

# Determination of spawning stock-recruitment relationships of Bigeye croaker *Micropogonias megalops* in the Gulf of California based on a multi-model inference approach

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Received 26 June 2024 / Accepted 18 July 2025

Handling Editor: Dr. Verena Trenkel

**Abstract** – Determining the relationship between spawning stock biomass and recruitment (*SS-R*) in exploited populations is one of the most important biological and ecological aspects for sustainable management. It requires identification of optimal models that qualitatively and quantitatively represents this relationship for specific stocks. In the present study, annual *SS-R* abundance data (1995–2020) for Bigeye croaker *Micropogonias megalops* in the Gulf of California were analyzed using a multi-model approach. Time series of different lengths were used for model fitting to examine how time series lengths influenced *SS-R* estimation. The tested models were: Beverton-Holt, Ricker, Cushing and Shepherd, which have structural differences and are frequently used in fisheries science. Results showed that there is no single ‘best’ model to describe the *SS-R* relationship of the species. However, there were models with relative higher descriptive power such as the Cushing and Shepherd density-dependent models according to the Akaike Information Criterion; the difference between models was more evident for longer time series (18 to 26 yr). Mean recruitment was similar for all models in each time series, ranging from 57.76 to 58.23 million individuals in the full 1995–2020 series. Recruitment was variable with a positive trend over time, showing lowest levels in 2002 and highest in 2010 and 2015. Estimates of the *steepness* parameter ranged from  $h=0.25$  to 0.29. The multi-model approach helped to better understand the *SS-R* relationship of *M. megalops*, which can be considered for subsequent fishery assessments and management decisions.

**Keywords:** Spawning stock / recruitment / information theory / fishery / management

## 1 Introduction

The relationship between spawning stock biomass and number of offspring, also called spawning stock (*SS*)-recruitment (*R*) relationship (*SS-R*), is one of the most important biological aspects of fisheries management (Britten et al., 2016; Skoglund et al., 2022). The relationship is the

basis of management decisions, abundance predictions and sustainability of harvested populations (Doll and Jacquemin, 2019). Globally, determination of *SS-R* has become one of the key ecological aspects, but also, one of the most difficult to obtain for exploited species (Zhu et al., 2012; Maunder and Thorson, 2019).

Regularly, *SS-R* of a given population is described through mathematical models (Yang and Yamakawa, 2022), among which the Beverton and Holt (1957) and Ricker (1975) models are the most frequently used ones (Shertzer and Conn, 2012).

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Beverton-Holt (B-H) describes an asymptotic compensatory relationship, involving intraspecific competition for resources, while Ricker defines a dome-shaped relationship, with an overcompensation effect that may be induced by cannibalism in the population (Acha et al., 2012). There are other less used models such as Cushing, Shepherd and Gamma, which present their own structural characteristics and descriptive power for population abundance data (Doll and Jacquemin, 2019).

For *SS-R* analysis, biomass series of spawning stock and recruits are used, which can be catch observations and age/length abundance estimates, such as those obtained from Virtual Population Analysis (VPA) (Yang and Yamakawa, 2022). The models that best describe a given *SS-R* data set are specific to each population. Therefore, population specific model selection is important to estimate recruitment and to determine management and conservation measures (Cury et al., 2014; Skoglund et al., 2022). Ecologically, the *SS-R* relationship of marine fish may depend on environmental conditions such as temperature and food availability during early life stages (Olsen et al., 2011; Acha et al., 2012). In addition, changes in recruitment over time are related to variables such as temperature, chlorophyll concentration and overfishing (Zhu et al., 2012; Britten et al., 2016). But also, there is evidence that recruit abundance is not entirely stochastic and can be determined by spawning stock size (Shertzer and Conn, 2012; Cury et al., 2014). For this reason, nonlinear functions assuming density-dependence may be adequate to describe *SS-R* relationships for demersal stocks with tendency to reaching an equilibrium or carrying capacity for recruitment (Ouyang et al., 2023).

Recently, *SS-R* estimates have been performed using a meta-analysis approach, where multiple fish stocks worldwide were included (Yang and Yamakawa, 2022). However, results of average stock relationships may not represent well particular stocks (Shertzer and Conn, 2012; Yang and Yamakawa, 2022). Using such general relationships would be potentially counterproductive for specific resource management, as the quantitative information and biological interpretation of a general *SS-R* relationship may be unreliable. Therefore, in order to provide information on *SS-R* and recruitment variability for specific resource management, their assessments must also be stock specific (Maunder and Thorson, 2019; Skoglund et al., 2022). An alternative to reduce uncertainty of meta-analyses, and simultaneously identify an optimal *SS-R* function for a particular stock, is the multi-model inference approach. This methodology considers several functions and uses statistical information criteria to select the ‘best’ model (Burnham and Anderson, 2002; Katsanevakis and Maravelias, 2008; Burnham et al., 2011). As a result, estimates and biological interpretation are stock specific.

This study analyzes *SS-R* data for Bigeye croaker *Micropogonias megalops* (Gilbert, 1890), a demersal fish species endemic to the Gulf of California, mainly concentrated in the north of the region (NGC) (Froese and Pauly, 2023). Its reproduction period and major availability to fishing is March–August. However, mature females are present at all times and continuous recruitment can occur (Arzola-Sotelo et al., 2018). The species is caught commercially by the artisanal fleet, finfish fleet and occasionally appears as bycatch of shrimp trawlers (Ramírez-Rodríguez, 2017; Arzola-Sotelo et al., 2018, 2022). The fishery began in the 1990s due to the interest by the surimi industry in Southeast Asia, and currently continues

to contribute raw material to this industry (Aragón-Noriega et al., 2010; Tirado-Pineda, 2019; Arzola-Sotelo, 2024). The Bigeye croaker fishery has been important in terms of catch volume, economic value and continues as one of the few alternatives with constant incentives and positive impacts for society in the NGC (Aragón-Noriega et al., 2015; Arzola-Sotelo et al., 2022). This is in spite of ecological problems in the NGC leading to protection measures and fishing prohibition in several areas of the region (Erisman et al., 2015; Arzola-Sotelo et al., 2018). The measures are part of the Mexican Government’s strategy to reduce incidental mortality of vaquita (*Phocoena sinus* Norris and McFarland, 1958) by illegal fishing activities targeting totoaba *Totoaba macdonaldi* (Gilbert, 1890) (Rodríguez-Quiroz et al., 2019).

Despite the economic and social importance of Bigeye croaker, this fishery has been characterized by a lack of specific management rules and, until recently, current stock biological-fishing aspects and abundance were unknown (Arzola-Sotelo et al., 2018, 2022). Recent studies addressed aspects of its population dynamics such as growth, reproduction, mortality and status, finding that the population maintains high abundance and good stock condition (Arzola-Sotelo et al., 2022; Urias-Sotomayor et al., 2022). However, the *SS-R* relationship of *M. megalops* is still unknown and its determination could contribute valuable information for fisheries management. A first attempt of analyzing the species’ recruitment has been conducted considering different scenarios of natural mortality and exploitation in a Stock Reduction Analysis, which assumes recruitment is constant over time (Urias-Sotomayor et al., 2022).

In this work, four *SS-R* models were fitted to Bigeye croaker *SS* and *R* abundances which were estimated through Length Cohort Analysis (LCA) for the period 1995–2020. The ‘best’ fitting models, curve shapes and parameters values were explored using a multi-model inference approach (MMI). In addition, annual recruitment was estimated based on the ‘best’ fitting *SS-R* model of the species. Resampling the data, the effect of the length of the time series was explored to ensure robustness of conclusions.

