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Research Article

Understanding the effects of uncertainty on catch series over data-limited stock assessment and harvest strategies of Brazilian southern red snapper (*Lutjanus purpureus*) fishery

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ABSTRACT. Catch time series are still the only historical information to assess many global fisheries, and the low quality of catch data is one of the major issues in quantifying the condition of stocks and sustainable exploitation levels for most Brazilian fisheries. Data-limited methods for stock assessment and management strategy evaluation were applied to the southern red snapper (SRS; *Lutjanus purpureus*) fishery in Brazil, enabling the assessment of the effects of uncertainty on historical catch series over stock status estimations and management strategy performance. We estimated biomass trends and reference points through catch-only stock assessment with four combinations of the available catch time series. Using management strategy evaluation methods, we also evaluated the capacity of different strategies to avoid overfishing, maintain population sustainability, and achieve yield optimization and stability. The differences in catch series affect the assessed variables: stock status results range from 0.28 to 0.43 of virgin biomass, current fishing mortality varies from 28 to 53% above sustainable levels, and sustainable yield results range from 5,320 to 7,580 t. Early uncertainty in the SRS catch series has the greatest impact on absolute estimations and sustainable yield. Still, recent misreporting strongly influences current fishing mortality and catch limit estimations. Under this uncertainty, static management strategies based on effort control and constant catch tend to be more sensitive and riskier, resulting in the poorest performance on sustainability criteria, especially in pessimistic scenarios. Dynamic procedures based on regular biomass estimations tend to be more conservative and robust, with better performance in avoiding overfishing and achieving yield stability.

Keywords: *Lutjanus purpureus*; Brazilian southern red snapper; data-limited; stock assessment; management strategy evaluation; management procedures

INTRODUCTION

The southern red snapper (hereafter SRS; *Lutjanus purpureus*) is one of the most important fishery resources exploited in Brazil. Catches are mainly intended for the USA, a market that represents 25% of the Brazilian seafood annually exported (MMA/SEAP 2018, Comex Stat 2022). The SRS has a wide distribution range, from the northeastern coast of Brazil (State of Bahia) up to the Caribbean Sea. The species is also commercially exploited in French Guiana, Venezuela, Colombia, Martinique, and Santo Domingo (FAO 2020). Data on total landings have been available since 1950 for the Brazilian domestic fleet and indicate a development period until 1970, a decline during the 1980s, and a relatively stable condition over the past 25 years, with catches varying around 6,000 t per year (MMA/SEAP 2018, FAO 2020).

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In Brazil during the 1970s and 1980s, stock assessments suggested a maximum sustainable yield (MSY) ranging between 3,600 and 6,800 t for the SRS local stock (Santos & Coelho 1974, Ivo & Souza 1988). These values are consistent with recent catch trends, indicating that the population is possibly healthy and has been harvested sustainably. Recent assessments, on the other hand, suggest that the population is subject to growth overfishing due to observed reductions in fish size, weight, and age composition in catches (Ivo & Souza 1988, Souza 2002, Resende et al. 2003, Bentes et al. 2017).

The SRS fishery in Brazil has experienced significant conflicts over the last few decades. In 2014, the Brazilian Ministry of the Environment, following the National Policy for Biodiversity (Brasil 2002), assessed the SRS as vulnerable to extinction according to the International Union for Conservation of Nature (IUCN) criteria (Brasil 2014). An SRS Rebuilding Plan (SRS-RP; MMA/SEAP 2018) was developed, including management measures such as limited entries, minimum landing sizes, no-take areas, and closed seasons, with recommendations to set a total allowable catch (TAC) for the SRS fishery.

As with many fisheries around the globe (Costello et al. 2012, Froese et al. 2012), one of the main challenges to scientific management in Brazil is the low consistency of historical data for reliable estimations of population conditions and catch limits, with the SRS fishery being a central issue due to the conflicts mentioned above (Dias et al. 2022). As a global demand, “data-limited” methods have emerged over the past decade as a tool to support decision-making with limited information through both stock assessment (Froese et al. 2012, Martell & Froese 2012) and management strategy evaluation approaches (Carruthers et al. 2016, Carruthers & Hordyk 2018a). While stock assessment methods approximate sustainable yield and stock depletion, management strategy evaluation illuminates fishing strategies that can work well across various situations.

Many time series on total landings are publicly available for the SRS fishery. One is found in the Food and Agriculture Organization FishStat database (FAO 2020), and the other was compiled for the SRS-RP (MMA/SEAP 2018). These two series show great discrepancies, especially in the early stages of the fishery. While the FAO data show a peak of about 15,000 t landed during the 1970s and volumes above the 8,000 t level frequently, the SRS-RP data present landings peaking at 7,500 t, with few years of total landings above the 6,000 t level (Fig. 1). From 1996 to 2015, the data are identical. For the following period, data on total landings are unavailable due to an interruption in fisheries statistics programs, and total volumes of SRS landed can only be inferred from Brazil’s export database. This database, however, does not capture volumes of SRS traded in the domestic market, so catches are likely higher than those reported there.

Uncertainty in catch data may mislead managers in identifying current stock status and lead to management actions that could result in overfishing (Martell & Froese 2012). In this article, we quantify this problem for the SRS fishery by applying data-limited methods to understand how uncertainties in catch series might influence the perception of stock status and the expected performance of different harvest strategies and control rules. These methods include data-limited stock assessments (Froese et al. 2012, Martell & Froese 2012) and management strategy evaluation (Carruthers et al. 2016, Carruthers & Hordyk 2018a).

There is a consensus that catch-only methods for stock assessment alone are limited in defining absolute biomass, stock status, and exploitation rate, yet are more confident in their MSY suggestions (Fitzgerald et al. 2018, Zhang et al. 2018, Dowling et al. 2019, Free et al. 2020, Palomares et al. 2020). To be useful for management, authors suggest that these methods may be integrated into ensemble models and combined with Management Strategy Evaluation (MSE) analysis (Free et al. 2020, Bouch et al. 2021). The MSE simulates fish population dynamics and fishery operations to test the performance of different Management Procedures (MPs) (Butterworth & Punt 1999, Smith et al. 1999, De Oliveira & Butterworth 2004, Punt et al. 2014). It allows forecasting the consequences of these different management procedures and their probabilities of achieving overarching management objectives related to sustainability and profitability.

This paper explores the marginal effects of uncertainty in the SRS catch series on stock status perceptions, catch limits estimations, and the biological and economic performances of different management strategies, including effort control, catch-based, and depletion-based methods.

MATERIALS AND METHODS

Fishery information

Historical catch series for the SRS are available from different sources that present highly discrepant values for the early stages of the fishery activity. The FAO

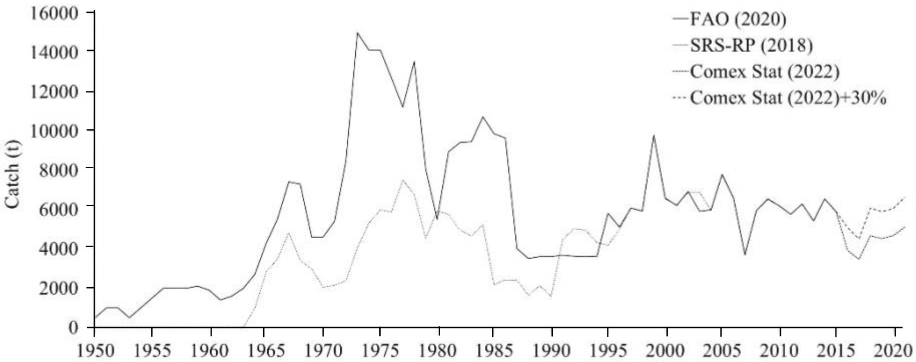

Figure 1. Historical catch series obtained in the literature for southern red snapper (SRS) fishery in Brazil. FAO (2020) data from 1950 to 2020 are available at the website: (https://www.fao.org/fishery/statistics-query/en/capture/capture_quantity). SRS-RP (2018) is a National publication by the Ministry of Environment available at the website: (https://www.gov.br/agricultura/pt-br/assuntos/aquicultura-e-pesca/pesca/planos-derecuperacao/Plano_de_Recuperacao_do_Pargo.pdf). Comex Stat (2022) data are exportation records from the Ministry of Industry, Foreign Trade and Services available at the website: (http://comexstat.mdic.gov.br/pt/geral/85323) and used to represent the recent catches, with an alternative scenario that increases it in 30% to represent the domestic consumption.

