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Research Article

Relative growth stages of an important sciaenid fish from the tropical eastern Pacific Ocean: the striped croaker *Cynoscion reticulatus*

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ABSTRACT. *Cynoscion reticulatus* has been a significant resource in the Mexican Pacific for over 20 years. However, it lacks management measures due to a lack of biological-fishery information. For this reason, this study aimed to analyze the relative growth using a multimodel approach to facilitate and increase the accuracy of using structured models to estimate biomass. Therefore, three models were compared to determine which best describes the species' ontogeny. The results showed that a broken line model can aptly describe the species' relative growth, as it identifies the point of change in the growth trend. It pinpointed the same relative growth pattern in both sexes; in males, the growth switched from positive allometric to negative allometric after 34.2 cm total length (TL), whereas in females, it occurred after 33.3 cm TL. This growth pattern was linked to the species' reproductive physiology. The information gathered is crucial for fisheries assessment, as it can serve as input data in dynamic models of low or high complexity, offering swiftly obtained information for stock evaluation, allowing the determination of a resource's status and estimating biomass to manage target species appropriately.

Keywords: *Cynoscion reticulatus*; Scianidae; fisheries; relative growth; multi-model approach; allometry

INTRODUCTION

The striped croaker (*Cynoscion reticulatus*) has been an important resource in the Gulf of California and the central Mexican Pacific for over 20 years (DOF 2004, Robertson et al. 2024). It is captured all year round as a targeted resource by the artisanal fishery and is commonly used as a bycatch by shrimp boats (DOF 2004). Due to its economic and food importance for coastal communities, this and other croaker species were added to the Mexican fisheries management plan (DOF 2021). However, a lack of information regarding its population dynamics could yield negative results in the management effects of wild populations (Gebremedhin et al. 2021) and increase problems in effective marine fishery governance, which leads to higher competition, conflicts, and sustainability of the resource (Pomeroy et al. 2016).

Biological and fishery data on the striped croaker *C. reticulatus* are limited, but some relevant aspects stand out. This species inhabits estuarine and marine waters at depths ranging from 1 to 101 m, and its distribution extends from southern Baja California and the Gulf of California to Colombia (Robertson et al. 2024). In the southeastern Gulf of California, the reproductive season of *C. reticulatus* has been observed to last from April to August (Carrillo-Isiordia et al. 2023), a pattern that aligns with the findings of Ortiz et al. (2021) in the central Pacific region of Guatemala. Additionally, the size at sexual maturity (L_{50}) has been estimated at 24.5

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cm standard length (SL) in females and 23.6 cm SL for males along the coast of Nayarit (Carrillo-Isiordia et al. 2023). Meanwhile, on the coast of Mazatlán, a L_{50} of 24.48 cm SL has been recorded (Sánchez-Valdez et al. 2024), while in the central Pacific of Guatemala, a L_{50} of 30.5 cm total length (TL) for females and 31.3 cm TL for males has been documented (Ortiz et al. 2021). The maximum recorded size for males is 90 cm TL (Fisher et al. 1995, Robertson et al. 2024).

However, in the case of the striped croaker, *C. reticulatus*, no data on age or individual growth allow us to understand the age at which they reach sexual maturity because most reports on sizes come from artisanal fisheries, which capture few organisms in the juvenile phase (with sizes less than 23 cm TL) and show a higher frequency of adult individuals, whose sizes range between 29 and 38 cm TL (Ortiz et al. 2021). The maximum size recorded for males is 90 cm TL (Fisher et al. 1995, Robertson et al. 2024). These data are fundamental for understanding the biology and population dynamics of the striped croaker, which in turn is crucial for the sustainable management of this species.

Various population parameters provide relevant information for age/length structure models. However, due to these models' logistical complexity and economic cost, obtaining the necessary data can be challenging (Kumolu-Johnson & Ndimele 2010), particularly when obtaining high-quality information that enables accurate stock assessments and effective management recommendations. On the other hand, specimens' weight and size data provide rapid and easier access to information on growth, as they allow an estimation of relative growth and morphometric intra- and interpopulation comparisons (Tesch 1968, Delgadillo-Calvillo 2012).

