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Morphometric Growth Characteristics and Body Composition of Fish and Amphibians

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Abstract

Describing animal growth through the nonlinear models allows a detailed evaluation of their behavior, besides revealing important information of the response to a particular treatment. In this chapter, the parameters of mathematical models (Gompertz, Von Bertalanffy, Logistic and Brody) for live weight, feed and protein intakes, total and standard lengths and nutrient deposition are described systematically and comprehensively. Also the relative growth and allometric coefficients of body components in relation to body weight of fish and amphibians are described, explaining better the use of the allometric equation and classifying the growth of the body components.

Keywords: mathematical models, allometry, body components

1. Introduction

The growth of an animal is directly related to its weight gain, constituted by water retention, protein, fat, and minerals, the quantity of which may vary from organism to organism. The order of formation of tissues and bone, muscle or fat, depending on the physiological maturity, that is, the development of each tissue occurs in an isometric way, besides that each component stimulates its growth in different phases of the animal life [1, 2]. Through this sequence, the final target of the nutrients in the animal's body has been observed. It is therefore important to know the weight and/or age at which the body growth rate declines and most part of

the nutrients goes to the adipose tissue due to the increased demand for energy expenditure [3]. Research is needed to determine the body growth in order to describe well the increased animal production. However, a proper animal's physical growth requires good maintenance conditions which are provided by the bone structure, whose development should be closely linked to the development of muscles for obtaining optimal body growth [4].

In aquatic animals, the adipose tissue may occur as individual deposits, like visceral fat existing in the form of body fat [5]; or less diffusely distributed in muscles, liver, skin, kidneys, lungs, bones, and connective tissues [6]. The fat deposits in tadpoles are acquired from the genes that are transferred to them from their parents [7]. However, other factors also contribute to the accumulation of fat in animals, such as diet and environmental conditions [8].

Animal growth is directly related to the feed it receives and the climate conditions of the region where it is found. Moreover, it is also associated with other factors such as the genetics, biotype, race, weight, age, and body state [9]. Emmans [10] stated that an ideal method of calculating nutritional requirements and indicating an animal's feed intake during its development is first to start discovering its growing potential. The nutrient requirements and development of an animal are fully interconnected. Through the understanding of these interactions, it is therefore, possible to find out the nutritional deficiencies, and to obtain the maximum animal performance while discerning the limits of production and making the appropriate changes to improve the animal productivity [11].

2. Animal growth characteristics

Growth involves an increase in the size of the animal, accompanied by the changes in body components, the latter being known as "development." The body components change in response to the age-related changes in cellular structures and functions [12]. Growth begins after fertilization of the ovum and ends when the body gains the adult weight [13].

Muscle growth in fish differs from that in mammals and continues for much of the life cycle [14] or fishes do not stop growing even after breeding. In mammals, Gómez et al. [15] described that weight gain is produced by three processes—the hyperplasia, an increase in the number of muscle cells; the hypertrophy, an enlargement of the cells; and metaplasia, the transformation of cells. Thus, animal growth is a cellular response to different internal and external factors.

In fish, three phases of muscle formation are distinguished: the first phase leads to the formation of embryonic muscle fibers that are grouped as undifferentiated myoblasts, which are the source of subsequent growth. In the second phase, the yolk sac larvae are observed, the differentiation of the germinal and proliferative zone of the myoblasts, where the dorsal and ventral apex of the myotomes is observed. Thirdly, the myoblasts on the surface of the embryonic muscle fibers are activated in a process that can continue for the entire life [15].

In amphibians, more precisely in bullfrog tadpoles, the life cycle is divided into three phases—embryonic, larval, and metamorphosis. The embryonic stage constitutes the period of fertilization and development within the egg. The second stage, larval, begins with the hatching of the egg

and the entire period of development of the tadpole. In the third and last phase, metamorphosis, the tadpole changes into an adult amphibian [16]. Gosner [17], while taking into consideration the morphological changes that occur in the three phases, subdivided them into 46 developmental stages. The first embryonic phase includes the 1–25 stages; the second phase, of body growth and early development of the hind limbs, includes the 26–35 stages. During the stages 36–41, the stabilization of the corporal growth and the development of hind limbs occur and, in 42–46 stages, the metamorphosis ends up with the externalization of the forelimbs, reabsorption of the tail, and modification of the mandible. However, the bullfrog, like all anuran amphibians, is carnivorous during the adult (terrestrial) phase, generally requiring higher levels of protein in its diet than those of other eating habits [18–21].

2.1. Factors regulating the animal growth

The growth of an animal depends on the genotype-environment interaction and factors such as quality and quantity of food, management, and health status. Body weight and length are the main parameters for producers (breeders) to determine whether the feeding level is adequate or not. For the diet to meet rapid growth is essential to understand the relationships between the weight or length and growth, so if the food is insufficient for maintenance and growth, the latter may inhibit or cease altogether [22].

In addition to weight and feed consumption, growth is influenced by other factors, which often interact with the amount of feed and body weight. According to Hephher [22], these factors can be internal and external (environmental) factors. Thus, for example, some species show a clear difference according to sex ranging from 5 to 10% [23]. Dutta [24] describes that males of *Xiphophorus* and *Poecilia* reach a “specific size,” however the females continue to grow after maturity while the rate of growth decreases over time. Another example is tilapia, where males grow faster than females, even yet in common carp (*Cyprinus carpio*) and eel (*Anguilla anguilla*), there is a greater growth of the female in relation to the male [22].

