

# Protecting spawners in vulnerable fishery resources. The case of groupers in the southern Mexican Caribbean

## Protección de desovantes en recursos pesqueros vulnerables. El caso de los meros en el sur del Caribe mexicano.

Eloy Sosa-Cordero\* ✉, José Manuel Castro Pérez\*\* & Angélica Ramírez González\*

### Abstract

Based on a declining function of natural mortality  $M_a$  with age, with juveniles living in shallow waters, and assuming there is a refugium (natural or regulatory) for adults in deeper waters, Caddy (2018) developed a conceptual model for a fishery targeting juveniles as an alternative to achieve a healthy spawning stock. In the present work, we explore this option for two species of groupers, Black grouper (*Mycteroperca bonaci*) and Nassau grouper (*Epinephelus striatus*) in the southern Mexican Caribbean. Vulnerability to the fishery of these groupers increases during the winter, when they form spawning aggregations. Using fishery parameters estimated for both species in BR Banco Chinchorro during 2003-2004, we examine the changes in the spawning potential ratio (SPR) with fishing mortality  $F$  under three scenarios: *A*)  $M$  constant -Selectivity, asymptotic (logistic); *B*)  $M$  at age- Selectivity, asymptotic (logistic); *C*)  $M$  at age- Selectivity, dome-shaped. For a given level of fishing mortality  $F$ , the SPR index consistently attained higher values in *B*) and *C*) compared to *A*), the conventional assumption. For all scenarios, when  $F$  increased, the ages with greater contribution to the spawning potential were progressively younger. Based on our results, is highly probable that the grouper fishery in Biosphere Reserve (BR) Banco Chinchorro targeting sub-adults and younger adults can maintain a healthy spawning stock of adults. The latter being conditioned to avoid increases on fishing effort and any changes in the current fishing method: free-diving and spearfishing. We encourage to conduct further research on this fishery, and to develop monitoring programs to track changes on the status of these highly valued groupers.

**Keywords:** Spawning potential ratio, data-limited fishery, LIME method, selectivity,  $M$ -at-age

### Resumen

A partir de una función decreciente de la mortalidad natural  $M_a$  con la edad, con juveniles que habitan aguas someras y suponiendo que existe un refugio (natural o por regulación) para adultos en aguas más profundas, Caddy (2018) planteó un modelo conceptual de una pesquería dirigida a juveniles como una alternativa para tener un *stock* reproductivo saludable. En el presente trabajo exploramos esta opción para dos especies de meros, el negrillo (*Mycteroperaca bonaci*) y el mero del Caribe (*Epinephelus striatus*) en el sur del Caribe mexicano. La vulnerabilidad a la pesca de estos meros aumenta durante el invierno, cuando forman agrupaciones reproductivas. Mediante el uso de parámetros pesqueros estimados para ambas especies durante 2003-2004, se revisaron los cambios en la razón potencial reproductivo (SPR, siglas en inglés) con respecto a la mortalidad por pesca  $F$  en tres escenarios: *A*)  $M$  constante, selectividad asintótica (logística); *B*)  $M$ -por-edad, selectividad asintótica (logística); *C*)  $M$ -por-edad, selectividad en forma de

\* Departamento de Sistemática y Ecología Acuática/ECOSUR-Unidad Chetumal. Ave. Centenario km 5.5, 77014 Chetumal, Quintana Roo, México ✉Corresponding author: esosa@ecosur.mx

\*\* Tecnológico Nacional de México. Instituto Tecnológico de Chetumal. División de Posgrado e Investigación. Ave. Insurgentes núm. 330, Col. David Gustavo Gutiérrez. 77013 Chetumal, Quintana Roo, México.

domo. Para un determinado nivel de mortalidad por pesca  $F$ , el índice SPR sistemáticamente alcanzó valores más altos en  $B$ ) y  $C$ ) en comparación con  $A$ ), la suposición convencional. En todos los escenarios, conforme aumentó  $F$ , las edades con mayores contribuciones a potencial reproductivo fueron cada vez más jóvenes. Con base en nuestros resultados, es muy probable que la pesquería de meros en la RB Banco Chinchorro, dirigida a subadultos y adultos jóvenes pueda mantener un *stock* de adultos en condición saludable. Esto último condicionado a evitar aumentos en el esfuerzo de pesca y algún cambio en el actual método de pesca: buceo libre y arpón. Recomendamos efectuar más investigación acerca de esta pesquería y desarrollar programas de monitoreo para seguir los cambios en el estado de estos meros altamente valiosos.

**Palabras clave:** razón de potencial reproductivo, pesquería con datos limitados, método LIME, selectividad,  $M$ -por-edad.

## Introduction

Fisheries analysis addresses fishery systems' inherent complexity and uncertainty, with multiple processes at various spatiotemporal scales as well as the economic and social dimensions of fishing activity. A multidisciplinary approach is required to deal with such a broad range of issues. Consequently, in the last decade, the vision of fisheries as social-ecological systems (SSE) advanced toward consolidation (McGinnis & Ostrom 2014, Palomo & Hernández-Flores 2019). In recent years, concern for the state of fishery resources on a global scale has continued to grow (FAO 2020, Melnychuk *et al.* 2020), the same as the persistent aspiration to achieve sustainable use.

Advances in fisheries science continue, as exemplifies the new generation of quantitative methods for stock assessment under data-limited circumstances (Hordyk *et al.* 2015, 2016, Froese *et al.* 2018, Rudd & Thorson 2018, Dichmont *et al.* 2021). On the other hand, questions remain that warrant further efforts by fisheries management scholars and practitioners. One interesting issue, at first glance counterintuitive, is the development of fisheries targeting sub-adult fish while maintaining a healthy adult spawning stock (Abella *et al.* 1997). The capture of sub-adults apparently contradicted a basic tenet of the dominant paradigm of fisheries theory, which recommends postponing the catch of fish, allowing them to participate at least once, on average, in the reproductive process before removal by fishing (Froese 2004).

In a review of Mediterranean fisheries, Caddy (1993) referred to the juvenile fishery and suggested that stock assessment there should prioritize maintaining the spawning stock and the stock-recruitment relationship rather than maximizing yield per recruit. Later, he contributed to research on the coastal fishery for juvenile hake *Merluccius merluccius* (Linnaeus

1758) in the Mediterranean (Abella *et al.* 1997, Caddy & Seijo 2002). This fishery remained healthy despite fishing pressure on juveniles/sub-adults (Abella *et al.* 1997). Then, the onset of exploitation of adults in deeper waters by other fleets resulted in the deterioration of the coastal fishery (Caddy 2018). Thus, the feasibility of the sub-adult fishery relied on the existence of a refugium (natural or artificial) that helped to maintain a healthy reproductive stock of adults in deeper waters, also being responsible for supplying sub-adults to inshore waters (Caddy 2018).

One motivation for the present work is to explore the feasibility, in the Mexican Caribbean, of a grouper fishery based on catching sub-adults while maintaining a healthy reproductive stock of adults. Of course, this possibility must consider the circumstances and factors prevailing in the region. Among multiple research questions on the subject, this paper examines the behavior of the spawning potential ratio (SPR), a widely used index in data-limited fisheries. In particular, on how this index responds to increasing levels of fishing mortality  $F$ , under three scenarios of natural mortality  $M$  and fishing selectivity.

