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Assessment of the stock status of blackfin tuna *Thunnus atlanticus* in the Southwest Atlantic Ocean: a length-based approach

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ABSTRACT

This is the first assessment of blackfin tuna *Thunnus atlanticus* stock status. The aim of the present study was to estimate the status of its Southwestern stock using length-based models. A total of 1929 individuals was gathered in four years of length data (1998–2019). Two length-based models were applied, Length-Based Spawning Potential Ratio (LBSPR) and Stock Synthesis Data-limited tool (SS-DL) and five scenarios combining a set of growth parameters (asymptotic length-L_∞, and growth constant-K) were built to accommodate different life histories available in the literature. The natural mortality (M) was estimated through four empirical methods. Given that the fishery only selects mature fish, length at selectivity were larger than the length at first maturity and high relative fishing mortality were found at most scenarios, even with high spawning potential ratio (SPR) values. The LBSPR estimated higher values of SPR, it presented a steeper decline than SS-DL between 1998 and 2019. In addition, growth parameters influence the estimation of the virginal stock, and intermediate M/K values seems to represent better the estimated length composition, given the low historical catch of the species. A declining pattern in SPR was observed over time with a reduction of 12% according to LBSPR and 7% decrease based on SS-DL methods. However, the overall evaluation of the Southwestern Atlantic stock of blackfin tuna in 2019 revealed an SPR range of 0.41 to 0.63, suggesting sustainable exploitation. Even with the limited data, we could have a proxy of stock status estimation by using length-based models which highlights the importance of such data. However, due to the high uncertainty of the results, better collection of catch, effort and length data should be considered. Additionally, SS-DL seems to estimate better SPR values when variability of growth parameters are placed for a given species.

1. Introduction

Stock assessment of large tunas have been performed regularly, and a variety of management procedures are in place to protect them from overfishing (Pons et al., 2017). However, although small tuna species represent 17% of total reported catch of tuna and tuna-like species in the Atlantic to the International Commission for the Conservation of Atlantic Tuna (ICCAT, https://www.iccat.int/en/accesingdb.html) only two out of 12 small tuna species had their stock recently assessed in the Atlantic Ocean (Juan-Jordá et al., 2015; Pons et al., 2017, 2019a,b; Lucena-Frédou et al., 2021). The majority of small tuna stocks are classified as data-limited due to the insufficient data availability to support a fully integrated stock assessment model, therefore remaining unassessed (Juan-Jordá et al., 2015; Kindong et al., 2020; Lucena-Frédou et al., 2021; Cope et al., 2023). Since stock assessments are the basis for taking the most appropriate management measures to ensure a sustainable and healthy population (Punt et al., 2006; Hilborn et al., 2020), the lack of basic knowledge makes these species stocks vulnerable to several stressors like overfishing and climate change effects (Pons et al., 2019b; Lucena-Frédou et al., 2021). Furthermore, it is well known that highly migratory fish, such as tunas, lack physical barriers and have weak population structure throughout large geographic areas (Pecoraro et al., 2018; Nikolic et al., 2020), which increases the complexity of defining the stocks to be assessed and managed. Thus, the urgent need for data that will support stock assessments and consequently inform management measures is evident.

The blackfin tuna *Thunnus atlanticus* is one example of unassessed small tuna species and is distributed exclusively in

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the West Atlantic from Massachusetts, USA (40° N) to South Brazil (35° S) (Mahon and Mahon, 1986; Zavala-Camin et al., 1991; Cardoso et al., 2021). This species is an important target for artisanal and recreational fisheries of many developed and developing countries in the West Atlantic (e.g., Cuba, Venezuela, Bermuda, Dominican Republic, Brazil, USA) (Carles Martin, 1991; Luckhurst et al., 2001; Freire et al., 2015; ICCAT, 2006; Narváez et al., 2017). Moreover, recent studies reported that blackfin tuna populations are divided in those of Northwestern (NWA) and Southwestern (SWA) Atlantic (Saxton, 2009; Saillant et al., 2022). Some few fishery-dependent data information are available regarding its stock in the NWA. For example, Lucena-Frédou et al. (2021) reported a slight decline in the mean size from 70 to 60 cm in the purse seine catches, but a stable trend in annual mean length in general, and Saillant et al. (2022) reported a noticeable increase of 70% in its landings from USA recreational fishing from the 80's to 2019. Regarding SWA stock, a single report of estimated catches was found from 1993 to 2001 where removals were 33.5 (from 16.8 to 48.6) tons a year on average (Freire et al., 2015). However, no assessment was performed for both stocks up to date. Moreover, many tuna stocks had decreased over time in the SWA (Lucena-Frédou et al., 2021), which increase the need for the assessment of blackfin tuna SWA stock.

