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SOUTH ATLANTIC BLUE SHARK STOCK ASSESSMENT 1971-2021 USING STOCK SYNTHESIS

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SUMMARY

*This document describes the development of the South Atlantic blue shark (*Prionace glauca*) stock assessment using Stock Synthesis. The model runs from 1971 to 2021 and was fit to length composition by sex for eight fleets and four abundance indices. Life-history parameters were sex-specific with values based on the ICCAT Shark Working Group recommendations. Steepness and natural mortality at age were fixed at independently estimated values. Model improvements during the stock assessment meeting included changes in the life history parameters, time-blocks for CPUE time series and the implementation of a two-stage data weighting approach. Diagnostics for the final reference case model demonstrated fast and stable convergence, good retrospectives, and a robust solution across different starting values The estimated spawning output time series for the final reference case indicate a decreasing stock from the late 1980s to the early 2010s, a slight recovery until 2017, and a new slight decrease until 2021. Fishing mortality increased significantly from the late 1980s, reaching its all-time high in the early 2010s, decreasing fast until mid-2010s and increasing again in the last seven years.*

RÉSUMÉ

Le document décrit le développement de l'évaluation du stock de requin peau bleue de l'Atlantique Sud (Prionace glauca) au moyen du modèle Stock Synthesis. Le modèle couvre la période allant de 1971 à 2021 et a été ajusté aux données de composition des longueurs par sexe pour huit flottilles et quatre indices d'abondance. Les paramètres du cycle vital étaient spécifiques au sexe et les valeurs étaient basées sur les recommandations du Groupe d'espèces sur les requins de l'ICCAT. La pente et la mortalité naturelle par âge ont été fixées à des valeurs estimées de manière indépendante. Les améliorations apportées au modèle au cours de la réunion d'évaluation du stock comprenaient des changements dans les paramètres du cycle vital, la division en blocs temporels des séries temporelles de CPUE et la mise en œuvre d'une approche de pondération des données en deux étapes. Les diagnostics du cas de base du modèle final ont démontré une convergence rapide et stable, de bonnes rétrospectives et une solution robuste pour différentes valeurs de départ. Les estimations des séries temporelles de la reproduction pour le cas de base final indiquent un stock en baisse de la fin des années 1980 au début des années 2010, un léger rétablissement jusqu'en 2017 et une nouvelle légère baisse jusqu'en 2021. La mortalité par pêche a augmenté de manière significative à partir de la fin des années 1980, atteignant son niveau le plus élevé au début des années 2010, diminuant rapidement jusqu'au milieu des années 2010 et augmentant à nouveau au cours des sept dernières années.

RESUMEN

Este documento describe el desarrollo de la evaluación de stock de tiburón azul del Atlántico sur (Prionace glauca) utilizando Stock Synthesis. Los ensayos del modelo abarcan desde 1971 hasta 2021 y se ajustó a la composición por tallas por sexo para ocho flotas y cuatro índices de abundancia. Los parámetros del ciclo biológico eran específicos para cada sexo, con valores basados en las recomendaciones del Grupo de especies de tiburones de ICCAT. La inclinación y

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la mortalidad natural por edad se fijaron en valores estimados independientemente. Las mejoras introducidas en el modelo durante la reunión de evaluación de stock incluyeron cambios en los parámetros del ciclo biológico, bloques temporales para las series temporales de CPUE y la aplicación de un enfoque de ponderación de datos en dos etapas. Los diagnósticos del caso de referencia final del modelo mostraban una convergencia rápida y estable, buenas retrospectivas y una solución robusta a través de diferentes valores de partida Las series temporales de producción de desove estimadas para el caso de referencia final muestran un stock decreciente desde finales de la década de 1980 hasta principios de la década de 2010, una ligera recuperación hasta 2017 y una nueva ligera disminución hasta 2021. La mortalidad por pesca aumentó significativamente desde finales de la década de 1980, alcanzando su máximo histórico a principios de 2010, disminuyendo rápidamente hasta mediados de 2010 y aumentando de nuevo en los últimos siete años.