### *The grouper fishery*

Groupers are fish of the family Epinephelidae of ecological importance for their role as predators in coastal-marine environments, particularly in rocky bottoms and coral reef ecosystems. They have high economic and social value as a significant target resource in small-scale fisheries in tropical seas worldwide. Numerous grouper species inhabit the Gulf of Mexico and the Caribbean Sea, including the Red Grouper *Epinephelus morio* (Valenciennes 1828), which together with the Black Grouper *Mycteroperca bonaci* (Poey 1860) and Gag *Mycteroperca microlepis* (Goode & Bean 1879) are the main grouper species subject to fishing in the Campeche Bank (Gimenez-

Hurtado *et al.* 2005, Coronado-Castro *et al.* 2013, Monroy-García *et al.* 2014, Renán *et al.* 2022).

In the Mexican Caribbean, with geographical borders corresponding to the state of Quintana Roo (Mexico), in the northern sector, with an extensive continental shelf, the grouper fishery has similar features to that of the Campeche Bank, including the same main species aforementioned, as well as the operation of two fleets, artisanal or small-scale and semi-industrial (Sosa-Cordero *et al.* 2009, Ramos Miranda *et al.* 2013). In contrast, in the southern Mexican Caribbean, which has a narrow shelf, the main species are the Nassau grouper *Epinephelus striatus* (Bloch 1792) and the Black Grouper *M. bonaci* (Sosa Cordero *et al.* 2009, Castro Pérez *et al.* 2011). Only the artisanal, small-scale fleet operates there, precisely the same as in the Banco Chinchorro Biosphere Reserve (Castro Perez *et al.* 2011).

Groupers have biological and ecological characteristics such as slow growth, large size, and late maturity that make them a resource prone to overexploitation. Their reproductive biology is quite complex. The black grouper *M. bonaci* presents protogyny; at hatching, they are all females, and only after the first maturation does a fraction of fish change sex and become males. The same happens in the grouper *E. striatus*. Another relevant feature in both species, usually territorial and solitary habits, is the formation of reproductive aggregations that predictably concur each year at specific sites and dates around the full moon. Such breeding behavior makes their populations highly vulnerable to fishing during the mass mating season. In response, managers have applied spatiotemporal management tools, such as closures during the breeding months in Mexico and other Caribbean countries or the closure of fishing of traditional fish spawning aggregation sites.

Regarding the management tools mentioned earlier applied in both grouper species, the question arises: What happens the rest of the year, outside the reproductive months, across the fishing areas where these species occur? In this context, the feasibility of a grouper fishery based on the capture of sub-adults and young adults becomes interesting. It makes sense to explore this option using the information from the grouper fishery in the Biosphere Reserve (BR) Banco Chinchorro, where free diving and spearfishing are the only

fishing methods employed (Sosa Cordero *et al.* 2009, Castro Pérez *et al.* 2011). The latter restricts fishing effort to shallow waters, depth <15-18 m, and reduces the fishing vulnerability to large adults inhabiting deeper waters >18-20 m, particularly during the months outside the reproductive season, typically from November/December to February/March.

This paper examines the behavior of the spawning potential ratio SPR, a widely used index in data-limited resource assessment. The information from the grouper fishery in the BR Banco Chinchorro allows us to explore the feasibility of harvesting sub-adults and young adults while maintaining a healthy reproductive stock. Thus, we analyzed in detail the variation of the SPR index at increasing levels of fishing mortality  $F$  under three scenarios with different patterns of natural mortality  $M$  with age and fishing selectivity.

## Materials and methods

The grouper fishery in the Biosphere Reserve (BR) Banco Chinchorro is considered data-limited given the absence of a regular monitoring program (Sosa Cordero *et al.* 2009, Castro-Pérez *et al.* 2011). To our knowledge, there is no additional information on the fishery, apart from the data collected in surveys from 2003-2004 (Castro-Pérez *et al.* 2011), which we analyzed in this paper. The total yearly catch of grouper did not discriminate species, and there are no available annual samples of length/age composition, nor indices of abundance, *e.g.*, catch per unit effort.

Data for both grouper species were collected monthly from August 2003 to June 2004 in the Banco Chinchorro grouper fishery, only using free diving and speargun as fishing method (Castro Pérez *et al.* 2011). Specimens in the sample were measured for total length (TL) to the nearest centimeter and gutted weight in kilograms. Firstly, we grouped the length data by month and then pooled it to represent the entire period in histograms with a bin amplitude of 4 cm for *E. striatus* and 5 cm for *M. bonaci* (Fig. 1).

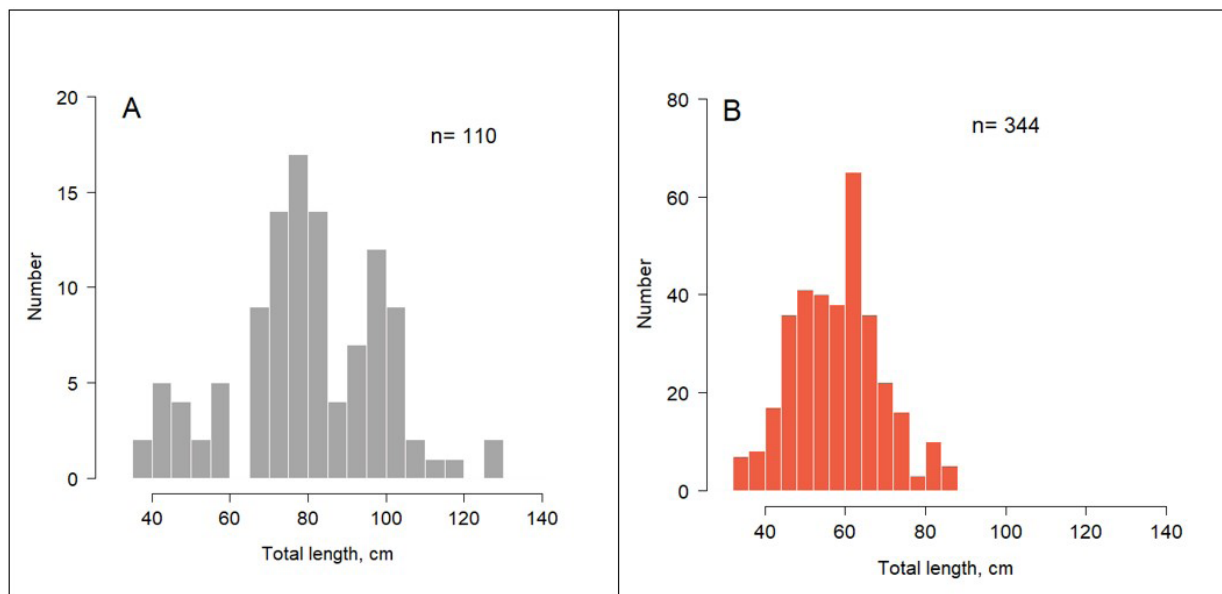


Fig. 1. Total length (TL) in cm frequency distribution for two main species in the grouper fishery of Biosphere Reserve Banco Chinchorro during 2003-2004; A) *Mycteroperca bonaci*, length interval of 5 cm; B) *Epinephelus striatus*, length interval 4 cm.