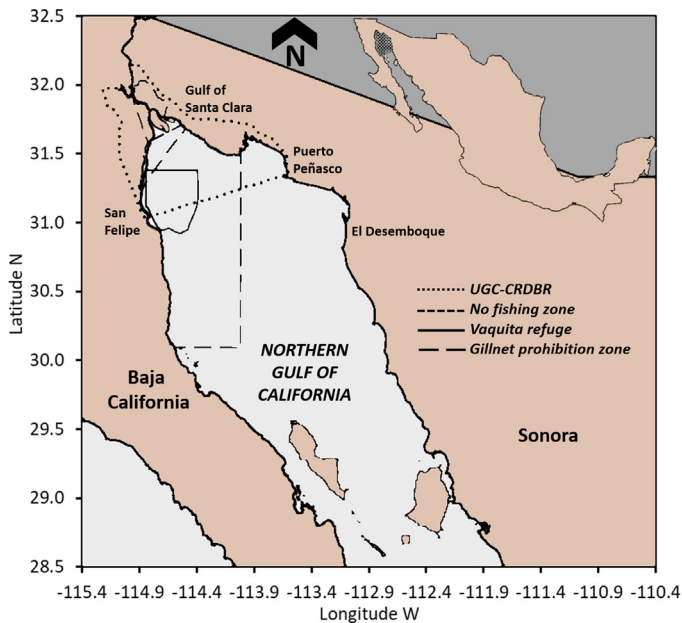
## 2 Materials and methods

### 2.1 Study area

The study area corresponds to the northern region of the Gulf of California (NGC) (Fig. 1), between limits 31.755–28.998° N and 114.904–112.156° W. This is an area of 60 thousand km<sup>2</sup> with average depth of 200 m (Brusca et al., 2017). Climate is temperate, characteristic of the California Province, which is a bioregion of relatively cold waters (23.43 °C) and high eutrophic type (1.81 mg/m<sup>3</sup>) compared to the rest of the gulf (López-Martínez et al., 2023). The NGC is a highly productive area that supports several of the most important fisheries in Mexico, including the Bigeye croaker *Micropogonias megalops* fishery (Erisman et al., 2015; Brusca et al., 2017).

### 2.2 Catches

Annual catch data (tons) of *M. megalops* (1995–2020) were obtained from artisanal fleets (small boats) and industrial fleets (fin-fishing boats and shrimp trawlers) from different sources:



**Fig. 1.** Sampling area of Bigeye croaker *Micropogonias megalops*, where commercial fishing grounds are located in NGC. UGC-CRDBR: Upper Gulf of California and Colorado River Delta Biosphere Reserve.

Aragón-Noriega et al. (2010), Rodríguez-Quiroz et al. (2010) and Tirado-Pineda (2019). In addition, databases of the National Commission of Fisheries and Aquaculture (CONAPESCA), the Secretariat of Agriculture, Livestock, Water Resources, Fisheries and Aquaculture (SAGARHPA), the Office of Agricultural and Livestock and Fisheries Information System of the State of Sonora (OIAPEs), and the Agrifood and Fisheries Information Service (SIAP) were consulted as well as catch data from arrival records of fishing offices in Puerto Peñasco and Golfo de Santa Clara, Sonora, Mexico (2014–2020).

### 2.3 Biological data and analysis

Biological information was obtained on *M. megalops* individuals from commercial catches from artisanal and industrial fisheries in NGC. Specifically, for the years 2010–2012 and 2020, biological data consisted of total length ( $TL$ , mm) and total weight ( $TW$ , g). Additionally,  $TL$  and  $TW$  data for 1996–1999 reported by Román-Rodríguez (2000) and available in the CONABIO database (Data Bank, SNIB-CONABIO) were used: <http://www.conabio.gob.mx/institucion/cgi-bin/datos.cgi?Letras=L&Numero=298>.  $TL$ - $TW$  relationships were obtained by nonlinear estimation:

$$TW = a * TL^b \quad (1)$$

Where  $TW$  is individual total weight in g,  $TL$  is total length in mm,  $a$  is a constant and  $b$  is the growth coefficient. If  $b=3$  growth is isometric and if  $b \neq 3$  growth is allometric (Ricker, 1975; Bagenal and Tesch, 1978). A Student  $t$ -test was performed to determine whether  $b$  was significantly different from isometric growth (Zar, 1999). Length frequency

distributions and biometric relationships were assumed as constant for nearby years to those with biological information in the time series (1995–2020). Thus, the 1996 information was assumed and applied to 1995, the 1999 to 2000–2005, the 2010 to 2006–2009, the 2012 to 2013–2015, and the 2020 to 2016–2019.

### 2.4 Abundance-at-length estimates

Abundances per length class ( $TL$ ) of *M. megalops* for each year (1995–2020) were obtained through Jones Length Cohort Analysis (LCA) (Jones, 1981; Quinn and Deriso, 1999). This is a length-based virtual population analysis, and determines abundance and fishing mortality at each length, as well as recruitment (Blackhart et al., 2006). The analysis used frequency distributions for  $TL$  intervals and their corresponding average weight obtained through the species  $TL$ - $TW$  relationship. Here,  $W_{sample_i}$  is the summed weight of observed individuals in each year, which jointly with the annual catch weight was used to obtain the scaling factor following the equation:

$$EF_i = \frac{W_{catch_i}}{W_{sample_i}} \quad (2)$$

$W_{catch}$  is total catch weight in year  $i$  and  $W_{sample_i}$  is weight of the population sample in year  $i$ . The scaling factor was applied to the frequency of each  $TL$  interval, thus obtaining the number of individuals for each  $TL$  in the catch ( $C_i$ ). These values were used by LCA to estimate the total abundance in number of individuals and biomass at length for each year in the time series (López-Martínez et al., 2020).

Natural mortality ( $M$ ) and length at first sexual maturity ( $L_{50}$ ) values used for estimation were obtained from Arzola-Sotelo et al. (2022), who estimated overall values for Bigeye croaker during 2000, 2010 and 2020. Here,  $M$  and  $L_{50}$  were also assumed constant for all length classes in year  $i$  and for nearby years to those with estimates: 2000 (1995–2005), 2010 (2006–2015) and 2020 (2016–2019). Annual spawning stock abundance ( $SS$ ) of *M. megalops* was obtained by summing the biomass of individuals with  $TL \geq L_{50}$  (2000 = 409.45, 2010 = 357.87 and 2020 = 367.51 mm). Respectively, recruitment ( $R$ ) was obtained by the sum of individuals with  $TL \leq 173.64$ , 223.39 and 182.63 mm, corresponding to an age of less than one year according to the species growth parameters reported by Arzola-Sotelo et al. (2022) and the inverse von Bertalanffy equation (Mackay and Moreau, 1990).

### 2.5 Studying the effects of time series length

In order to analyze the effect of the length of the time series on  $SS$ - $R$  relationship estimation, data set simulations based on Bigeye croaker information were performed. For this, in addition to the full LCA  $SS$ - $R$  series from 1995–2020 (26 yr), series of 15, 16, 17, 18, 19, 20, 21, 22, 23, 24 and 25 yr were obtained and analyzed. This to denote time series lengths where convergence of results and, therefore, certainty in the determination of the species  $SS$ - $R$  relationship is achieved.

## 2.6 Determination of spawning stock-recruitment relationships

To determine the ‘best’ spawning stock ( $SS$ ) and recruitment ( $R$ ) relationship ( $SS$ - $R$ ) for *M. megalops*, a multi-model (MMI) selection approach was performed. For this  $SS$  (tons) and  $R$  (individuals) data from the full LCA 1995–2020 time series (26 yr) and for different time series lengths (15 to 25 yr) were used (Burnham and Anderson, 2002; Burnham et al., 2011). Four  $SS$ - $R$  models were included, which present different curves and are commonly used in fisheries management and ecology (Ricker, 1975). Models and parameters, curve trajectories and theoretical bases are described below according to Doll and Jacquemin (2019). The first model was Beverton-Holt B-H, which incorporates density-dependent effects within a species life stage for population size regulation:

$$R = \frac{\alpha * SS}{1 + \beta * SS} \quad (3)$$

Here and for subsequent  $SS$ - $R$  models,  $R$  refers to the number of recruits during the year ( $t + 1$ ),  $SS$  is the spawning stock,  $\alpha$  is interpreted as the productivity parameter and  $\beta$  is a control parameter on the level of density-dependence. B-H model projects linear increase in recruits as spawners increase until a density-dependent mechanism forces the relationship to an asymptote or maximum productivity.