KEYWORDS

Stock assessment, South Atlantic, Blue shark

1. Introduction

Stock Synthesis (SS) is an integrated statistical catch-at-age model widely used for many stock assessments (Methot and Wetzel 2013). SS integrates many critical underlying processes of stock dynamics (mortality, recruitment, selectivity, growth, etc.) that produce observed catch, size, age composition, and CPUE indices. A proper assessment should model these inputs together due to possible correlations between them, which will help to ensure that uncertainties in the input data are appropriately accounted for in the assessment (Walter *et al*. 2018). The feature of modeling all the inputs together makes SS appropriate to account for all the processes in the stock dynamics.

The Standing Committee on Research and Statistics (SCRS) of the International Commission for the Conservation of Atlantic Tunas (ICCAT) has historically considered the existence of two distinct blue shark (BSH, *Prionace glauca*) stocks in the Atlantic Ocean (South and North). This advice is followed here. Total landings, from the southern stock increased sharply from the 1970s to 1996, when they reached 30,000 tons, remained around 24,000 tons until 2010, and in 2011 reached 37,000 tons. From 2012 to 2017, it remained in lower level of around 25,000 ton and increased again in the last four years (2018-2021), remaining around 34,000 tons.

This paper presents the results of the Stock Synthesis analyses for the blue shark in the South Atlantic. The two-sex model covered the period from 1971 to 2021 and includes catches and size composition from eight fleets and indices from four fleets (**Figure 1**). A preliminary base case model configuration was tested using maximum age and reproductive parameters as recommended by data preparatory meeting (Anon, 2023), a steepness value of 0.55 (Cortes *et al.* 2016), the growth parameters estimated by Jolly *et al*. (2013), and the respective M (natural mortality) at age vector by sex estimated with the Charnov *et al.* (2013).

After the preliminary model runs were presented to the ICCAT blue shark stock assessment group, some modifications were required in the life-history parameters in order to improve the fits to the length compositions and to consider updated parameters. The changes in the life-history parameters included using the same growth parameters for both sex estimated from Joung *et al*. (2017), considering the results from this study as more representative of the stock, since it covered a wider sampling area and using an updated steepness value of 0.8 provided in SCRS/2023/115 (Cortes and Taylor, 2023) and a natural mortality at age vector provided in SCRS/2023/115 (Cortes and Taylor, 2023).

Other modifications included a two-stage Francis (2011, 2017) data weighting approach implemented to iteratively tune, “right-weight,” the variance adjustment factors for both fleet-specific relative abundance indices (CPUE) (Stage 1) and fleet-specific size data distributions (length composition) (Stage 2). Francis (2011) describes the two-stage approach to assign variance adjustment factors to different data inputs (e.g., first to fleet-specific relative abundance indices, and second to fleet-specific size data distributions) within an integrated stock assessment model. In stage one, variance adjustment factors are applied to the fleet-specific relative abundance indices externally to the integrated stock assessment model. In stage two, variance adjustment factors are applied to fleet-specific size data distributions within the integrated stock assessment model.

Other modification included using time blocks for the CPUE for two fleets, Brazil and Japan, as it was recognized that the catch reporting and blue shark retaining may have changed over time and that could be reflecting in the standardized cpue trends.

Other model sensitivity exploration and diagnostics included testing a range of equilibrium recruitment parameter (R_0) values, retrospective analysis, jittering initial parameters, and application of some of the diagnostics presented by Carvalho *et al.* (2020). Basic equations and technical specifications underlying Stock Synthesis can be found in Methot and Wetzel (2011). In these models, we use SS version V3.30.21.00.

2. Methods

2.1 Model Spatio/Temporal Structure

A one-area, two-sex model with an annual time step was constructed for the South Atlantic blue shark stock. The eight-fleet structure was designed to discriminate the seven fleets responsible for 95% of the total catches in the last five years, with a single fleet that pools catch from all the remaining fleets, accounting for less than 5% of total catches in the last five years as a single fleet (**Table 1**). The functional assumption of the fleet selectivity curves by sex and fleet was determined based on size composition distributions, and the selectivity parameters were freely estimated (**Table 2**).

2.2 Temporal domain and initial conditions

The model starts in 1971 and runs to 2021. Conditions were assumed to be near-virgin in 1971 with three fleets (BRA, CHI_TAI and JPN) operating in the initial period. An annual time step was considered for the model, with fishing assumed to occur throughout the year. Individual indices were adjusted to account for the timing within the year when the index occurred. No time blocks were imposed.

