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# Assessment of the exploitable biomass of thread herring (*Opisthonema* spp.) in northwestern Mexico

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**Abstract**

In recent years, the small pelagic fishery on the Pacific northwest coast of Mexico has significantly increased fishing pressure on thread herring *Opisthonema* spp. This fishery is regulated using a precautionary approach (acceptable biological catch (ABC) and minimum catch size). However, due to fishing dynamics, fish aggregation habits and increased fishing mortality, periodic biomass assessments are necessary to estimate ABC and assess the resource status. The Catch-MSY approach was used to analyze historical series of thread herring catches off the western Baja California Sur (BCS, 1981–2018) and the Gulf of California (GC, 1972–2018) to estimate exploitable biomass and target reference points in order to obtain catch quotas. According to the results, in GC, the maximum biomass reached in 1972 (at the beginning of fishery) and minimum biomass reached in 2015; the estimated exploitable biomass for 2019 was $42.2\times10^4$ t; and the maximum sustainable yield (MSY) was $15.4\times10^4$ t. In the western BCS coast, the maximum biomass was reached in 1981 (at the beginning of fishery) and minimum biomass was reached in 2017; the estimated exploitable biomass for 2019 was $3.2\times10^4$ t; and the MSY was $1.2\times10^4$ t. Both stocks showed a decrease in biomass over the past years and were currently near to point of full exploitation. The results suggest that the use of the Catch-MSY method is suitable to obtain annual biomass estimates, in order to establish an ABC, to know the current state of the resource, and to avoid overcoming the potential recovery of the stocks.

**Key words:** Catch-MSY, thread herring, exploitable biomass estimate

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## 1 Introduction

Thread herring *Opisthonema* spp. includes five species distributed in tropical and subtropical coastal waters of the American continent (Berry and Barret, 1963). Four of them distributed in the Pacific Ocean, *Opisthonema libertate*, *O. medirastre*, *O. bulleri* and *O. berlangai*, the first three are distributed from the middle part of the western coast of Baja California Sur (BCS), including the Gulf of California (GC), to Ecuador (Whitehead and Rodríguez-Sánchez, 1995; Berry and Barrett, 1963), while *O. berlangai* is restricted off the Galapagos Islands (Berry and Barret, 1963). The last species of the genus, *O. oglinum* is located in the Atlantic Ocean, from the southern Gulf of Maine to Brazil, including the Gulf of Mexico and the Caribbean (Cervigón and Bastida, 1974).

Small pelagic fish are among the most important fishery resources in northwestern Mexico. Their exploitation began in 1929 with low catch levels due to low demand for human consumption and the low carrying capacity of the Mexican fleet (Diario Oficial de la Federación, 2012). Changes in national and international demand, as well as growth in the number and technology of fishing vessels, have led to fishery yields representing 30% of annual fishery catches and 10% of the economic value of this fishery in Mexico (Comisión Nacional de Acuicultura y Pesca, 2011; Nevárez-Martínez et al., 2014). This resource comprises several species, including herring and anchovy (Comisión Nacional de Acuicultura y Pesca, 2011; Nevárez-Martínez et al., 2014). However, the Pacific sardine (*Sardinops sagax*) and the thread herring (*Opisthonema* spp.) represent 80% of the total catch of small pelagic fish in Mexico. Since the beginning of the 21st century, the biomass of the Pacific sardine has decreased considerably in the eastern Pacific, first in Canada, then in the United States, and since 2012 in Mexico. Zwolinski and Demer (2012) assumed that the decrease in biomass of the Pacific sardine stock in California was related to recruitment failures due to the effect of environmental change on seasonal movements to feeding areas.

Due to the decrease in biomass of the Pacific sardine, the Mexican fleet has redirected its fishing effort mainly to the thread herring, which is exploited in GC and on the western coast of

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BCS. Thread herring catch includes *O. libertate, O. medirastre* and *O. bulleri*, official reports do not discriminate catch by species and are generically reported as thread herring. However, *O. libertate* comprises the most important proportion (between 50% and 70%) of the thread herring catch (Ruiz-Luna and Lyle, 1992; Jacob-Cervantes, 2010; Vega Corrales, 2010; Ruiz-Domínguez and Quiñonez-Velázquez, 2018).

Historically, the average yield (1972–2017) of the small pelagic fishery was 375 000 t, 46% were Pacific sardine and 24% were thread herring; however, over the past decade the catches of these resources has shown important changes, with values changing to 33% (Pacific sardine) and 32% (thread herring). Among the effects due to the increase in fishing pressure on fish stocks are, among others, the decrease in the average individual size due to the removal by fishing of larger organisms, as a consequence of the accumulated mortality and selectivity of fishing nets. The thread herring fishery is managed with a precautionary approach (Diario Oficial de la Federación, 2012), and an acceptable biological catch (ABC) in reference to maximum sustainable yield. In addition, a minimum catch size has been established, and a maximum of 20% of the annual catch of fish is less than the minimum catch size (Diario Oficial de la Federación, 2019).

However, due to the fishing dynamics (purse seine) and aggregation habits of small pelagic fish, the potential use of other management measures such as catch quotas could be of great benefit to the resource. The fishing quotas would correspond to the annual biomass estimates. This approach has proven effective in various fisheries, achieving stock stabilization, and preventing and even reversing stock collapse (Costello et al., 2008).

The objective of the present study was to assess the exploitable biomass and the target reference points (TRP) of thread herring, based on the historical series of catch data that includes the three thread herring species found in northwestern Mexico. The Catch-MSY method developed by Martell and Froese (2013) for resources with limited information was used. This approach allows creating estimates of catch quotas with reference to the maximum sustainable yield (MSY).

## 2 Materials and methods

Information encompassing 37 a (1981–2018) of landings at Bahía Magdalena (ports of Adolfo López Mateos and San Carlos) on the western BCS coast and 46 a (1972–2018) of landings in the GC (ports of Mazatlán, Guaymas and Yavaros) were used for this analysis (Figs 1a and b). The time series were independently processed according to official fishing regulations (Diario Oficial de la Federación, 2019). This regulation defines the western coast of BCS and the GC as different fishing zones, with an exclusive thread herring fleet and the boats cannot fish in both fishing zones. Furthermore, the areas include independent fishing stocks (Pérez-Quiñonez et al., 2018).

Additionally to the catch series, a priori $r$ and $k$ values (parameters of the Schaefer's dynamic biomass model), an interval of probable values of the relative stock size during the first $(\lambda_{01}, \lambda_{02})$ and last $(\lambda_1, \lambda_2)$ year of the catch series, and an interval of the estimated natural mortality ($M$) were required to estimate biomass.

The Catch-MSY method uses Schaefer's (Schaefer, 1954) production model (Eqs (1) and (2)) to estimate the annual biomass for a given pair of $r$ and $k$ values.

$$B_t = k \times l_0, \tag{1}$$

$$B_{t+1} = \left[B_t + rB_t \times \left(1 - \frac{B_t}{k}\right) - C_t\right], \tag{2}$$

where $B_{t+1}$ is the biomass estimated at the beginning of year $t$+1 and for consecutive years in the time series; $B_t$ is the biomass at the beginning of year $t$; $C_t$ is the catch at year $t$; $r$ is the intrinsic rate of population growth; $k$ is the habitat carrying capacity of the stock; and $l_0$ is a randomly selected value in a uniform distribution within the range $\lambda_{01}$ to $\lambda_{02}$..

The Catch-MSY method states that relative stock size intervals ($B/k$) must be specified at the beginning and present of the time series. The $\lambda_{01}$ to $\lambda_{02}$ interval for the first year is 0.5–0.9, if the catch with respect to the maximum catch is less than 0.5; otherwise, it is 0.3–0.6. For the last year (more recent), the $\lambda_1$ to $\lambda_2$ interval is 0.01–0.4, if the catch with respect to the maximum catch is less than 0.5; otherwise, it is 0.3–0.7. These levels were assigned by Martell and Froese (2013), based on the analysis of 146 stocks, with information obtained from the Stock Summary Database and the RAM legacy Stock Assessment Database (Ricard et al., 2012).