The second model was Ricker, which incorporates density-independent mechanisms resulting in a negative response to recruitment. In this case, density-dependent effects may occur in situations where spawning stock inhibits juvenile fish prior to recruitment:

$$R = SS * e^{\alpha - \beta * SS} \quad (4)$$

It presents a dome-shaped curve, where maximum recruitment is a function of maximum spawning.

The third model was Cushing, which is a simple model with less influence of density-dependence:

$$R = \alpha * SS^\gamma \quad (5)$$

Here  $\gamma$  is a density-dependent index, when  $\gamma = 1$  model is linear with origin at 0, when  $\gamma > 1$  recruitment increases without reaching an asymptote and when  $\gamma < 1$  recruits approach an asymptote resulting from density-dependent effects.

Finally, the Shepherd model, which represents a generalization of the B-H, Ricker and Cushing functions:

$$R = \frac{\alpha * SS}{1 + \beta * SS^\gamma} \quad (6)$$

when  $\gamma = 1$  the model corresponds to B-H, when  $\gamma > 1$  it represents a dome-shaped model such as Ricker, and when  $\gamma < 1$  recruitment increases indefinitely as in a Cushing-type model.

Parameter estimation of  $SS$ - $R$  models was performed using a maximum likelihood approach (Haddon, 2011).  $SS$ - $R$  model selection was done using the Akaike Information Criterion in

its corrected version ( $AICc$ ) obtained by (Burnham and Anderson, 2002; Katsanevakis and Maravelias, 2008):

$$AICc = (2 * -LL) + (2 * \kappa) + \frac{2 * \kappa(\kappa + 1)}{n - \kappa - 1} \quad (7)$$

where  $\kappa$  is the number of parameters in each model.

$AICc$  differences ( $\Delta_m$ ) of each  $SS$ - $R$  model were given by:

$$\Delta_m = AICc_m - AICc_{min} \quad (8)$$

where  $AICc_{min}$  represents the  $AICc$  for the ‘best’  $SS$ - $R$  model among the candidates ( $AICc_m$ ). Models with  $\Delta_m < 2$  or  $\Delta_m < 7$  were considered competitive for  $SS$ - $R$  description (Burnham and Anderson, 2002; Burnham et al., 2011).

For each  $SS$ - $R$ , the probability that a given model was the ‘best’ among the set was obtained through Akaike weight ( $w_m$ ) given by (Burnham and Anderson, 2002):

$$w_m = \frac{\exp(-\frac{1}{2}\Delta_m)}{\sum_{m=1}^4 \exp(-\frac{1}{2}\Delta_m)} \quad (9)$$

For multi-model inference, model predictions were then averaged across models using the Akaike weights as weighting factors.

Confidence intervals (C.I. 95%) for model parameters were obtained by constructing likelihood profiles, using log likelihood values ( $LL$ ) and fitted parameters values (Hilborn and Mangel, 2013). All intervals were estimated based on  $\chi^2$  distributions (Zar, 1999). Confidence intervals were defined as all  $\theta$  values that satisfy the inequality:

$$2[LL(Y|\theta) - LL(Y|\theta_{best})] < \chi^2_{1,1-\alpha} \quad (10)$$

$LL(Y|\theta_{best})$  is the loglikelihood for the most probable value for each parameter in  $\theta$  and  $\chi^2_{1,1-\alpha}$  comes from a  $\chi^2$  distribution with 1 degree of freedom at confidence level of  $1-\alpha$ .

## 2.7 Interannual variation in recruitment

Interannual variation of recruitment ( $R_\theta$ ) was obtained by calculating standardized anomalies considering the estimates given by the ‘best’ models for full LCA time series (26 yr) and for different time series lengths (15 to 25 yr), using the following equation:

$$R_{\theta,i} = \frac{X_i - \mu}{\sigma} \quad (11)$$

$R_\theta$  is recruitment standardized anomaly in year  $i$ ;  $X_i$  is recruitment fitted value by the optimal model in year  $i$ ;  $\mu$  is mean recruitment value; and  $\sigma$  is the standard deviation of annual estimates (Arzola-Sotelo et al., 2022).

## 2.8 Steepness parameter estimation

In order to have some idea of how the *M. megalops* stock responded to fishing pressure during the study period, parameter *h aka steepness* was estimated, defined as spawning

**Table 1.** Parameters and fitted values of total length (*TL*)-total weight (*TW*) relationship of Bigeye croaker *Micropogonias megalops* in NGC. Value of *a* is equation slope, *b* growth coefficient and its confidence interval (95%), *R*<sup>2</sup> is coefficient of determination, *P* value is probability value of Student's *t*-test, and Growth type according to allometry test: I stand for isometric growth and A+ for positive allometric growth.

| Year | <i>n</i> | <i>a</i>  | <i>b</i> | Lower <i>b</i> | Upper <i>b</i> | <i>R</i> <sup>2</sup> | Student's <i>t</i> test ( <i>P</i> value) | Growth |
|------|----------|-----------|----------|----------------|----------------|-----------------------|-------------------------------------------|--------|
| 1996 | 24       | 0.0000050 | 3.12     | 2.97           | 3.27           | 0.9876                | 0.11842                                   | I      |
| 1997 | 455      | 0.0000070 | 3.08     | 3.05           | 3.11           | 0.9889                | 0.00000                                   | A+     |
| 1998 | 485      | 0.0000100 | 3.00     | 2.97           | 3.03           | 0.9881                | 0.97931                                   | I      |
| 1999 | 35       | 0.0000070 | 3.07     | 2.78           | 3.35           | 0.9346                | 0.64372                                   | I      |
| 2010 | 126      | 0.0000008 | 3.44     | 3.33           | 3.55           | 0.9691                | 0.00000                                   | A+     |
| 2011 | 50       | 0.0000030 | 3.27     | 3.15           | 3.39           | 0.9841                | 0.00004                                   | A+     |
| 2012 | 618      | 0.0000200 | 2.96     | 2.86           | 3.05           | 0.8539                | 0.38196                                   | I      |
| 2020 | 238      | 0.0000040 | 3.17     | 3.14           | 3.19           | 0.9954                | 0.00000                                   | A+     |

biomass decrease to 20% of its unexploited level (Mangel et al., 2010; Haddon, 2011). For this, the B-H spawning stock-recruitment curve was reparametrized, now including the *h* parameter:

$$R = \frac{\alpha * (h * SS)}{1 + \beta * (h * SS)} \quad (12)$$

This reparametrized B-H *SS-R* model was fitted as described above for Bigeye croaker full LCA time series (26 yr) and for time series of different lengths (15 to 25 yr).

### 3 Results

#### 3.1 Fish biometrics and spawning stock-recruitment series

Length-weight (*TL-TW*) relationships were obtained for 2,031 individuals of *Micropogonias megalops* for the years 1996–1999, 2010–2012 and 2020. The mean value of growth coefficient was *b* = 3.137, showing two growth types over time, isometric (I) during 1996, 1998, 1999 and 2012, and positive allometric (A+) during 1997, 2010, 2011 and 2020 (Tab. 1). Fitted biometric relationships were applied to years with missing data: *TL-TW* values of 1996 were applied to 1995, 1999 to 2000–2005, 2010 to 2006–2009, 2012 to 2013–2015 and 2020 to 2016–2019.

Cumulative catch (1995–2020) was 93,433 tons, with annual mean of 3,593 tons and standard deviation (S.D.) of 3,201 t. Conversion of global catch in weight to number individuals resulted in 190.86 million specimens of Bigeye croaker. LCA estimated cumulative (1995–2020) total stock biomass of 787,670 tons and 3,817 million of individuals. Annual biomass estimates by length class were summed to obtain estimates for spawning stock (*SS*) (tons) and recruits (*R*) (individuals). Spawning stock biomass represented 30.88% (243,218 tons) of total biomass and 11.11% (424.30 million) of total individuals. Meanwhile, *R* represented 8.17% (64,336 tons) of total weight and 40.33% (1,539 million) of stock individuals. The remaining individuals (older than recruits but not yet mature) represented 60.75% in weight and 48.55% in numbers (Fig. 2).