2.3 Biology

Figure 2 shows the main biological relationships against age and size for the South Atlantic BSH for the preliminary model. A two-sex model was assumed, and spawning output was considered the summed mass of all mature females fish. Recruitment was estimated as age 0 fish, and the model assumed a plus group age of 16. A logistic model with parameters a=-24.99 and b=0.136 (Mas *et al*. 2023) which resulted in size at 50% maturity of 183 cm FL for females. First mature age was considered to be five years and age at 50% maturity was estimated at 7 years according to the used growth curve. The fecundity relationship was estimated according the linear relationship with size LS = -23.65501 + 0.27966*FL (N = 423, R2 = 0.129), estimated by Mas *et al*. 2023). Growth was modeled with a von Bertalanffy two parameters (L1 and L2) formulation and initially input $L\infty$ = 279 cm, k=0.11 and L0 = 47 cm according to Jolly *et al.* (2013). A large CV was set for the young (0.2) and old fish (0.2) due to the uncertainty within the growth parameters and to cover observations of larger fish. The overall South Atlantic Blue Shark length-weight relationship was used to convert the size to weight (W=1.1E-06FL^3.35) (Montealegre-Quijano, 2007).

For the final reference case, the growth, maximum age and natural mortality were changed from the preliminary model configuration. Growth was considered the same for both sex and modeled with a von Bertalanffy two parameters (L1 and L2) formulation and initially input $L\infty$ = 291.8 cm, k=0.13 and L0 = 47 cm according to Joung *et al*. (2017) (Figure 3). A large CV was set for the young (0.2) and a smaller for the old fish (0.1) due to the uncertainty within the growth parameters.

The updated natural mortality at age vector (M) was obtained independently of the stock assessment model with life history invariant methods described in document SCRS/2023/115 (Cortés and Taylor 2023; Pers. Comm. E. Cortés 7/5/2023) and summarized below in **Table 3**.

2.4 Stock- recruitment relationship

A standard Beverton-Holt stock recruit relationship was assumed. The spawning biomass was considered equal to the female's mature population's biomass according to the maturity schedule outlined in the biology section. Parameters of the stock-recruitment relationship (steepness and sigmaR) were fixed at 0.55 and 0.5 for the preliminary base case model, respectively. Equilibrium recruitment (R0) was estimated without a prior. Deviations from the stock-recruitment relationship were assumed to follow a lognormal distribution estimated on a log scale as N(0, sigmaR) variates with a min and max of -5 and 5, respectively. Zero recruitment deviations were assumed until the start of informative data on size structure (continuous length composition series from the main fleets), i.e., annual deviates were only estimated from 1995 to 2019.

For the final reference case the steepness value was fixed at 0.8 as estimated by the SCRS/ 2023/115 by Cortes and Taylor (2023).

2.5 Total catch (Task 1)

The total catches were calculated by the ICCAT Secretariat (**Table 1**, **Figure 3**) for the fleets presented above. Catch in mass was used in the model for all fleets, and was assumed to be known essentially with a CV of 0.01.

2.6 Size frequency information

The ICCAT Secretariat provided size frequency data by fleet in the format of annual counts per size bin (**Figure 4**). The length compositions of years with less than 100 measured individuals per sex were excluded from the analysis, considering these years as not representative. Measurements were in cm fork length (FL) and modeled with 5 cm length bins between 15 and 395 cm. Length composition data were modeled assuming a multinomial distribution and the number of samples was considered as the Natural Logarithm of the total number of individuals for each year as it provides computational advantages.

2.7 Catch per unit effort data

Standardized indices of catch per unit effort, CPUE, were available based on the ICCAT Shark Working Group recommendations from the 2023 Blue shark Data Preparatory Meeting for four of the eight longline fishing fleets (FS1_EU_SPN, FS2_BRA, FS3_CHI_TAI, and FS4_JPN) (**Figure 5**). CPUE indices were assumed to have a lognormal error structure. No time-blocks on indices were modeled. A data weighting approach was used to iteratively tune (re-weight) variance adjustment factors for fleet-specific abundance indices (CPUE) following the Courtney *et al.* (2017).

For the final reference case a time-block was used for the standardized CPUE indices for the Brazil (BRA) and Japan (JPN) fishing fleets. The time-blocks were established from the beginning of the index time series (1992 for BRA and 1994 for JPN) until 2007 and from 2008 until 2021 for both fleets.

