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Population dynamics and growth modelling of *Oreochromis aureus* in the Josefa Ortiz de Domínguez reservoir, Sinaloa, Mexico

Dinámica poblacional y modelación del crecimiento de *Oreochromis aureus* en la presa Josefa Ortiz de Domínguez, Sinaloa, México

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ABSTRACT

Tilapia fish *Oreochromis aureus* represents the main source of income for the fishing sector in the Josefa Ortiz de Dominguez reservoir, Sinaloa, Mexico. It is of utmost importance to provide biological-fishery information to lay the foundation for the proper management of this species. Based on information from monthly commercial fishery samples collected from October 2011 to April 2012 in this reservoir, growth was modeled using the Schnute growth model, and the best submodel (cases) was selected according to the Akaike Information Criterion (AIC). The maturity size for females and selectivity for total organisms was estimated with the logistic model. From the 1,689 tilapia analyzed, sizes ranged from 125-305 mm total length (TL) for females and 125-370 TL for males. The best cases of the Schnute growth model were 2 and 5 according to the AIC. The estimated mature length for females was 197 mm TL. Based on the assessments of growth, size at maturity, and selectivity, data suggest that the commercial fishery may be having a direct negative impact on the *O. aureus* tilapia broodstock and juveniles in this reservoir.

KEY WORDS: Blue tilapia, El Sabino reservoir, maturity size, selectivity, Akaike.

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RESUMEN

La tilapia *Oreochromis aureus* es la principal fuente de ingresos del sector pesquero en la presa Josefa Ortiz de Domínguez, Sinaloa, México. Es de suma importancia aportar información biológico-pesquera, con la finalidad de sentar las bases para un adecuado manejo de esta especie. Con información de muestreos mensuales de la pesca comercial realizados de octubre de 2011 a abril 2012 en dicho embalse, se realizó la modelación del crecimiento a través del modelo de Schnute y se eligió al mejor submodelo (casos) según el criterio de información de Akaike (AIC). La talla de madurez para las hembras y la selectividad para el total de los organismos fue estimada con el modelo logístico. De 1,689 tilapias analizadas, las tallas fluctuaron de 125-305 mm de longitud total (TL) para las hembras y de 125-370 TL para machos. Los mejores casos del modelo de Schnute fueron el 2 y 5 de acuerdo al AIC. La talla de madurez estimada para hembras fue de 197 mm de TL. De acuerdo a los estimados de crecimiento, talla de madurez y selectividad, podemos deducir que la pesca comercial puede estar causando un impacto negativo, directamente a los reproductores y juveniles de la tilapia *O. aureus* en este embalse.

PALABRAS CLAVE: Tilapia azul, presa el sabino, talla de madurez, selectividad, Akaike.

Introduction

Tilapia (genus *Oreochromis*) are a group of fish known for their fast growth, year-round reproduction (with parental care), and sexual maturity size reached in a short time. These characteristics make them efficient in establishing and proliferating in almost any type of aquatic ecosystem (Küçük *et al*., 2013; Al-Wan & Mohamed, 2019). Tilapia have been introduced into water bodies (ponds, rivers, lakes, reservoirs, etc.) almost worldwide, they are widely cultivated in the tropics and subtropical zones (Norato, 2005; Gómez-Ponce *et al*., 2011). They have a high reproductive rate and are therefore fast-growing and easily marketed, and are therefore considered low-cost and easy to acquire (FAO, 2009; Gómez-Ponce *et al*., 2011).

In Mexico, this nonnative organism was introduced in the 1960s (Cantor, 2007). Since then, most of the artificial reservoirs in Mexico and in particular, Sinaloa state, have allowed the establishment of important fisheries based on the exploitation of the *Oreochromis* genus (tilapia). This situation has improved the living standards in rural communities surrounding these water bodies, thus making freshwater fishery one of the most important (ranking 5th in fisheries and aquaculture) in Mexico (Beltrán-Álvarez *et al*., 2009; Gómez-Ponce *et al*., 2011; Vázquez-Vera & Chávez-Carreño, 2022). Regionally, the state of Sinaloa is positioned as one of the main producing entities in the country, with more than 6,000 tons (t) annually (Beltrán-Álvarez *et al*., 2009; Vázquez-Vera & Chávez-Carreño, 2022).

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In the north of Sinaloa, particularly in the municipality of El Fuerte, the Josefa Ortiz de Domínguez reservoir (El Sabino) is located, where the average annual production per tilapia fishery is 500 t (Beltrán-Álvarez *et al*., 2015). In this reservoir, the capture and commercialization of tilapia is the main activity carried out by the surrounding communities (301 fishermen and 299 boats), contributing to maintaining life quality.

Some reservoirs (in Sinaloa only the Luis Donaldo Colosio dam “Huites”) operate under an Official Mexican Norm (NOM) published for the regulation of these reservoirs, which protects reproductive cycles of the main commercial species, establishes closed seasons, fishing gear, etc. Despite this, only two (Ignacio Allende reservoir, San Miguel de Allende, Guanajuato, and Cebolletas reservoir, Coroneo, Guanajuato) have an integrated management plan, based on technical aspects of the biological-fishing, limnological and socioeconomic fields, whose purpose is to provide an instrument to regulate fishing activity in the reservoirs (INAPESCA, 2021).

Among the technical parameters of the biological-fishery field, growth estimation is one of the main aspects of population evaluations (population biomass is related to individual growth) (Curiel-Bernal *et al*., 2021). Currently, several studies have estimated tilapia growth in various freshwater bodies in Mexico, based on direct methods such as the interpretation of layers in the hard parts of the fish (scales and otoliths) (Jiménez-Badillo, 2006; Ramírez, 2007; Valdez-Leyva, 2008; Beltrán-Álvarez *et al*, 2009; Ortega-Lizárraga, 2010; Gómez-Ponce *et al*., 2011), or through indirect methods such as size frequency population analysis (Ramos-Cruz, 1995; Hernández-Montaño, 2006; Peña-Messina *et al*., 2010; Arellano-Torres *et al*., 2013). However, in most of the aforementioned studies, growth estimates have been obtained by a single method or model, without a quantification of the uncertainty associated with these estimates.

Hence, the present work aimed to determine size structure, length-weight relationship, sexual maturity, and growth modeling of the blue tilapia *Oreochromis aureus* (Steindachner, 1864) population in the Josefa Ortiz de Domínguez reservoir in El Fuerte, Sinaloa state, to provide information on these population parameters and including the uncertainty associated with the estimation, thus contributing to better evaluation for the exploited population.

Material and Methods

Study area

The Josefa Ortiz de Dominguez dam is located 15 km west of the city of El Fuerte, Sinaloa state, and 90 km northwest of Los Mochis city, Sinaloa. Geographically, it is located at 26° 26’ N and 108° 42’ W, 101 meters above sea level. The reservoir has a storage capacity of 590,000,000 m^3 (volume variation between 100 and 500 million m^3) and a storage capacity of 37,000,000 m^3. The dam crest length is 2,730 m and a maximum height of 44 m. It is fed by water from the

Alamos River and El Fuerte River and also receives excess water from the Miguel Hidalgo dam (CONAGUA, 2014). According to Beltrán-Álvarez *et al*. (2015), the lowest water temperature values in this reservoir occur from December to February (winter 18.2 °C) and the highest in August (summer 33.8 °C). The recorded water temperature in this reservoir in December and February was 20.5 °C at the surface and the bottom (20 m), the temperature was 1 °C lower than the surface in both months. In April, June, and October, surface temperatures were 23.2, 28.0, and 28.5 ºC respectively. In April there was a thermal gradient between 8 and 14 meters, with a mixing layer extending from the surface to 8 meters. In June and October, the mixing layer is located from the surface to 15 meters.

