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DEVELOPING A NEW TOOL BASED ON A QUANTILE REGRESSION MIXED-TGC MODEL FOR OPTIMIZING GILTHEAD SEA BREAM (*Sparus aurata* L) FARM MANAGEMENT

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Abstract

In this work, a seasonal quantile regression growth model for the gilthead sea bream (*Sparus aurata* L) based on an aggregation of the quantile *TGC* models with exponent 1/3 and 2/3, named the "*Quantile TGC-Mixed Model*", is presented. This model generalizes the proposal of Mayer *et al.* (2012) in the sense that the new model is able to describe the evolution of weight distribution throughout an entire production cycle, which could be a powerful tool for fish farm management. The information provided by the model simulations enables us to estimate total fish production and final fish size distribution, and helps to design and simulate production and sales plan strategies considering the market price of different fish sizes, in order to increase economic profits. The most interesting alternative in the studied case results in sending all production when 0.25 quantile fish reach 600 g, although on each fish farm it would be necessary to evaluate optimum strategy depending on its own quantile regression model, the production cost and the market price.

Keywords: Modelling fish growth, quantile regression, growth in marine cages, Thermal Growth Coefficient (*TGC*), fish farm management.

1.- Introduction

Optimization of fish farm management is necessary to maintain and increase production profitability and ensure the sustainability of aquaculture. Aspects related with feeding management are very important, but are usually studied in terms of nutrient levels, ingredients and feeding rates, among other factors. Nevertheless, fish stock aspects such as seasonal growth, density, optimum harvest size and weight dispersion, among others, are largely unknown in Mediterranean marine species, although some studies have been carried out (Gasca-Leyva, E. Hernández, J.M., Veliov, V.M., 2008; Araneda, M.E.; Hernández, J.M., Gasca-Leyva, E., 2011, 2011; Araneda, M.E., Hernández, J.M., Gasca-Leyva, E., Vela, M.A., 2013; Dominguez-May, R., Hernández J.M., Gasca-Leyva, E., 2011; Sánchez-Zazueta, E.; Hernández, J.M.; Martínez-Cordero, F.J., 2013).

In recent years, production of gilthead sea bream (*Sparus aurata* L) and sea bass (*Dicentrarchus labrax* L) has increased and consequently the sale price has declined, making it necessary to adjust production costs (feed, fingerling, labour, etc.) and increase income. An alternative to improve income could be the added value of new products (fillet, pre-cooking, etc.), but also through optimization of the production process and stock management, for example by optimizing feed ingredients (Martínez-Llorens, S., Tomas-Vidal, A., Jover, M., 2012), food rations (León, C. J., Hernández, J. M., Gasca-Leyva, E., 2001), optimum stocking (Seginer & Halachmi, 2008) or harvesting size in RAS (Seginer & Ben-Asher, 2011). In current offshore marine systems, classification of fish by size is not actually possible, as at the end of the production cycle a variability of sizes is obtained and the final income depends on the percentage of fish size at harvesting, as the sale price depends on fish weight.

To estimate and optimize several management aspects, it is essential to have good growth models adapted to each species and area of production. A large number of papers in recent years (Baer, A., Schultz, C., Traulsen, I., Krieter, J., 2011; Dumas A., France, J., Bureau, D., 2007, 2010; Dumas & France, 2008; Libralato & Solidoro, 2008; Mayer, P., Estruch, V.D., Blasco, J., Jover M., 2008, Mayer, P., Estruch, V.D., Martí, P., Jover M., 2009; Moses, M. E., Hou, C., Woodruff, W. H., West, G. B., Nekola, J. C., Zuo, W., Brown, J. H., 2008; Seginer & Halachmi, 2008) aim to describe and predict the growth of fish with different objectives. Almost all of them have in common that only the dynamic of the average value of the time-dependent weight is described by means of simple or multiple regression models, but weight dispersion is considered by few authors; for example, Mayer *et al*. (2009) in gilthead sea bream with quantile regression growth models, Hurtado-Herrera, M., Dominguez-May, R., Gasca-Leyva, E., (2013), in tilapia and Araneda *et al.* (2013) in white shrimp using characteristic growth curves for different fish sizes.

The Thermal-unit Growth Coefficient (*TGC*) model was reported by Mayer *et al*. (2008, 2009) and Mayer, P., Estruch, V. D., Jover, M., (2012) in gilthead sea bream. When determining the production conditions, the *TGC* model becomes an interesting management tool for describing growth in marine farms in the western Mediterranean. Mayer *et al.* (2012) establish two periods of growth for gilthead sea bream, using a simple regression mixed model for the mean of the weight based on two *TGC* models corresponding to two different exponents.

Except in recirculating systems, water temperature varies throughout the year, and for this reason, following previous works (Ursin, 1963; Akamine, 1993 Moreau, 1987, Fontoura & Agostinho, 1996; Hernández *et al.*, 2003; León, C.J., Hernández, J.M., León-Santana, M., 2006; Seginer & Halachmi; 2008; Dumas & France, 2008), Mayer *et al.* (2012), included a sinusoidal temperature curve in the growth models to simulate the seasonal *TGC* growth.

As mentioned above, in most of the studies that explore weight dynamics using mathematical models a simple description of the evolution of the mean weight at a given time interval is considered, which is acceptable as a reasonable exercise of simplification. However, in aquaculture the starting point is an initial population of fish provided by the hatchery whose weight follows a statistical distribution, which can be estimated from representative initial samples. It is undisputable that in-depth knowledge of various sizes in a batch at the end of the cycle would facilitate management in the aquaculture farm and knowledge of sizes could be obtained from the statistical distribution of the weight. Therefore, it seems reasonable to describe the evolved body weight distribution. Thus, in the event of achieving a good description of the changes in weight distribution versus time, a complete statistical description of the weight would be available at any time, and not only a simple average value.

Quantile regression (Koenker & Bassett, 1978) helps estimate the evolution of the growth data distribution and is very suitable for analysing data in contexts characterized by heteroscedasticity, such as reference charts in medicine, survival analysis, financial and economics research or environment modelling (Yu, K., Lu & Z., Stander, J., 2003; Vaz, S., Martin, C. S., Eastwood, P. D., Ernande, B., Carpentier, A., Meaden, G. J., & Coppin, F., 2008). Linear quantile regression estimates multiple rates of change, providing more complete information about the relationships between variables than that obtained from linear least square regression (Cade & Noon, 2003). Quantile regression has proved to be a powerful tool for the detection of different growth patterns caused by environmental conditions and the characteristics of the fish population provided by the hatcheries (Mayer *et al*. 2009).

The aim of the current paper consists of developing a quantile regression approach to the gilthead sea bream growth in commercial production conditions, based on previous work presented in Mayer *et al.* (2012). Quantile regression is a radically different and alternative approach compared with the least-squares regression approach. So, a new study of *TGC* models is required, with different powers and focused on suitability of the mixed model from the quantile regression. Using a simulation model based on the *TGC*-Mixed model, which considers the different stages throughout the growth period and the local sea water temperature curve, a dynamic management tool for fish farms will be test to improve fish stock growth estimates, optimizing production and maximizing profits considering the market sale price of fish.

