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Research Article

Length-Based Spawning Potential Ratio (LB-SPR) for Red Grouper (*Epinephelus morio*) and Associated Species in the Commercial Fishery of the Yucatan Peninsula, Mexico

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The study calculated the Length-Based Spawning Potential Ratio (LB-SPR) for several species, including red grouper (*Epinephelus morio*), black grouper (*Mycteroperca bonaci*), gag grouper (*M. microlepis*), yellowtail snapper (*Ocyurus chrysurus*), lane snapper (*Lutjanus synagris*), hogfish (*Lachnolaimus maximus*), and white grunt (*Haemulon plumierii*). Data were obtained from the small-scale commercial fleet operating in the red grouper fishery on the Campeche Bank within the Yucatan Peninsula. Monthly records of total length (cm) from April 2017 to May 2018, totaling 10,182 fish, were collected from five fishing ports along the Yucatan Peninsula coast. Biological data, such as growth and reproductive patterns and exploitation parameters were gathered from scientific literature. The LB-SPR package on the R Core Team platform was utilized for analysis. Despite being the largest, groupers exhibited immaturity ($SL_{50} < L_{50}$) and low Spawning Potential Ratio (SPR). Red and black groupers showed particularly low SPR values (0.10 and 0.05, respectively), indicating a looming risk of local extinction. The gag grouper achieved the highest SPR value (0.26) among groupers, although it was very close to the minimum critical value (i.e., 0.20). Snappers, hogfish, and white grunt were generally captured in the adult state ($SL_{50} > L_{50}$). Yellowtail, hogfish, and white grunt displayed high SPR values (0.44, 0.72, and 0.98, respectively). Lane snapper had a low SPR (0.28) but fell within the range for maintaining satisfactory stock productivity, albeit with reduced yields. The findings emphasize the urgent need to adjust the current management framework for the red grouper fishery, focusing on improving fishing gear selectivity to address heightened pressure on both juvenile groupers and adult lane snapper. Implementing these measures is crucial to mitigate the risks of local extinction and population decline for each species.

1. Introduction

The reproductive output, i.e., the production of viable eggs, and subsequent recruitment processes, which are subject to environmental factors, leading to natural fluctuations in marine populations over time and space, constitutes crucial components in the dynamics of marine populations [1, 2]. Such fluctuations result from changes in both biotic and abiotic factors that affect growth and mortality rates during early life stages [2].

In marine populations, the frequency and timing of offspring release are determined by temporal reproductive patterns, which exhibit high variability in marine fishes and play a crucial role in their reproductive success throughout their lifespan [3]. The reproductive biology of a species has a profound impact on its productivity and, consequently, its ability to withstand exploitation or any human disturbance [4]. The reproductive process is essential for ensuring the sustainability of fisheries, highlighting the importance of evaluating and managing marine fisheries to protect and conserve the spawning populations of specific stocks [5]. Therefore, it is of paramount importance to quantify productivity in relation to reproductive potential (RP) and recruitment [4].

Stock depletion, caused by overfishing of recruitment, results in a decline in marine populations, leading to significant economic losses [6–8]. Furthermore, the increased fishing pressure on larger and older individuals, crucial for reproductive output, exacerbates the adverse impacts of overfishing [9, 10].

Currently, over fifty percent of marine fish stocks are actively being exploited up to their maximum sustainable yield, with approximately one-third of these stocks already experiencing overexploitation [8, 11]. This concerning trend is particularly evident in Mexican fishery resources, where more than a quarter of them are overfished [12]. Among these resources is the red grouper stock (*Epinephelus morio*, Epinephelidae) [13, 14], and its associated species [15], which are the primary targets of the red grouper fishery–the largest commercial fishery in the Yucatan region [16, 17].

Stock assessment is a complex and costly process [18, 19]. In fisheries where stock dynamics have not been evaluated, the negative effects of overfishing may not be immediately apparent. As a result, there is an imminent risk of collapse before these issues are recognized [8, 10, 18, 20].

Small-scale or artisanal fisheries, distinguished by the use of traditional manual techniques, small vessels in shallow coastal waters, and relatively modest individual catches [21, 22], encounter challenges in data collection, particularly regarding age data, due to limited resources and expertise. As a result, researchers and managers heavily depend on length composition data [23]. Effectively assessing and managing them is a complex and challenging task, particularly when using traditional fishing models [12, 24, 25]. Hence, assessment methods and management procedures must optimize the use of the limited data available to account for significant uncertainties [20].

Length-based methods have been developed for populations with limited data, which help assess stock status and provide valuable management information, including reference points like fish growth and mortality rates. These methods enhance our understanding of fish population dynamics [23, 26, 27]. In this context, the length-based spawning potential ratio method (LB-SPR), an equilibrium-based model developed for assessing spawning potential in fisheries with limited data [18, 19], represents a valuable tool with implications for the sustainable management of small-scale fisheries.

The Spawning Potential Ratio (SPR) of a fish stock represents the portion of unfished reproductive capacity that remains under specific levels of fishing pressure [23, 28–30]. It helps predict whether a population will decline, remain stable, or increase based on its ability to sustain itself [31].

Spawning Potential Ratio (SPR) is widely recognized for its significance in the field of sustainable fisheries management, as it plays a pivotal role in informing decision-making and conservation efforts. This metric is particularly relevant in the context of data-poor fisheries, providing valuable insights into the impact of fishing activities on stock productivity [23, 28]. Therefore, the aim of this study is to assess the Length-Based Spawning Potential Ratio (LB-SPR) of seven marine fish species captured in the artisanal red grouper fishery in the Yucatan Peninsula.

2. The Fishery and Biology Overview

2.1. The Red Grouper Fishery. The Campeche Bank (CB) region in the Southern Gulf of Mexico (GoM) is one of the most significant fishing zones (Figure 1). The diversity of demersal species, including red grouper (*Epinephelus morio*), octopus (*Octopus maya* and *O. americanus*), sea cucumber (*Isostichopus badionotus*), spiny lobster (*Panulirus argus*), and common snook (*Centropomus undecimalis*), among others, has contributed to the highly productive fisheries developed in this region [25, 32, 33].

The red grouper fishery, which targets *E. morio* within the grouper-snapper complex, has significantly contributed to the growth and development of the Yucatan fishing industry since the 1970s, thanks to the substantial production and economic value of *E. morio* [16, 17, 25, 34, 35]. Nevertheless, the depletion of red grouper biomass due to overfishing has precipitated the collapse of the fishery, leading to a reduction in its overall productivity [12, 36].

The grouper-snapper complex encompasses several species, with the most significant in terms of catch being black grouper (*Mycteroperca bonaci*), gag grouper (*Mycteroperca microlepis*), yellowtail snapper (*Ocyurus chrysurus*), and lane snapper (*Lutjanus synagris*) [16, 17, 25, 37]. Recently, the hogfish (*Lachnolaimus maximus*) and the white grunt (*Haemulon plumierii*) have emerged as promising alternative resources of significant value for artisanal, subsistence, and recreational fisheries in response to the decline of red grouper in the southern Gulf of Mexico [38–40]. Those species exhibit different growth and reproductive patterns according to their life histories (Figure 2).

In the Campeche Bank, the small-scale fishing fleet employs various fishing methods, including handline, longline, nets, speargun, harpoon diving, and trolling with rod and lure [17]. The species targeted in the commercial red grouper fishery are primarily caught using bottom longline and handline methods that involve hooks and bait of various types and sizes [17, 34, 45].

The handline, or cord, consists of a main line known as "reinal," carrying one to three straight hooks (size 7 to 10), either short or long-shanked. Monofilament thread (size 60 to 90) is used, accompanied by a lead weight to sink the bait quickly [17]. The bottom longlines typically consist of a mainline, gangions with hooks, buoyancy aids, and lead weights, operated anchored to the bottom using heavy objects as ballast, and can be manually or hydraulically retrieved [17, 35, 45]. The gear operates in the sea, fixed to the bottom at varying depths, with each longline carrying 150 to 500 curved hooks, also known as "guachinanguero" or "eagle claw" [17].