(2020) database comprises catches from 1950 to 2015, while the SRS-RP (MMA/SEAP 2018) presents a catch series from 1964 to 2010. Volumes of SRS exported by Brazilian companies are available on the foreign trade statistics webpage (Comex Stat 2022) and represent the only data source for the SRS fishery from 2015 onwards. Interviews with companies involved in processing and trading the SRS suggested that the domestic market for the species does not exceed 30% of the total landings, so we used this value in scenarios to account for catch uncertainty in recent years. We considered four scenarios with different catch and trade data combinations for the initial and final periods to understand how they impact management recommendations for the SRS fishery (Fig. 1, Table 1).

The four scenarios considered were named: Cases A1 (CA1) and A2 (CA2), which consist of FAO (2020) data from 1950 to 2015, followed by export data from 2016 to 2021 (CA1) and this increased by 30% (CA2) for the final period (2016-2021), and Cases B1 (CB1) and B2 (CB2), scenarios in which data from 1964 to 2010 was replaced by the SRS-RP (MMA/SEAP 2018) records, with the same two scenarios based on exported catches from 2015 to recent years, respectively (Table 1). Thus, catch data for the intermediate period, from 1995 to 2015, are almost identical for all scenarios, with the observation uncertainty restricted to the periods 1950-1995 and 2015-2021.

Life history parameters

Bentes et al. (2017) compiled much of the information available for SRS in Brazil, including parameters that define the dynamics and life strategy of the species, such as individual growth rates, size at first maturation, and natural mortality, among others. For growth and size at first maturation parameters, we adopted the average of the values found in the literature (Table 2). In contrast, we made new calculations based on empirical models for age at first maturation and natural mortality parameters (Tables 2-3).

Previous studies on SRS growth in Brazil estimate that the species has an asymptotic length, on average, around 100 cm (92.9-115.0 cm), annual growth rates between 0.06 and 0.13 yr^{-1}, with a mean of 0.10 yr^{-1}, and a theoretical age at zero length of -1.28 years (Table 2). These average values were used in the recalculation of two important parameters for the present study: (a) average age at first maturation, calculated based on the average length at first maturation, and (b) natural mortality, calculated with empirical methods, both presented below. The average lengths at first maturation found in the literature varied between 39.25 and 43.67 cm, and the results of the recalculation of the average ages at first maturation resulted in ages between 3.61 and 4.35 years (Table 2).

Natural mortality for SRS in N/NE Brazil has been estimated in several studies using different approaches, compiled by Bentes et al. (2017), with values reported between 0.25 and 0.35 yr^{-1}. In the present study, we used the average values of the growth parameters mentioned. We applied both empirical methods already used for SRS, such as those by Rikhter & Efanov (1977) and Pauly (1980), as well as others not yet applied, such as Jensen (1997) and Alagaraja (1984).

Table 1. Scenarios of the catch series assessed in the present study, including their sources and respective periods. [*]The period with data absence for southern red snapper Rebuilding Plan SRS-RP (MMA 2018) at the end of the initial period, from 2010 to 2015, was fulfilled by FAO (2020) data. [**]In these scenarios, catch obtained from export records (Comex Stat, 2022) was increased by 30% as an approximation of domestic consumption.

Scenario	Initial period		Final period	
	Source	Years	Source	Years
CA1	FAO (2020)	1950-2015	Comex Stat (2022)	2016-2021
CA2			" +30%[**]	"
CB1	MMA (2018)	1964-2010[*]	Comex Stat (2022)	"
CB2			" +30%[**]	"

Table 2. Growth parameters for southern red snapper (SRS) found in the literature and compiled by Bentes et al. (2017). Average lengths at first maturation (Lm_{50} (cm)) of SRS found in the literature and average ages at first maturation (Tm_{50} (years)) recalculated in the present study. *****As cited in Bentes et al. (2017). L_∞: asymptotic length; *k*: individual growth rate; t_0: age at length zero; L_{max}: maximum length; A_{max}: maximum age; Lc_{50}: length at 50% of selectivity; Lc_{95}: length at 95% of selectivity.

Source	L_∞ (cm)	k (yr^{-1})	t_0 (years)
Lima (1965)*	97.67	0.12	0.00
Menezes & Guesteira (1974)*	98.86	0.09	-2.70
Ximenes & Guesteira (1988)*	92.90	0.10	-2.80
Souza (2002)*	115.00	0.09	0.00
Rezende (2008)*	103.75	0.06	-3.45
Sarmento (2012)*	94.00	0.13	0.00
Sarmento (2012)*	100.00	0.12	0.00
Mean	100.31	0.10	-1.28
Standard deviation	7.43	0.03	1.61
Maturity	Lm_{50} (cm)		Tm_{50} (years)
Souza et al. (2003)	43.67		4.35
Sarmento (2012)	39.50		3.65
Bentes et al. (2017)	39.25		3.61
Mean	40.81		3.87
Longevity	L_{max} (cm)		A_{max} (years)
Souza (2002)	103		33
Weight×length	a		b
Bentes et al. (2017)	1.57		2.87
Selectivity	Lc_{50} (cm)		Lc_{95} (cm)
Souza & Ivo (2004)	31		41

The results were significantly lower than those reported in previous studies, varying between 0.106 and 0.229 yr^{-1}, with an overall mean of 0.181 yr^{-1} among the six methods applied here (Table 3). The estimated values are closer to those reported for the Gulf of Mexico snapper (*Lutjanus campechanus*), of 0.094 yr^{-1} for the vulnerable fraction (ages 2+), a species widely studied and often considered to be the same as that found in Brazil (Marval-Rodríguez et al. 2022).

Data-limited stock assessment

The method presented by Froese et al. (2023) for stock assessment consists of an advanced state-space Bayesian method used to fit a surplus production model (Schaefer 1954, 1957) of population dynamic to catch data:

$$B_{t+1} = B_t + r(1 - B_t/k)B_t - C_t \qquad (1)$$

where *Bt* is the biomass and *Ct* is the catch in year *t*, *r* (yr^{-1}) is the intrinsic rate of population growth, and *k* is the environment's carrying capacity for this population. It estimates *r* and *k* parameters and based on it, the main reference points: maximum sustainable yield (MSY), fishing mortality that attain MSY (F_{MSY}) and the biomass level needed to produce MSY (B_{MSY}), as well as the stock status (B/B_{MSY}) and fishing mortality rates

Table 3. Natural mortality (M) and confidence intervals (CI) estimated in the present study based on empirical methods and life history parameters obtained in the literature.