Relative growth has historically been estimated using the potential model ($W = aL^b$), where the exponent b is used to define whether the proportions of the organism stay relatively the same (isometric, $b = 3$) when the organism has a lower growth rate than the body as whole (negative allometric, $b < 3$) or their weight increases at a faster rate than their length (positive allometric, $b > 3$). However, b has been shown to shift continuously or abruptly at specific points during the individual's lifespan (Froese 2006, Katsanevakis et al. 2007, Rabaoui et al. 2007). Several variables, like metabolic rate, reproduction, and critical survival events, affect the growth rate of the species (Wong et al. 2021).

Therefore, when investigating whether an organism exhibits more than one growth phase, it is critical not to choose *a priori* model without understanding the basic assumptions. For example, the classical linear model (L) assumes that allometry remains constant as body size increases ($b = b_1$ = constant) (Rabaoui et al. 2007, Rodríguez-Domínguez et al. 2018). However, the growth pattern of fish tends to vary according to their life history characteristics (McCann & Shuter 1997). Therefore, Ricker (1975) points out that fish experience abrupt changes in their growth during early ontogeny (less than two years). Therefore, it is necessary to integrate data on size and weight from the early stages of development to adulthood to understand the factors that influence these ontogenetic changes.

In this sense, other models can describe different growth patterns in organisms. For example, the quadratic (Q) and cubic (C) models assume that there is non-linearity in the relationship between Ln Y and Ln L and that b changes continuously with increasing body size. On the other hand, the broken line and two-segment (TS) models assume a marked morphological change at a specific size $L = B$. The BS model depicts two straight-line segments with different slopes intersecting at $L = B$. In contrast, the TS model depicts two straight line segments that do not intersect, indicating a discontinuity point at $L = B$, where the slopes of the segments (i.e. b) may be the same or different (Rabaoui et al. 2007). Finally, the three-segment (ThS) and four-segment (FS) models assume that b takes three or four constant values (b_1, b_2, b_3, and b_4, respectively) between two or three breakpoints (B_1, B_2, and B_3).

The usage of several models (e.g. cubic, linear, quadratic, broken line, two- and three-segments) and evaluation techniques (information theory) (Burnham & Anderson 2002, Katsanevakis et al. 2007, Rodríguez-Domínguez et al. 2018) for relative growth, helps to reduce uncertainty and increase the precision of estimates. Some of them consider more than one stage of relative growth, allowing for a greater understanding of the reflection of biological processes that organisms exhibit throughout their lives in terms of the length-weight relationship.

In this regard, weight-length relationships are valuable tools for converting lengths into biomass, assessing fish conditions, and comparing growth in different areas (Froese 2006, Froese et al. 2011). These relationships consider, on the one hand, the early development of the species and, on the other, reproductive physiology as possible determinants of changes in growth (Ricker 1975, Fontoura et al. 2010). Furthermore, in fisheries lacking historical catch records, these relationships help to predict biomass and determine indicators of the current state of the fishery using data-poor stock assessment models, such as length-based models (Zhang & Megrey 2010).

The present study seeks to identify possible changes in the relative growth of *C. reticulatus* associated with ontogenetic development (sexual maturity) to use as input data in fishery modeling to increase precision in stock assessment (catch at size-structured models). In this way, the strength of this approach applied to population dynamics and fisheries management is twofold: 1) identifying relevant inflection points in the development of organisms, which, as demonstrated in the present work, can be taken as indirect estimates of the mean size at sexual maturity when there is no information on the gonadal stage at the size of the organisms to be analyzed; 2) when using size-structured biomass estimation models (e.g. catch-at-size), a common procedure is to estimate the weights of organisms based on allometric values (a and b), where organisms are traditionally assumed to have a constant relative growth rate throughout their development. However, this approach allows for the generation of specific allometric values for the different developmental stages of each species, thereby enabling more accurate estimates of spawning or recruit biomass, which directly leads to the ability to establish more realistic catch quotas. Now, considering that the reproductive process entails a high energetic cost and causes a decrease in the relative growth rate (McCann & Shuter 1997), we hypothesized that *C. reticulatus* would present two growth phases, with an inflection point associated with the average size at sexual maturity.

The information obtained here fills the gaps in the biological information of an economically important resource in the tropical eastern Pacific coasts. It could reinforce fishery regulation measures with precise information on the length-weight relationship at different maturity rates.

