Hidrobiológica 2024, 34 (2): 121-131

UNIVERSIDAD AUTÓNOMA METROPOLITANA
Casa abierta al tiempo
Unidad Iztapalapa

HIDROBIOLÓGICA

http:/hidrobiologica.izt.uam.mx

ISSN: 2448-7333

OPEN ACCESS
Research Article
August, 2024

Stocks assessment and reference point estimations for the snappers fishery (Perciformes: Lutjanidae) in the Gulf of Mexico, 1980-2019

Análisis poblacional y estimación de puntos de referencia para la pesquería de pargos (Perciformes: Lutjanidae) en el Golfo de México, 1980-2019

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Recibido: 04 de septiembre de 2023. *Aceptado:* 31 de enero de 2024. *Publicado:* agosto de 2024.

ABSTRACT

Background. In Mexico, the Gulf of Mexico snapper's fishery contributes 30% of the national snapper landings through a multi-species fishery where red *Lutjanus campechanus* (Poey, 1890), yellowtail *Ocyurus chrysurus* (Bloch, 1791) and lane *Lutjanus synagris* (Linnaeus, 1758) are the main target species. **Goals**. To evaluate the stock status of the three main species and to calculate reference points: Catch at Maximum Sustainable Yield (*MSY*), Biomass associated with *MSY* (B_{MSY}) and Fishing Mortality associated with *MSY* (F_{MSY}) for the management of these fisheries in the Gulf of Mexico. Historical official landings records were used in the application of the Monte Carlo method C-MSY. **Results**. The most probable maximum intrinsic rate of population increase (*r*) and carrying capacity of environment population (*k*) values for the C-MSY method were for *L. campechanus* 0.56 and 35,109 t, for *O. chrysurus* 0.56 and 13,814 t; and for *L. synagris* 0.55 and 1,932 t. *MSY* values found were 4,964 t, 1,953 t and 269 t respectively. B_{MSY} values were 17,554 t, 6,907 t and 966 t respectively. F_{MSY} values were 0.28 for *L. campechanus* and *O. chrysurus*, and 0.27 for *L. synagris*. **Conclusions**. This study shows that only the *L. synagris* stock is overfished, while *O. chrysurus* is the only stock experiencing overfishing. To maintain the *L. campechanus* stock at healthy levels we recommend a total allowable catch (TAC) of 4,467 t per year. To reduce overfishing and maintain the *O. chrysurus* stock at healthy levels we recommend a TAC of 1,562 t. Finally, to rebuild the *L. synagris* stock and prevent overfishing, we recommend a TAC of 215 t.

Key words: C-MSY method, *Lutjanus campechanus*, *Lutjanus synagris*, *Ocyurus chrysurus,* snapper's fishery management.

RESUMEN

Antecedentes. En México, la pesquería de pargos del Golfo de México contribuye con el 30% de las capturas nacionales de este recurso a través de una pesquería multiespecífica en la que, el huachinango *Lutjanus campechanus* (Poey, 1890), la rubia *Ocyurus chrysurus* (Bloch, 1791) y la villajaiba *Lutjanus synagris* (Linnaeus, 1758) son las principales especies objetivo. **Objetivos**. Con el fin de evaluar el estado de las poblaciones de las tres principales especies de pargos y calcular puntos de referencia para el manejo de estas pesquerías en el Golfo de México. **Métodos.** Se utilizaron registros históricos de desembarques en la aplicación del método Monte Carlo (C-MSY). Los puntos de referencia estimados incluyeron: Captura al Máximo Rendimiento Sostenible (*MSY*), biomasa asociada al *MSY* (B_{MSY}) y Mortalidad por Pesca asociada al *MSY* (F_{MSY}). **Resultados.** Los valores más probables de la máxima tasa intrínseca de crecimiento poblacional (*r*) y capacidad de carga de cada población (*k*) obtenidos por el método C-MSY fueron, para *L. campechanus* 0.56 y 35,109 t; para *O. chrysurus* 0.56 y 13,814 t; y para *L. synagris* 0.55 y 1,932 t. Los valores de *MSY* encontrados fueron de 4,964 t, 1,953 t y 269 t respectivamente, mientras que los valores de B_{MSY} fueron 17,554 t, 6,907 t y 966 t respectivamente. Finalmente, los valores de F_{MSY} fueron de 0.28 para *L. campechanus* y *O. chrysurus*, y 0.27 para *L. synagris*. **Conclusiones**. Este estudio muestra que solo la población de *L. synagris* se encuentra sobrepescada, mientras que la población de *O. chrysurus* es la única experimentando sobrepesca. Con el fin de mantener la población de *L. campechanus* en niveles saludables, se recomienda una captura total anual permisible (TAC) de 4,467 t. Para reducir la sobrepesca y mantener la población de *O. chrysurus* en niveles saludables, se recomienda una TAC de 1,562 t. Finalmente, para reconstruir la población de *L. synagris* y prevenir su sobrepesca, se recomienda una TAC de 215 t.

Palabras clave: método C-MSY, *Lutjanus campechanus*, *Lutjanus synagris*, *Ocyurus chrysurus,* manejo pesquería pargos.

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To quote as:
García-Caudillo, J. M., A. Balmori-Ramírez & R. Morales-Azpeitia. 2024. Stocks assessment and reference point estimations for the snappers fishery (Perciformes: Lutjanidae) in the Gulf of Mexico, 1980-2019. *Hidrobiológica* 34 (2): 121-131.

INTRODUCTION

Mexican snapper fisheries on both coasts of Mexico average an annual production of 21 thousand tonnes with an annual average revenue of 65 million US dollars (CONAPESCA, 2020a). Snapper fisheries in the Gulf of Mexico contribute with 30% of the national landings through a multi-species snappers' fishery that includes the following species: red (*L. campechanus),* yellowtail (*Ocyurus chrysurus)*, lane (*Lutjanus synagris)*, vermilion (*Rhomboplites aurorubens*), cubera (*Lutjanus cyanopterus*), mutton (*L. analis*), grey (*L. griseus*), blackfin (*L. buccanella*), silk (*L. vivanus*) and dog (*L. jocu*) (DOF, 2018).

Red, yellowtail, and lane snapper are the main target species for the Gulf of Mexico fishery, and are the most important species for Mexican exports to the US market, contributing an annual average of 85% of the total landings (CONAPESCA, 2020b). In Mexico, two types of fleets participate officially in the snapper fishery in the Gulf of Mexico, the large-scale fleet (1,250 vessels with length above 10.5 meters) and small-scale fleet (9,550 boats with length below 10.5 meters), using various methods and fishing gears: longlines, hand lines, "bicycles", diving. While red snapper is typically targeted and captured by the both fleets, yellowtail and lane snapper are more often targeted and captured by the small-scale fleet (DOF, 2018).

