point (d), and $m$ is a parameter of shape, with the property that $m^{1/(1-m)}$ is the ratio of weight at $t_i$ to $W_A$ (Richards, 1959; Aggrey, 2002).
**Von Bertalanffy Model**

The following equation describes the Von Bertalanffy growth model:

$$W_t = W_A \left( 1 - B \ast e^{(-K \ast t)} \right)^3$$

where $W_t$ is the BW of the chickens at time $t$, $W_A$ is the asymptotic weight or mature weight, $K$ is the specific maximum growth rate ($[g \text{ d}^{-1}]$), $g^{2}\text{d}^{-2}$ is the square sum of the error, and $B$ is an integration constant. Age at maximum growth rate or age at the inflexion point ($t_i$) and BW at the inflexion point age ($W_i$), are estimated as follows: $t_i = ln(3B)/K$ and $W_i = W_A \times 8/27$ (Bertalanffy, 1957; Goshu and Koya, 2013).

**Statistical Analysis**

Data were analyzed using the PROC NLIN procedure (Marquardt algorithm) version 9.3 (SAS Institute Inc., 2011). Three goodness-of-fit criteria were used to select the best model: 1) Adjusted coefficient of determination, $AR^2 = 1 - \left( \frac{(n-1) \times (1 - R^2)}{(1-q)} \right)$; 2) Akaike information criterion, $AIC = n \times ln(SSE/n) + 2q$; 3) Bayesian information criterion, $BIC = n \times ln(SSE/n) + q \times ln(n)$. Where, $R^2$ is the determination coefficient of each data set, $q$ is the number of model parameters, $n$ is the number of observations, SSE is the square sum of the error, and $\ln$ is the natural logarithm function. Likewise, for some parameters of each growth model, their confidence intervals (CI) with $\alpha = 0.05$ were obtained using the profile-likelihood program (Royston, 2007).

**RESULTS**

**Body Weights of Male and Female Mexican Creole Chickens**

The observed initial weights of males and females were very similar (37.23 ± 3.95 and 36.19 ± 3.52 g, respectively), the corresponding estimated hatching weights were ($W_0$) 33.42 and 33.14 g. Either according to standard deviation or width of CI, the group of females showed more precision than that of males. Only the Gompertz-Laird model use $W_0$ as a parameter. The observed BW of Creole chickens was higher in males than in females, a trend that was observed from hatching to 133 d of age. At the end of the observation period (Table 1), the weight of females represented 69% (1,571.06 ± 242.16) of the weight of males (2,776.34 ± 364.55). The asymptotic weights ($W_A$) of females ranged from 63 to 64% (Tables 2 and 3) with respect those of males and showed more precision, either according to the CI or the standard deviation. These values were lower than those observed at the end of the experimental period (69%, Table 1) and differed little between them (1%).

**Goodness-of-Fit Criteria and Parameters of the Growth Models**

The Gompertz-Laird model showed more frequently, a better goodness-of-fit than the others. In 10 of 12 (3 criteria × 4 models) values of females, this model showed the highest $AR^2$ and the lowest values of $AIC$ and $BIC$ (Table 3). Also, in the group of males, all 12 values of $AR^2$, $AIC$, and $BIC$ were the best using the Gompertz-Laird model (Table 2).

**Values of the Gompertz-Laird Model Parameters**

The DCP3 set of males had the lowest specific initial growth rate ($L$, 0.098200 d$^{-1}$), however, the specific growth rate at maturation was also low ($K$, 0.021971 d$^{-1}$). The DCP3 set of females also showed low values of $L$ and $K$: 0.095772 and 0.023833 d$^{-1}$, respectively.

The age at maximum growth for the sexes was similar among the four sets of DCP ($t_i$: 68.03 to 68.24 d, males, $t_f$: 58.03 to 58.59 d, females, Tables 2 and 3). Also, the asymptotic weight of males ranged from 2,910.29 to 2,923.83 g and that of females ranged from 1,832.13 to 1,848.56 g (Tables 2 and 3). That is, the age at maximum growth as well as the asymptotic weight had low variation among the DCP sets of the Gompertz model.