MATERIALS AND METHODS

Sampling

An average of 22 specimens were collected monthly from December 2020 to December 2021 from artisanal commercial fishery landings at the Port of Mazatlán, Sinaloa. The fleet operates from Barras de Piaxtla (23°36'N, 106°54'W) to Chametla (22°45'N, 106°02'W) and uses two fishing gears: 1) 300-m long gillnets with 3 to 3.5" mesh size, and 2) 900-m long by 70-m deep bottom longlines with 12/0 circular hooks (Mustad 39960-D). For each specimen, the total length (TL, cm) and total weight (TW, g) were recorded. Then, sex was assigned after visual confirmation of gonadal morpho-chromatic characteristics.

Parameter estimation and model selection

The length and weight outliers were reduced through logarithmic transformation to evaluate the relative growth of the species. Data conditions were compiled a priori to each selected model (Table 1). The parameters for each model are as follows: lineal model: a_1 and b_1. Broken line: a_1, b_1, b_2 and B_1. Three-segment model: $a_1, a_2, a_3, b_1, b_3, b_4, B_1, and\ B_2$ $a$djusted in the models, and "B" values are the inflection points of two linear trends with different slopes (Rodríguez-Domínguez et al. 2018). The parameters a and b in a simple linear regression typically represent the intercept and slope, respectively. The intercept reflects the body shape and condition of the organism, while the slope indicates the relative growth rate. These parameters are derived from length and weight data that have been linearized through a logarithmic transformation (Froese 2006). The B values represent the size at the inflection point between different trends in relative growth or allometry. The inflection point (B) distinguishes a change in the trends of relative growth associated with biological processes related to reproductive development.

The allometric parameter estimators (θ) were obtained by adjusting the models to the total linearized length-weight data, minimizing the negative logarithm of maximum likelihood, and assuming a normal probability distribution through Newton's direct search algorithm (Eq. 1).

$$-lnLl = -\sum_{i=1}^{n} ln\left(\frac{1}{\sqrt{2\pi\sigma^2}}exp^{\left(-\frac{(Pt_i-Pt_{est})^2}{2\sigma^2}\right)}\right) \quad (1)$$

Once the models were adjusted and the most probable parameters given the data were obtained, we estimated the allometric values for each TL value for each model (Table 2). Once each b value was estimated for each TL_i value, a graph was created for each evaluated model.

Selection of the best-fit model and confidence intervals

The best-fit model was selected based on the Akaike information criterion (AIC) corrected for small samples (AIC_c) (Burnham & Anderson 2002) (Eq. 2), which considers that the model with the lowest AIC_c (AIC_{cmin}) is the best fit to describe relative growth.

Table 1. Candidate models for evaluating the length-weight relationship in the striped croaker *C. reticulatus* off the coast of southern Sinaloa.

Model	Equation
Linear	$ln(TW) = a + bln(TL)$
Broken line	$ln(TW) = a + bln(TL)\ si\ x < B\ y\ ln(TW) = a_2 + b_2 ln(TL) si\ x > B$
Three-segment	$ln(TW) = a_1 + b_1 ln(TL) si\ x < B_1, ln(TW) = a_2 + b_2\ ln(TL) si\ x\ B_1 < x > B_2\ yln(TL)$ $= a_3 + b_3 ln(TL) si\ B_1 > B_2$

Table 2. Arithmetic equations to estimate allometric coefficients based on the multimodel estimate of the striped croaker *C. reticulatus* length-weight relationship off the southern Sinaloa coast. $b_1, b_2\ and\ b_3$: estimated parameters from every model, and $B, B_1, and\ B_2$ values: inflection points of two linear trends with different slopes (Rodríguez-Domínguez et al. 2018).

Model	Equation
Linear	$b = b_1$
Broken line	$b_1 < B > b_2$
Three-segment	$b_1 < B_1 > b_2 < B_2 > b_3$

$$AIC_c = ((-2lnLl) + (2k)) + (2 \times k \times (k+1))/(n-k-1) \quad (2)$$

where -$lnLl$ is the likelihood value resulting from each adjusted model, and k is the number of parameters in the model.