2.- Material and Methods

2.1. Mathematical models

The continuous and linearized growth model used by Mayer *et al.* (2012) was considered:

$$W^{b}(t) = W_0^{b} + TGC_b \cdot ST(t_0,t). \qquad (1)$$

where $ST(t_0,t)$ (sometimes written *ST* for simplicity) represents the accumulated effective temperature (ºC) in the time interval $[t_0,t]$ (days), $ST(t_0, t_0)=0$, W_0 (g) is the initial weight (when t=t_0) and b is a dimensionless parameter which takes the values b =1/3 and b=2/3.

The function that provides the water temperature at each time, $T(t)$ (°C), is equal to the derivative with respect to time t of $ST(t_0,t)$, i.e. $dST(t_0,t)/dt=T(t)$. Considering for each day, i, i=1,2,…,n, the mean of the daily temperature, T_i , an immediate discrete-time version of (1), is obtained (2)

$$W_n^b = W_0^b + TGC_b \cdot \sum_{i=1}^{n} T_i, \quad n = 1,2,\ldots \qquad (2)$$

If b=1/3, then we have the designated *TGC* model (Cho, 1992). Note that the function $T(t)$ can take different expressions depending on environmental conditions (Akamine, 1993).

The equation (1) could be expressed in an equivalent integral form

$$W^b(t) = W_0^b + k \cdot b \cdot \int_{t_0}^{t} T(t) \cdot dt \qquad (3)$$

i.e.

$$W(t) = \left(W_0^b + k \cdot b \cdot \int_{0}^{t} T(t)\, dt \right)^{\frac{1}{b}} \qquad (4)$$

In the case of marine farms in Mediterranean fixed locations, the time-dependent water temperature develops according to regular annual periods of 365 days modelled by the function $T(t)$ (ºC) (Mayer *et al.*, 2012)

$$T(t) = T_m + T_D \cdot \sin\left(\frac{2\pi}{365} \cdot (t - \alpha) \right) \qquad (5)$$

, where $t \geq 0$, and T_m (ºC) is the average annual temperature, T_D (ºC) is the amplitude and α is a tuning parameter· The fitted values for the parameters of the temperature function $T(t)$, described in (5), corresponding to the sea area where the studied marine farm is located, are T_m=18.8525, T_D=-6.6997 and α=312.4609 and, in the case of gilthead sea bream, it is more appropriate to use the effective temperature, $T(t)$-12, instead of $T(t)$ (Mayer *et al.*, 2012). So, the weight at the day t, $W(t)$ (g), is obtained

$$W(t) = \\ = \left(W_0^b + TGC_b \cdot \left((T_m - 12) \cdot (t - t_0) - T_D \frac{365}{2\pi} \left(\cos\left(\frac{2\pi(t-\alpha)}{365} \right) - \cos\left(\frac{2\pi(t_0-\alpha)}{365} \right) \right) \right) \right)^{\frac{1}{b}} \quad (6)$$

From the basic model described by the equation (6), three quantile regression models were developed to simulate the indeterminate seasonal growth of gilthead sea bream. Two of them were obtained by fitting the data to equation (2), assuming the values b=1/3 and b=2/3 (as in Mayer *et al.*, 2012), and the quantiles 0.025, 0.05, 0.10, 0.20, 0.25, 0.30, 0.40, 0.50, 0.60, 0.70, 0.75, 0.80, 0.90, 0.95 and, 0.975. The third model was built by aggregation of the two models mentioned before, establishing two stages of growth for each quantile.

2.2. Data description, statistical analysis and design of the models

Models have been developed considering actual data on final weight and its corresponding actual values of accumulated effective temperature, starting at the beginning of the cycle from several samples corresponding to 20 batches of farmed gilthead sea bream in real conditions of growth (Mayer *et al.* 2008, 2009, 2012). More specifically, the actual weights of 22805 fish were used for the fitting. Sampling and biometrics were performed at various times in the course of the production cycle in each batch.

With the actual paired data available (sum of effective temperatures and weight), the quantile regression fitting was performed considering the discrete model (7)-(8)

$$W_{f,\tau} = \left(A_{b,\tau} + TGC_{b,\tau} \cdot ST\right)^{\frac{1}{b}} \qquad (7)$$

i.e.

$$W_{f,\tau}^{b} = A_{b,\tau} + TGC_{b,\tau} \cdot ST \qquad (8)$$

with b=1/3 and b=2/3. Values for $A_{b,\tau}$ and $TGC_{b,\tau}$ were estimated by means of quantile regression, using the "*quantreg*" procedure available in package R (Koenker, 2008), for the quantiles τ =0.025, 0.05, 0.10, 0.20, 0.25, 0.30, 0.40, 0.50, 0.60, 0.70, 0.75, 0.80, 0.90, 0.95 and, 0.975. According to the generic model (7)-(8) and (2), values $A_{b\tau,}$ correspond to estimations of initial weight raised to the power b, $W_{0,\tau}^{b}$, b=1/3, b=2/3, which should be approximately equal to the corresponding percentiles obtained by analysing the weight distribution corresponding to the start of cycle in the case of a good fit. These two models, b=1/3, b=2/3, are integrated into one by computing the critical points of change in the growth dynamic, in a similar way to that described in Mayer *et al.* (2012). The non-zero solutions for W in (9) for the different τ quantiles are theoretical critical values of the weight in which the instantaneous rate of change, in terms of weight depending on accumulated temperature, is the same for both models.

$$\frac{TGC_{1/3,\tau}}{1/3} \cdot W^{2/3} = \frac{TGC_{2/3,\tau}}{2/3} \cdot W^{1/3} \qquad (9)$$

So, the hypothesis is assumed that in the critical values of the weight a smooth transition from the dynamic described by the model given by (7) with b=1/3 to the dynamic described by the model with b=2/3 occurs.

Once the values $W_{0,\tau}$ and $TGC_{b,\tau}$, have been computed to estimate the evolution of the weight distribution of gilthead sea bream, two simulation models were considered for each quantile from equation (6) with b=1/3 and b=2/3, and assuming the temperature function, $T(t)$, given in (5). These models were designated the seasonal quantile 1/3-*TGC* model and the seasonal quantile 2/3-*TGC* model, respectively.

From the seasonal quantile models 1/3-*TGC* and 2/3-*TGC*, taking into account the critical values of the weight obtained previously, the definitive simulation model, named quantile seasonal *TGC*-Mixed model was built by aggregation.

The values $A_{b,\tau} = W_{0,\tau}^{b}$ and $TGC_{,\tau}$', obtained by means of quantile regression, after linearization (Eq. 8), for models with b=1/3 and b=2/3, are shown in Table 1. It is necessary to remark that the value $A_{2/3,0.025}=-0.517<0$ is unacceptable because $A_{2/3,0.025}=W_{0,0.025}^{2/3}$ and the result of squaring a number cannot be negative.

Table 2 shows the quantile critical weight values of the weight, $W_{c,\tau}$, and the sum of effective temperatures, ST_{τ}, at which the critical weight values are reached.

Fig. 1 shows the actual data (black points) and the graph of the fitted quantile models for τ=0.025, 0.05, 0.25, 0.50, 0.75, 0.95 and 0.975. The dashed line corresponds to the quantile τ=0.50. The *TGC*-1/3 model, the *TGC*-2/3 model and the *TGC*-Mixed model are represented in Fig. 1 a, b and c, respectively. Note that Fig. 1 a shows clearly that the *TGC*-1/3 model tends to overestimate weight as from a certain moment in the growth cycle.