**Precision of the Gompertz-Laird Model Parameters**

The precision of parameters is considered higher, as long as the confidence interval is small. With males and females, all Gompertz-Laird model parameters ($W_0$, $L$, and $K$) obtained with DCP3 showed smaller CI, than the other DCP sets (Tables 2 and 3). The $W_0$ of females, were more precise than that of males, however $L$ and $K$ showed a lesser precision (Tables 2 and 3).

**DISCUSSION**

Modeling growth characteristics of poultry is important for both management and genetic improvement. The precision of the prediction equation is essential in choosing the appropriate model for the data collected. It is common practice to collect growth data on the Mexican Creole chickens at different time periods. Thus, the effect of DCP on the precision of models predicting their growth becomes important and worth investigating.

**Goodness-of-Fit Criteria and Parameters of the Growth Models**

In general, the Gompertz-Laird model showed the best goodness-of-fit as judged by the $AR^2$, $AIC$, and $BIC$. These values were also better in males than in females. Selvaggi et al. (2015) indicated that the goodness-of-fit of a specific model depends, among other factors, on sampling methods, genotype, and sex of the
birds. Likewise, based on 622 reports carried out from 1970 to 2016 (Narinç, 2017) reported that the nonlinear models more frequently used to obtain chickens’ growth curves were: Gompertz-Laird: (38.26%), Logistic: (29.75%), Richards: (17.52%), and Von Bertalanffy: (14.47%). The results were however different from that reported by Mata-Estrada et al. (2020), who found that the Von Bertalanffy model followed by that of Gompertz-Laird, best described the growth curve of Mexican Creole chickens. Other reports on indigenous chickens (Norris et al., 2007; Zhao et al., 2015; Adenaike et al., 2017), broilers (Topal and Bolukbasi, 2008; Koushandeh et al., 2019), guinea fowl (Nahashon et al., 2006), and quail (Rossi et al., 2017) reported that the Gompertz-Laird function, better fit the growth curves compared to the other models.

Values of the Gompertz-Laird Model Parameters

The high value of \( L \) (initial specific growth rate) and low of \( K \) (specific maturation growth rate), shown by the male data (0.098200 and 0.021971 \( \text{d}^{-1} \)), respectively, compared to the corresponding values of females (0.095772 and 0.023833 \( \text{d}^{-1} \)), respectively, indicate that males grew faster than females (higher value of \( L \)) and decrease slower than females (lower value of \( K \)). The initial specific growth rate (\( L, \text{d}^{-1} \)) is affected by sex (Jaap, 1970), with males recording higher values (Mignon-Grasteau, 1999). Mata-Estrada et al. (2020) found the same trend but with lower values: males (0.0765 \( \text{d}^{-1} \)) and females (0.0751 \( \text{d}^{-1} \)). Similarly, Mignon-Grasteau (1999) reported a similar pattern with very close values for males (0.1001 \( \text{d}^{-1} \)) and females (0.0979 \( \text{d}^{-1} \)) while Aggrey (2002) reported lower data (0.0908 \( \text{d}^{-1} \); 0.0804 \( \text{d}^{-1} \)), respectively.

The same trend for \( K \) using Mexican Creole chickens was reported by Mata-Estrada et al. (2020), the values of males (0.0195 \( \text{d}^{-1} \)) were higher than those of females (0.0210 \( \text{d}^{-1} \)). On the contrary, using Athens-Canadian chickens, Aggrey (2002) showed an opposite trend of \( K \): males 0.0224 \( \text{d}^{-1} \), females 0.0216 \( \text{d}^{-1} \). Therefore, the data presented by Mata-Estrada et al. (2020) is in concordance with data from the current study with Mexican Creole chickens.

