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The Growth Pattern of Pterosaurs Based on Logistic Growth Model

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ABSTRACT. *Fictional dragon becomes a new member of the real world family. As an old member, human need to know its origin and evolution, in order to get along with each other in the earth. Based on incomplete data and reasonable assumptions, we analyze the growth pattern of pterosaurs to obtain the function relation between weight and wingspan. With the estimation of height ratio of Daenerys and Drogon, we estimate the wingspan of a 6 year old Drogon, which is 59 meters. Putting the wingspan data into weight-wingspan function, we obtain the weight of Drogon, which is 34.031 tons. The result is of importance to the research of food intake of dragons. Finally, we build a toy ecosystem for dragon and the principles for dynamics of system are well found.*

KEYWORDS: *Pterosaurs, Logistic growth model, Weight estimation*

1. Introduction

In Game of Thrones season one, 'Mother of Dragons' Daenerys Targaryen hatched three dragons-Drogon, Rhaegal, and Viserion during her husband's funeral. The dragons grow with a stunning fast speed. Drogon, which is the largest and most aggressive of Daenerys' three dragons, has already had the size of a small jumbo jet in Game of Thrones season seven. The dragons only feed on cooked meat. They can do the cooking by breathing out their own flame. The dragons also possess the ability for a long-distance flying.

2. Date acquisition of the dragons

It's impossible to obtain data of the dragons from the real world because the dragons are fictional. In order to obtain more accurate data, we analyzed the dragon size and the related information based on the television series 'Game of Power' and

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related information, then we get the wingspan data of Drogon and Balerion, as shown in Figure 1.

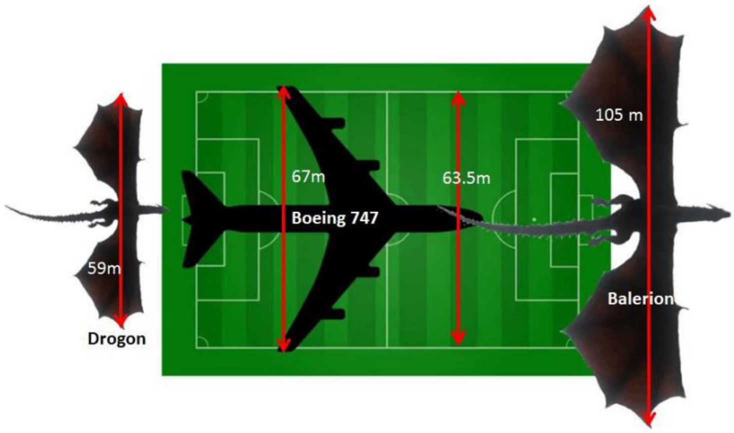

Figure. 1 The wingspan data of Drogon and Balerion

Figure 1 shows the wingspan of Drogon is similar to the width of a football field and the shape of Drogon is similar to a Boeing 747. By comparison, the young dragon Drogon has a wingspan of 59 meters, while the adult dragon Balerion has a wingspan of 105 meters.

Next we calculate dragon's weight by using the functional relationship between the wingspan and mass. We choose the wingspan and mass of the pterosaur, which was actually real, to get the fitting function. Literature [1] analyses the relationship between the wingspan and weight of pterosaurs. Based on this we try to analyze the functional relationship between the wingspan and mass of the dragons. Then we use the wingspan data to calculate the dragon's weight.

3. Estimation of the dragon's weight

Biologists and ecologists who study extinct animals argue that it is inaccurate to assume that the weight of an animal is only related to its wingspan. Recent studies suggest that the reason why pterosaurs can fly in such a large size is more closely related to the weight of pterosaurs and the width of their wings. Based on the results of literature [1], we obtained the data of wingspan and mass of pterosaurs as shown in Figure2, and made an exponential regression analysis of wingspan and mass of pterosaurs based on the data.

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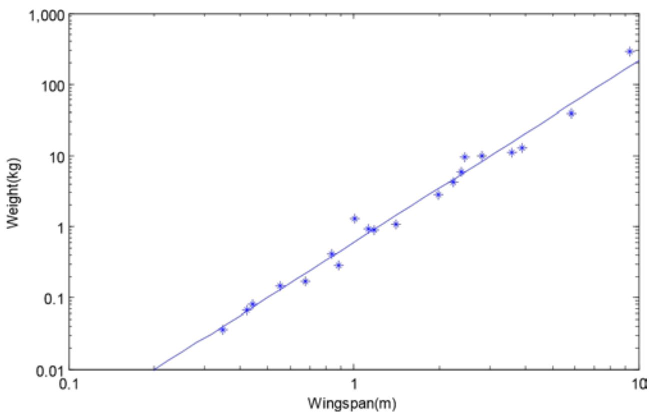

Figure. 2 Wingspan and mass regression curve

Through exponential regression analysis, we conclude that the wingspan and mass function relationship of pterosaurs satisfies $m_{pter} = 0.595w^{2.553}$. Accordingly, we speculate that pterosaurs weighed 19740 kg when their wingspan reached 59 meters, but it doesn't mean that the weight of the dragon also satisfies the function. According to many movies and TV materials, dragon of the same size are always much stronger than pterosaur. Therefore, we should take the weight ratio of dragon to pterosaur into consideration.Based on the relevant data[2], we know that Drogon (6 years old) weighs about 33 tons. Accordingly, we get the ratio estimation 1.7 , which leads to $m_{dragon} = 1.7m_{pter} = 1.01w^{2.553}$.

The weights of the 6 year old Drogon and the 220 year old Balerion are around 33559 kg and 146180 kg by calculation. Based on the above results, we get the wingspan and weight data of dragons at different ages, as shown in Table 1.

