INTRODUCTION

Growth can be defined as an increase in body size per unit of time (Tompić et al., 2011). Modeling growth curves of animals is a necessary tool for optimizing the management and efficiency of animal production (Köhn et al., 2007). However, growth can only be attained under nonlimiting conditions. For example, food needs to be available ad libitum; the nutrient content must at least meet the required ratios in relation to energy; intake must not be constrained by the bulk of the food or the presence of toxins; and environmental factors such as high temperature and disease must not constrain intake (Emmans and Kyriazakis, 1999). An animal’s genetic potential for growth can be described in terms of its growth curve (Emmans and Fisher, 1986).

The available literature on ostrich growth used data from South African farms and modeled only the Gompertz growth function (du Preez et al., 1992; Cilliers et al., 1995; Cooper, 2005). In Brazil, ostrich production began in 1995 with the importation of the first animals from Italy (Carrer et al., 2005). In 2006, the estimated number of commercially farmed birds in the country was 335,425, according to the Brazilian Ostrich-Rearing Yearbook (Anuário da Estrutucultura Brasileira, 2005/2006). Despite the size of the national flock, no studies describing its growth are available. The objective of this study was to fit growth curves using nonlinear and linear functions to describe the growth of ostriches in the Brazilian population.

MATERIALS AND METHODS

The data used for the growth analysis came from commercial flocks and were provided by the Brazilian Ostrich Rearing Federation (Associação dos Criadores de Avestruz do Brasil), based in São Paulo, SP, Brazil. This institute approved the use of this data to perform this research. A total number of 441 BW records from 58 hens and 54 cockerels measured from hatching to 383 d of age were used. The animals were crossbreds from the African Black, Red Neck, and Blue Neck breeds. The exact proportions of these genetic groups within each animal were unknown.

Figure 1 shows animals of the African Black breed. Figure 1a shows a triplet consisting of 1 cockerel (at the center) and 2 hens. They are 8-yr-old animals with an approximate BW of 150 kg and approximate height of 2.20 m. Figure 1b shows 8-mo-old male and female chicks, with no visible sexual differentiation in plumage, with approximate BW and height of 75 kg and 1.80 m, respectively.

After the chicks had hatched, they were weighed, tagged around the neck for identification, and trans...
ferred to small pens. At night, they were housed in a controlled environment with a minimum temperature of 25°C. When the birds reached 3 mo of age, they were moved to larger pens and were no longer housed. At 6 mo of age, the birds were transferred again to larger pens. The birds’ diet was composed of pasture grass, specific industrial food with added citric pulp, and water ad libitum.

Figure 1. An African Black triplet consisting of one cockerel (at the center) and 2 hens (a); male and female African Black chicks (b). Photos courtesy of Celso da Costa Carrer (Faculdade de Zootecnia e Engenharia de Alimentos, Universidade de São Paulo). Color version available in the online PDF.
To estimate the BW at a certain age, two 3-parameter nonlinear growth functions and a polynomial growth function were fitted to the ostrich BW data. The equations for the growth models applied are given in Table 1.

The model parameters were estimated and the statistical analysis was carried out using the R software version 2.14.2 (R Development Core Team, 2012). The nonlinear and linear modeling was carried out using the NLS and LM procedures, respectively. The LM procedure used the least-squares method and the nonlinear regression the Gauss-Newton algorithm. The initial values for the curve parameters were estimated from earlier reports (du Preez et al., 1992; Cilliers et al., 1995).

The goodness-of-fit of the functions was assessed using $R^2$ and the Akaike information criterion (AIC). The $R^2$ is defined as the proportion of the total sum of squares that is explained by the model. The range is 0 ≤ $R^2$ ≤ 1. Values closer to 1 indicate better fit (Fars, 2004). The AIC is defined as

$$
AIC = -2 \ln(L_m) + 2m,
$$

where $L_m$ is the maximized log-likelihood and $m$ is the number of parameters in the model. Lower AIC values indicate the preferred model (Akaike, 1973).

The $t$-test was used to investigate whether the estimates were significantly different from zero and to compare nonlinear model parameter estimates for cockerels and hens. The inflection points of the nonlinear functions and the third-order polynomial were calculated.

The equations for calculating the inflection points of these functions are given in Table 1.