The assessment of stocks is very complex, and is associated with the nature of the fishery (i.e. multispecific, sequential, share), scientists often lack the data necessary to perform robust stock assessments for many fisheries. Fortunately, relatively low-cost and data-poor assessment methods exist to estimate basic information about the stock and the fishery (Honey *et al*., 2010; Carruthers *et al*., 2014; ICES 2014; Rosenberg *et al*., 2014; Rivera-Parra *et al*., 2022) and to provide fishery managers with decision-making tools to manage resources with a precautionary approach in the absence of specific stock or species information (MFNZ, 2008; DAWE, 2018).

Objectives. In this study, we assess the stock status of the three-snapper species of primary interest for the commercial fishing sector in the Mexican Gulf of Mexico *L. campechanus, O. chrysurus* and *L. synagris,* and estimate the appropriate reference points for their management.

MATERIALS AND METHODS

Area of Study. The study area includes the Gulf of Mexico waters offshore the Mexican States of Tamaulipas, Veracruz, Tabasco, Campeche and Yucatan.

Methods. Public official landings records were obtained from the National Commission for Aquaculture and Fisheries (CONAPESCA) and were used in the application of the Monte Carlo method (C-MSY) described by Froese *et al.,* (2017). Also, a management options outcome analysis was conducted by applying the Schaefer model, to test the effect of limiting catch or fishing mortality, and evaluate the effect of these limitations on biomass trends and the risk of exceeding the proposed Limit Reference Points (LRPs).

Catch history for each stock**.** The live weight landings data were taken from the National Information System for Aquaculture and Fisheries (CONAPESCA, 2020a, b). This database includes red, yellowtail and lane snapper landing reports for 1980-2019.

Stocks assessment. For this study, and given the lack of available reports about their population genetic variability (Sustainable Fisheries Partnership 2021a, 2021b and 2021c), each snapper species was considered to be a single stock that coincides with their management as single units in the Mexican Gulf of Mexico (DOF, 2012). The fishery reference points (*MSY,* F_{MSY}, and B_{MSY}), as well as the relative size of the population (B/*k*) and the exploitation rate (F/F_{MSY}) were estimated using C-MSY (Froese *et al*., 2017). In this method the most probable *r* is selected under the Monte Carlo method in the tip of the triangle among the highest viable *r*-values instead of at the center, as did earlier versions of Catch-MSY (Martell & Froese, 2013), due to the definition of *r* as the maximum rate of increase growth for the population in question. The initial biomass was calculated as:

$$B_0 = \lambda_{i1} k \exp(\nu\, t) \qquad \text{Eqn 1}$$

and the biomass of the following years as:

$$B_{t+1} = \left[B_t + rB_t\left(1 - \frac{B_t}{k}\right) - C_t\right]\exp(\nu\, t) \qquad \text{Eqn 2}$$

Where:

B_t = Biomass at time t

B_{t+1} = Biomass one time-step after t

r = maximum intrinsic rate of population increase,

k = carriying capacity,

C_t = Capture at time t, and

σv = process error standard deviation.

To consider the reduced recruitment at extremely depleted stock sizes, such as predicted by common stock–recruitment functions (Beverton & Holt 1957; Ricker 1975, and Barrowman & Myers 2000), the C-MSY method incorporates a linear decline of surplus production when biomass falls below 0.25 *k* (Equation 3).

$$B_{t+1} = \left[B_t + 4\frac{B_t}{k} r\left(1 - \frac{B_t}{k}\right) - C_t\right]\exp(\nu\, t) \qquad \text{Eqn 3}$$

The initial and final Biomass percentage ranges were determined with the value of the maximum catch and the values of the catches of the initial and final year (Martell & Froese, 2013; Froese *et al*., 2017), it was assumed that the initial proportional biomass of the snapper stocks, at the beginning of the time-series (B/*k* = λ_{i1}, λ_{i2}), varied between 50% and 90% for the red snapper, 50% and 70% for the yellowtail snapper, and between 30% and 60% for lane snapper of their respective carrying capacities (*k*), and in last year (B/*k* = λ_{f1}, λ_{f2}), between 30% and 70% for the red and yellowtail snapper stocks and between 30% and 40% for the lane snapper stock. The biologically plausible range for *r* for species with medium resilience (0.2 < < 0.8 Froese *et al.,* 2017) was accepted as suitable for the three snapper stocks. The input value of CV for each of the three stocks was set at 0.2 (20%), assuming that the landings data could be inaccurate (as is common for small-scale fleets, according to Arreguín-Sánchez & Arcos-Huitrón, 2011), and the σ (*v*) value set to 0.1. All cases started with 30,000 MCMC iterations to determine the most viable *r*-*k* pairs. The values of *r* and *k* estimated relate to standard fisheries reference points, such that

$$MSY = k/4, \qquad 4$$

$$B_{MSY} = 0.5\, k, \qquad \text{Eqn 5}$$

$$F_{MSY} = 0.5\ , \qquad \text{Eqn 6}$$

If the reduction in recruitment at very low stock sizes ($B/k < 0.25$), then

$$F_{MSY} = 0.5 \quad 4\ B/k. \qquad \text{Eqn 7}$$

Kobe plots were constructed for each species (Aires-da-Silva & Maunder, 2011; Schirripa, 2016), which show the relative stock size (B/B_{MSY}) on the x-axis and the exploitation rate (F/F_{MSY}) on the y-axis, thus displaying the stock status over time with point estimates in different colored quadrants: green (not overfished, not overfishing), yellow and orange (overfished or overfishing), and red (overfished and overfishing). Kobe plots can be used to help select reference points when developing a management strategy (Kell *et al.,* 2014).

Different countries define an overfished status in different ways. In the case of Mexico, the National Fisheries Chart (DOF, 2023), defines the status as the relative position of a population attribute or variable against a target reference point that indicates the condition of the population and classifies the status into three categories:

1. Exploited at the Maximum Sustainable Limit, where the value of the biomass ratio (Current/Target) =1
2. With Development Potential, where the value of the biomass ratio (Current/Target) >1
3. Deteriorated, where the value of the biomass ratio (Current/Target) <1

While the Mexican regulatory framework does not have equivalent definitions for “overfished” and “overfishing”, in this work we consider that a stock is overfished at any value of B/B_{MSY} below 1.0, consistent with the definition of deteriorated, and that a stock is experiencing overfishing at any value of F/F_{MSY} above than 1.0.