The Brazilian Exclusive Economic Zone (EEZ) holds most of the SWA distribution area of blackfin tuna, playing an important role to coastal fisheries in some Brazilian regions (Freire et al., 2015). For example, in the Northeastern (Baía Formosa — RN), this species is targeted by small hand line vessels and off Northern and Southwestern it is harvested as bycatch of larger tuna, billfish, and shark longline fisheries (Vieira et al., 2005; Freire et al., 2015). Despite the importance of blackfin tuna to food security in some locations in Brazil, continuous time series of catch are unavailable in ICCAT database for the South Atlantic Ocean. Moreover, the discontinuity in data collection is a reality in developing countries (Reis, 1992) and this gap hampers the application of more robust stock assessment models. However, several size samples have been collected by Brazilian research projects along time, which increases the amount of models to evaluate the stock status.

In addition, size composition data are more applicable than catch data to stock assessment of small tuna species (Pons et al., 2019a; Lucena-Frédou et al., 2021). Therefore, many well-studied length-based assessment models can be employed for the effective management of many fish populations (Hilborn and Walters, 1992), thus also to the SWA blackfin tuna stock. Two methods were applied in the present study, the Length-Based Spawning Potential Ratio (LBSPR; Hordyk et al., 2014, 2015) and Stock Synthesis Data Limited tool (SS-DL; Cope, 2020). LBSPR is a methodology that uses representative length compositions in a population model based in equilibrium and compare the sampled and the expected unfished size structure (Hordyk et al., 2015). SS-DL was recently created to implement many common data-limited methods in a single framework using the age structured Stock Synthesis to assess data-limited stocks (Methot and Wetzel, 2013; Cope, 2020).

Moreover, assuming that the size composition is representative from the exploited population, these models estimate a biological reference point entitled spawning potential ratio (SPR), which is commonly used as an indicator for recruitment overfishing in data-limited fisheries (Hordyk et al., 2014; Chong et al., 2019). SPR determines limits and targets referential points to subsidize management decisions (Brooks et al., 2010; Hordyk et al., 2015; Sun et al., 2018; Pons et al., 2019a; Chong et al., 2019). Virginal stocks have a SPR of 100%, which decreases when the stock is submitted to a certain fishery (Hordyk et al., 2014). Additionally, to estimate SPR values, LBSPR also use life history ratios, as M/K, F/M and Lm/L_∞ (M, natural mortality; K, growth coefficient; F, fishing mortality; Lm, length at maturity; L_∞, asymptotic length) (Hordyk et al., 2014). However, this is also a problem for blackfin tuna in the SWA, because most of life-history parameters (e.g., L_∞ and K) are estimated for NWA (*i.e.,* Garcia and Bosh, 1986; Doray et al., 2004; Adams and Kerstetter, 2014; Gutierrez, 2022). Freire et al. (2015) is the single study that presents values for SWA assessing growth parameters with length-frequency data from the late 90's. Life history information is crucial to assess fish species stocks and length-based models are very sensible to these parameters (Hordyk et al., 2014). Additionally, M is the most difficult parameter to estimate in natural populations (Lee et al., 2011). Therefore, in the present study scenarios divided by a set of growth parameters and M/K values were created to test uncertainty of SPR estimation.

Given the commercial importance to some localities of Brazilian coast and the lack of information to assist in the proper management of blackfin tuna stock in the Southwest Atlantic Ocean, this study aimed to provide its stock status by comparing SPR values estimated from two length-based methods. Additionally, we investigated the impact of five scenarios of growth parameters and three M/K values in the SPR to provide novel information about differences of these two methods, which can be applied to other species, including small tunas species.

2. Methodology

2.1. Study area and length data

The proposed methodology to assess the stock status of blackfin tuna is shown in Fig. 1. Blackfin tuna *Thunnus atlanticus* fork length (FL) data were gathered from several sources, between 1998 and 2019, to assess the Southwestern Atlantic stock encompassing most of the Brazilian coast. The data sources included:

(a) Programa de avaliação do potencial sustentável de recursos vivos na zona econômica (REVIZEE): a fishery-independent survey throughout the Northeast Brazil;

(b) Scientific expeditions to Saint Peter and Saint Paul Archipelago (SPSPA): a fishery-dependent monitoring throughout the SPSPA;

(c) Landings at TAMAR/ICMBio Center – GEFMar ES/RJ Project (TAMAR): a fishery-dependent monitoring throughout the Brazilian states of Espírito Santos and Rio de Janeiro (Fig. 2).

Since FL data (size classes = 2.0 cm) did not follow the necessary assumptions for the parametric test, we employed the nonparametric Kruskal–Wallis test followed by Dunn's post-hoc to test differences among years and regions due to differences in fishing gears employed to harvest blackfin tuna (Table 1).