To obtain the quantile *TGC*-Mixed model, the quantile *TGC*-1/3 model and the quantile *TGC*-2/3 model are coupled for each quantile, τ, in the critical weight values which are obtained considering that instantaneous growth rates based on the cumulative effective temperature must be the same for the quantile *TGC*-1/3 models and the quantile *TGC*-2/3 models. The non-zero critical values of weight are obtained by solving $W_{c,\tau}$ in (9): $W_{c,\tau} = 1/8\ (TGC_{2/3,\tau} /\ TGC_{1/3,\tau})$ g. So, the *TGC*-1/3 model is considered until the weight reaches the critical weight. From that moment on, the *TGC*-2/3 model is considered for estimating the weight, assuming the critical weight as the initial weight. This coupling of the *TGC*-1/3 and *TGC*-2/3 gives rise to the *TGC*-Mixed model. Fig. 1 b justifies that the *TGC*-2/3 model explains the growth better than the *TGC*-1/3 model, starting from a certain point in the growth period, and this property is inherited by the *TGC*-Mixed model in Fig. 1 c.

Valuation of the goodness of fit is not immediate in the case of quantile regression. So, the overall analysis of the quantile model's goodness of fit was approached from various angles. On one hand, by computing the coefficient $R^1(\tau)$, $\tau \in\ ]0,1[$ (Koenker & Machado, 1999), which is a natural analogue of Coefficient of Determination, R^2. While R^2 is a global measure of goodness of fit in terms of residual variance, $R^1(\tau)$ is a local measure of goodness of fit for a particular quantile τ, and measures the relative success of the model at a specific quantile, in terms of an appropriately weighted sum of absolute residuals. The of value of $R^1(\tau)$, $\tau \in\ ]0,1[$ also lies between 0 and 1, and considering $R^1(\tau)$ as a function of τ, we can obtain a global measure of goodness of fit of the quantile regression in the range $\tau \in [\tau_0, \tau_1] \subset\ ]0, 1[$, by means of the average value of the function $R^1(\tau)$ in the interval $[\tau_0, \tau_1]$, $R^1_{[\tau_0,\tau_1]}$, which is computed as is shown in (10):

$$R^1_{[\tau_0,\tau_1]} = \frac{\int_{\tau_0}^{\tau_1} R^1(\tau)d\tau}{\tau_1 - \tau_0} \qquad (10)$$

In practice, we only have discrete information from the functions $R^1(\tau), \tau \in [\tau_0, \tau_1]$ for the three models, which correspond to the specific τ values considered in the quantile regression fit. So, we compute approximations to the $R^1_{[0.025,0.975]}$ coefficients for the three models, approximating the integrals (10) numerically by means of the trapezoids method.

The goodness of fit valuation is completed by comparing the distribution of the initial weights of fishes provided by the hatchery and those obtained in the last sampling, with the theoretical distributions deducted from the quantile model. By means of Pearson's Chi-square test, the discrepancy between the observed and the theoretical distributions are evaluated, indicating whether the differences between the two distributions, if any, are due to chance. It is interesting to examine the value of chi-square statistic χ^2, which allows us to assess the degree of similarity between the theoretical distribution and the empirical distribution deducted from the actual data. The fit between the two distributions is greater if the value of the statistic χ^2 is smaller. In addition, the *p*-value lets us assess whether the hypothesis that the two distributions could really be the same is acceptable.

The outcome is that the *TGC*-Mixed model is the one which best fits the actual evolution of the weight distribution depending on the cumulative effective temperature, taking into account the different goodness of fit results. To analyse the goodness of fit in all three models, the $R^1(\tau)$ values for the considered quantiles and the average value for the function R_{τ}^{1}, $\tau \in [0.025, 0.975]$, denoted $R_{[0.025,0.975]}^{1}$, were computed (Table 3). The global valuation of the goodness of fit given by $R_{[0.025,0.975]}^{1}$ is similar for the 2/3 and the *TGC*-Mixed models, and clearly worse for the 1/3 *TGC*-model.

The assessment of the goodness of fit is completed by comparing the actual weights of the initial samplings and the last actual sampling weights (represented by the quantiles computed from the data) with the theoretical quantiles of the initial and final weights provided by the models, respectively (Table 4 and Table 5). From Table 4, we can accept that the estimated distribution of the initial weight, obtained from the 1/3 *TGC* model quantile regression fitting (which coincides initially with the *TGC* Mixed model), is the same as the initial distribution of weight deduced from the actual data (p-value=0.99). On the other hand, we can reject that the estimated distribution of the initial weight, obtained from the 2/3 *TGC* model quantile regression, is the same as the initial weight distribution deduced from the actual data (p-value<0.0001).

The analysis of the weight distribution of the last sample is summarized in Table 5, which shows that we reject the hypothesis that the estimated distribution for the final sample is the same as the weight distribution deduced from the actual data for the three models. However, although that the p-values would be especially interesting as indicators of the level of match between distributions, the Chi-Square value provides a good measure to establish which model better fits the actual distribution. When observing Chi-square values in table 5, we may deduce that the *TGC*-Mixed model is the one that better fits the distribution corresponding to the last sample of weights. Table 5 also shows that the *TGC*-Mixed model is the best fitting central quantiles and that *TGC* 1/3 model overestimates the weight with respect to the last sample of actual data for all quantiles, but mainly for the upper quantiles. From the above results, it can be deduced that the *TGC*-Mixed model is the one that best fits the evolution of the weight distribution depending on the cumulative effective temperature.

To simulate the growth of gilthead sea bream, two seasonal quantile regression models based on equation (6) are established: the seasonal quantile *TGC*-1/3 model (b=1/3) and the seasonal quantile *TGC*-2/3 model (b=2/3). Next, from the former models, *TGC*-1/3 and *TGC*-2/3, we constructed the seasonal quantile *TGC*-Mixed model:

$$W_{f,\tau}(t) = \left(W_{0,\tau}^{\frac{1}{3}} + TGC_{1/3,\tau} \cdot ST(t_0, t) \right)^3, \quad \text{if } W_{f,\tau}(t) < W_{c,\tau} \qquad (11)$$

$$W_{f,\tau}(t) = \left(W_{0,\tau}^{\frac{2}{3}} + TGC_{2/3,\tau} \cdot ST(t_0, t) \right)^{\frac{3}{2}}, \quad \text{if } W_{0,\tau,}(t) \geq W_{c,\tau} \qquad (12)$$

For each quantile, τ, to estimate final weights greater than the critical weight, $W_{c,\tau,}$, we consider the model curve corresponding to the *TGC*-1/3 model until it reaches the critical weight (Table 2), and following that moment, considering the critical weight as the initial weight and resetting the initial time in the cumulative temperature function *ST*, the final weight will be estimated using the curve corresponding to the *TGC*-2/3 model.

Therefore, for each quantile τ, up to a final weight less than $W_{c,\tau}$, the *TGC*-Mixed model coincides with the *TGC*-1/3 model. In the case of an initial weight greater than or equal to $W_{c\tau}$ g, the *TGC*-Mixed model coincides with the *TGC*-2/3 model. The *TGC*-Mixed model leads to a continuous curve representing the final weight for the considered quantiles of gilthead sea bream. Moreover, the curves are also differentiable at all times because the *TGC*- Mixed model is constructed so that when the weight is exactly $W_{c\tau}$ g, the derivatives of the functions that define the models *TGC*-1/3 and *TGC*-2/3 coincide.