2.2. Growth Pattern

2.2.1. Groupers. Those fish are long-lived, slow-growing fish that reach sizes greater than 100 cm and can live more than 20 years [46]. In the CB region, groupers exhibit slow growth characterized by growth stanzas, distinct growth stages marked by abrupt changes in growth rate, due to variations in their ontogenetic development [47, 48]. Groupers in this

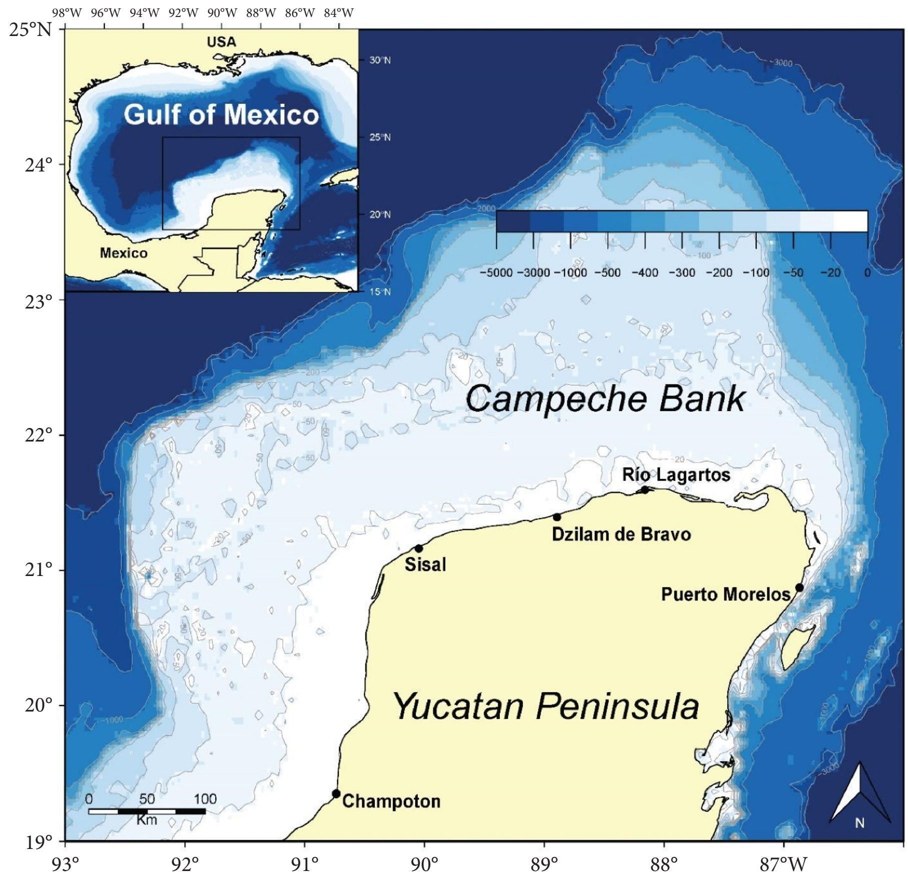


Figure 1: Map of the study area in the Yucatan Peninsula, indicating the fishing ports where the length data of the captured fish was recorded.

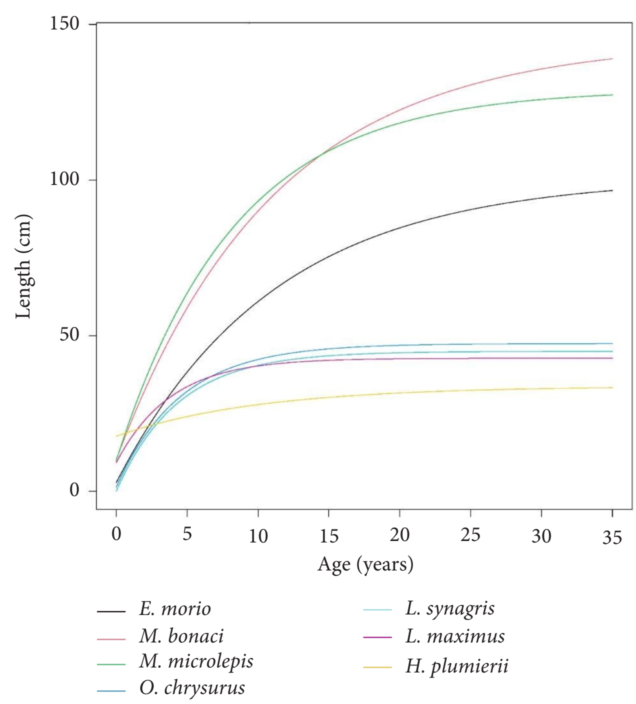


Figure 2: The growth curves for the red grouper (*E. morio*) and associated species in the Campeche Bank region, according to the Von Bertalanffy model, are based on growth parameters reported by Mexicano-Cíntora [41]; McBride and Richardson [42]; Oribe-Pérez et al. [39]; Sierra Castillo et al. [43]; and Renán et al. [44].

region typically have a medium longevity and a variable lifespan. Red grouper (*E. morio*) can live anywhere from 13 to 33 years, black grouper (*M. bonaci*) from 18 to 30 years, and gag grouper (*M. microlepis*) from 17 to 33 years [44].

2.2.2. Snappers. This group is made up of long-lived species, growth rates vary geographically due to differences in feeding habits and genetics. They can reach ages between 10 and 19 years [41, 49–57].

Yellowtail snapper (*O. chrysurus*) exhibits rapid growth during the first two years, followed by a decline around the five-year mark, and eventually stabilize over the next nine years, reaching lengths of up to 84 cm [50, 53, 54, 56–59]. Gear selectivity and exploitation levels can impact growth rates, reducing the abundance of larger-sized fish [50, 54, 56]. In southern and southeastern regions of the GoM, the growth pattern exhibits negative allometry ($b < 3$) [48, 60]. Along the coasts of Veracruz, individuals can reach sizes of up to 60 cm [60]. In the CB region, individuals grow slowly attaining sizes of up to 54 cm and a lifespan of up to 15 years [41, 48, 61].

Lane snapper (*L. synagris*) exhibit geographical and sexual differences in their growth patterns. Growth pattern is characterized by growth stanzas, with rapid grow during the first year but gradually slows down in the second year. Subsequently, growth progressively decreases each year until it reaches nearly asymptotic values at around age 9 [55]. Generally, males display a faster growth rate and achieve larger sizes than females [51, 52]. In the western Atlantic Ocean individuals can reach sizes of up to 38 cm and have a lifespan of 19 years [55]. Along the northern Gulf of Mexico and the coasts of Florida larger lane snappers can reach sizes of up to 51.2 cm [51]. In the Caribbean populations individuals can reach sizes up to 71 cm, often showing an allometric negative growth pattern, and a lifespan of 14 years [52, 62–64]. In CB region, individuals reach size up to 43 cm, females typically being larger than males [65].

2.2.3. Associated Species. Hogfish (*L. maximus*) can grow to sizes of up to 84 cm and have a lifespan of up to 19 years [42, 66]. In the eastern Gulf of Mexico, they exhibit a bathymetric distribution pattern associated with size and age, likely influenced by high fishing pressure nearshore (<30 m), where smaller individuals are more commonly found [66]. In CB region, growth is also appearing to be influenced by fishing pressure [67]. The pattern growth is allometric negative ($b < 3$). Individual can reach sizes up to 54 cm [48, 67, 68].