2.2. Life history

Five scenarios were created to test the uncertainty on growth and mortality parameters with data available in the literature (Table 2). All information regarding blackfin tuna growth parameters were included to design the Scenarios. The scenarios were formulated to assess the different impacts of growth parameters across methods calculation and stocks in the Southwest and Northwest Atlantic regions. The selected data were maximum length, von-Bertalanffy parameters (L_∞, K, and t_0), and natural mortality (M). The length at first maturity at 50% (L_{50}) for the study area were available to separated sex (females, L_{50} = 48 FL and males, L_{50} = 55, FL; Bezerra et al., 2013). The length at first maturity at 95% (L_{95}) was estimated from the logistic curve of L_{50} (Bezerra et al., 2013). Therefore, the mean L_{50} and L_{95} between male and female were calculated. M was estimated to each scenario through the online tool (http://barefootecologist.com.au/shiny_m.html) with

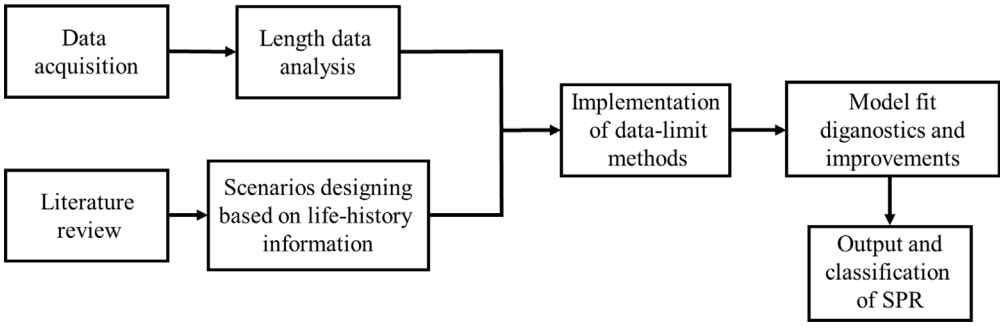

Fig. 1. Flow chart of the proposed methodology to assess the stock status of blackfin tuna in the Southwest Atlantic Ocean.

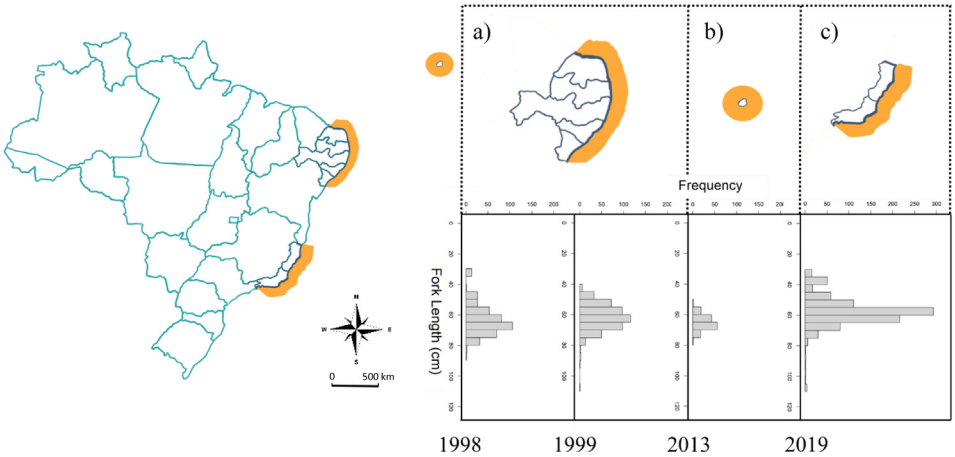

Fig. 2. Study area and length composition by year and data source of SWA blackfin tuna *Thunnus atlanticus* stock (a, REVIZEE; b, SPSPA; c, TAMAR).

Table 1
Time-block for the selectivity parameters set in the SS-DL model for the SWA blackfin tuna *Thunnus atlanticus* stock (n, number of individuals; SPSPA, Saint Peter and Saint Paul Archipelago; ES, Espírito Santo state; RJ, Rio de Janeiro state).

Time-block	Years	*n*	Source	Area	Gear
1	1998 and 1999	410 and 491	REVIZEE	Brazilian northeast	Longline
2	2013	139	SPSPA	SPSPA	Handline
3	2019	889	TAMAR	ES - RJ	Pole and line

Table 2
Growth and mortality parameters of blackfin tuna *Thunnus atlanticus* available in literature (L_∞, asymptotic size; K, growth rate; M, natural mortality; M/K1, M = 1.02; M/K2, M = 0.72; M/K3, M = 0.42; L_∞ is described in FL (cm)).