The initial weight (\( W_0 \)) estimated by the Gompertz model for males and females (33.42 and 33.14 g, respectively) was 3.81 and 3.05 g lower than the observed values with the chickens of the current study (37.23 and 36.19 g, respectively); however, Mata-Estrada et al. (2020) obtained higher values (53.5 and 51.1 g, respectively). In another study with random mating unimproved chicken population, Aggrey (2002) also estimated higher values of hatching weights for males and females (44.6 and 47.5 g, respectively).

Mignon-Grasteau (1999) and Aggrey (2002) showed that asymptotic weight (\( W_A \), g) was higher in males compared to females. The values of \( t_i \) and \( W_A \) in this study were: 68.15 d and 2917.79 g (males) and 58.36 d and 1843.23 g (females); Mata-Estrada et al. (2020), reported that for males and females, \( t_i \) was higher (69.80 and 60.80 d) and \( W_A \) lower (2083.1 and 1839.1 g) than the values obtained in the present study. The data of males showed greater values of \( t_i \) and \( W_A \) than those of females. This indicates that the growth rate of females begins to decrease faster than that of males (higher \( t_i \)), and therefore they reach a lower final weight, a lower asymptotic weight (\( W_A \)).

Precision of the Gompertz-Laird Model Parameters

For all the models evaluated, those with smaller CI also had the highest precision. In the current study, there were 13 parameter estimates per sex, out of which 8 and 7 parameters for males and females (62, and 54%), respectively had small CI in the DCP3 data set. In the DCP4 data set, 38% of male and 46% of female parameter estimates had smaller CI. It appears that in general, DCP3 resulted in more precision outcomes than DCP4.

For the data to which the Gompertz-Laird model were applied, the CI for both sexes for all parameters of DCP3 regarding \( W_0, L, \) and \( K \) were smaller than all the other DCP sets.

When the Gompertz-Laird model was applied to data from both sexes, the CI for all parameters (\( W_0, L, \) and \( K \)) for the DCP3 set was smaller when compared with other DCP sets.

Aggrey (2008) suggested that the accuracy of data collection and the precision of the estimated parameters should be considered prior to choosing a particular growth model. Also, because the \( L \) and \( K \) parameters are related to the maximum and asymptotic weight of the Gompertz-Laird model, the precision of these estimates has to be high if they were to be used in a genetic improvement program (Grossman and Bohren, 1985; Barbato, 1991; Manjula et al., 2018; Faraji-Arough et al., 2019).

In conclusion, based on the higher adjusted \( R^2 \), Akaike and Bayesian information criteria, the Gompertz-Laird model showed the best goodness-of-fit, for growth data of the Mexican Creole chicken. Judging from the CI values, it is recommended that the chickens be weighed every third day from hatching to 63 d and subsequently every 14 d until 133 d of age.

ACKNOWLEDGMENTS

D. Z.-C. expresses his gratitude to the National Council of Science and Technology (CONACyT) for the scholarship granted to carry out his Doctorate in Science studies.

DISCLOSURES

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the study reported.
REFERENCES

Adenaike, A. S., U. Akpan, J. E. Udoh, M. Wheto, S. O. Durosaro, A. J. Sanda, and C. O. N. Ikorobi. 2017. Comparative evaluation of growth functions in three broiler strains of Nigerian chickens. Perspect J. Trop. Agric. Sci. 40:611–620.

Aggrey, S. E. 2002. Comparison of three nonlinear and spline regression models for describing chicken growth curves. Poult. Sci. 81:1782–1788.

Aggrey, S. E. 2008. Accuracy of growth model parameters: effects of frequency and duration of data collection, and missing information. Growth Develop. Aging. 71:45–54.

Barbato, G. F. 1991. Genetic architecture of growth curve parameters in chickens. Theor. Appl. Genet. 83:24–32.