In this study, the relative stock size interval $(\lambda_{01}, \lambda_{02})$ during the first year was considered to be 0.99–1.0 (virgin biomass) because the beginning of the data series coincides with the beginning of fisheries in the area. For the most recent year, the $\lambda_1, \lambda_2$ values of relative stock size were estimated according to the state of fishing exploitation, according to Martell and Froese (2013).

For the a priori values of the $k$ parameter, this study selected as lower and upper limits the maximum catch of the data series and 50 times the maximum catch, respectively. Martell and Froese (2013) suggested that the resilience values found on FishBase should be used to obtain $r$ values, if there is no other option. This study evaluated the effect of two options (FishBase vs. $r$ estimate) on model parameterization. To estimate $r$, this study used the same approach as Zhang et al. (2018), who used Sullivan's empirical equation (Sullivan, 1991) (Eq. (3)), which includes $K$ and $w_\infty$ parameters from von Bertalanffy's model. The $K$ and $L_\infty$ estimates (from which $w_\infty$ was estimated) were obtained from Ruiz-Domínguez and Quiñonez-Velázquez (2018), using the equation proposed by Sullivan (1991) for non-gadid stocks:

$$r = 0.947 + 1.189K - 0.095 \ln w_\infty. \tag{3}$$

$M$ estimates were taken from Ruiz-Domínguez and Quiñonez-Velázquez (2018), with information from 2012 to 2015.

The information used to parameterize the Catch-MSY method is included in Table 1. The $r$ interval in the first column corresponds to a pair of values that comprise the estimate using Sullivan's equation (Sullivan, 1991) where, substituting the $K$ (von Bertalanffy) and $w_\infty$ values:

$$r = 0.947 + 1.189\,(1.41) - 0.095\ln\,(129.3) = 2.16. \tag{4}$$

The second $r$ interval (second column) corresponds to the 95% confidence intervals estimated for *O. libertate* with $r$=0.90, as reported in FishBase (Froese and Pauly, 2019).

The $k$ interval was estimated from the catch data for each fishing area. The level of depletion in the first year of the series was considered minimal (virgin biomass). It was considered to be between 30% and 70% during the last year for both areas.

Once the model was parameterized for each fishing area (western BCS coast and GC), a total of 30 000 Monte Carlo iterations were carried out to estimate annual biomass using the equilibrium surplus production model by Schaefer (1954). Based on $r$ and $k$ pairs of values selected from the data intervals, assuming a uniform distribution (where each $r$ and $k$ pair of values has the same probability of being selected), and through the use of a Bernoulli distribution as Likelihood function ($LL$), the $r$ and $k$ pairs of values that met the three following conditions ($LL$=1)

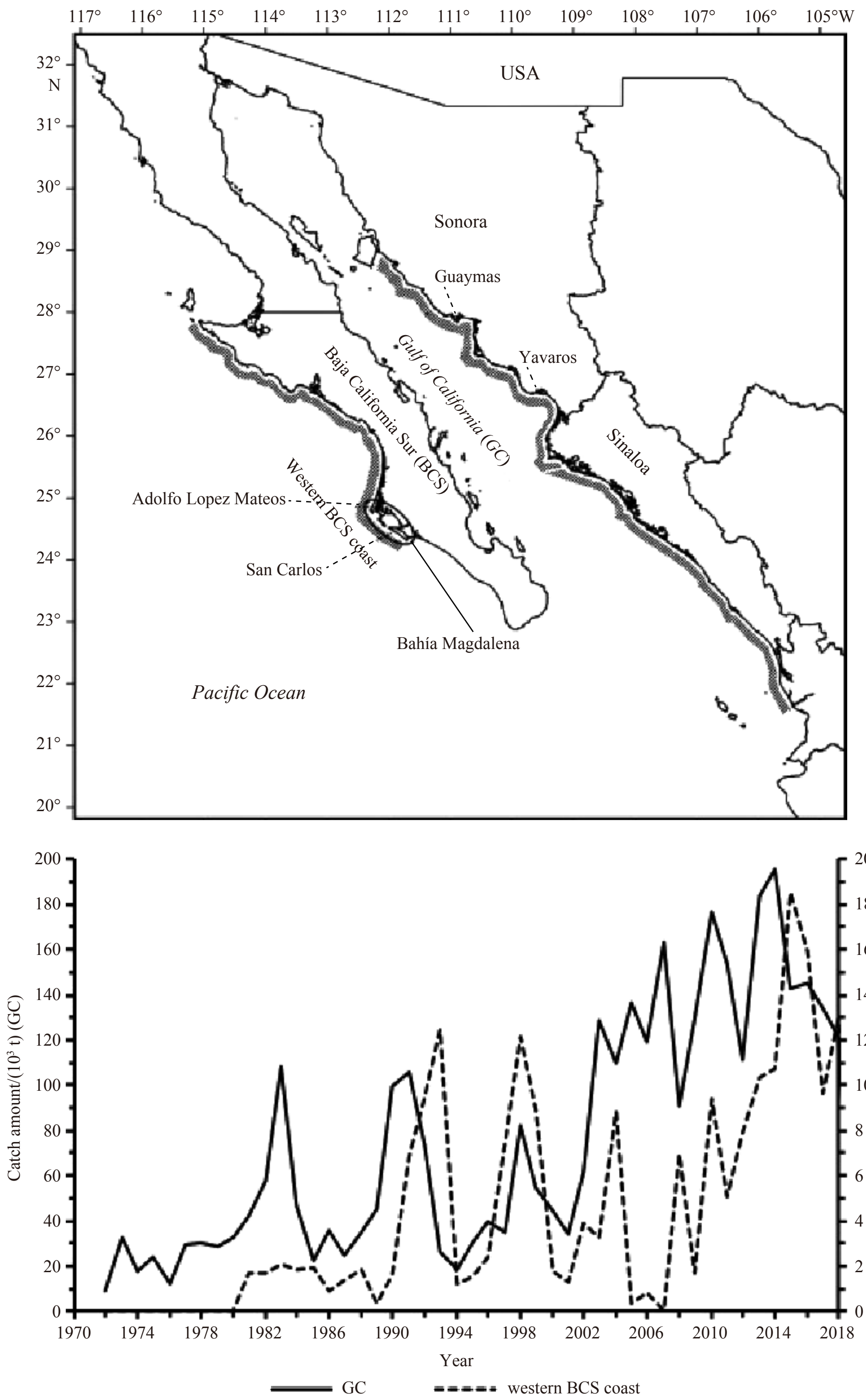


**Fig. 1.** Study area in northwestern Mexico (a) and historical series of catches of thread herring (*Opisthonema* spp.) stocks (b). The geographical location of landing ports (the dotted lines show the location of each port) and fishing areas (shaded area) of the herring fleet that uses purse seine nets are shown. The oval shows the location of Bahía Magdalena.

were selected:

(1) The stock does not collapse before the last year in the catch series;

(2) The stock does not surpass the carrying capacity assumed a priori;

(3) The estimated biomass in the last year of the catch series is within the range of stock decrease assumed a priori ($\lambda_1$, $\lambda_2$).