When the female has a lower weight than its male counterpart, the values of the initial growth rate, the inflection point and the asymptotic weight are smaller; nevertheless, it has less time to reach maturity. These differences of precocity between the sexes can be observed in the growth of the different tissues [23, 25], in some genetic characteristics, and in the physiological state of the animal. The growth of some fish decreases when they reach to sexual maturity. Some species of the genus *Oncorhynchus* and *Anguilla* migrate to spawn and die. On the other hand, the *Salmo salar* can repeat this procedure many times, that is, its individuals feed and grow between each spawn. In case of some tropical fish such as Heterandria, the growth is interrupted when the animal reaches a “specific size” [24]. External factors included that affect growth are the temperature, light, and water quality, which may interact with the genotype of the fish and amphibians and can induce variations in the muscle growth rate [26].

In frog culture, the time of production of the “imago,” to reach slaughter weight can range from 77 [27] to 166 days [28]. The main interference factor is the temperature because it directly influences the metabolism of the animal. Similar to all anuran amphibians, the bullfrog is dependent on the temperature of the environment in which it is found [29]. Sometimes, an increase in the water temperature above the level considered to be optimal for bullfrog may

influence growth performance. Braga and Lima [30], observed a better growth and weight gain of bullfrogs with a live weight between 37 and 90 g at the temperature between 25.1 and 30.4°C. Figueiredo et al. [31] already have observed the better performance parameters in bullfrogs weighing more than 100 g at temperature between 27.6 and 28.2°C. The environmental temperature also affected the adipose and hepatic tissue weights, presenting the higher values at temperatures of 27.27 and 26.81°C, respectively [32].

2.2. Mathematical models for describing animal growth

According to Tedeschi [33], models are mathematical representations of the mechanisms governing natural phenomena that may not be fully recognized, controlled, or understood. A mathematical model is an equation or set of equations which represent the behavior of a system, where there is a correspondence between the variables of the model and the quantities observed [34]. According to Dumas et al. [26], mathematical models are analytical solutions for the differential equations that can be adjusted to the growth data using non-linear regression. Likewise, regression analysis uses the relationship between two or more quantitative variables, so that one variable can be assumed as a function of another. The main objectives of regression analysis are based on three purposes: description, control, and prediction [35].

The modeling process includes the definition of objectives, construction of a diagram to identify the main factor involved in the system to be modeled, formulate the appropriate mathematical functions, collection of the data to estimate the parameters, solving equations, evaluation and verification of the model and programming the simulation [36].

Growth in animals can be explained by mathematical functions. These functions can predict the development of live weight, which helps to evaluate the productivity of a breed under a specific breeding condition [15, 37]. Growth can usually be described and predicted using conventional mathematical models, since it does not occur in a chaotic way [26]. In order to understand the random variation between the measurements of an animal, growth curves can be used with the aim of adjusting and standardizing the variation of weight and age during the life of an individual.

Growth models have been used to provide a mathematical summary of the development of animal growth or its parts as a function of time [34]. The growth model expression is used to describe an analytical function described by a single equation: $y = f(t)$, where “ y ” is the response variable (weight) that depends on the functional relationship, which is established as a function of the independent variable “ t ” (time).

According to Thornley and France [34], growth models can be categorized according to the functional behavior “ f ” as curves describing a decreasing yield (Monomolecular), those which have a sigmoidal behavior with a inflection point (e.g., Logistic, Gompertz, and Schumacher) and those with a flexible inflection point (as Von Bertalanffy, Richards, Lopez, and Weibull).

Growth curves which involve a series of measurements of some interest over time (body weight, body composition, diameter, and longitude) [38] are usually adjusted under controlled

conditions, and are the first steps in predicting nutrient requirements for animals of different genotypes [26, 39]. Moreover, they evaluate various parameters such as growth rate, maturity rate at different ages and weight at slaughter time and thus allow and help in establishing zoo technical breeding programs [15].

According to Brown and Rothery [40], each model has the ability to calculate an estimate of mean weight at maturity and early maturity periods. The closest asymptote is the weight at maturity, as a constant condition relative to a model for body composition under productive environments. Dumas et al. [26] showed that the growth trajectory of the animals presents an initial phase of acceleration, and the levels when the animal is close to its adult stage or induces its reproductive growth, being called the growth inhibition phase (**Figure 1**). Many species of fish, molluscs, crustaceans, and amphibians can even grow after reaching the maturity size and the final stage of growth presents a greater plasticity [26].

2.3. Models applied for growth assessment

To describe the growth in fish and amphibians, it is common to use nonlinear mathematical models. The most used models are included, the Brody, Gompertz, Logistic, Richards, and von Bertalanffy [40–44], however, there is a much larger range of functions that can be used to help in the simulation of body growth and body components such as, the scales, skin, viscera, fillet or nutrients such as, the protein, fat, and ash content. These functions are used in simulation models to estimate the body composition of animals at any stage of development, requiring little information on their growth and initial body composition [26].