Candidate Reference Points. There is no universally recognized best method for setting fisheries targets and limits, however, the establishment of reference points is intended to form a key part of a harvest strategy that promotes sustainability for the target fishery. The fishery should be managed such that the population biomass fluctuates near a target reference point (TRP) in alignment with the fishery management objectives, which may be, for example, *MSY* (MFNZ, 2008) or Maximum Economic Yield (*MEY*). The risk of the population biomass declining to less than the limit reference point (LRP) should be low. We suggest that the biomass TRP (B_{TRP}) is set as equal to the B_{MSY} estimate, to prevent recruitment overfishing (Haddon *et al*., 2012; Carruthers *et al*., 2014; Froese *et al*., 2015 & Froese *et al*., 2017), a biomass LRP (B_{lim}) of 0.5 B_{MSY} should be used. In addition, we suggest an LRP related to fishing mortality (F_{lim}) be set at the value of F_{MSY} calculated by the model.

Therefore, the reference points suggested include:

$$B_{TRP} = B_{MSY} \qquad \text{Eqn 8}$$

$$B_{lim} = 0.5\ B_{MSY} \qquad \text{Eqn 9}$$

$$F_{lim} = F_{MSY} \qquad \text{Eqn 10}$$

Based on C-MSY results, candidate values for appropriate TRPs and LRPs were established for each stock. A management options outcome analysis was conducted by applying the Schaefer model to evaluate the effect of constant catch and constant fishing mortality management strategies. For catch limits, the values tested were *MSY*, the lower 95% confidence interval of *MSY*, and different values in between. For fishing mortality limits, F_{lim} as well as 0.9, 0.8 and 0.7 F_{lim} were tested. The probability that the biomass of the stock will be above B_{TRP}, between B_{TRP} and B_{lim} or below the B_{lim} in 2025 was also evaluated.

RESULTS

Stocks assessment and status. The assumed parameter values and *r* and *k* output results of the C-MSY method for the three stocks are presented in Table 1 and Figure 1 for each stock. The most viable of *r-k* pair values for the three snapper stocks estimated by the model were for red and yellowtail snapper an equal value of maximum net productivity *r*, while the lane snapper stock yielded a slightly lower value of *r*. Regarding the values of *k*, the highest value was obtained by red snapper stock while the lowest value was yielded by lane snapper stock.

Target and Limit Reference Points estimation. The fishery and stock parameters estimated by the C-MSY assessment (*MSY*, B_{TRP} and F_{lim}) for the three snapper stocks, and the candidate reference points associated with these parameters that are proposed for management purposes are presented in Table 2.

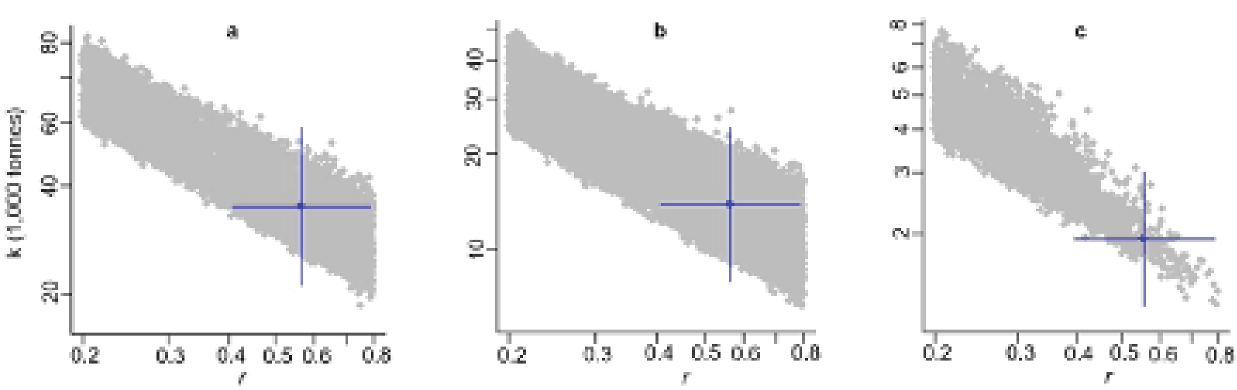

Figure 1. Most probable combinations of *r* and *k* for a) red snapper b) yellowtail snapper and c) lane snapper stocks. Viable *r-k* pairs fulfilling the conditions are show in grey. Most probable *r-k* pair is marked with the blue cross that includes confidence limits.

Table 1. Assumed parameter values (column A) and output results of the C-MSY assessment for the three snapper stocks (column B).

Stock	A Prior range values				B Carrying capacity Median (lower and upper limit of the 95% confidence interval)	
	Initial biomass relative $\lambda_{i1} - \lambda_{i2}$	Final biomass relative $\lambda_{f1} - \lambda_{f2}$	r	*ki* (tonnes)	r	*k* (tonnes)
Red snapper	0.5 – 0.9	0.3 – 0.7	0.2 – 0.8	8,100 – 130,000	0.56 (0.40 – 0.78)	35,109 (21,186 – 58,179)
Yellowtail snapper	0.5 – 0.7	0.3 – 0.7		3,540 – 56,600		13,814 (7,858 – 24,283)
Lane snapper	0.3 – 0.6	0.3 – 0.4		481 – 7,690	0.55 (0.39 – 0.78)	1,932 (1,245 – 2,997)

r = maximum rate of increase growth for the examined population; k_i = range of carrying capacity at the first year of the series time; $\lambda_{i1} - \lambda_{i2}$ = initial proportional biomass of the snapper stocks, at the beginning of the time-series, of their respective carrying capacities; $\lambda_{f1} - \lambda_{f2}$ = final proportional biomass of the snapper stocks of their respective carrying capacities in last year.

Red snapper (*Lutjanus campechanus*). The *MSY* estimated was 4,964 t. For this stock, landing values show a trend of increase and decrease, at the beginning (1980-1993) and at the end (2014-2019) of the series, with values above the *MSY*, where it reaches its maximum value (7,205 t) in 1993 exceeded the upper CI of *MSY*, and an intermediate period in which catches regularly remain below the lower CI of *MSY* (Fig. 2a). The biomass associated with *MSY*, or B_{TRP}, estimated was 17,554 t. During the time series analyzed, the stock biomass trajectory oscillated above the B_{TRP} (Fig. 2b). The biomass decreased, beginning in 1984, to levels close to the B_{TRP} in the mid-1990s then increased to levels close to the upper limit of B_{TRP}. This biomass was stable for approximately 10 years then again decreased but remained above B_{TRP}. Fishing mortality (F) throughout the time series compared to the F_{lim} of 0.28 is shown in Figure 2c. The annual fishing mortality was far below the F_{lim} value throughout most of the time series, except for a brief period in the early 1990s during which the fishing mortality increased, reaching a maximum value in 1993 of 0.31 (above the F_{lim}) but then decreased to levels below F_{lim} and ending the time series with a fishing mortality value for the last year (F_{2019}) of 0.17.