The pairs of values that did not meet these conditions were discarded (*LL*=0) (Eq. (5)).

$$LL\left(\text{Data}|\theta\right)=\left\{\begin{matrix}1, & \lambda_1\leqslant\dfrac{B_{n+1}}{k}\leqslant\lambda_2\\ 0, & \lambda_1>\dfrac{B_{n+1}}{k},\dfrac{B_{n+1}}{k}>\lambda_2\end{matrix}\right\}. \tag{5}$$

**Table 1.** Entry data for the Catch-MSY method

| Stock | $r$/a$^{-1}$ (estimated) | $r$/a$^{-1}$ (FishBase) | $k$ ($C_{max}$ – $50C_{max}$) | $\lambda_{01}$–$\lambda_{02}$ | $\lambda_1$–$\lambda_2$ | $M$ |
|---|---|---|---|---|---|---|
| Gulf of California | 2.0–2.5 | 0.59–1.35 | 195 847–9 792 350 | 0.99–1 | 0.3–0.7 | 0.5–0.8 |
| Western BCS coast | 2.0–2.5 | 0.59–1.35 | 18 542–927 080 | 0.99–1 | 0.3–0.7 | 0.5–0.8 |

Note: $r$, population growth rate; $k$, carrying capacity; and $M$, natural mortality. BCS represents Baja California Sur.

where $\theta$ is $r$, $k$ pairs value; $n$ is number of years in the data series.

Finally, the geometric mean and percentiles (2.5% and 97.5%) of biomass estimated with the selected $r$ and $k$ values was obtained. This study estimated the target reference points and percentiles (2.5% and 97.5%) with these parameters, using the following equations by Schaefer (1954).

Biomass at which maximum sustainable yield is obtained:

$$B_{\rm MSY} = \frac{k}{2}. \tag{6}$$

Maximum sustainable yield:

$$\text{MSY} = \frac{rk}{4}. \tag{7}$$

Fishing mortality at the maximum sustainable yield:

$$F_{\rm MSY} = \frac{r}{2}. \tag{8}$$

Exploitation rate at the maximum sustainable yield:

$$E_{\rm MSY} = \frac{F_{\rm MSY}}{F_{\rm MSY} + M} \times [1 - \exp(-F_{\rm MSY} - M)]\,. \tag{9}$$

Control rule or overfishing limit (OFL):

$$\text{overfishing limit} = B_{2019} \times E_{\rm MSY}, \tag{10}$$

where $B_{2019}$ corresponds to the following year.

Once the historical estimates of biomass per stock were obtained, this study evaluated the state of the resource (Ruelas-Peña et al., 2013).

$$Est = \frac{Bt_{\rm current}}{B_{\rm MSY}}, \tag{11}$$

where $Bt_{\rm current}$ is average of the estimated biomass over the past 5 a (2015–2019). $B_{\rm MSY}$ is biomass at which maximum sustainable yield is obtained.

According to Ruelas-Peña et al. (2013), values of $Est$=1 are equivalent to a stock subject to full exploitation, values less than 1 mean that the stock is being overexploited, and values larger than 1 mean that the stock is underexploited.

## 3 Results

### 3.1 *Catch analysis*

#### 3.1.1 *Gulf of California*

The thread herring fishery began in the GC in 1972 with low catch levels, averaging 2.5×10$^4$ t during the first decade. These yields have increased importantly over the years, to reach an average yield of 14.9×10$^4$ t over the past decade (Fig. 2a).

Two time periods in the annual yields were identified (U-test=8, $p$<0.05). The first period began in 1972 and ended in 2001 ($\bar{x}$=4.2×10$^4$ t, standard deviation $s$=2.6×10$^4$ t); it is considered the low yield period. The lowest historical catch of the fishery was recorded during this time period (8.9×10$^3$ t in 1972). The second time period lasted from 2002 to 2018 ($\bar{x}$=13.5×10$^4$ t, $s$=3.3×10$^4$ t). It was characterized by high yields; the highest historical catch of this fishery was recorded during this time period (19.5×10$^4$ t in 2014) (Fig. 2a).

Independently of the two time periods identified, there were high yields in the years 1983, 1990, 1991, 1998, 2003, 2005, 2007, 2010, 2013, and 2014 of the catch series.

#### 3.1.2 *Western BCS coast*

During the first decade of this fishery on the western BCS coast, fishing was carried out mainly within Bahía Magdalena with low yield (1.5×10$^3$ t). Later, yields presented great variations, but with a positive trend, until they reached an average >1×10$^4$ t from 2012 to the present (Fig. 2b). In this area, two time periods were also identified in the catch series (U-test=12, $p$<0.05). The first period encompassed from 1981 to 2011 ($\bar{x}$=3.9×10$^3$ t, $s$=3.7×10$^4$ t); the greatest variations in annual yields and the lowest historical catches in the fishery (9.2×10$^2$ t in 2006) were recorded during this period. The second period comprised from 2012 to 2018 ($\bar{x}$=1.2×10$^4$ t, $s$=3.7×10$^3$ t); higher yields and the highest historical catch (1.8×10$^4$ t in 2015) were recorded during this time period.

Peaks were identified in the catches in 1993, 1998, 2004, 2009, 2010, and 2015.

### 3.2 *Estimated target reference points*

Out of 30 000 iterations performed as part of scenario 1 simulations, no $r$ or $k$ pairs of values were selected according to the model criteria. Under scenario 2, a total of 560 pairs of values were selected for the GC (Fig. 3a) and 541 pairs of values for the western BCS coast (Fig. 3b).

#### 3.2.1 *Gulf of California*

The selected $r$ and $k$ values were within the ranges of 0.591–1.346 and 43.9×10$^4$–11.1×10$^5$ t, respectively (Figs 4a and b). Regarding the TRP calculations, the MSY was between 12.6×10$^4$ t and 17.7×10$^4$ t (Fig. 4c), and the $B_{\rm MSY}$ was between 21.9×10$^4$ t and 58.5×10$^4$ t (Fig. 4d). The $F_{\rm MSY}$ was between 0.296 and 0.673 (Fig. 4e), the $E_{\rm MSY}$ was between 0.181 and 0.390 (Fig. 4f), and the OFL was between 4.3×10$^4$ t and 17.1×10$^4$ t (Fig. 4g). The position data (geometric mean and percentiles) of these estimates are shown in Table 2. In fishery management, the geometric mean of each estimate is considered to be the TRP and the percentiles are the confidence intervals. This study observed that in years prior to 2003 catches were marginal with respect to the MSY, from 2005 to 2017 they fluctuated within the confidence intervals, and they were above the upper confidence interval in 2010, 2013, and 2014 (Fig. 4h). However, when interannual variations were eliminated by averaging over the past 5 a ($\bar{x}$=14.7×10$^4$ t), the catch obtained was between the MSY and the upper MSY confidence interval, denoting full exploitation of the resource. This is also suggested