Method	M (CI)
Pauly (1980)	0.225 (0.20-0.24)
Alagaraja (1984)	0.163 (0.14-0.18)
Taylor (1958)	0.106 (0.09-0.12)
Jensen (1997a)	0.152 (0.13-0.18)
Jensen (1997b)	0.229 (0.20-0.26)
Rikhter & Efanov (1977)	0.212 (0.17-0.25)
Mean (min-máx)	0.181 (0.09-0.26)

(F/F_{MSY}). The main advantages of these methods are the use of a complete Bayesian approach with Monte Carlo Markov Chain (MCMC) modeling, and the use of an Artificial Intelligence (AI) neural network to predict biomass priors from catches.

A significant improvement is the introduction of multivariate normal priors for *r* and *k* in logarithmic space, replacing the previous uniform distributions. It allows for a simplified determination of these parameters' "best" combinations (Froese et al. 2023). The Schaefer surplus production model is fed by the catch, prior distributions for resilience or productivity (*r*), and biomass/carrying capacity ratios (B/*k*) at different moments of the time series.

In our model parametrization we assume low resilience according to the Froese et al. (2023) classification, adopting a prior *r* range between 0.1 and 0.4. This range includes values that classify the species as having low to medium resilience, as suggested on the species summary webpage of FishBase (www.fishbase.org; Froese & Pauly 2023), and those indicated by the empirical relationship $r \sim 2M$ (where $r = 0.362$). The prior distribution for biomass in the first year was assumed to be uniform between 0.75 and 1.0 of the estimated carrying capacity.

Management Strategy Evaluation (MSE)

With the biological parameters of growth (L_∞, *k*, and t_0), natural mortality (M), longevity (A_{max} and L_{max}), maturity (L_{50} and T_{50}), weight/length relationship (*a* and *b*), and selectivity (Lc_{50} and Lc_{95}), presented in Tables 2-3, the population dynamics can be modeled. The variables estimated with the data-limited stock assessment (depletion, B_{MSY}/B_0, and F_{MSY}/M) approximate the initial conditions to start the MSE simulations. MSE analyses were done using openMSE, an R package developed for building operating models and conducting MSE for various fisheries (Hordyk et al. 2023). The system is modeled through four main components: a) the stock, b) the fleet, c) the observations, and d) the implementation (Fig. 2). Population and fishery dynamics were represented by an operating model with i) an age-length structured model guided by parameters presented in Tables 2 and 3, ii) stock initial conditions (depletion) and recruitment derived from stock assessment estimations, iii) constant effort projected for the fleet, and iv) selectivity informed by L_{50} and L_{95} parameters. All simulations assumed perfect management implementation and depletion-based procedures were considered a triannual stock status update.

The operating model was conditioned with stock assessment results in two ways: (a) initial recruitments (R_0) are back-calculated for each scenario using the biological parameters and the estimations of *k* and (b) depletion (stock status) was used as input for current conditions to start projections. Projected recruitments are modeled by the Beverton-Holt stock-recruitment relationship (Beverton & Holt 1957), with standard deviations between 0.1 and 0.3, following a log-normal distribution. Values of reference points (B/B_{MSY}, F_{MSY} and MSY) were calculated based on the stock-recruitment relationship and biological parameters of T_{50}, steepness (*h*, which we assumed to vary between 0.7-0.8), and R_0, by maximizing the yield curve (Hordyk et al. 2023). Process errors associated with all other biological parameters were assumed to be 10%, with uniform distribution, and simulations were performed to reproduce the SRS fishery for 30 years of projection.

We tested 11 data-limited MPs that can be classified into three main categories: 1) effort control, which represents the status quo of the SRS fishery; 2) catch-based, with static catch limits based on the mean (historical, recent, or a percentage of it) catch; and 3) depletion-based, control rules that adjust the TAC based on stock depletion estimations (Carruthers et al. 2014, Carruthers & Hordyk 2018b; Table 4). In practical MSE applications, MPs should be discussed with all stakeholders before being tested through an MSE to improve their applicability and acceptance after the decision-making process. Nevertheless, this process can be arduous and demands much more time and resources than the theoretical analysis proposed here. Therefore, we chose to test simple and well-known MPs that are easy to understand and can be implemented with minimal demands if their results are satisfactory. The MP's acronyms are: curE: current effort, AvC: average catch, CurC: current catch, CC: constant catch, MCD: mean catch depletion, MCD5010: mean catch depletion with 5010 rule, DCAC:

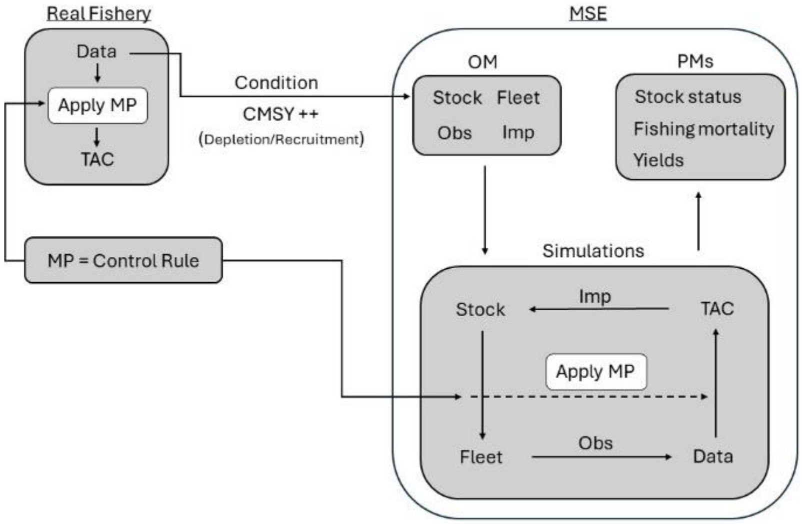

Figure 2. Conceptual representation of the management strategy evaluation used in the present study. The operating model (OM) simulates the dynamics of the stock simulations and fleet with the observations (Obs) and implementation (Imp) of the recommendations (total allowable catch, TAC) and the variables used to compare the Management Procedures (MPs) performances through MPs.

depletion corrected average catch, DCAC: depletion corrected average catch with 5010 rule, DBSRA: depletion-based stock reduction analysis, DBSRA5010: depletion-based stock reduction analysis with 5010 rule. The 5010 rule is a typical harvest control rule, also called “ramped control”, that linearly throttles back the TAC when depletion is below 50% down to zero at 10% of unfished biomass (Free et al. 2022).

MPs were used in two stages of the study: i) the simulations performed during the MSE analysis and ii) the TACs calculation using real fishery and biological data. Details of the mathematical formulation of the MPs used can be found in the openMSE package user guide (Hordyk et al. 2023). The entire flow of information and simulations can be visualized (Fig. 2).

The population was projected in each simulation, and all the main reference points (B_{MSY}, F_{MSY} and MSY) were recalculated. Yearly outputs for these parameters were compared to reference points by Performance Metrics (PMs), a predefined criteria set usually associated with the probability of achieving biological reference points and fishery yield efficiency. PMs allow for comparing the performance of management procedures against fisheries management objectives, such as reducing the probability of overfishing or achieving maximization and stability in fisheries’ yields. The following PMs were used in the present study:

- Probability of not overfishing (PNOF): the percentage of simulations with $F < F_{MSY.}$
- Probability of 100% of sustainable biomass (P100): the percentage of simulations with $B > B_{MSY.}$
- Probability of annual yield stability (AAVY): the percentage of simulations with annual variability in the yields < 10%.
- Mean yield relative to optimum (PMSY): the general mean yield obtained in projections relative to MSY (in this case, the indicator is a proportion, not a probability).

Total allowable catch (TAC)

TACs were calculated through 1000 simulations, assuming a CV of 10% with normal distribution to the input catch data, depletion, and biological parameters. In this phase, these values were used directly on the MP's formulas, resulting in estimations of catch limits. For depletion-based procedures, stock status (B/B_0) and the management parameters (B_{MSY}/B_0 and F_{MSY}/M) are obtained from stock assessment.