Bertalanffy, V. L. 1957. Quantitative laws in metabolism and growth. Q. Rev. Biol. 32:217–231.

COLPOS (Colegio de Postgraduados). 2016. Reglamento para el uso y cuidado de animales destinados a la investigación en el Colegio de Postgraduados. Accessed Nov. 2016.http://www.colpos.mx/norma_interna/REG_USO_CUIDADODEANIMALES.pdf.

Dagnino, S. J. 2014. Intervalos de confianza. Rev. Chil. Anest. 43:129–133.

Faraji-Arough, H., M. Rokouei, A. Maghsoudi, and M. Mehri. 2019. Evaluation of non-linear growth curves models for native slow-growing kharaz chickens. Poult. Sci. J. 7:25–32.

Goshu, A. T, and P. R. Koya. 2013. Derivation of in vivo growth functions in three broiler strains of Nigerian chickens. Poult. Sci. 92:133–140.

Huang, D., N. O. Ndinga, and A. Aygül. 2017. Growth curve analyses in poultry science. World Poult. Sci. J. 73:1–13.

Laird, A. K., S. A. Tyler, and A. D. Barton. 1965. Dynamics of normal growth. Growth. 29:233–248.

Leeb, H., and B. M. Pötscher. 2009. Model selection. Pages 889–925 Handbook of Financial Time Series. T. Mikosch, JP. Kreiß, R. Davis and T. Andersen, eds. Springer, Berlin, Heidelberg, Germany.

Manjula, P., P. Hee-Bok, D. Seo, N. Choi, S. Jin, S. J. Ahn, K. N. Heo, B. S. Kang, and L. Jun-Heon Lee. 2018. Estimation of heritability and genetic correlation of body weight gain and growth curve parameters in Korean native chicken. Asian-Australas. J. Anim. Sci. 31:26–31.

Mata-Estrada, A., F. González-Cerón, A. Pro-Martínez, G. Torres-Hernández, J. Bautista-Ortega, C. M. Becerril-Pérez, A. J. Vargas-Galicia, and E. Sosa-Montes. 2020. Comparison of four nonlinear growth models in Creole chickens of Mexico. Poult. Sci. 99:1995–2000.

Mignon-Grasteau, S. 1999. Genetic parameters of growth curve parameters in male and female chickens. Br. Poult. Sci. 40:44–51.

Nhahushon, S. N., S. E. Aggrey, N. A. Adefope, and A. Amenyanu. 2006. Modeling growth characteristics of meat-type guinea fowl. Poult. Sci. 85:943–946.

Naring, D., E. Karaman, M. Z. Firat, and T. Aksoy. 2010. Comparison of non-linear growth models to describe the growth in Japanese quail. J Anim Vet Adv 9:1961–1966.

Naring, D., N. O. Naring, and A. Aygül. 2017. Growth curve analyses in poultry science. World Poult. Sci. J. 73:1–13.

Norris, D., J. W. Ngambi, K. Benyi, M. L. Makgahlele, H. A. Shimelis, and E. A. Nesanwumi. 2007. Analysis of growth curves of indigenous male Venda and Naked Neck chickens. S. Afr. J. Anim. Sci. 37:21–26.

Osei-Amponsah, R., B. B. Kayang, A. Nanzie, P. F. Arthur, and I. M. Barchia. 2011. Characterisation of local Ghanaian chickens: growth performance evaluation based on Richards growth model and genetic size scaling. Trop. Anim. Health. Prod. 43:1195–1201.

Osei-Amponsah, R., B. B. Kayang, and A. Nanzie. 2013. Phenotypic and genetic parameters for production traits of local chickens in Ghana. Anim. Genet. Res. 53:45–50.

Osei-Amponsah, R., B. B. Kayang, A. Nanzie, I. M. Barchia, and P. F. Arthur. 2014. Evaluation of models to describe temporal growth in local chickens of ghana. Iran. J. Appl. Anim. Sci. 4:855–861.