Scenario	Author	Study area	Method	L_∞	K	M	M/K1	M/K2	M/K3
1	Garcia and Bosh (1986)	Cuba (Northeast)	Dorsal spine	78	0.33	0.522	3.09	2.18	1.27
2	Doray et al. (2004)	Martinique Island	Otolith	71.4	0.73	1.113	1.39	0.98	0.57
3	Adams and Kerstetter (2014)	USA (Florida)	Otolith	95.3	0.28	0.441	2.79	1.97	1.15
4	Gutierrez (2022)	Gulf of Mexico	Otolith	82.4	0.37	0.572	3.64	2.57	1.50
5	Freire et al. (2015)	Brazil (Northeast)	Length frequency	92	0.65	0.982	1.56	1.10	0.64

four empiric models: $M = aK^bL_\infty^c$ (Then et al., 2015); M = 1.5 K (Jensen, 1997); $Mx_m = 3$ b (Jensen, 1996); $M = Cm^a e^{(b/Tkelvin)}$ (Hamel, 2015). Moreover, to explore the influence of M/K in length composition and SPR, M was defined as the highest (M1 = 1.02), and lowest (M3 = 0.42) values of confidence interval and the mean (M2 = 0.72) value of the five M values estimated (Table 2).

2.3. Length-based methods

The following length-based models were used to assess the SWA blackfin tuna stock:

(1) Length-based Spawning Potential Ratio (LBSPR):

The LBSPR method is the most consistent and accurate when compared to other length-based assessment models, according to Chong et al. (2019). This method requires as input representative length compositions, and the following life-history parameters: (i) the M/K ratio, (ii) the mean asymptotic length (L_∞), (iii) the L_{50} and (iv) L_{95}. The model assumes logistic selectivity and estimates the selectivity-at-length and the F/M ratio, which in turn are used to calculate the spawning potential ratio (SPR) based on the natural mortality (Hordyk et al., 2015).

(2) Stock Synthesis Data-Limited Tool (SS-DL):

The Stock Synthesis Data limited tool (SS-DL) is a statistical catch-at-age modeling framework that uses likelihood-based methods allowing multiple data sources to be incorporated to

Table 3
Models parameters and how they were treated (fixed or estimated) of the SWA blackfin tuna *Thunnus atlanticus* stock (WBF, weight-based fecundity).

Parameters	SS-DL			SS-DL treatment	LBSPR	LBSPR treatment
L_{50} (cm)	51.5			Fixed	47.12	Fixed
L_{95} (cm)	56.5			Fixed	51.53	Fixed
Length (cm)–weight (g) *alpha*	0.0128			Fixed	N/A	N/A
Length (cm)–weight (g) *beta*	2.86			Fixed	N/A	N/A
WBF coefficient	0.001			Fixed	0.001	Fixed
WBF exponent	1			Fixed	1	Fixed
Steepness	0.7			Fixed	N/A	N/A
Initial recruitment ($\ln R_0$)	8.08			Fixed	N/A	N/A
	Time-block					
	1	2	3			
Length at 50% selectivity (cm)	48	61	42	Estimated	–	Estimated
Length at peak selectivity (cm)	55	69	47	Estimated	–	Estimated

characterize population dynamics through time (Cope, 2020). The SS-DL tool allows the SPR estimation by using the stock synthesis framework adapted to data-limited situations. This method requires as input a representative length composition, and the life-history parameters as M, the von Bertalanffy growth parameters (L_∞, K and t_0), L_{50} and L_{95}, the coefficients and exponents of the weight-length and the weight-fecundity relationships, the stock-recruitment parameters, steepness, and initial recruitment ($\ln R_0$).

The selectivity was assumed to be logistic, since fishing gears often select larger individuals and catch over schools. The selectivity parameters were freely estimated in three time-blocks, since input data came from different fishing gears, regions and data source (Table 1). The built model also assumed constant catch. In addition, the steepness value was fixed at 0.7, as estimated with the *FishLife* package (Thorson, 2019), while initial recruitment was freely estimated in the model.

2.4. SPR

SPR was classified in four groups, under (>0.4), moderate ($0.3 < \text{SPR} \leq 0.4$), recovering or subject to over ($0.2 < \text{SPR} \leq 0.3$), and over exploitation ($\leq$0.2). Two of these categories have been employed as a target (0.3–0.4) and limit (0.2) reference points to an accurate and proper removal of the stock (Mace and Sissenwine, 1993; Mace, 1994; Clark, 2002).

All statistical analysis were performed using R (version 3.4.4). We employed the packages *LBSPR* (Hordyk et al., 2015; https://github.com/AdrianHordyk/LBSPR) to apply LBSPR model and the r4ss ("R Code for Stock Synthesis" Taylor et al., 2022; https://github.com/r4ss/r4ss) to apply SS-DL (Cope, 2020; https://github.com/shcaba/SS-DL-tool.git).

3. Results

3.1. Length data

Fork length (FL) data was available to 1929 individuals from landings samplings between the years 1998, 1999, 2013 and 2019. FL ranged from 30.3 to 109 cm (60.76 ± 9.51), and the mean FL differed among years with the most recent one presenting the lowest mean length (Kruskal–Wallis = 700.6; df = 6; $p = 0$).

3.2. Length-based approaches and life history

Length data were considered representative of blackfin tuna population due to the large number of individuals sampled each year and the normal distribution of each size composition. In addition, the fit of the modeled size composition to the observed data was considered satisfactory to all years, models and scenarios (Supplementary material 1). Table 3 shows parameters used to all scenarios by the LBSPR and SS-DL methods.