From the full LCA time series (26 yr length), *SS-R* data pairs were obtained for the generation and analysis of different time series lengths, including: 1995–2020 (26 yr), 1996–2020 (25 yr), 1997–2020 (24 yr), 1998–2020 (23 yr), 1999–2020 (22 yr),



**Fig. 2.** Average stock structure (1995–2020) in weight and numbers of Bigeye croaker *Micropogonias megalops* in NGC from Jones Length Cohort Analysis (LCA).

2000–2020 (21 yr), 2001–2020 (20 yr), 2002–2020 (19 yr), 2003–2020 (18 yr), 2004–2020 (17 yr), 2005–2020 (16 yr) and 2006–2020 (15 yr).

#### 3.2 Multi-model inference approach

Four *SS-R* models were fitted to spawning stock and recruit abundance data from LCA series of different lengths (15 to 26 yr). For each time series, relationships were fitted in biomass for *SS* (tons) and numbers for *R* (ind). Parameter values for each model and confidence intervals (95%) for the full time series (1995–2020) are shown in Table 2. For the 15 yr length series, all models had similar descriptive power for the species *SS-R* data ( $\Delta_m < 2$ ), however, in the following time series (16 yr and longer), the Cushing and Shepherd models showed higher descriptive power (Tab. 3). The multi-model fitted curves and the ‘best’ model for the full LCA time series (1995–2020) are shown in Figure 3. All fitted models presented relatively close values of residual standard deviations ( $\sigma$ ) within each time series, but lower  $\sigma$  values for Cushing and Shepherd models and for longer time series lengths (Fig. 4).

#### 3.3 Annual recruitment estimates

Annual mean recruitment estimates showed similar values for all models withing each series length, but closer mean *R*

**Table 2.** Parameter values with confidence intervals (95%) obtained by likelihood profiles for each model for *Micropogonias megalops* in NGC. Output parameter values are shown for SS–R data for the full Jones Length Cohort Analysis (LCA) 1995–2020 time series (26 yr). Parameter  $\alpha$  is the number of recruits per spawner interpreted as the productivity parameter,  $\beta$  is a control parameter on the level of density-dependence, and  $\gamma$  is an index of density-dependence.

| Model and parameters | Value     | C.I. (95%) Inf. | C.I. (95%) Sup. |
|----------------------|-----------|-----------------|-----------------|
| B-H                  |           |                 |                 |
| $\alpha$             | 194.07    | 181.32          | 207.36          |
| $\beta$              | 18,583.77 | 16,625.06       | 20,525.45       |
| Ricker               |           |                 |                 |
| $\alpha$             | 0.010     | 0.009           | 0.011           |
| $\beta$              | 0.000     | 0.000           | 0.000           |
| Cushing              |           |                 |                 |
| $\alpha$             | 0.030     | 0.027           | 0.033           |
| $\gamma$             | 0.731     | 0.717           | 0.743           |
| Shepherd             |           |                 |                 |
| $\alpha$             | 0.033     | 0.031           | 0.034           |
| $\beta$              | 0.163     | 0.177           | 0.209           |
| $\gamma$             | 0.350     | 0.340           | 0.361           |

values as the series became longer (1995–2020 close to 60 million) (Tab. 4). In general, models predicted annual variable estimates of  $R$ , with low values for 2002, increase during 2010, a notable decline in 2011, recovery in 2015 and stable recruitment values at the end of series (2016–2020) with mean value of 91.49 million of individuals according to Cushing model ( $w_m = 50.84\%$ ) (Fig. 5). Variation in species recruitment through standardized anomalies ( $R_\theta$ ) and its general trend are shown in Figure 6 for the full 1995–2020 time series and for different time series lengths.  $R_\theta$  showed a positive trend over time (1995–2020), with the lowest value in 2002 (–1.35), the highest in 2010 (1.52) and 2015 (1.87), and  $R_\theta = 1.06$  for the last year of the series.

### 3.4 Steepness estimates

The refitted B-H model steepness ( $h$ ) values ranged from 0.25 to 0.29 among series with different length. Mean recruitment values ranged from 57.76 to 79.61 million individuals. For the full 1995–2020 time series  $h = 0.29$  and mean recruitment value was 57.76 million individuals of Bigeye croaker (Tab. 5).

## 4 Discussion

Understanding the relationship between spawning stock abundance (SS) and recruits ( $R$ ) is crucial for fisheries management (Maunder and Thorson, 2019). These aspects were analyzed for Bigeye croaker *Micropogonias megalops* in the NGC, a population that has been exploited under data-limited management conditions for nearly three decades (Froese et al., 2017; Arzola-Sotelo et al., 2022). In recent years, updated information on growth, length at first reproduction, mortality, abundances, catches and reference points for

management was obtained (Aragón-Noriega et al., 2015; Arzola-Sotelo et al., 2022; Urias-Sotomayor et al., 2022). Using this information led to the creation of the abundance series (SS–R) analyzed here: LCA 1995–2020. Construction of series also required information on length-weight relationships, which indicated isometric and positive allometric growth, depending on year. Variation in  $b$  values may be due to different factors such as food availability, season, sex and maturity (Ali et al., 2016; Jisr et al., 2018). The NGC is globally recognized for being a highly productive region, therefore it is likely that *M. megalops* finds favorable environmental conditions in the region to exhibit a growth ranging from “ideal growth” ( $b = 3$ ) to heavier ( $b > 3$ ) (Brusca et al., 2017; Jisr et al., 2018; López-Martínez et al., 2023).

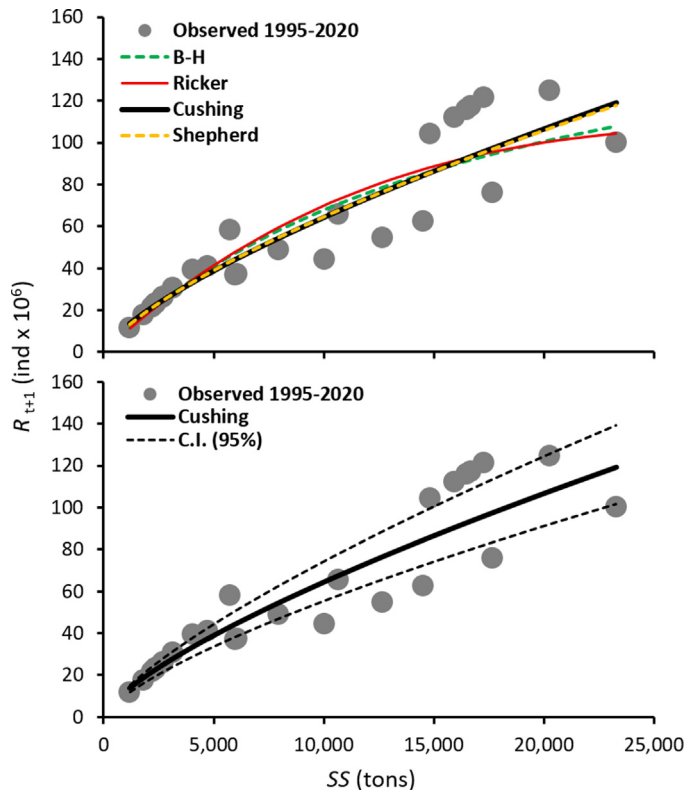
The collected biological information contributed to the abundance series construction, since the LCA series was obtained from annual length-frequency estimates of catches, biometric relationships, growth parameters and natural mortality estimates of the species (Jones, 1981; Quinn and Deriso, 1999). Abundance obtained by LCA, based on all this biological and fishery data, can be highly informative for other population estimates such as relative biomass, survivals, recruits and spawning stock size (Jones, 1981; Quinn and Deriso, 1999; Arzola-Sotelo et al., 2022). In fact, LCA estimates have functioned as input values in stock production models for Bigeye croaker; and, in this work, derived estimates of recruitment that accords to previous reports (Froese et al., 2017; Arzola-Sotelo et al., 2022; Urias-Sotomayor et al., 2022).