### RESULTS

Table 2 shows the estimated fitting parameters, their SE, $R^2$, and inflection points of the Gompertz and logistic functions. Parameter A of the nonlinear growth curves, which can be interpreted as the asymptotic final BW, was greater in the Gompertz function than in the logistic function, both for cockerels and for hens ($P < 0.05$). Parameter C, which can be interpreted as the instantaneous relative growth rate, was also greater in the logistic function than in the Gompertz function, both for cockerels and for hens ($P < 0.05$). There were no significant differences in mature weights and instantaneous relative growth rates between cockerels and hens, for either of the nonlinear growth functions. The logistic curve showed higher $R^2$ values both for hens and for cockerels.

According to the nonlinear functions, the hens reached the inflection point at an earlier age than the cockerels. However, the third-order polynomial function showed the opposite. Both of the nonlinear functions showed that the cockerels had greater BW at the inflection point.

Table 3 shows the estimated fitting parameters, their SE, $R^2$, AIC, and inflection points of the third-order polynomial fit. The intercept ($d_0$) can be interpreted as the mean BW at hatching. The estimate of $d_0$ was negative but not significantly different from zero. The

### Table 2. Estimated parameters, SE, inflection point, $R^2$, and Akaike information criterion (AIC) for 2 nonlinear growth curves

<table>
<thead>
<tr>
<th>Model</th>
<th>Sex</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>$t_i$</th>
<th>$y_i$</th>
<th>$R^2$</th>
<th>AIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logistic</td>
<td>Female</td>
<td>101.7 (2.124)$^a$</td>
<td>34.99 (4.269)</td>
<td>0.019 (0.001)$^a$</td>
<td>185.060</td>
<td>50.85</td>
<td>0.938</td>
<td>1,605</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>103.7 (2.815)$^a$</td>
<td>34.99 (4.269)</td>
<td>0.019 (0.001)$^a$</td>
<td>185.060</td>
<td>50.85</td>
<td>0.938</td>
<td>1,605</td>
</tr>
<tr>
<td>Gompertz</td>
<td>Female</td>
<td>120.4 (5.441)$^b$</td>
<td>1.55 (0.063)</td>
<td>0.009 (0.001)$^b$</td>
<td>169.656</td>
<td>44.28</td>
<td>0.938</td>
<td>1,605</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>124.9 (7.174)$^b$</td>
<td>1.465 (0.066)</td>
<td>0.008 (0.001)$^b$</td>
<td>173.842</td>
<td>45.97</td>
<td>0.924</td>
<td>1,571</td>
</tr>
</tbody>
</table>

$^a,b$ Means within a column with different superscripts differ significantly ($P < 0.05$).

1$^a$A = asymptotic final BW (kg); B = function-specific parameter; C = instantaneous relative growth rate.

2Standard errors are between parentheses.

$^3t_i = age (d)$ at point of inflection; $y_i = BW (kg)$ at point of inflection.
estimate of the regression coefficient of the first power
term \((d_1)\) was also not significantly different from zero.

Among the polynomial and nonlinear functions, the
logistic curve showed the highest \(R^2\) and lowest AIC
values, both for hens and for cockerels. Except for the
third-order polynomial parameters with estimates not
significantly different from zero, all the models showed
small SE, thus indicating accurate estimates of the pa-
rameters.

Figures 2 and 3 show the results from all the models
applied to the hens and cockerels, respectively. Visu-
ally, all 3 growth models showed similar fits from the
start to the end of the growth period. The third-order
polynomial showed a slightly decrease in BW at the
end of the growth period. The Gompertz model sug-


ggested that growth had not stopped at the end of the
period. The logistic model showed the best fit of all the
models.

