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Ability of non-linear mixed models to predict growth in laying hens

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ABSTRACT - In this study, the Von Bertalanffy, Richards, Gompertz, Brody, and Logistics non-linear mixed regression models were compared for their ability to estimate the growth curve in commercial laying hens. Data were obtained from 100 Lohmann LSL layers. The animals were identified and then weighed weekly from day 20 after hatch until they were 553 days of age. All the nonlinear models used were transformed into mixed models by the inclusion of random parameters. Accuracy of the models was determined by the Akaike and Bayesian information criteria (AIC and BIC, respectively), and the correlation values. According to AIC, BIC, and correlation values, the best fit for modeling the growth curve of the birds was obtained with Gompertz, followed by Richards, and then by Von Bertalanffy models. The Brody and Logistic models did not fit the data. The Gompertz nonlinear mixed model showed the best goodness of fit for the data set, and is considered the model of choice to describe and predict the growth curve of Lohmann LSL commercial layers at the production system of University of Antioquia.

Key Words: chickens, mathematical models, poultry, regression analysis, weight gain

Introduction

Growth can be defined as body weight gain or weight gain of body parts with age. This process is influenced by genetic and environmental conditions. A common practice in poultry production is to measure the increase in body mass of birds to control and modify the external conditions that affect their weight gain (Oliveira et al., 2000; Agudelo Gómez et al., 2008; Aggrey, 2009).

Mathematical models have been applied to poultry production for the study of performance events through their simplification and characterization. An example is the construction of the curve-fitting models that relate the age of the bird with its weight, which allows estimating the age at which the animal stops growing, when it reaches sexual maturity, and characterizing the different phases of growth in the hen (Laird, 1965; Grossman et al., 1985; Grossman and Koops,1988; Galeano-Vasco and Cerón-Muñoz, 2013).

The modeling of growth performance in laying hens is an elaborate process due to the use of parameters which are difficult to interpret from a biological perspective, and the difficulty to predict the events that are influenced by the variation of the observations in time (Aggrey, 2002; Aggrey, 2009; Galeano-Vasco et al., 2013).

An alternative is the use of nonlinear mixed models, which include the fixed effects that refer to the population mean of the parameter and random effects that indicate the differences between the mean value of the parameter and the adjusted value for each individual (Wang and Zuidhof, 2004). For Littell et al. (2000), the fixed effects correspond to the expected values, while the random effects are the variance and covariance of the observations. Therefore, applying mixed models to longitudinal measurements of growth allows quantifying the variability between animals and in each animal. Other advantages of these models are that they can handle unbalanced data and have a flexible covariance structure (Pinheiro and Bates, 1995; Aggrey, 2009), because in the animal investigation it is common to have data with dependence structures, missing values and lack of normality.

The current study was designed to compare Von Bertalanffy, Richards, Gompertz, Brody and Logistics non-linear regression models for their ability to estimate the growth curve in hens. The models were modified to include random effects (mixed models). We used weight records from Lohmann LSL layers obtained on a commercial egg farm in Antioquia, Colombia.

Material and Methods

The data used in this study were obtained from 100 Lohmann LSL hens, randomly selected from a flock of birds

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located on La Montaña Farm, at University of Antioquia, located in the municipality of San Pedro de los Milagros (Antioquia, Colombia) at 6°19'19" North latitude, 1°37'40" West longitude and 2,350 m altitude. Average outdoor, maximum and minimum temperatures in this region are 15 ºC, 22 ºC and 7 °C, respectively.

At 0-13 weeks of age birds were reared in floor pens and then moved into cages which housed 4 birds/cage (730 cm^2 hen^{-1}). The birds were identified and then weighed from day 20 after hatch until they were 553 days of age. From 0-2 wk, all birds received a starter diet followed by a grower diet, which was fed to nine weeks of age. The developer and layer diets were fed from 10-16 and 17-80 wk of age, respectively (Table 1). The chickens consumed fresh and purified water *ad libitum* at all times. Supplemental heating was provided from 0-6 weeks, and no environmental control was provided afterwards.