The AIC_i ($\Delta_i = AIC_{ci}$-$AIC_{mcmin\ \mathrm{mc}}$) differences were estimated to evaluate the statistical significance for each model. From a series of eigenvectors, a range was created: Δ_i values under 2 have a strong statistical significance, and models with Δ_i values between 4 and 7 have intermediate statistical signal, and Δ_i values above 10 have no statistical significance and should be omitted from the analysis.

Once the model with the lowest AIC_c value was identified, the 95% confidence intervals (% CI) of the "B_i" estimate (size at the inflection point) were calculated based on the likelihood profile calculation, assuming a χ^2 distribution with m degrees of freedom (Polacheck et al. 1993) (Eq. 3).

$$CI = 2\left[L\left(\frac{y}{P}\right) - (L(\frac{y}{P_{est}})\right] \le x^2_{1,1-\alpha} \quad (3)$$

where $L\left(\frac{y}{P}\right)$ is the negative likelihood logarithm of the most probable value of the parameter, $L\left(\frac{y}{P_{est}}\right)$ is the negative likelihood logarithm of the parameter within the likelihood profile, and $x^2_{1,1-\alpha}$ is the value of the x^2 distribution at a 1-α (α = 0.05) confidence level and (df = 1) degree of freedom.

Influence of sexual maturity on the relative growth of *C. reticulatus*

Comparations were done between the average size at sexual maturity (L_{50} = 27.5 cm; 95% CI = 14.52-40.46 cm) estimated by Sánchez-Valdez (2024) and the present study (best-selected model) accurately described the changes in the relative growth of the striped croaker, which will allow us to compare the size where the inflection point in the species' relative growth occurred, using the Student's *t*-test (Zar 2000), considering each size as a mean and the confidence estimates of each parameter as the variance. Suppose no differences between the two evaluated samples are identified. In that case, it is considered that the potential changes in the dynamics of relative growth are directly influenced by the recruitment of specimens to the spawning stock or parent population.

RESULTS

Sampling

Two hundred and eighty-four *C. reticulatus* specimens were captured in one-year sampling (Table 3); however, five organisms did not meet the criteria to be selected, as lacerations in the body affected the measures of length and weight, 53% of specimens (n = 148) were males and 47% (n = 131) were females. Males ranged in size between 28.4 and 49.4 cm TL, with a mean of 38.88 cm (Fig. 1a), while females ranged in size between 29.9 and 49.2 cm TL, with a mean of 38.22 cm (Fig. 1b). For the weights, males ranged between 225 and 1,104.8 g TW, with an average of 586.84 g (Fig. 1e) and females ranged between 225 and 1,157 g TW, with a mean of 546.8 g (Fig. 1f).

Relative growth and inflection points

Apart from the male three-segment model, all results were able to predict the species' growth. Results showed that models over two segments exceed the species' growth stages and do not reflect their biological

Table 3. Number of *C. reticulatus* organisms obtained per month in the southern coast of Sinaloa.

2020	December	40
2021	January	0
	February	30
	March	12
	April	33
	May	34
	June	0
	July	25
	August	25
	September	16
	October	30
	November	27
	December	12

meaning. For this reason, the male three-segment model was excluded from *a posteriori* analyses (Table 4, Fig. 2).

The results showed similar values to the inflection points. The broken line model identified the inflection point at 34.2 and 33.3 cm TL for males and females, respectively. The female three-segment model identified two inflection points, one at 32.5 cm TL and the second at 44.7 cm TL (Fig. 2).

Selection of the best-fit model and confidence intervals

There was a difference in sex for the best-fit model; for males, the linear model had the lowest AICc value. The results showed that the relative growth of males stays constant throughout their ontogenetic development, with a negative allometric value ($b = 2.82$). Similar results were given by the broken line model whose AICc values were close to the linear model, $b = 3.25$ at sizes up to 34.2 cm TL; at larger sizes, allometry decreased to a value of $b = 2.74$. The best-fit model for females was the broken line model, which showed an important change, with positive allometry at $b = 4.36$ at sizes up to 33.3 cm TL; at larger sizes, allometry decreased substantially down to $b = 2.75$, with negative allometry. Similar results were found in the linear model ($b = 2.81$). Considering that the broken line model better described the allometric coefficient, confidence intervals were calculated for the inflection point. The confidence intervals for $b = 3.33$ cm TL were 33.08 to 33.55 cm TL.