RESULTS

Stock assessment

Carrying capacity (*k*) values were markedly distinct between the four scenarios of input catch data. The average *k* was estimated to range from 138,000 to 241,000 t for scenarios CB1 and CA2, respectively.

Table 4. Management Procedures (MPs) used in the present study, including its theoretical definition, data requirements, formulation, and authors. B_y: biomass at year y, E_y: effort at year y, C_y: capture for year y, D: depletion, or the current level of the population concerning the original, $B_{MSY}/B0$, relationship between optimal and virginal biomass, obtained from Zhou et al. (2012); and F_{MSY}/M: relationship between optimal fishing mortality and natural mortality, obtained from Thorson et al. (2012). TAC: total allowable catch, curE: current effort, AvC: average catch, CurC: current catch, CC: constant catch, MCD: mean catch depletion, MCD5010: mean catch depletion with 5010 rule, DCAC: depletion corrected average catch, DCAC: depletion corrected average catch with 5010 rule, DBSRA: depletion-based stock reduction analysis, DBSRA5010: depletion-based stock reduction analysis with 5010 rule.

MP Type	Definition	Requirements	TAC calculation	Author(s)
Effort control				
curE	Constant "status quo" fishing effort	-	$E_y = E_{y-1}$	Carruthers & Hordyk (2020)
Catch-based				
AvC	Average Historical Catch	Catch	$\frac{\sum_{y=1}^{n=y-5} C_y}{n}$	"
CurC	Current Catch	"	$C_y = C_{y-1}$	Geromont & Butterworth (2015b)
CC1	AvC last 5 years	"		"
CC4	70% of CC1	"	$\frac{\sum_{y=1}^{n=y-5} C_y}{n} * 0.7$	"
Depletion-based				
MCD	AvC weighted by depletion	Catch, depletion	$2D*AvC$	Carruthers & Hordyk (2020)
MCD5010	MCD with 5010 rule	"	if $B > 50\ B_0$; $TAC = MCD$ if $10B_0 < B < 50\ B_0$; $TAC = 2.66B/B_0 + 33.3MCD$ if $B < 10B_0$, $TAC = 0$	"
DCAC	MCD with potential yield	Catch, depletion, $\frac{B_{MSY}}{B_0}$ and $\frac{F_{MSY}}{M}$	$\frac{\frac{\sum_{y=1}^{n} C_y}{n}}{n + (1 - D)/Ypot}$, $Ypot = \frac{B_{MSY}}{B_0}\frac{F_{MSY}}{M} M$	MacCall (2009)
DCAC5010	DCAC with 5010 rule	"	if $B > 50\ B_0$; $TAC = DCAC$ if $10B_0 < B < 50\ B_0$; $TAC = 2.66B/B_0 + 33.3DCAC$ if $B < 10\ B_0$; $TAC = 0$	Harford & Carruthers (2017)
DBSRA	Stock Reduction Model	Catch, depletion, $\frac{B_{MSY}}{B_0}$, $\frac{F_{MSY}}{M}$, $L_{50\%}$, K, L_∞ and t_0	$M\frac{F_{MSY}}{M} D B_0$	Dick & MacCall (2011)
DBSRA5010	DBSRA with 5010 rule	"	if $B > 50\%B_0$; $TAC = DBSRA$ if $10\%B_0 < B < 50B_0$; $TAC = 2.66B/B_0 + 33.3DBSRA$ if $B < 10B_0$; $TAC = 0$	Harford & Carruthers (2017)

Differences were also observed for the average *r*, ranging from 0.12 yr^{-1} in scenario CA1 to 0.16 yr^{-1} in CB2. MSY estimates were also affected by the differences between the catch series, varying from 5,320 to 7,580 t for scenarios CB1 and CA2, respectively (Table 5).

Despite the differences in the catch series, all scenarios consistently indicated that SRS is experiencing overfishing, with current mortality rates relative to the reference points (F/F_{MSY}) varying between 1.28 and 1.53 (scenarios CB1 and CA2, respectively). Regarding the stock's biomass status, all scenarios suggested that the SRS is overfished. However, scenarios that considered FAO catch data suggested that the stock is in worse condition (average value of B/B_{MSY} varying between 0.56 and 0.59), with current biomass representing between 28 and 30% of the pristine biomass. Scenarios that considered the SRS-RP catch data suggested the stock is slightly overfished, with current biomass between 14 and 24% below the target levels (Table 5).

Trends of relative biomass for the CAs scenarios showed a sharp decline between the 1970s and 1990s, followed by a period of stability until 2000, and then another decreasing trend over the last 20 years. The CBs scenarios, on the other hand, indicated that the biomass was not severely impacted until the 2000s, with average values remaining above the target levels until nearly 2010. However, the sharper decreasing trend that started in 2000 and continued over the next 20 years led the stock to be currently considered overfished (Fig. 3). Trajectories of fishing mortality show that, in the CAs scenarios, overfishing has occurred for at least 50 years, except for a short period during the 1990s when catches were lower. In the CBs scenarios, the stock was subject to overfishing later, with the most optimistic scenario, CB2, indicating that overfishing has been taking place only over the past 10 years (Fig. 3).

Management Strategy Evaluation

Simulated projections

Effort control management procedure (curE) presented stable behavior for biomass and fishing mortality in all scenarios, maintaining, at least on average, levels around the starting values throughout all the projected years. Nevertheless, this is not as clear when other results are evaluated in detail, especially for yields, as we will see later (Fig. 4).

Almost all the catch-based MPs (AvC, CC1 and CurC) produced similar projections, showing stability in all variables over time. The dispersion around the mean values of biomass and exploitation was higher, suggesting the probability of worsening the stock status by applying these MPs is significant. The only exception observed for catch-based MPs was CC4, which sets a TAC 30% below the last five years' average. This conservative catch-based TAC promoted a significant population recovery and a reduction in overfishing right from the beginning of implementation in all scenarios tested. Yields, however, remained below the MSY even after the stock had recovered, as this MP is not adaptive, meaning it does not adjust the TAC according to biomass or depletion rates (Fig. 4).

On the other hand, DBSRA and DBSRA5010 showed important differences between scenarios. While in CA1, the results of these procedures were conservative, especially the latter, suggesting reductions in catch under a more cautious approach, in the CBs, the less pessimistic depletion results in higher catches in the initial years, which negatively impacts the future biological condition, mainly in the last scenario. Among the depletion-based MPs, DCAC results were relatively aggressive in the CAs scenarios, especially CA1, with higher catches in the first years of projection, similar to the catch-based MPs. Despite the initial reductions in catches, the subsequent increase reduces the stock's biomass below the target reference point. MCD and MCD5010, in turn, promote an initial reduction in catches and balance their future improvements with the maintenance of biological health in the pessimistic CAs scenarios while keeping the stability of all variables in the CBs scenarios.

Catch limits and performance indicators

The overall TAC calculations vary from 2,532 to 6,653 t (Table 6). Within scenarios, CA1 results in lower TAC suggestions for almost all MPs, but especially in depletion-based procedures, except for AvC and CurC, both of which have high values (Fig. 5). In CA2, TAC was high for recent catch-based methods but is reduced when depletion is also considered. In CB1, lower variability was observed between MPs, with reduced TAC values only in CC4 and DCAC5010. The CB2 scenarios were the most optimistic, with higher TAC suggestions for most strategies. Catch-based procedures generally resulted in higher values across all scenarios, while depletion-based methods tended to be more conservative. The DBSRA5010 strategy was the most sensitive, reaching a difference of more than 3,300 t between scenarios, while DCAC and CC4 were the most stable, showing the smallest anomalies in TAC (Fig. 5).