Life history parameters from the literature, mostly values reported in the region or close areas, included the von Bertalanffy growth model, length/age at first maturity, and parameters  $\alpha$  y  $\beta$  of the weight-length relationship (Table 1). Based on the maximum lifespan in years (Table 1), we estimated natural mortality  $M$  with two indirect methods according to Durueil *et al.* (2021). For each species, a constant  $M$ ,  $M_c$  was estimated with the *Estimator Tmax* method given by:

$$M_c = \exp((1.55 - 1.066 \cdot \log((tmax)))) \quad \text{eq. 1}$$

Also, we estimated a vector of  $M$  values as a function of age  $a$  with the *Estimator Lta* method:

$$M_a = M_c \cdot L_{ta} / L_a \quad \text{eq. 2}$$

Where:  $M_c$  is the value of constant  $M$  given above, and  $L_{ta}$  is the length corresponding to the  $ta_{ht}$  age in years, from which it is appropriate to assume a constant  $M$  (Durueil *et al.* 2021). The age  $ta_{ht}$  was defined as:

$$ta_{ht} = [(2/\log P)+1] \cdot tmax \quad \text{eq. 3}$$

Where:  $P=0.018$  is a value estimated by Durueil *et al.* (2021).

With the length data in BR Banco Chinchorro in 2003-2004 and life history parameters (Table 1), the length-based integrated mixed effects (LIME) method (Rudd & Thorson 2018) was applied to only length data, to make a first stock assessment, separately for each species. This assessment was a minor objective of the present work. It was a means to gather information needed to analyze the behavior of the spawning potential ratio SPR. The LIME method produced estimates of fishing mortality  $F$  for the period 2003-2004,  $F_c$ , parameters SL50 and SL95 of the logistic model of selectivity and maturity at age for the populations of both grouper species in the BR Banco Chinchorro. The LIME method was applied using the code in R language (Rudd & Thorson 2018).

Table 1.

Life history parameter values used as input in the LIME method to conduct the stock assessment of groupers in Banco Chinchorro (BR) and to estimate the natural mortality rate  $M$  by indirect methods

Parameters	Black grouper, <i>Mycteroperca bonaci</i>	Nassau grouper, <i>Epinephelus striatus</i>	Notes, sources
Growth, VBGF			
$L_{\infty}$ (cm, TL)	144.82	80.2	
$k$ (1/year)	0.09 (0.09, 0.10)	0.155	<i>M. bonaci</i> (Mb): Renán <i>et al.</i> (2022)
$t_0$ (year)	-0.81 (-0.96, -0.67)	-0.832	<i>E. striatus</i> (Es): Stock <i>et al.</i> (2021)
CVL	--	0.092	
Lifespan			
$t_{max}$ (years)	33	29	Mb: Renán <i>et al.</i> (2022) Es: Sadovy & Eklund (1999)
Maturity ( %), age			
50% A50 (years)	5.5	5	Mb: Renán <i>et al.</i> (2022) Es: Sadovy & Eklund (1999), L50 = 47.4 cm TL, equivalent to 4.94 years
100% A100 (years)	8	7	Mb: Renán <i>et al.</i> (2022) Es: Sadovy & Eklund (1999), L95 = 55.7 cm TL, equivalent to 6.82 years
Weight-Length relationship			
$\alpha$ intercept	$1.04 \cdot 10^{-5}$	$1.604 \cdot 10^{-5}$	Mb: Velázquez-Abunader <i>et al.</i> (2021); Es: This study.
$\beta$ slope	3.0902	2.97	Total weight in kg, total length TL in cm.

The spawning potential ratio SPR is a widely used index in data-limited fisheries, helpful to define both target (TRP) and limit reference points (LRP) associated with fishing mortality  $F$  (Ogle 2016, Hordyk *et al.* 2015, 2016). In such fisheries, the lack of information often precludes obtaining more elaborate indicators such as TRP or LRP, e.g., the maximum sustainable yield (MSY) and the corresponding fishing mortality,  $F_{mys}$ . The spawning potential ratio SPR consists of the quotient of the reproductive potential  $P$  at a given level of fishing mortality  $F$ :  $P_{fished}$  ( $F > 0$ ), and the reproductive potential in the absence of fishing,  $P_{unfished}$  ( $F = 0$ ); that is

$$SPR = P_{fished} / P_{unfished}$$

The reproductive potential  $P$  is the sum of the product of three vectors:  $pr_{mat}$ , the proportion of fish (females) that reach maturity at age  $a$ ;  $fec$ , the fecundity in the number of eggs produced, on average, by a female of age  $a$ ; and, the cumulative annual survival of fish at age  $a$ . The latter is the cumulative product at age  $a$  of  $\exp(-(M + sel_a \cdot F))$  with natural mortality  $M$ , selectivity  $sel_a$ , and fishing mortality  $F$ . If the age-specific fecundity is unknown, it is approximated by  $w_a$ , the biomass or weight of fish at age  $a$  (Rudd & Thorson 2018). We applied this approximation to both species in this work. It is important to note that the SPR index assumes no density-dependent effects on reproductive activity or egg production. To calculate the SPR index values under three scenarios for both species, we followed

the procedure after Ogle (2016) and their code in the R program.

Fishing selectivity was represented in two ways, asymptotically with the logistic model and as a dome-shaped curve. The LIME method produced estimates of the parameters LS50 ( $L_s^{50}$ ) and LS95 ( $L_s^{95}$ ) of the logistic selectivity model as a function of length according to the equation:

$$S_j = 1 / \left( 1 + \exp \left\{ - \left[ \ln(19) (j - L_s^{50}) \right] / (L_s^{95} - L_s^{50}) \right\} \right) \quad \text{eq. 4}$$

Working with LIME, this logistic curve of selectivity with length is internally transformed into selectivity with age  $a$  in years. In the present work, all our analyses of selectivity considered age instead of length.

We represented the dome-shaped selectivity according to Rudd & Thorson (2018), with a curve having two branches: one ascending branch given by the logistic model (above), followed by a descending branch. The latter obeys an expression of the normal distribution used in selectivity models with the length for gillnets (Sparre & Venema 1998), according to the equation:

$$S_L = \exp \left[ - \frac{(L - L_m)^2}{2 \cdot s^2} \right] \quad \text{eq. 5}$$

Where:  $L_m$ : is the optimal length of maximum selectivity and  $s$  is the standard deviation of a normal distribution. In the present work, all the selectivity analyses considered age instead of length, as indicated before in the logistic case. The dome-shaped curve was applied directly to age data; therefore, we used optimal age  $a_m$  instead of  $L_m$ . In both species, the values of  $a_m$  preceded the age where the descending branch of the selectivity curve began, with values from the latter equation (Fig. 2). In *E. striatus*,  $a_m = 12$  years and  $s = 8.5$ , the descending branch of the curve began at age 13 years (Fig. 2B). For *M. bonaci*,  $a_m = 21$  years and  $s = 7$ , and the descending branch started at age 23 (Fig. 2A).