White grunt (*H. plumierii*) grows following a determinate (i.e., asymptotic) or indeterminate growth pattern [69, 70]. Individuals can reach sizes up to 41 cm and have a lifespan of up to 18 years [39, 70, 71]. Typically, males exhibit larger sizes than females [40, 70]. In CB region, individuals can attain sizes of up to 40 cm and a potential lifespan of up to 17 years [39].

2.3. Reproductive Strategies. Reproductive traits, such as size and age at maturity, sex ratio, fecundity, spawning time, and duration, display significant phenotypic plasticity across various fish populations. Therefore, it is essential to understand the specific reproductive strategies of each population. This knowledge is crucial for establishing local guidelines on sustainable fishing mortality thresholds, which may include measures such as closed areas and seasons, as well as enforcing minimum landing size regulations [4].

2.3.1. Groupers. Groupers (Epinephelidae) from the CB exhibit a monandrous protogynous hermaphroditic reproductive strategy [72–75]. The red grouper (*E. morio*), black grouper (*M. bonaci*), and gag grouper (*M. microlepis*) show remarkably similar reproductive cycles.

The red grouper reproduces seasonally, with peak spawning occurring in late winter and early spring (January–March) [72]. Females reach sexual maturity (50% maturity level, L_{50}) at a length of 50.9 cm fork length (FL), and sexual inversion or sex change typically occurs at a mean size of 59.7 cm FL [72]. The current fecundity pattern is unknown, and it is unclear whether it follows a determinate or indeterminate type [76].

Regarding the black grouper, mature females can be found from October to June, with a peak spawning period occurring from January to February [73]. Females reach sexual maturity (L_{50}) at a length of 72.1 cm FL and sexual inversion typically occurs at an average size of 103.3 cm FL [73].

Gag groupers spawn from December to March, with the highest spawning activity observed between January and March [74]. Females reach maturity (L_{50}) at 72.1 cm FL and sexual inversion occurs at 103 cm FL. Finally, spawning aggregation behavior is commonly observed in black grouper populations across various regions, including the Gulf of Mexico, the Caribbean Sea, and Bermuda. Similar behavior is also documented in gag grouper populations along the continental shelf on both the east and west coasts of Florida [73, 74, 77–79].

2.3.2. Snappers. Snappers (Lutjanidae) exhibit two distinct reproductive patterns among continental and insular populations [80]. In the CB region, exhibit the reproductive strategy typical of continental populations. The yellowtail snapper (*O. chrysurus*) displays an extended spawning period, primarily occurring during spring and autumn [61]. Individuals reach maturity at a small size (L_{min} = 14 cm FL), with an L_{50} of 21.3 cm FL for females. This snapper exhibits multiple spawning events synchronized with the new moon phase throughout the 9-month spawning season [61]. Lane snapper (*L. synagris*) primarily reproduces between March and July, with spawning peaks occurring in May and July. Larger size classes (36.0 cm FL) are predominantly composed of females that reach maturity at an L_{min} of 15 cm FL and an L_{50} of 17.8 cm FL [65]. Both snappers exhibit asynchronous development of oocytes and batch fecundity; the yellowtail snapper can produce up to 160,000 oocytes, while the lane snapper can produce up to 200,000 oocytes [61, 65].

2.3.3. Associated Species. The hogfish (*L. maximus* Labridae) is identified as a monandric protogynous hermaphrodite [81]. Nevertheless, the presence of ovotestes exhibiting internal morphology similar to ovaries in larger individuals raises the possibility of diandric hermaphroditism [82]. Females' hogfish are batch spawners; the mating exhibits a harem structure [81, 83]. Reproductive seasonality varies considerably across its geographical distribution. In the CB region, it exhibits the longest annual spawning period, spanning 11 months, with peak spawning events occurring between February and May [84]. Females reach maturity at an L_{50} of 15 cm FL , with an $L_{\min}$ of 13.9 cm FL. Sexual inversion occurs within a size range of 21 to 40 cm FL, at a P_{50} of 32 cm FL [84]. Oocyte development and batch spawning follow an asynchronous pattern, characterized by a homogeneous distribution of oocyte stages [38].

The white grunt (*H. plumierii* Haemulidae) is a Gonochoric species with no evident sexual dimorphism [40]. The reproductive pattern of the white grunt varies across different populations within its geographical distribution [40, 85]. In the CB region, this Haemulidae species reproduces annually for seven months, from February to August, with the peak spawning event occurring in May [40]. Females reach maturity (L_{50}) at 15.22 cm total length (TL) and exhibit asynchronous oocyte development. They have indeterminate fecundity, capable of producing batches of up to 40,000 oocytes [40].

3. Methods

3.1. Study Area. The Campeche Bank region consists of a shallow submarine plain with a large extension and a small slope (maximum depth: 200 m), located between the Tabasco-Campeche Basin and the Yucatan Strait, between 18° and 24° north latitude and 87° and 93° north longitude (Figure 1). This zone is valuable as a fishing area due to the presence of high-value species [86, 87].

3.2. Data Collection. Monthly sampling was conducted between April 2017 and May 2018, in five fishing ports along the Yucatan Peninsula coast: Champoton (Campeche), Sisal, Dzilam de Bravo, and Río Lagartos (Yucatan), and Puerto Morelos (Quintana Roo).

Sampling was conducted across seven fish species caught by the commercial small-scale fishing fleet, which include red grouper (*E. morio*), black grouper (*M. bonaci*), gag grouper (*M. microlepis*), yellowtail snapper (*O. chrysurus*), lane snapper (*L. synagris*), hogfish (*L. maximus*), and white grunt (*H. plumierii*).

The total length (TL) of each specimen was measured in centimeters (cm). Moreover, data on each species' length at sexual maturity (L_{50}), which represents the length at which 50% of females become sexually mature for the first time [72], as well as their von Bertalanffy maximum length (L_{∞}), growth rate (K), and natural mortality rate (M), were collected from scientific literature (Table 1).

3.3. Length-Based SPR Model Overview. When addressing recruitment overfishing in fish populations with lower resilience, an SPR (Spawning Potential Ratio) of 0.4 is commonly recognized as an indicator for the Maximum Sustainable Yield (MSY) [90]. The minimum acceptable levels of SPR to ensure stocks maintain satisfactory productivity range from 0.20 to 0.30 [28]. A drop below 0.20 in SPR indicates a risk of decline, particularly in juvenile fish supply. When SPR falls below 0.10, populations may rapidly decline and even face local extinction [31].

The length-based SPR assessment method evaluates the impact of harvesting on a population's reproductive capacity. In unexploited or unfished fish stocks, the natural SPR is 100% or 1.0, but fishing activities can reduce it to a specific proportion of the unfished level, represented as $SPR_{X\%}$ or <1.0. Harvesting fish before they reach sexual maturity results in a 0% SPR, significantly diminishing their ability to reproduce [18, 22, 31].

To estimate the spawning potential ratio (SPR) of a fish population using size composition data from an exploited stock, the LB-SPR model relies on key parameters (Table 2). These parameters include fish length data, size classes, the von Bertalanffy asymptotic length, the length at which 50% maturity (L_{50}) is reached, and the length at which 95% maturity (L_{95}) is attained.

Additionally, the model takes into account the ratio of natural mortality to the von Bertalanffy K coefficient, which is denoted as the M/K ratio. According to Hordyk et al. [23, 91], the M/K ratio reveals less variability than natural mortality (M) across different stocks and species. It combines catch size composition with an estimate of local size at maturity to determine a population's ability to replenish itself after fishing [23, 91]. Furthermore, exploitation parameters are taken into account. These include the length at 50% selectivity (SL_{50}), the length at 95% selectivity (SL_{95}), and the F/M ratio [19, 30, 92].