Sampling and biometric measurements

From October 2011 to April 2012, six monthly samplings were carried out (2 sampling days each month, during October, November, January, February, March, and April), directly from the commercial catches of active fishermen in different points of the reservoir. The small boats (fiberglass canoes) used were generally about 10 m long, with 75 HP outboard motors. The fishing gear used was gillnets from 100 to 200 m long, with different mesh sizes: $2^{7/8}$ (7.3 cm), $3^{1/8}$ (7.9 cm), $3^{1/4}$ (8.3 cm), and $3^{1/2}$ (8.9 cm) inches. The use of different mesh sizes by the fishermen ensured that the samples were representative of both of size and sex of the organisms.

Measurements were taken of 1,689 tilapia *O. aureus* from commercial catches. Biometrics consisted in recording total length (TL) and total weight (TW), using a 1 mm precision ichthyometer and a 5,000 g capacity and 1 g precision digital scale (Ohaus, model YS2101), respectively.

Total Length-Total Weight Ratio

The total length-to-total weight relationship (TL-TW) was estimated for the total of the analyzed organisms, for each sex and month, adjusting the information (length-weight) to the potential model (Ricker, 1975): $TW = a * (TL)^b$, where *TW* is the total weight, *TL is total* length, *a* is the intercept and *b* is the slope (allometry coefficient). The degree of association *r* was used as a criterion for adjustment. A 95 % confidence level was estimated for *b*, and a Student's t-test (Zar, 1999) was applied to determine isometry (H_0: $b = 3$, $\alpha = 0.05$). If the slope value is equal to 3, then it is considered isometric growth and if is different from 3, it is considered allometric (Ricker, 1975; Bagenal & Tesch, 1978).

Multinomial analysis and growth modeling

The length of the measured organisms was compared and the Kolmogorov-Smirnov test was used to establish whether there was a difference in length between sex by month and in general (Gotelli & Ellison, 2004).

Considering length frequencies in 10 mm intervals by sex in each sampling season, a multinomial analysis was performed to identify the modal groups. The analysis was based on the

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observed distribution of the frequency histograms, such that the estimate of each modal group (*a*) was calculated using a normal probabilistic density function, according to the following:

$$F_i = \sum_{a=1}^{n}\left[\left(\frac{1}{\sigma a\sqrt{2\pi}}\right)e^{\frac{(xi-\mu a)^2}{2\sigma a^2}}\right] * P_a$$

where F_i is the expected frequency of the size interval *i* for the whole sample; (xi) is the midpoint of the *i* size interval; μa is the mean size of the group a and P_a is the weight factor of the cohort. a. The analysis was adjusted using the maximum likelihood method:

$$-LL_{\{X|\mu a,\sigma a,Pa\}} = \sum_{i=1}^{n} f_i Ln\left(\frac{F_i}{\sum F_i}\right) - \left(\sum f_i - \sum F_i\right)^2$$

where $-LL_{\{X|\mu a,\sigma a,Pa\}}$ is the negative likelihood of the data for parameters μa, σa, and Pa, f_i is the observed total frequency of the size class, and F_i is the estimated total frequency for the group of length i according to the multinomial model (Montgomery *et al*., 2010; Haddon, 2011). Finally, the modal groups were separated by two methods: the separation index (SI) using the following equation (Sparre & Venema, 1997):

$$SI = 2 * \frac{(\mu_n - \mu_i)}{(\sigma_n + \sigma_i)}$$

where μ_n and μ_i are the TL average of modal groups *n* and *i*, respectively; σ_n and σ_i are the standard deviations of modal groups *n* and *i*, respectively. Therefore, if *SI* > 2, then it is feasible to separate the normal components from the observed frequencies (Sparre & Venema, 1997). The other method was the Akaike Information Criterion, where the lower the AIC_c the better fit of the number of length groups was selected; from the following formula:

$$AIC_c = AIC + \frac{2k(k+1)}{n-k-1}$$

$$AIC = 2(k - LL)$$

where: k is the number of parameters of each model, n is the number of observations and LL is the logarithmic maximum likelihood function.

The mean lengths of each of the identified modal groups were plotted on a time scale. The probable number of cohorts supporting growth was obtained by modal progression through time in an ordered sequence (Montgomery *et al*., 2010). The above allowed a visual comparison through time, thus making it possible to generate alternative hypotheses based on an accurate modal progression.

Subsequently, with the same modal progressions, growth parameters were estimated with the five separate cases of the Schnute growth model (Schnute, 1981), one of these (case 5), is a special case based on the von Bertalanffy growth function, which was described by Baker *et al*. (1991). Baker's derivatives are equivalent to circumstances in which no direct information on length at a specific age is available (Quinn & Deriso, 1999). The five cases are as follows:

Case 1 (assuming $a \neq 0$ y $b \neq 0$)

$$\gamma_2 = [y_1^b * exp^{-a\Delta t} \varepsilon^b (1 - exp^{-a\Delta t})]^{1/b}$$

Case 2 (assuming $a \neq 0$ y $b = 0$)

$$\gamma_2 = exp[Ln(y_1) * exp^{-a\Delta t} * Ln(\varepsilon)(1 - exp^{-a\Delta t})]$$

Case 3 (assuming $a = 0$ y $b \neq 0$)

$$\gamma_2 = (y_1^b + \varepsilon^b \Delta t)^{\frac{1}{b}}$$

Case 4 (assuming $a = 0$ y $b = 0$)

$$\gamma_2 = y_1 * \varepsilon^{\Delta t}$$

Case 5 (assuming $a > 0$ y $b = 1$)

$$\gamma_2 = [y_1 * exp^{-a\Delta t} + \varepsilon(1 - exp^{-a\Delta t})]$$

In all five cases y_1 y y_2 are the average lengths for the same cohort at the analyzed times t_1 y t_2, a is the theoretical initial relative growth rate at age zero (units of the year $^{-1}$), b is related to the inflection point in the "S" shape of the growth curve, Δt is the time elapsed between t_1 and t_2, and ε is an asymptotic length or theoretical maximum length (L_∞)which is equivalent to the von Bertalanffy growth model.

The cases of the Schnute growth model were fitted using the maximum likelihood function (Haddon, 2011). LL (Haddon, 2011), considering additive and multiplicative error:

$LL\ (\Phi|data) = \left(-\frac{n}{2}\right) * [Ln\ (2\pi) + 2 * Ln(\sigma) + 1]$ for additive error and multiplicative error. $LL\ (\Phi|data) = \left(-\frac{n}{2}\right) * [Ln\ (2\pi) + 2 * Ln(\sigma) + 1] - \sum_{i=1}^{n} Ln(x_i)$.

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Where Φ represents the parameters of the model, *n is* the number of observations and σ the standard deviation estimated from the data and was calculated as follows: $\sigma = \sqrt{\frac{\sum(TL_{obs} - TL_{cal})^2}{n}}$ considering additive error or $\sigma = \sqrt{\frac{\sum(LnTL_{obs} - LnTL_{cal})^2}{n}}$ for multiplicative error, where LT_{obs} is the total observed length, LT_{cal} is the calculated total length and *n* is the number of *TL* data observed.