2.8 Model Diagnostics

Model convergence was assessed using the Carvalho *et al*. (2021) flow chart. The first diagnostic was whether the Hessian (i.e., the matrix of second derivatives of the likelihood concerning the parameters) inverts. The second measure observed the joint residuals plot and ensured that they were randomly distributed. The third measure was the retrospective analyses conducted on the reference-case model with five-year retrospective peels. The fourth measure analyzed the model prediction skill by completing model-based hindcasting. The fifth diagnostic was a jitter analysis of parameter starting values to evaluate whether the model has converged to a global solution rather than a local minimum. Starting values of all estimated parameters were randomly perturbed by 10%, and 50 trials were run.

Likelihood profiles for the final reference case model were conducted to assess the information content in the model with regards to estimation of one critical parameter associated with the equilibrium recruitment parameter, R_0. The R_0, has been commonly profiled since it represents an ideal global scaling parameter given that unfished (virgin) recruitment is proportional to unfished biomass (Maunder and Piner, 2015; Wang *et al*., 2014).

3. Results

3.1 Model diagnostics

3.1.1 Preliminary base case model

Overall, the preliminary base case model showed relatively good diagnostic performance, good convergence properties, and stable estimation. The model presented a good fit to the length compositions as well to the index of all the fleets (**Figure 6**). The final gradient of the base case was notably small (0.0000196034), and the Hessian matrix for the parameter estimates was positive definite. The models run relatively fast (~2 minute and 40 seconds) and show good convergence properties. Following, a comprehensive set of model diagnostics are presented for the preliminary base case model.

The joint residual plots for the preliminary base case showed a random pattern for the residuals of the fits to the index for all fleets with some outliers for the FS2_BRA, FS3_CHI_TAI and FS4_JPN fleets (> 0.5 or < -0.5) but without a significant impact on the overall pattern (**Figure 7**). The residuals of the length composition fit also showed a random pattern for all fleets with just one outlier for the FS4_JPN (**Figure 7**).

The retrospective performance is overall good (**Figure 8**), all falling within the confidence intervals of the different runs. The scale of spawning output and recruitments changed very little as the final years were removed from the analysis. Retrospective fits for the indices were overall good (**Figure 9**), except for the fits to the years between 2011 and 2020 for the FS2_BRA index that fits lower values than the observed ones as well as for the initial years of the FS4_JPN that fits higher values than the observed ones. The overall fits to the indices change very little retrospectively.

When analyzing the model prediction skills, most of predicted observations for all four fitted CPUE indices and all eight length compositions fell within the hindcast evaluation period 2017–2021 (**Figure 11**). However, the MASE scores > 1 for the FS2_BRA and FS4_JPN fleets indices indicate that they have lower prediction skill than the FS1_EU_SPN and FS3_CHI_TAI indices. Four of the eight length compositions showed low predictive skill with MASE scores >1 (FS2_BRA, FS3_CHI_TAI, FS4_JPN, FS6_NAMB), while the other four showed good predictive skill, MASE < 1 (**Figure 10**).

The jittered model shows high stability in the log-likelihood with different starting values (**Figure 11**). All 50 jitter model runs converged, with 30 model runs at the total negative likelihood estimated value of the base case model run (894.12 likelihood units), and 13 model runs had total negative likelihood values close to the base case value and 7 had values larger than 910 (**Figure 11**). The jittered model was robust to the initial values of the parameters and gave no evidence that the base case model converged to a local minimum of the objective function instead of the global minimum.

3.1.2 Final reference case model

Overall, the final reference case model showed good diagnostic performance, good convergence properties, and stable estimation. The model improved the fit to the length compositions as well to the index of all the fleets in relation to the preliminary base case (**Figure 12**). The final gradient of the base case was notably small (0.0000723827), and the Hessian matrix for the parameter estimates was positive definite. The models run relatively fast (~2 minute and 2 seconds) and show good convergence properties. Following, a comprehensive set of model diagnostics are presented for the preliminary base.

The joint residual plots for the final reference case showed a negative residuals of the fits to the index for all fleets in the beginning of the time series with some outliers for the FS2_BRA_TB1, and FS3_CHI_TAI fleets (>0.5 or < -0.5) but without a significant impact on the overall pattern (**Figure 13**). The residuals of the length composition fit also showed a random pattern for all fleets with just one outlier for the FS4_JPN (**Figure 13**).