The LCA series of *M. megalops* covered 26 yr of fishery in NGC (1995–2020). Worldwide, time series used for SS–R analysis of fish populations contain on average 34 yr of data (Ricard et al., 2012). However, recent studies have been conducted if the time series included at least 20 consecutive years (Yang and Yamakawa, 2022). For this study, simulation of time series of different length (15 to 26 yr) from the LCA provided several analysis scenarios for SS–R estimation (Magnusson and Hilborn, 2007; Haddon, 2011). Based on this, time series of different length were constructed and it was possible to conclude that longer representative data series lead to convergence to determinate the species SS–R relationship. It was noted that in the shortest time series (2006–2020, 15 yr) there is no clear relationship, where all the models presented descriptive power (Burnham et al., 2011). While in longer time series, such as the 18 yr (2003–2020) and up to 26 yr (1995–2020), a density-dependent and asymptotic SS–R relationship is more clearly shown (Doll and Jacquemin, 2019). In these cases, the Cushing and Shepherd models presented a better description of the spawning stock-recruitment relationship for the Bigeye croaker (Burnham et al., 2011). Therefore, the length of the full time series (1995–2020) analyzed was considered sufficient for SS–R determination for *M. megalops*.

The analysis of SS–R series of different length assisted in finding models that ‘best’ described the spawning stock and recruitment relationship, and also, species annual recruitment. Estimates comparison revealed that all the models presented some descriptive power of the Bigeye croaker SS–R relationship. However, the Cushing model best described the SS (tons) –  $R$  (ind) relationship for the 1995–2020 series. Specifically, the SS (tons) –  $R$  (ind) data combination has been also used in other studies, e.g. Shimoyama et al. (2007), Olsen et al. (2011), Lee et al. (2012) and Shertzer and Conn (2012).

**Table 3.** Model statistics for spawning stock–recruitment models for the full Jones Length Cohort Analysis (LCA) 1995–2020 time series (26 yr) and for shorter time series lengths (15 to 25 yr) of *Micropogonias megalops* in NGC. Value of  $k$  is the number of parameters for each model;  $AICc$  is corrected Akaike Information Criterion,  $\Delta_m$  is Akaike differences and  $w_m$  is Akaike weight for each model.

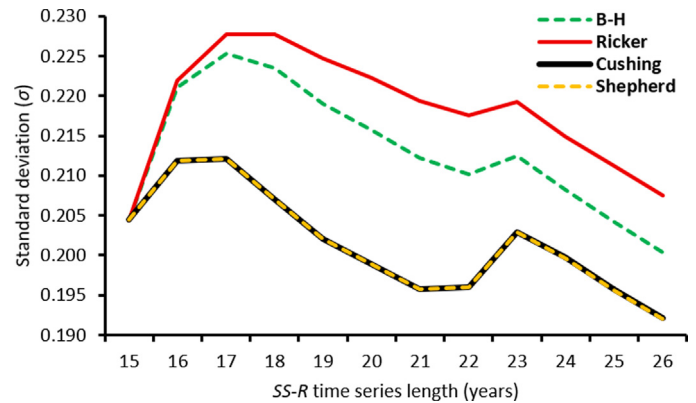
| <i>SS-R</i> series | Length (years) | Model    | $k$ | $AICc$ | $\Delta_m$ | $w_m$ (%) |
|--------------------|----------------|----------|-----|--------|------------|-----------|
| 1995–2020          | 26             | B-H      | 2   | −8.35  | 2.17       | 17.20     |
|                    |                | Ricker   | 2   | −6.53  | 3.99       | 6.91      |
|                    |                | Cushing  | 2   | −10.52 | 0.00       | 50.84     |
|                    |                | Shepherd | 3   | −9.10  | 1.42       | 25.05     |
| 1996–2020          | 25             | B-H      | 2   | −6.99  | 2.13       | 17.45     |
|                    |                | Ricker   | 2   | −5.30  | 3.81       | 7.52      |
|                    |                | Cushing  | 2   | −9.12  | 0.00       | 50.56     |
|                    |                | Shepherd | 3   | −7.67  | 1.45       | 24.47     |
| 1997–2020          | 24             | B-H      | 2   | −5.72  | 1.99       | 18.32     |
|                    |                | Ricker   | 2   | −4.19  | 3.51       | 8.54      |
|                    |                | Cushing  | 2   | −7.71  | 0.00       | 49.44     |
|                    |                | Shepherd | 3   | −6.23  | 1.47       | 23.70     |
| 1998–2020          | 23             | B-H      | 2   | −4.47  | 2.09       | 17.65     |
|                    |                | Ricker   | 2   | −3.02  | 3.55       | 8.52      |
|                    |                | Cushing  | 2   | −6.57  | 0.00       | 50.27     |
|                    |                | Shepherd | 3   | −5.05  | 1.52       | 23.56     |
| 1999–2020          | 22             | B-H      | 2   | −4.66  | 3.08       | 12.07     |
|                    |                | Ricker   | 2   | −3.13  | 4.60       | 5.63      |
|                    |                | Cushing  | 2   | −7.74  | 0.00       | 56.31     |
|                    |                | Shepherd | 3   | −6.19  | 1.55       | 25.99     |
| 2000–2020          | 21             | B-H      | 2   | −3.94  | 3.40       | 10.56     |
|                    |                | Ricker   | 2   | −2.54  | 4.80       | 5.24      |
|                    |                | Cushing  | 2   | −7.34  | 0.00       | 57.85     |
|                    |                | Shepherd | 3   | −5.77  | 1.57       | 26.35     |
| 2001–2020          | 20             | B-H      | 2   | −2.99  | 3.24       | 11.27     |
|                    |                | Ricker   | 2   | −1.80  | 4.44       | 6.19      |
|                    |                | Cushing  | 2   | −6.23  | 0.00       | 56.96     |
|                    |                | Shepherd | 3   | −4.63  | 1.60       | 25.58     |
| 2002–2020          | 19             | B-H      | 2   | −2.17  | 3.05       | 12.14     |
|                    |                | Ricker   | 2   | −1.19  | 4.02       | 7.46      |
|                    |                | Cushing  | 2   | −5.22  | 0.00       | 55.78     |
|                    |                | Shepherd | 3   | −3.58  | 1.64       | 24.62     |
| 2003–2020          | 18             | B-H      | 2   | −1.21  | 2.75       | 13.56     |
|                    |                | Ricker   | 2   | −0.53  | 3.43       | 9.65      |
|                    |                | Cushing  | 2   | −3.95  | 0.00       | 53.54     |
|                    |                | Shepherd | 3   | −2.28  | 1.67       | 23.25     |
| 2004–2020          | 17             | B-H      | 2   | −0.73  | 2.05       | 17.24     |
|                    |                | Ricker   | 2   | −0.35  | 2.43       | 14.27     |
|                    |                | Cushing  | 2   | −2.78  | 0.00       | 48.09     |
|                    |                | Shepherd | 3   | −1.07  | 1.71       | 20.41     |
| 2005–2020          | 16             | B-H      | 2   | −1.15  | 1.35       | 21.18     |
|                    |                | Ricker   | 2   | −1.02  | 1.48       | 19.87     |
|                    |                | Cushing  | 2   | −2.50  | 0.00       | 41.61     |
|                    |                | Shepherd | 3   | −0.75  | 1.75       | 17.34     |
| 2006–2020          | 15             | B-H      | 2   | −3.27  | 0.00       | 29.47     |
|                    |                | Ricker   | 2   | −3.27  | 0.00       | 29.53     |
|                    |                | Cushing  | 2   | −3.25  | 0.03       | 29.15     |
|                    |                | Shepherd | 3   | −1.45  | 1.83       | 11.85     |



**Fig. 3.** Multi-model fitting (above) to the LCA SS-R full 1995–2020 time series (26 yr) for Bigeye croaker *Micropogonias megalops* in NGC. The model with higher explanatory power according to  $AIC_c$  (below) and confidence intervals (95%) are also shown.