These models contain several common parameters though there are variations regarding their interpretation and content, and are possible to associate any biological meaning to each of them [25]. Gompertz, $Y = A \exp(-\exp(-b(t - T)))$; Von Bertalanffy, $Y = A(1 - K \exp(-Bt))^3$; Logistic, $Y = A(1 + K \exp(-Bt))^{-1}$; and Brody, $Y = A(1 - K \exp(-Bt))$. The parameters used in these models are defined as: Y = measurement values (g or cm); t = experimental days; A = body

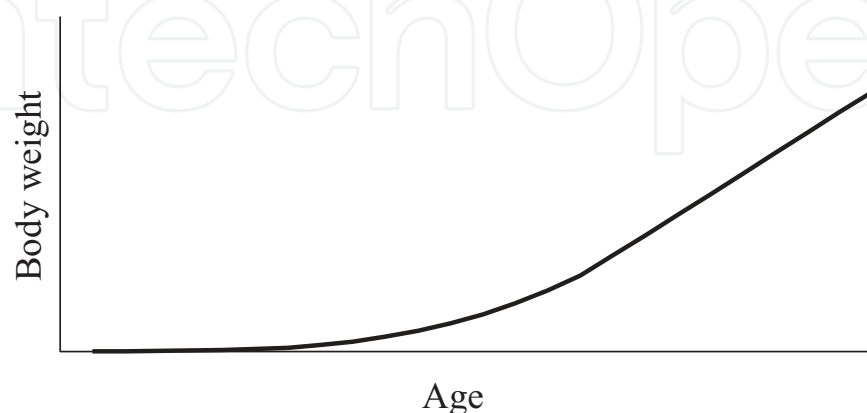


Figure 1. Typical growth trajectory in fish (source: Dumas et al. [26]).

weight or length at maturity; K = scale parameter with no biological interpretation for the Von Bertalanffy, Logistic, and Brody models; b and B = growth rate at maturity; T = growth rate at maturity for the Gompertz model, where it represents the day of maximum growth. These parameters can be estimated by the modified Gauss-Newton method, through the program of SAS by procedure "PROC NLIN" (nonlinear regression).

2.4. Assessment of the accuracy of mathematical models

According to Tedeschi [33], the evaluation of the accuracy of a model is an essential step in the modeling process which indicates the level of precision in the prediction adjustments. The evaluation of the model can and should proceed up to the level of the predicted results (upper level) and up to the level of the assumptions (lower level), while the parameters should be determined by the researchers. Unfortunately, this is not always possible, and some "tuning" or "calibration" of the parameters is usually necessary. A higher evaluation may consider model properties, such as simplicity, fit plasticity, applicability, and quality and quantity of prediction adjustment.

According to Santos et al. [45], to choose the model that best fits the data, the following criteria are considered: mean square of residue (MSR), coefficient of determination (R^2), and biological interpretability of parameters.

Some criteria can be used to select the models and describe correctly that which one is better for a given data. The most commonly used adjustment quality evaluators are determination coefficient (R^2) [46, 47], adjusted coefficient of determination ($R^2_{aj.}$) [48], the mean squared error (MSE) [46, 47]; value of the Akaike criterion (AIC) [47, 48], value of the Bayesian information criterion (BIC) [47, 48]; convergence percentage (C%) [47, 48], the number of iterations (NI) [44, 45, 46]; mean absolute deviation of residues (MADR) [49–51], dispersion of the waste estimated by the models and the distribution of studentized waste [50].

The adopted set of adjustment evaluators should be fitting to assist in the decision making of the choice of the better model studied. Evaluation criteria for selecting an appropriate model should be well adopted, since information provided by fit quality assessors can indicate that which model is most appropriate to describe the body growth of a population [52, 53].

2.5. Mathematical models for evaluating animal growth

Each animal species has a particular growth curve where it should be in a suitable and non-limiting environment. The fact that several aspects such as maturity, composition, and deposition rates of body nutrients can interfere with the growth curve should be emphasized. Therefore, care must be taken in choosing the best model, since there are a lot of models that will fit one's data. However, attention should be paid about those who describe the growth of animals with greater precision and clarity according to their age. Once the wrong model has been chosen, the error will be reflected in future researches and feeding programs.

In the ongoing nutrition research, several studies on the application of mathematical models are available about amphibians and fish. Thus, some of the previous literature has been chosen to characterize their application in research studies. Next will be described the weight or length of the animal at maturity (A) and growth rate relative to maturity (K) of some species.

As for the parameter A that refers to the asymptotic weight, Amancio et al. [54] evaluated fitting of five mathematical models (Gompertz, Logistic, Linear Hyperbolic, Quadratic, and Logarithmic Quadratic) to describe the growth curve of genetically improved farmed tilapia (GIFT) Nile tilapia (*Oreochromis niloticus*). Nile tilapia fingerlings of the initial weight 2.4 g stocked in 20 concrete tanks of 2 m³ with a density of 25 m⁻³ fish for a period of 180 days. An asymptotic weight of 763.6 g in the Gompertz model and 509.8 g in the Logistic model was reported. These values are lower than those found by Carvalho [55], who worked with several families of tilapia in a genetic improvement program, using the Gompertz model and found values of 3921.4 g (family 40), 4554.7 g (family 6), and 4613.5 g (family 53).

Similarly, the values for the T parameter were obtained, which refers to the age at the inflection point of 186.6 days of the Gompertz model and 208.2 days of the logistic model. These values also are less than those found by Carvalho [55], such as 495.4 days (family 53), 479.8 days (family 6), and 415.2 days (family 40). It is then realized that such differences of the variety between the Nile tilapia families imply that studies can still be carried out for the improvement of the variety in question, as well as the validation and concluding the fish growth, or even studies for the formation of a new variety.

In conclusion, Carvalho [55] concludes that Gompertz model was the one that better adjusted the characteristics evaluated in the study of growth curves of Nile tilapia. Similar result was seen by Hernandez-Llamas and Ratkowsky [56] and Katsanevakis and Maravelias [57] evaluating mathematical models to describe the fish growth. However, in a study carried out by Aguilar [58], using the Chitralada variety of Nile tilapia, a better adjustment of body growth rate for the von Bertalanffy model, Gompertz, and Logistic has been found. The other models also presented a satisfactory fit with the estimated asymptotic weight between 614.13 and 820.44 g. On the other hand, Costa et al. [59] used the Brody, von Bertalanffy, Logistic, Gompertz, and exponential models evaluating the growth of the Chitralada, GIFT, and red Nile tilapia lines and observed that the fit of the exponential model was the most adequate. In the present experiment, the Gompertz model was the one that better adjusted the data.