The retrospective performance is overall good (**Figure 14**), all falling within the confidence intervals of the different runs. The scale of spawning output and recruitments changed very little as the final years were removed from the analysis. Retrospective fits for the indices presented a slight improvement with the time-blocks for BRA&UY and JPN CPUE indices from the previous preliminary model (**Figure 15**). The overall fits to the indices change very little retrospectively.

When analyzing the model prediction skills, most of predicted observations for all fitted CPUE indices fell within the 7 years hindcast evaluation period 2015–2021 (**Figure 16**). However, the MASE score > 1 for FS2_SPN indicates that it has lower prediction skill than the other indices.

The jittered final reference case model shows high stability in the log-likelihood with different starting values (**Figure 17**). All 200 jitter model runs converged, with 114 model runs at the total negative likelihood estimated value of the base case model run (179.302 likelihood units), and 71 model runs had total negative likelihood values close to the base case value (difference <10 likelihood units) and 15 had larger differences than 10 likelihood units (**Figure 17**). The jittered model was robust to the initial values of the parameters and gave no evidence that the base case model converged to a local minimum of the objective function instead of the global minimum.

3.2 Model results

3.2.1 Preliminary base case model

Estimated selectivity's at length generally reflected assumed patterns of the fisheries (**Figure 18**, **Tables 2 and 4**). The doming of the FS1_EU_SPN, and FS11_EU_POR are pretty steep but follows the steep single mode length compositions presented by these fleets. The selectivity for the FS2_BRA females follows the observed size composition in which larger females are much less representative than larger males in the catches (**Figure 4**).

The estimated stock-recruitment relationship indicates no distinct positive relationship between spawning output and recruitment (**Figure 19**). High recruitments were predicted with small SSF and low recruitment events with high spawning output with high interannual variability in estimated recruitment deviations (**Figure 19**).

Overall, the length composition data reasonably fit with few systematic departures (**Figure 6**). Problematic departures can be seen in the Pearson residuals, where one would look for solid patterned trends (**Figure 20**).

The spawning output, and depletion in spawning output relative to MSY time series indicate a decreasing stock from the late 1980s to the early 2000s, remaining relatively low during the 2000s to the early 2010's (**Figure 21**). From the 2010s to 2017 it recovered and presented a slight decrease until the end of the time series (**Figure 21**). The recruitment time series showed an increasing pattern in the first five years of the times series and then a highly variable pattern with a dynamic deviation from zero through time (**Figure 21**).

3.2.2 Final reference case model

Estimated selectivities at length generally reflected assumed patterns of the fisheries (**Figure 22**, **Tables 2** and **5**). The doming of the FS1_EU_SPN, and FS11_EU_POR and FS8_NMB are pretty steep but follows the steep single mode length compositions presented by these fleets. The selectivity for the FS2_BRA females follows the observed size composition in which larger females are much less representative than larger males in the catches (**Figure 4**).

The estimated stock-recruitment relationship indicates no distinct positive relationship between spawning output and recruitment and showed an improvement from the preliminary model (**Figure 23**). The recruitment variability decreased from the previous estimated relationship, which is consistent with the expected from long-lived top predator species like blue shark (**Figure 23**).

Overall, the length composition data reasonably fit with few systematic departures (**Figure 6**). Problematic departures can be seen in the Pearson residuals, where one would look for solid patterned trends (**Figure 24**).

The spawning output, and depletion in spawning output relative to MSY time series for the final reference case indicated a steeper decrease of the stock from the late 1980s to the early 2010s, in relation to the preliminary base case model (**Figure 25**). The recovery from the 2010s to 2017 was less pronounced for the final case in relation to the preliminary model (**Figure 25**). The final reference case also estimated a slight decrease from 2017 until the end the time series. The recruitment estimations showed an increasing pattern in the first five years of the times series and much less variability for the final reference case in relation to the preliminary estimates, but with dynamic deviations from zero through time (**Figure 25**). The estimated spawning output ratio time series for the final reference showed that the stock has always remained above the spawning output that generates MSY (**Figure 25**).

Fishing mortality was estimated as simple sum of the full F's by fleet, (apical Fs). In general, F steadily increased from the 1990s until early 2010's when reached its all-time high in 2011 (F=1.33) (**Figure 26**). After a decrease, F increased again in the model terminal years, reaching high values, estimated at 1.16 (**Figure 26**).