The MMI approach has been mentioned as appropriate for SS-R model selection by Shimoyama et al. (2007), Galindo-Cortes et al. (2010) and Doll and Jacquemin (2019). Particularly, Galindo-Cortes et al. (2010) analyzed the Pacific sardine (*Sardinops sagax*) in the Pacific Current, where none of SS-R models tested showed strong data descriptive power ( $w \geq 90\%$ ). Nevertheless, for ecological inference purposes researchers may consider competitive models those with  $\Delta \leq 2$  and  $\Delta \leq 7$  (Burnham and Anderson, 2002; Galindo-Cortes et al., 2010; Burnham et al., 2011). In the present work, all four models were competitive for each time series length according to  $\Delta_m$ , however, in longer time series Cushing and Shepherd models had more descriptive power. This indicates a density-dependent mechanism with recruitment being inversely proportional to spawner abundance as assumed by the B-H, and also plausible for the Bigeye croaker stock (Lowerre-Barbieri et al., 2017; Ouyang et al., 2023). Therefore, the species recruitment seems to depend on population density in the presence of limited and unequal resources and reach an equilibrium or carrying capacity ( $k$ ) (Van Poorten et al., 2018). Carrying capacity  $k$  for the species has been estimated between 22,186–24,797 tons (Urias-Sotomayor et al., 2022) and 39,698–48,331 tons in NGC (Arzola-Sotelo et al., 2022).

The fact that more than one SS-R model showed descriptive power for LCA series scenarios might be explained by uncertainty in data. Uncertainty is inherent in data analysis, as



**Fig. 4.** Residual standard deviations ( $\sigma$ ) of the four SS-R models fitted for Bigeye croaker *Micropogonias megalops* in NGC. Values of  $\sigma$  for the full 1995–2020 time series (26 yr) and for shorter time series lengths (15 to 25 yr) are shown.

data could include measurement errors or reflect natural variation in stock abundances (Doll and Jacquemin, 2019). Description of SS-R relationships are difficult to obtain, since quantity and quality of data to be analyzed, as well as the type of models tested, have important influence on the level of error associated with estimates (Hilborn and Walters, 1992; Skoglund et al., 2022). In the process, not considering uncertainty can lead to biases in determining the type of spawning stock-recruitment relationship, as well as in recruitment levels (Walters, 1985; Ludwig and Walters 1981). This can lead to incorrect management decisions and then affect populations production and fisheries (Maunder and Thorson, 2019; Skoglund et al., 2022). For this reason, performing analysis on series of different length through a multi-model inference approach (MMI) was preponderant in our quest to reduce uncertainty in SS-R and annual recruitment estimates of *M. megalops* (Burnham and Anderson, 2002; Burnham et al., 2011; Haddon, 2011).

Due its wide usage, good fit to demersal fish SS-R data, and that it is similar to the Cushing model (asymptotic curve, density-dependence), the Beverton-Holt model may also be used for Bigeye croaker SS-R analysis (Lee et al., 2012; Shertzer and Conn, 2012; Cury et al., 2014). In the present work, the B-H model was refitted by considering a steepness ( $h$ ) parameter, defined as spawning biomass decrease to 20% of its unexploited level (Lee et al., 2012; Mangel et al., 2010, 2013). The steepness parameter is linked to population productivity and regulation, and allows estimating management quantities based on biological reference points and related indicators (Shertzer and Conn, 2012; Mangel et al., 2013). In addition, it is intrinsically linked to the resilience of an exploited stock and determines its average productivity in a stationary environmental regime (Mangel et al., 2010). The steepness is bounded at  $0.2 \leq h \leq 1.0$ , where relatively high values indicate that recruitment reaches its asymptote at relatively low spawning stock sizes and environmental variation is an important factor (Haddon, 2011; Shertzer and Conn, 2012). For *M. megalops* the estimated  $h$  ranged from 0.25 to 0.29, indicating relatively low values with less pronounced curvature and a more apparent spawning stock

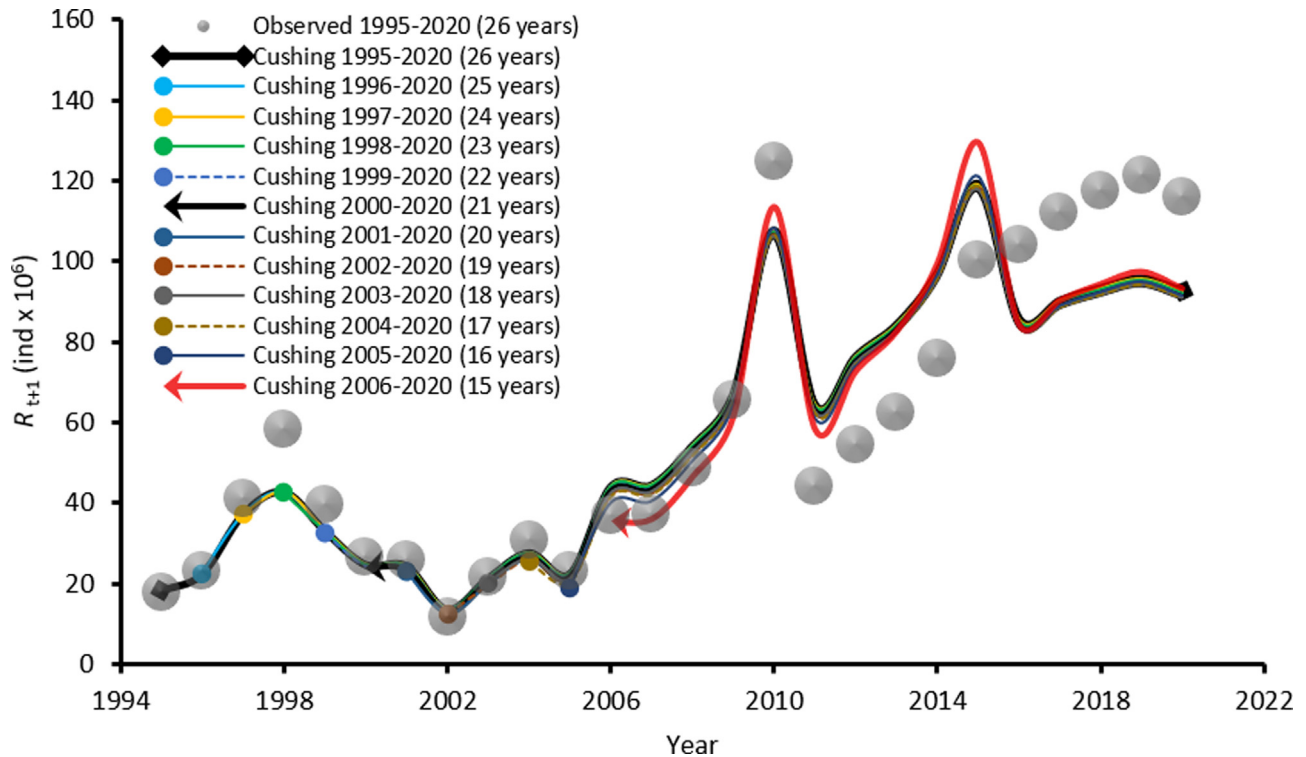
**Table 4.** Summary statistics for Jones Length Cohort Analysis (LCA) data series and model derived estimates of recruits  $R$  (millions of individuals). Values obtained for the full 1995–2020 time series (26 yr) and for shorter time series lengths (15 to 25 yr) for *Micropogonias megalops* in NGC. Mean, minimum and maximum recruitment values across the different time series are shown.