Richards, F. J. 1959. A flexible growth function for empirical use. J. Exp. Bot. 10:290–300.

Robertson, T. B. 1923. The chemical basis of growth and senescence. Monographs of Experimental Biology. J. B. Lippincott Cie., Philadelphia, PA.

Rossi, R. M., D. O. Grieser, V. A. Conselvan, and S. M. Marcato. 2017. Growth curves in meat-type and laying quail: a Bayesian perspective. Sem. Ciencias Agr. Londrina 38:2743–2754.

Royston, P. 2007. Proportional likelihood for estimation and confidence intervals. Stata J 7:376–387.

SAS Institute Inc.. 2011. SAS/STAT® 9.3 User’s Guide. SAS Institute Inc., Cary, NC.

Selvaggi, M., V. Laudadio, C. Dario, and V. Tufarelli. 2015. Modelling growth curves in a nondescript Italian chicken breed: an opportunity to improve genetic and feeding strategies. J. Poult. Sci. A. 52:288–294.

Topal, M., and S. C. Bolukbasi. 2008. Comparison of nonlinear growth curve models in broiler chickens. J. Appl. Anim. Res. 34:149–152.

Zhao, F., S. Li, H. Huang, C. Li, Q. Wang, and L. Xue. 2015. Comparative study on growth and developmental model of indigenous chicken breeds in China. Open J. Anim. Sci. 5:219–223.
Table 1. Means and standard deviations of BW of Mexican Creole chickens from hatching to 133 d of age.

| Age (d) | Male (n = 146) | Female (n = 116) |
|---------|----------------|------------------|
| 0       | 37.23 ± 3.95   | 36.19 ± 3.52     |
| 3       | 45.86 ± 7.01   | 43.13 ± 5.88     |
| 6       | 55.08 ± 10.56  | 51.66 ± 8.30     |
| 7       | 59.18 ± 12.20  | 55.15 ± 9.04     |
| 9       | 69.56 ± 15.11  | 65.43 ± 11.67    |
| 12      | 88.37 ± 19.11  | 82.11 ± 15.59    |
| 14      | 103.72 ± 23.02 | 95.56 ± 19.28    |
| 15      | 113.79 ± 24.96 | 105.18 ± 21.03   |
| 18      | 140.88 ± 30.44 | 129.50 ± 26.95   |
| 21      | 172.03 ± 37.52 | 156.08 ± 33.55   |
| 24      | 209.42 ± 44.11 | 189.82 ± 39.60   |
| 27      | 250.36 ± 52.73 | 225.11 ± 48.26   |
| 28      | 265.02 ± 56.36 | 236.61 ± 50.80   |
| 30      | 293.37 ± 62.07 | 260.92 ± 55.39   |
| 33      | 339.29 ± 69.78 | 299.98 ± 63.97   |
| 35      | 377.25 ± 78.60 | 329.70 ± 71.25   |
| 36      | 397.67 ± 81.93 | 345.47 ± 73.84   |
| 39      | 450.76 ± 90.13 | 389.62 ± 82.20   |
| 42      | 503.55 ± 101.37| 429.09 ± 88.89   |
| 45      | 551.08 ± 108.13| 466.91 ± 92.29   |
| 48      | 609.41 ± 115.05| 507.14 ± 97.30   |
| 49      | 628.51 ± 120.92| 519.90 ± 100.68  |
| 51      | 671.94 ± 127.91| 553.42 ± 103.93  |
| 54      | 740.25 ± 138.56| 604.97 ± 109.32  |
| 56      | 781.01 ± 144.29| 634.10 ± 112.63  |
| 57      | 812.53 ± 148.12| 655.53 ± 116.16  |
| 60      | 874.73 ± 156.82| 702.84 ± 118.97  |
| 63      | 941.87 ± 169.53| 747.63 ± 125.40  |
| 70      | 1,104.06 ± 196.15| 865.06 ± 134.75  |
| 77      | 1,269.57 ± 217.27| 973.09 ± 146.80  |
| 84      | 1,440.31 ± 242.77| 1,081.42 ± 164.33|
| 91      | 1,599.97 ± 267.16| 1,169.98 ± 170.47|
| 98      | 1,753.15 ± 292.47| 1,255.14 ± 179.65|
| 105     | 1,889.15 ± 302.86| 1,322.52 ± 189.79|
| 112     | 1,999.15 ± 314.54| 1,383.25 ± 198.66|
| 119     | 2,113.48 ± 333.62| 1,440.18 ± 207.60|
| 126     | 2,205.58 ± 346.65| 1,503.31 ± 222.58|
| 133     | 2,276.34 ± 364.55| 1,571.06 ± 242.16|