For the comparison of the Schnute growth model cases and to select the best case describing TL as a function of time, Akaike's corrected form scores (AIC_c) were performed. The lowest *AIC* $score_c$ is the one that will define the best case of the model (Burnham & Anderson, 2002; Katsanevakis, 2006) and is expressed by:

$$AIC_c = AIC + \frac{2k(k+1)}{n-k-1}$$

$$AIC = 2(k - LL)$$

where k is the number of parameters of each model, *n* is the number of observations and LL is the maximum likelihood function.

The difference (Δi) in the AIC_c of a given model for the AIC_{min} of the best model was estimated as follows:

$$\Delta i = AIC_c - AIC_{min}$$

There are three possible outcomes. If Δi > 10, the candidate model should be discarded because it does not describe the observed growth and is not compatible with the data. Second, if 4 < Δi < 7, the model partially supports and weakly explains the growth data. Third, if Δi < 2, then the candidate model adequately describes the collected growth data (Burnham & Anderson, 2002).

The normalized weights for each model were estimated (Akaike, 1983; Burnham & Anderson, 2002) using the Akaike weights (ωi). This index takes a proportional form and is given by:

$$\omega i = \frac{e^{(-0.5\Delta_i)}}{\sum_{k=1}^{4} e^{(-0.5\Delta_i)}}$$

Confidence intervals (L_{inf} and L_{sup}) were estimated for growth parameters of all cases based on the likelihood profiles and the x^2 distribution (Venzon & Moolgavkar, 1988). The confidence interval was defined as all values of θ that satisfy the following inequality:

$$2(L(Y|\theta_{best})) < x^2_{1,1-\alpha}$$

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where: $L(Y|\theta_{best})$ is the negative log-likelihood of the most probable value of. θ y $x^2_{1,1-\alpha}$ is the value of x^2 with one degree of freedom at the confidence level $1-\alpha$. The 95 confidence interval for θ encompasses all values θ that are twice the difference between the negative likelihood of θ and the negative likelihood of the best estimate of θ that is less than 3.84 (Haddon, 2001), using the following estimator:

$$L(Y|\theta) = L(Y|\theta_{best}) - \frac{x^2_{1,1-\alpha}}{2}$$

With the parameter values of the winning cases, the different growth curves were estimated.

Sex ratio and size at maturity

The sex of each organism was identified by direct observation of external morphology. The male; female ratio (M:H) was estimated by month and overall for the entire study period. A chi-square test (X^2) was applied to determine if there was any statistical difference between sex ratios, based on the null hypothesis of a 1:1 ratio.

To determine the size at which 50 % of the females were mature (mature size or L_{50}), the stages of sexual maturity were taken into account according to the modified scale of Holden & Raitt (1975): Stage I (immature), sex organs very small near the spine, transparent, colorless or gray, oocytes not visible to the naked eye; Stage II (maturing), ovaries translucent or opaque with blood capillarity, occupying about half of the abdominal cavity, oocytes visible as granular matter; Stage III (mature), ovaries occupy 2/3 to the full length of the abdominal cavity, pinkish orange with superficial blood vessels visible; Stage IV (Spawned), ovaries contracted about half the length of the abdominal cavity. Ovaries may contain opaque, mature, disintegrating, or darkened to translucent egg remains.

The estimation of mature size or $L_{50\%}$ was performed by calculating the cumulative relative frequency per length interval, this was fitted to the model used by Brouwer & Griffiths (2005) with the following equation: $Pi = \frac{1}{1+exp^{-(L_i - L_{50})/\alpha}}$, here Pi is the ratio of (mature females, stage III and IV) / (total number of females of a given size); Li is the total length in mm and L_{50} is the length corresponding to 50 % of mature individuals and *a* is the width of ogive. The model was fitted by maximizing the negative log-likelihood (-Log-likelihood):

$$-LL = \sum_{i=1}^{n}\left[m_i\, ln\left(\frac{pm_i}{1-pm_i}\right) + n_i ln(1-pm_i) + ln\left(\frac{n_i}{m_i}\right)\right]$$

where: n is the total number of females in class *i* and *m* is the number of mature females in class *i*. Confidence intervals for size at maturity were estimated based on probability profiles.

Selectivity Curve

Calculation of the selectivity curve was obtained with sizes of the total analyzed organisms, by fitting the following logistic equation (Gulland, 1983):

$$S(L_t) = \frac{1}{1 + e^{S_1 - S_2\,(L)}}$$

where: S is the selectivity, L_t is the length of the organism or size class, and S_1 and S_2 are constants of the linear equation relating net size and size of captured organisms. The result is presented as a probability (or percentage) that the organism escapes from the net through the mesh due to its size (Sparre & Venema, 1997).

Results

From October 2011 to April 2012, 1,689 *O. aureus* specimens were analyzed, of which 1,044 were males and 645 were females (Figure 1a). The length-weight relationship for both sexes throughout the study generally showed a high degree of association (r = 0.98, $p < 0.001$, Table 1 and Figure 1b). The slope value (*b*) for both sexes during the whole study, expresses an isometric type growth ($p > 0.05$, Table 1 and Figure 1b). Similarly, the length-weight relationship for separate sexes (females and males) during the whole study showed a high degree of association (r > 0.98, $p < 0.001$, Table 1). The value of slope (*b*) for males expressed isometric growth ($p > 0.05$, Table 1), while for females the value of slope (*b*) was different from 3 ($p < 0.05$, Table 1).

Table 1. Parameters of the length-weight relationship per month for females and males of *Oreochromis aureus* in the Josefa Ortiz de Domínguez reservoir, El Fuerte Sinaloa, Mexico.

Sampling	Sex	N	*a*	*b*	*r*	*p* (t-student)
Oct 2011	Female	89	0.000005	3.186 ± 0.222	0.943	0.125
	Male	170	0.000001	3.449 ± 0.139	0.941	0.030*
Nov 2011	Female	177	0.000011	3.080 ± 0.064	0.989	0.077
	Male	283	0.000025	2.939 ± 0.061	0.984	0.100
Jan 2012	Female	107	0.000007	3.191 ± 0.117	0.970	0.101
	Male	184	0.000013	3.068 ± 0.061	0.977	0.236
Feb 2012	Female	71	0.000003	3.331 ± 0.076	0.993	0.017*
	Male	144	0.000034	2.876 ± 0.064	0.988	0.050
Mar 2012	Female	141	0.000011	3.093 ± 0.052	0.993	0.076
	Male	163	0.000014	3.050 ± 0.063	0.988	0.196
Apr 2012	Female	60	0.000011	3.077 ± 0.173	0.952	0.363
	Male	100	0.000009	3.123 ± 0.081	0.983	0.141
Total	Female	645	0.000007	3.170 ± 0.037	0.984	0.014*
	Male	1044	0.000016	3.011 ± 0.028	0.98	0.356
	Both sexes	1689	0.000015	3.029 ± 0.022	0.981	0.140

* Indicates significant differences in the value of slope *b* ($p < 0.05$) * indicates significant differences of slope *b* ($p < 0.05$)

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The length-weight relationship by month for female tilapia *O. aureus*, showed a high association degree (r > 0.94, $p < 0.001$), with the highest correlation values in February and March (r = 0.99, $p < 0.001$) and lowest values in October (r = 0.94, $p < 0.001$) and April (r = 0.95, $p < 0.001$, Table 1). Likewise, values of slope (*b*) for females by month showed isometric-type growth in October, November, January, March, and April ($p > 0.05$, Table 1); during February the value of slope (*b*) was different from 3 ($p < 0.05$, Table 1).