Analysis of the relationship between allometric changes and average size at sexual maturity

There were no significant differences in the L_{50} and the size at the point of inflection (B) for females ($t = -0.77665$, $P = 0.5186$). Although the range of values compared differed considerably, the results should be kept the same; they should be used cautiously.

DISCUSSION

Results reinforced the previous hypothesis that both sexes of *C. reticulatus* have two growth phases: positive allometric growth (prior to the first reproductive event) and negative allometric growth. These results point directly to the reproductive physiology of this species. No significant differences were found when comparing the inflection point determined with the broken line model and the L_{50} of females.

There were changes in the relative growth of the striped croaker during ontogenetic development. Positive allometry was detected in males at sizes up to 34.2 cm TL and negative allometry at larger sizes. The same pattern was detected in females (b < at 33.2). These results suggest a significant weight increase in *C. reticulatus* in preparation for the reproductive event before the inflection point; it could be seen as energy accumulation (Grau et al. 2009, Militelli et al. 2013). This growth pattern seems to be repeated in the *Cynoscion* genus: Ortiz et al. (2021) reported negative allometric growth for females and isometric growth for males in Guatemala; In Mexico, Bautista-Romero et al. (2012) reported negative allometric growth for Oaxaca; and Nieto-Navarro et al. (2010) and Torrescano-Castro et al. (2016), reported isometric growth for the southern part of Sinaloa and Nayarit. Also, two types of growth have been reported for the Gulf croaker (*C. othonopterus*): depensatory growth in the first years of life and compensatory growth after the inflection point (Mendoza-Mendivil 2020). However, the potential model describes the growth, and it does not identify inflection or cut-off points that indicate changes in growth (Ricker 1975, Katsanevakis et al. 2007, Rabaoui et al. 2007).

The two-phase growth in the *Cynoscion* genus could explained by the decompensatory and compensatory growth; the first phenomenon is presented when variability in length increases with time or age, and the second when variability in length decreases with time or age (Gurney et al. 2007). In the case of the striped croaker *C. reticulatus*, energy is channeled towards gonadal development during the organism's first reproductive event; this process decreases somatic growth because energy resources are finite (Wootton 1992) leading to a permanent compensation between