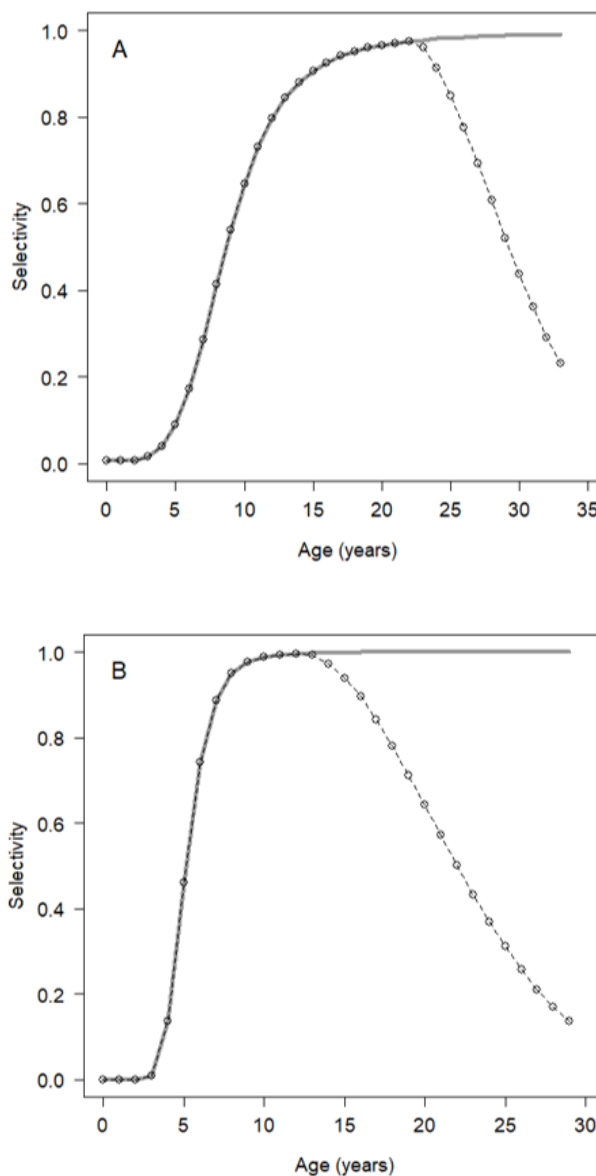


Fig. 2. Fishing selectivity in the grouper fishery of Biosphere Reserve Banco Chinchorro according to the logistic model (solid line) and a dome-shaped curve (dashed line, circles), for A) *Mycteroperca bonaci*, and B) *Epinephelus striatus*

The three scenarios referred to in the reproductive potential ratio SPR analysis were constructed as follows:

A) Natural mortality  $M$  constant ( $M_c$ ) and asymptotic selectivity following the logistic model.

B) Natural mortality  $M$  varied with age ( $M_a$ ) and asymptotic selectivity according to the logistic model

C) Natural mortality  $M$  variable with age ( $M_a$ ) and selectivity follows a dome-shaped curve. Results

**Results**

*Population parameter estimates*

The LIME method (Rudd & Thorson 2018) applied to only length data from available samples of

total length (LT, cm) of *Epinephelus striatus* and *Mycteroperca bonaci* in the period 2003-2004, produced for each species estimates of fishing mortality  $F$ , selectivity parameters LS50 and LS95 from the logistic model, and the index of spawning potential ratio SPR (Table 2). As an input to LIME, we need natural mortality rates  $M$  (1/year) constant ( $M_c$ ) previously estimated as 0.13 and 0.113 applying the indirect method *Tmax estimator* (Durueil *et al.* 2021), based on the maximum ages ( $T_{max}$ ) 29 and 33 years for *E. striatus* and *M. bonaci*, respectively (Table 2).

**Table 2.**

Estimates of the fishing mortality rate  $F$ (1/year), spawning potential ratio SPR index and selectivity parameters of the logistic curve resulting from the LIME method, and an estimate of natural mortality rate  $M$ (1/year) through the method *Estimador Tmax* (Dureuil *et al.* 2021)

Parameter/Index	Nassau grouper <i>Epinephelus striatus</i>	Black grouper <i>Mycteroperca bonaci</i>
Fishing mortality rate $F$ (1/año)	0.13	0.40
Spawning potential ratio, SPR	0.42	0.19
Selectivity, logistic model		
LS50 (TL, cm)	48.31	83.21
LS95 (TL, cm)	53.79	111.88
Natural mortality $M$ (1/año)		
$M_c$ , <i>Estimador Tmax</i>	0.13	0.113

We also estimated age-specific values of natural mortality  $M$  for each species with the indirect method *Lta estimator* (Durueil *et al.* 2021). The latter, according to a formula based upon constant  $M$  ( $M_c$ ) from the *Tmax estimator*, and *Lta*, the length corresponding to the age  $ta_{ht}$  from which it is

appropriate to assume constant  $M$  (Durueil *et al.* 2021). Thus, with estimates of  $M_c$ , 0.13 and 0.113, and *Lta* 72.8 and 114.5 cm LT, for *E. striatus* and *M. bonaci*, respectively (Table 2), we estimated values of the *M-at-age* vector for each species (Table 3).

Table 3.

Estimates of natural mortality rate  $M$ -at-age obtained using the method *Estimador Lta* (Dureuil *et al.* 2021) in this work

Age (years)	<i>Epinephelus striatus</i>	<i>Mycteroperca bonaci</i>
0	0.978	1.276
1	0.478	0.597
2	0.333	0.402
3	0.264	0.309
4	0.224	0.255
5	0.199	0.220
6	0.181	0.196
7	0.168	0.178
8	0.159	0.164
9	0.151	0.153
10	0.145	0.144
11	0.141	0.137
12	0.137	0.131
13	0.134	0.126
14	0.131	0.122
15	0.130 <sup>a</sup>	0.118
16	0.130	0.115
17	0.130	0.113 <sup>a</sup>
18	0.130 <sup>b</sup>	0.113 <sup>b</sup>

Notes: a)  $ta_{ht}$  = 14.6 years for *E. striatus*, and 16.6 years for *M. bonaci*; b)  $M$  is constant onwards until the maximum age of 29 years in *E. striatus*, and 33 years in *M. bonaci*.

#### Variation of the SPR index with fishing mortality $F$ .

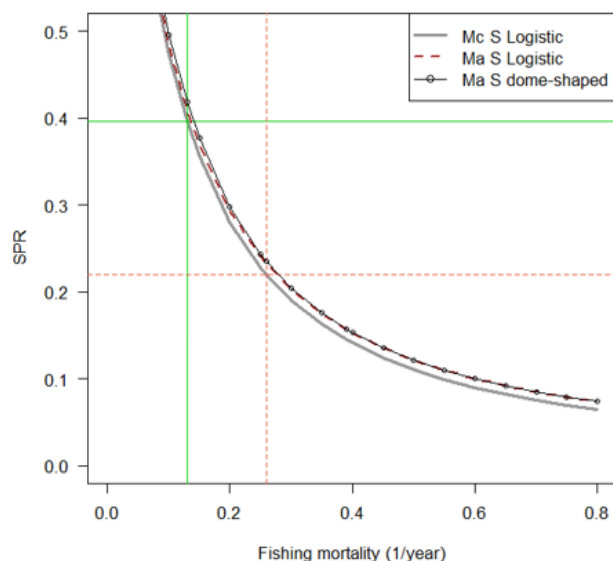
The variation of the spawning potential ratio SPR index with the level of fishing mortality  $F$  was analyzed separately for both grouper species to examine whether the SPR displays different patterns or behavior in response to changes in  $F$  values under three scenarios: A) Conventional, constant  $M$  ( $M_c$ ) and asymptotic selectivity, logistic model; B) Age-varying  $M$  ( $M_a$ ) and asymptotic selectivity, logistic model; and C) Age-varying  $M$  ( $M_a$ ) and selectivity, dome-shaped curve. The latter is probably the most realistic scenario since it reproduces the scheme in sub-adult fish fisheries off the Mediterranean, already described and analyzed (Caddy 1993, Abella *et al.* 1997, Caddy 2018).