The length-weight relationship by month for male tilapia *O. aureus*, showed a high association degree (r > 0.94, $p < 0.001$), with the highest correlation values in February and March (r = 0.98, $p < 0.001$) and lowest values in January (r = 0.97, $p < 0.001$) and October (r = 0.94, $p < 0.001$). The values of slope (*b*) for males by month showed isometric-type growth in November, January, February, March, and April ($p > 0.05$, Table 1); the value of slope (*b*) was different from 3 during October ($p < 0.05$, Table 1).

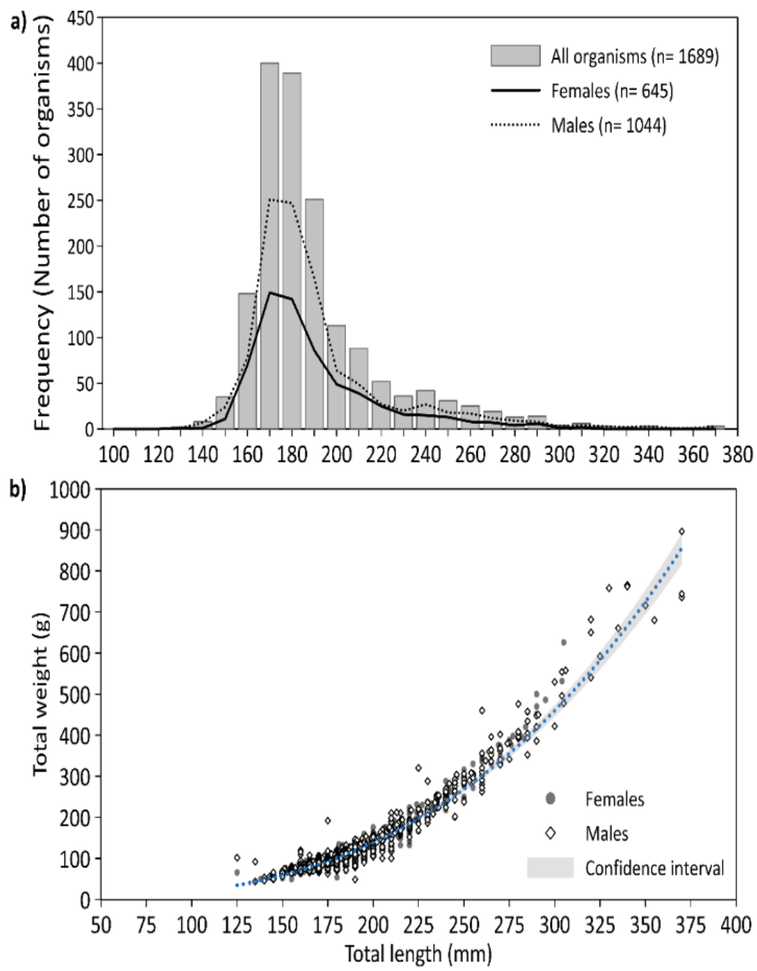

Figure 1. Monthly length structure (a) for females, males and both sexes and length-weight relationship (b) for *Oreochromis aureus* in the Josefa Ortiz de Domínguez reservoir, El Fuerte, Sinaloa, Mexico.

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The weight frequency distribution was measured by separate sexes of *O. aureus* tilapia, showing a range from 44 to 896 g in males ($\bar{X}$ 129 ± 99.7) and for females from 50 to 626 g ($\bar{X}$ 124 ± 74.4). No significant differences were found in the weight of both sexes, even though males weighed more than females (Table 2). In females, the length ranged from 125 to 305 mm TL ($\bar{X}$ 186.7 ± 28.5), and in males from 125 and 370 mm TL ($\bar{X}$ 188.3 ± 33.7) (Table 2 and Figure 1a). No significant differences were found when comparing size distribution between males and females (Kolmogorov-Smirnov p = 0.673). The comparison between months of frequency distribution for females with respect to males showed that only in October there were significant differences (p = 0.009).

A multinomial analysis was applied to size structures in female tilapia *O. aureus*, showing modal groups from one to three per month and four groups in March 2012 (Figure 2). For males, a multimodal behavior was observed with two and four groups per month and five modal groups in March 2012. Modal progression identified four cohorts for females and six cohorts for males (Figure 2).

The best models for growth estimation parameters of *O. aureus* tilapia (as indicated by the quality estimators AIC_c, Δ_i y ω_i) with the additive error were: cases 2 and 5 for both sexes (Table 3). In females, case 2 was estimated at L_∞= 310.7 mm of TL and a value of parameter *a* = 1.7; with case 5, we estimated *a* L_∞= 328.8 mm of TL and a value of *a* = 1.2. In males, with case 2, *a* = 362.9 mm TL and a value of *a* = 1.2 were estimated. L_∞= 362.9 mm of TL and a value of the parameter *a* = 2.2; with case 5, a = 410.6 mm of TL and a value of a = 1.2 were estimated. L_∞= 410.6 mm of TL and the value of parameter *a* = 1.2. Table 3 shows the values of each case for females and males with their respective confidence intervals.

Table 2. Statistics of sizes and weights for females, males and both sexes of *Oreochromis aureus* in the Josefa Ortiz de Domínguez reservoir, El Fuerte, Sinaloa, Mexico.

	Males	Females	Both sexs
TL mm (Min-Max)	125 - 370	125 - 305	125 - 370
Mean	188.3	186.7	187.6
Stand dev	33.7	28.5	31.8
TW g (Min-Max)	44 – 896	50 - 626	44 - 896
Mean	129.0	124.3	127.2
Stand dev	99.6	74.3	90.8