Thus, the transition from the quantile *TGC*-1/3 model to the quantile *TGC*-2/3 model occurs smoothly, without sharp points.

The quantile regression fit for the *TGC*-1/3 model and *TGC*-2/3 model provides two values for each quantile: the initial weight and the value of the *TGC*. Therefore, when considering the different quantiles, each model provides an empirical distribution of the initial weight (Table 4). The fit of the data to the *TGC*-1/3 Model provides a theoretical well fitted distribution of the initial weights of the fish supplied by the hatchery, i.e. the theoretical distribution practically coincides with that deduced from the analysis of the samples corresponding to the beginning of the cycle. Moreover, the initial weight distribution deduced from the quantile 2/3-Model is not consistent with the actual initial weights. From an inferential approach, it could be interesting to prove that the *TGC* values corresponding to the different quantiles are significantly different, from the statistical point of view. If the *TGC* corresponding to different quantiles is not different, the growth only depends on the initial weight. But this is not the case. Using the ANOVA test proposed in Koenker & Bassett (1982) we studied the behaviour of the quartiles (τ=0.25, 0.50 and 0.75) and found that the differences for the *TGC* corresponding to the quartiles are statistically significant for the *TGC*-1/3 model (p-value<0.000) and for the *TGC*-2/3 model (p-value<0.000). So, to describe the evolution of the weight distribution over time, we need to know the distribution of the initial weight and the *TGC* values associated with the different quantiles. A smaller Chi-square value in tables 4 and 5 means that the distributions are more similar. The p-value indicates to what extent it would be reasonable to accept the hypothesis that the distributions compared are identical. By and large, it is desirable that the actual and the estimated distributions should coincide at the beginning of the cycle, and moreover that the actual and estimated distributions at the end of the cycle are compatible, i.e. do not differ too greatly. In this sense, the excellent goodness of fit of the initial weights provided by the quantile *TGC*-1/3 Model is a fundamental aspect inherited by the mixed model. On the other hand, the quantile *TGC*-2/3 model provides a better overall fit compared to that obtained from the quantile *TGC*-1/3 model, as the *TGC*-2/3 model fits the weights better at later stages of the cycle, which is not only evident observing the Fig. 1, but also from the values $R_1(\tau)$ and $R^1_{[0.025,0.975]}$ (Table 3). This positive feature of the quantile 2/3-Model is also inherited by the mixed model. Therefore, we can say that the quantile *TGC*-Mixed model captures the best features of the *TGC*- 1/3 and *TGC*-2/3 models.

Note the great importance of a good fit of the model to the sample distribution at the outset, as the model should explain the generic distribution of the weight of the fishes provided by the hatchery. On the other hand, requiring an excellent fit of the weight distribution obtained from the model to the final sample has relative importance. Obviously, the actual weights at the end of the cycle may be above or below expectations. To validate the model from the point of view of the weight distribution at the end of the cycle, it would be reasonable to see that the results are within what the experience of the marine farm indicates as reasonable margins for the actual production, which is sufficiently justified for the *TGC*-2/3 and the *TGC*-Mixed models (Table 5). In summary, taking into account the results for establishing the goodness of fit for the three models, the *TGC*-Mixed model is the best model for explaining the growth over the entire production cycle.

3.- Results and discussion

In a similar way as in Mayer *et al.* (2012), the development of the quantile *TGC*-Mixed model indicates a range of weights in which a change in the growth dynamic should be considered. In 95% of the cases, in the time period when the sum of effective temperatures is in the interval that goes from 1144 ºC to 1642 ºC, i.e. when the weights are in the interval from 70.7 to 189.17 g, the growth dynamic changes. Moreover, the change occurs earlier for larger fish than for smaller ones (see Table 2). The results agree with those obtained in Mayer *et al*, 2012, where a weight around 117g is suggested for establishing a point in the change of the dynamics of the evolution of the mean of the weights from the *TGC*-1/3 model to the *TGC*-2/3 model.

We developed a MATLAB© script, which allows us to make simulations introducing a start date of the cycle and an end date as the inputs. As an example of growth simulation using the quantile *TGC*-Mixed model, the evolution of growth distribution for several batches (starting in mid-March, mid-May, mid-July and mid-September, i.e. at days 75, 136, 197 and 259, respectively, of a year considering that January 1 is the day 1) is shown (Fig. 2). In all cases, for a better view of the behaviour, the figures represent the period until the curve corresponding to the 0.20 quantile reaches a weight equal to 500 g.

The curves obtained from simulation of the quantile *TGC*-Mixed model are similar to those used in paediatrics to assess the growth of children, except that in our case we obtain the curves adapted to the starting date of the production cycle, i.e. the starting date of growth.

Note that it would be necessary for each fish farm to dispose of its own and characteristic quantile growth curves, which would be obtained on the basis of local temperature and data from historical growth in many batches. A continuous feedback process could be considered for improving the curves by adding information on growth of new batches. For correct use of the quantile model by the fish farm manager, the quantile curves could serve as a reference to evaluate the general evolution in time of the weight distribution of a batch on the farm. For example, growth can be assessed by comparing the relative position of the quantiles of a sample with those deduced from the curves.

Knowledge of the weight distribution at any time allows us to obtain approximations of any statistical value, which is an important tool for fish farm managers. To this end, it should be necessary to consider mainly the curves corresponding to core values (quantiles 0.25-0.75), because the lowest and highest curves, corresponding to the lowest and highest quantile values, respectively, represent the extreme variability of production in the plant. In Fig. 3, a simulation of several gilthead sea bream batches was performed, starting in March, May, July and September, considering the different weight intervals when the three quantiles, 0.25, 0.50 and 0.75 reach the weights 400, 500 and 600 g, which will allow the evaluation of several alternatives and sale values. It can be observed that there are practically no differences in the final distribution of the final weights for different simulated batches, in each interval of weight and quantile. Nevertheless, there are important differences for the number of days that the quantiles need to reach, for example, 400, 500 or 600 grams (Fig. 4). It can be seen that fish in quantile 0.75 take less time (407, 466 or 531 days respectively, as average of simulated four batches) than those belonging to quantile 0.50 (443, 524 or 602 days), or quartile 0.25 (508, 587 or 662 days). If technology for size sieving in marine cages was available, big fish from the 0.75 quartile could be sold first and fish from the 0.25 quartile last, optimizing fish management and achieving economic benefits, but this is currently not possible, so fish farm managers have to decide the time for harvesting. Obviously, the production cost is reduced when the growth cycle is shorter, but the total fish biomass sold and sales income will also be lower, so an equilibrium point for optimizing profit must be evaluated.

In Table 6, an estimation of final biomass and economic value is shown in each weight interval, which was developed for different alternatives, mean fish weight (400, 500 and 600 g) and quantiles (0.25, 0.50 and 0.75), considering the average of four batches. For biomass estimation, we considered 300000 fish per cage and 85% survival, if we have an estimation of the total number of fish, for each day of the cycle, the quantiles curves allows us knowing the biomass corresponding to any quantile, the biomass corresponding to each interval of weights and obviously the total biomass. For economic value, we obtained the sales price of different sea bream sizes from a commercial fish farm in the Mediterranean Sea.