Table 5. Estimated parameters and variables of interest for SRS in the present study using the CMSY++ method for four different scenarios of historical catch series, with lower and upper confidence levels of 95%. CA1, CA2, CB1 and CB2 are the four catch time series scenarios considered, and the parameters and variables are: *r* is the population intrinsic growth, *k* is the carring capacity, MSY is the maximum sustainable yield, F/F_{MSY} is the rate of current fishing mortality relate to the fishing mortality of MSY, B/B_{MSY} is the rate of current biomass relate to the biomass of MSY, B/B_0 is the rate of current biomass relate to the virginal biomass, B_{MSY}/B_0 is the rate of biomass of MSY relate to the virginal biomass and F_{MSY}/M is the rate of fishing mortality of MSY relate to the natural mortality.

Parameter/ Variable	Scenario			
	CA1	CA2	CB1	CB2
r	0.12 (0.08-0.16)	0.13 (0.08-0.16)	0.15 (0.09-0.21)	0.16 (0.1-0.21)
k (‘000 t)	233 (170-375)	241 (175-399)	138 (105-214)	142 (107-225)
MSY (‘000 t)	7.15 (5.2-9.7)	7.58 (5.4-10.7)	5.32 (4.0-6.7)	5.66 (4.2-7.4)
F/F_{MSY}	1.32 (0.65-4.94)	1.53 (0.74-4.82)	1.28 (0.65-2.52)	1.38 (0.73-2.86)
B/B_{MSY}	0.56 (0.28-0.85)	0.59 (0.32-0.88)	0.76 (0.49-1.12)	0.86 (0.52-1.20)
B/B_0	0.28 (0.14-0.43)	0.30 (0.16-0.44)	0.38 (0.24-0.56)	0.43 (0.26-0.60)
B_{MSY}/B_0	0.52 (0.47-0.58)	0.52 (0.47-0.58)	0.51 (0.46-0.56)	0.51 (0.46-0.56)
F_{MSY}/M	0.34 (0.31-0.38)	0.34 (0.31-0.38)	0.42 (0.38-0.46)	0.45 (0.40-0.49)

The capacity to avoid overfishing varied from perfect performance, with a 100% probability for both MCD procedures in all scenarios, to 38% probability using AvC in the most pessimistic scenario, CA1. This catch-based procedure affected PNOF the most, significantly improving its performance in CB scenarios. However, MCDs were the most robust, achieving perfect performance for this PM.

The DBSRA procedure exhibited remarkable behavior, with poor PNOF performance even decreasing in more optimistic depletion scenarios, and the P100 indicator always being low. For the P100 indicator, we also observed catch-based procedures showing high variability and many poor results in CAs scenarios, except for CC4, which was more conservative and stable, and in the CB2 scenario, where performance was better. For both indicators, PNOF and P100, most performances improved through scenarios, with DBSRA5010 being the most stable (Fig. 5).

Variability in yield was notably higher for effort control (curE), with almost zero probability of maintaining catches within 10% variability between years, showing high negative anomalies (>80%) and the poorest performance in the AAVY indicator across all scenarios. Poor performance was also observed for DBSRA5010 and CurC in the CAs scenarios. All other MPs presented very good and stable performances in the AAVY indicator (Fig. 5). The mean yield relative to the optimum, P_{MSY}, also showed more stable results than conservative indicators, with the worst performance for CC4, at 62% of MSY in CB2, and the best values for DBSRA and DBSRA5010, exceeding MSY in CB1 and CB2.

DISCUSSION

Stock assessment

For the SRS, differences between available catch series during the early stages of the fishery are high, exceeding 3.5 times in some years, and are inconsistent over more than 40 years (MMA/SEAP 2018, FAO 2020). Furthermore, the misreporting of recent catches due to lack of monitoring can reach 30%, according to stakeholders. These uncertainties are significant enough to affect local stock assessments and management, and here, we attempt to quantify this effect. The differences in the catch series impact the estimation of model parameters, generating varying levels of depletion, exploitation rates, MSY values, and the expected performance of management strategies, with stronger effects arising from uncertainty in the early catch data. Rudd & Branch (2016) and Van Beveren et al. (2017), using surplus production and state-space models, respectively, similarly found that unreported catches result in an underestimation of stock biomass and impact MSY reference points. Still, the mechanisms are difficult to identify because these effects are confounded with observation and process errors associated with the models.

When considering the FAO (2020) catch series, which had higher values in the early decades, the virgin population levels and MSY estimations were higher. This effect can be explained by the approach used to define *k* priors in CMSY++, which considers the maximum historical catch to set the limits of *k* priors (Froese et al. 2023). On the other hand, a long period of