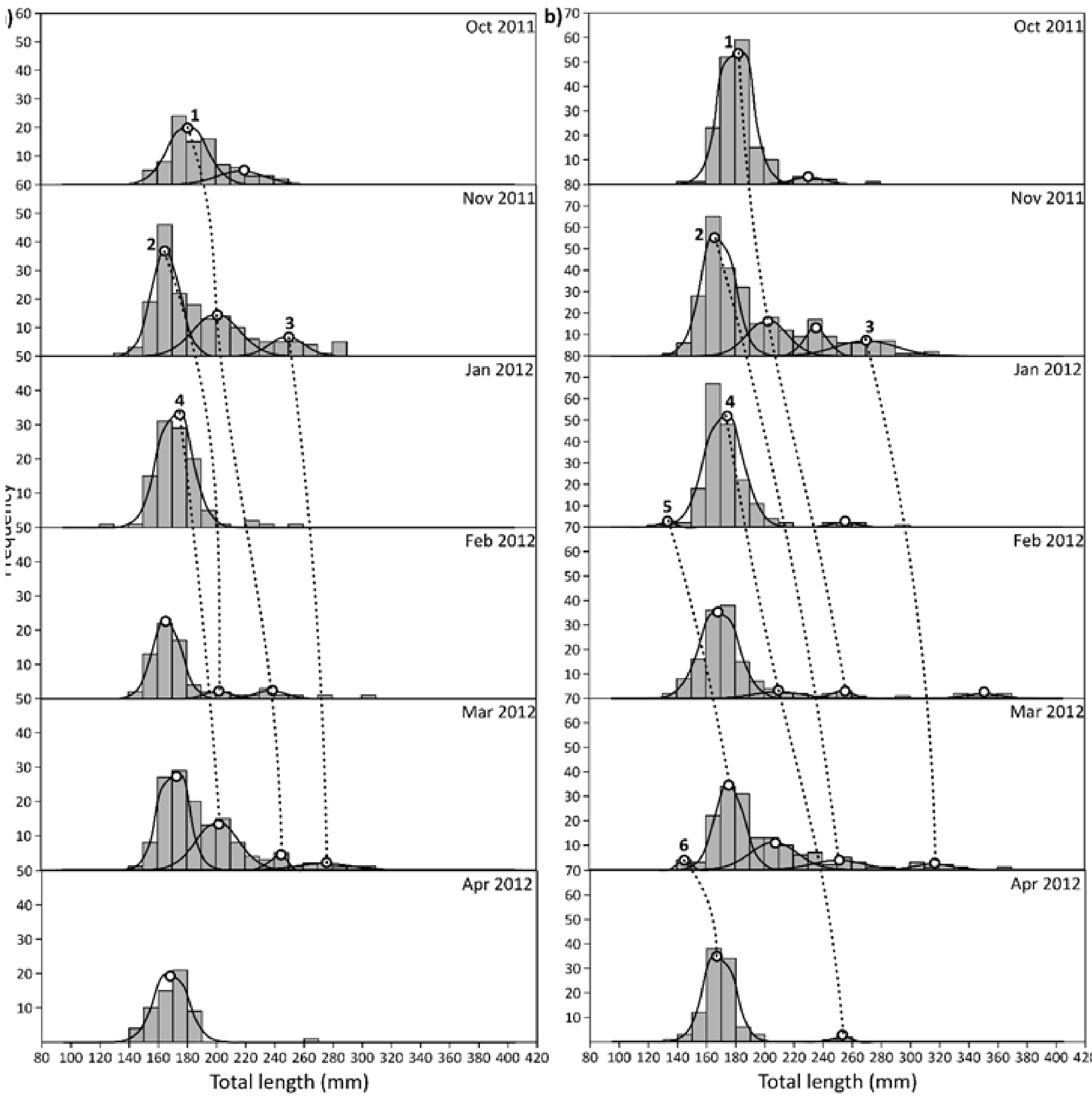

Figure 2. Monthly length structure (bars), modal groups (white circles centered on each curve) and modal progression of the individual cohorts (dotted line labeled numerically in chronological order of occurrence) for females (a) and males (b) of *Oreochromis aureus* in the Josefa Ortiz de Domínguez reservoir, El Fuerte, Sinaloa, Mexico.

Table 3. Model quality estimators (AIC_c, Δi y ωi) and estimated growth parameters (a, b y $L_\infty(\varepsilon)$) for the five cases analyzed from the Schnute model for females and males of *Oreochromis aureus*.

Model	AIC_c	Δi	wi	*a* (IC)	*b* (IC)	$L_\infty(\varepsilon)$ (IC)
Females						
Case 1	51.6	9.7	0.00	2.9 (2.48-3.37)	-1.99 (-1.14- -3.0)	292.9 (278.8-308.3)
Case 2*	**41.9**	**0.0**	**0.43**	**1.7 (1.46-2.01)**		**310.7 (294.2-327.8)**
Case 3	43.4	1.4	0.21		3.1 (2.3-4.84)	259.5 (243.1-274.6)
Case 4	51.1	9.2	0.00			1.6 (1.28-2.05)
Case 5**	**42.3**	**0.4**	**0.36**	**1.2 (0.98-1.37)**		**328.8 (310.4-347.2)**
Males						
Case 1	62.3	5.6	0.03	2.1 (1.92-2.38)	0.06 (0.04-0.07)	364.8 (347.6-382.4)
Case 2*	**56.7**	**0.0**	**0.52**	**2.2 (1.97-2.45)**		**362.9 (345.8-380.5)**
Case 3	60.1	3.4	0.09		2.2 (1.67-2.9)	314.0 (293.9-333.3)
Case 4	75.3	18.6	0.00			2.3 (1.63-3.02)
Case 5**	**57.5**	**0.8**	**0.36**	**1.2 (1.09-1.36)**		**410.6 (389.7-431.5)**

The best models are indicated in bold, * Indicates best model and ** second best model.

The growth modeling (growth curves) for both female and male *O. aureus* tilapias can be seen in figure 3 for both cases and confidence intervals of the best models are shown in figure 4. L_∞ and *a* of the best models are shown in figure 4. An average model was estimated since the two best cases did not reach a ω_i= 0.90, so it cannot be declared as the best model.

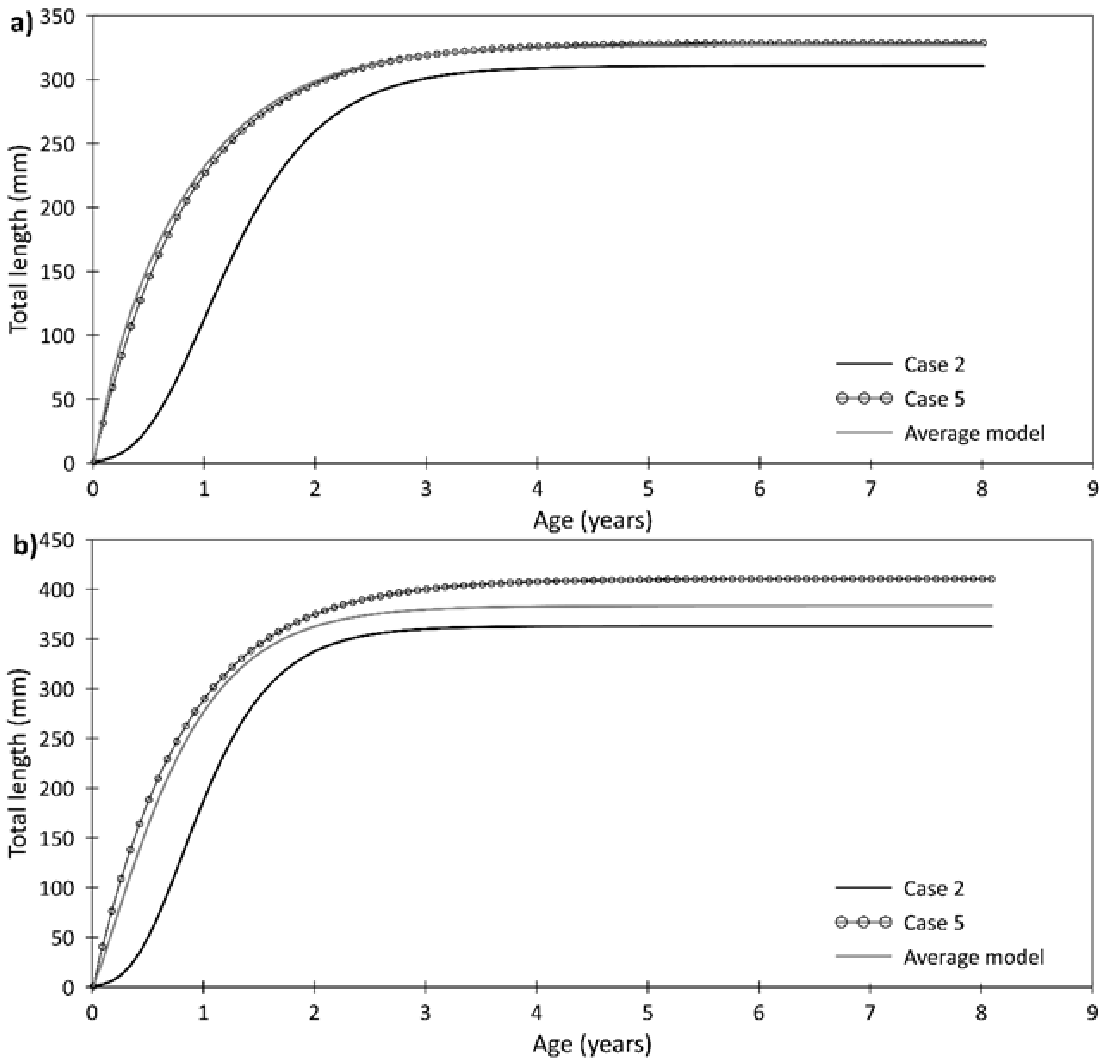

Figure 3. Growth curves for females (a) and males (b) adjusted with cases 2, 5 and average of the Schnute model, in *Oreochromis aureus* from the Josefa Ortiz de Domínguez reservoir, El Fuerte, Sinaloa, Mexico.