Scenario A) Constant  $M$  ( $M_c$ ) and selectivity given by the logistic model is viewed as conventional because, currently, it is the most common assumption in fisheries analysis. As in most techniques, the LIME method we used in the stock assessment of exploited populations (stocks) of the two species presented here also assumes this scenario (Table 2).

In *Epinephelus striatus*, the variation of SPR with  $F$  did follow similar patterns among scenarios. However, the SPR values for scenarios B) and C) were consistently higher compared to those for scenario A), conventional (Fig. 3). To examine the response of the SPR to changes in fishing mortality  $F$ , we present the contribution curves of each age to the average egg production during lifespan. The increasing  $F$  levels were equivalent to one, two, and three times the natural mortality  $M$  and the curve in the absence of fishing,  $F = 0$  (Fig. 4).

In scenario A), as fishing mortality  $F$  increased from no fishing ( $F = 0$ ) to  $F = 1M$  and  $F = 2M$ , we observed a diminution in the total value of the reproductive potential  $P$  index. The ages with the highest contribution to total egg production shifted to the left, to lower ages (Fig. 4). Without fishing, ages eight to 12 made larger contributions, with 6.61, 6.89, 6.88, 6.68 and 6.36% each, together amounting 33.2% of the total of  $P = 13.576$  (Fig. 4). With  $F = 1M$ , ages 6 to 10 contributed the highest percentages with 9.4, 11.02, 11.02, 10.2 and 8.8% each, accumulating 50.62% of the total value of



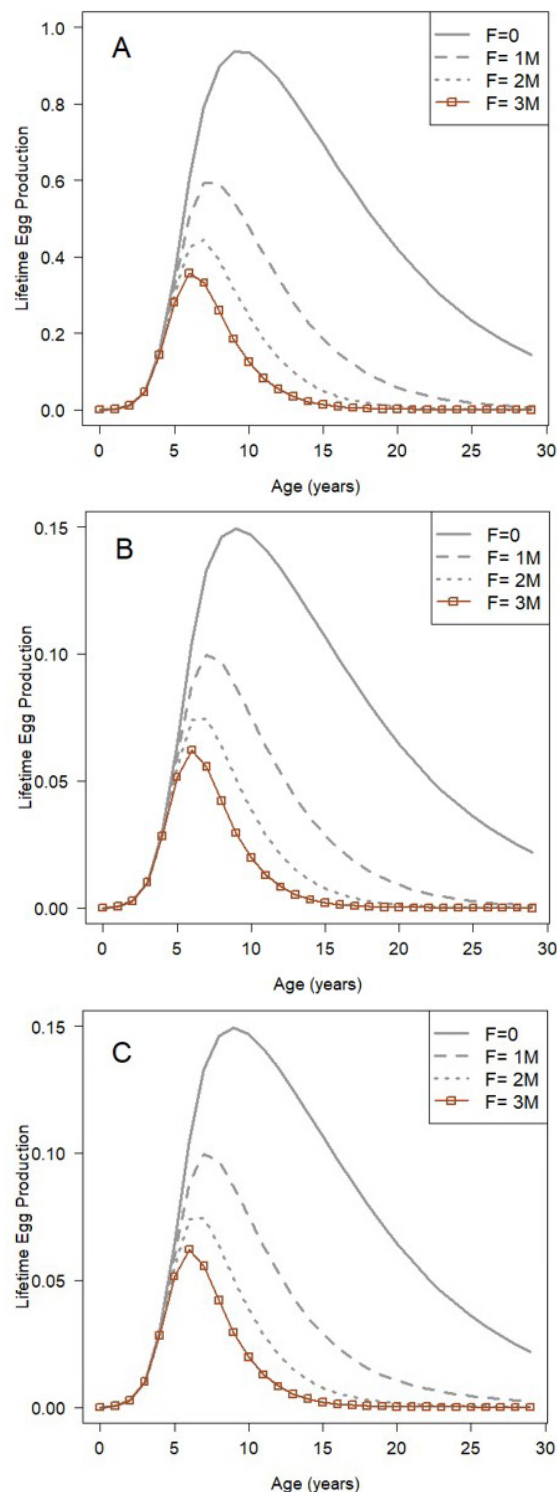


**Fig. 3.** Variation of the index of spawning potential ratio SPR with fishing mortality  $F$  for *Epinephelus striatus*, under the three scenarios of natural mortality  $M$  (Constant  $M_c = 0.13$ , age-dependent  $M_a$ ) and selectivity according to the logistic or dome-shaped curve. Are also indicated the current level of  $F$ ,  $F_c = 0.13 = 1M_c$  (solid line, vertical) its corresponding value of  $SPR = 0.3965$  (solid line, horizontal), and  $F = 0.26 = 2M_c$  (dashed line, vertical) and its value of  $SPR = 0.2197$  (dashed line, horizontal).

$P = 5.3824$ . For  $F = 2M$ , ages 5 to 9 had the higher contributions with 10.19, 14.24, 14.87, 13.14, and 10.63% each, representing 63.1% of the total value of  $P = 2.9828$  (Fig. 4).

Similar trends resulted in *E. striatus* in the remaining scenarios. Under **B**), variable  $M$  with age and logistic selectivity, with no fishing ( $F = 0$ ), ages seven to 12 had the highest contributions in percentage, with 6.19, 6.80, 6.94, 6.83, 6.56, and 6.2%, together amounting up to 39.52% of the total value of  $P = 2.1508$  (Fig. 4). For  $F = 1M$ , the more significant contributions were from ages six to 11, with 10.04, 11.34, 11.01, 9.91, 8.56 and 7.23%, which represented 58.1% of the total value of  $P = 0.87782$ . For  $F = 2M$ , ages five to 10 contributed the highest percentage, with 11.16, 14.81, 14.89, 12.78, 10.13, and 7.70% each, accumulating together 71.5% of the total value of  $P = 0.4998$  (Fig. 4). In scenario **C**), we observed a behavior very similar to **B**), with  $F = 2M$ , ages 5 to 10 together contributed to 70.7% of the total value of  $P = 0.50523$ .

In *Mycteroperca bonaci*, the variation of SPR with  $F$  did not show distinct patterns between the



**Fig. 4.** Variation of the index of average lifetime egg production with age for *Epinephelus striatus* under three scenarios: **A**) Natural mortality  $M$  constant,  $M_c = 0.13$ , and selectivity according to a logistic curve; **B**) Natural mortality  $M$  varies with age,  $M_a$ , and selectivity following a logistic curve; **C**) Natural mortality  $M$  varies with age,  $M_a$  and selectivity follow a dome-shaped curve. In each scenario are shown the curves with different levels of fishing mortality  $F$ , from  $F = 0$  (No fishing),  $F = 1M$  current level,  $F = 2M = 0.26$  and  $F = 3M = 0.39$ .

scenarios. Although SPR values in scenarios B) and C) were consistently higher compared to SPR from scenario A) (Fig. 5). To examine the response of the SPR index with changes in  $F$ , we present the curves of the contribution of each age group to the average egg production during its lifespan. Given the  $F$  values as multipliers of  $M_c$  natural mortality and compared to the curve in the absence of fishing,  $F = 0$  (Fig. 6).

