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RESEARCH NOTE

Modeling the individual growth of the Pacific oyster *Crassostrea gigas* cultivated in the Gulf of California using the von Bertalanffy model

Modelando el crecimiento individual de la ostra japonesa *Crassostrea gigas* cultivado en el Golfo de California mediante el modelo de von Bertalanffy

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Abstract. This study demonstrate the advantage of multi-model approach to calculate the growth of *Crassostrea gigas* cultivated in the Gulf of California. The generalized von Bertalanffy growth model (VBGM) and its modification to represent the seasonal variations (VBGM seasonal) were tested. The parameters of each model and their confidence intervals were computed using the maximum-likelihood method. The best-fitting model was selected using the Akaike information criterion (AIC). According to the AIC, the VBGM seasonal best described the growth of the *C. gigas*. The conclusion was that *C. gigas* exhibits a seasonal growth pattern under the cultivation conditions of the present study.

Key words: Akaike Information Criterion, seasonal growth model, von Bertalanffy

INTRODUCTION

The Pacific oyster *Crassostrea gigas* (Thunberg, 1795) is cultivated in the Mexican Pacific coast and in the Gulf of California. It was introduced to Mexico in 1972 (Góngora-Gómez *et al.* 2012), since then many studies have been dealing with the growth performance of this species. However, the growth has been analyzed in an empirical way, but there is no studies so far modeling the growth. Chávez-Villalba *et al.* (2010) described the growth of *C. gigas* from a coastal lagoon and marine environment in central Gulf of California just as monthly increments in size. They mentioned that the growth was rapid during the first month of cultivation, but slower in the following two months. The text of this study clearly shows how the growth of Pacific oysters has been explained from the point of view of aquaculture studies. This means that when conducting growth experiments with *C. gigas*, the procedure is to report the time needed to reach market size. The growth rate in these studies is the simple relation of the final length or weight at the end of the cultivated period, in comparison to the initial length or weight (Martínez-Córdova & Robles 1990, Marshall & Dunham 2013).

When cultivating Pacific oysters it is important to note that environmental variables show seasonal changes and growth performance should be understood under those conditions. Therefore, the few studies modeling the Pacific oyster growth

have been limited to the use of von Bertalanffy growth model (Harding & Mann 2006, Lartaud *et al.* 2010). If the objective is to determine the growth pattern of any aquaculture of fishery resource, a multi-model approach must be used (Castillo-Vargasmachuca *et al.* 2016). These authors summarize and classify the types of present growth models and compare the advantage and disadvantage between different models. So, it is important just to mention that the growth trajectories described by most of the models are sigmoidal or curvilinear shape. Aquaculture studies commonly apply the von Bertalanffy growth model (VBGM), that is a sigmoidal shape, but seasonal VBGM describe a curvilinear trajectory. In others words with the same models it is possible to describe sigmoidal or curvilinear growth curves. Many studies on *C. gigas*, worldwide, have noted a seasonal growth (Dégrement *et al.* 2005, Chávez-Villalba *et al.* 2010, Mizuta *et al.* 2012) but this has not been modeled. The seasonal growth could be modeled by using a modification of the traditional von Bertalanffy growth model (VBGM) that allows the description of seasonal oscillations of length (García-Berthou *et al.* 2012). The objective of this study was to model the individual growth of *C. gigas* cultivated in a subtropical coastal lagoon of the Gulf of California testing two models; the generalized von Bertalanffy growth model (VBGM no seasonal) and its modification to represent the seasonal variations (VBGM seasonal).

MATERIALS AND METHODS

The study was conducted at Ensenada-Pabellones lagoon (Sinaloa State) on the east side of the Gulf of California. The oyster were cultivated in the Ensenada Pabellones (24°20-35'N; 107°20-55'W) lagoon system (10 m deep) located on the central coast of the Sinaloa state, Mexico. The climate of this region is warm, with a rainy season from June to September-October and dry season from November to May. Oyster aquaculture in the bay is just for local and regional markets. The oysters were cultivated in Nestier plastic trays attached to long lines. The cultivation period was from March 2010 to April 2011. The data derived from an experiment that used different stocking densities; 14 and 42 oyster per tray. Measurements were performed every two weeks *in situ* at each sampling after the oysters were cleaned and scraped to remove attached epifauna. In each occasion, 50 oysters per tray were randomly selected and measured (shell height) to the nearest 0.01 mm using a vernier caliper.