In the same way as evaluated for fish, in amphibians more specifically in bullfrog tadpoles, different models (Gompertz, Brody, von Bertalanffy, and Logistic) were applied for evaluation and simulation of their growth [50]. The values of the parameters found for each growth model adopted in weight and total length have been found in the study of Mansano et al. [50]. The Gompertz, von Bertalanffy, and Logistic, were the only featured models in which the convergence criterion was achieved; however, the Brody model did not converge for the observed data set of weight and length. A possible explanation may be that the model does not have an analytical solution of the normal equations, being the estimations of the parameters of the nonlinear models obtained by iterative algorithms [60]. The weight at maturity or asymptotic weight (A) found for the logistic model (8.90 g) was the one with the lowest value, followed by the Gompertz model (10.66 g), which was lower than that found by the model von Bertalanffy (13.36 g) [50]. For the total length at maturity, parameter A presented the same behavior. The simulated values for parameter A adopted in the study are biologically interpretable for bullfrog tadpoles.

The parameter of B of the Gompertz, von Bertalanffy, and Logistic models represents the growth rate relative to maturity, and the lowest value of this parameter represents the highest

weight and total length at maturity [61]. In the study of Mansano et al. [50], the logistic model presented the highest value, among the three models that were presenting the lowest weight and total length at maturity. Inversely, the von Bertalanffy model presented the lowest B value for the parameter B and, consequently, higher weight and total length at maturity. In the same study of the evaluation of these models, the R^2 values found for all the models were excellent >0.98 , with small differences for both live weight and total length. However, R^2 is not a good differentiator for choosing nonlinear models [60]. From the mean squared error (MSE) found for the models, it can be seen that there was no difference between the studied models, for both live weight and total length. In the absolute average deviation (AAD) evaluation, it was possible to verify that the von Bertalanffy and Logistic models underestimated the values. They presented lower values than those observed in the initial weight studies which are a serious error to be considered. Since for animals such as bullfrog tadpoles that have an initial weight around 0.1 g, it cannot be considered that an animal has a negative weight because it is biologically impossible.

In a study of captive bullfrog during its terrestrial phase, Pereira et al. [62] tested two nonlinear models. The authors have found quite different values among which the estimated value of A for live weight of 1051.5 g of the Gompertz model was considered high to represent the study period. Bullfrog specimens may reach this value throughout their life with more than 2 years. However, the estimated value for mean weight of 343.7 g of the logistic model was considered adequate for the growing period of the “Frogllets” until the slaughter weight, since the frogs had an average weight of 214.56 g with 126 days. The adjusted K value for live weight of 0.0088 (g/day) by Gompertz model presented the same incoherence for the A value of the same model. Since it is believed that the bullfrog presents a maximum growth rate during the period of the 126 experimental days, estimated as 0.0313 (g/day) by logistic model with its maximum peak at 109th day of the experiment.

According to Pereira et al. [62], the logistic model presented a characteristic of estimating baseline values lower than the Gompertz model, underestimating the initial live weight in the mean of 4.12 g. This behavior was also observed in bullfrogs created in mini bays, where the logistic model underestimated the initial weight by 21.8 g [51], and the study performed in 294 days with frogs beyond the slaughter weight range. These values underestimated by any type of model provided can be considered that this value is not negative, since no animal is born with a negative weight. It is important to point out that the results found in the previous literature aimed finding the equations representing growth may vary among the various species of amphibians and the conditions adopted [6]. The choice of a suitable growth model is important, since it can have a decisive effect on the results of simulation of an ecological dynamics model. For example, the logistic model has been indicated to describe growth over short periods of time (days and months) and in environments that have some control such as nutrition [63].

The use of nonlinear models may have a wide application area, using the Gompertz model described by Mansano et al. [50], to describe the growth curve and body composition (protein crude, fat, water, and ash content) of bullfrog tadpoles [64] (**Table 1**). In addition to the evaluation and simulation of growth using Gompertz model, it was possible to verify that which of

Variable	Diet	Parameter		
		Pm	b (per day)	t^*
Live weight (g)	ED	10.66 ± 1.0517^a	0.0558 ± 0.0088	38.195 ± 2.2956
	CD	9.54 ± 0.4174^b	0.0590 ± 0.0044	37.571 ± 0.9918
P value		0.0028	0.3628	0.3020
Total length (mm)	ED	120.0 ± 3.8715	0.0394 ± 0.0022	21.813 ± 1.0297
	CD	122.1 ± 3.1691	0.0371 ± 0.0016	23.516 ± 0.8630
P value		0.3124	0.2764	0.1046
Partial length (mm)	ED	37.26 ± 1.0098^a	0.0415 ± 0.0023	16.465 ± 0.8371
	CD	35.56 ± 0.8304^b	0.0425 ± 0.0021	15.978 ± 0.7135
P value		0.0199	0.5618	0.4519
Cumulative food intake (g)	ED	15.19 ± 0.6551	0.0482 ± 0.0026	42.563 ± 1.0919
	CD	15.33 ± 0.5732	0.0485 ± 0.0023	42.656 ± 0.9413
P value		0.5828	0.7863	0.5979
Cumulative protein intake (g)	ED	4.56 ± 0.1970^b	0.0482 ± 0.0026	42.563 ± 1.0919
	CD	5.42 ± 0.5732^a	0.0485 ± 0.0023	42.655 ± 0.9413
P value		0.0001	0.7863	0.8405
Total body protein (mg)	ED	873.8 ± 0.1837^a	0.0478 ± 0.0122	43.759 ± 2.3173
	CD	697.0 ± 0.0373^b	0.0672 ± 0.0062	41.271 ± 1.0896
P value		0.0265	0.0817	0.2525
Total body water (mg)	ED	$9.103.8 \pm 0.8588^a$	0.0564 ± 0.0088	37.461 ± 2.2084
	CD	$8.168.8 \pm 0.3603^b$	0.0599 ± 0.0048	36.467 ± 1.0097
P value		0.0028	0.5940	0.1574
Total body fat (mg)	ED	469.4 ± 0.0864	0.0568 ± 0.0154	43.961 ± 3.9850
	CD	421.5 ± 0.0330	0.0592 ± 0.0061	46.103 ± 1.6829
P value		0.6612	0.4787	0.1197
Total body ash (mg)	ED	195.6 ± 0.0444	0.0443 ± 0.0105	48.064 ± 2.932
	CD	169.6 ± 0.0124	0.0528 ± 0.0043	47.024 ± 1.706
P value		0.1044	0.0545	0.7943