**DISCUSSION**

Growth is an important attribute of organisms and
the efforts to predict it that have been made can be
seen in the large number of functions that have been

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Table 3. Estimated parameters, SE, inflection point, \(R^2\), and Akaike information criterion (AIC) for third-order polynomial growth model

<table>
<thead>
<tr>
<th>Sex</th>
<th>(d_0)</th>
<th>(d_1)</th>
<th>(d_2)</th>
<th>(d_3)</th>
<th>(t_i)</th>
<th>(y_i)</th>
<th>(R^2)</th>
<th>AIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female</td>
<td>1.768 (1.049)</td>
<td>-0.040 (0.030)</td>
<td>2.000 (0.300)</td>
<td>-5.000 (0.500)</td>
<td>3.85</td>
<td>0.005</td>
<td>0.938</td>
<td>1,598</td>
</tr>
<tr>
<td>Male</td>
<td>1.622 (1.255)</td>
<td>0.005 (0.038)</td>
<td>2.000 (0.300)</td>
<td>4.000 (0.600)</td>
<td>2.70</td>
<td>0.004</td>
<td>0.924</td>
<td>1,568</td>
</tr>
</tbody>
</table>

\(d_0 = \) intercept; \(d_1 = \) regression coefficient; \(d_2 = \) regression coefficient \((\times 10^{-3})\); \(d_3 = \) regression coefficient \((\times 10^{-6})\).

\(t_i = \) age \((d \times 10^{-9})\) at point of inflection; \(y_i = \) BW (kg) at point of inflection.

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Figure 2. Growth curves of females. Observed data are shown as circles; lines are modeled curves using the estimated parameters of each of
the following functions: (a) logistic, (b) Gompertz, and (c) third-order polynomial. \(y = \) predicted BW (kg) at age \(t\) (d).
created (Fekedulegn et al., 1999; Wellock et al., 2004). Among the nonlinear functions, the logistic and Gompertz functions were chosen for this study because of their economy of parameters and ability to describe relative growth rate as a simple function of size. They can also describe continuous growth, sigmoid forms, asymptotes, inflection points, and parameters with biological interpretations. All these properties are desirable in nonlinear growth models (Wellock et al., 2004). The third-order polynomial was chosen because of its resemblance to nonlinear growth functions.

The R² values calculated for all the models were very similar, but the logistic growth function showed a slightly higher value. The logistic growth function also showed the smallest calculated AIC value. The R² measures linear associations and is therefore a goodness-of-fit measurement that is more appropriate for linear models. The AIC is a more appropriate goodness-of-fit measurement for use in comparisons between linear and nonlinear models and functions with different numbers of parameters.

The estimates for the parameters A and C, which can be interpreted as mature BW and instantaneous relative growth rate, respectively, were similar to those found in previous studies on ostrich growth. du Preez et al. (1992) found mature BW estimates of 102.1 ± 3.72 kg for cockerels and 98.4 ± 4.2 kg for hens and instantaneous relative growth rate estimates of 9.7 ± 0.43 (×10⁻³) for cockerels and 9.0 ± 0.44 (×10⁻³) for hens. Cilliers et al. (1995) found mature BW estimates of 119.22 ± 2.48 kg for cockerels and 122.30 ± 3.47 kg for hens and instantaneous relative growth rate estimates of 9.10 ± 0.28 (×10⁻³) for cockerels and 8.50 ± 0.41 (×10⁻³) for hens.

The values for inflection points relating to age that were found in this study (Tables 2 and 3) were also similar to what has been reported in the literature. du Preez et al. (1992) found an inflection point for age, which was interpreted as the age at maximum weight gain, of 163 d for cockerels and 175 d for hens. Cilliers et al. (1995) found inflection points for age of 180.83 d for cockerels and 199.20 d for hens.

The Gompertz model suggested that growth had not stopped at the end of the period. This may be an indication that the birds in this study were not fully matured at the end of the period.

Figure 3. Growth curves of males. Observed data are shown as circles; lines are modeled curves using the estimated parameters of each of the following functions: (a) logistic, (b) Gompertz, and (c) third-order polynomial. y = predicted BW (kg) at age t (d).
According to R² and the AIC, the third-order polynomial showed a good fit. Tompić et al. (2011) found a similar result. Compared with the nonlinear models, linear models lack parameters with biological interpretation, but such models can be linearized and their parameters estimated by means of linear regression.

Further studies are needed to understand ostrich growth in Brazil. Ideally, study data sets should contain a large number of birds, each with the same number of BW records, collected at regular intervals that are not too close, so that the measurements are neither correlated nor too distant, such that there are not enough classes. The present study suggests that the logistic model is appropriate for describing ostrich growth, both for cockerels and for hens.

ACKNOWLEDGMENTS

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