3.4. SPR Analysis. The LB-SPR analysis was conducted for each species using the LB-SPR package [93] on the R Core Team [94] platform. The R script by Hordyk [92], was configured with the biological and exploitation parameters from Table 2. The LB-SPR package's default configuration applies the growth-type-groups (GTG) methodology as proposed by Walters and Martell [29]; as cited in [30].

The GTG LB-SPR model assumes established life history parameters and utilizes an equilibrium per-recruit model to determine relative fishing mortality, selectivity-at-length, and the spawning potential ratio based on representative catch-at-length data [30]. Furthermore, the GTG-LB-SPR model incorporates variable *M* in terms of size and utilizes the life history ratio M/K. This is done in conjunction with assessments of size-at-maturity and asymptotic size (L_{∞}), along with length composition data.

This comprehensive approach is used to evaluate the spawning potential ratio (SPR) of data-limited stocks that exhibit size-dependent selectivity patterns, allowing for the consideration of Lee's phenomenon [30].

4. Results

A total of 10,182 fish were caught between April 2017 and May 2018 (Table 3). The associated species, hogfish (*L. maximus*) and white grunt (*H. plumierii*), were the most abundant in the

Table 1: Population parameters of species associated with the red grouper fishery from the literature.

Species		L_∞ cm, TL	K yr^{-1}	M yr^{-1}	L_{50} cm, FL or TL	F $(y-1)$	Location	Reference
Epinephelus morio	I	100.9	0.090				Campeche bank (CB)	[44]
				0.13			CB	[44]
					50.9		CB	[72]
						0.37	CB	[36]
Mycteroperca bonaci	II	144.8	0.090				CB	[44]
				0.14			CB	[44]
					72.1		CB	[73]
						0.45	CB	[15]
M. microlepis	III	129.2	0.120				CB	[44]
				0.17			CB	[44]
					72.1		CB	[74]
						0.18	CB	[15]
Ocyurus chrysurus	IV	47.5	0.220				CB	[41]
				0.2			Southeast US	[88]
					21.3		CB	[61]
						0.36	CB	[15]
Lutjanus synagris	V	45	0.230				Tela, Honduras	[43]
				0.41			Tela, Honduras	[43]
					17.8		CB	[65]
						2.71	CB	[15]
Lachnolaimus maximus	VI	42.8	0.259				South Florida, US	[42]
				0.65			Q. Roo. Mex.	[68]
					15.03		CB	[38]
						1.35	CB	[15]
Haemulon plumierii	VII	33.8	0.100				CB	[39]
				1.02			CB	[89]
					15.22		CB	[40]
						1.95	Los Frailes, Venezuela	[71]

Table 2: Biological and exploitation parameters analyzed in the LB-SPR model for the red grouper fishery and associated species.

	Definition	Species						
		I	II	III	IV	V	VI	VII
Input								
L_∞ (cm)	Asymptotic size	100.90	144.80	129.20	47.50	45.00	42.80	33.80
M (y^{-1})	Natural mortality	0.13	0.14	0.17	0.20	0.41	0.65	1.02
K (y^{-1})	Growth coefficient	0.09	0.09	0.12	0.22	0.23	0.26	0.10
M/K	M/K ratio	1.44	1.56	1.42	0.91	1.78	2.51	10.20
F (y^{-1})	Fishing mortality	0.37	0.45	0.18	0.36	2.71	1.35	1.95
L_{50} (cm)	Length at 50% maturity	50.90	72.10	72.10	21.30	17.80	15.03	15.22
Estimated								
L_{95} (cm)	Length at 95% maturity	77.10	85.53	84.21	23.40	19.90	29.04	17.24
SL_{50} (cm)	Length at 50% selectivity	40.70	51.00	51.00	33.00	27.50	30.70	26.80
SL_{95} (cm)	Length at 95% selectivity	51.50	73.00	78.10	44.00	34.62	36.00	32.50
F/M	F/M ratio	2.85	3.21	1.06	1.80	6.60	2.08	1.91

catch ($n = 5{,}119$), followed by the snappers (yellowtail snapper *O. chrysurus* and lane snapper *L. synagris*, $n = 3{,}621$), and the groupers (red grouper—*E. morio*, black grouper *M. bonaci*, and gag grouper *M. microlepis*, $n = 1{,}042$).

Among the species, white grunt (*H. plumierii*) was the most abundant in the catch ($n = 4{,}767$), followed by lane snapper (*L. synagris*, $n = 2{,}536$), and yellowtail snapper (*O. chrysurus*, $n = 1{,}085$).

4.1. Fish Length. The length of the fish exhibited variability (Figure 3; Table 3). Among the caught species, groupers (red grouper, black grouper, and gag grouper), were the largest fish, spanning from 29.0 to 87.0 cm TL.

Gag grouper show off the largest average length at 54.3 cm TL, with an individual range of 31.0 to 87.0 cm TL (±13.06); black grouper followed with an average length of 52.83 cm TL, ranging from 25.0 to 85.0 cm TL (±10.28),

Table 3: Number of specimens and biometric data per species.

Species	n	TL (cm)			
		Min	Max	Mean	Sd
Epinephelus morio	435	29.00	69.50	41.19	5.86
Mycteroperca bonaci	368	25.00	85.00	52.83	10.28
M. microlepis	239	31.00	87.00	54.32	13.06
Ocyurus chrysurus	1,085	21.00	47.00	33.00	6.49
Lutjanus synagris	2,536	20.00	45.00	28.04	3.73
Lachnolaimus maximus	752	20.00	40.50	30.00	3.22
Haemulon plumierii	4,767	18.10	34.00	26.89	3.00
Total	10182				

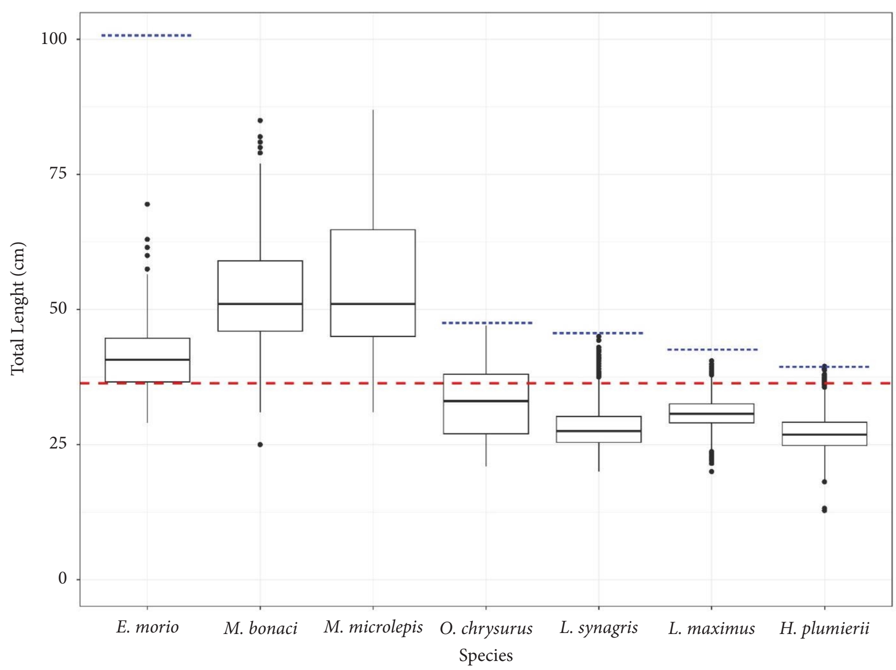


Figure 3: Boxplot illustrating the total length of red grouper (*E. morio*) and associated species. The black horizontal lines represent the median total length (cm) for each species, the boxes indicate the interquartile range, and the whiskers denote the 95% confidence intervals. The red dotted line (---) signifies the Minimum Legal Size (MLS) for red grouper, set at 36.3 cm TL. The dotted blue (---) lines indicate the L_∞ for each species (For *M. bonaci* and *M. microlepis*, the respective L_∞ values exceed the range of the axis scale; refer to Table 2 for details).

while red grouper measured an average length of 41.2 cm TL, spanning from 29.0 to 69.5 cm TL (±5. 86).