The overall sex ratio for *O. aureus* tilapia was 1.6 M:1 H, showing significant differences ($p < 0.05$), with male dominance. Monthly sex ratio behavior only in March 2012 showed no significant differences ($X^2 = 1.6$ and $p > 0.05$, Table 4).

The estimated mature length or L_{50} for female *O. aureus* tilapia was 197.2 mm TL (Figure 5a). Confidence intervals estimated using likelihood profiles indicate that female *O. aureus* tilapia can mature between 191.8-203 mm TL (Figure 5b).

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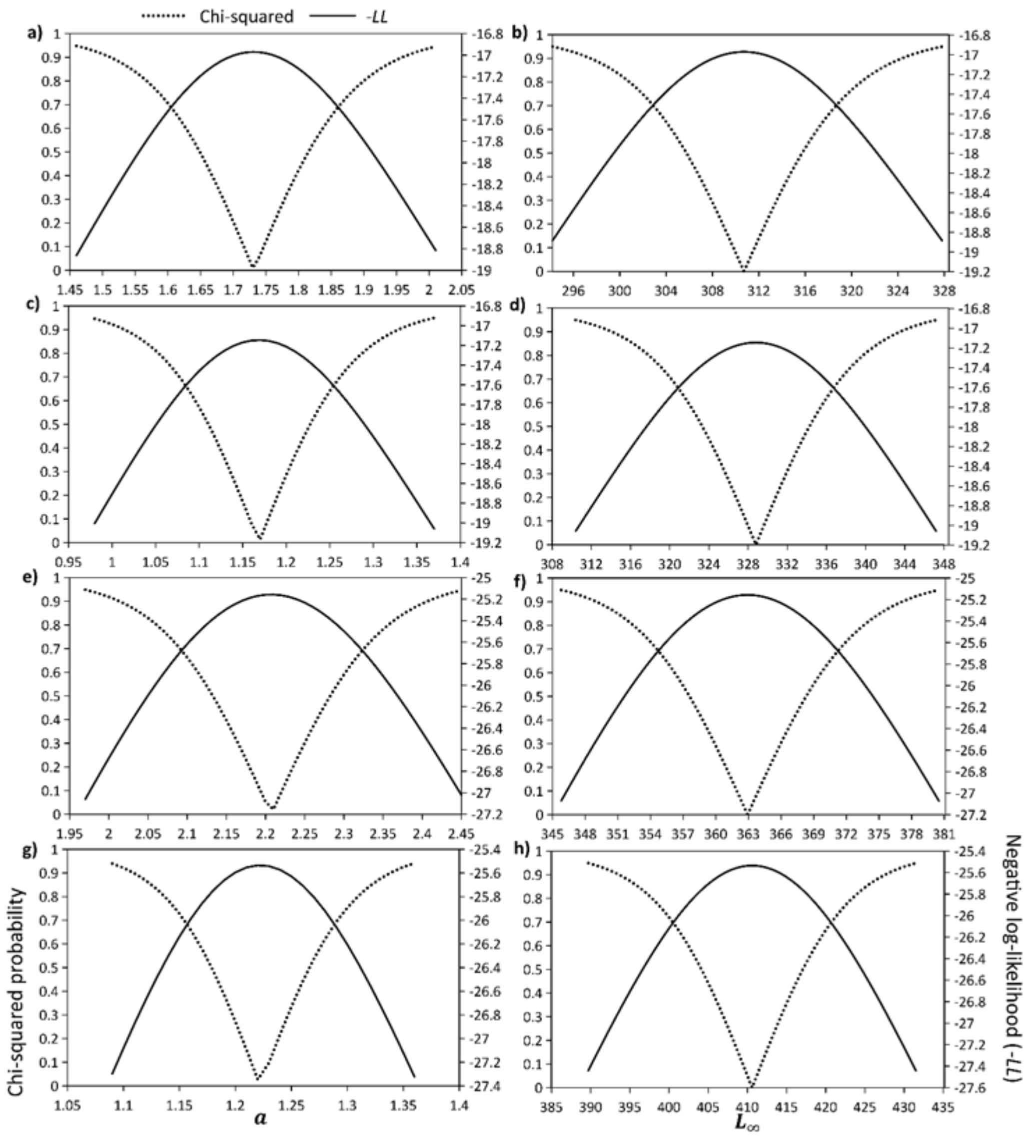

Figure 4. Confidence intervals of L_∞ and a estimated by means of likelihood profiles for cases 2 and 5. Females case 2 (a-b) and case 5 (c-d), males case 2 (e-f) and case 5 (g-h).

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Table 4. Sex ratio of *Oreochromis aureus* per month and total in the Josefa Ortiz de Domínguez reservoir, el Fuerte Sinaloa, México.

Samplings	Females	Males	Total	Proportion (M:H)	X^2	*p*
Oct 2011	89	170	259	1.9:1	25.3	< 0.05
Nov 2011	177	283	460	1.6:1	24.4	< 0.05
Jan 2012	107	184	291	1.7:1	20.4	< 0.05
Feb 2012	71	144	215	2.0:1	24.8	< 0.05
Mar 2012	141	163	304	1.2:1	1.6	0.2*
Apr 2012	60	100	160	1.7:1	10.0	0.002
Total	645	1044	1689	1.6:1	94.3	< 0.05

* Indicates no significant differences between the Males:Females ratio.