Abbreviation: n, sample size.

1Only 262 Creole chickens reached the end of the study. The percentage of mortality was 8.4%.
Table 2. Parameters estimated for the Gompertz-Laird, Logistic, Richards, and Von Bertalanffy model in the growth curve of Mexican Creole chickens (Males \( n = 146 \)) using different data collection periods.

| Model               | DCP1 \( (N = 2,190) \) | DCP2 \( (N = 2,920) \) | DCP3 \( (N = 3,942) \) | DCP4 \( (N = 4,672) \) |
|---------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| **Gompertz**        |                          |                          |                          |                          |
| Hatching BW \( (W_0, g) \) | 32.63 (26.99, 38.86) | 32.31 (26.35, 38.97) | 33.42 (29.96, 37.07) | 33.27 (29.52, 37.27) |
| CI 95%              | 0.099162 (0.091721, 0.107393) | 0.099441 (0.091722, 0.108010) | 0.098200 (0.093575, 0.103118) | 0.098301 (0.093383, 0.105522) |
| CI 95%              | 0.022081 (0.021069, 0.023118) | 0.022086 (0.021080, 0.023117) | 0.021971 (0.021311, 0.022641) | 0.021962 (0.021280, 0.022958) |
| Age of maximum growth \( (t_i, d) \) | 68.03 | 68.13 | 68.15 | 68.24 |
| Asymptotic weight \( (W_A, g) \) | 2,910.29 | 2,915.63 | 2,917.79 | 2,923.83 |
| AR²                 | 0.94035 | 0.92668 | 0.94584 | 0.94105 |
| AIC                 | 29,192.00 | 39,701.19 | 50,843.27 | 61,757.94 |
| BIC                 | 29,214.77 | 39,725.10 | 50,868.39 | 61,783.73 |
| **Logistic**        |                          |                          |                          |                          |
| Specific maturation growth rate \( (K, d^{-1}) \) | 0.044261 (0.042871, 0.045691) | 0.043505 (0.042164, 0.044902) | 0.045905 (0.044943, 0.046886) | 0.044739 (0.043789, 0.045703) |
| CI 95%              | 0.090280 (0.087190, 0.093992) | 0.090275 (0.087119, 0.094491) | 0.090194 (0.087814, 0.093619) | 0.090191 (0.087812, 0.093603) |
| CI 95%              | 0.035043 (0.034531, 0.035556) | 0.034531 (0.034321, 0.035744) | 0.034530 (0.034321, 0.035744) | 0.034530 (0.034321, 0.035744) |
| Age of maximum growth \( (t_i, d) \) | 73.97 | 74.58 | 72.24 | 73.30 |
| Asymptotic weight \( (W_A, g) \) | 2,404.53 | 2,418.89 | 2,357.90 | 2,381.50 |
| AR²                 | 0.93848 | 0.92523 | 0.94309 | 0.93895 |
| AIC                 | 29,258.99 | 39,758.55 | 51,039.07 | 61,921.41 |
| BIC                 | 29,281.76 | 39,782.47 | 51,064.19 | 61,947.21 |
| **Richards**        |                          |                          |                          |                          |
| Specific maturation growth rate \( (K, d^{-1}) \) | 0.008462 (0.007659, 0.009222) | 0.008509 (0.007719, 0.009255) | 0.008262 (0.007691, 0.008811) | 0.008298 (0.007732, 0.008842) |
| CI 95%              | 0.001563 (0.001393, 0.001733) | 0.001536 (0.001384, 0.001688) | 0.001112 (0.001036, 0.001188) | 0.001111 (0.001036, 0.001188) |
| CI 95%              | 0.428 | 0.428 | 0.428 | 0.428 |
| Age of maximum growth \( (t_i, d) \) | 68.55 | 68.90 | 68.23 | 68.47 |
| Asymptotic weight \( (W_A, g) \) | 3,782.47 | 3,782.47 | 3,782.47 | 3,782.47 |
| AR²                 | 0.93548 | 0.92523 | 0.94309 | 0.93895 |
| AIC                 | 29,298.99 | 39,782.47 | 51,064.19 | 61,947.21 |
| BIC                 | 29,321.76 | 39,782.47 | 51,064.19 | 61,947.21 |
| **Von Bertalanffy** |                          |                          |                          |                          |
| Specific maturation growth rate \( (K, d^{-1}) \) | 0.014544 (0.013612, 0.015504) | 0.014822 (0.013892, 0.015780) | 0.013858 (0.013264, 0.014463) | 0.014189 (0.013567, 0.014823) |
| CI 95%              | 0.022081 (0.021069, 0.023118) | 0.022086 (0.021080, 0.023117) | 0.021971 (0.021311, 0.022641) | 0.021962 (0.021280, 0.022958) |
| CI 95%              | 68.01 | 65.33 | 68.24 | 67.20 |
| Asymptotic weight \( (W_A, g) \) | 3,468.60 | 3,431.41 | 3,604.64 | 3,549.83 |
| AR²                 | 0.94034 | 0.92668 | 0.94584 | 0.94105 |
| AIC                 | 29,219.09 | 39,701.98 | 51,064.19 | 61,947.21 |
| BIC                 | 29,221.55 | 39,731.88 | 51,064.19 | 61,947.21 |