Pm = weight or length at maturity; b (per day) = maturation rate; t^* (days) = time of maximum growth rate. Means in the same column followed by different superscript letters differ significantly ($P < 0.05$, F test). **Source:** Elaboration of the authors. $Wt = sWm \times \exp \times (-\exp \times (-b \times (t - t^*)))$, where Wt = nutrient weight (g) of the animal at time t , expressed as a function of Wm ; Wm = nutrient weight (g) at maturity of the animal; b = maturation rate (per day); t^* = time (days) when the growth rate is maximal. ¹ED = 26.23% digestible protein and 32.68% crude protein; ²CD = 37.92% crude protein.

Table 1. Parameter estimates obtained with the Gompertz equation for live weight, feed and protein intake, total and partial lengths and nutrient deposition of bullfrog tadpoles fed the experimental (ED)¹ and commercial (CD)² diets.

Age (days)	Protein (g/dia)		Lipid		Water	Ash	
	CONS	DEP*	CONS	DEP*	DEP*	CONS	DEP*
1	0.0058	0.00064	0.0008	0.00016	0.0104	0.00109	0.00005
12	0.0155	0.00399	0.0023	0.00128	0.0569	0.00294	0.00053
20	0.0254	0.00796	0.0037	0.00293	0.1069	0.00482	0.00126
29	0.0414	0.01147	0.0061	0.00485	0.1475	0.00787	0.00201
42	0.0537	0.01207	0.0079	0.00600	0.1497	0.01019	0.00226
54	0.0642	0.00947	0.0094	0.00527	0.1155	0.01218	0.00179
63	0.0608	0.00711	0.0089	0.00711	0.0862	0.01155	0.00134

*Deposition values were estimated by the derivative of the Gompertz equation.

Table 2. Consumption (CONS) and deposition (DEP) of nutrients according to age of bullfrog tadpoles.

the diets presented the best performance for the animals. Thus, it was possible to conclude that the Gompertz model provided a good fit of the data to describe the morphometric growth curve and carcass nutrient deposition of bullfrog tadpoles. A higher growth rate and nutrient deposition was observed for tadpoles receiving the experimental diet (26.23% digestible protein).

On the basis of the estimated equation, growth rates (g/day) were calculated as a function of time (t) by the derivative $dWt/dt = bWt \exp(-b(t - t^*))$ of the equation described by Winsor [65].

Still taking as an example the Gompertz equation, the growth, consumption, and nutrient deposition rates (g/day) as a function of time (t) can be calculated by means of the derivative of the equation $dY/dK = bPt \exp(-b(t - t^*))$, Winsor [65]. These parameters are very simple to obtain, an example of which is their estimation by the modified Gauss-Newton method using nonlinear regression using the NLIN procedure of SAS or another statistical program.

It was possible to verify that the values of the consumption, deposition, protein, fat, moisture, and ash content weights showed as the tadpoles gained body protein weight, there was an increase in the deposition of the other nutrients. After deposition of nutrients in the tadpole body, ash, protein, and water deposition occurred in the initial phase (**Table 2**). The authors concluded that nutrient consumption is greater than the nutrient deposition in the carcass of the bullfrog tadpoles (*Lithobates catesbeianus*) and the high protein content of 57.53% of the commercial feed used is not fully utilized by the bullfrog tadpoles.

3. Relative growth and allometric coefficients of body components of fish and amphibian

3.1. Allometric growth

The body composition of the fish changes throughout the life cycle and its utilization is affected by endogenous (species, size) and exogenous factors such as time of year and diet

composition [66]. According to Bureau et al. [67], the nutritional factors of the rations such as the balance of available amino acids, essential amino acids, amount of protein and the ratios of protein: energy is important in the deposition of protein and lipid in the tissues. Therefore, during the growth, there are seasonal changes in body composition, associated with the endocrine states and the special physiological stages. At the reproduction stage, there occur the syntheses and reserves of new tissues [26]. In order to analyze this dynamics, the nutrient prediction models can be used. These are mechanistic models which are used to define the destination of dietary nutrients, considering the use of amino acids, fatty acids and their precursors [26]. Thus for example, the amount of protein in the body can be described by means of a growth function. However, the increase in water, ash, and lipid deposition may be linked to protein to determine the whole body growth [39].