Yellowtail snapper (*Ocyurus chrysurus*). The *MSY* estimated for this stock was 1,953 t. The annual landings remained stationary below the MSY until 2015, varying between 1,000 t and 1,750 t, from which an increasing trend is observed reaching a maximum value of 3,176 t above the upper CI of *MSY* in the last year of the period analyzed (Fig. 2d). The B_{TRP} estimated was 6,907 t. The stock biomass gradually increased to around 9,900 t in 2016 (well above the B_{TRP}) (Fig. 2e), then decreased but remained above B_{TRP} at the end of the studied period. Fishing mortality (F) is below F_{lim} throughout the time series, but beginning in 2015 F increased markedly, being located above F_{lim} in the last two years, finishing the time series with F_{2019} of 0.39, above the upper CI of F_{lim}.

Table 2. Fishery and stock parameters estimated by the C-MSY assessment and candidate reference points for management of the three snapper stocks.

Stock	Reference Points Estimated by C-MSY method — Median (lower and upper limit of the 95% confidence interval)			Candidate Reference Points for management — Target	Limit	
	MSY (Tonnes)	B_{MSY} (Tonnes)	F_{MSY}	$B_{TRP} = B_{MSY}$ (Tonnes)	$B_{lim} = 0.5B_{MSY}$ (Tonnes)	$F_{lim} = F_{MSY}$
Red snapper	4,964 (3,506 – 7,027)	17,554 (10,593 - 29,090)	0.28 (0.20 - 039)	17,554	8,777	0.28
Yellowtail snapper	1,953 (1,229 – 3,104)	6,907 (3,929 – 12,142)		6,907	3,454	
Lane snapper	269 (214 - 338)	966 (623 - 1,498)	0.27 (0.19 – 0.39)	966	483	0.27

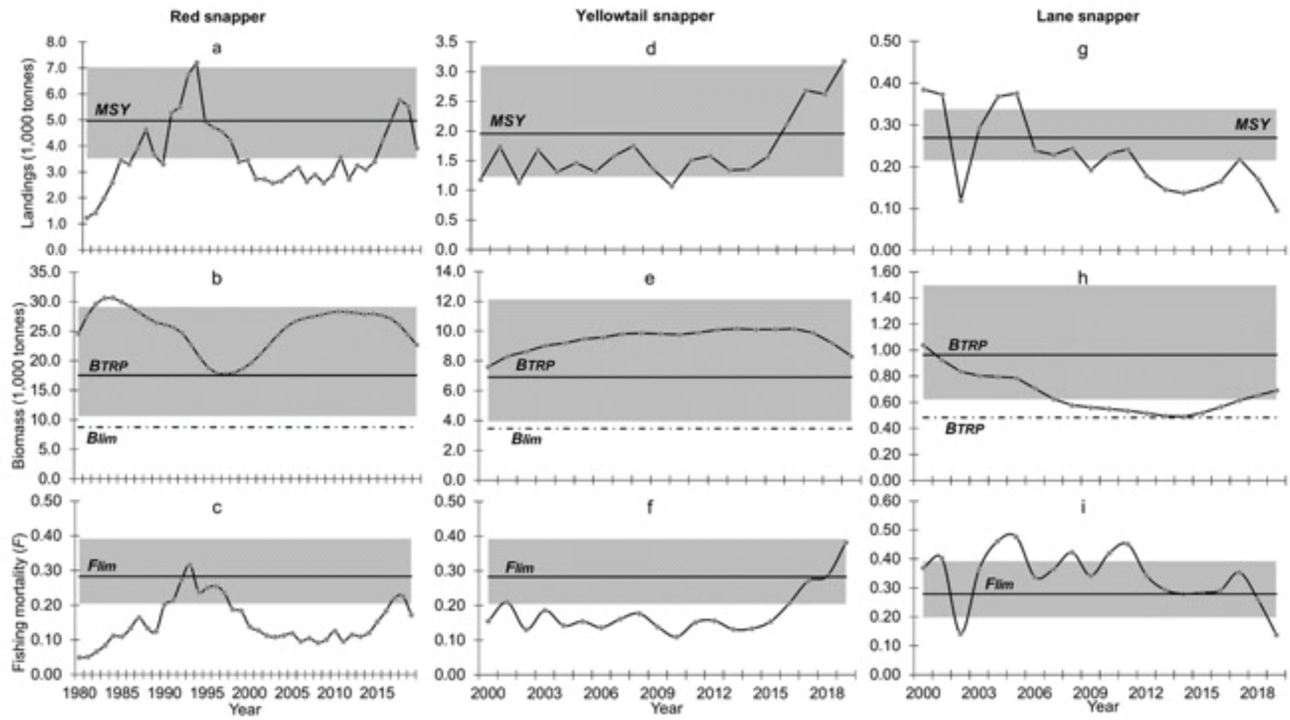

Figure 2. Results for the Monte Carlo-based C-*MSY* assessment for the red snapper, yellowtail snapper and lane snapper stocks. Panels a, d and g) Landings and *MSY* (95% confidence interval shown in gray), panels b, e and h) Stock biomass trajectory and B_{TRP} (95% confidence interval shown in gray) and B_{lim} (dash-dot line), panels c, f and i) Fishing mortality and F_{lim} (95% confidence interval shown in gray).

Lane snapper (*Lutjanus synagris*). The *MSY* estimated for this stock was 269 t. The landings values fluctuated above and below the MSY confidence intervals during the first third of the series until 2005 (Fig. 2g), after which the landings decreasing trend is observed until reaching its lowest value (95 t) below the lower CI of *MSY* in the last year. The B_{TRP} estimated was 966 t. The stock biomass (Fig. 2h) was estimated to be between the B_{TRP} and the B_{lim} during most of the time series, initially showing a decreasing trend reaching values close to the B_{lim} until 2014, then with an increasing trend at the end of the period. Figure 2i shows F compared to the F_{lim} of 0.27 throughout the studied period. At the beginning of the time series, the annual fishing mortality drastically decreased to values below the lower CI of the F_{lim}, then increased until reaching a maximum value in 2005 (F = 0.44), above the upper CI of the F_{lim}. F values varied around the upper CI until 2011, then decreased and reached a minimum value in the last year (F_{2019} = 0.12), below the lower CI of the F_{lim}.