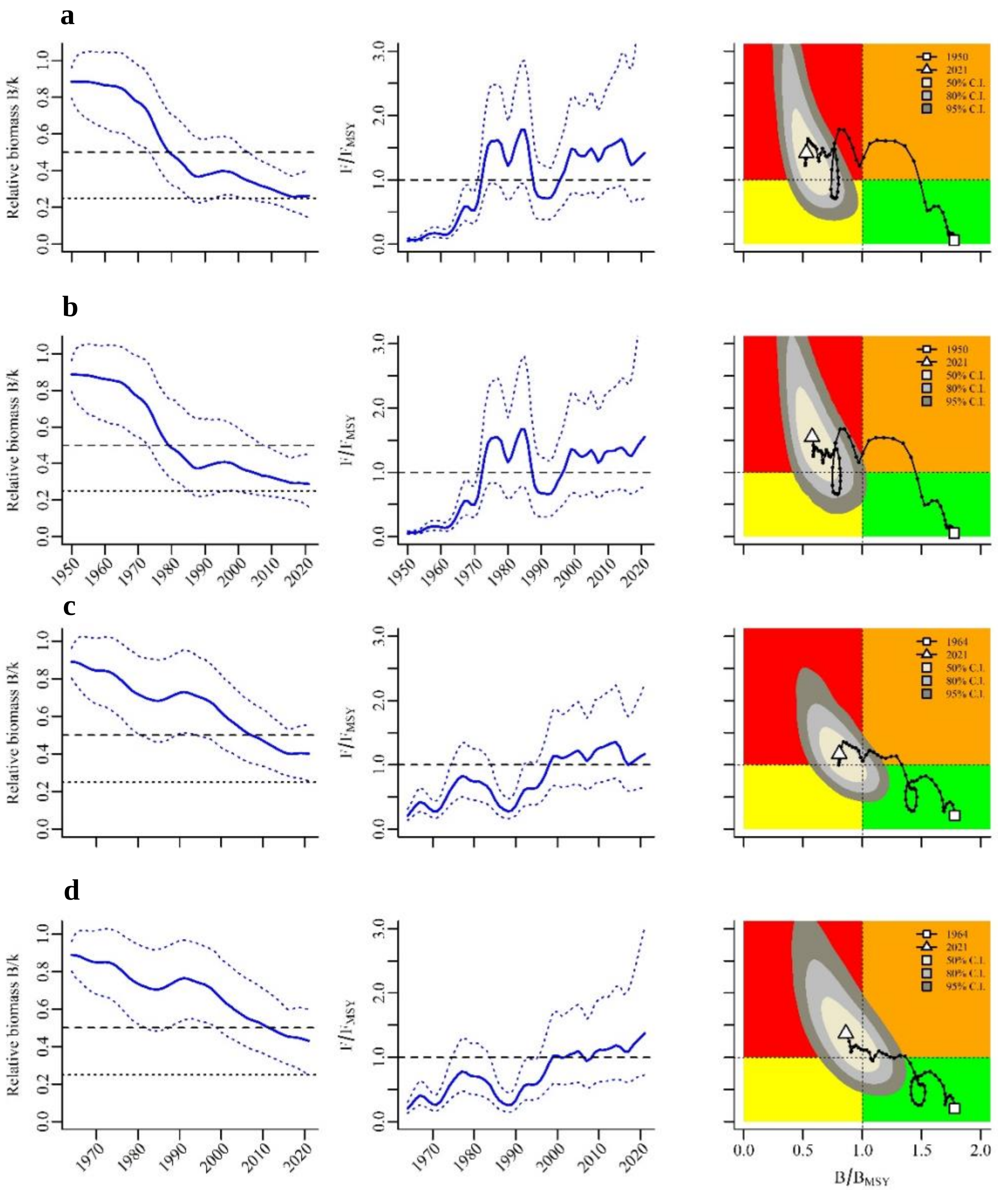

Figure 3. Results of historical trends of stock size, fishing mortality, and Kobe Plots for southern red snapper Brazilian fishery considering four scenarios, a) CA1, b) CA2, c) CB1, and d) CB2 of catch series in CMSY++ analysis. Horizontal black dashed lines indicate the target reference points of B_{MSY} (0.5B/*k*) and F_{MSY} in biomass and fishing mortality plots, respectively. In contrast, black dotted lines indicate the limit reference point of 50% of B_{MSY} (0.25B/*k*) in biomass plots. Blue dotted lines indicate 95% confidence limits in B/*k* and F/F_{MSY} plots. In the phase diagram (right column), the colors mean: red: stock overfished and suffering overfishing; orange: stock healthy but suffering overfishing; yellow: stock is overfished but not suffering overfishing and green: stock is healthy and not suffering overfishing.

high catches in this series (during the 1970s and 1980s) maintained fishing mortality above sustainable levels, reducing population size and increasing depletion levels. The assessment based on the FAO catch series indicates that current catch levels are below the MSY estimations, even when considering domestic consumption (exports plus 30%). However, the stock is still overfished due to the high level of depletion. These results provide evidence that stable yields have been obtained over the last 40 years from a population that is significantly reduced (28-30% B_0) due to severe overfishing in the 1970s and 1980s, as also suggested by previous studies (Ivo & Souza 1988, Souza 2002, Resende et al. 2003, Bentes et al. 2017).

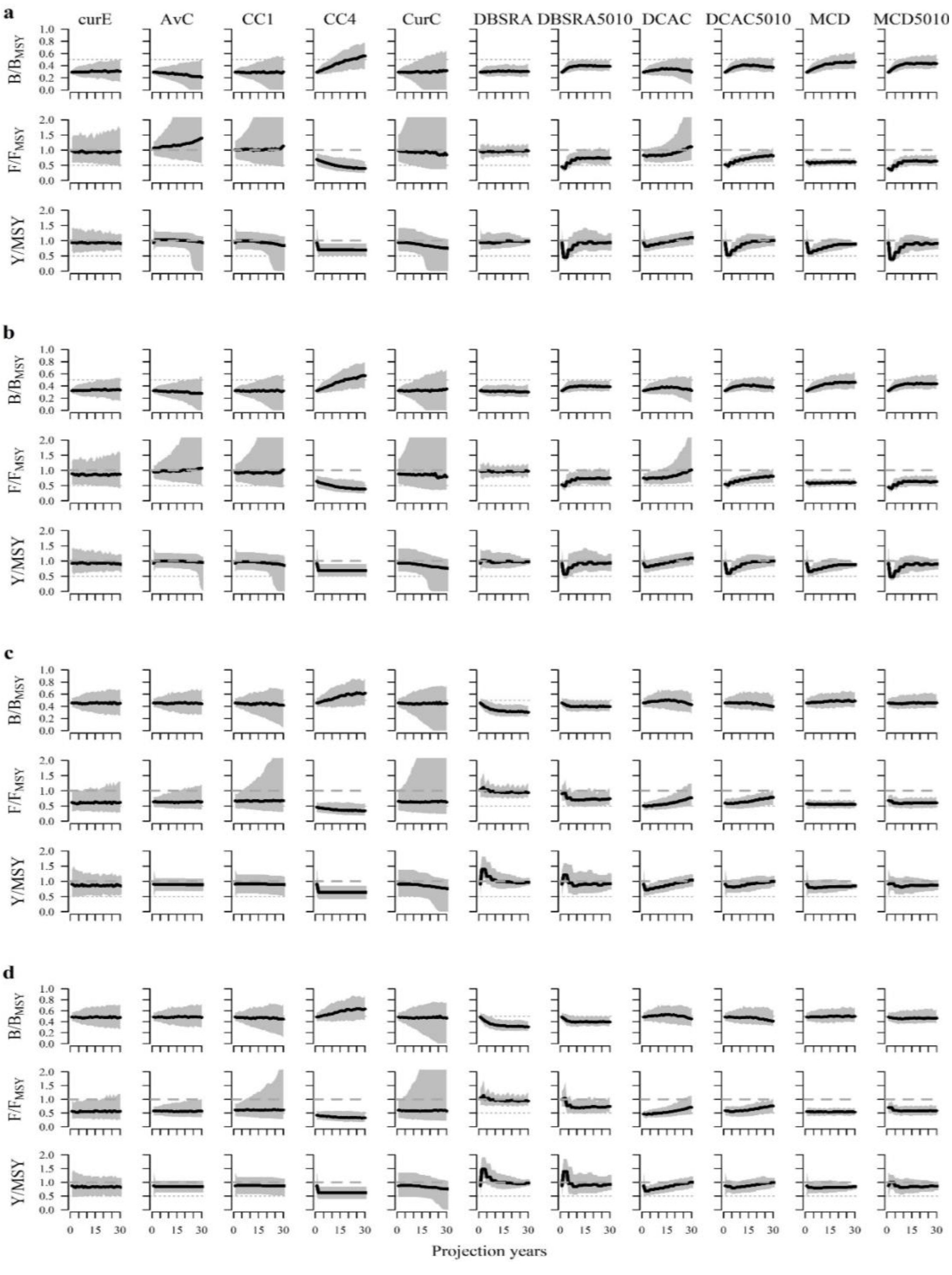

Figure 4. Projections of variables of interest obtained for four scenarios, a) CA1, b) CA2, c) CB1 and d) CB2 in MSE analysis for Brazilian southern red snapper analysis. Black lines indicate the mean of 250 simulations, while gray areas indicate the 90% confidence limits. The Management Procedures considered are curE: current effort, AvC: average catch, CurC: current catch, CC: constant catch, MCD: mean catch depletion, MCD5010: mean catch depletion with 5010 rule, DCAC: depletion corrected average catch, DCAC: depletion corrected average catch with 5010 rule, DBSRA: depletion-based stock reduction analysis, DBSRA5010: depletion-based stock reduction analysis with 5010 rule. Variables are: yield related to maximum sustainable yield (Y/MSY), stock biomass related to those needed to attain MSY (B/B_{MSY}) and fishing mortality related to those needed to attain MSY (F/F_{MSY}).

Table 6. Estimated values of total allowable catch (TAC; t), probabilities to avoid overfishing (PNOF), reach sustainability (P100), yield stability (AAVY), and the proportion of MSY (PMSY) obtained from Management Procedures (MPs) in MSE analysis for four different scenarios of SRS fishery catches, ordered by PNOF decreasing rank. The MPs considered are: curE: current effort, AvC: average catch, CurC: current catch, CC: constant catch, MCD: mean catch depletion, MCD5010: mean catch depletion with 5010 rule, DCAC: depletion corrected average catch, DCAC: depletion corrected average catch with 5010 rule, DBSRA: depletion-based stock reduction analysis, DBSRA5010: depletion-based stock reduction analysis with 5010 rule.