Five nonlinear models used for the analysis of growth curves were adapted to mixed models, with the inclusion of random parameters:

(1) Brody (Brody, 1945):

$$y_{ij} = (\beta_0 + b_{0i}) * (1 - \beta_1 \exp^{(\beta_2 + b_{2i}) * t_{ij}}) + \varepsilon_{ij}$$

(2) Logistic (Verhulst, 1838):

$$y_{ij} = (\beta_0 + b_{0i}) * (1 - \exp^{-\beta_1 * t_{ij}})^{-1} + \varepsilon_{ij}$$

(3) Gompertz (Gompertz, 1825):

$$y_{ij} = (\beta_0 + b_{0i}) * \exp^{-\beta_1 * \exp(-\beta_2 + b_{2i}) * t_{ij}} + \varepsilon_{ij}$$

(4) Von Bertalanffy (Bertalanffy, 1938):

$$y_{ij} = (\beta_0 + b_{0i}) * (1 - \beta_1 * \exp^{(-\beta_2 + b_{2i}) * t_{ij}})^3 + \varepsilon_{ij}$$

(5) Richards (Richards, 1959):

$$y_{ij} = (\beta_0 + b_{0i}) * (1 - \beta_1 * \exp^{(-\beta_2 + b_{2i}) * t_{ij})^{-(1/m)}} + \varepsilon_{ij}$$

In which y_{ij} = body weight (g) of the i-th bird at the j-th time; t = time, age in days; β_0= fixed component of the model, associated with the asymptotic weight when t tends to infinity (percentage of maturity with respect to adult weight); β_1= fixed component of the model, defined as the adjusting parameter when Y≠0 or t≠0; β_2= fixed component of the model, representing the maturity index expressed as a proportion of the percentage of maximum growth with regard to the adult weight of the bird; b_{0i} and b_{2i} = random effects associated with the β_1 and β_2 fixed effects, which in turn define the variance and covariance of the observations for each fixed effect for the i-th bird; m = asymptotic weight proportion corresponding to the inflexion point; and ε_{ij}= residual effect associated with the i-th bird at j-th time.

The residue and the random effects were assumed to be independent and normally distributed with zero mean and constant variance.

$$\varepsilon \sim N\left(0, \sigma_e^2\right) \text{ and } \begin{bmatrix} b_0 \\ b_2 \end{bmatrix} \sim N\left[\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma^2_{b_{0i}} & 0 \\ \sigma_{b_{02}} & \sigma^2_{b_{2i}} \end{bmatrix}\right]$$

The models were compared using log maximum likelihood (-2 Log L), Akaike's information criterion (AIC) (Akaike, 1974), and Bayesian information criterion (BIC) (Schwartz, 1978). Lower AIC and BIC values indicate a better model fit to the original data. The correlation between observed and predicted data was obtained with the Pearson method. For data analysis and model-programming, NLMIXED procedures of SAS (Statistical Analysis System, version 9.0) was used.

Results and Discussion

Based on information on the body weight data used to model the growth curve with the nonlinear mixed models (Table 2) we calculated the weight gain (body weight $week_{n+1}$ - body weight $week_n$).

The average daily feed intake (Table 3) between weeks 3-10 was 3.67 g higher than the average level recommended by the guide. This effect was greater between weeks 8 and 10 (5.6 g/hen/day), with an average gain of 80 g/week, presenting a peak increase in weight at week 7 (122.7 g). The purpose of providing more food in these weeks was to increase the weight of the birds before they were moved to the cages. Between weeks 14 and 17, we observed a decrease of 1.53 g to below average 71.4 g of feed intake

Table 1 - Nutritional composition of diets supplied to the birds in the evaluation period

Nutrients	Type of diet					
	Starter	Grower	Developer	Layer diets		
				Special	Phase 1	Phase 2
CP (g kg^{-1} as fed)	214	200	170	180	170	160
ME (Mcal/kg)	3.00	2.91	2.78	2.85	2.85	2.85

CP - crude protein, ME - metabolizable energy.
Starter - 1 to 2 weeks; Grower - 3 to 10 weeks; Developer - 11 to 16 weeks; Special - 17 to 45 weeks; Phase 1 - 46 to 58 weeks; Phase 2 - before 58 weeks.

recommended by the management guide, as a result of adaptation of the bird to the cage, the drinking system, feeders and social interactions with other birds. A similar trend occurred in the weight gain from 153 to 74.65 g/week in this same period.