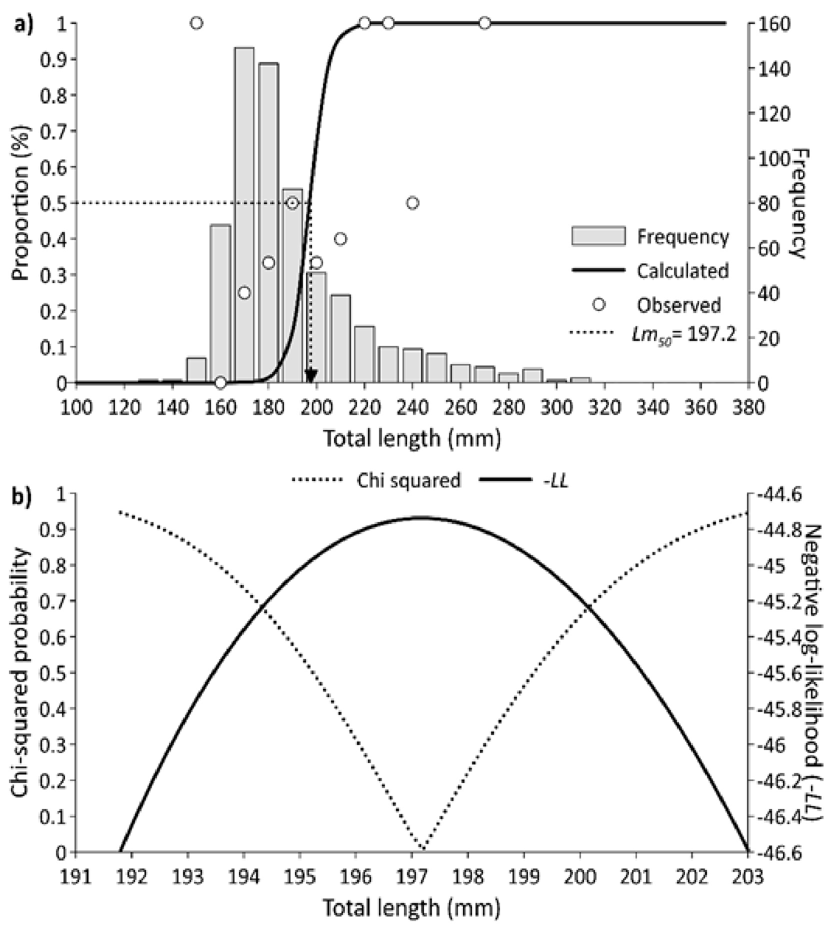

Figure 5. Size at maturity or L50% (a), likelihood values, and confidence intervals of size at maturity (b) for females of Oreochromis aureus in the Josefa Ortiz de Domínguez reservoir, El Fuerte, Sinaloa, Mexico.

The size at which 50 % of the organisms were caught was estimated at 175 mm TL. It was also determined that more than 75 % of the total catches were smaller than 200 mm TL, as a consequence of the selectivity of the nets used in the commercial catch (Figure 6).

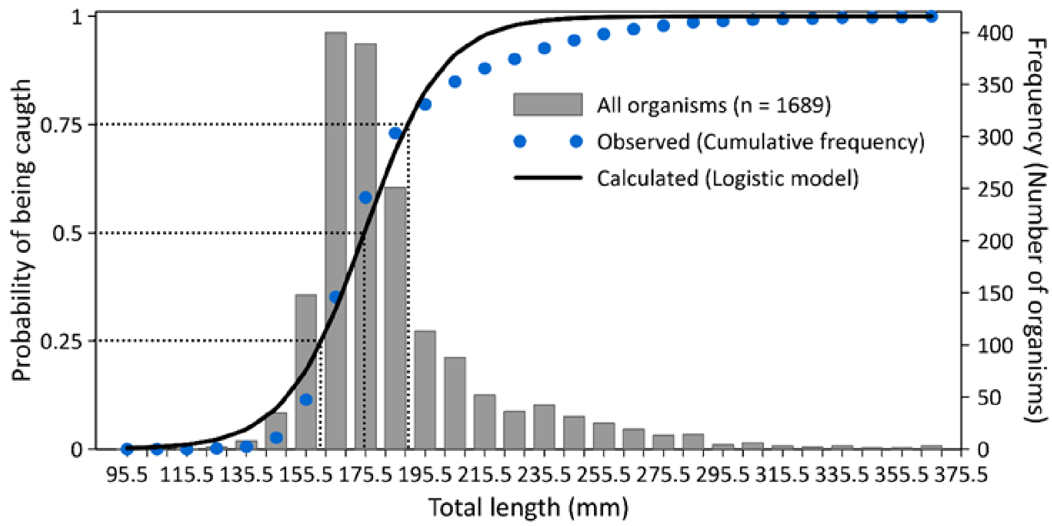

Figure 6. Probability of capture (selectivity curve) of the sizes of *Oreochromis aureus* in the Josefa Ortiz de Domínguez reservoir, El Fuerte, Sinaloa, Mexico.

Discussion

The primary use of water from the Josefa Ortiz de Domínguez reseroir is for agricultural irrigation in the valleys of El Fuerte and El Carrizo, Sinaloa, and to a lesser degree, for drinking water supply for the populations downstream of the dam. The original water use in this reservoir did not prevent the establishment of fisheries such as catfish, carp, bass, and tilapia, the latter of which is one of the most important, with an average production per fishery of 500 t (Beltrán-Álvarez *et al*., 2015). Tilapia fish capture (from January to April and from August to December) and its commercialization is the main activity carried out in the communities on the shores of the reservoir, helping to maintain quality of life standards, providing a source of food and employment for more than 300 fishermen and their families, settled in communities on the shores of this reservoir (Álvarez-Anaya, 2008).

In this study, the size range for both sexes of tilapia *O. aureus* was from 125 to 370 mm TL, similar to that reported by some authors for this same species in different reservoirs in Sinaloa: Sánchez (2000) in the Luis Donaldo Colosio reservoir (170-320 mm TL), Beltrán-Alvarez *et al*.

(2006) at Gustavo Díaz Ordaz reservoir (120-350 mm TL), Álvarez-Anaya (2008) at Josefa Ortiz de Domínguez reservoir (87-336 mm TL), Beltrán-Álvarez *et al*. (2009), at Sanalona reservoir (125-345 mm TL), and Beltrán-Álvarez *et al*. (2014), at Eustaquio Buelna reservoir (90-272 mm TL). Despite the above, and based on the selectivity analysis performed (Figure 6) of the total organisms in this study, it was observed 75 % at sizes between 125 to 194 mm TL. The same was observed by Álvarez-Anaya (2008), reporting that more than 75 % of the *O. aureus* tilapia organisms captured with trawls of different mesh sizes (21/2, 23/4, 3, 31/8, 31/4, 31/2 inches) and trawls, corresponded to sizes less than 225 mm TL.

Although there is a recommendation for a minimum catch size of 260 mm TL and the use of a 3-inch mesh size for catching tilapia in this reservoir (Beltrán-Álvarez *et al*., 2015), compliance with these recommendations is not always respected. As documented by Beltrán-Álvarez *et al*. (2015) and evidenced in this study, commercial catches are carried out with different mesh sizes of 21/2, 2 3/4, 27/8, 31/8, 31/4, and 31/2 inches. Likewise, Álvarez-Anaya (2008) and the present study determined that, due to the selectivity of the fishing gear used, more than 75% of the catches are smaller than 225 mm TL (smaller than the minimum recommended size), which may be the cause of this decrease in the size of the organisms caught each fishing season and, thus, the decrease in the volume of catches of tilapia *O. aureus* in this reservoir.

The size at maturity or L_{50} estimated for female tilapia *O. aureus* in this work was 197.2 (191.8-203) mm TL, which is reached at one year of age, similar to and within the range of that estimated by some authors for this same species in different reservoirs in Sinaloa: 197 mm TL (139.4 g) by Belmont (2003) at Aurelio Benassini Vizcaíno reservoir “El Salto”, 195 mm TL (124.2 g) by Guardado (2006) at José López Portillo reservoir “El Comedero” and 195 mm TL (147 g) by Álvarez-Anaya (2008) at Josefa Ortiz de Domínguez reservoir. Other studies carried out in different reservoirs in Mexico for this same species, recorded mature sizes greater than those estimated in the present study: 235 mm TL by Ramos-Cruz (1995), in the Benito Juárez reservoir (Oaxaca), 236.7 mm by Hernández-Montaño & Orbe (2002), in the “Zimapán”, Hidalgo-Querétaro, and 251 mm TL by Orbe *et al*. (2002), in the Aguamilpa reservoir, Nayarit.