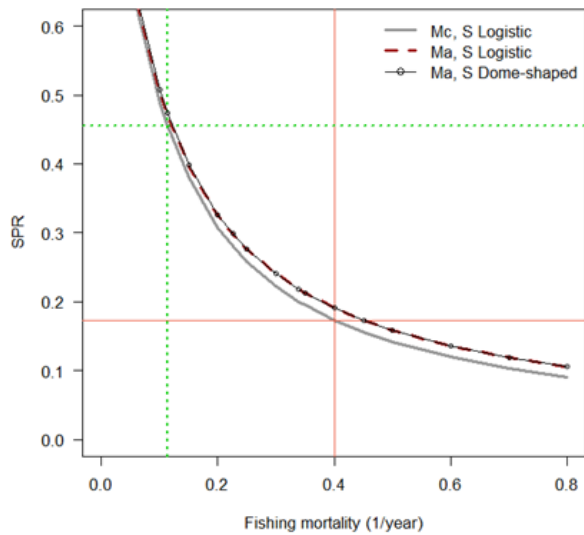


Fig. 5. Variation of the index of spawning potential ratio SPR with fishing mortality  $F$  (1/year) for *Mycteroperca bonaci* under three scenarios of natural mortality  $M$ , constant ( $M_c$ ) or  $M$ -at-age ( $M_a$ ) and selectivity, logistic or dome-shaped. Are also indicated two levels of  $F$ , the current  $F_c = 0.4$  ( $3.5M$ ), and  $F = 1M = 0.113$ , and their corresponding SPR values, 0.1734 and 0.4560. The latter calculated under the conventional assumption of  $M_c$  and logistic selectivity.

In scenario A), as fishing mortality  $F$  increased from no fishing ( $F = 0$ ) to  $F = 1M$ ,  $F = 2M$ , and the  $F = 0.4 = 3.54M$  estimated for 2003-2004, we recorded a reduction in the total value of the reproductive potential  $P$  index. The ages that contributed most to total egg production shifted to the left, to lower ages (Fig. 6). Without fishing, ten age classes nine to 18 had the higher contributions in percentage, from 4.43 to 5.27% each, together accounting for 49.6% of the total value of  $P = 67\ 343$ . With  $F = 1M$ , ages seven to 16 contributed with the higher percentages, from 4.8 to 8.25% each, accumulating 72.6% of the total value of  $P = 30\ 711$ . At the level of  $F = 3.54M$ , ages five to 13 years made larger contributions, from 4.73 to 14.56% each, amounting to 87.66% of the total value of  $P = 11.6758$  (Fig. 6).

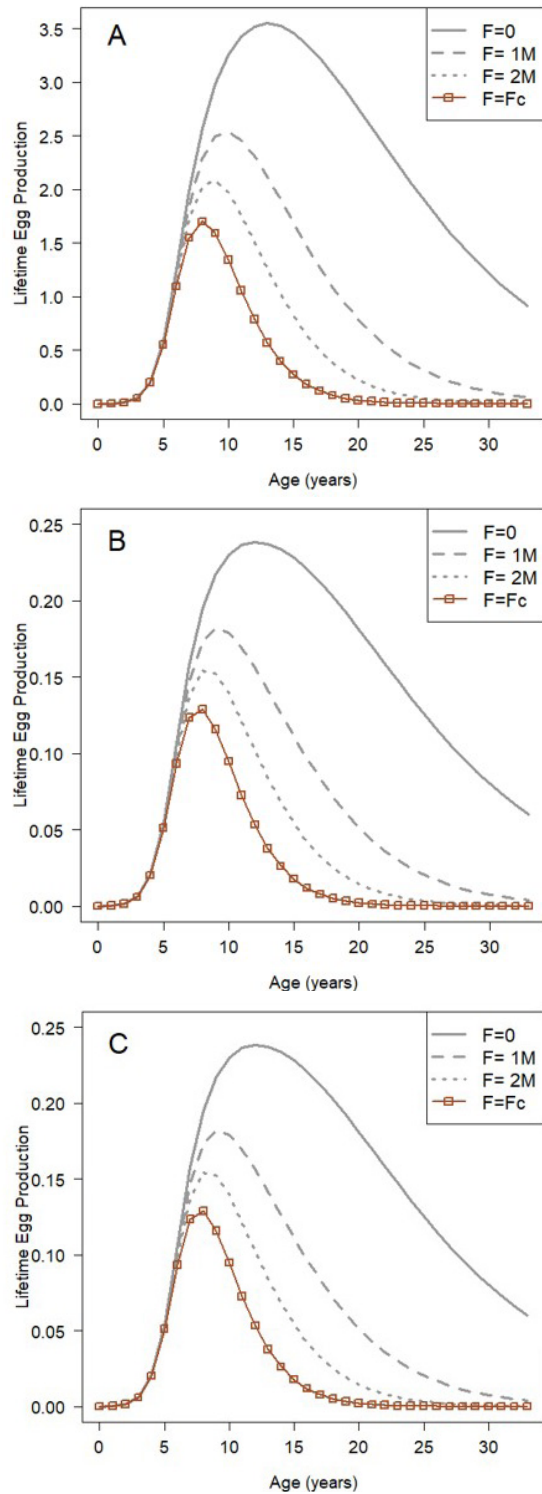


Fig. 6. Variation of the index of average lifetime egg production with age for *Mycteroperca bonaci* under three scenarios: A) Natural mortality  $M$  constant,  $M_c = 0.13$ , and selectivity according to a logistic curve; B) Natural mortality  $M$  varies with age,  $M_a$ , and selectivity following a logistic curve; C) Natural mortality  $M$  varies with age,  $M_a$  and selectivity follow a dome-shaped model. In each scenario are shown the curves with different levels of fishing mortality  $F$ , from  $F = 0$  (No fishing),  $F = 1M$ ,  $F = 2M = 0.26$ ,  $F = 3M = 0.39$ , and the current level  $F_c = 0.4$  ( $3.54M$ ).

We observed similar trends in *M. bonaci* in the remaining scenarios. In B), with age-dependent  $M$  values  $M_a$  and logistic selectivity, without fishing ( $F = 0$ ), ages nine to 18 years contributed with higher percentages, from 4.42 to 5.19% each, jointly representing 49.12% of the total value of  $P = 4.5924$  (Fig. 6). When  $F = 1M$ , ages six to 16 made larger contributions with percentages from 4.48 to 8.4% each, amounting 73.23% of the total value of  $P = 2.1632$ . At  $F$ ,  $F_c = 0.4$  (3.54M), ages five to 13 contributed with the highest percentages, from 4.32 to 14.69% each, together amounting 87.9% of the total value of  $P = 0.8766$  (Fig. 6).

In scenario C), we recorded a behavior quite similar to B). When  $F = 1M$ , ages six to 16 had contributions from 4.44 to 8.34% each, accounting for 72.7% of the total value of  $P = 2.1784$  (Fig. 6). For  $F = 2M$ , ages six to 14 contributed from 4.95 to 11.23% each, representing 77.0% of the total value of  $P = 1.3724$ . At the  $F$  level,  $F_c = 0.4$  (3.54M), ages 5 to 13 made larger contribution in percentages from 4.32 to 14.69% each, amounting to 87.9% of the total value of  $P = 0.8768$  (Fig. 6).