3.3. M/K and F/M ratios and selectivity

With the employment of different scenarios, a good distribution of M/K values were found, which increases data reliability (Supplementary material 2). A logistic selectivity curve was employed to estimate length at 50% and 95% at first capture (SL_{50} and SL_{95}, respectively) by year. Although were found differences among scenarios in selectivity, all scenarios presented higher length at first capture than length at first maturity used as input (L_{50} = 51.5 FL and L_{95} = 56.5 FL; estimated from Bezerra et al., 2013) and a slight decrease of 1 cm in SL_{50} and 1.3 cm in SL_{95} in average (Fig. 3a, Supplementary material 3). However, the only scenarios with F/M < 1 were the Scenario 1 to all time-series and Scenario 2 for the late 90's, both with the highest mortality. In addition, the first four scenarios presented F/M between 0.69–9.88 and Scenario 5 presented the highest values of F/M found in the class of 15–20 with the lowest mortality and higher variation to all time series (Fig. 3b).

3.4. SPR

SPR output differed between methods. LBSPR shows higher values than SS-DL to all time-series, with the exception of Scenario 5. However, LBSPR results show high variability between different mortalities and life-history scenarios. Additionally, LBSPR showed a more marked depletion in the average SPR from 0.62 to 0.40 (12%) while and SS-DL showed a slight decrease from 0.43 to 0.30 (7%). In 2019, the LBSPR model indicated that 60% of Southwestern Atlantic blackfin tuna stock scenarios demonstrated to be underexploited, 20% fell within the range of 0.3 and 0.4, 20% within 0.2 and 0.3 and 20% were classified as overexploited. On the other hand, when the SS-DL model was utilized 26.7% of scenarios showed an underexploited stock, 26.7% had an SPR within the target of 0.3–0.4, 20% fell within the range of 0.2 and 0.3, and 26.6% showed overexploitation (Fig. 4).

When comparing the SPR for the same scenarios throughout the time, the LBSPR showed a decrease of 0.95 to 0.80 in the

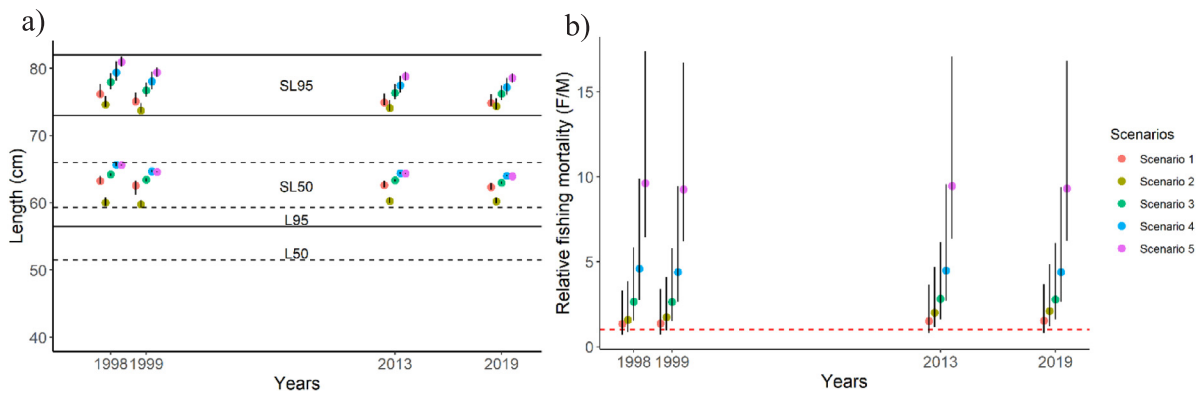

Fig. 3. Length at 50% (SL50) and 95% (SL95) at first capture (a) and relative fishing mortality (F/M) (b) at first the SWA blackfin tuna stock by LBSPR model (red line, F/M = 1). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