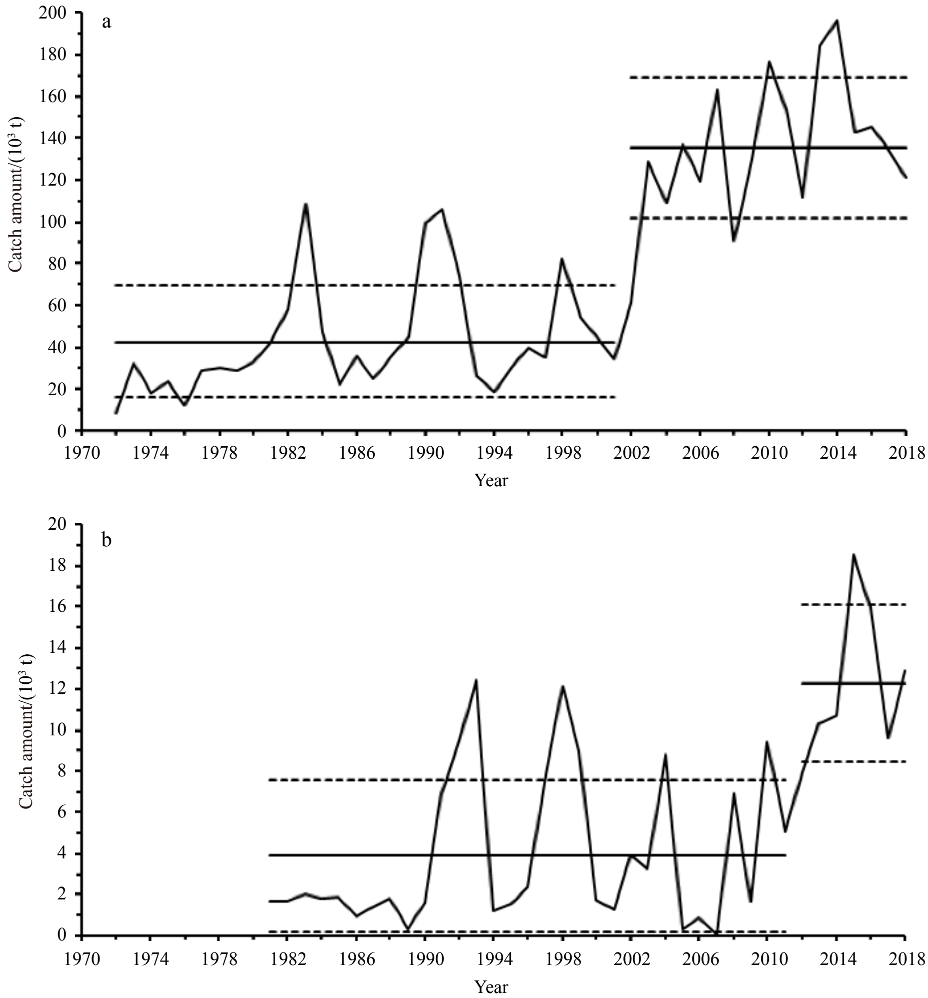


**Fig. 2.** Historical series of thread herring catches in the Gulf of California (a) and off the western BCS coast (b). Solid horizontal lines represent average catches and dotted horizontal lines represent standard deviation.

by estimates of stock size ($B/B_{MSY}$) and exploitation ($F/F_{MSY}$), above and below 1.0, respectively (Fig. 4i).

3.2.2 *Western BCS coast*

The selected *r* and *k* values were within the ranges of 0.591 and 1.072 and between 4.2×$10^4$ t and 9.5×$10^4$ t, respectively (Figs 5a and b). Regarding the calculation of the target reference points, the MSY was between 8.9×$10^3$ t and 1.5×$10^4$ t (Fig. 5c). The $B_{MSY}$ was between 2.1×$10^4$ t and 4.7×$10^4$ t (Fig. 5d), the $F_{MSY}$ was between 0.296 and 0.536 (Fig. 5e), the $E_{MSY}$ was between 0.182 and 0.329 (Fig. 5f), and the OFL was between 2.417×$10^3$ t and 1.3×$10^4$ t (Fig. 5g). Position data are shown in Table 3. The comparison of annual fishery yields and the MSY and confidence intervals showed that in years prior to 2002 fishery yields were low, except for 1993 and 1998, when the lower MSY confidence interval was surpassed; this was an isolated event in the trend of catches during this period. However, after 2012, yields increased considerably and fluctuated within the MSY confidence intervals; these were exceeded in 2015 and 2016 (Fig. 5h) when the interannual variation was eliminated. Averaging over the past 5 a ($\bar{x}$ = 1.3×$10^4$ t), catches obtained were between the MSY and the upper confidence interval, like in the GC, which suggests that the resource is at a stage of full exploitation (Fig. 5i).

### 3.3 *Estimated biomass and state of the resource*

The annual biomass was estimated and the geometric mean and percentiles (2.5% and 97.5%) were calculated for each stock using each pair of selected *r* and *k* values (Figs 6a and b).

3.3.1 *Gulf of California*

The historical biomass of this stock can be divided into two stages: the first was characterized by little interannual variation, with estimates ranging from 71.8×$10^4$ t in 1972 to 64.9×$10^4$ t in 2003; the estimate for 1972 was the highest in the series, coinciding with the beginning of the fishery and the virgin biomass of the resource. The second stage could be described as a period of accelerated decline, in which the estimated biomass decreased from 57.5×$10^4$ t in 2004 to 42.2×$10^4$ t in 2019, this stage was characterized by presenting high interannual variability together with a marked downward trend, during which, the lowest estimate of the historical series was obtained (37.9×$10^4$ t in 2015).

The analysis of the state of the resource resulted in a value of *Est*=1.09; this suggested that the resource was fully exploited. Results showed that the biomass average between 2015 and 2019 was only 9% above the point of greatest stock productivity (*k*/2) and the minimum biomass to obtain MSY ($B_{MSY}$) (Fig. 6b). If a new period of biomass decrease occur, the resource would quickly enter a phase of overexploitation.

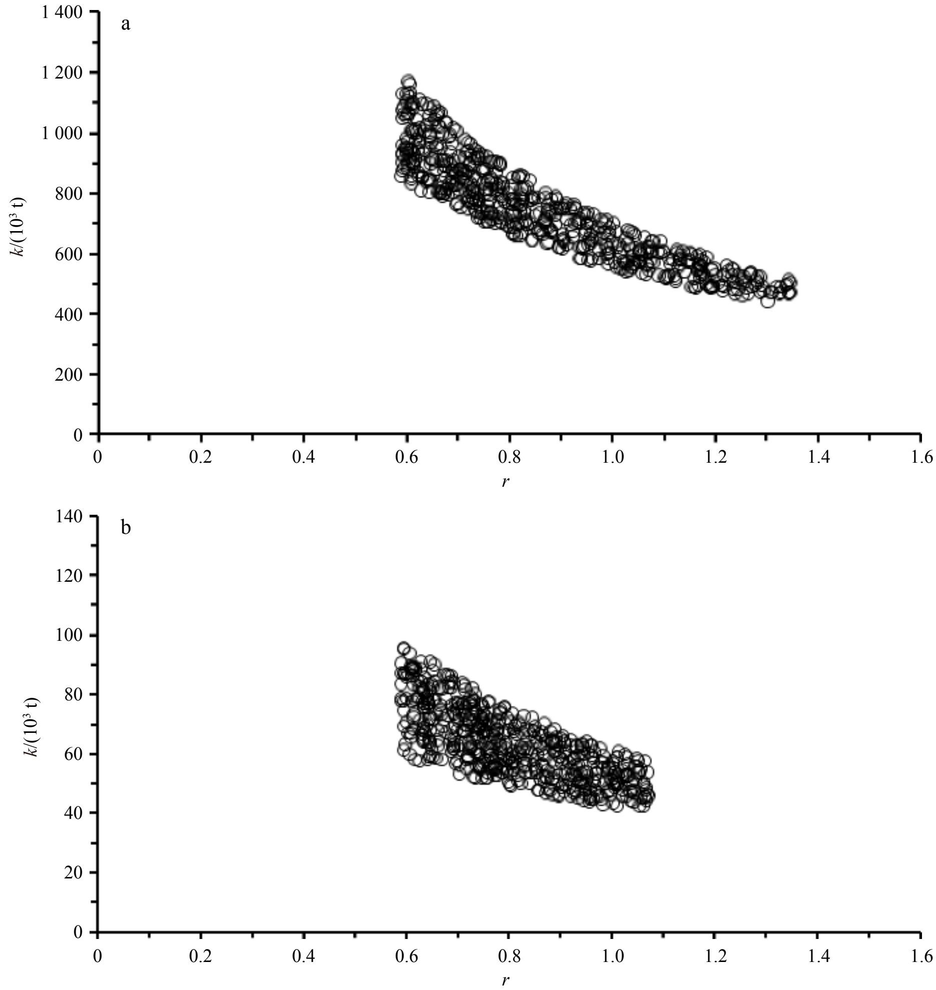


**Fig. 3.** Dispersion of selected *r* and *k* pairs. a. GC and b. western BCS coast.

3.3.2 *Western BCS coast*

The historical biomass for this stock could also be divided into three stages. The first presented high stability between 1981 and 1991; estimates for this period fluctuated between $6.1\times10^4$ t and $6\times10^4$ t, showing minimal changes in biomass, as was seen for the GC; the biomass estimated for the first year of the time series was the highest in the series. The second stage comprised the years between 1992 and 2008; biomass estimates ranged from $6.1\times10^4$ t to $4.5\times10^4$ t; these values indicated a period of high variability. The third stage encompassed the years from 2009 to 2019; biomass at the beginning of the period was $5.4\times10^4$ t and $3.2\times10^4$ t at the end, which suggested accelerated decrease.