Snappers (yellowtail and lane snapper) along with associated species (hogfish and white grunt) displayed smaller sizes compared to groupers. Among them, yellowtail snapper shows off the largest length in average at 33.0 cm TL, ranging from 21.0 to 47.0 cm TL (±6.49). Following this, lane snapper measured 28.0 cm TL on average, with an individual range of 20.0 to 45.0 cm TL (±3.73).

The associated species showed some degree of similarity in size to the snappers. Hogfish, at an average length of 30.0 cm TL, exhibited the largest size range, spanning from 20.0 to 40.5 cm TL (±3.22). On the other hand, white grunt, with an average length of 26.9 cm TL, represented the smallest fish in terms of average length, ranging from 18.1 to 34.0 cm TL (±3.00).

4.2. Length-Based SPR Analysis

4.2.1. Selectivity Pattern and Maturity. The size selectivity pattern (SL_{50}, the selectivity at 50% of the catch) varied among the groupers, snappers and associated species (Figure 4). For groupers (Figures 4(a)–4(c)), red grouper (SL_{50} = 40.7 cm TL and L_{50} = 50.9 cm FL), black grouper (SL_{50} = 51.0 cm TL and L_{50} = 72.1 cm FL), and gag grouper (SL_{50} = 51.0 cm TL and L_{50} = 72.1 cm FL); the SL_{50} values were smaller than the size of first maturity (L_{50}). This suggests that 50% of the fish caught were juvenile or immature individuals.

For snappers, yellowtail snapper (SL_{50} = 33.0 cm TL, L_{50} = 21.3 cm FL) and lane snapper (SL_{50} = 27.5 cm TL, L_{50} = 17.8 cm FL); and associated species, hogfish (SL_{50} = 30.7 cm TL, L_{50} = 15.0 cm FL) and white grunt

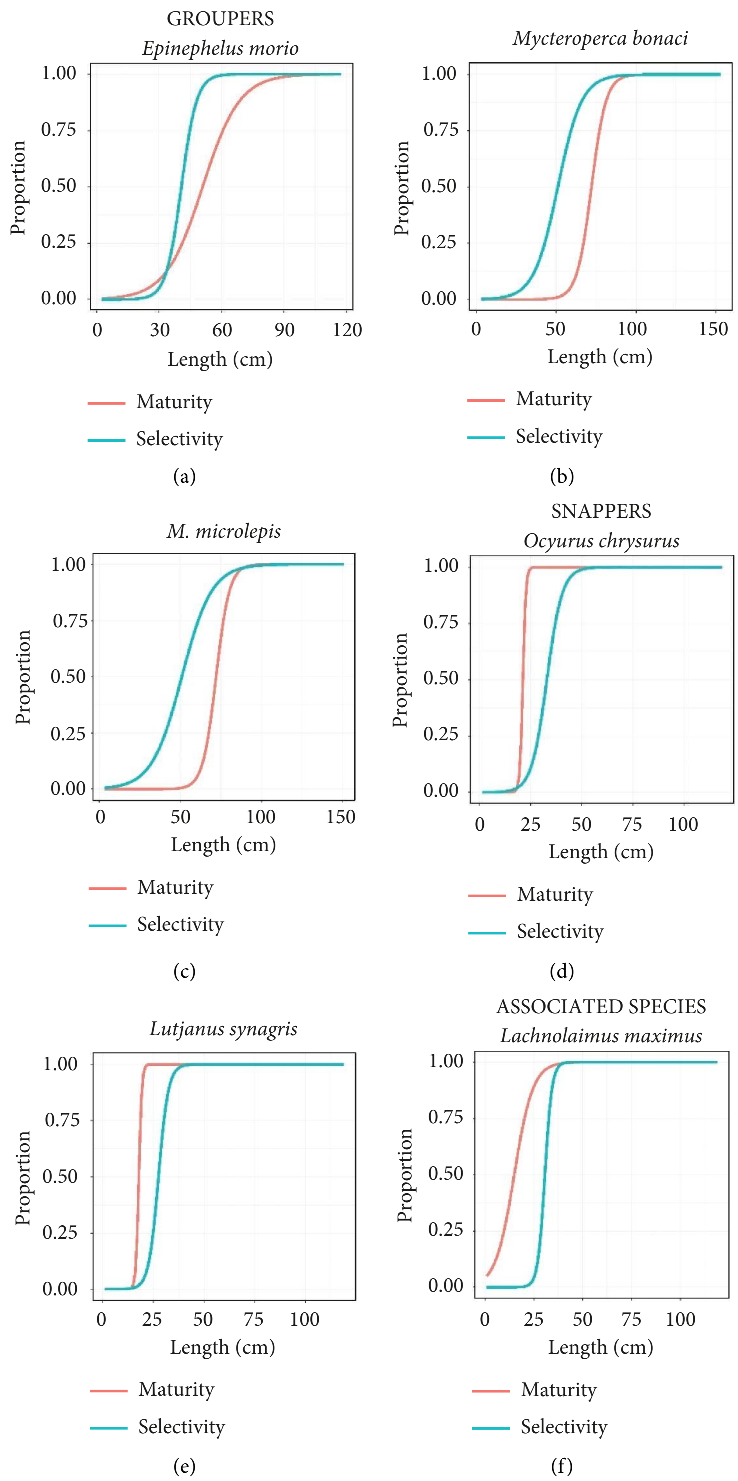
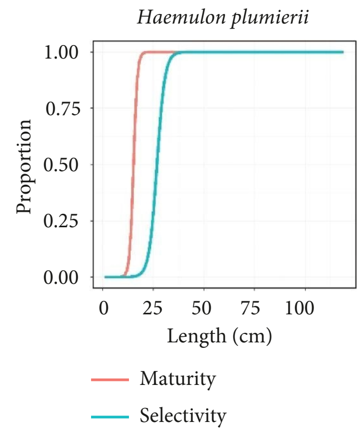


Figure 4: Continued.



(g)

Figure 4: Selectivity pattern at 50% of the Catch (SL_{50}) and the length at which 50% maturity is reached (L_{50}) for the species within the mero-pargo complex, (a) *E. morio*, (b) *M. bonaci*, (c) *M. microlepis*, (d) *O. chrysurus*, (e) *L. synagris*. Additionally, associated species are depicted: (f) *L. maximus*, (g) *H. plumierii*.