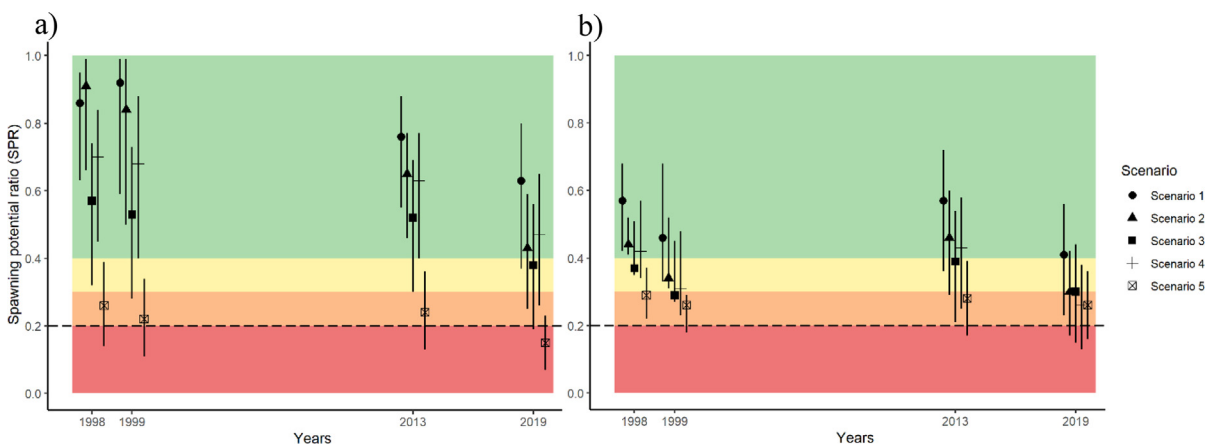

Fig. 4. SPR by year with the available length composition data estimated by LBSPR (a) and SS-DL (b) models to SWA blackfin tuna *Thunnus atlanticus* stock according to different estimations based in length (green, SPR > 0.4; yellow, 0.3 < SPR ≤ 0.4; orange, 0.2 < SPR ≤ 0.3; red, SPR ≤ 0.2; dashed line, SPR = 0.2). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

most optimistic scenario and of 0.14 to 0.07 in the most pessimistic scenario from the late 90's to 2019 (Table 4). Additionally, Scenario 5 shows very low SPR values when estimated in LBSPR diverging from the other scenarios whose parameters were estimated in the NWA. The SS-DL resulted in lower SPR values when compared with the LBSPR method, and lower variability among different mortalities and model scenarios. However, when comparing the results for the same scenarios through time, the SS-DL showed smaller changes from 0.68 to 0.56 in the most optimistic scenario and from 0.37 to 0.16 in the most pessimistic scenario from the late 90's to 2019 (Table 4).

The LBSPR method estimated a greater decrease of 12% in average of the SPR, while the SS-DL estimated a slight decreased of 7% in average of SPR from late 90's to 2019. Overall, blackfin tuna in the Southwest Atlantic is being properly exploited. However, there is a recognized need for enhanced efforts in data collection to mitigate the potential for future overexploitation.

3.5. Virginal stock composition

Differences were found among scenarios and M/K when compared the estimated virginal and current length composition with LBSPR. All estimated virginal composition increased the frequency of larger individuals (>80 cm) when lower values of M/K were employed. The same is true for the scenarios, which Scenario 1 showed the lowest and Scenario 5 the highest frequencies of larger individuals (>80 cm) due to input values of L_∞ found in literature for blackfin tuna. In addition, the highest and mean values of M/K seem to estimate more realistic frequencies of individuals to the observed length composition (Supplementary material 4).

4. Discussion

In the present study was provided, for the first time, evidence of the status of the Southwest Atlantic blackfin tuna stock by comparing the spawning potential ratio (SPR) estimated with two length-based methods. Both methods resulted in similar trends of decreasing SPR through time, despite differences on the absolute values and the rate of changes.

Many factors may influence the accessibility of data necessary for an accurate stock assessment of fish species, such as discontinuity of data collection, species misidentification and their low commercial value (Arocha et al., 2012; Fenton et al., 2015; Freire et al., 2015). However, in this study were gathered four years of size composition from three data sources throughout the SWA blackfin tuna stock distribution. These data were considered representative of blackfin tuna population due to the large number of individuals sampled each year and the normal distribution of each size composition. In addition, size composition and mean size differed among years and regions, indicating differences in blackfin tuna catch composition in the SWA. These discrepancies are related to distincts geographical areas, collection timeframes and the implementation of diverse fishing gears to capturing blackfin tuna in the SWA (Fenton et al., 2015).

Table 4
SPR by scenario, M/K and estimated by LBSPR and SS-DL models to SWA blackfin tuna stock according to different estimations based in length (green, SPR > 0.4; yellow, 0.3 < SPR ≤ 0.4; orange, 0.2 < SPR ≤ 0.3; red, SPR ≤ 0.2; M/K1, M = 1.02; M/K2, M = 0.72; M/K3, M = 0.42).

Scenarios	M/K	LBSPR				SS – DL			
		1998	1999	2013	2019	1998	1999	2013	2019
Scenario 1	M/K1	0.95	0.99	0.88	0.8	0.68	0.68	0.72	0.56
	M/K2	0.86	0.92	0.76	0.63	0.57	0.46	0.57	0.41
	M/K3	0.63	0.59	0.55	0.37	0.42	0.32	0.36	0.23
Scenario 2	M/K1	0.99	0.99	0.77	0.59	0.52	0.52	0.6	0.42
	M/K2	0.91	0.84	0.65	0.43	0.44	0.34	0.46	0.3
	M/K3	0.66	0.5	0.46	0.25	0.41	0.31	0.29	0.17
Scenario 3	M/K1	0.74	0.73	0.69	0.56	0.51	0.45	0.54	0.44
	M/K2	0.57	0.53	0.52	0.38	0.37	0.29	0.39	0.3
	M/K3	0.32	0.28	0.3	0.19	0.35	0.27	0.21	0.15
Scenario 4	M/K1	0.84	0.88	0.77	0.65	0.57	0.48	0.58	0.38
	M/K2	0.7	0.68	0.63	0.47	0.42	0.31	0.43	0.26
	M/K3	0.45	0.4	0.4	0.26	0.34	0.23	0.25	0.13
Scenario 5	M/K1	0.39	0.34	0.36	0.23	0.29	0.29	0.39	0.36
	M/K2	0.26	0.22	0.24	0.15	0.22	0.18	0.28	0.26
	M/K3	0.14	0.11	0.13	0.07	0.37	0.26	0.17	0.16