Abbreviations: AR², adjusted coefficient of determination; AIC, Akaike information criterion; BIC, Bayesian information criterion; CI, confidence intervals; DCP, data collection periods; n, sample size; N, total number of data.

DCP1 (weights recorded weekly from hatching to 63 d, and every 2 wk, from 63 to 133 d of age), DCP2 (weights recorded weekly from hatching to 133 d of age), DCP3 (weights recorded every third day, from hatching to 63 d, and every 14 d, from 63 to 133 d of age) and DCP4 (weights recorded every third day, from hatching to 63 d, and weekly, from 63 to 133 d of age).

The higher the AR², and the lower the width of CI, as well as the AIC and BIC values, the better the model was considered.
Table 3. Parameters estimated for the Gompertz-Laird, Logistic, Richards, and Von Bertalanffy model in the growth curve of Mexican Creole chickens (Females n = 116) using different data collection periods.

| Model              | DCP1 (N = 1740) | DCP2 (N = 2320) | DCP3 (N = 3132) | DCP4 (N = 3712) |
|--------------------|-----------------|-----------------|-----------------|-----------------|
|                    | Hatchling BW (W₀, g) | CI 95% (g)         | CI 95% (g)         | CI 95% (g)         |
| Gompertz           | 33.17  (27.86, 38.95) | 32.21  (26.72, 38.23) | 33.14  (29.87, 36.58) | 32.54  (29.07, 36.20) |
|                    | 11.09             | 11.51             | 6.71              | 7.13              |
|                    | 0.095481          | 0.097151          | 0.095772          | 0.096833          |
| CI 95%             | 0.088160, 0.103590 | 0.089639, 0.105606 | 0.090166, 0.100785 | 0.091847, 0.102165 |
|                    | 0.015430          | 0.016067          | 0.007919          | 0.003138          |
|                    | 0.023747          | 0.024036          | 0.023933          | 0.024023          |
|                    | 0.002299          | 0.002196          | 0.001473          | 0.001508          |
|                    | 58.59             | 58.10             | 58.36             | 58.03             |
|                    | 1,848.56          | 1,832.79          | 1,843.23          | 1,832.13          |
|                    | 0.94172           | 0.92966           | 0.94484           | 0.94204           |
|                    | 21,810.60         | 29,615.12         | 38,126.30         | 46,161.31         |
|                    | 21,832.45         | 29,638.12         | 38,150.50         | 46,186.19         |
| Logistic           | 0.044991          | 0.044373          | 0.04706           | 0.045947          |
|                    | 0.003180          | 0.003028          | 0.001422          | 0.001422          |
|                    | 66.49             | 66.78             | 64.69             | 65.38             |
|                    | 1,594.87          | 1,595.84          | 1,564.38          | 1,570.85          |