Table 6 presents several benchmarks estimated with the final reference case model. The estimated spawning output ratio relative to MSY was 1.193 (SD = 0.18) for the terminal year of the time series (2021) while F/F_{MSY} was 1.162 (SD = 0.18) (**Table 6**). The MSY was estimated at 26,209.6 (SD = 1,255.71) metric tons (**Table 6**).

3.3 Likelihood profiles

The likelihood profiles for the critical parameter R0 was explored for the final reference case model. Considering the tested equilibrium recruitment R_0 profile (7-10), the gradient of the likelihood for the penalty on the lengths was greater than other data sources. The second strongest gradient in the log-likelihood profile was observed for the recruitment deviations (**Figure 27**). The gradient of the likelihood profile supported by the index is lower than those supported by the penalty for the lengths and recruitment deviations. Therefore, the indices are the least informative data for the estimation of initial recruitment. Estimates were sensitive to the R_0 assumption in general. Lower R_0 values provided higher depletion estimates with lower spawning output relative to MSY values and vice-versa.

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Table 1. Task 1 landings input for the South Atlantic Blue shark reference model.

Fleet ID	1	2	3	4	5	6	7	8	
YearC	FS1_EU_SPAIN	FS2_BRA	FS3_CHI_TAI	FS4_JPN	FS5_URY	FS6_NAMB	FS11_EU_POR	FS10_Else	Grand total
1971	0	87	3,513	1,132	0	0	0	0	4,732
1972	0	68	4,439	760	0	0	0	0	5,267
1973	0	91	4,290	2,479	0	0	0	0	6,860
1974	0	263	3,526	666	0	0	0	0	4,454
1975	0	290	3,138	643	0	0	0	0	4,071
1976	0	206	3,811	489	0	0	0	0	4,507
1977	0	217	3,534	5,765	0	0	0	0	9,515
1978	0	207	3,496	6,800	0	0	0	0	10,504
1979	0	294	3,341	7,628	0	0	0	0	11,263
1980	0	892	3,090	8,655	0	0	0	0	12,638
1981	0	370	3,048	4,442	64	0	0	0	7,924
1982	0	575	3,187	9,579	234	0	0	0	13,576
1983	0	441	2,235	2,813	460	0	0	0	5,950
1984	0	264	1,438	7,601	655	0	0	0	9,959
1985	0	318	1,666	6,156	362	0	0	0	8,501
1986	0	425	3,733	7,717	128	0	0	0	12,003
1987	0	535	4,260	4,707	85	0	0	0	9,587
1988	5,195	657	3,992	7,016	68	0	0	0	16,928
1989	9,135	660	5,338	6,807	57	0	0	0	21,997
1990	7,292	959	8,798	8,058	79	0	0	0	25,185
1991	6,811	742	7,066	6,560	40	0	0	0	21,219
1992	6,683	1,475	10,217	4,748	107	0	0	0	23,229
1993	8,247	1,138	5,792	7,834	84	0	0	33	23,128
1994	9,386	888	8,636	7,659	84	0	0	69	26,721
1995	13,351	1,113	7,784	5,556	57	0	847	102	28,809
1996	11,378	1,069	11,628	4,852	259	0	867	105	30,158
1997	5,272	2,317	9,558	4,397	180	0	1,336	45	23,106
1998	5,574	2,173	8,771	3,720	248	0	876	140	21,502
1999	7,173	2,668	8,390	3,134	118	0	1,110	408	23,001
2000	6,951	1,683	9,064	2,951	81	0	2,134	226	23,089
2001	7,743	2,173	6,061	1,667	66	0	2,562	536	20,809
2002	5,368	1,971	8,445	1,447	85	0	2,324	2,528	22,166
2003	6,626	2,166	7,228	5,469	480	0	1,841	2,910	26,719
2004	7,366	1,667	6,005	2,680	462	0	1,863	2,358	22,403
2005	6,410	2,523	5,045	1,660	376	0	3,184	7,394	26,593
2006	8,724	2,591	2,433	3,282	232	0	2,751	4,433	24,446
2007	8,942	2,645	2,177	3,653	337	0	4,493	4,323	26,572
2008	9,615	2,013	1,843	5,521	359	0	4,866	2,624	26,841
2009	13,099	1,274	1,356	3,768	942	0	5,358	625	26,422
2010	13,953	1,500	1,625	5,336	208	0	6,338	3,013	31,974
2011	16,978	1,980	2,142	4,242	725	0	7,642	3,977	37,685
2012	14,348	1,607	2,147	4,447	433	0	2,424	2,328	27,734
2013	10,473	1,008	2,287	3,509	130	0	1,646	1,745	20,799
2014	11,447	2,551	2,240	3,232	0	2,471	1,622	2,690	26,253
2015	10,133	2,420	1,854	2,277	0	2,137	2,420	1,257	22,498
2016	10,107	1,334	1,992	2,127	0	2,775	5,609	1,472	25,417
2017	11,488	2,177	2,053	3,112	0	1,357	6,663	1,706	28,555
2018	13,515	3,011	1,372	3,495	0	3,290	8,015	1,814	34,514
2019	18,497	3,784	861	2,513	0	2,474	6,753	2,525	37,408
2020	14,717	3,435	1,338	2,116	0	4,120	7,350	798	33,873
2021	16,778	4,629	1,052	1,639	0	3,237	5,524	902	33,761