A selectivity analysis was carried out for the total number of organisms analyzed in this study, and an average catch size was estimated (the size at which 50 % of the organisms were caught) of 175 mm TL. When comparing the present results with the mature size for female tilapia *O. aureus* of 197.2 (192-203) mm TL, it can be inferred that more than 50 % of the organisms (females) are being captured below their first maturity size. This, together with the fact that more than 75 % of the total catches are smaller than 200 mm TL (as a consequence of the selectivity of the small mesh size nets used in commercial catches), would be directly impacting the reproductive and juvenile population, which would harm the population and, therefore, on the sustainability of the fishery of this resource.

Despite these negative impacts observed in this work and which are caused by fishing, we must take into account the tilapia fry planting programs that are carried out on an annual-biannual or tri-annual basis in the reservoirs of the state of Sinaloa. This type of restocking program (planting of fingerlings) carried out by federal and state authorities provides a respite from the fishing pressure that is exerted season after season on commercial species in these reservoirs (Beltrán-Álvarez *et al*., 2015). However, to date in this reservoir there is no formal evaluation of the status of the tilapia resource, nor improvements or population increases due to restocking programs.

Other parameters that could be counteracting the negative impacts observed (mainly caused by fishing) are the rapid growth, year-round reproduction (with parental care), and sexual maturity size reached in a short time, of *O. aureus* tilapia. These characteristics make this species successful to establish and proliferate in almost any type of aquatic ecosystem (Küçük *et al*., 2013; Beltrán-Álvarez *et al*., 2015; Al-Wan & Mohamed 2019).

Obtaining the best possible estimates of individual growth parameters is essential in fisheries management and aquaculture studies, as growth is a key component of population dynamics. Population biomass is related to individual growth because fish grow in response to seasonal and local environmental conditions at a time or location (Curiel-Bernal *et al*., 2021). The importance is reflected in a large amount of scientific literature on individual growth in fisheries and aquaculture.

With the multinomial analysis carried out in this study, 2 to 6 modal groups (cohorts) were estimated in the monthly size frequencies obtained from commercial catches of tilapia *O. aureus* in the Josefa Ortiz de Domínguez reservoir (Figure 2). Jiménez-Badillo (2006) found 3 to 6 cohorts of tilapia *O. aureus* in Infiernillo reservoir, Michoacán. Leonce-Valencia & Defeo (1997), and Jiménez-Badillo (2006) mention that in fish populations (such as tilapia), it is common to observe a mixture of cohorts, as a consequence of the multiple spawning and continuous recruitments that this species presents throughout the year. Therefore, it is of utmost importance to determine the influence that each group of monthly data has on the estimation of growth parameters.

The Schnute growth model used for growth estimation in the present research consists of a differential equation that forms eight families of curves as a function of the parameter values. It is a general four-parameter growth model whose alternative solutions contain the preceding models as special cases. Maximum likelihood was used as a criterion since its use provides a better solution to adequately estimate growth parameters, as it is a more robust test than traditional methods (Katsanevakis, 2006). In addition, the selection of the most appropriate model or case, based on information theory has been recommended as a better and more robust alternative than traditional approaches (Katsanevakis, 2006; Cerdenares-Ladrón de Guevara *et al*., 2011). The advantage of using model quality estimators (AIC_c, Δi y ωi) is that tested cases (models) can be hierarchically ordered according to their fit to the data and the average parameters for a growth model can be obtained.

The range of the estimated value of L_∞ in the present study, both for females and males of tilapia *O. aureus*, is similar or with slight differences to that reported by Beltrán-Álvarez *et al*. (2014), in Eustaquio Buelna reservoir, Sinaloa, where they estimated a value of. L_∞= 357 for females and 294 mm TL for males and to that reported by Beltrán-Álvarez *et al*. (2009), at the Sanalona reservoir, Sinaloa, where they estimated a value of L_∞= 428 for females and 414 mm TL for males.

The variation in growth parameters that may occur is mainly due to the size range (as a consequence of the selectivity of the nets used in the commercial catch), the sample size used, and the reliability of the sampling. The different methods and criteria for determining growth can also affect the results of each study (Álvarez-Anaya, 2008; Beltrán-Álvarez *et al*., 2009; Beltrán-Álvarez *et al*., 2014; Curiel-Bernal *et al*., 2021). The growth curves estimated with cases 2 and 5 indicate that males, compared to females of *O. aureus* tilapia, reach a size close to their theoretical maximum length in a shorter time.

Similarly, when comparing the slopes in the length-weight relationship of females and males, significant differences were found. The same was recorded for tilapia *O. aureus* by Sánchez (2000) at Huites reservoir, Ramírez (2007) at Varejonal reservoir, and Valdez-Leyva (2008) at Sanalona reservoir, where males were significantly larger than females. In contrast, Beltrán-Álvarez *et al*. (2009), and Beltrán-Álvarez *et al*. (2014), at Sanalona and Eustaquio Buelna reservoirs, found that females reached a length close to their theoretical maximum length in a shorter time. The possible causes of the difference in the growth of *O. aureus* tilapia could be the availability of food, water temperature, dissolved oxygen, pH, and transparency of the different reservoirs, in addition to the intrinsic variables of the species, such as the genetic capacity to support or adapt to changes in the environment or gene pool, physiology, reproductive stage, etc.

As determined in the present study, male tilapia *O. aureus* reaches a size close to their theoretical maximum length in a shorter time, a sex ratio of 1.6 M:1 H was also estimated, which is statistically different from the theoretical ratio of 1:1. Meza *et al*. (1998), Álvarez-Anaya (2008), and Valdez-Leyva (2008) in the Bacurato, Josefa Ortiz de Domínguez and Sanalona reservoirs, respectively, mention that males dominated over females. Peña-Messina *et al*. (2010) mention that the females of some fish such as tilapia, after fertilization tend to move to deeper sites and places with vegetation for incubation and protection of offspring, while males move to shallower feeding areas, thus increasing the possibility of being captured.

Conclusions

According to the tests performed in the present study, (selectivity, size at first maturity, and growth), it is suggested that the commercial catch of *O. aureus* during the study was composed of a high percentage (>75 %) of juveniles and spawners, which could harm the population and, therefore, on the sustainability of the resource. Despite these negative impacts observed on the population, there are restocking programs (fry planting) in this reservoir, which provide a respite from fishing pressure. In addition, the features of *O. aureus*, such as rapid growth, year-round reproduction, and sexual maturity size reached in a short time, make this species very successful and prolific.

Even though the information used for the present work is not recent, it provides biological-fishery information on tilapia in this reservoir, where there is no formal evaluation of the exploited population, much less a management plan that defines technical aspects of the biological-fishery, limnological and socioeconomic fields, which allows regulating the fishing activity, which is of great importance for the livelihood of the communities surrounding this reservoir.

Authors contribution

Project proposal, organization, preparation, and conduct of sampling, biometric data collection in the field and for laboratory analysis, participation in data analysis, size frequency analysis, calculation of total length-to-total weight ratio, and principal drafters of manuscript, P Hernández-Sandoval and CH Rábago-Quiroz; Organization, preparation, and conduct of sampling, biometric data collection in the field and sampling for laboratory analysis, biometric data analysis for age and growth determination, use of specialized software, JD Ruiz-García and JG Padilla-Serrato; Data analysis for the determination of sex ratio, gonadic maturity and length at first sexual maturity, data analysis, drafting and revision of the manuscript, SP Díaz-Camacho, JD Magaña-Correa, KJ Moreno-Rentería, and JA Ávila-Díaz.

All authors of this manuscript have read and accepted the published version of this manuscript.

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Conflict of interest

The authors declare that they have no conflicts of interest.

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