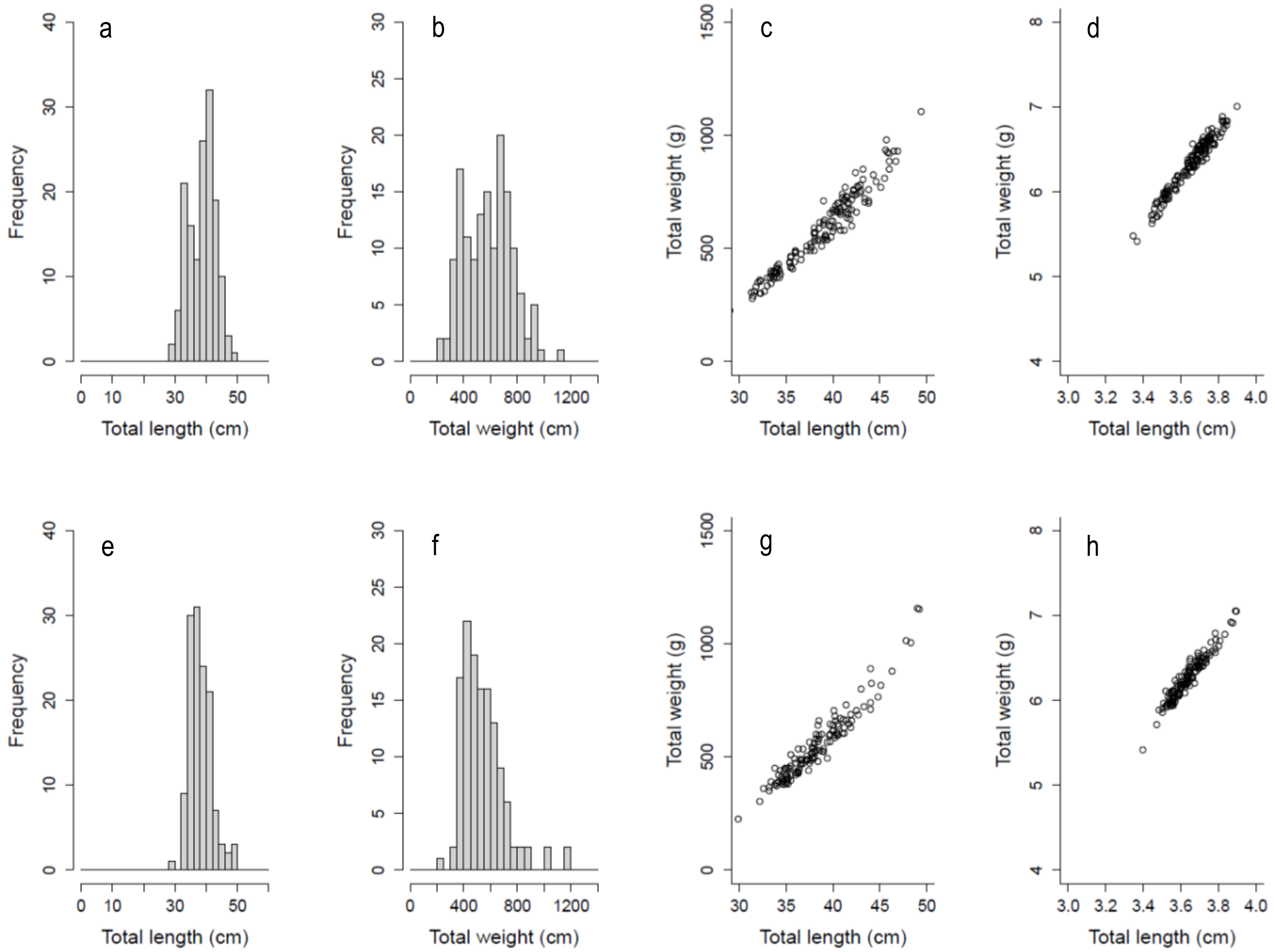

Figure 1. Size structure of a) males and e) females, weight structure of b) males and f) females, length-weight data dispersion for c) males and g) females, length-weight linearized (ln) data dispersion for d) males and h) females, of the striped croaker *C. reticulatus* in southern Sinaloa.

Table 4. Estimates were obtained from the fit in each model and the selection of the best growth model by sex for the striped croaker, *C. reticulatus*, in southern Sinaloa. $a_1, a_2, a_3, b_1, b_2, b_3, B_1$ and B_2: estimated parameters from every model evaluated, $-lnLl$: likelihood value resulting from each adjusted model, k: number of parameters in the model, AIC$_c$: small sample Akaike results, and ΔAIC$_c$: Akaike differences.

Sex	Model	a_1	a_2	a_3	b_1	b_2	b_3	B_1	B_2	$-lnLl$	AIC$_c$	ΔAIC$_c$
Males	Linear	3.982			2.821					21.633	25.72	0.00
	Broken line	5.483			3.250	2.740		3.532		19.716	25.88	0.17
	Three-segment	4.494	5.411	6.382	2.964	3.202	3.439	3.722	3.777	15.795	28.39	2.67
Females	Linear	3.953			2.809					24.476	28.56	1.56
	Broken line	9.381			4.360	2.755		3.506		20.828	26.99	0.00
	Three-segment	8.141	3.632	9.054	3.990	2.721	4.131	3.480	3.800	18.211	30.81	3.81

growth and reproduction (Jones & Johnston 1977, Ware 1980, 1982, Browne 1982, Roff 1983, Reznick 1985, Winemiller & Rose 1992, Enberg et al. 2012, Folkvord et al. 2014). However, some marine teleost fish can modify their growth rate as a function of their environment's biotic and abiotic conditions; this phenomenon is called "countergradient variation" and allows the fish to adapt somatic development to environmental conditions (Salgado-Cruz 2020).