Utilizing length-at-age data, two models were evaluated to determine which model best represented the data. These models were the seasonal von Bertalanffy (Haddon 2001), and the general von Bertalanffy growth model (VBGM). These models are described below.

The VBGM is given by

$$L(t) = L_{\infty}(1 - e^{-k(t-t_0)}) \quad (1)$$

where:

$L(t)$ = length at age t

t = age at size $L(t)$

L_{∞} = mean length of very old organisms (asymptotic length parameter)

k = determines how fast L_{∞} is reached (curvature parameter)

t_0 = is the hypothetical age at which the organism has zero length (initial condition parameter)

The seasonal VBGM (Haddon 2001) is given by:

$$L_t = L_{\infty} \left(1 - e^{-\left[C_1 \sin\left(\frac{2\pi(t-s_1)}{52}\right) + C_2 \sin\left(\frac{2\pi(t-s_2)}{p}\right) + K(t-t_0) \right]} \right) \quad (2)$$

where:

C = magnitude of the oscillations above and below the non-seasonal growth curve.

s = starting point in time for the sine wave (relates to phase).

p = period of the second cycle

The number 52 indicates that time scale is in weeks. The parameters showing subscript 2 are the same only duplicate for each cycle. The other constants, k , L_{∞} , and t , were described before in VBGM.

The models were fitted using maximum likelihood based on the following equation:

$$LL(\Phi|data) = -\left(\frac{n}{2}\right) (Ln(2\pi) + 2 * Ln(\sigma) + 1) \quad (3)$$

where ϕ represents the parameters of the models and σ represents the standard deviations of the errors, calculated using the following equation:

$$\sigma = \sqrt{\frac{\sum (LnL_{obs} - Ln\hat{L})^2}{n}} \quad (4)$$

Model selection was performed using the bias-corrected form (AIC_c) of the AIC (Burnham & Anderson 2002). The model with the lowest AIC_c value was chosen as the best model:

$$AIC_c = AIC + \frac{2k(k+1)}{n-k-1} \text{ and } AIC = 2 * (-LL) + 2k \quad (5)$$

where: LL is the log-likelihood, n is the number of observations and k is the number of parameters in each model.

The Δ_i values were calculated as the differences between the AIC_c of each model (AIC_i) and the AIC_c with the lowest value (AIC_{min}):

$$\Delta_i = AIC_i - AIC_{min} \quad (6)$$

The plausibility of each model (the weight of evidence for model i) was estimated using the following formula for the Akaike weight (w_i):

$$w_i = \frac{e(-0.5\Delta_i)}{\sum_{k=1}^2 e(-0.5\Delta_k)} \quad (7)$$

The 95% confidence interval of growth model parameters (θ), were estimated after Venzon & Moolgavkar (1988) using the likelihood profile method. These estimations are based on chi square distribution with d degrees of freedom. The confidence interval was defined as all values of θ that satisfy the inequality:

$$2(L(Y|\theta) - L(Y|\theta_{best})) < \chi^2_{1,1-\alpha} \quad (8)$$

where $L(Y|\theta_{best})$ is the negative log-likelihood of the fitted value of θ and $\chi^2_{1,1-\alpha}$ are the values of the chi square distribution with $d=1$ (3.84).

RESULTS AND DISCUSSION

A total of 2600 oysters were measured in a cultivation period of 58 weeks. The smallest size was 6.0 mm and the highest was 176.7 mm. The average size at the beginning of the study was 12.03 ± 4 mm and averaged size at the harvest time was 124.6 ± 12 mm.

The criterion proposed by Burnham & Anderson (2002) is that models with $\Delta_i > 10$ are not supported by the data and should not be considered for parameter estimation. The analysis of data produced Δ_i values higher than 18 for the no seasonal models at both densities (Table 1). The AIC selected the seasonal model as the best model at both densities. The plausibility of seasonal model was 100% with density of 14 and 99.9% using density of 42. The trajectories of the curves are showed in Fig. 1. The likelihood profile of the asymptotic length obtained in the seasonal model is in Fig 2. The highest asymptotic length was obtained in density of 42 (Table 1).

The growth rate varies according to different factors, and the interaction between them is complex, so many authors coincide that the main variables are the temperature and food availability (Gangnery *et al.* 2003, García-Berthou *et al.* 2012). The importance of each of the factors depends on the characteristics of cultivation areas. Gangnery *et al.* (2003) could not relate the seasonal variation of the growth of oysters to the variation of the concentration of food in the Thau lagoon (Mediterranean coast of France). However, they found that annual variations in temperature matched with variations in growth. The oysters that they seeded in spring were grown faster than the oyster seeded in autumn, while both groups grew during a similar period of time.