Table 2. Fleet ID, length-based selectivity pattern, and index usage for the eight fleets used in the South Atlantic Blue shark reference model. Female (F), Male (M), Double Normal (DN), Logistic (LG), Yes (Y), No (N).

Fleet ID.	Fleet	Selectivity	Index	start	end
1	FS1_EU_SPAIN	DN (F and M)	Y	1988	2021
2	FS2_BRA	LG (M) and DN (F)	Y	1971	2021
3	FS3_CHI_TAI	LG (F and M)	Y	1971	2021
4	FS4_JPN	LG (F and M)	Y	1971	2021
5	FS5_URY	LG (F and M)	Y(+BRA)	1975	2021
6	FS6_NAMB	LG (F and M)	N	1981	2013
7	FS11_EU_POR	DN (F and M)	N	1995	2021
8	FS10_Else	LG (F and M)	N	1993	2021

Table 3. Natural mortality at age for the preliminary base case model estimated with the Charnov *et al* (2013) approach (left) and for the final reference case estimated by Cortes and Taylor (2023) (right).

Age	M at age		
	Preliminary base case model		Final reference case
	Females	Males	Pooled sex
0	0.68	0.97	0.25
1	0.49	0.62	0.23
2	0.38	0.46	0.21
3	0.32	0.37	0.20
4	0.27	0.31	0.20
5	0.24	0.27	0.19
6	0.22	0.25	0.19
7	0.20	0.23	0.19
8	0.19	0.21	0.19
9	0.17	0.20	0.19
10	0.16	0.19	0.19
11	0.16	0.18	0.19
12	0.15	0.17	0.18
13	0.15	0.17	0.18
14	0.14	0.17	0.18
15	0.14	0.16	0.18
16	0.14	0.16	0.18
17			0.18
18			0.18
19			0.18
20			0.18
21			0.18
22			0.18

Table 4. Parameter estimates, phases initial values and standard deviations for the South Atlantic Blue shark preliminary base case model.