It is worth noting that the exploitation rates seen in Figures 2 (c, f, i) are consistent with the landings presented in Figure 2 (a, d, g) for each population evaluated.

Figure 3 shows Kobe plots for red, yellowtail and lane snapper fisheries in the Gulf of Mexico, which show the evolution of fishery exploitation over time. For the red snapper stock (Fig. 3a), the trajectory of the different points shows that this fishery remained at healthy levels (green quadrant) for most years of the time series, with 94.3% probability that the present condition of the red snapper fishery is above the B_{TRP}. There is a 4.1 % probability that the stock is below the B_{TRP} but without overfishing occurring (yellow quadrant); a 0.9% probability that the stock is above the B_{TRP} but with overfishing occurring (orange quadrant), and the probability that the stock is both below the B_{TRP} and experiencing overfishing (red quadrant) is 0.7%. For yellowtail snapper stock (Fig. 3b), the trajectory of the different points shows that this fishery remained at healthy levels (green quadrant) for most of the period, and by the end, there is a high probability (75.5%) that the stock is currently healthy but experiencing overfishing (orange quadrant). There is a 14.4% probability that the stock is above the B_{TRP} and overfishing is not occurring (green quadrant) and a 10% probability that the stock is below the B_{TRP} (overfished) and experiencing overfishing (red quadrant). It is of note that stock status remained in good condition for many years but rapidly changed over the last four years to move into a less favorable status where overexploitation is occurring at an increasing rate. For the lane snapper fishery, the Kobe plot (Fig. 3c) shows the stock below the B_{TRP} and experiencing overfishing (red quadrant) until 2017 with values very close to B_{lim} (below which the population would be considered at risk) and in the last year being below the B_{TRP} but not experiencing overfishing (yellow quadrant) with a high probability (100%).

Management Options Outcome Analysis. Figure 4 and Table 3 show the biomass projections to 2025 for the three snapper stocks resulting from the management options outcome analysis, expressed as percentages of the *MSY* and F_{lim}. The expectation is that a catch at *MSY* would yield biomass at B_{TRP}. With a harvest strategy of catches equal to the *MSY* of each species, the red snapper stock biomass decreases slightly

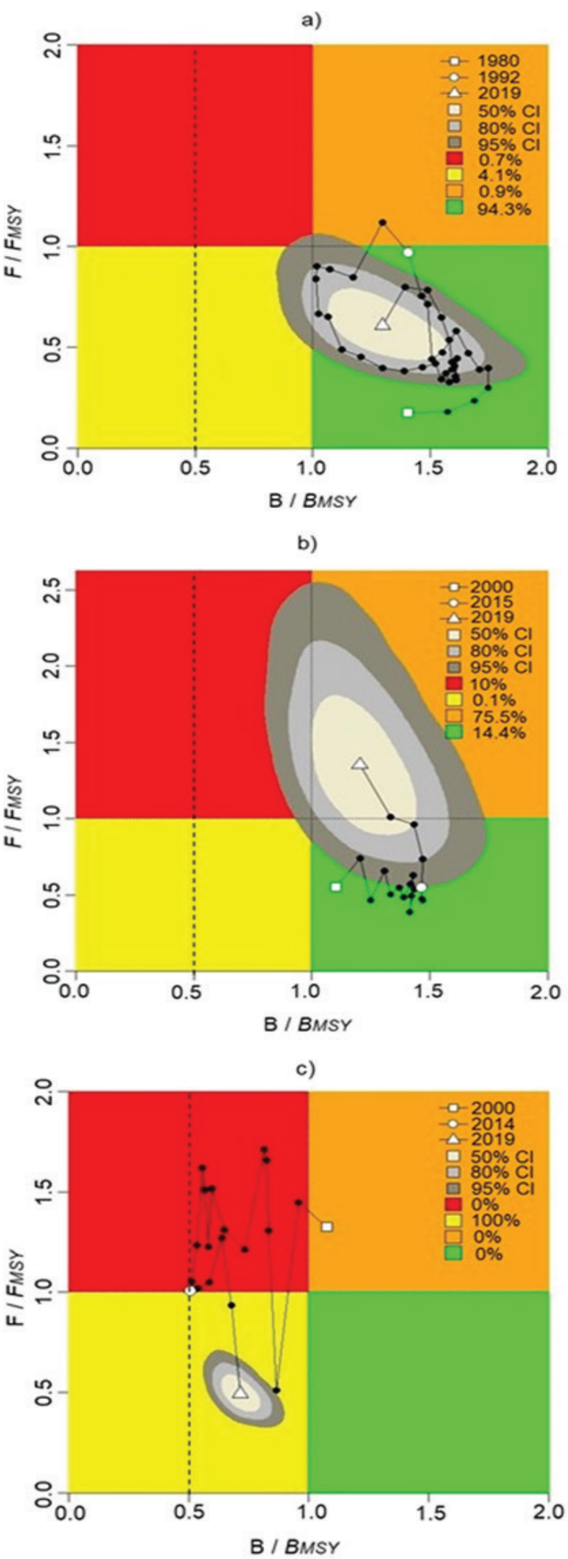

Figure 3. Kobe plots for a) red snapper b) yellowtail snapper and c) lane snapper. The dashed line shows the B_{lim}. Gray areas indicate iso-probabilities for the final year, 2019.

but remains above the B_{TRP} (Fig. 4a), while for yellowtail snapper the stock biomass remains stable at a value equal to B_{TRP} (Fig. 4b), and for the lane snapper the stock biomass remains constant at a value below the B_{TRP} but within the lower CI (Fig. 4c). With catch values of 0.9 *MSY*, the red and yellowtail snapper stocks remain at biomass levels higher than B_{TRP} but within the confidence interval, and the lane snapper stock biomass increases to a level close to B_{TRP} by 2025. With catch values limited to the *MSY* lower confidence interval, the biomass values increase, approaching the upper B_{TRP} confidence interval by 2025 for red and yellowtail snapper populations and above B_{TRP} for the lane snapper population. For the lane snapper stock, the catch values at the lower CI and 0.8 are almost equal and the projection with these strategies is coincident (Fig. 4c). Only the yellowtail snapper stock presents an option of catch equal to 0.7 *MSY*, for the other stocks this catch value is less than the value of the lower CI. Note that the projected catch values are long-term averages and do not reflect real-world annual variability.

Considering the limitation of fishing mortality as a second strategy, in Figure 4(d, e) we observe that establishing fishing mortality at F_{lim} maintains the red and yellowtail snapper populations at or just above the B_{TRP}; this same harvest strategy allows the lane snapper population (Fig. 4f) to recover to a level slightly below B_{TRP} by 2025. With fishing mortality limited to 0.9F_{lim} as a harvest strategy, the stock biomass values by 2025 for all three snapper stocks are above the B_{TRP} (Table 3).