Table 1. Akaike information criterion (AIC), Akaike differences (Δ_i), Akaike weights (W_i) and estimated asymptotic length (L_∞) for each variation of von Bertalanffy growth model and density data set / Criterio de información de Akaike (AIC), diferencias de Akaike (Δ_i), ponderación de Akaike (W_i) y longitud asintótica (L_∞) estimada para cada variación del modelo de crecimiento de von Bertalanffy y para cada grupo de datos

Models	k	AIC	Δ_i	W_i (%)	Asymptotic length (mm)
Cultivation density 14					
Seasonal	7	-86.86	0.00	100	185.96
No-seasonal	3	-35.19	51.70	0.00	90.38
Cultivation density 42					
Seasonal	7	-56.65	0.00	99.99	240.21
No-seasonal	3	-38.62	18.00	0.01	102.28

k = number of parameter each model

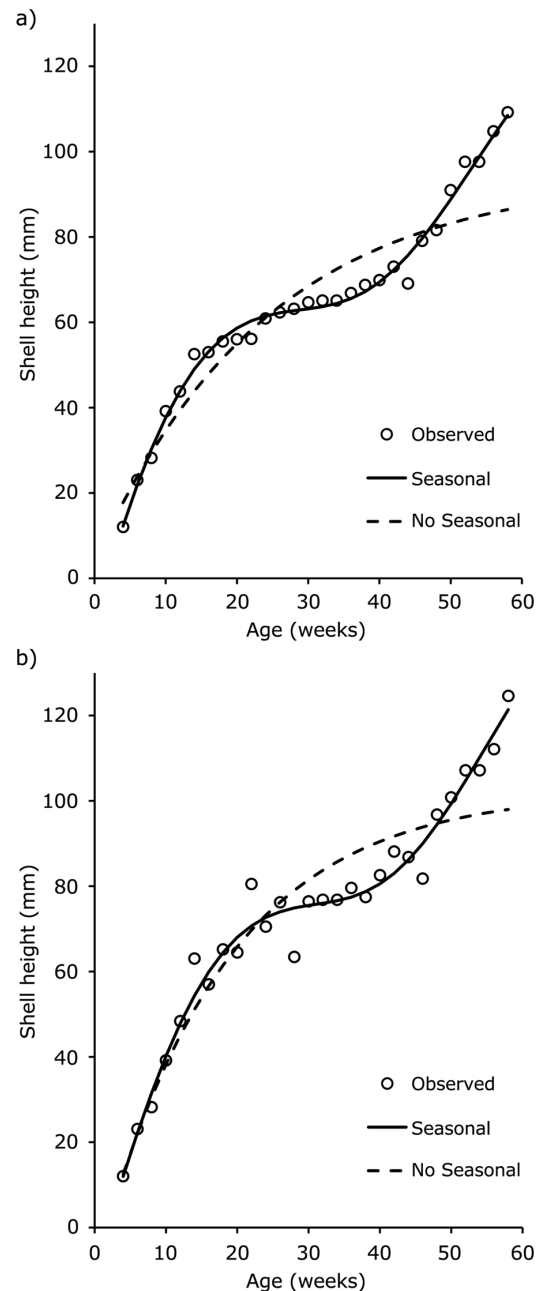


Figure 1. Growth curves generated by seasonal and no-seasonal of von Bertalanffy growth model for *Crassostrea gigas* from the Gulf of California. a) Cultivation density of 14 oyster m^{-2} , b) Cultivation density of 42 oyster m^{-2} / Curvas de crecimiento generadas con el modelo de crecimiento estacional y no estacional de von Bertalanffy para la ostra japonesa *Crassostrea gigas* del Golfo de California. a) Cultivado a una densidad de 14 ostras m^{-2} , b) Cultivado a una densidad de 42 ostras m^{-2}