Fish production increases with fish weight in each quantile, and also the total sales value, and both are highest for the 0.25 quantile in relation to the 0.50 and 0.75 quantiles, as when 0.25 quantile fish reach the fish mean weight (i.e. 400, 500 and 600 g), there are many bigger fish (Fig. 3). The higher production figures (174 tons) and value (897 thousand euros) are obtained by considering quantile 0.25 and 600 g, and lower production (87 tons) and value (372 thousand euros) by alternatively considering quantile 0.75 and 400 g. Obviously, the time for growth until the fish reach a higher weight, 662 and 407 days respectively, entails a higher production cost, so a new approach becomes necessary.

Income value of sales in relation to days and production volume are presented in Fig. 5. Daily value (€day^{-1}) increases in large fish for all quantiles, being maximum for 0.25 quantile, and a similar trend is obtained for total value per unit of production (€ Kg^{-1} fish). Nevertheless, daily value per production (€ Kg^{-1} fish day^{-1}) is opposite, and high values are obtained by considering quantile 0.75 and 400 g, and lower by alternatively considering quantile 0.25 and 600 g.

Thus, sale strategies could be designed with the aim of sending fish in the interval 400-500, 500-600 or 600-700 g, when these weights are reached, first by the 0.75 quantile, then by the 0.50 quantile and finally by the 0.25 quartile (Table 7). It seems that the most profitable alternative would be to send 158 tons of fish weighing 600-700 g, with a sale income of 752 thousand euro, but if the market accepts a great variability of fish, from 200 to 800 g, the maximum income would be when the 0.25 quantile reaches 600 g (Table 6), because the sent biomass has reached a maximum, 174 tons, and the income would be around 897 thousand euro.

Nevertheless, the selected strategy should be applied on each fish farm, taking production cost and the market price into account, because if the value of small or large fish was lower, the economic results could be very different. For example, Seginer & Ben-Asher (2011) reported an increase in sale price related with gilthead sea bream weight and although production cost in a RAS system also rose with fish size, the profit was higher as the harvest size increased.

5.- Conclusions

The quantile regression *TGC*-Mixed model specifically developed for the plant provides a good global representation of the variability of fish growth in the fish farm over the entire production cycle. Thus, the growth model allows simulations of growth, providing the variability of the weight throughout the production cycle and values closer to reality of the total biomass, and its size distribution which is the most important. The information obtained from the growth simulation provided by the model is very powerful because it allows us to design and simulate sales plans taking the sale price into consideration, with a view to optimizing management and economic profits on each fish farm.

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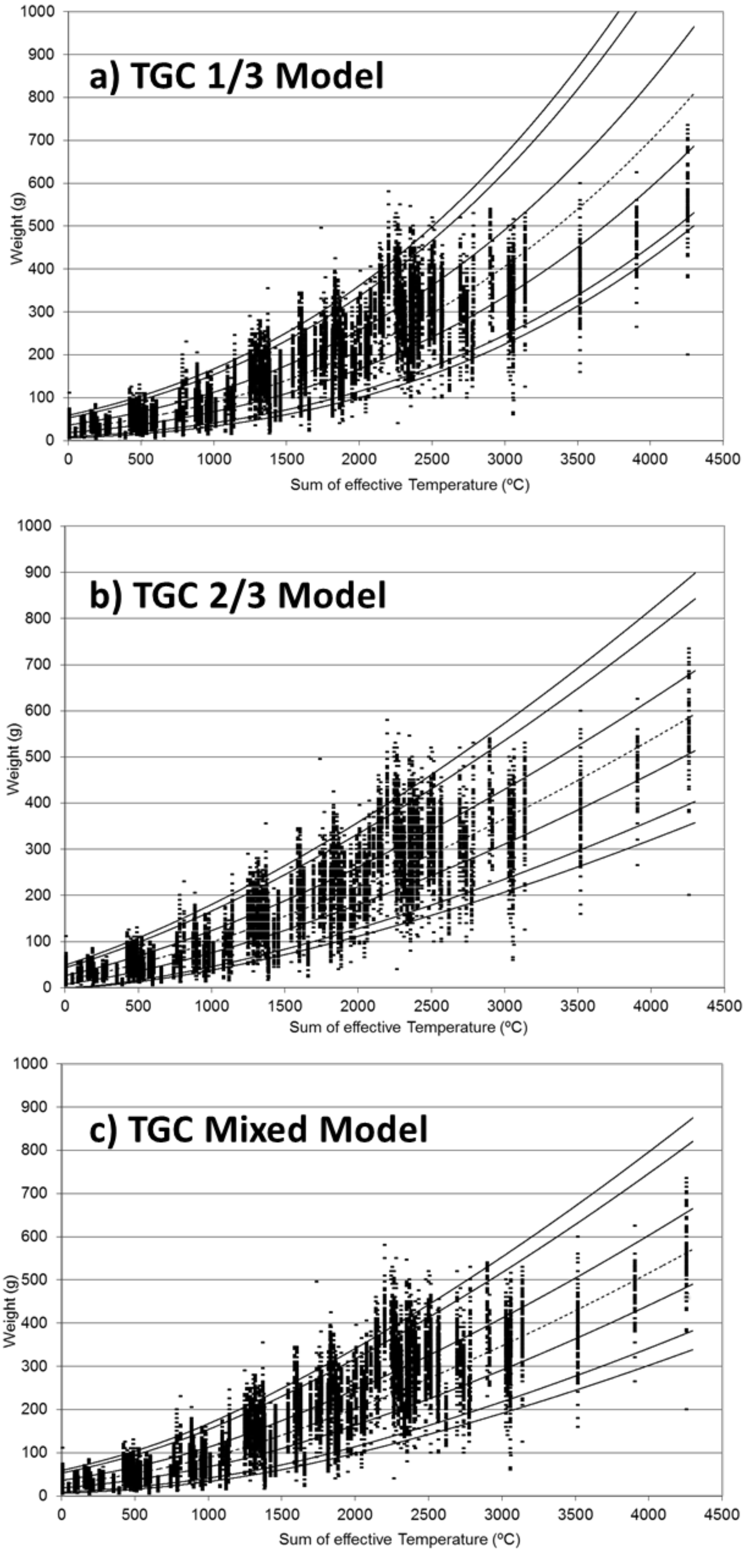
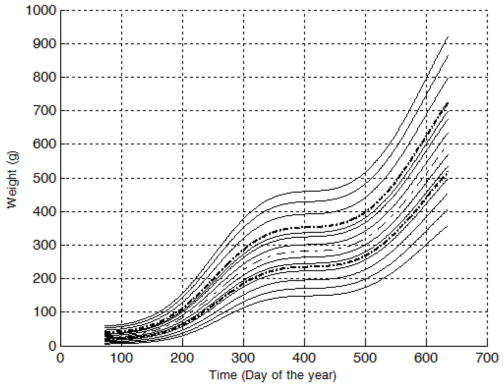
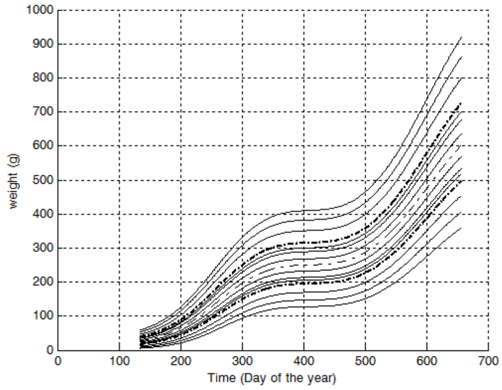