The greatest average weight gains were observed between weeks 14 and 23, reaching a maximum value of 163 g/bird at 144 days (20.6 weeks). Previous reports (Grossman and Koops, 1988; Kwakkel et al., 1993) indicate that the increase in bird weight is associated with sexual maturity and precedes the onset of the egg production cycle of the bird, and is also defined as the third phase of growth. Weeks 18 through 20 showed an increase in the average level of feed intake (87 g), which could have an effect on the increasing weight gain of birds of 74.65 to 147.5 g/week in the aforementioned period. Following this plan, feed restriction was applied between weeks 22 and 27, reaching 113.3 g/hen/day at week 28 (1.3 g above the theoretical intake). From weeks 28 to 80, the average intake per bird day was 2.4 g higher than that recommended by the management guide throughout the period, and weight gain was stabilized at an average of 0.6 g/week.

The Gompertz model had the best fit for modeling the growth curve of the birds, according to AIC and BIC (Table 4). In a descending order, models were ranked as follows: Gompertz, Richards, and Von Bertalanffy. Pearson's correlation coefficients were higher than 0.957 for the three models, indicating good fit and high ability to predict weight gain during the rearing, growing, and laying periods. The Brody and Logistic models did not fit the growth curve, so they were not considered in the results.

The graphs of the residuals showed that all models underestimate weight from days 100 to 150, a period that coincided with the onset of laying, indicating changes in body weight of birds that the models did not estimate (Figure 1).

The β_0 value of the parameters estimated by Richards and Gompertz models was over 1,500 to 1,600 g, which is the weight range proposed by Lohmann® (Table 5). The β_0 estimation by Von Bertalanffy was below the weight range. The estimation and analysis of the asymptotic weight is essential to evaluate and project the flock efficiency, as underweight animals have delayed onset of sexual maturity and tend to lay fewer eggs (Kirikçi et al., 2007).

According to Gompertz, weight at the inflection point ($Y_i = \beta_0/e$) was 610.85 g, reached at 59 days of age. The weight proportion at the inflection point with respect to the asymptotic weight (Y_i/β_0) was 36.79%, confirming that Gompertz model has a fixed inflection point at 37% of the asymptotic weight, as stated by Tabatabai et al. (2005).

Table 2 - Body weight data of Lohmann LSL hens used to model the growth curve with nonlinear mixed models

Day	Mean	SD	Day	Mean	SD	Day	Mean	SD	Day	Mean	SD	Day	Mean	SD
21	187	31.99	70	749.00	56.78	154	1562.76	84.57	317	1636.41	94.16	490	1647.46	91.33
28	214.30	40.26	85	902.33	80.79	168	1562.94	84.15	338	1631.55	86.52	554	1692	121.45
36	301.23	49.51	98	1054	82.02	196	1625.61	92.31	378	1607.12	107.78	532	1676.50	127.07
42	386.37	52.05	114	1192	60.91	224	1629.33	90.2	408	1695.73	117.13	546	1706.90	110.70
52	509.04	55.73	123	1266.65	74.37	270	1628.13	101.10	422	1679.46	111.54	553	1689	97.66
56	582.96	63.53	133	1415.41	110.66	277	1633.39	105.02	452	1715.25	93.07			
65	681.12	61.61	144	1561.72	95.04	291	1601.77	86.35	484	1717.91	84.37			

Day - day of measurement; Mean - average hen weight; SD - standard deviation.

Table 3 - Differences between the amount of feed intake per bird day^{-1} and the amount recommended by the management guide of Lohmann LSL hens (weeks 1 to 25)

Week	Dif	Week	Dif	Week	Dif	Week	Dif	Week	Dif	Week	Dif	Week	Dif	Week	Dif	Week	Dif
1	0.74	4	1.41	7	3.25	10	7.42	13	6.47	16	−0.47	19	82.09	22	−9.01	25	−6.79
2	0.61	5	1.25	8	7.06	11	3.77	14	−0.41	17	−3.72	20	92.30	23	−10.79		
3	1.65	6	1.92	9	5.42	12	3.46	15	5.00	18	−1.97	21	87.68	24	−8.82		

Dif - actual feed intake (g/hen/day) – theoretical feed intake (g/hen/day).