The analysis of the state of the resource resulted in a value of *Est*=1.16; therefore, the stock was at the point of full exploitation. The average biomass between 2015 and 2019 surpassed by 16% the point of greatest stock productivity ($k/2$) and the $B_{MSY}$ (Fig. 7b). However, the stock biomass kept a negative trend and it was necessary to look into possible causes, suggesting the implementation of a precautionary management strategy.

## 4 Discussion

### 4.1 *Method selection*

One of the main problems when evaluating this fishery is that the Mexican herring fleet catches indistinctly *O. libertate*, *O. medirastre*, and *O. bulleri* in GC. Therefore, if an age or size structured model was used, the extrapolation to catches would have a high degree of uncertainty. Due to this, estimations of biomass were performed considering the three species of the *Opisthonema* genus in GC as one undifferentiated resource. Moreover, the information was grouped taking into account the presence of two fishery stocks, one off the western BCS coast and one in GC. This was done according to the regionalization of fishery areas established in Diario Oficial de la Federación (2019), where landing ports on the western BCS coast (Ports Adolfo López Mateos and San Carlos for thread herring) corresponded to "Region A", and landing ports in GC (Guaymas, Yavaros, and Mazatlán) corresponded to "Region B".

The time series of structured data was short, which would also limit the benefits of an analytical method structured by ages or sizes. This study therefore decided to use the Catch-MSY method (Martell and Froese, 2013) based on the "Analysis of stock reduction" by Kimura and Tagart (1982). This model is part of the surplus production models or dynamic biomass models that are the simplest fishery evaluation models in existence and only consider changes to exploitable biomass (Schaefer, 1954, 1957; Ricker, 1975; Hilborn and Walters, 1992; Polacheck et al., 1993). This simplifies population dynamics into a single function, where the stock is considered undifferentiated biomass (Haddon, 2011), as is the case for this multi-specific fishery. Moreover, one

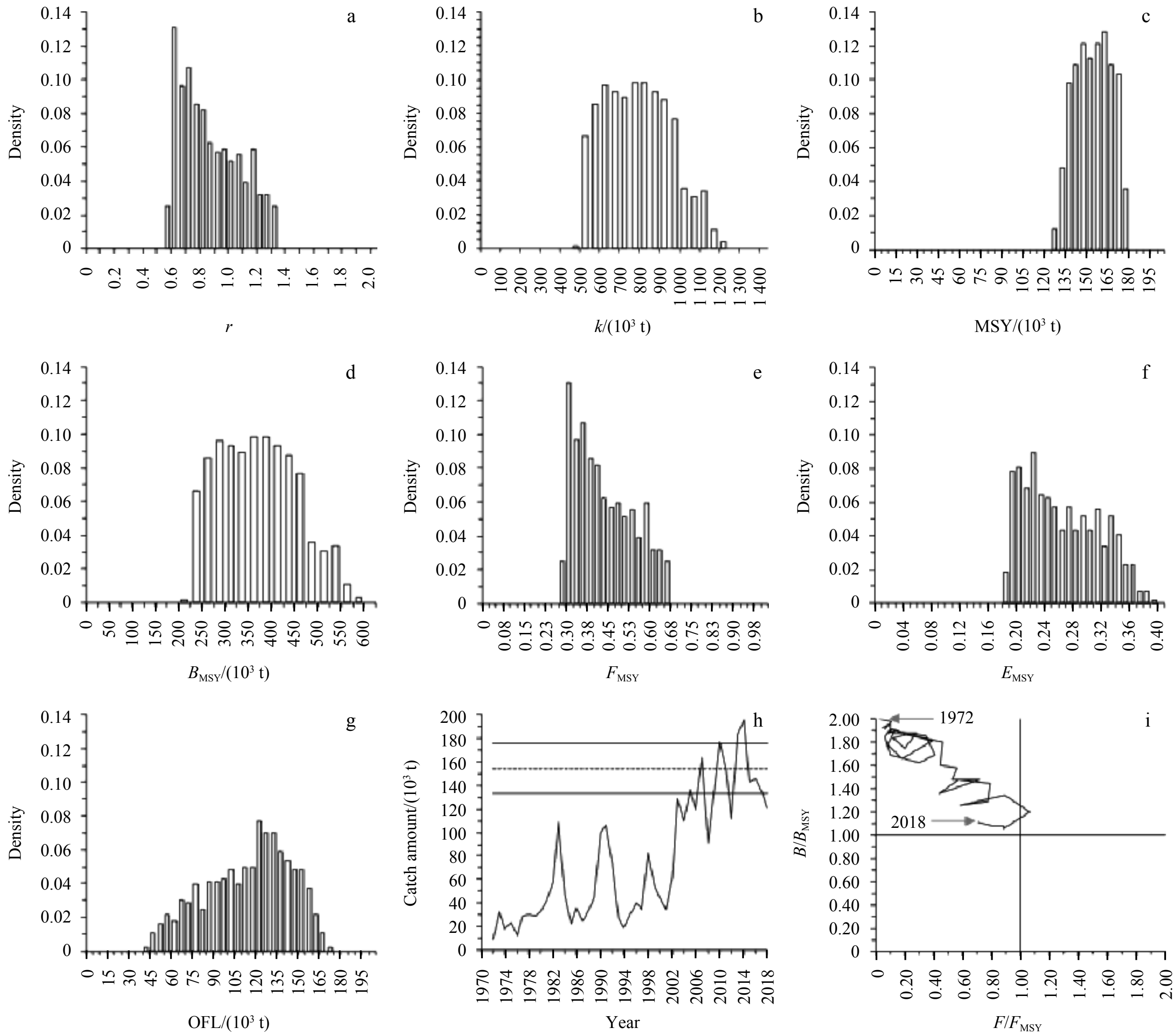


**Fig. 4.** Simulation of the target reference points, estimated based on the accepted *r* and *k* pairs of values for the thread herring population of the Gulf of California, and comparison of fishery yield and maximum estimated sustainable yield. Dotted line and solid lines in h represent the estimated MSY and the confidence intervals, respectively.