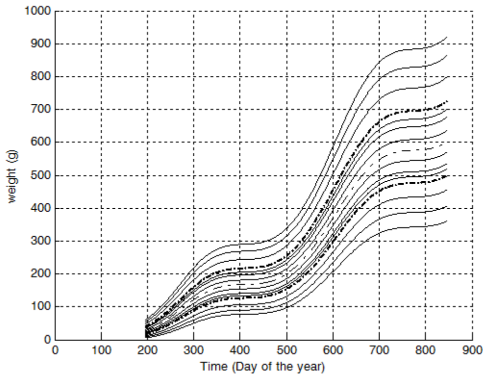
Figure 1. Growth curves of sea bream considering three quantile models:
TGC-1/3, TGC-2/3 and Mixed model (dashed curves corresponding to 0.50 quantile and, from bottom to top, the curves corresponding to the quantiles 0.025, 0.05, 0.25, 0.50, 0.75, 0.95 and 0.975).



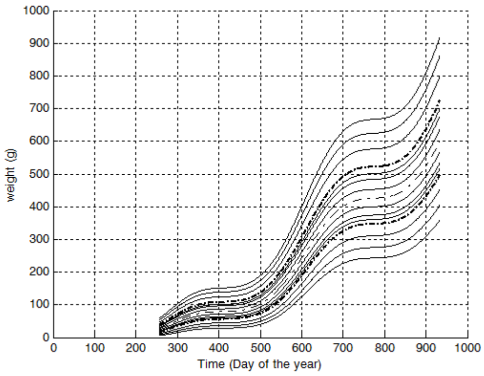
a) March Batch



b) May Batch



c) July Batch



d) September Batch

Figure 2. Simulation of sea bream growth considering four batches: March, May, July and September (Dashed curves corresponding to 0.5 quantile and, from bottom to top, the curves corresponding to the quantiles 0.025, 0.05, 0.1, 0.2, 0.25, 0.30, 0.40,0.50, 0.60, 0.70, 0.75, 0.80, 0.9, 0.95 and 0.975, bold dashed lines correspond to quantiles 0.20 and 0.80).

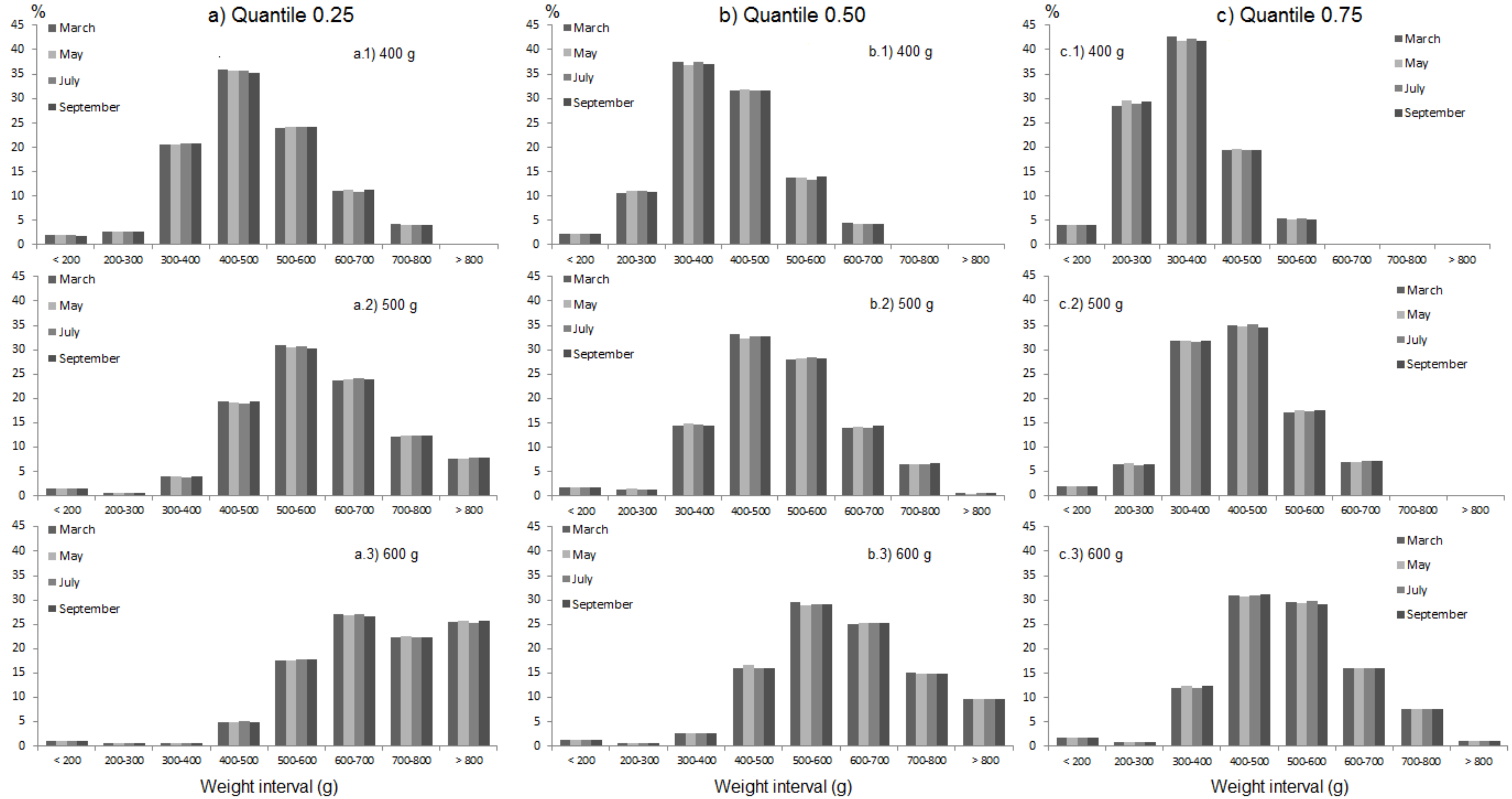


Figure 3. Simulation of percentage of gilthead sea bream in each weight interval when the quantiles (0.25, 0.50 and 0.75) reach the weights 400, 500 and 600 g