Table 4 - Classification based on information criteria and correlation value of non-linear mixed models used to evaluate growth of Lohmann LSL hens

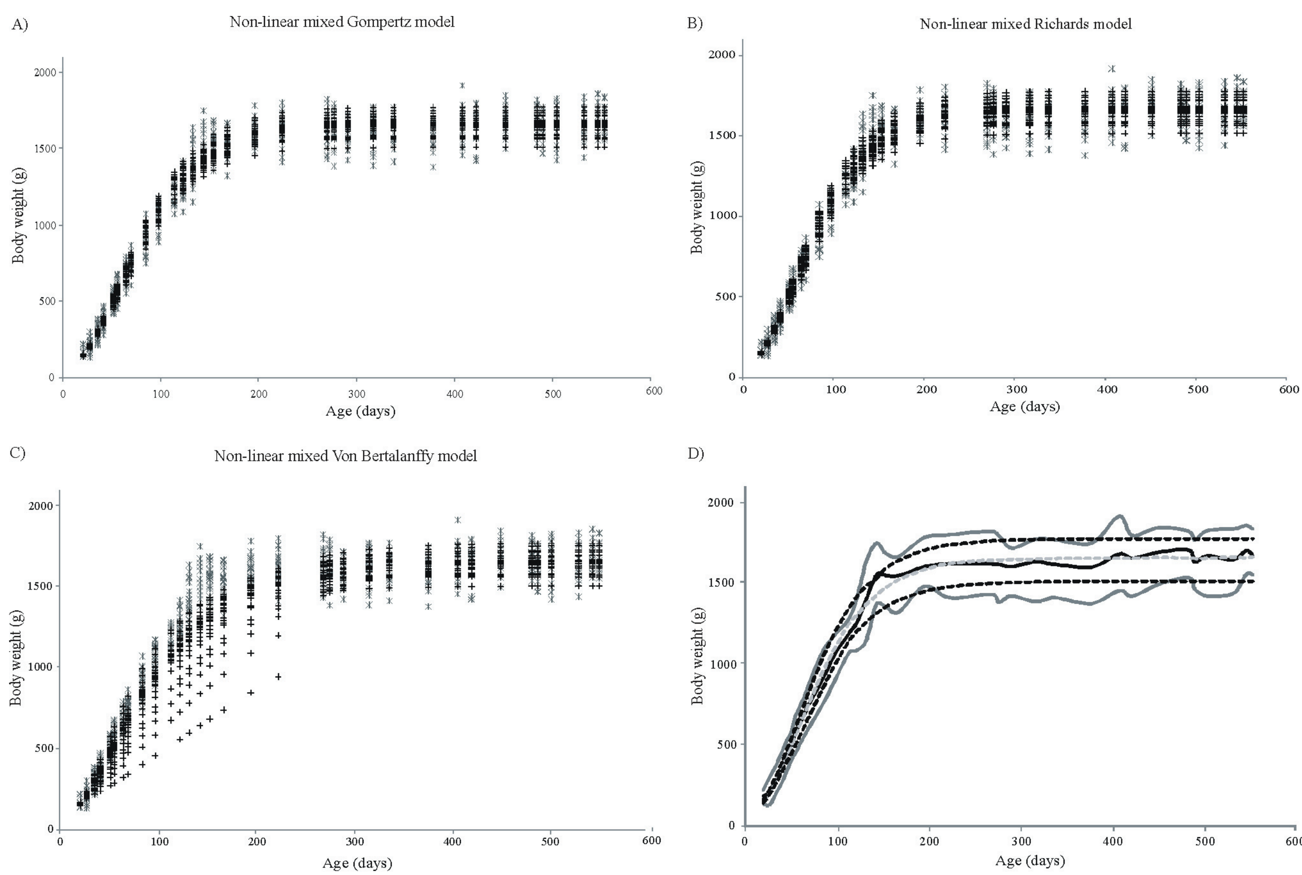
Model	−2 Log likelihood	AIC[1]	BIC[1]	Correlation[2]
Gompertz	8405.4	8419.4	8428.2	0.991*
Richards	8408.0	8424.0	8434.1	0.990*
Von Bertalanffy	8464.3	8478.3	8487.1	0.957*

[1] Low values indicate better fit of the model to the data.
[2] Correlation between observed and predicted data obtained with the Pearson method.
* P<0.001.

Table 5 - Parameters estimated by nonlinear-mixed growth models used to evaluate Lohmann LSL birds

Parameters	Models		
	Gompertz	Richards	Von Bertalanffy
β_0	1660.46±15.5	1678.28±18.6	1483.59±50.1
b_0	72.68±11.9	80.08±14.3	192.84±51.4
β_1	2.44±3.7E^{-02}	5.54E^{-04}±6.9E^{-04}	0.55±1.2E^{-02}
β_2	2.30E^{-02}±5.1E^{-04}	2.24E^{-02}±5.4E^{-04}	2.74E^{-02}±7.4E^{-04}
b_2	1.84E^{-03}±3.6E^{-04}	1.84E^{-03}±4.5E^{-04}	1.36E^{-02}±2.5E^{-03}
m	2.29E^{-03}		
e	73.37±2.01	72.64±2.22	72.51±1.99

β_0, β_1 and β_2 - estimated fixed parameters; b_0 and b_2 - estimated random parameters; m - asymptotic weight proportion corresponding to the inflexion point in Von Bertalanffy model, Scientific notation a*E^{-n} where *E* is equal to 10, *n* is an integer, and *a* is any real number; e - error of estimation.