In the case of *C. reticulatus*, we can associate the allometric growth rate (inflection point) change with an important physiological change, such as the organisms

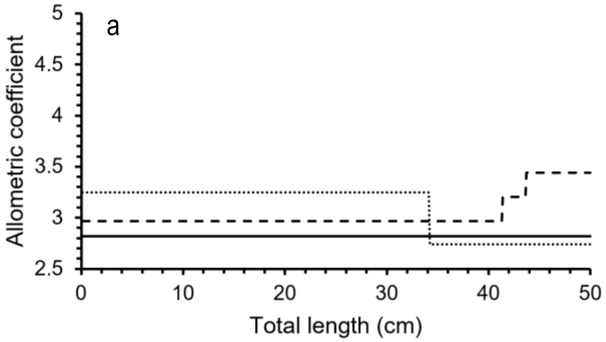

Figure 2. Allometric coefficients by size estimated for each candidate model for *C. reticulatus* a) males and b) females off the southern Sinaloa coast. The solid line represents the linear model, the broken line represents the broken line model, and the dashed line represents the three-segment model.

reaching sexual maturity. Although many factors can indeed modify the size or timing of reproductive processes, authors such as Rowe et al. (1991), Hutchings & Jones (1998), and Dufour et al. (1999) suggest that body growth and energy reserve accumulation act as one of the first indicators of the onset of the pre-maturity stage. These changes are perceptible in the present study through the analysis of relative growth in the species, as there is undoubtedly a shift in energy allocation during this stage. Once the first reproductive event begins, energy is redirected towards gonadal development, a process that reduces somatic growth and triggers a permanent trade-off between growth and reproduction (Jones & Johnston 1977, Ware 1980, 1982, Browne 1982, Roff 1983, Reznick 1985, Winemiller & Rose 1992). Specifically, energy is allocated to oogenesis in females and spermatogenesis in males (Salgado-Cruz 2020), both complex processes. For teleost fish, oogenesis in females can be divided into four phases: 1) primary growth, 2) cortical alveoli formation, 3) vitellogenesis, and 4) maturation (Wallace & Selman 1981, Tyler & Sumpter 1996), while male spermatogenesis is divided into three phases: 1) mitotic phase, 2) meiotic phase, and 3) spermiogenic phase (Nóbrega et al. 2009).

The processes described above require significant energy (Salgado-Cruz 2020), and sexual maturation is the reproductive parameter most commonly used in traditional population assessment models. It is considered the trait expected to have the greatest impact on an organism's fitness (Stearns 1992). For this reason, there is increasing evidence that, in most marine teleost species, somatic growth and reproduction are closely related (Le Gac et al. 1993).

However, while the results of this study are interesting, it is important to acknowledge the limitations of studies such as this one. In this case, this study is based on fishery-dependent data; therefore, the fishing gear determines the data. It is more frequent in large mature organisms than in immature ones (<L_{50}). The first stage of ontogenetic development might not be fully represented since the number of organisms below 30 cm is low compared to those above this size. Therefore, the results must take this consideration into account.

When comparing the mean size of sexual maturity *vs*. the inflection point in relative growth for the females of this species, the confidence intervals for each estimate (used in this case as measures of dispersion for each estimate) differ widely. Although the estimates for both parameters are very similar, the difference in the amplitude of one estimate may obscure the other, resulting in the inability to identify significant differences. The next step will be to conduct targeted sampling to evaluate this relationship more deeply in this and other associated species.

Although allometry is a less studied parameter than others, it is important to remember that allometry can decrease drastically in both sexes at certain sizes. An appropriate model is needed to describe each stage during ontogenetic development (Katsanevakis et al. 2007, Espino-Barr et al. 2008) or to identify differences in relative growth between phenotypes, as individuals can exhibit different growth patterns in response to environmental factors (phenotypic plasticity) (Lorenzen 2016).

Therefore, we highlight in the present study the importance of using multimodel inference to select the best-fit model to describe growth, avoiding the *a priori* selection of a model (potential model), and the information provided here can be used to complement and evaluate the stock of striped croaker to create regulation measures promptly, as this species continues to increase in importance in the socio-economic tendencies of the Mexican coastal fishery catches.

Credit author contribution

M. Ruiz-Domínguez: conceptualization, formal analysis, methodology, supervision, validation, visualization, writing - original draft; M. de los Á. Maldonado-Amparo: data curation, methodology, writing - review & editing; J.Á. Payán-Alcacio: writing - original draft, writing - review & editing; J.A. Maldonado-Coyac: data curation, methodology, writing - original draft, writing - review & editing.

Conflict of interest

The authors declare no potential conflict of interest in this manuscript.

Data availibity

Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

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