Figure 5 shows the management outcome analysis results considering different values for constant catch limit and the resulting probability curves for the likelihood of the stock size falling below B_{lim} remaining between the B_{lim} and the B_{TRP}, and rising above B_{TRP}.

With an annual catch value equal to *MSY* the probability of the red snapper stock size declining below the B_{lim} by 2025 is 0.04, while the probability that the stock will be above B_{lim} but below B_{TRP} is 0.29, and for being at or above B_{TRP} is 0.67 (Fig. 5a). With respect to the yellowtail snapper stock and an annual catch equal to MSY, there is a probability of 0.31 for the biomass declining below the B_{lim} by 2025, a probability of 0.24 for the biomass being between B_{lim} and the B_{TRP}, and a probability of 0.46 for being at or above B_{TRP} (Fig. 5b). For the lane snapper stock and an annual catch value equal to *MSY*, the probability of the stock size declining below B_{lim} by 2025 is 0.31, the probability that it falls between the B_{lim} and the B_{TRP} is 0.64 and that it falls above the B_{TRP} the probability is 0.05 (Fig. 5c). With an annual catch value at the lower limit of the confidence interval of the estimated *MSY* for each stock, the probabilities that the biomass will fall above the B_{TRP} are 0.87, 0.66 and 0.16 for red, yellowtail and lane snapper stocks, respectively, while the probability of the yellowtail snapper stock size declining below B_{lim} is 0.13, and the probabilities that the biomass declines below the B_{lim} for the other stocks is negligible.

DISCUSSIONS

Many authors have described the process of development of a fishery through changes in landings over time, often with a "boom and bust" character (Caddy, 1984; Rapport *et al.*, 1985; Welcomme 1995; Grainger & Garcia, 1996; Froese & Kernell-Reyes, 2002). The analyzed period shows a different behavior of the landings for each stock, while the *Lutjanus campechanus* presents a time-series in which different phases of the establishment of a formal fishery can be observed, *O. chrysurus* and *L. synagris* gained growing commercial importance and

Table 3. Results of the management options outcome analysis projected to 2025 for the three stocks including constant catch and constant fishing mortality as potential management tools. Outputs are long-term averages.

Stock		2019	2025 Harvest strategy 1 (restricted constant catch)					Harvest strategy 2 (restricted constant fishing mortality)			
			MSY	$0.9MSY$	$0.8MSY$	$0.7MSY$	Lower CI MSY	F_{lim}	$0.9F_{lim}$	$0.8F_{lim}$	$0.7F_{lim}$
Red snapper	Catch (t)	3,918	4,964	4,467	3,971	**3,475***	3,506	5,188	5,042	4,825	4,530
	F	0.17	0.23	0.19	0.16		0.13	0.28	0.25	0.22	0.19
	B/B_{MSY}	1.29	1.21	1.32	1.41		1.49	1.04	1.12	1.21	1.30
	F/F_{MSY}	0.61	0.82	0.68	0.56		0.47	1.00	0.90	0.80	0.70
Yellowtail snapper	Catch (t)	3,176	1,953	1,758	1,562	1,367	1,229	1,960	1,909	1,831	1,723
	F	0.38	0.27	0.22	0.17	0.14	0.12	0.28	0.25	0.22	0.19
	B/B_{MSY}	1.20	1.01	1.14	1.26	1.37	1.47	1.00	1.08	1.17	1.26
	F/F_{MSY}	1.35	0.98	0.78	0.63	0.51	0.42	1.00	0.90	0.80	0.70
Lane snapper	Catch (t)	95	269	242	215	**188***	214	261	255	245	231
	F	0.13	0.32	0.25	0.19		0.19	0.27	0.25	0.22	0.19
	B/B_{MSY}	0.71	0.84	1.00	1.14		1.14	0.97	1.05	1.13	1.22
	F/F_{MSY}	0.49	1.18	0.89	0.70		0.69	1.00	0.90	0.80	0.70

*** Indicates catch values below the lower confidence interval of respective *MSY***

increasing fishing pressure due to the low capture of red snapper reported in 2006 (Brulé *et al*., 2009).

This study indicates that in the last year of the analyzed time-series (2019), red and yellowtail snapper stocks were not overfished while the lane snapper was. While Overfishing was not occurring for red and lane snappers, yellowtail snapper was experiencing overfishing (Table 3). Other studies conducted in specific areas in the Gulf of Mexico (Monroy *et al*., 2004, Brulé *et al*., 2009) report for the red snapper (*L. campechanus*) an "Exploited at Maximum Sustainable Yield" status, while lane (*L. synagris*) and yellowtail (*O. chrysurus*) were in the phase of increasing exploitation (Brulé *et al*., 2009). Also, the latest version of the National Fisheries Chart (DOF 2023) in the Red snapper and Snappers chapter, indicates that, for 2018, the red snapper biomass is close to the biomass that would generate the maximum sustainable yield.

Through most of the time series the lane snapper biomass was consistently between the candidate B_{TRP} and B_{lim} and the fishing mortality was above the candidate F_{lim}. (Fig. 2), this population shows some indications of potential recruitment problems with relative biomass values close to 0.25 of B / *k*., coinciding with Díaz de Leon *et al.* (2004) that analyzed the health status of 28 fishery management units in the Gulf of Mexico, determining that 79% were overexploited and that 25% required urgent attention, including the snapper species.

Regarding the biomass estimates of each stock, the CV value used in the model was 0.2 (20%), assuming that the landings could be lower or higher than those registered. Cisneros-Montemayor & Cisneros-Mata (2018) mention that the annual unrecorded fishing in Mexico is on the order of 40%, this phenomenon can affect the stock biomass estimates; according to Merrill & Branch (2016), if the unrecorded catch is constant over time the actual total biomass would be higher than the estimates in this work but with a similar biomass trajectory. Given this uncertainty, it is important to focus more on biomass trajectories rather than specific point estimates, and to consider the wide confidence intervals around the fishery and stock parameters estimated by the model.

The forward projections of stock status in the management options outcome analysis indicate that the red and yellowtail snapper stocks are likely to maintain their non-overfished status by 2025 in all the constant catch and constant fishing mortality limits tested. For lane snapper a management strategy equal to 0.8*MSY* or F<0.9F_{lim} is likely to generate stock biomass above the target biomass by 2025. With the above-mentioned management strategy of 0.8*MSY* or 0.9F_{lim}, the yellowtail snapper is likely to no longer be experiencing overfishing in 2025.