**Table 2.** Position data of the selected parameters of the model and estimated target reference points (Gulf of California)

| | $r$ | $k$ | MSY | $B_{MSY}$ | $F_{MSY}$ | $E_{MSY}$ | OFL |
|---|---|---|---|---|---|---|---|
| Geometric mean | 0.830 | 722 362 | 154 054 | 361 181 | 0.427 | 0.260 | 109 939 |
| Percentile (2.5%) | 0.600 | 476 781 | 132 755 | 238 390 | 0.300 | 0.192 | 53 645 |
| Percentile (97.5%) | 1.294 | 1 082 784 | 175 293 | 542 259 | 0.649 | 0.368 | 161 721 |

of the main advantages of these models is that they require few data, compared with more complex approaches (Prager, 1994). If catch and effort data are representative of the exploited stock, the surplus production models provide information of the same quality or even better quality than models structured by age (Haddon, 2011). However, independently of the model, the precision of biomass estimates will always depend on the quality of the data and on a correct parameterization. If possible, it is important to compare the biomass estimates and TRP obtained with those reported in the literature that were obtained using other methods. Two thread herring biomass estimates were presented for the first time during the XXVII workshop on small pelagic fish (11–13 June 2019, La Paz, BCS). The first estimate analyzed the 1972–2018 catch series of the thread herring population in the GC with a structured model (ASAP), whereas the second estimate was a hydroacoustic evaluation of the southern GC during spring 2018. Results for the GC indicate that over the past 10 a, exploitable biomass has been above 922 000 t and $B_{MSY}$ is 460 101 t. Results of the hydroacoustic evaluation indicated that the total biomass estimate was within a range of 749 538–1 034 650 t. Although these estimates are not directly comparable, it is clear that they are notably higher than those obtained in the present study. Another detail to highlight from these biomass estimates is that the authors reported that biomass showed a trend toward stability and that it would probably increase if conditions were favorable. Moreover, they considered that the re-

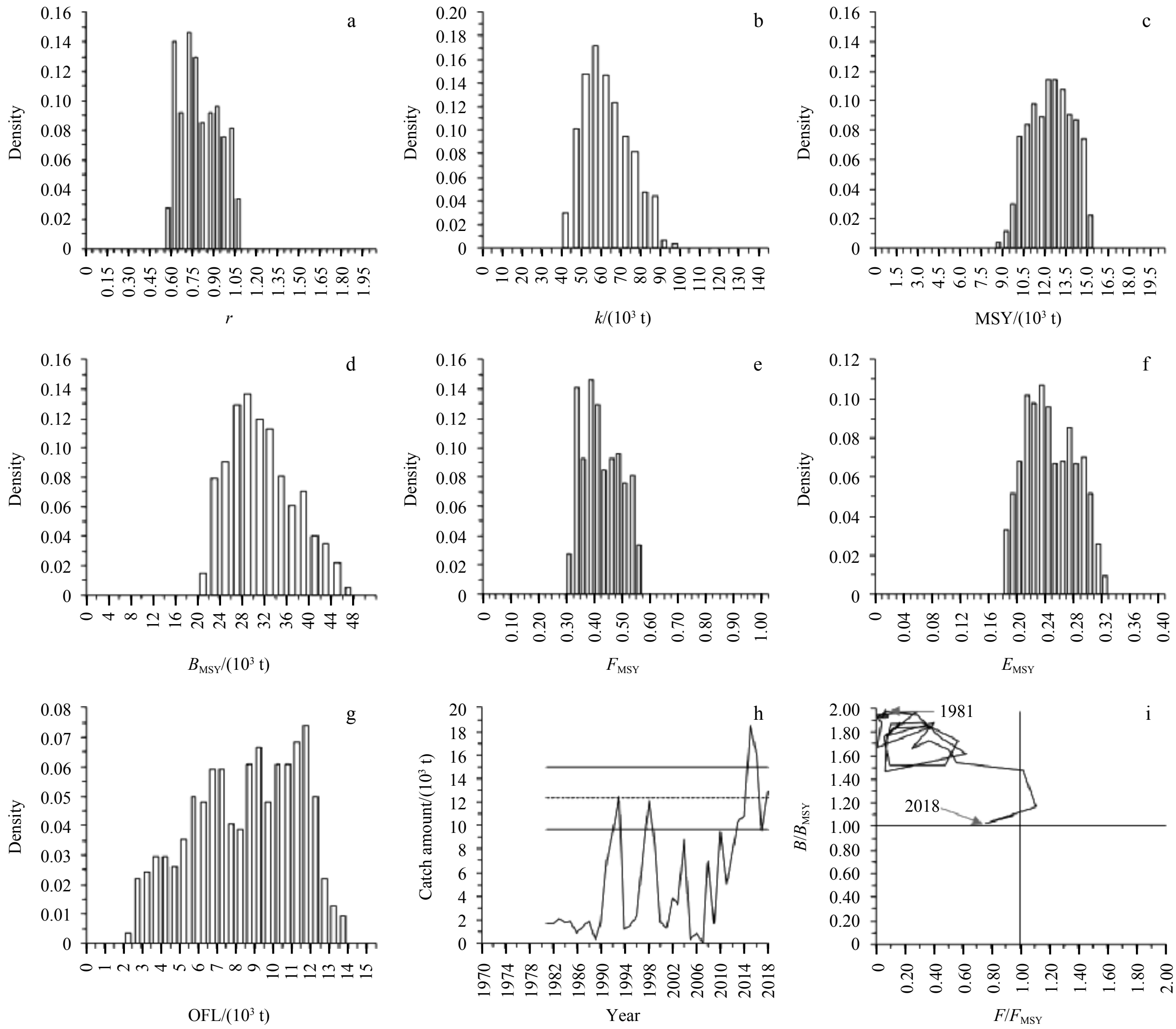


**Fig. 5.** Simulation of the target reference points, estimated based on the *r* and *k* pairs of accepted values for the thread herring population on the western BCS coast, and comparison of fishery yield and estimated maximum sustainable yield. Dotted line and solid lines in h represent the estimated MSY and the confidence intervals, respectively.

**Table 3.** Position data of the selected model parameters and estimated target reference points (the western BCS coast)

| | $r$ | $k$ | MRS | $B_{MSY}$ | $F_{MSY}$ | $E_{MSY}$ | OFL |
|---|---|---|---|---|---|---|---|
| Geometric mean | 0.794 | 62 151 | 12 343 | 31 075 | 0.397 | 0.245 | 7 923 |
| Percentile (2.5) | 0.599 | 44 963 | 9 661 | 22 481 | 0.300 | 0.189 | 2 934 |
| Percentile (97.5) | 1.058 | 88 243 | 14 979 | 44 122 | 0.529 | 0.313 | 12 881 |

source was underexploited and very close to optimum exploitation (XXVII Workshop on small pelagic fish). Unfortunately, only the abstracts from both studies are available, and this study was unable to access the full papers because they are in development. Therefore, discussing possible causes of differences in biomass estimates between the Catch-MSY vs. ASAP and hydroacoustic approaches is not possible, and rather than identifying strengths or limitations of the approaches which would be in an unknown domain, due to the lack of the methodological details and assumptions.

### 4.2 *Parameterization of the dynamic biomass model*

The present study tried to reduce bias during the model parameterization process by evaluating two different intervals of values of the population growth rate. Estimations using Sullivan's equation (Sullivan, 1991) were not favorable, as no pair of *r*-*k* values met the selection criteria in both stocks evaluated. A similar result was reported by Zhang et al. (2018) that used Catch-MSY to evaluate three fisheries (*Trichiurus japonicas*, *Larimichthys polyactis* and *L. crocea*) in the east of the China sea areas. The estimates of *r* from the Sullivan equation (Sullivan, 1991), were only not effective for *L. crocea* by not generating combinations of *r*-*k* that meet the method's assumptions. The authors considered that this was a result of using indistinctly information from different decades in the estimation of *r*, over a period during which the ecologic strategy of this species changed from *k*-type to *r*-type