In order to account for the variablity in gear types and data sources for length data, three time-blocks were used in the SS-DL model for selectivity parameters. This approach successfully yielded satisfactory fits to the observed length compositions. However, in LBSPR a single curve of selectivity was employed to all time-series. Moreover, SS-DL model incorporates parameters such as steepness and recruitment, which are not necessary in the LBSPR. Therefore, the notable disparities observed in the outputs of different models can be attributed to the distinct approaches employed by each model in addressing selectivity, as well as the incorporation of more complex life history relationships within the SS-DL. LBSPR presented higher variability in the estimated SPR values throughout the time-series compared to SS-DL. This may happen due to the effect and importance of parameters to LBSPR model, which is very sensible to input parameters (Hordyk et al., 2014). Therefore, when high variability of parameters is assigned for a given species, SS-DL shows better performance giving a less biased estimation of SPR. However, LBSPR presents less SPR variation for more depleted populations (Hordyk et al., 2015). Consequently, Scenario 5 displays less variability among mortalities compared to the other scenarios.

The M/K ratio influences the shapes of the unfished length composition and the von Bertalanffy curve is directed related to the SPR (Hordyk et al., 2014). Although the range of M/K reported in the literature for fish varies a lot (Pauly, 1980; Beverton, 1992), the M/K = 1.5 is often used when data are not available for all parameters (Hordyk et al., 2014). However, M/K values were specified, so the main bias was associated with the estimations of L_∞ due to the approximation using maximum observed length. We found significant divergence among and within scenarios between models, by examining a wide range of M/K (0.5–3.4). The reported effects of misspecifying $L\infty$ and M/K have the potential to induce failures in the classification of stock status and subsequent management recommendations (Medeiros-Leal et al., 2023). Additionally, the great variation of M/K values employed shows the variability of M in each scenario. Life history as expressed in the M/K ratio proved to be a valueble predictor of length-based mortality estimators, demonstrating superior performance in high-M/K scenarios compared to low-M/K scenarios (Huynh et al., 2018). In situations characterized by low M/K, both length-based methods presented notably low SPR. The efficacy of length-based methods is strongly affected by the M/K ratio exhibiting suboptimal performance at low M/K scenarios (Hordyk et al., 2015; Huynh et al., 2018). Huynh et al. (2018) futher indicated that in low-M/K situations length-based methods are prone to positive bias, leading to the overestimation of mortalities even in equilibrium conditions. These findings raise concerns regarding the application of length-based methods in populations with low-M/K characteristics. When M/K is low, the peak of the length-frequency distribution may not correspond to the true length of full selectivity. Thus, scenarios with intermediate and high-M/K values would be considered more appropriate to assess blackfin tuna SWA stock.

A logistic selectivity curve was assumed, revealing that in all examined scenarios, the lengths at selectivity (SL) were consistently greater than the lengths at maturity (Lm). When length at selectivity is higher than maturity, fishing gear do not target immature fish and selects larger individuals. This selection strategy allows smaller individuals to reproduce at least once prior to being caught, thereby mitigating fishing impact and contibuting

to the sustainability of the spawning biomass (Froese, 2004). However, a slight decline in SL values (1.0 and 1.3 cm) over time was observed in the majority of the scenarios. Moreover, a significant proportion of the scenarios exhibited considerably high values of F/M and the M/K ratio. The F/M ratio can serve as an indicator of the relative intensity of fishing pressure, as it is commonly utilized as a proxy for fishing at maximum sustainable yield (e.g., FMSY = 0.75; Zhou et al., 2012) by employing a scalar multiple of M. Therefore, differences found in relative fishing mortality explain the uncertainty associated to the current SPR estimation by LBSPR model, since different reduction of individuals in each length class compared to the virginal composition classes results in different SPR values. Moreover, since fishing gear only selects mature individuals, a sustainable fishery (high SPR) with very high F/M may be present, and SPR values declining at a slower rate, requiring much higher F/M values to reduce SPR under 0.4 (Hordyk et al., 2014), which is the case for most scenarios. In addition, SS-DL revealed that SL was lower than Lm in 2019 (Table 3). This may happen due to the recent blackfin tuna expansion in the SWA to the Brazilian South, which adults individuals are being caught increasingly more throughout the time (Cardoso et al., 2021).