## Discussion and conclusions

The stock assessment for the Nassau grouper *Epinephelus striatus* and Black Grouper *Mycteroperca bonaci* in BR Banco Chinchorro using length data collected from 2003-2004 deserve a brief reference. The assessment of the status of each species separately with the LIME method, without assuming equilibrium and minimal information: an annual length sample of the commercial catch, allowed us to estimate fishing mortality  $F$ , SPR index, and logistic model selectivity parameters. Accordingly, *E. striatus* was subject to fishing pressure  $F = 0.113$ , equivalent to  $1M$  and  $SPR = 0.40$ ; in contrast, *M. bonaci* suffered a fishing mortality rate  $F = 0.40$ , equivalent to  $3.54M$  and  $SPR$  of 0.19. Thus, in addition to life history differences, we found that both species experienced different levels of exploitation according to LIME results. Data limitations imply high uncertainty in the  $F$  estimates and preclude using alternatives to double-check these first LIME results. These results also differ from the status of these species in the IUCN Red List of Threatened Species, which lists *E. striatus* as “critically endangered” (Sadovy *et al.* 2018), while *M. bonaci* is classified as “near

threatened” (Padovani *et al.* 2018). Thus, during 2003-2004 in the BR Banco Chinchorro, these species presented a conservation status opposite to the IUCN classification.

The following results come from analyses that are the primary objectives of the work, which consisted of unpacking the SPR index used to evaluate the state of resources with limited data, as in the case of the species analyzed here. In *E. striatus*, a species subjected to moderate fishing pressure, with fishing mortality  $F_c = 1M$ , the analysis of the SPR index with increasing values of  $F$  under different scenarios did not reveal any differences or notable changes in the patterns of variation of SPR. We observed that the SPR values were consistently higher in scenarios B) and C) compared to SPR values in scenario A), conventional. It was clear that reproductive potential  $P$  became more dependent on younger ages in all scenarios as fishing pressure increased from  $F = 0$  to  $F = 2M$  and  $F = 3M$ . Given that *E. striatus* was in better condition, this analysis allows us to anticipate, in general terms, what this species might face if there were future increases in fishing mortality  $F$  compared to what prevailed during 2003-2004.

In the case of *M. bonaci*, which supported a high fishing mortality  $F$ ,  $F_c = 0.4$ , equivalent to 3.54 times the natural mortality  $M_c = 0.113$ , under all three scenarios, the pattern of variation of SPR index with  $F$  levels did not show any substantial differences nor visible changes. We only noted that the values of SPR were consistently higher in alternative scenarios B) and C) compared to scenario A), conventional. It was also clearly observed that reproductive potential values were more dependent on younger ages and younger adults in all three scenarios as fishing pressure increased from  $F = 0$  to  $F = 2M$  and  $F = 3M$ . Based on practical experience, in the fishing grounds accessible to local fishers, it is less common to find *M. bonaci* than *E. striatus* (Sosa Cordero *et al.* 2009, Castro-Pérez *et al.* 2011). In addition to differences in abundance, it is also likely that *M. bonaci* occupies deeper water habitats, out of the reach of free-diving -the only fishing method used in BR Banco Chinchorro. Provisionally, on a precautionary basis, until there is a way to contrast these LIME results, *M. bonaci* should be considered subject to excessive fishing pressure, showing signs of increased vulnerability to fishing.

From methods assuming that prevail the conditions of scenario A), we obtain estimates of fishing

mortality  $F$ , which we used as input to calculate the spawning potential ratio SPR under three distinct scenarios, including A). In this context, it is difficult to avoid, in part, circular reasoning. However, if we accept our estimates of fishing mortality  $F$  for *E. striatus* and *M. bonaci* as given values, it is possible to analyze their significance in each scenario considered. Indeed, if *E. striatus* supported a fishing pressure  $F = 0.13$ , equivalent to  $1M$  during the study period, the SPR value corresponding to each scenario would be 0.3965, 0.4081, 0.4181, for scenarios A), B), and C), respectively. In the case of *M. bonaci*, for fishing mortality  $F = 0.40$ , equivalent to  $3.54M$ , the SPR index value in each scenario would be given by 0.1734, 0.1909, and 0.1909 for A), B), and C), respectively. Consistently, in both species, we observed a progressive increase in the SPR index value when going from scenario A) to C), which suggests a better resource state if B) and C) are verified. Since it is highly probable that conditions of scenario C) occur, future assessments must use a dome-shaped selectivity and a vector of age-dependent natural mortality ( $M_a$ ) to obtain realistic estimates of fishing mortality  $F$  and SPR index. Although the size of the differences in SPR reported in the present work were relatively small, their magnitude could also depend on the accuracy of the estimates of the selectivity parameters, especially in the dome-shaped curve, which requires more effort to obtain. Currently, two of the most widely used data-limited fisheries programs, LBS-PR (Hordyk *et al.* 2015, 2016) and LIME (Rudd & Thorson 2018), lack options to include  $M$  as a vector age-dependent values and do not estimate parameters for dome-shaped selectivity.

This kind of analysis based on minimal information (only length) and hypothetical scenarios is inappropriate for guiding management decisions. Instead, it is directed more at stimulating reflection on possible alternatives and weighting directions for new lines of research. The small-scale fishery of groupers in the central and southern Mexican Caribbean, where only operates an artisanal fleet with a fishing method restricted to coastal waters (Sosa Cordero *et al.* 2009, Castro Pérez *et al.* 2011), is *de facto* a fishery based on the capture of sub-adult and young adult fish, limiting its action to depths  $<20$  m. In the BR Banco Chinchorro, as long is avoided any increases in fishing effort and unchanged the fishing method with low effects on the reproductive stock of adult

*E. striatus* and *M. bonaci*, the current regulation (a two-month closed season for all groupers, February 1st to March 31th) seems useful. In order to maintain a healthy reproductive stock in deeper waters in the southern Mexican Caribbean it is necessary to complement the closed season by monitoring the spawning aggregation at traditional sites, inside and outside marine protected areas. It is also necessary to define the minimum legal size for both species, applicable in this shallow water visual fishery. It is urgent to implement basic fishery monitoring programs for groupers and other reef fish, locally known as *escama*, obtaining estimates of the size of the spawning aggregations in traditional sites annually and recruitment indices via sampling of juvenile abundance. All these proposals are feasible as they illustrate a program that began over a decade ago in the Cayman Islands (Waterhouse *et al.* 2020, Stock *et al.* 2021). Finally, this grouper fishery has ample potential for further research and management, considering conceptual models and alternatives developed by Caddy (2018).

## References

- Abella AJ, JF Caddy, F Serena. 1997. Do natural mortality and availability decline with age? An alternative yield paradigm for juvenile fisheries, illustrated by the hake *Merluccius merluccius* fishery in the Mediterranean. *Aquatic Living Resources* 10(5): 257-269. DOI: 10.1051/alr:1997029
- Caddy JF. 1993. Some future perspectives for assessment and management of Mediterranean fisheries. *Scientia Marina* 57(2-3): 121-130.
- Caddy JF. 2018. Conserving spawners and harvesting juveniles. Is this a better alternative to postponing capture until sexual maturity? In: JC Seijo, JG Sutinen (eds.). *Advances in fisheries bio-economics. Theory and Policy*. Routledge. EE. UU. pp: 25-57.
- Caddy JF, JC Seijo. 2002. Reproductive contributions foregone with harvesting: a conceptual framework. *Fisheries Research* 59(1-2): 17-30. DOI: 10.1016/S0165-7836(02)00011-5
- Castro Pérez JM, G Acosta González, JE Arias González. 2011. Characterizing spatial and temporal reef fisheries in Chinchorro Bank Biosphere Reserve, northern Mesoamerican Reef System. *Hidrobiológica* 21(2): 197-209.
- Coronado-Castro E, S Salas, T Brulé. 2013. Estimación de la composición de las capturas y la cuasi-renta