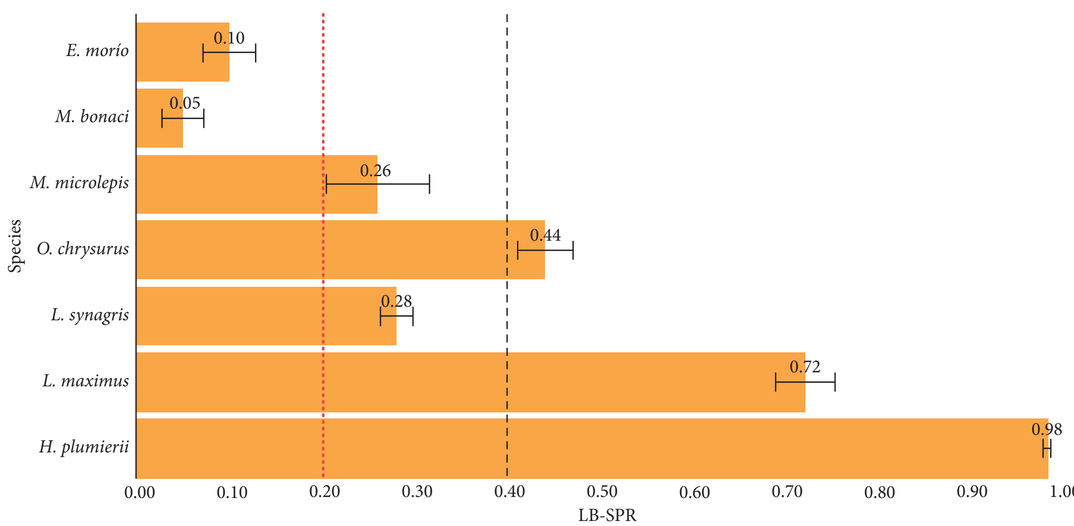


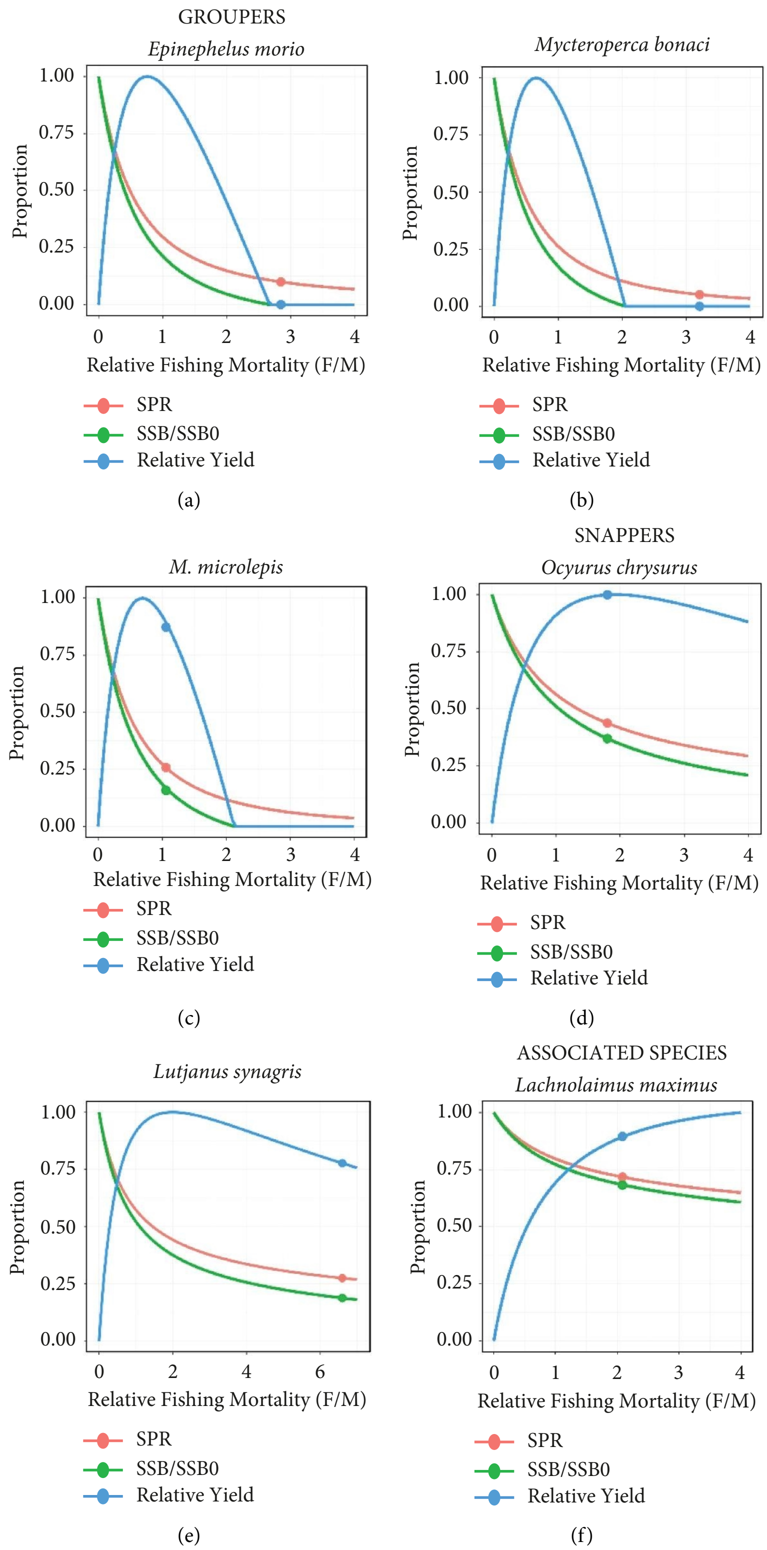
Figure 5: Bar plot illustrating the Spawning Potential Ratio (SPR) using the LB-SPR Model for the red grouper fishery and its associated species. The black dotted line (---) indicates the SPR reference value, while the red dotted line (---) represents the critical minimum SPR value and whiskers denote the 95% confidence intervals. A SPR below 0.20 suggests an elevated risk of decline, particularly in the supply of juvenile fish.

($SL_{50} = 26.8$ cm TL, $L_{50} = 15.2$ cm FL) (Figures 4(d)–4(g)); the size selectivity pattern differed from that of groupers, as the SL_{50} values exceeded the respective L_{50}. This suggests that 50% of the caught fish were mature or adult individuals.

4.2.2. Spawning Potential Ratio. The Length-Based Spawning Potential Ratio (LB-SPR) analysis indicated variable Spawning Potential Ratio (SPR) values for the species of the red grouper fishery and associated species that were analyzed (Figure 5). Among them, groupers exhibited the lowest values of SPR, all of them under the reference value (0.40).

The values registered ranged from 0.05 to 0.26, with gag grouper recorded the highest SPR value (0.26), although it was so close to the minimum critical value (i.e., 0.20). In the other hand, red grouper and black grouper, recorded values of SPR below the critical minimum (0.10 and 0.05, respectively). In the snapper group, yellowtail snapper (0.44) recorded a value just slightly above the reference value (0.40), whereas lane snapper (0.28) recorded the lowest SPR among this group, falling under the reference value. On the other hand, the associated species, hogfish and white grunt, recorded the best overall values (0.72 and 0.98, respectively), surpassing the reference for SPR.

4.2.3. Fishing Pressure (F/M) and Relative Yield. The fishing pressure (F/M) and Relative Yield values differed among groupers, snappers, and associated species (Figure 6). The LB-SPR analysis indicated that the F/M was high for red grouper (2.85) and black grouper (3.21) (Figures 6(a) and 6(b)). For both species, the Relative Yield has



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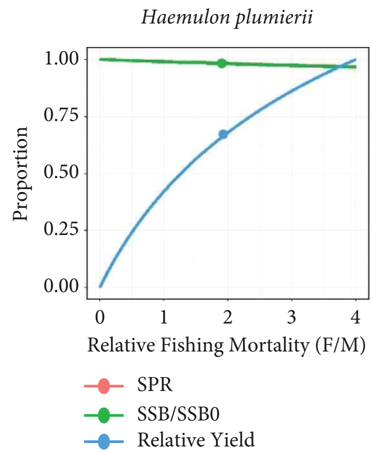

(g)

Figure 6: Representation of the fishing pressure (F/M), Relative Yield and the Spawning Stock Biomass (SSB/SSB_0) of the grouper-snapper complex species, (a) *E. morio*, (b) *M. bonaci*, (c) *M. microlepis*, (d) *O. chrysurus*, (e) *L. synagris*; as well as associated species, (f) *L. maximus* and (g) *H. plumierii*.

exceeded its maximum value, and the Spawning Stock Biomass (SSB/SSB_0) has reached its minimum value. In the case of gag grouper, although the F/M is lower (1.06), the maximum relative yield has also been exceeded, leading to a decrease in both the yield and SSB/SSB_0 (Figure 6(c)).