CA1						CA2					
MP	TAC (t)	PNOF	P100	AAVY	PMSY	MP	TAC (t)	PNOF	P100	AAVY	PMSY
MCD5010	2680	1.00	0.93	0.99	0.80	MCD5010	3142	1.00	0.96	0.99	0.81
MCD	3570	1.00	0.89	1.00	0.82	MCD	3832	1.00	0.93	1.00	0.82
DCAC5010	2993	0.98	0.88	1.00	0.88	CC4	4084	0.98	0.91	1.00	0.70
CC4	3139	0.97	0.85	1.00	0.70	DCAC5010	3344	0.98	0.91	1.00	0.88
DBSRA5010	2532	0.82	0.80	0.74	0.95	DBSRA5010	2892	0.81	0.83	0.76	0.97
DCAC	4343	0.71	0.64	0.98	0.97	DCAC	4498	0.79	0.76	0.98	0.96
DBSRA	3388	0.59	0.51	1.00	1.00	curE	-	0.63	0.63	0.01	0.96
curE	-	0.56	0.50	0.01	0.96	CC1	5817	0.59	0.59	0.92	0.94
CurC	5116	0.55	0.49	0.80	0.85	CurC	6624	0.59	0.58	0.84	0.87
CC1	4487	0.52	0.48	0.89	0.93	DBSRA	3670	0.57	0.56	1.00	1.00
AvC	5755	0.38	0.39	0.92	0.99	AvC	5965	0.56	0.56	0.97	0.99
CB1						CB2					
MP	TAC (t)	PNOF	P100	AAVY	PMSY	MP	TAC (t)	PNOF	P100	AAVY	PMSY
MCD5010	3815	1.00	0.99	1.00	0.83	MCD	4757	1.00	0.99	0.99	0.82
MCD	4107	1.00	0.98	1.00	0.84	MCD5010	4657	1.00	0.99	0.99	0.82
CC4	3136	0.99	0.97	1.00	0.67	CC4	4086	0.99	0.99	0.98	0.62
DCAC5010	3489	0.98	0.97	1.00	0.88	DCAC5010	3869	0.99	0.98	0.99	0.82
DCAC	3843	0.91	0.92	1.00	0.92	DCAC	4050	0.96	0.96	0.99	0.83
AvC	4878	0.83	0.83	0.99	0.93	AvC	5048	0.96	0.94	0.99	0.83
curE	-	0.78	0.83	0.01	0.91	curE	-	0.92	0.95	0.00	0.83
DBSRA5010	3752	0.77	0.87	0.68	1.00	CC1	5848	0.88	0.91	0.97	0.86
CC1	4473	0.72	0.77	0.95	0.93	CurC	6653	0.83	0.87	0.93	0.83
CurC	5080	0.70	0.76	0.86	0.85	DBSRA5010	4769	0.73	0.88	0.70	1.10
DBSRA	3865	0.57	0.65	1.00	1.10	DBSRA	4895	0.55	0.70	0.99	1.10

In contrast, the catch series published in the SRS-RP started 14 years later and did not show the high values observed in the 1970s and 1980s (MMA/SEAP 2018). As a result, the estimations indicate smaller absolute values for *k*, MSY, and current biomass but more stable trends and better current population conditions. Fishing mortality exceeded target levels only in the late 1990s, allowing the population to retain about 38-43% of its initial biomass, with lower levels of current overfishing. Despite the more optimistic results regarding stock status, these scenarios estimate lower MSY values and current catches may be excessive. The general conclusion is that higher catches at the beginning of the time series result in worse current conditions but higher potential yields if the population is allowed to recover, likely due to the estimation of a higher virgin biomass and stock productivity. Conversely, lower catches in the early years resulted in smaller values for potential yield but better population conditions, with higher levels of current depletion.

Uncertainty in recent catch data was less important for estimating model parameters and MSY, but it did have a notable effect on current fishing mortality and relative variables. This effect was more pronounced for fishing mortality in the FAO catch scenarios, while SRS-RP data models were more sensitive to relative biomass estimations (depletion). In general, assuming domestic consumption of 30% over the exploitation records for the last six years (2016-2021) increases estimations of *k*, MSY, and both absolute and relative biomass, indicating better conditions for the population, but results in higher levels of current overfishing (38-53%).