The management options outcome analysis also shows that for red snapper, all of the management strategies tested in this study generate a low risk of breaching the LRP and a fairly high likelihood of biomass being above the candidate B_{TRP}. For yellowtail snapper, even catches at 0.8 and 0.7*MSY* have a substantial risk of breaching the LRP even though there is a greater than 50% probability of the biomass being at or near the candidate B_{TRP}. For lane snapper, catches at 0.8*MSY* have a low risk of breaching the LRP but also have a low likelihood of yielding biomass above the candidate B_{TRP}; instead, the management strategies tested in this study are most likely to generate lane snapper biomass between the candidate B_{lim} and B_{TRP}.

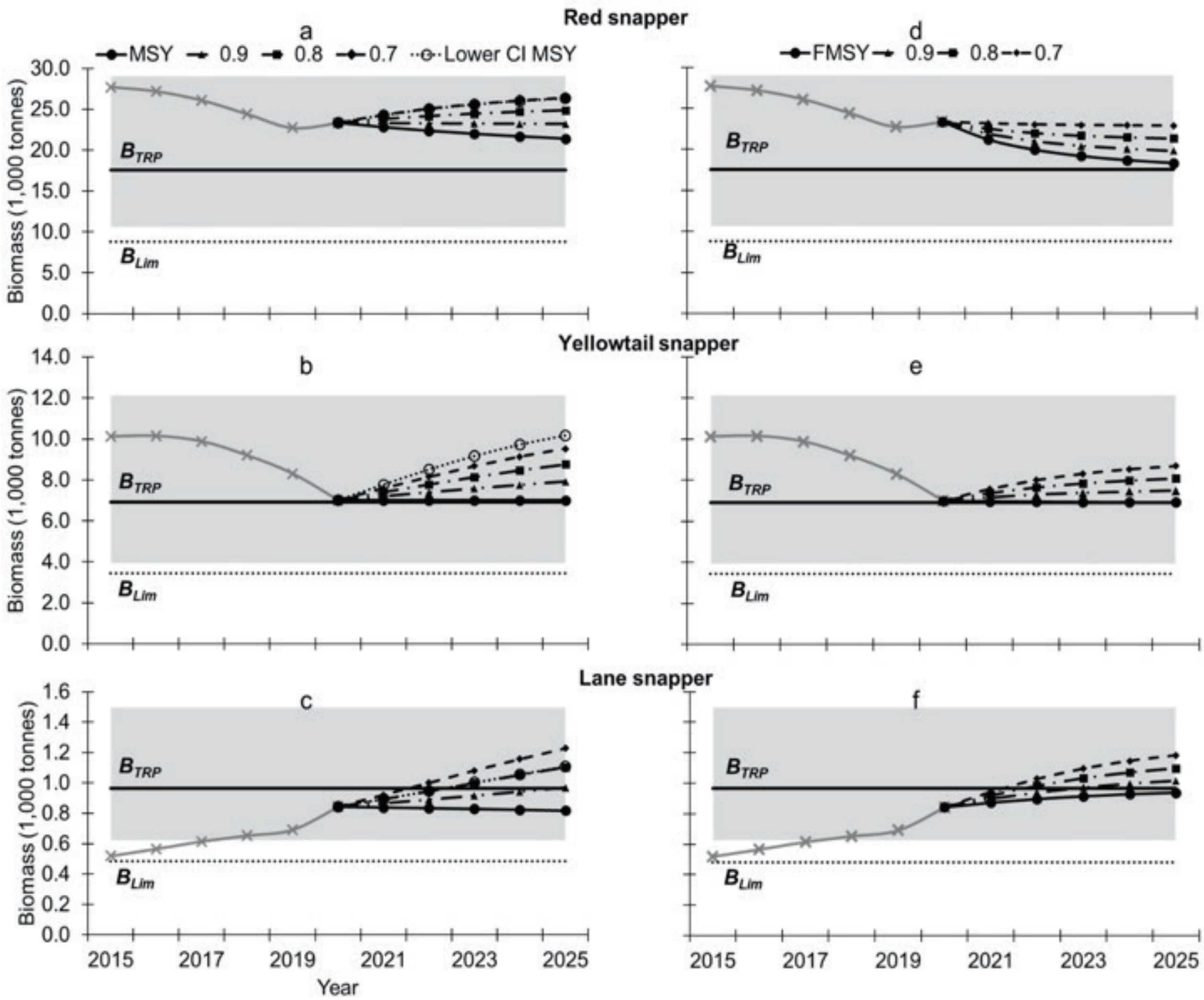

Figure 4. Results of the management options outcome analysis projected to 2025 for the three stocks. Panels a, b and c show the results of constant catch limits as the management parameter, including the (i) *MSY*, (ii) the lower confidence interval of *MSY*, and (iii) 0.7, 0.8 and 0.9 *MSY*. Panels d, e and f show the results of constant fishing mortality as the management parameter, including F_{lim} and three lesser F values (0.9, 0.8 and 0.7 F_{lim}). B_{TRP} is shown by solid lines (confidence intervals shown in gray); B_{lim} is shown by dotted lines.

These graphs can be used to help managers select catch limits that align with their tolerance for the risk of breaching LRPs. Managers can use this information to balance the need to maintain a healthy stock with the need to provide fishers the opportunity to harvest more fish. Note that this data-poor assessment methodology comes with a great level of inherent uncertainties, thus a more conservative LRP breach risk should be considered, especially in situations where inadequate enforcement of catch limits is likely. The UN Fish Stocks Agreement (United Nations Organization 2001) advises that the risk of breaching LRP should be “very low”. For some stocks an acceptable risk of breaching the LRP would normally be between 0 and 10% ($0 < p < 0.1$) (Cordue, 2014). The probability that the snapper stocks present a greater than 10% risk of breaching the LRP (horizontal and vertical gray dot lines on Fig. 5) occurs with constant catches greater than 5,550 t, 1,110 t, and 231 t for the red, yellowtail, and lane snapper stocks, respectively.

Given that populations are very dynamic and can change size rapidly, it is important from a management perspective the speed needed by managers to respond to changes in the fishery and stock in order to keep the stock status in good condition, as well as the improvement of population assessment methodologies over time, the fishery should be managed such that the population biomass fluctuates near a target reference point (TRP) in alignment with the fishery management objectives, which may be, for example, *MSY* (MFNZ, 2008), considering that risk of the population biomass declining to less than the limit reference point (LRP) should be low (Table 2, Fig. 5).