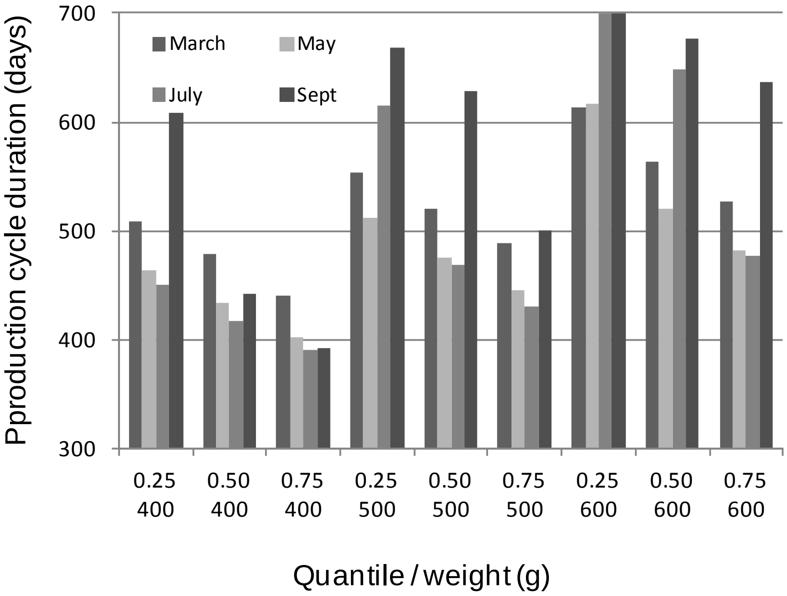


Figure 4. Duration of production cycle (days) of gilthead sea bream computed so that the quantiles 0.25, 0.50 and 0.75 reach the weights 400, 500 and 600 g

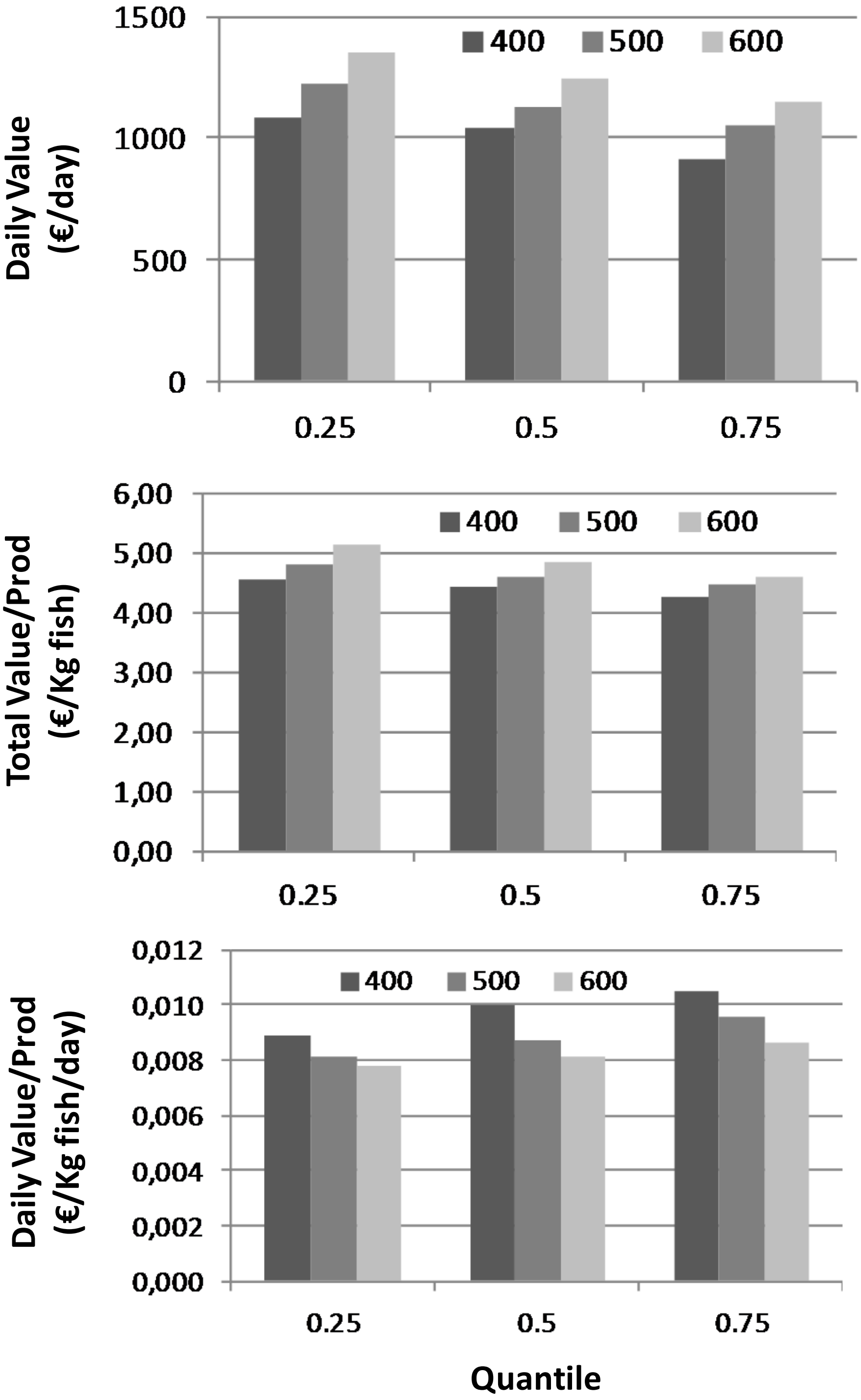


Figure 5. Economic values of sea bream sales in each weight interval for the quantiles 0.25, 0.50 and 0.75, and weights 400, 500 and 600 g

Table 1. Estimated values of $A_{b,\tau}$ and $TGC_{b,\tau}$ for the two quantile models TGC-1/3 and TGC-2/3

Quantile (τ)	$A_{1/3,\tau}$	$TGC_{1/3,\tau}$	$A_{2/3,\tau}$	$TGC_{2/3,\tau}$
0.025	1.783	0.001432	-0.517	0.011841
0.05	2.047	0.001407	0.291	0.012687
0.10	2.289	0.001415	1.443	0.013387
0.20	2.540	0.001433	3.309	0.013769
0.25	2.627	0.001441	3.886	0.014014
0.30	2.720	0.001443	4.569	0.014167
0.40	2.856	0.001459	5.608	0.014553
0.50	2.994	0.001471	6.488	0.014910
0.60	3.110	0.001494	7.368	0.015288
0.70	3.250	0.001510	8.277	0.015755
0.75	3.302	0.001530	8.776	0.016067
0.80	3.391	0.001540	9.420	0.016303
0.90	3.598	0.001570	11.104	0.017163
0.95	3.758	0.001600	12.341	0.017878
0.975	3.893	0.001615	13.391	0.018542

Table 2. Sum of effective temperature and sea bream weight at the critical point

Quantile (τ)	ST_τ	$Wc,_\tau$
0.025	1642	70.7
0.05	1749	91.6
0.10	1725	105.9
0.20	1580	110.9
0.25	1551	115.0
0.30	1517	118.3
0.40	1461	124.1
0.50	1410	130.2
0.60	1343	133.9
0.70	1303	142.0
0.75	1274	144.8
0.80	1235	148.3
0.90	1190	163.3
0.95	1143	174.4
0.975	1144	189.2

Table 3.-Values of goodness coefficient $R^1(\tau)$ and of $R^1_{[0.025\text{-}0.975]}$ for the three quantile models: TGC-1/3, TGC-2/3 and *TGC*-Mixed Model