|                    | 0.03866           | 0.03709           | 0.03905           | 0.03905           |
|                    | 21,899.71         | 29,638.12         | 38,150.50         | 46,186.19         |
|                    | 21,921.55         | 29,638.12         | 38,150.50         | 46,186.19         |
| Richards           | 0.008498          | 0.008738          | 0.008407          | 0.008497          |
|                    | 0.0001530         | 0.000122          | 0.0001135         | 0.0001071         |
|                    | 57.88             | 57.69             | 57.67             | 57.54             |
|                    | 1,884.17          | 1,848.38          | 1,896.56          | 1,859.71          |
|                    | 0.031459          | 0.03798           | 0.032237          | 0.032351          |
|                    | 21,812.05         | 29,638.12         | 38,150.50         | 46,186.19         |
|                    | 21,839.36         | 29,645.74         | 38,156.45         | 46,193.74         |
| Von Bertalanffy    | 0.016540          | 0.017133          | 0.016075          | 0.016581          |
|                    | 0.0002022         | 0.0002013         | 0.000138          | 0.0001375         |
|                    | 54.43             | 53.23             | 55.40             | 54.27             |
|                    | 2,097.08          | 2,049.99          | 2,136.54          | 2,093.24          |
|                    | 0.93369           | 0.96672           | 0.91620           | 0.95053           |
|                    | 0.77169, 1.11268  | 0.79606, 1.15404  | 0.80808, 1.03045  | 0.83720, 1.07071  |
|                    | 0.34159           | 0.35798           | 0.32237           | 0.23351           |
|                    | 21,812.05         | 29,616.99         | 38,126.20         | 46,162.64         |
|                    | 21,839.36         | 29,645.74         | 38,156.45         | 46,193.74         |
|                    | 0.94171           | 0.92964           | 0.94486           | 0.94203           |
|                    | 21,812.05         | 29,616.99         | 38,126.20         | 46,162.64         |
|                    | 21,839.36         | 29,645.74         | 38,156.45         | 46,193.74         |

Abbreviations: n, sample size; N, total number of data; DCP, data collection periods; CI, confidence intervals; AR², adjusted coefficient of determination; AIC, Akaike information criterion; BIC, Bayesian information criterion.

DCP1 (weights recorded weekly from hatching to 63 d, and every 2 wk, from 63 to 133 d of age), DCP2 (weights recorded weekly from hatching to 133 d of age), DCP3 (weights recorded every third day, from hatching to 63 d, and every 14 d, from 63 to 133 d of age) and DCP4 (weights recorded every third day, from hatching to 63 d, and weekly, from 63 to 133 d of age).

The higher the AR², and the lower the width of CI, as well as the AIC and BIC values, the better the model was considered.