▬ ▬: estimated upper and lower limit; ▬ ▬ : average estimated data; ▬▬ : average actual data; ▬▬ : actual data lower and upper limits.
++ weight estimated by the model; ** actual weight.

Figure 1 - Growth curves of Lohman LSL birds, estimated by the models: Gompertz (A), Richards (B) and Von Bertalanffy (C) and projected growth curve by the Gompertz model for Lohmann LSL hens under the University of Antioquia production system (D).

When parameter m is equal to one in the Gompertz and Richards models, the inflection point is at the same place (Nahashon et al., 2006). Parameter m value was 2.29E-03, so the inflection point by both models differed. For the Richards model, weight at the inflection point was 623.53 g ($Y_i = \beta_0/(m+1)^{(1/m)}$) at 61 days of age. Therefore, Gompertz and Richards models placed the inflection point between weeks 8 and 9 of the bird age.

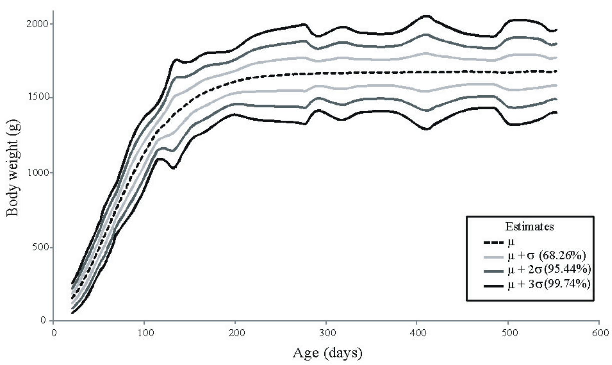
With regard to growth, birds reached 89% of the asymptotic weight ($\bar{x}$ = 1403±118.7 g) at 133 days of age, and 94% ($\bar{x}$ = 1553±98.8 g) at 144 days. Therefore, the estimated weight of the birds was 90% of the adult weight at 140 days (starting production or sexual maturity). A goal in raising laying hens is to avoid early maturity (before 18 weeks), because under such circumstances precocious birds tend to lay low-weight eggs (Rafart et al., 2006). In addition to weight, other factors such as feed management, nutrient intake, and the lighting program (duration of photo-stimulation and light intensity) affect the age at which birds reach sexual maturity (Joseph et al., 2003).

The Gompertz and Richards models share a similar pattern throughout the curve (Figure 1). As reported by Oliveira (2000), both models fit well the initial weights. On the other hand, parameters generated by the Von Bertalanffy model were skewed until day 224 and thereafter their trend was similar to the other models.

Two graphs are plotted for the expected growth projection based on the information generated by the Gompertz-Laird model. In the first graph, the ideal weights should fall between the purple lines, tending to fit the average demarcated by the blue line (Figure 1).

The weight dispersion of the population was assigned to one of three ranges created based on increases of one, two, or three standard deviations from the mean (Figure 2).

These graphical models allow evaluating the physical development of Lohmann LSL flocks at the farm of the University of Antioquia, as they correspond to the response of the birds under the conditions of that production system.



μ- mean; σ - standard deviation.

Figure 2 - Projected growth curve of Lohmann LSL hens using the Gompertz model based on population deviations, for the production system of the University of Antioquia.

Conclusions

The Gompertz and Richards models can be used to estimate bird weights for Lohmann LSL hens by projecting growth curves. The determining factor for selecting the Gompertz model as the best is that it has fewer parameters to estimate than the Richards model, facilitating the processes of estimation and model derivative. The Logistic, Brody, and Von Bertalanffy models have flaws in the process of convergence and fit to the growth curve of these birds.

Although the ability to estimate and fit by the Gompertz and Richards models are similar, the former has the best fit to the variability of animal weight with increasing age.

This paper provides a model to evaluate poultry development, allowing to know the system productive parameters and to determine optimal growth ranges for Lohmann LSL birds under environmental conditions and farm management.

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