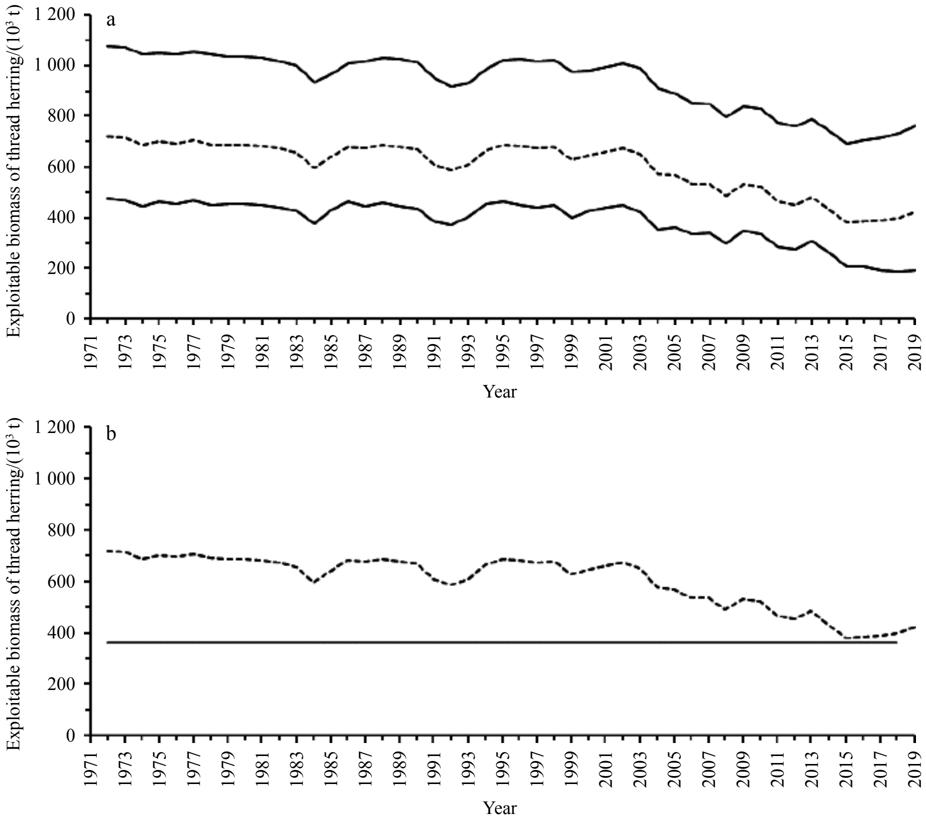


**Fig. 6.** Historical series of exploitable biomass of thread herring estimated for the Gulf of California. Dotted line represents geometric mean, solid lines in a represent 2.5% and 97.5% percentiles, and solid line in b represents $B_{MSY}$.

(Xu and Liu, 2007; Zhu et al., 2009). However, this study consider that in the present study the absence of *r*-*k* pairs of values meeting the selection criteria when parameterizing the model using the interval of *r* values from Sullivan's equation (Sullivan, 1991) is a result of the sensibility of this equation to high growth rates in length and a corresponding lower increase in weight like the ones from any small pelagic fish from tropical or subtropical waters; according to Sullivan (1991), non-gadoid stocks equation was formulated using information from a diverse group of stock that comprises small pelagic schooling fish, Pacific halibut and other flatfishes; however, most of the stocks were caught in the northern Atlantic Ocean, where physical conditions are considerably different from those in the thread herring distribution area, as evidence, data temperature (mean annual surface temperature) related to each stock used to stablish Sullivan's equations are shown in his paper, for the non-gadoid group, the range of temperature of the stocks was in 3–15°C, and *Opisthonema* spp. inhabits waters with a mean temperature of 24°C (Vera and Vera, 2016). Besides that, $K$ and $w_\infty$ parameters for non-gadoid group were in range of 0.05–0.7 and 25–31 000 g respectively, which disagreed with biological parameters of tropical and subtropical fishes. Therefore, the equation provided overestimated *r* values in the present study. The opposite was observed when the model was parameterized using the *r* estimates from FishBase, based on two evaluations of the *O. libertate* stock. The new pair of values coincided with high population growth rates according to Martel and Froese (2013) categorization, typical of pelagic fish such as the thread herring, this was reflected in the number of selected *r*-*k* pairs for each stock.

### 4.3 *Exploitable biomass and stocks status*

As a result, the biomass estimates and TRP obtained using the Catch-MSY method suggested that the stocks (the GC and western BCS coasts) decreased in biomass over the years and were currently very close to the full exploitation point. This result is far from being positive because although both stocks are near the point of highest productivity $\left(\frac{1}{2}k\right)$, the trend of biomass over the past few years is negative. The biomass of the thread herring stock in the GC decreased 26.5% from 2004 to 2009 and the biomass on the western BCS coast decreased 41.2% from 2009 to 2018. Therefore, an adaptive management approach should be used. Otherwise, if this trend continues, the biomass of both stocks could be below the $B_{MSY}$ over the short term; this would be indicative of overexploitation. Furthermore, in recent years, catches have exceeded the MSY estimate, which, combined with an increase in fishing mortality, has led to significant negative changes in the biomass of both stocks. This suggests that the management strategies that historically have been used to exploitation control of the resource have not been the most effective to adequately get with the changes in population dynamics and to fishery pressure, this is mainly due to the lack of periodic updates of management measures, e.g., minimum capture size among others.

### 4.4 *Method effectiveness*

Estimates using the Catch-MSY method have been criticized with the argument that they do not have the robustness and precision of estimates obtained using structured models. It has been said that this method could overestimate the carrying capacity

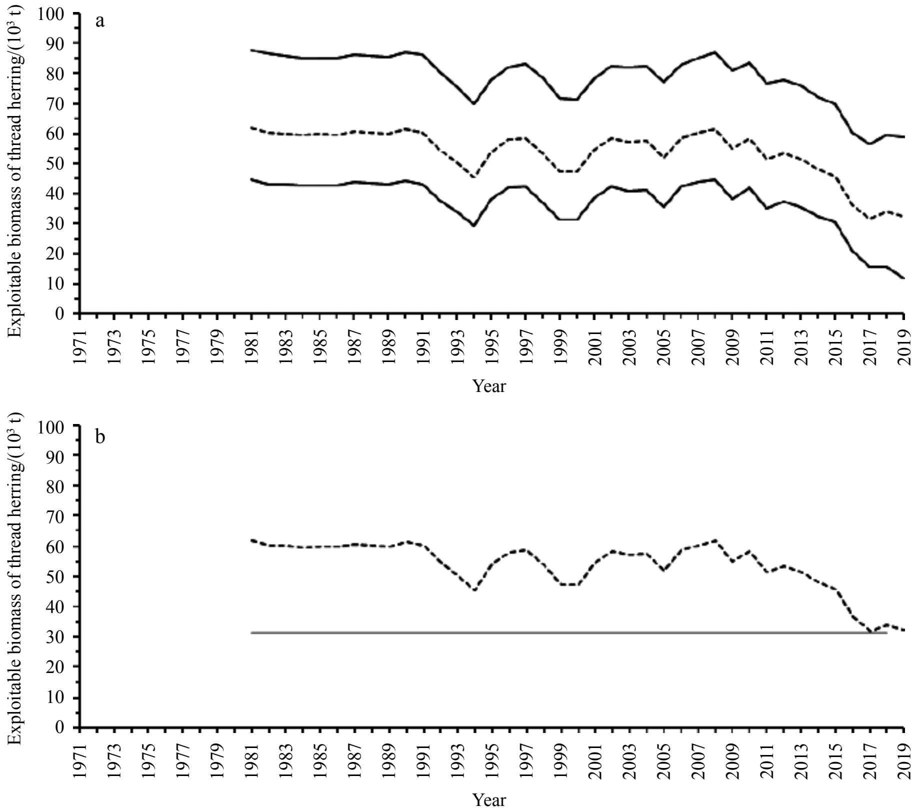


**Fig. 7.** Historical series of exploitable biomass of thread herring estimated for the western BCS coast. Dotted line represents geometric mean, solid lines in a represent 2.5% and 97.5% percentiles, and solid line in b represents $B_{MSY}$.