- de diferentes flotas dirigidas a la pesquería de mero rojo en Yucatán, México. *Proceedings of the Gulf and Caribbean Fisheries Institute* 65: 375-383.
- Dichmont CM, RA Deng, N Dowling, AE Punt. 2021. Collating stock assessment packages to improve stock assessments. *Fisheries Research* 236: 105844. DOI: 10.1016/j.fishres.2020.105844
- Dureuil M, WH Aeberhard, KA Burnett, RE Hueter, JP Tyminski, B Worm. 2021. Unified natural mortality estimation for teleosts and elasmobranchs. *Marine Ecology Progress Series* 667: 113-129. DOI: 10.3354/meps13704
- Froese R. 2004. Keep it simple: three indicators to deal with overfishing. *Fish and Fisheries* 5(1): 86-91. DOI: 10.1111/j.1467-2979.2004.00144.x
- Froese R, H Winker, G Coro, N Demirel, AC Tsikliras, D Dimarchopoulou, G Scarcella, WN Probst, M Dureuil, D Pauly. 2018. A new approach for estimating stock status from length frequency data. *ICES Journal of Marine Science* 75(6): 2004-2015. DOI: 10.1093/icesjms/fsy078
- FAO. 2020. *The State of World Fisheries and Aquaculture 2020. Sustainability in action*. FAO. Rome. 206p. DOI: 10.4060/ca9229en
- Giménez-Hurtado E, R Coyula-Perez-Puelles, SE Lluch-Cota, AA Gonzalez-Yañez, V Moreno-García, R Burgos-de-la-Rosa. 2005. Historical biomass, fishing mortality and recruitment trends of the Campeche Bank red grouper (*Epinephelus morio*). *Fisheries Research* 71(3): 267-277. DOI: 10.1016/j.fishres.2004.09.001
- Hordyk A, K Ono, JD Prince, CJ Walters. 2016. A simple length-structured model based on life history ratios and incorporating size-dependent selectivity: application to spawning potential ratios for data-poor stocks. *Canadian Journal of Fisheries and Aquatic Sciences* 73(12): 1787-1799. DOI: 10.1139/cjfas-2015-0422
- Hordyk A, K Ono, S Valencia, N Loneragan, J Prince. 2015. A novel length-based empirical method of spawning potential ratio (SPR), and test of its performance, for small-scale data-poor fisheries. *ICES Journal of Marine Science* 72(1): 217-231. DOI: 10.1093/icesjms/fsu004
- Melnichuk MC, N Baker, D Hively, K Mistry, M Pons, CE Ashbrook, C Minto, R Hilborn, Y Ye. 2020. Global trends in status and management of assessed stocks: achieving sustainable fisheries through effective management. *FAO Fisheries and Aquaculture Technical Paper* 665: 152p. DOI:10.4060/cb1800en
- Monroy-García C, G Galindo-Cortes, A Hernández-Flores. 2014. Mero, *Epinephelus morio* en la península de Yucatán. In: LFJ Beléndez-Moreno, E Espino-Barr, G Galindo-Cortes, MT Gaspar-Dillanes, L Huidobro-Campos, E Morales-Bojórquez (eds.). *Sustentabilidad y Pesca Sustentable en México. Evaluación y Manejo*. Instituto Nacional de Pesca. México. pp: 245-276.
- McGinnis M, E Ostrom. 2014. Social-ecological system framework: initial changes and continuing challenges. *Ecology and Society* 19(2): 30. DOI: 10.5751/ES-06387-190230
- Ogle DH. 2016. *Introductory Fisheries Analyses with R*. Chapman and Hall/CRC Press. EEUU. 338p.
- Padovani-Ferreira B, AA Bertoni, DA Pollard, B Erisman, E Sosa-Cordero, LA Rocha, A Aguilar-Perera, T Brule. 2018. *Mycteroperca bonaci*. The IUCN Red List of Threatened Species 2018: e.T132724A46916253. DOI: 10.2305/IUCN.UK.2018-2.RLTS.T132724A46916253.en
- Palomo LE, A Hernández-Flores. 2019. Application of the Ostrom framework in the analysis of a social-ecological system with multiple resources in a marine protected area. *PeerJ* 7: e7374. DOI: 10.7717/peerj.7374
- Ramos Miranda J, D Flores Hernández, A Sosa López, E Sosa Cordero, J López Rocha, F Arreguín Sánchez, A Ramírez González. 2013. Manual de indicadores y metodología para la aplicación del enfoque ecosistémico en las pesquerías en Yucatán, Campeche y Quintana Roo. RNIIPA/COFUPRO/UAC. México. 121p.
- Renán X, T Brulé, G Galindo-Cortes, T Colás-Marrufo. 2022. Age-based life history of three groupers in the southern Gulf of Mexico. *Journal of Fish Biology* 101(4): 857-873. DOI: 10.1111/jfb.15145
- Rudd MB, JT Thorson. 2018. Accounting for variable recruitment and fishing mortality in length-based stock assessments for data-limited fisheries. *Canadian Journal of Fisheries and Aquatic Sciences* 75(7): 1019-1035. DOI: 10.1139/cjfas-2017-0143
- Sadovy Y, AM Eklund. 1999. Synopsis of biological data on the Nassau grouper, *Epinephelus striatus* (Bloch, 1792) and the Jewfish, *E. itajara* (Lichtenstein, 1822). *NOAA Technical Report NMFS 146-FAO Fisheries Synopsis* 157: 68p.
- Sadovy Y, A Aguilar-Perera, E Sosa-Cordero. 2018. *Epinephelus striatus*. The IUCN Red List of Threatened Species 2018: e.T7862A46909843. 20p.
- Sosa-Cordero E, A Ramírez-González, J Olivares-Escobedo. 2009. Programa de ordenamiento pesquero del Estado de Quintana Roo.1.- Pesquería de meros y especies afines. Informe Final. CONAPESCA-SAGARPA/El Colegio de la Frontera Sur-Chetumal. México. 17p.
- Sparre P, SC Venema. 1998. Introduction to tropical fish assessment. Part 1. Manual. *FAO Fisheries Technical Paper* 306.1 Rev. 2: 407p.

Stock BC, SA Heppell, L Waterhouse, IC Dove, CV Pattengill-Semmens, CM McCoy, PG Bush, G Ebanks-Petrie, BX Semmens. 2021. Pulse recruitment and recovery of Cayman Islands Nassau Grouper (*Epinephelus striatus*) spawning aggregations revealed by in situ length-frequency data. *ICES Journal of Marine Science* 78(1): 277-292. DOI: 10.1093/icesjms/fsaa221

Velázquez-Abunader, I, T Brulé, MA Cabrera, JA López-Rocha. 2021. Length-weight relationships of four finfish commercial species from the southern

Gulf of Mexico. *Latin American Journal of Aquatic Research* 49(2): 369-375. DOI:10.3856/vol49-issue2-fulltext-2505

Waterhouse L, SA Heppell, CV Pattengill-Semmens, C McCoy, P Bush, BC Johnson, BX Semmens. 2020. Recovery of critically endangered Nassau grouper (*Epinephelus striatus*) in the Cayman Islands following targeted conservation actions. *Proceedings of the National Academy of Sciences* 117(3): 1587-1595. DOI: 10.1073/pnas.1917132117

*Received:* May 2, 2022.

*Accepted:* December 12, 2022.