Table 1 Wingspan and weight for a dragon at different ages

Age(years)	*0*	*1*	*6*	*220*
Wingspan(m)	unspecified	unspecified	59	105
Weight(kg)	10	35	34,031	147,990

4. Logistic growth model

For further analyzation, we choose a suitable model to fit the growth law of dragon. Consider that the dragons grow continuously, $\mathrm{growthFunc}(t)$ should accord with monotonic increment. According to the growth law of animals in reality, the growth of body weight is relatively slow at birth because of their small size;

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when they are growing up, their body weight increases rapidly; and when they reach maturity, even though their body weight is still increasing, but the growth will be extremely slow. Based on the above analysis, we choose Logistic function [4] for further study. Some improvements are made to fit the growth law of dragons better.

The improved growth function $\mathrm{growthFunc}(t)$:

$$\mathrm{Logistic}(t)=\frac{a}{1+be^{-kt}} \Rightarrow \mathrm{growthFunc}(t)=\frac{a}{1+be^{-kt}}+c$$

In order to describe the growth law of the dragon, we adopt the method of minimizing the mean square error *err* to solve the parameters, that is, to solve the minimization of the following problems. The *err* formula for minimizing mean square error:

$$\min_{A,B,k,c} err=\sum_{i=1}^{m}\left(y_i-\mathrm{growthFunc}(t_i)\right)^2$$

Formula *a*,*b*,*k*,*c* denotes the parameters of $\mathrm{growthFunc}(t)$; t_i , y_i denotes the dragon's age and weight in the *i* th stage. *m* denotes the total number of sampling points, and the data provided in Table 1 is obviously $m=4$.

In order to minimize *err* , we consider the gradient descent method. To solve this problem, we need to find the partial derivatives of each parameter. The formulas are as follows:

$$\begin{bmatrix} \dfrac{\partial err}{\partial a} \\ \dfrac{\partial err}{\partial b} \\ \dfrac{\partial err}{\partial k} \\ \dfrac{\partial err}{\partial c} \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{m}\left(\dfrac{a}{\left(1+be^{-kt_i}\right)^2}+\dfrac{c-y_i}{1+be^{-kt_i}}\right) \\ \sum_{i=1}^{m}\left(\dfrac{ae^{-kt_i}\left(y_i-c\right)}{\left(1+be^{-kt_i}\right)^2}-\dfrac{a^2e^{-kt_i}}{\left(1+be^{-kt_i}\right)^3}\right) \\ \sum_{i=1}^{m}\left(\dfrac{a^2bt_ie^{-kt_i}}{\left(1+be^{-kt_i}\right)^3}+\dfrac{ab\left(c-y_i\right)t_ie^{-kt_i}}{\left(1+be^{-kt_i}\right)^2}\right) \\ \sum_{i=1}^{m}\left(\dfrac{a}{1+be^{-kt_i}}+c-y_i\right) \end{bmatrix}$$

Based on the above partial derivation, we use the fminunc function of MATLAB to solve the parameters of this part. See the code provided in the annex for details. The results are shown in Table 2.

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Table 2 Parameter Estimation of Logistic Growth Model

Project	*a*	*b*	*k*	*c*
Logistic	146520	689.1	0.889	-341.94

Based on Table 2, we compare the known weight with the estimated weight by Logistic function, and draw the comparison results, as shown in Figure 3.

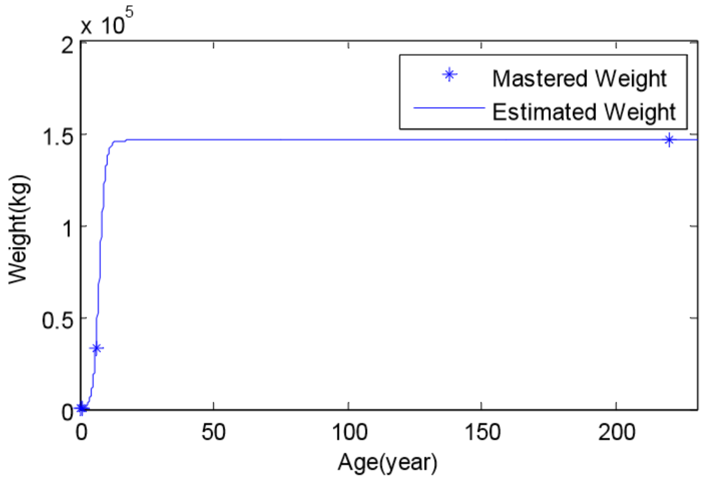

Figure. 3 Comparison between the known Weight and the estimated Weight

Through Figure 3, we find that the estimated weight information from logistic model is very close to the real to weight information. Furthermore, we use the formula:

$$relativeError = \frac{\sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(y_i - \text{growthFunc}\left(t_i\right)\right)^2}}{\frac{1}{m}\sum_{i=1}^{m} y_i}$$

Calculating the relative error, and find that relative error is only 0.22%. Obviously, relative error is very small, which shows that we can fit the growth law of dragons well based on the weight information we have. According to the growth law of the dragon, a simple ecosystem is established to study the relationship between the predators and the preys.

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5. Conclusion

Based on incomplete data and general principles in nature, we adopt several reasonable assumption which is verified by studies of pattern of dragon. The research routine follow the way of Pterosaur, and our finding show that dragon is the biggest flying species in the world, has similar growth curve and wingspan dependent weight principle with only different scaling constant. Some numerical methods and statistical regression analysis are adopted in the treatment of weight growth data and wingspan-weight relation. Stabilities of the ecology dynamic system is studied via principle of biology/ecology. The routine of research on incomplete data analysis of animal behavior and body pattern is vital. It belong the spirit of inverse estimation/problem.

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