Regarding snappers (Figures 6(d) and 6(e)), the F/M was lower for yellowtail snapper (1.80) but highest for lane snapper (6.60). In relation to Relative Yield, the analysis indicates that the yellowtail snapper has reached its maximum level. At this point, the analysis also shows a decrease in SSB/SSB_0. Similarly, for lane snapper, the maximum Relative Yield has been exceeded, resulting in a decrease in the SSB/SSB_0 as well.

For the associated species (Figures 6(f) and 6(g)), the F/M ratio was higher for hogfish (2.08) than for white grunt (1.91). In these species, the Relative Yield has not yet reached its maximum, and the levels of SSB/SSB_0 are at their best overall, particularly for white grunt.

5. Discussion and Conclusions

This study represents the first assessment of the Spawning Potential Ratio for the red grouper fishery species in the coastal waters of the Yucatan Peninsula. The following discussion presents the most relevant results and explores its implications for the sustainable management of the red grouper fishery.

5.1. The LB-SPR Analysis. Length-based stock assessment methods, such as LB-SPR, along with others like the length-based Thompson and Bell approach, length-based integrated mixed effects, and length-based risk analysis, are widely acknowledged for their consistency and accuracy [95]. However, to ensure the accuracy and precision of evaluation results, it is crucial that the collection of length data accurately represents the length compositions of the entire population, taking into consideration the random spatial distribution of fish and the scattered nature of the samples [95].

In this study, we could not observe specimens of the seven species below the recorded minimum length values due to sampling limitations. Nevertheless, our research provides a reasonably robust initial approximation, which has aided in assessing the spawning potential of both the target and associated species in the artisanal red grouper fishery of the Campeche Bank.

5.2. Spawning Potential Ratio of the Grouper-Snapper Complex

5.2.1. Groupers. Hordyk et al. [23] emphasize that capturing a substantial proportion of immature juvenile individuals significantly diminishes spawning and recruitment, even at low fishing mortality (F/M) levels. This phenomenon aligns with our findings for groupers.

Although groupers were larger in size among the captured fish, they were found to be immature ($< L_{50}$) and displayed low SPR values. Notably, both red grouper and black grouper fell below the critical minimum value for SPR (0.10 and 0.05, respectively). For both species, these results suggest a high risk of local extinction. As for gag grouper, while its SPR value (0.26) continues to ensure that stocks maintain satisfactory productivity (0.20–0.30), it remains dangerously close to the critical minimum value for SPR (i.e., 0.20), posing an imminent risk of population decline.

Groupers have been subjected to significant fishing exploitation, resulting in declines in their abundance, size, spawning aggregations, and species composition [96]. Groupers from Campeche Bank are highly vulnerable to overfishing due to their extended lifespan, larger size-age thresholds for sexual maturity, and the low M and K indices [44, 75, 76]. For instance, the red grouper reaches $L_{50} = 50.9$ cm FL, $P_{50} = 9.3$ years; the black grouper achieves $L_{50} = 72.1$ cm FL, $P_{50} = 13.6$ years; and the gag grouper attains $L_{50} = 72$ cm FL, $P_{50} = 11.6$ years [44, 72–74].

The red grouper population, particularly, has undergone a decline in biomass from 1986 to 2000. This decline is attributed to reduced size in both the spawning stock and recruitment of 1-2-year-olds. The cause of this decline can be traced back to heightened fishing pressure on juvenile and preadult groupers, specifically those in the 2-3 age group, which has recorded the highest fishing mortality rate at 0.37. Consequently, this has led to a reduction in commercial catches from 14,410 to 9,797 tons [36]. This trend persists despite the established management scheme for the fishery, with catches further dropping to less than 4000 tons [14].

The increased fishing pressure on juvenile red grouper primarily results from the activities of the small-scale artisanal fleet. This fleet predominantly targets juvenile red grouper due to their substantial abundance in the fishing areas along the shallow waters of the Yucatan coastline [13, 36, 37, 72, 97]. The heightened vulnerability of this age group to fishing gear, specifically the bottom longline, commonly employed in the red grouper fishery by this fleet [98], contributes to the increased capture.

The distribution pattern and migrations across the Campeche Bank constitutes an additional contributing factor. Juvenile red grouper (i.e., 20 to 30 cm TL) are typically found in shallow coastal waters within the depth range of 15 to 25 meters. In contrast, sexually mature adults (measuring ≥51 cm TL) are commonly observed in deeper waters (>30 m) [36, 72, 99]. During the reproductive season in winter-spring, juvenile groupers move to shallower waters in the central-eastern region, whereas adult fish undertake migrations to deeper waters, typically at depths ranging from 35 to 60 meters. Subsequently, in spring-summer, juveniles shift their habitat to northern areas, while adults migrate westward, crossing the vicinity of Dzilam de Bravo and Rio Lagartos [100].

The susceptibility of groupers from Campeche Bank to overfishing appears to be influenced by various factors. Notably, their distinct biology, distribution patterns, and potential migrations across the Campeche Bank contribute significantly to this susceptibility. These specific factors play a crucial role in the observed trend of overfishing, particularly in recruitment and growth. This trend has resulted in a decline in the ecological performance of the red grouper fishery, thereby impacting the economic and social sectors at the artisanal level as underscore by Rincón–Sandoval and López–Rocha [101] in their evaluation of the red grouper fishery's performance using the Fishery Performance Indicators (FPI) framework proposed by Anderson et al. [8].

Furthermore, climate change presents an added threat to groupers, particularly the red grouper, currently facing overexploitation, as indicated by recent analyses conducted by Brulé et al. [76]. The authors observed that increasing water temperatures may disrupt their reproductive cycles, sexual differentiation, sex reversal, and sex ratio, potentially reducing fertility.

5.2.2. Snappers and Associated Species. The snappers, including yellowtail and lane snapper, were observed to be smaller in size. Nevertheless, they were primarily captured in the adult state, specifically after reaching sexual maturity (i.e., $SL_{50} > L_{50}$), along with associated species such as hogfish and white grunt. Our findings regarding the adult catch of snappers align with the results reported by Brulé et al. [37], who noted that adults of yellowtail and lane snapper are predominantly captured in the Campeche Bank.

The snappers and associated species are early maturing, achieving gonadal maturity at smaller size-age thresholds (i.e., yellowtail snapper, $L_{50} = 21.3$ cm FL, [61]; lane snapper $L_{50} = 17.8$ cm FL, [65]; hogfish, $L_{50} = 15.03$ cm FL, [84]; white grunt, $L_{50} = 15.22$ cm TL, [40]). Among these species, yellowtail, hogfish, and white grunt exhibit SPR above the reference (i.e., >0.40), despite facing substantial fishing pressure (F/M = 1.80, 2.08 and 1.91, respectively). For lane snapper, despite individuals being captured as adult with size near their L_∞ (45 cm), the SPR was quite low (0.28). Although it still falls within the recommended range of 0.20–0.30 for maintaining satisfactory stock productivity, it is close to the critical minimum (i.e., 0.20).

The results for lane snapper align with the findings by Hordyk et al. [23]. The authors emphasized that, despite a high fishing mortality (F/M) ratio among mature individuals due to pronounced selectivity, the fishery remains sustainable, albeit with reduced yields. This phenomenon can be attributed to the fact that older fish typically demonstrate higher annual fecundity and spawn over a more extended season [1]. However, it should be noted that not all mature female fish lay eggs during the spawning season, and females undergoing their initial spawning at the age of 1 year exhibit the least likelihood of reproduction, as exemplified by the spotted seatrout (*Cynoscion nebulosus*) [5].

For lane snappers, continuous spawning occurs throughout the year, particularly among older and larger females (i.e., 41.9 to 56.0 cm). These individuals exhibit higher fecundity, reaching up to nearly 600,000 oocytes, in contrast to their smaller counterparts [52, 55, 63–65, 102].