3.2. Equations for predicting allometric growth

The isometric and allometric relationships based on regression analysis are still successful to estimate the body composition in fish and other animals in the production sector [26]. The different genotypes may differ in aspects that are estimated from growth curves, such as the maturity, body composition at maturity, fat content, and maturity rates of the body chemical components. The chemical composition varies over time [39]. The energy gain can be predicted using the bioenergetic models, but these do not provide much information on the chemical composition and biomass gain [26].

Allometry refers to changes in the different dimensions of body parts that are correlated with changes in the whole body [68]. According to Thornley and France [34], allometry means growth of a part of the body (W_1) related to a different proportion of the whole body (W). It may be expressed as follows: $y = aX^b$, where a is the normalization constant, b is the dimensions of allometric parameters. This equation can be linearized as follows: $\ln y = \ln a + b \ln X$. When the value of b is equal to 1, the growth is considered isogonic and the rates of development of Y and X are similar in the considered growth interval. In the case of b being greater than 1, the growth is called heterogenic positive and the growth rate of Y is greater than X , characterizing a late development. When the value of b is less than 1, the growth rate of Y is less than X characterizing an early development.

3.3. Allometric evaluation to describe growth variables

As an example, in a study conducted with the freshwater angelfish [69], it was possible to better understand the applicability of allometry. The allometric coefficients for length, weight, protein, fat, ash, and water were determined. The allometric equations and their components in addition to the coefficient of determination (R^2) of the standard length (SL), head length (HL), height (H) and width (W) ratios are shown in **Table 3**. For the height component, the value of b was 1.095 indicating that the fish presented a positive allometric growth or isogonic growth ($b = 1$), that is, from 30 to 233 days of age, the height increased by the same magnitude as the standard length.

Other components, such as the head length and width, showed an early growth ($b < 1$), increased at a lower rate than height, but with more intensity in the final phase of the growth

Components	Coefficients $Ln a$	B	R^2
Head length	-0.678	0.907	0.907
Height	-0.728	1.095	0.900
Width	-1.029	0.749	0.886
Weight	-10.25	3.060	0.989

Length (L), width (W), weight and standard length (SL), natural logarithm of the normalization constant ($Ln a$), dimensions of allometric parameters.

Table 3. Allometric coefficients of *P. scalare* juveniles from 30 to 233 days of age in relation to the standard length.

period (**Figure 2**). According to Santos et al. [70], head growth is early to ensure feed consumption during the early stages of fish growth; in late adult years there is a late growth.

In this study, males and females were kept together in the aquariums and it was not possible to estimate the sex ratio due to the difficulty in identifying sexual dimorphism in the early stages of growth. The difference between the growth rates of the different parts of the fish was more noticeable throughout the structuring period and stabilized when they got maturity level.

In production fish, it is useful to know the growth of the fillet in relation to its body weight in order to estimate the possible slaughter weight of the animal. Gomiero et al. [44] evaluated the development of fillet in relation to body weight in Piracanjuba fish, which presented an isogonic growth. According to the results obtained by Almeida et al. [71] about *Oreochromis niloticus* grown in a semi-intensive system, the fillet growth was smaller than the body growth, whereas in an intensive rearing system, the fillet presented an enlargement equal to the body weight with a value of $b = 0.9690$.

Taking as an example, the result of the analysis of the standard length and weight ratio of freshwater angelfish presented in **Figure 3a** and **b**, we can observe that this fish has an isogonic growth indicating a proportional increase in weight and length. In **Figure 3b**, the

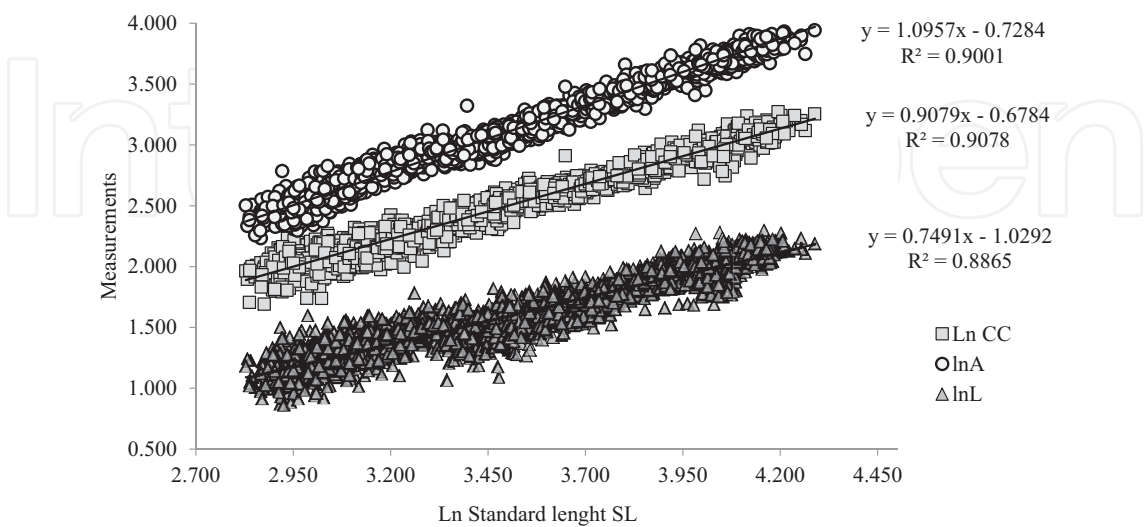


Figure 2. Allometric lengths of head (H), height (H), width (W), and standard length (SL) in *P. scalare* from 30 to 233 days of age.