| SS- $R$ series | Length (years) | Values | Data      |           | Modelled recruitment |        |         |          |
|----------------|----------------|--------|-----------|-----------|----------------------|--------|---------|----------|
|                |                |        | SS (t)    | $R$ (ind) | B-H                  | Ricker | Cushing | Shepherd |
| 1995–2020      | 26             | Mean   | 9,354.53  | 59.21     | 57.76                | 58.23  | 57.86   | 57.81    |
|                |                | Min    | 1,195.38  | 11.63     | 11.73                | 11.21  | 13.60   | 13.33    |
|                |                | Max    | 23,280.05 | 124.74    | 107.92               | 104.50 | 119.06  | 117.73   |
| 1996–2020      | 25             | Mean   | 9,656.37  | 60.88     | 59.37                | 59.83  | 59.45   | 59.41    |
|                |                | Min    | 1,195.38  | 11.63     | 11.69                | 11.14  | 13.71   | 13.46    |
|                |                | Max    | 23,280.05 | 124.74    | 108.06               | 104.86 | 118.79  | 117.74   |
| 1997–2020      | 24             | Mean   | 9,960.60  | 62.46     | 60.89                | 61.35  | 60.98   | 60.93    |
|                |                | Min    | 1,195.38  | 11.63     | 11.61                | 11.04  | 13.66   | 13.41    |
|                |                | Max    | 23,280.05 | 124.74    | 108.33               | 105.35 | 118.89  | 117.81   |
| 1998–2020      | 23             | Mean   | 10,188.38 | 63.39     | 61.76                | 62.25  | 61.82   | 61.81    |
|                |                | Min    | 1,195.38  | 11.63     | 11.55                | 10.99  | 13.53   | 13.41    |
|                |                | Max    | 23,280.05 | 124.74    | 108.38               | 105.50 | 118.76  | 118.26   |
| 1999–2020      | 22             | Mean   | 10,391.10 | 63.63     | 62.01                | 62.55  | 61.96   | 61.96    |
|                |                | Min    | 1,195.38  | 11.63     | 11.30                | 10.75  | 13.20   | 13.20    |
|                |                | Max    | 23,280.05 | 124.74    | 108.25               | 105.90 | 117.81  | 117.80   |
| 2000–2020      | 21             | Mean   | 10,693.08 | 64.78     | 63.12                | 63.67  | 63.01   | 62.99    |
|                |                | Min    | 1,195.38  | 11.63     | 11.07                | 10.55  | 12.88   | 12.89    |
|                |                | Max    | 23,280.05 | 124.74    | 108.64               | 106.63 | 117.75  | 117.68   |
| 2001–2020      | 20             | Mean   | 11,092.37 | 66.71     | 64.99                | 65.53  | 64.84   | 64.84    |
|                |                | Min    | 1,195.38  | 11.63     | 10.85                | 10.33  | 12.61   | 12.61    |
|                |                | Max    | 23,280.05 | 124.74    | 109.33               | 107.65 | 118.10  | 118.10   |
| 2002–2020      | 19             | Mean   | 11,536.20 | 68.85     | 67.09                | 67.59  | 66.90   | 66.85    |
|                |                | Min    | 1,195.38  | 11.63     | 10.56                | 10.06  | 12.28   | 12.33    |
|                |                | Max    | 23,280.05 | 124.74    | 110.28               | 108.99 | 118.57  | 118.31   |
| 2003–2020      | 18             | Mean   | 12,110.69 | 72.03     | 70.21                | 70.62  | 69.89   | 69.87    |
|                |                | Min    | 2,208.11  | 21.48     | 18.24                | 17.54  | 20.05   | 20.09    |
|                |                | Max    | 23,280.05 | 124.74    | 111.68               | 110.92 | 117.67  | 117.54   |
| 2004–2020      | 17             | Mean   | 12,693.19 | 75.01     | 73.15                | 73.45  | 72.80   | 72.69    |
|                |                | Min    | 2,370.14  | 23.06     | 18.44                | 17.85  | 20.54   | 20.74    |
|                |                | Max    | 23,280.05 | 124.74    | 114.25               | 113.90 | 118.65  | 118.07   |
| 2005–2020      | 16             | Mean   | 13,289.26 | 77.78     | 75.95                | 76.10  | 75.55   | 75.55    |
|                |                | Min    | 2,370.14  | 23.06     | 16.83                | 16.50  | 18.87   | 18.86    |
|                |                | Max    | 23,280.05 | 124.74    | 118.60               | 118.49 | 121.09  | 121.10   |
| 2006–2020      | 15             | Mean   | 14,017.21 | 81.42     | 79.61                | 79.60  | 79.66   | 79.66    |
|                |                | Min    | 5,967.40  | 36.72     | 35.27                | 35.29  | 35.38   | 35.37    |
|                |                | Max    | 23,280.05 | 124.74    | 128.27               | 128.07 | 129.60  | 129.56   |

and recruitment relationship (Shertzer and Conn, 2012; Mangel et al., 2013). This  $h$  parameter in *M. megalops* could be also explored in future work through age-structured or surplus production models, in seeking for more information about population size and catch rates to optimize management and consequent economic benefits (Zhu et al., 2012).

In this study, Bigeye croaker recruitment depended on spawning stock biomass, which is the demographic fraction that has been targeted by fishing since the early 1990s in the

NGC (Aragón-Noriega et al., 2010; Arzola-Sotelo et al., 2022). In this sense, the increase in catches over time and the positive trend in recruitment are evidence of stock robustness and resilience to exploitation (Arzola-Sotelo et al., 2022; Urias-Sotomayor et al., 2022). Recruitment of demersal stocks, such as *M. megalops*, and other stocks, can be negatively affected by overfishing (Britten et al., 2016; Maunder and Thorson, 2019). Despite this, the literature mentions that resilient stocks possess the capacity to recover in reproductive processes and



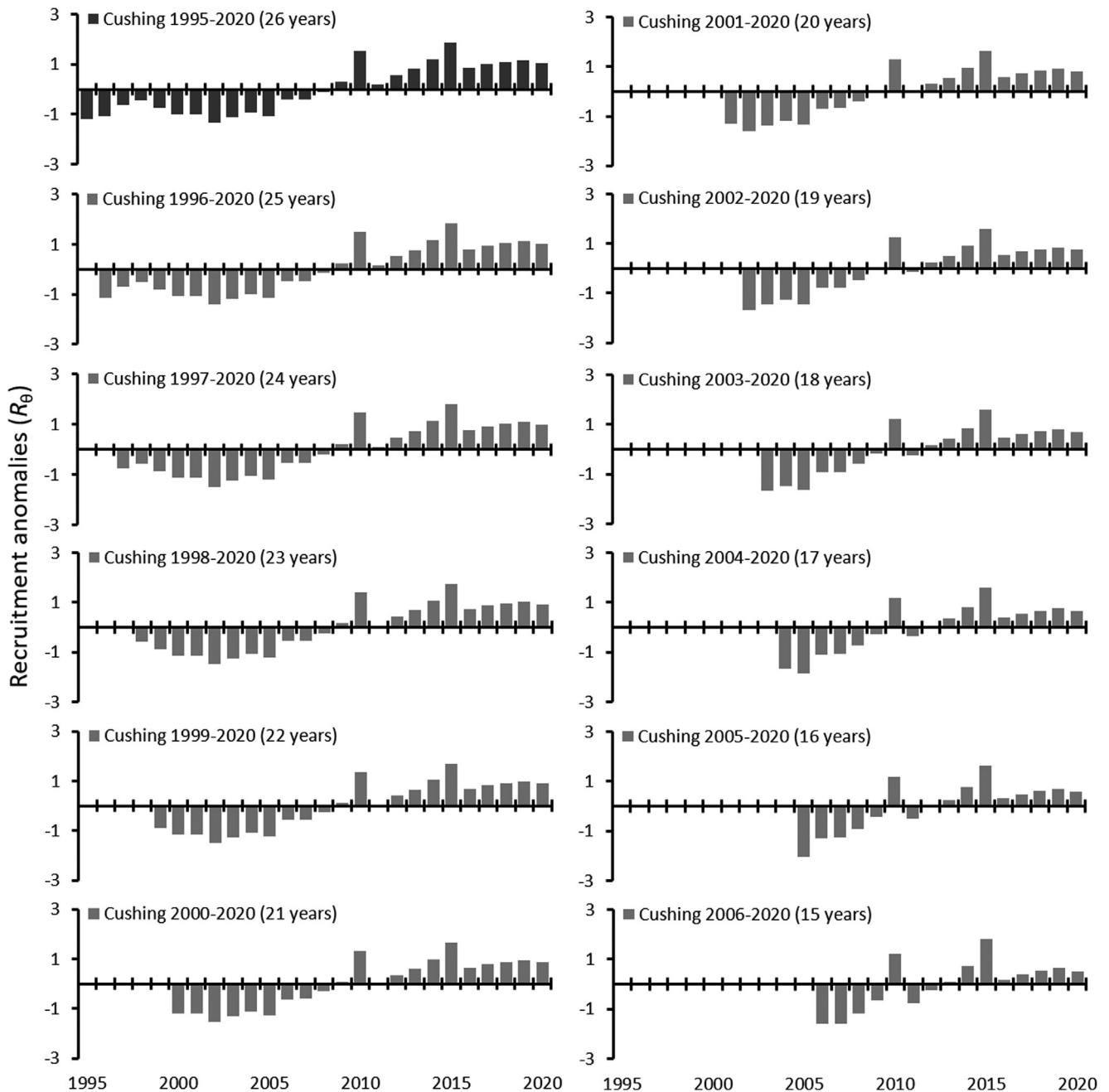
**Fig. 5.** Annual recruitment (individuals) estimated by *SS-R* models with higher explanatory power according to *AICc* for Bigeye croaker *Micropogonias megalops* in NGC. Recruitment estimates are presented for the full 1995–2020 time series (26 yr) and for shorter time series lengths (15 to 25 yr).