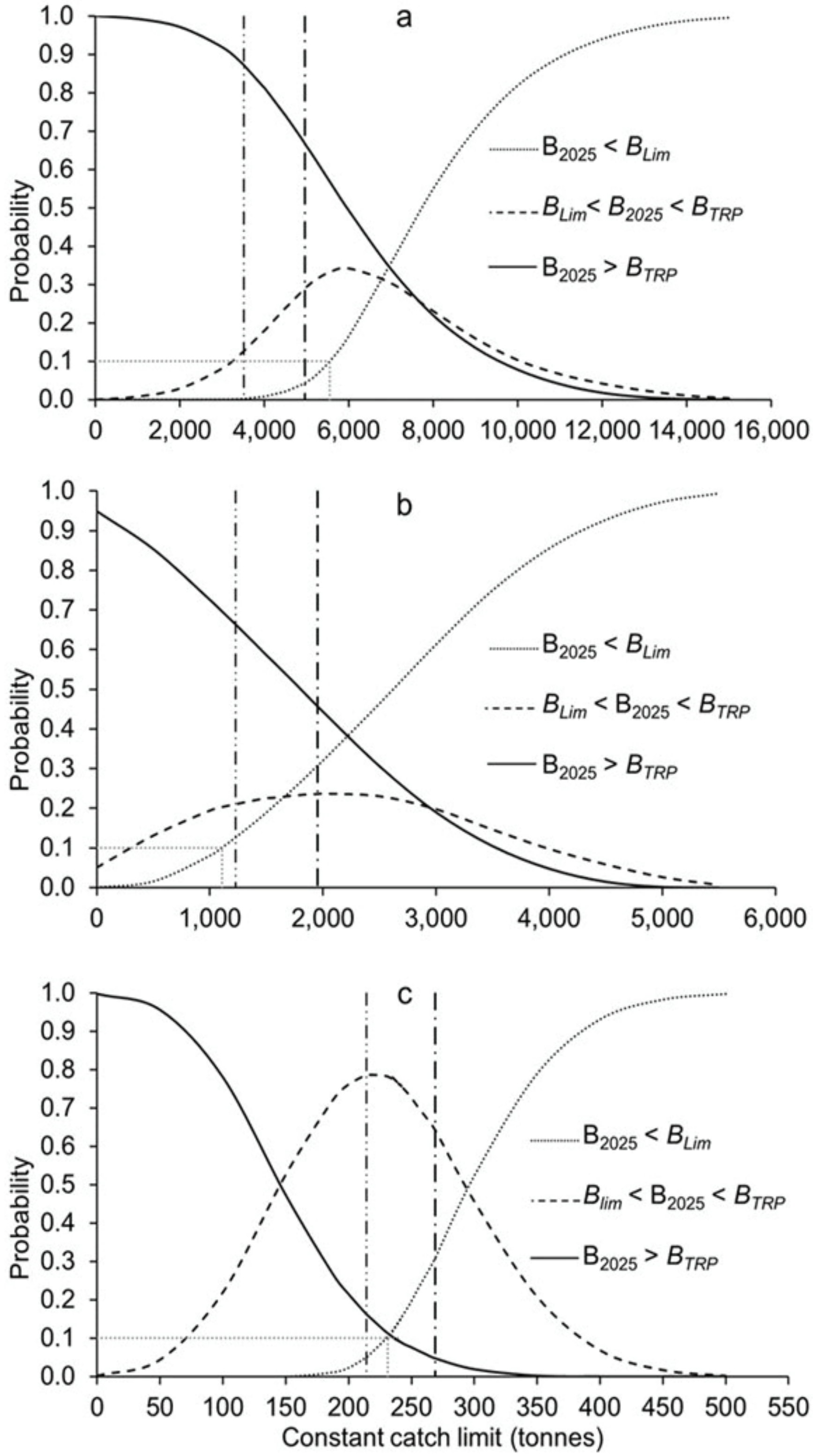

Figure 5. Probability curves resulting from the management options outcome analysis using constant catch limits for (a) red snapper, b) yellowtail snapper and c) lane snapper. The lines shown the likelihood of stock biomasses falling below B_{lim} (dotted line), remaining between B_{lim} and B_{TRP} (dashed line) and rising above B_{TRP} (solid line) by 2025. The vertical lines show the *MSY* estimate (dash-dot line) and the lower confidence interval of *MSY* (dash-dot-dot line). The horizontal and vertical gray dot lines show the catch value at the probability of 10% (p = 0.1) LRP breach risk.

In addition, the characteristics of the fishery and its multispecific and sequential aspects (Monroy *et al.*, 2010; Coronado & Salas, 2012), the implementation of any management strategy should consider variables in its development, such as spatial and seasonal restrictions. Monroy *et al.*, (2010) mentions that in Yucatan Sate the capture of red snapper occurs along all the year; however, is in the February-July period when the highest landings occur. Coronado and Salas, (2012) developed an analysis to determine the operative characteristics of the fleets that work these species, finding significative differences in the CPUE for each fleet. The National Fisheries Chart (2023) shows the capture trends for each state for red snapper and snappers in general. This differences should be considered as components in the implementation of any management strategy agreed by the different stakeholders involved in the fishery.

In order to maintain the red snapper stock at healthy levels (i.e. fluctuating around B_{MSY}), we recommend establishing, implementing and enforcing an annual catch of 4,467 t (=0.9*MSY*). To reduce overexploitation and maintain the yellowtail snapper stock at healthy levels (~ B_{MSY}) we recommend an annual catch of 1,562 t (=0.8*MSY*). For the lane snapper stock, we recommend an annual catch of 215 t (=0.8*MSY*), which should return the stock close to B_{MSY} in a five-year period after implementation and also avoid future overexploitation. Because of the low probabily of this management strategy returning the stock to a size above the candidate B_{TRP}, this stock should be re-evaluated within a few years of TAC implementation to ensure that it is responding as desired. Brulé *et al*. (2009) considers, among others, the implementation of catch quotas as management strategy for species overexploited or exploited at maximum sustainable yield (*L. campechanus*) or in a growing exploitation stage (*L. synagris* and *O. chrysurus*).

Likewise, the technical factsheet for Red Snapper and Snappers of the National Fisheries Chart (2023), recommends a variable harvest rate as a management strategy. In this study we developed projections to assess the stock biomass behavior in response to different *F* values lower than F_{lim} (Table 2) to maintain the stocks at healthy levels.

ACKNOWLEDGMENTS

The authors would like to thank the Walton Family Foundation and Sustainable Fisheries Partnership Foundation for their support of this research. Special thanks to Megan Westmeyer and Dr. Geoff Tingley for their scientific advice and editorial review of this project. Thanks to the anonymous reviewers of this journal.

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