	$R^1(\tau)$		
Quantile (τ)	1/3-Model	2/3-Model	Mixed-Model
0.025	0.500	0.521	0.412
0.05	0.552	0.539	0.462
0.10	0.677	0.617	0.546
0.20	0.689	0.651	0.611
0.25	0.615	0.622	0.581
0.30	0.667	0.631	0.645
0.40	0.636	0.608	0.659
0.50	0.575	0.728	0.600
0.60	0.592	0.618	0.690
0.70	0.578	0.622	0.686
0.75	0.588	0.636	0.630
0.80	0.559	0.615	0.674
0.90	0.529	0.578	0.638
0.95	0.614	0.643	0.651
0.975	0.624	0.649	0.657
$R^1_{[0.025,0.975}$	**0.576**	**0.627**	**0.627**

Table 4.-Values of the actual quantiles and estimated quantiles for the initial weight

	Initial weight $W_{0,\tau}$			
Quantiles (τ)	Actual data (n=1133)	1/3-Model	Mixed-Model	2/3-Model
0.025	9.00	5.67	5.67	-
0.05	11.00	8.58	8.58	0.16
0.10	14.00	12.00	12.00	1.73
0.20	17.00	16.38	16.38	6.02
0.25	18.00	18.14	18.14	7.66
0.30	20.00	20.12	20.12	9.76
0.40	23.80	23.30	23.30	13.28
0.50	26.00	26.85	26.85	16.53
0.60	28.00	30.09	30.09	19.99
0.70	35.00	34.33	34.33	23.81
0.75	37.00	36.00	36.00	26.00
0.80	40.00	39.00	39.00	28.91
0.90	48.00	46.56	46.56	37.00
0.95	52.00	53.07	53.07	43.36
0.975	58.00	59.00	59.00	49.00
Chi-Square		3.33	3.33	919
d.f.		14	14	13
p-value		0.99	0.99	<0.0001*

Table 5.-Values of the actual quantiles and estimated quantiles for the final weight considering three models: *TGC*-1/3, *TGC*-2/3 and *TGC*-Mixed model

	Final weight (last sample)			
Quantiles	Actual (*n*=74)	1/3-Model	2/3-Model	Mixed-Model
0.025	384.1	487.2	351.4	332.3
0.05	433.3	517.2	396.5	375.5
0.10	463.0	572.1	445.4	420.9
0.20	500.0	642.4	486.0	462.8
25	511.3	669.5	505.2	481.8
0.30	515.0	693.4	521.2	497.7
0.40	526.0	742.6	553.9	529.6
0.50	540.0	789.8	583.7	561.1
0.60	560.0	846.1	615.1	593.5
0.70	580.5	903.1	652.4	652.4
0.75	607.5	942.2	676.3	654.5
0.80	620.0	980.5	698.1	677.7
0.90	678.5	1082.7	770.3	747.7
0.95	701.8	1175.9	829.8	807.6
0.975	716.8	1243.8	885.0	861.3
Chi^2		1342	104	90
d.f.		14	14	14
P- value		<0.0001	<0.0001	<0.0001

Table 6.- Simulation of biomass and value of gilthead sea bream (considering a mean batch of 300000 fish and a survival of 85%, and selling price from a commercial fish farm in Mediterranean Sea) by weight interval, average production duration (days) from the beginning of the cycle until the curves $W_{f\ 0.25}$, $W_{f\ 0.50}$ and $W_{f\ 0.75}$ corresponding to when 0.25, 0.50 and 0.75 quartiles reach 400, 500 and 600 g, respectively.

Weight Interval	Mean Weight	Sale Price	W 0.25 =	400 g	508 days	W 0.25 =	500 g	587 days	W 0.25 =	600 g	662 days
(g)	(g)	(€)	%	Production	Value	%	Production	Value	%	Production	Value
< 200	150	1,9	1,9	717	1341	1,5	574	1073	1,2	459	858
200-300	250	3,7	2,7	1705	6327	0,7	446	1656	0,6	383	1419
300-400	350	4,4	20,6	18408	81363	4,0	3525	15582	0,6	536	2367
400-500	450	4,5	35,7	40937	185036	19,3	22089	99844	5,0	5766	26063
500-600	550	4,5	24,1	33800	152777	30,6	42952	194141	17,8	24894	112523
600-700	650	4,8	11,1	18315	87731	23,9	39656	189951	26,9	44504	213174
700-800	750	4,8	4,1	7793	37331	12,4	23667	113366	22,4	42840	205204
> 800	850	6,1	0,0	0	0	7,8	16798	101797	25,6	55434	335929
Total				**121.676**	**551.904**		**149.707**	**717.409**		**174.815**	**897.536**
Increment							28.031	165.505		25.108	180.127
Weight Interval	Mean Weight	Sale Price	W 0.50 =	400 g	443 days	W 0.50 =	500 g	526 days	W 0.50 =	600 g	598 days
(g)	(g)	(€)	%	Production	Value	%	Production	Value	%	Production	Value
< 200	150	1,9	2,2	842	1574	1,7	650	1216	1,4	536	1001
200-300	250	3,7	10,9	6933	25721	1,4	893	3311	0,7	446	1656
300-400	350	4,4	37,3	33268	147044	14,6	13053	57693	2,7	2365	10454
400-500	450	4,5	31,7	36376	164418	32,8	37581	169864	16,2	18590	84025
500-600	550	4,5	13,7	19214	86848	28,3	39621	179085	29,2	40988	185266
600-700	650	4,8	4,3	7086	33941	14,2	23454	112343	25,2	41810	200272
700-800	750	4,8	0,0	0	0	6,6	12623	60462	15,0	28592	136955
> 800	850	6,1	0,0	0	0	0,6	1246	7553	9,7	21079	127738
Total				**103.718**	**459.546**		**129.119**	**591.528**		**154.406**	**747.367**
Increment							25.401	131.981		25.286	155.839
Weight Interval	Mean Weight	Sale Price	W 0.75 =	400 g	407 days	W 0.75 =	500 g	466 days	W 0.75 =	600 g	531 days
(g)	(g)	(€)	%	Production	Value	%	Production	Value	%	Production	Value
< 200	150	1,9	4,1	1549	2897	2,1	803	1502	1,7	650	1216
200-300	250	3,7	29,1	18535	68766	6,6	4176	15492	0,8	526	1951
300-400	350	4,4	42,2	37641	166374	31,8	28382	125446	12,2	10866	48029
400-500	450	4,5	19,4	22290	100752	34,9	40019	180886	31,0	35544	160658
500-600	550	4,5	5,3	7433	33598	17,4	24439	110462	29,5	41304	186692
600-700	650	4,8	0,0	0	0	7,1	11727	56171	16,1	26644	127626
700-800	750	4,8	0,0	0	0	0,2	430	2061	7,7	14726	70539
> 800	850	6,1	0,0	0	0	0,0	0	0	1,1	2276	13792
Total				**87.449**	**372.387**		**109.975**	**492.021**		**132.536**	**610.503**
Increment							22.526	119.634		22.561	118.482

Table 7.- Estimation of biomass and sales income of gilthead sea bream, considering three strategies of interval weight sale (400-500, 500-600 and 600-700 g) by classifying fish and sequential sale of fish from 0.75, 0.50 and 0.25 quartile.

Sale weight (g)	**Biomass** (tons)	**Sales Income** (€)	**Mean time** **(Days)**	**Sales Income /Days** (€)
400-500	114	511768	486	1053
500-600	139	628890	560	1123
600-700	158	752158	614	1225