Five scenarios were implemented in the analysis (Table 2). Scenario 1–4 were structured based on parameter estimates derived from the NWA and Scenario 5 was the only scenario representing parameters estimated using samples from the SWA. The purpose of integrating NWA life history information with SWA length composition was to assess the uncertainty associated with growth and mortality parameters in the assessment of blackfin tuna stock, since information about blackfin tuna population dynamics in the SWA remain poorly assessed with few studies addressing this issue (Bezerra et al., 2013; Freire et al., 2015). Scenario 5 demonstrated the lowest values of SPR among scenarios, with a particularly pronounced disparity when estimated by LBSPR model. This discrepancy was accompanied by the highest and potentially unrealistic values of F/M. It is important to note that the growth parameters used in the Scenario 5 were estimated solely from length only methods, which requires several assumptions, such as short and well-defined reproductive season, fast growth in the early ages and distinct modal length distributions. However, these assumptions may not accurately reflect the characteristics of blackfin tuna. This highlights the need for growth studies that employ using more precise ageing techniques.

Regarding the SPR values, Scenario 1 presented the most optimistic and Scenario 5 the most pessimistic values, while Scenarios 2–4 showed intermediate values of SPR. These differences may be related to the relationship of L_∞ and K parameters of the von Bertalanffy function found to be negatively correlated for the most part of fish species (Xiao, 1994; Pilling et al., 2002). Therefore, Scenario 1 is more optimistic due to relatively low values, and Scenario 5 is more pessimistic due to high values of both L_∞ and K parameters. Thus, differences may be attributed to distinct growth patterns exhibited by the two stocks under investigation, as well as variations in the methodologies employed among studies (e.g., spines, otoliths, length-composition), which can influence the estimation of the SPR values. Overall, Scenario 1 with intermediate M/K values might represent better the virginal composition of blackfin tuna SWA stock, since most part of the adults are selected by the fishing gears (Supplementary material 4). Therefore, considering the intermediate M/K values of Scenario 1, the analysis reveals that blackfin tuna in 2019, the most recent year examined, exhibit a range of SPR values between 0.63 and 0.41, as estimated by both LBSPR and SS-DL methods.

Moreover, the LBPSR seems to be more optimistic, with 80% of the scenarios indicating an underexploited (SPR $>$ 0.4) or moderately exploited (0.3 $<$ SPR $\leq$ 0.4) stock. The estimates from SS-DL are more pessimistic, with just 53.4% of scenarios indicating the same exploitation. Both methods indicate values below 0.2 towards the end of the time series, suggesting a potential risk of over-exploitation. Moreover, the trend in SPR values from LBSPR seems to be more reasonable throughout the years, considering the scarcity of harvest records for blackfin tuna in SWA since 1960 (Lucena-Frédou et al., 2021). However, SPR results obtained from SS-DL should be given due consideration, given to the considerable variability in SPR estimations by LBSPR, and the presence of high relative fishing mortalities (F/M $>$ 1) across most scenarios. Therefore, considering Scenario 1 from SS-DL, we may classify blackfin tuna SWA stock within the acceptable levels of exploitation (SPR $>$ 0.4). However, any direct fishing effort or mortality without management actions would likely put the stock at risk of falling below the 20% SPR critical threshold and becoming overexploited.

The fidings of this study highlight the need of accurately estimating life history parameters and implementing regular data collection initiatives for blackfin tuna in the SWA due to enhance the assessment of its stock status. Although data-limited models serve as the most viable approach for estimating stock status of species with limited data availability, it is crucial to acknowledge their limitation, such as the utilization of limited annual length data as time-series, and the associated uncertainties in life history parameters. Therefore, despite SPR ranged from 0.41 to 0.63, indicating a sustainable level of exploitation (SPR $>$ 0.4) for the SWA blackfin tuna stock in 2019, it is recommended to allocate additional efforts towards monitoring landings, collecting length composition sample and reporting catch data for blackfin tuna. This becomes particularly important considering the potential overexploitation faced by some larger tuna species (Lucena-Frédou et al., 2017a,b). Futhermore, studies investigating accurately the life history of blackfin tuna, with especic focus on growth parameters in the Southwest Atlantic, should be encouraged as these parameters significantly impact the model stock status estimation.

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CRediT authorship contribution statement

Lucas Santos: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Eidi Kikuchi:** Formal analysis, Methodology, Writing – review & editing. **Flávia Lucena-Frédou:** Conceptualization, Supervision, Writing – review & editing. **Natália Bezerra:** Data collection, Writing – review & editing. **Paulo Travassos:** Data collection, Writing – review & editing. **Fábio Hazin:** Data collection, Writing – review & editing. **Nilamon Leite-Júnior:** Data collection, Writing – review & editing. **Luís Gustavo Cardoso:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.rsma.2023.103061.

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