and fishing reference points by approximately 10%, which could lead to overestimating the estimated biomass and $B_{MSY,}$ however, it has been assumed that the estimates using this method are reliable and coincide with those of other approaches; additionally, to contend with a potential overestimation of biomass and $B_{MSY}$, those estimated in the lower confidence interval are recommended. Kimura and Tagart (1982) argued that all evaluation methods have weaknesses and that ascertaining which is more precise and which includes errors is a very complicated process. The original paper by Martell and Froese (2013) contrasted estimates obtained with the Catch-MSY method with 48 previously evaluated stocks (International Commission for the Exploration of the Sea–ICES and RAM legacy), using structured models and independent fishery indicators (Ricard et al., 2012) and did not detect significant differences in the estimates obtained between methods, which strengthens the evidence in favor of the robustness, veracity and applicability of this method. In this sense, various authors have evaluated important fishing resources around the world using this tool. Zhang et al. (2018) estimated the maximum sustainable yield for three fisheries (*T. japonicas*, *L. polyactis* and *L. crocea*) from the east of the China sea areas using the Catch-MSY of Martell and Froese (2013). The MSY estimates for the *T. japonicas* and *L. polyactis* fisheries were compared with those from various approaches. For *T. japonicas*, the MSY estimate ($7.76\times10^5$ t) was similar to the estimates of Xu et al. (2011) using the stock-recruitment model ($7.00\times10^5$ –$7.05\times10^5$ t), Wang and Liu (2013) using the surplus production model ($7.16\times10^5$ –$7.99\times10^5$ t) and the model of Bayesian state-space ($7.55\times10^5$ t) (Zhang and Chen, 2015). The estimate for *L. polyactis* ($13.79\times10^4$ t) was similar with those from Schaefer production model ($13.6\times10^4$ t) by Li et al. (2011), Bayes-based Pella-Tomlinson model ($11.4\times10^4$ t) and Fox model ($11.7\times10^4$ t) by Lin (2009). According to Zhang et al. (2018), the estimates from the Catch-MSY method are similar to the Schaefer production model because the Catch-MYS model is a transformation of the Schaefer production model, and tends to be better than other approachs. The authors considered that the results obtained with this method were satisfactory and it is a plausible option with few data requirements for the evaluation of various fish populations in China sea areas. Ji et al. (2019) evaluated the fishery and estimated reference points for largehead hairtail *T. lepturus* in the Yellow Sea and the Bohai Sea using Catch-MSY method, Bayesian state-space Schaefer surplus production model, classical surplus production models (Schaefer & Fox) performed by software CEDA (a catch effort data analysis) and ASPIC (a surplus production model incorporating covariates) based on annual fisheries statistics for China (1986–2012). They reported that all methods estimated similar MSY values ($19.7\times10^4$–$27.0\times10^4$ t), however, contrary to the rest of the methods, Catch-MSY and BSM produced reasonable values of *r* and *k*. Based on the parameters and MSY estimates, as well as empirical fishery and biological data, which suggests an overexploitation of the resource, the authors conclude that the BSM model provided the most adequate information for the management of the largehead hairtail in the Yellow Sea and the Bohai Sea. A future study would contrast this study's results of Cath-MYS approach against those of Catch-MSY and BSM models, analyzing the thread herring fishery data in northwestern Mexico. Enciso (2014) evaluated the *Cynoscion othonopterus* fishery in the upper GC, to obtain catch quotas as a management measure, using 3 methods: Catch-MSY, Thompson and Bell (1934) predictive model, and

Schaefer-Gordon bioeconomic model. Results obtained for the three models and those by other authors (Ruelas-Peña et al., 2013; Castro-González et al., 2013) were very similar (range from $3.1\times10^3$ t to $3.6\times10^3$ t), the authors concluded that the Catch-MSY method can be useful for the evaluation and management of this fishery in the upper GC. Rodríguez-Domínguez et al. (2014) evaluated the fishery of the crabs *Calinectes bellicosus* and *C. arcuatus* in the GC, for which no previous biomass estimates existed and assumed that obtained estimates were trustworthy. They also argued that due to the need for sustainable management, a simple method such as the Catch-MSY is useful for the management of this fishery.

Currently, many fisheries around the world need to be evaluated periodically, for sustainable management. Like the authors to which reference has been made, the Catch-MSY method was considered to be a suitable approach to assess and manage fisheries with insufficient data, the methods based on catch data offered a viable alternative to non-data poor fisheries were considered to conduct annual stock assessments that could be integrated into a fisheries modeling framework. However, the strength and weakness of this approach lie in its relative simplicity and precision in its parameterization. Therefore, it is very appropriate to have previous biomass estimates, and better if they come from different approaches, which will allow evaluating the bias of the estimates and will affect the definition of the status of the exploited stock. Thus, this study consider that biomass estimates obtained with the Catch-MSY method were adequate for the thread herring stocks off the northwestern Mexican coast. Based on these estimates, a management plan that controls mortality from fisheries through the assignation of quotas would be possible. García-Borbón (2009) stated that independently of the management scheme, knowing the size of the population and the fraction available for exploitation is essential. However, in most exploited populations, biomass evaluations are currently not very frequent. This is mainly due to the scarcity and difficulty of obtaining biological and fishery information (Enciso, 2014).

### 4.5 *Method limitations*

This study should point out that estimates for the two stocks (the GC and western BCS coast) were carried out using a method based on Schaefer's production model, which assumes that parameters are constant over time and does not take into account environmental effects on stock productivity, being this, the principal method limitation because hyperstability in catches could lead to biomass and TRP's overestimation. This is relevant because fish populations, especially pelagic fish, can be highly sensitive to environmental variability (Barange et al., 2009; Hsieh et al., 2009). In fact, small pelagic fish are recognized as being highly sensitive to environmental changes, which leads to important changes in their abundance and distribution (Perrotta et al., 2001). Fréon et al. (2005) commented that environmental variability can change fish distributions with considerable fishery implications, affecting migration patterns, appearance of others opportunistic or well adapted fishes and stock catchability. According to MacCall (1975) and Radovich (1976), this changes in catchability are characteristics of highly gregarious pelagic fish populations where catchability is a function of population biomass. The influence of environmental changes in small pelagic fish behavior in northwestern Mexico has been studied before (e.g., Ruiz-Luna and Lyle, 1992; Cisneros-Mata et al., 1995; Lanz et al., 2009), Lluch-Belda et al. (1986) commented that, variations in climate related to El Niño/Southern oscillation reflect substantial temporal changes in the distribution and abundance of small pelagic fishes in GC (Pacific sardine and thread herring). El Niño events affects school structure due to food production decrease, making fish schools dense but scarce (Ruiz-Luna and Lyle, 1992), when abundance of small pelagic fish decreases significantly in unfavorable environmental conditions and their tendency to form schools that make them susceptible to increases in exploitation rates (Zwolinski and Demer, 2012), due to decrease in abundance masked by relatively stable catches.

According to Post et al. (2002), it is called the “illusion of abundance”; when the stock is presumed healthy, fishing activities continue unabated, emergency management measures are not taken until both the fishery, and the stock are in trouble or close to collapse. Therefore, it is important to take into account the effect of environmental pressure on the ecological behavior of populations when making biomass estimates, thus, one of the riskiest scenarios when using the Catch-MSY method in biomass estimates lies in potential existence of hyperstability or “illusion of abundance” in the data series. The method assumes proportionality between the catch and the level of stock abundance, therefore, the biomass estimates would include a positive bias, negatively affecting the reference points and management recommendations. To reduce this bias, frequent (annual) biomass estimates are required to identify this type of anomaly in the catch data. Likewise, it is important to incorporate independent indicators of the fishery together with a precautionary approach in management strategies.

## 5 Conclusions

However, results obtained in this study show the current and historical outlook of biomass changes of thread herring stocks in northwestern Mexico, as well as the trend of biomass under the current fishery regime. This study considers that the Catch-MSY method is adequate to obtain annual biomass estimates of this resource, from which allowable annual catch quotas can be established and the state of the resource can be analyzed, avoiding surpassing the recuperation potential of the stocks.

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