**Table 5.** Parameter values obtained by refitting the B-H model including *steepness* (*h*) for *Micropogonias megalops* in NGC. Output values are shown for *SS-R* for LCA full 1995–2020 time series (26 yr) and for shorter time series lengths (15 to 25 yr). Value  $\alpha$  is the number of recruits per spawner interpreted as the productivity parameter,  $\beta$  is a control parameter on the level of density-dependence, *h* is *steepness* parameter,  $\sigma$  is standard deviation and *LL* is loglikelihood function. Mean, minimum and maximum recruitment values (millions) for the species are also shown.

| <i>SS-R</i> Series | Length (years) | $\alpha$ | $\beta$   | <i>h</i> | $\sigma$ | <i>LL</i> | Mean  | Min   | Max    |
|--------------------|----------------|----------|-----------|----------|----------|-----------|-------|-------|--------|
| 1995–2020          | 26             | 194.07   | 5,450.57  | 0.29     | 0.20     | 4.91      | 57.76 | 11.73 | 107.92 |
| 1996–2020          | 25             | 195.07   | 5,332.03  | 0.28     | 0.20     | 4.23      | 59.37 | 11.69 | 108.06 |
| 1997–2020          | 24             | 197.30   | 5,181.05  | 0.27     | 0.21     | 3.61      | 60.89 | 11.61 | 108.33 |
| 1998–2020          | 23             | 198.36   | 5,200.03  | 0.27     | 0.21     | 3.00      | 61.76 | 11.55 | 108.38 |
| 1999–2020          | 22             | 202.13   | 5,419.45  | 0.27     | 0.21     | 3.10      | 62.01 | 11.30 | 108.24 |
| 2000–2020          | 21             | 207.69   | 5,690.34  | 0.27     | 0.21     | 2.76      | 63.12 | 11.07 | 108.64 |
| 2001–2020          | 20             | 214.93   | 5,916.84  | 0.26     | 0.22     | 2.30      | 64.99 | 10.85 | 109.33 |
| 2002–2020          | 19             | 225.67   | 6,318.08  | 0.26     | 0.22     | 1.90      | 67.09 | 10.56 | 110.28 |
| 2003–2020          | 18             | 241.20   | 6,946.68  | 0.26     | 0.22     | 1.44      | 70.21 | 18.24 | 111.68 |
| 2004–2020          | 17             | 277.85   | 8,504.52  | 0.26     | 0.23     | 1.22      | 73.15 | 18.44 | 114.25 |
| 2005–2020          | 16             | 377.13   | 12,881.90 | 0.25     | 0.22     | 1.45      | 75.95 | 16.83 | 118.60 |
| 2006–2020          | 15             | 1,407.82 | 58,704.48 | 0.25     | 0.20     | 2.53      | 79.61 | 35.27 | 128.27 |

recruitment, therefore, in population abundance (Lowerre-Barbieri et al., 2017; Haimovici et al., 2021). Such characteristic has been reported for species of the same family (Sciaenidae) as *M. megalops*, in the southwestern Atlantic Ocean (coast of Brazil, Uruguay and Argentina), such as *Micropogonias furnieri*, *Cynoscion guatucupa*, *Macrodon atricauda* and *Umbrina canosai* (Haimovici and Cardoso, 2017; Haimovici et al., 2021). Early maturity, high fecundity, plasticity in growth and age at maturity in response to

decreasing density, make them relatively resilient compared to other fish families (Haimovici and Cardoso, 2017). Particularly, *M. furnieri*, was subject to high fishing pressure over four decades (1976–2017), and population size decreased approximately 90%. Stock recovery is probably explained by a combination of biological and fishery traits such as: flexibility in growth and first maturity, high reproductive potential, coastal spawning areas outside fishing grounds, and areas with abundant food for juveniles (Haimovici et al., 2021). Several



**Fig. 6.** Annual recruitment standardized anomalies ( $R_{\theta}$ ) for SS-R models with higher explanatory power according to  $AIC_c$  on *Micropogonias megalops* in NGC. Recruitment anomalies are presented for full 1995–2020 time series (26 yr) and for shorter time series lengths (15 to 25 yr).

of these aspects are likely to occur for *M. megalops*, as it is found in a region (NGC) globally noted for its high biological productivity (Brusca et al., 2017; López-Martínez et al., 2023). Furthermore, a recovery in biomass levels occurred probably in response to a decrease in fishing mortality during 2016–2020 in the region (Arzola-Sotelo et al., 2022; Urias-Sotomayor et al., 2022). The results obtained here support that stock recruitment depends on density-dependent factors; however, future work could investigate long-term environmental and/or fishery aspects that potentially affect *M. megalops* SS and biomass in NGC (Britten et al., 2016; Maunder and Thorson, 2019).

The MMI procedure has already been implemented for growth estimates of Bigeye croaker and other members of the family such as: Gulf corvina *Cynoscion othonopterus* Jordan and Gilbert, 1882 and the totoaba *Totoaba macdonaldi* Gilbert, 1890 (Arzola-Sotelo, 2014; Aragón-Noriega, 2014; Aragón-Noriega et al., 2015; Arzola-Sotelo et al., 2018; Curiel-Bernal et al., 2023). Nevertheless, the use of MMI for SS-R and annual recruitment described here is the first of its kind for the species and members of the family Sciaenidae in the region. This is an alternative method to analyses involving multiple fish stocks, such as meta-analyses, which provide non-specific inferences (Shertzer and Conn, 2012;

Yang and Yamakawa, 2022). Although MMI provides population specific inferences, the method is applicable to worldwide stocks. The results obtained contribute to increase the biological-ecological knowledge of the Bigeye croaker stock and the information is useful for its fisheries management in NGC.

## 5 Conclusion

This study determined through MMI that more than a single tested model had descriptive power on  $SS-R$  for *M. megalops* in NGC. Despite this, there were models with higher explanatory power according to the Akaike Information Criterion, such as the Cushing and Shepherd models. The analysis of series of different length helped to reduce uncertainty on determining the  $SS-R$  relationship and the annual recruitment of the species. The steepness estimation confirmed a more apparent density-dependent the  $SS-R$  relationship, with a less pronounced asymptotic curve. Future work could deepen the analysis of  $h$  and other potential influences on recruitment variation in the context of climate change. In addition, it is necessary to expand the series analyzed with more biological and catch data. The above in order to increasingly support  $SS-R$  estimates and other population dynamics analysis for Bigeye croaker. This would provide more biological-ecological knowledge on this resource aimed to precautionary management, conservation and optimal exploitation in NGC.

## Acknowledgments

The authors thank Eloisa Herrera Valdivia and Isadora Jyasu Moreno Pérez for logistical work and field assistance. In addition, to project PRONACE SEMARNAT-2018-1-A3-S-77965 CONAHCyT and EA. Arzola-Sotelo to CONAHCyT grant 413187.

## Data availability statement

The research data are available on request from the authors.

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**Cite this article as:** Arzola-Sotelo EA, López-Martínez J, Morales-Bojórquez E, Nevárez-Martínez MO, García-Morales R, Herrera-Cervantes H. 2025. Determination of spawning stock-recruitment relationships of Bigeye croaker *Micropogonias megalops* in the Gulf of California based on a multi-model inference approach. *Aquat. Living Resour.* 38: 14. <https://doi.org/10.1051/alr/2025011>