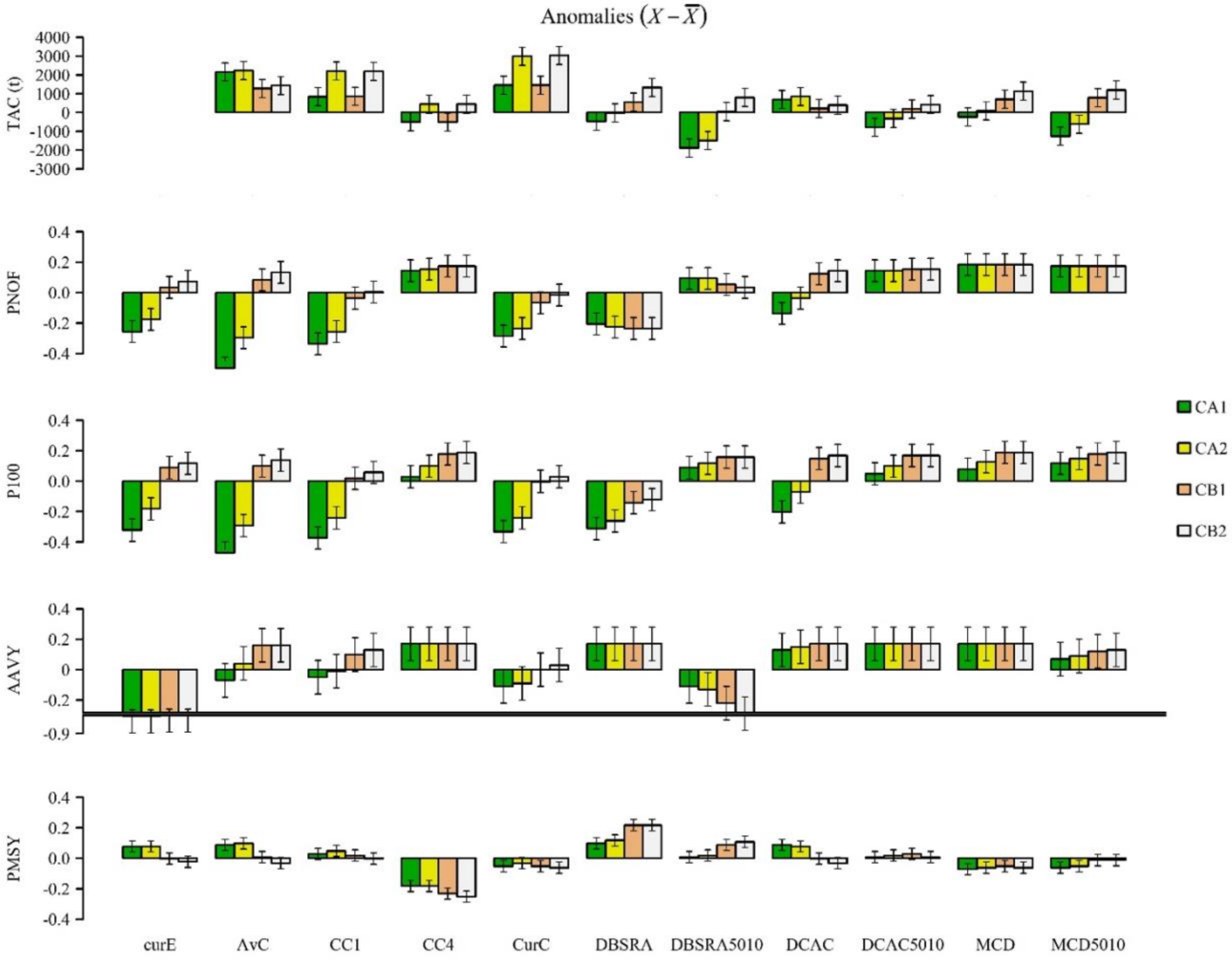

Figure 5. Anomalies on total allowable catch (TAC) and Performance Metrics **(**PMs) between estimations and its overall mean for four different scenarios (CA1, CA2, CB1 and CB2) and Management Procedures (MPs). The MPs considered are: curE: current effort, AvC: average catch, CurC: current catch, CC: constant catch, MCD: mean catch depletion, MCD5010: mean catch depletion with 5010 rule, DCAC: depletion corrected average catch, DCAC: depletion corrected average catch with 5010 rule, DBSRA: depletion-based stock reduction analysis, DBSRA5010: depletion-based stock reduction analysis with 5010 rule. The variable and PMs are: TAC; probability of not overfishing (PNOF); probability of optimal biomass (P100); probability of catch stability (AAVY) and probability of catch MSY (PMSY) and its overall means are TAC = 4,274 t; PNOF = 0.82; P100 = 0.82; AAVY = 0.95 and PMSY = 0.89.

Shi et al. (2020) found that catch-MSY, the precursor of CMSY++, tends to be more sensitive to variations in early and late catch values than to the length of the time series, and we detected that early uncertainty for SRS fisheries is more important than recent uncertainty. However, both types of uncertainty significantly affect the results. Bouch et al. (2021) found that CMSY tends to overestimate F/F_{MSY} and underestimate B/B_{MSY}, possibly introducing bias in our results in this way. On the other hand, our results reinforce previous evidence of overfishing (Fonteles-Filho 2007, MMA/SEAP 2018). If recent catches remain stable at around 6,000 t, the current fishing mortality level is problematic and unsustainable, demanding attention even with its possible overestimation. While in some scenarios, catch levels of around 7,000 t could be reached in an optimistic future as the stock recovers, in others, such levels are not acceptable at all. Suppose controversial data like SRS catches are to be used for management decisions. In that case, adopting more precautionary approaches, monitoring the stock's response, and looking for stronger evidence about its productivity are advisable.

Management performances

When observing the TACs suggested by the procedures tested here, catch-based strategies closer to recent average levels have consistently resulted in poor performance for sustainability indicators in our MSE simulations. The poor performance of static catch-based procedures, especially regarding sustainability, has been previously observed by Carruthers et al. (2014, 2016), highlighting that, if not buffered by a precautionary discount, these methods can perform even worse than maintaining constant effort if the stock is moderately depleted. Static catch-based strategies must be buffered preventively to improve sustainability performance, which leads to a loss of performance in yield metrics due to the lack of feedback mechanisms, confirming their poor yield-risk tradeoffs (Geromont & Butterworth 2015a). Our results corroborate such evidence, providing quantitative results on the disadvantages of catch-based strategies compared to adaptive ones and reinforcing the necessity of buffers to reduce the biological risk associated with static procedures.

Depletion-based methods present a mixed effect, with specific responses depending on variations in the catch series and stock status when recommending TACs. Our results confirm the behavior previously observed for the DCAC and DBSRA methods, which tend to be excessively optimistic for stocks at low population levels, overestimating sustainable catch limits (MacCall 2009, Carruthers et al. 2014, 2016, Wetzel & Punt 2015). These MPs resulted in higher TAC suggestions than other depletion-based methods, especially in pessimistic scenarios. Not coincidentally, the original DBSRA also presented risky results in both scenarios, showing low robustness in TAC estimations, as seen in previous studies (Arnold & Heppell 2015). Its conservative version, with the trigger-reduction rule at 10 and 40% of depletion (DBSRA5010), is more prudent under pessimistic conditions but still carries a high probability of future overfishing. Despite being commercially attractive at first glance, with higher TACs in the early years of implementation, DBSRA tends to show a reduction in yield afterward due to population depletion caused by the initial optimistic TACs.

The general behavior of each strategy across all scenarios is similar, with CC4, DCAC5010, and MCDs presenting more conservative and robust results. At the same time, other MPs, especially CurE, AvC, CC1, and CurC, were more aggressive, showing a higher probability of future overfishing. We highlight the behavior of the CurE, which represents the *status-quo* management for SRS. This approach was similar to maintaining recent catch levels but with the highest inter-annual catch variability, as historically observed. Because effort and catchability are assumed constant, we understand that these fluctuations follow stock fluctuations, so curE outperforms procedures with high levels of constant catch (CurC and CC1) on sustainability indicators. On the other hand, if there are issues with monitoring and controlling both effort and catches, as historically observed for the SRS fishery, market demand limitations (such as export controls) at lower levels could temporarily provide better results for stock conservation.

Depletion-based MPs are adaptive, with TACs varying according to biomass fluctuations, which usually increases their sustainability and sometimes their profitability. Due to their adaptive mechanisms, some of these MPs can perform better in sustainability even when suggesting higher TACs than static catch-based MPs, as we see when comparing CC4 and MCD. Depletion-based strategies, however, rely on regular assessments of stock status, which is uncommon in the Brazilian fisheries management framework (Dias et al. 2022). Given the initial context of poor data, lack of implementation experience, and unstable fisheries governance, more straightforward but conservative MPs may be preferable, as they are easier for stakeholders to embrace and require less effort from fisheries management authorities to implement.

The range of adaptive strategies already tested for data-limited fisheries is wide (Geromont & Butterworth 2015a, Cummings et al. 2016, Carruthers & Hordyk 2018a), including those based on relative indices of abundance or mean individual length. We evaluated the MCD procedure, a simple and effective adaptive strategy that showed the best general performance and robustness in our study. Previous studies show it can replace depletion estimates with some abundance index and outperform other depletion-based strategies (Carruthers & Hordyk 2018a). The regular estimation of a reliable relative index of abundance, based on catch per unit of effort, can be an important low-cost improvement to reduce uncertainties on population trends and to guide future TAC suggestions through index-based procedures (Geromont & Butterworth 2015b, Carruthers et al. 2016).

In the context of current SRS fishery management, we emphasize the importance of filling a historical gap in knowledge about possible SRS population trends, stock status, and fishery management risks. Despite the uncertainties described here and the advice to use data-limited methods carefully (Arnold & Heppell 2015, Dowling et al. 2019, Kell et al. 2022), we believe that our results provide important support for decision-makers when discussing quantitative management strategies for this fishery (MMA/SEAP 2018). In this sense, our main recommendation based on the results obtained is that, under the current uncertainty in basic data and its effects on stock status perception and the expected outcomes of the analyzed management strategies, this uncertainty should be considered. Pessimistic scenarios of input data, along with more conservative MPs, should be prioritized. Furthermore, considering all the scenarios assessed and the results of the MPs' performance, we suggest that, to ensure sustainability, strong efforts should be made to implement adaptive depletion-based procedures, such as MCD, based on regular stock assessments. If this is not feasible in the short term, TAC control should be adopted based on buffered levels of current catches, like CC4.

Credit author contribution

M. C. Feltrim: conceptualization, validation, methodology, data compilation, formal analysis, writing-original draft, supervision, review and editing; M. Dias: Funding acquisition, project administration, data compilation, supervision, review and editing. All authors have read and accepted the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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