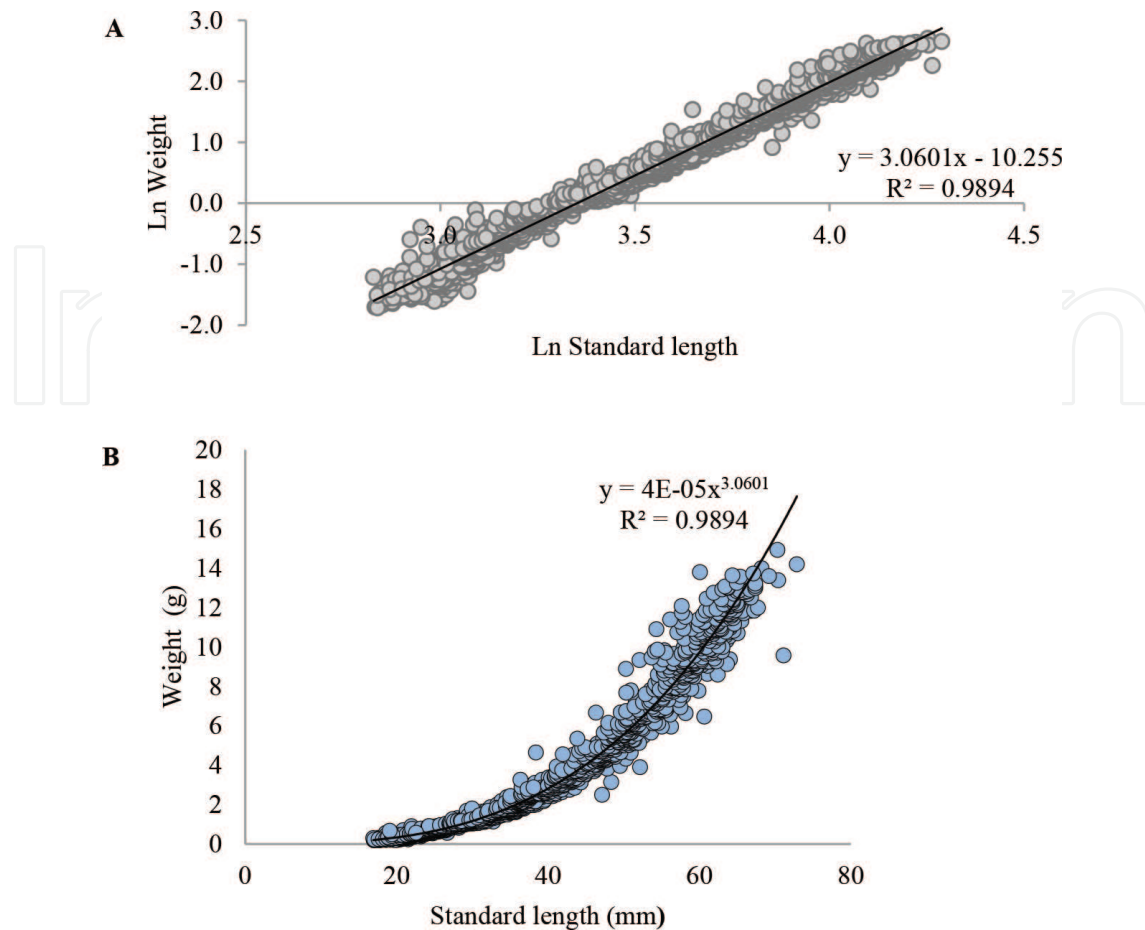


Figure 3. Allometric relationships between weight and standard length in *P. scalare* from 30 to 233 days of age. A is the linear regression and B is the determination coefficient.

exponential relation between standard length and weight can be observed. The coefficient of determination was 9.089 for the two regressions.

The value of b obtained for freshwater angelfish was 3.06 (**Figure 3a**). Results are close to those already found for the same and other fish species. For example, in *Arapaima gigas* grown in a semi-intensive system in the state of Amazonas, Tavares-Dias et al. [72] obtained for the coefficient b a value of 3.068. Silva-Júnior et al. [73] obtained a value of b between a range of 2.4 and 3.4 for 33 estuarine fish species. Sani et al. [74], studying 14 species of freshwater fish in India, also have found a range of the value of b between 2.4 and 3.52. These values are within the ideal for fish, which should be close to 3 [75]. The time of year had influence on the weight-to-length relationship in salmon (*Salmo trutta*); in winter, there was negative allometry and in the other seasons the growth was isometric for females, males, and the mixed group [76]. According to Tavares-Dias et al. [72], knowing the value of body weight can estimate the value of the standard length or vice versa.

Due to the difficulty in identifying the sexual dimorphism in the flag mites at the time of the beginning of the experimental phase, the fishes were not separated by sex, and for the biometric analysis, the fishes were randomly selected. In order to evaluate the length-to-weight

relationship in *Buglossidium luteum*, separating the fish in groups by sex and also in mixed groups, Ilkyaz et al. [77] concluded that although the length between sexes presented different values, the weight-length curves were very similar thereby growth was isometric for females, males, and for the mixed groups.

Several allometric relationships exist in the literature describing the relationship between surface area (SA) and body mass (BM) for different species of Anurans and these are frequently used in physiological studies. However for species of production such as bullfrog, little studies exist on such allometric relation. In the study conducted by Klein et al. [78], the bibliographic data such as, surface area (SA) (cm²) and body mass (BM) (g) was collected, and the allometric relationships between SA and BM were evaluated using linear regressions and phylogenetic generalized least squares (PGLS). Data from 453 specimens of 44 species were included. Intraspecific allometric relationships between SA and BM were determined for 18 species, of which 10 presented regressions significantly different from the respective family regression, four species showed a significantly different intercept- y , and three species exhibited a significantly different slope. Only the Bufonidae, Ranidae, and Hylidae families were represented by several species (9, 11, and 12, respectively) and with a larger number of specimens (54, 215, and 127, respectively). These three families showed significantly different OLS linear regressions on log-transformed data, with Hylidae being the steepest (0.7735 ± 0.0110), Bufonidae an intermediate (0.6772 ± 0.0220), and Ranidae the lowest slope (0.6091 ± 0.0114). The relationship between SA and BM for Anura could be described by linear regression $SA = 9.8537 BM^{0.6745}$ or by the regression of PGLS $SA = 8.7498 BM^{0.685}$.