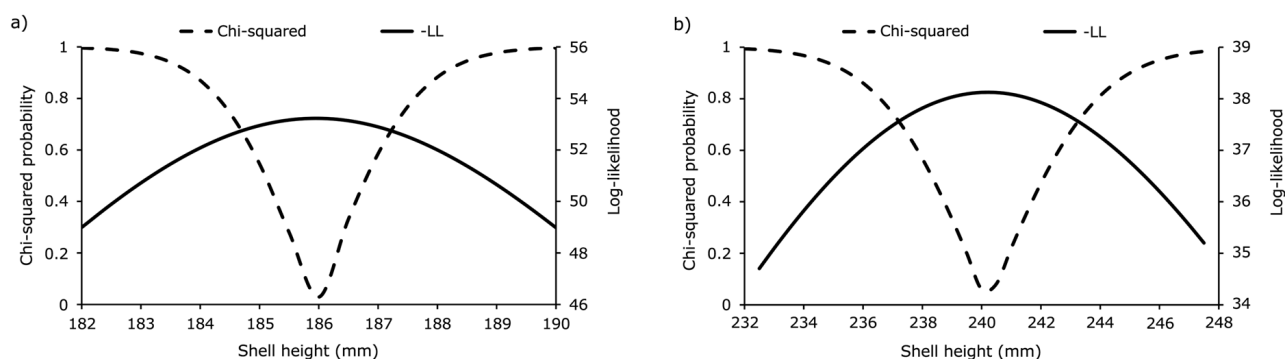


Figure 2. Likelihood profiles for the asymptotic length estimated for the seasonal growth model. a) Cultivated density of 14 oyster m⁻², b) Cultivated density of 42 oyster m⁻² / Perfiles de verosimilitud para la longitud asintótica calculada con el modelo estacional. a) Cultivado a una densidad de 14 ostras m⁻², b) Cultivado a una densidad de 42 ostras m⁻²

Normally, oystermen measure oysters at different time intervals to observe shell or weight increments during farming period. Thus, one of the main indicators of oyster performance in commercial as well as in management experiments is growth rates. Bivalve growth can be modeled using different strategies as statistical models (Gangnery *et al.* 2003), or ecophysiological models (Barillé *et al.* 1997), but these are difficult to apply because they need several complex prerequisites. In particular, for *Crassostrea* genus the no seasonal VBGM has been used to represent the curve that describes the growth in length (Harding & Mann 2006, Lartaud *et al.* 2010). Ruschel-Lopes *et al.* (2013) used six nonlinear models to evaluate the growth of the mangrove oyster *Crassostrea gasar* in Brazil. They found that logistic, Gompertz and VBGM were selected as good representative for growth pattern in this species. It is worth noting that former authors did not use a seasonal model and consequently an asymptotic no seasonal model was selected as the best. For these reasons, in the present study, two variation of the VBGM, the general model and the seasonal model, were applied.

Many studies have shown evidence that *C. gigas* presents a seasonal growth pattern (Dégremont *et al.* 2005, Chávez-Villalba *et al.* 2010, Mizuta *et al.* 2012), but this type of growth has not been modeled for the species. In many groups of marine animals, that include finfish and invertebrate, the seasonal growth has been endorsed to environmental variability, mainly temperature, but also to food availability (García-Berthou *et al.* 2012). Haddon (2001) mentioned that in non-tropical regions differences in growth rate within a year are so marked that is necessary to use modified models in order to represent adequately this variation. García-Berthou *et al.* (2012) mentioned that even in tropical latitudes, the growth of fishes and many other invertebrate taxa is often seasonal, depending in minor variations in temperature or other environmental variables.

Modeling seasonal growth has been controversial because in the literature are found different mathematical equations that pretend to describe this growth pattern. García-Berthou *et al.* (2012) made an explanation of how the different equations published, yield different parameters estimates with different biological interpretations. They also mentioned that the seasonal growth model proposed by Somers (1988), is the most popular because it is included in many fisheries software. Haddon (2001) recommended a little different one and offers a practical solution of it for a spreadsheet. For this reason, in the present study and in order to account the seasonal growth in *C. gigas* the modification to the von Bertalanffy curve were used, as proposed in Haddon (2001). The AIC, selected the seasonal model as the best describing the growth pattern in *C. gigas*. It is possible to conclude that *C. gigas* exhibits a seasonal growth pattern under the cultivation conditions of the present study. This conclusion illustrates that undoubtedly, *C. gigas* was cultivated in conditions under which oysters still not have achieved the full growth and the period analyzed in the present study may represent a small part of the total cycle of the species. This is notorious in Fig. 1; the harvest was completed when the oysters reached the commercial size, but it was evident that they still had growth potential to increase their size.

The results presented here are exploratory in terms of what was the environmental effect on growth. A detailed and formal analysis will require attention to environmental variables. These are beyond the scope of this study, but they are the subject of ongoing research by the authors. Nevertheless, it was observed that when temperature reached 30°C at week 20, the growth apparently stopped until week 40 when temperature dropped to 21°C. The conclusion is that undoubtedly, the VBGM-seasonal best described the growth of the *C. gigas*.

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