Trejo-Martínez et al. [65] verified this pattern for lane snapper within the Campeche Bank, highlighting that female, typically larger than males, exhibit an extended spawning period of 120 days. The researchers observed a significantly higher fecundity (>200,000 oocytes) among the largest females (46.0 cm), with no males being observed in the larger size classes (>36.0 cm FL).

The skewed gender ratio towards larger females, as observed by Trejo-Martínez et al. [65], contrasts with the findings of Luckhurst et al. [55] for lane snapper in Bermuda (western Atlantic Ocean). The latter researchers documented a higher proportion of males in the largest size category (>33 cm), attributing this trend to selective processes and competition during the capture phase. They proposed that larger males exhibit greater aggressiveness, resulting in higher success rates compared to females in interactions with fishing gear. Furthermore, they highlighted the possibility that distinct movement patterns between sexes on the fishing grounds may contribute to this observed phenomenon.

In this context, it is plausible that the bias observed by Trejo-Martínez et al. [65] towards females larger than 36.0 cm may be attributed to a decrease in the number of males due to heightened pressure on the latter. In this situation, larger females with greater reproductive potential could be in a condition of increased vulnerability to capture, resulting in a reduction in the proportion of these females in the population. This, in turn, poses a risk to decline in the stock of lane snapper.

On the other hand, lane snapper is vulnerable, like to other long-lived species, even under minimal levels of overexploitation [62]. Therefore, despite the heightened potential for spawning, it is imperative, in adherence to the precautionary principle, to alleviate the increased fishing pressure (F/M = 6.60) on adult lane snapper individuals on the Campeche Bank, to mitigate the risk of population decline (i.e., SPR <0.20).

For the associated species, hogfish, and white grunt, our findings align with the LB-SPR model, which produces high SPR for species whose captured individuals' sizes are close to L_{∞} [19]. Both species, particularly white grunt, exhibited the highest SPR values (0.72 and 0.98, respectively) among all studied species. Additionally, both species recorded maximum sizes (40.5 cm and 34.0 cm TL, respectively) that closely correspond to their respective L_{∞} values (i.e., 42.8 and 33.8 cm, respectively; Tables 2 and 3, Figure 3).

The observed SPR for hogfish (0.78) and, particularly, white grunt (0.98), closely approaches the natural SPR of 1.0, which is a typical value for unexploited or unfished fish stocks [22, 31]. This outcome can be attributed to the relatively recent commercial exploitation of both species in this region, which has emerged in response to the decline of the red grouper in the southern Gulf of Mexico [38–40] and has not yet been fully exploited.

5.3. Management Implications. The present results underscore the urgent necessity to alleviate the fishing pressure trend from the small-scale fleet targeting juvenile groupers fish, particularly for red grouper and black grouper, to mitigate the risk of local extinction.

The existing management framework involves measures aimed at preventing recruitment and growth overfishing, including fishing bans, minimum size limits (MSL), and restrictions on gear selectivity (i.e., size and type of hook and bait type). These management actions have been exclusively focused on the target species, red grouper (*E. morio*). However, this management approach has not proven entirely effective in controlling recruitment and growth overfishing, since the impact on juvenile red grouper persists, as indicated by several studies [97, 98].

An illustrative example of inefficiency in management of recruitment and growth overfishing is manifests in the MSL = 36.3 cm TL [103], that is smaller than the size at first maturity (L_{50} = 50.9 cm FL [72], for red grouper, as noted by Brulé et al. [97] and Renán et al. [44]). Those authors noted that even capturing fish above the MSL, >36.3 cm TL (considered as legal groupers), they still be individuals that have not reached sexual maturity (juveniles and preadults, $<L_{50}$). Nevertheless, adjusting the Minimum Size Limit (MSL) to match or exceed the L_{50} could present ethical and logistical challenges related to small-scale fishermen's access to the grouper resource. Consequently, this adjustment may result in the exclusion of this sector from the red grouper fishery [44, 97, 98].

Our results underscore the immediate necessity to reorient the current management approach. Particularly, it is crucial to address the capture of sublegal groupers (<MSL) by implementing necessary regulatory modifications. Achieving this objective requires precise modifications to the regulations governing the fishing gear used in the red grouper fishery, especially regarding gear selectivity (i.e., hook size and bait size), to reduce catches of immature fish. This recommendation aligns with prior suggestions by Brulé et al. [97] and Rincón–Sandoval et al. [98]. Furthermore, Brulé et al. [104] emphasizes the necessity of updating the size at first maturity for the red grouper (L_{50} = 50.9 cm FL; [72]) due to the intense fishing pressure on this resource over the past two decades.

The challenge of sublegal fish, identified by Rincón–Sandoval et al. [98], due to their increased susceptibility to fishing gear lacking sufficient size selectivity, poses a threat to sustainable fishing practices since the use of nonselective gear is detrimental to fishery resources [97, 105–107]. Effectively controlling and managing overfishing, which impacts both growth and recruitment, relies on the selectivity of gear influenced by factors such as hook size, bait, lures, and minimum size limits (MSL).

Recent research on fishing gear selectivity in the artisanal red grouper fishery at the Campeche Bank emphasizes the urgent need to reevaluate and adjust management strategies, particularly regarding fishing gear selectivity for the small-scale fleet. The findings indicate that the use of larger hooks leads to a decrease in sublegal fish in the catch (#11/0 = 71.3%, #12/0 = 69.2%, #13/0 = 59.4%) [97]. This reduction is further pronounced by the increase in bait size (from 4 to 8 cm) in deeper fishing areas (waters exceeding 20 m) (#14/0 = 14.8%, #15/0 = 7.5%) [98].

Rincón–Sandoval and López–Rocha [101] highlight that revising selectivity regulations carries dual advantages, encompassing ecological benefits (reduced capture of juveniles) and economic gains. This modification is poised to enhance both the red grouper stock and the livelihoods of fishermen by fostering increased capture of larger groupers, which command higher value per kilogram in the local market [108–110].

Furthermore, employing no-take marine reserves and areas with less intensive fishing could help alleviate intense fishing pressure. These reserves have demonstrated effectiveness in safeguarding grouper resources [96]. This approach enhances enforcement efficiency compared to complex catch and effort regulations, potentially reducing the necessity for collecting fisheries-dependent data. The positive outcome is attributed to a significant increase in the density and biomass of larger grouper species [96]. Currently, collaborative initiatives involving the State of Yucatan government, the academic community, the fishing industry, and nongovernmental organizations (NGOs) are in progress to establish the Fishing Refuge Zone Network along the Yucatan coast. These efforts are guided by NOM–049–SAG/PESC–2014 [103]. Noteworthy accomplishments include the successful inauguration of the inaugural fishing refuge zone in Celestun by the Ministry of Agriculture and Rural Development (SADER) and National Commission of Aquaculture and Fisheries (CONAPESCA) [111].

Additionally, adopting an ecosystem-based approach to manage the red grouper fishery could allow not only for the protection of the red grouper but also for safeguarding all the species within the grouper-snapper complex and preserving their respective habitats.

The present study represents the initial assessment of the Spawning Potential Ratio for seven commercially significant species captured by the red grouper fishery off the coast of the Yucatan Peninsula. The findings shed light on the strategies needed to prevent the local extinction of grouper resources currently diminished and associated species. Moreover, they provide a path toward sustainability for the red grouper fishery, thereby safeguarding the food security of the region and ensuring the well-being of communities dependent on fisheries resources in this area.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon request.

Disclosure

This document was created based on the research conducted during the postdoctoral fellowship (2023-2024) awarded by the Universidad Nacional Autónoma de México (UNAM) to Dr. Luis Alberto Rincón Sandoval.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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