3.4. Allometric evaluation for dynamics of macromolecules

With the allometric equations, it is possible to determine the relationship of body nutrients in relation to protein weight or live weight. Thus, nutrient prediction as a function of protein weight corrects changes in body fat related to diet [79]. The amount of protein may be described as a growth function, and then the growth of water, ashes, and lipids may be linked to protein to determine the growth rate of the whole body [39]. Although the lipid and ash contents separately are not good predictors of body weight [80].

Figure 4 shows the allometric coefficients for the freshwater angelfish body components. The allometric relationship between body protein and live weight showed an isogonic tendency ($b = 1.037$), protein increased in the same proportion as body weight and these observations agree with the study done by Dumas et al. [80] with trout. This can be explained by the fact that the weight of the protein is linked to the live weight [80] mainly by the muscular gain. The fat performance regarding live weight was higher and 1105 units of fat were deposited per unit of live weight. Fat is the most dynamic macromolecule, and its rate of change is easily affected by the temperature of the water in which the fish exist, amount of fat (energy) in the diet, in addition to if the diet that has a protein imbalance. For each component, the coefficient of determination R^2 was above 0.99 presenting a good fit of the model to the data.

In allometric study of Nile tilapia of GIFT strain, due to the body weight, Amancio et al. [81], found that as the fish gained body weight, there was an increase in the proportion of protein ($b = 1.039$), fat ($b = 1.089$) and ash ($b = 1.051$) and a reduction in body water ratio ($b = 0.983$).

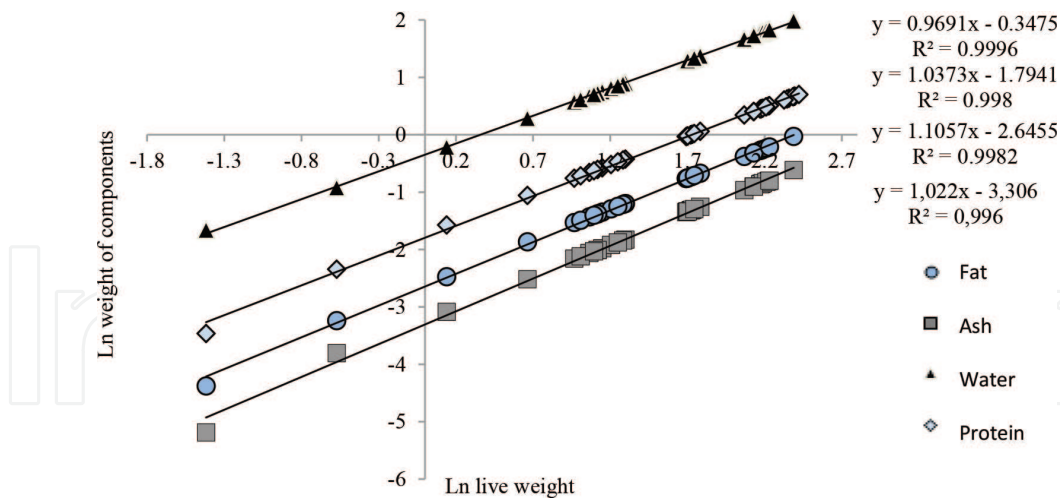


Figure 4. Allometric relationships between live weight and fat, ash, water and protein in *P. scalare* from day 30 to day 233 of age.

This lower water weight ratio may be a result of the increased fat proportions in the carcass, since this was the component that presented the highest allometric coefficient.

In the study conducted by Silva [82], it was verified that in Nile tilapia of supreme strain, the body nutrient that increases largely as body weight increases is fat, mainly to the detriment of moisture content. The inverse relationship between lipid and water contents in the fish muscle was also observed by Guinazi et al. [83], Caula et al. [84], and Neves [85]. Even with the use of allometric equations derivative, it is possible to gain weight of certain nutrients per gram of body weight or protein weight. According to Bureau et al. [67], protein deposition governs the growth of the animal, since for each gram of protein deposit, three and six grams of water deposited, while the deposition of lipids can be done by replacing the water.

Allometric equations are important in determining the relationship of body nutrients, organs, muscle, bone, and skin to protein weight or live weight. The equations can estimate the content of nutrients that the animal deposits are based on the protein weight or live weight [79]. Allometry has been used in mathematical modeling because the body composition of lipid-free dry matter does not change during animal development, but the lipid content of growing animals can be affected by the diet [86].

When allometry has been used in relation to the proportion of protein in the body, the differences between sex and lineages are small. Thus, the use of protein weight in allometric relationships makes the equations more precise. However, the development of allometric equations in relation to fasting live weight would be the most practical method to predict body weight and body nutrient deposition [79].

4. Final considerations

Growth models are useful tools that besides evaluating variables within a population, allow measures to improve the points of the curve, make a selection of the desirable characteristics

within a production system and allow improving the feeding strategies for the animals. For future allometric growth research in order to improve the standardization of values, different animal groups can be selected for conducting trials while separating them on the basis of their sex, age, sexual maturity, and the time of year.

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