Parameter	Value	Phase	Min	Max	Init	SD	Type
SR_LN(R0)	9.751	1	0.0	20	9.334	0.134	SRR
SR_regime_BLK1add_1970	-0.151	1	-5.0	5	-0.117	0.102	SRR
InitF_seas_1_flt_2FS2_BRA	0.001	1	0.0	0.2	0.001	0.000	F
InitF_seas_1_flt_3FS3_CHI_TAI	0.010	1	0.0	0.2	0.012	0.002	F
InitF_seas_1_flt_4FS4_JPN	0.009	1	0.0	0.2	0.010	0.002	F
Q_extraSD_FS3_CHI_TAI(3)	0.021	4	-0.3	0.3	0.021	0.061	CPUE
Size_DblN_peak_FS1_EU_SPN(1)	201.042	2	15.0	365	201.151	4.609	Sel
Size_DblN_top_logit_FS1_EU_SPN(1)	-2.830	1	-15.0	15	-2.237	1.020	Sel
Size_DblN_ascend_se_FS1_EU_SPN(1)	6.872	2	-4.0	12	6.896	0.209	Sel
Size_DblN_descend_se_FS1_EU_SPN(1)	6.664	1	-15.0	15	5.999	0.637	Sel
Size_DblN_end_logit_FS1_EU_SPN(1)	-3.220	1	-5.0	20	-2.661	1.602	Sel
Size_DblN_peak_FS2_BRA(2)	177.673	2	15.0	365	176.993	9.886	Sel
Size_DblN_ascend_se_FS2_BRA(2)	7.114	2	-4.0	12	7.143	0.383	Sel
Size_DblN_peak_FS3_CHI_TAI(3)	200.969	2	15.0	365	203.799	7.541	Sel
Size_DblN_ascend_se_FS3_CHI_TAI(3)	7.146	2	-4.0	12	7.236	0.329	Sel
Size_inflection_FS4_JPN(4)	143.446	2	50.0	190	143.691	4.322	Sel
Size_inflection_FS5_URY(5)	127.997	2	50.0	180	128.982	4.031	Sel
Size_95%width_FS5_URY(5)	36.649	3	0.0	100	38.140	5.048	Sel
Size_inflection_FS6_NAMB(6)	102.713	2	50.0	180	103.042	8.515	Sel
Size_95%width_FS6_NAMB(6)	48.704	3	0.0	100	51.751	16.575	Sel
Size_DblN_peak_FS11_EU_POR(7)	199.559	2	15.0	365	198.572	2.191	Sel
Size_DblN_top_logit_FS11_EU_POR(7)	-10.567	1	-15.0	15	-2.220	64.662	Sel
Size_DblN_ascend_se_FS11_EU_POR(7)	6.217	2	-4.0	12	6.186	0.147	Sel
Size_DblN_descend_se_FS11_EU_POR(7)	7.371	1	-15.0	15	6.000	0.183	Sel
Size_DblN_end_logit_FS11_EU_POR(7)	-4.966	1	-5.0	20	-2.010	1.056	Sel
Size_inflection_FS10_ELSE(8)	142.042	2	50.0	180	144.198	10.930	Sel
Size_95%width_FS10_ELSE(8)	52.762	3	0.0	100	55.037	12.826	Sel

Table 5. Parameter estimates, phases initial values and standard deviations for the South Atlantic Blue shark final reference case model.

Parameters	Value	Phase	Min	Max	Init	SD	Type
SR_LN(R0)	8.104	1	0.0001	20	8.121	0.054	SRR
SR_regime_BLK1add_1970	-0.029	1	-5	5	-0.030	0.101	SRR
InitF_seas_1_flt_2FS2_BRA	0.001	1	0	0.2	0.001	0.000	InitF
InitF_seas_1_flt_3FS3_CHI_TAI	0.010	1	0	0.2	0.010	0.001	InitF
InitF_seas_1_flt_4FS4_JPN	0.009	1	0	0.2	0.008	0.001	InitF
Size_DblN_peak_FS1_EU_SPN(1)	201.843	2	15	365	201.705	8.748	Sel
Size_DblN_top_logit_FS1_EU_SPN(1)	-3.080	1	-15	15	-3.119	2.398	Sel
Size_DblN_ascend_se_FS1_EU_SPN(1)	6.961	2	-4	12	6.958	0.388	Sel
Size_DblN_descend_se_FS1_EU_SPN(1)	6.640	1	-15	15	6.653	0.915	Sel
Size_DblN_end_logit_FS1_EU_SPN(1)	-4.985	1	-5	20	-4.985	0.477	Sel
Size_DblN_peak_FS2_BRA(2)	178.829	2	15	365	178.532	13.864	Sel
Size_DblN_ascend_se_FS2_BRA(2)	7.349	2	-4	12	7.346	0.516	Sel
Size_DblN_peak_FS3_CHI_TAI(3)	208.732	2	15	365	208.250	13.851	Sel
Size_DblN_ascend_se_FS3_CHI_TAI(3)	7.442	2	-4	12	7.430	0.492	Sel
Size_inflection_FS4_JPN(4)	137.560	2	50	190	137.232	6.992	Sel
Size_inflection_FS5_URY(5)	120.094	2	50	180	119.891	6.274	Sel
Size_95%width_FS5_URY(5)	37.672	3	0.01	100	37.474	10.068	Sel
Size_inflection_FS6_NAMB(6)	81.352	2	50	180	81.163	19.978	Sel
Size_95%width_FS6_NAMB(6)	51.794	3	0.01	100	51.458	60.384	Sel
Size_DblN_peak_FS11_EU_POR(7)	201.717	2	15	365	201.651	7.021	Sel
Size_DblN_top_logit_FS11_EU_POR(7)	-8.047	1	-15	15	-8.100	89.066	Sel
Size_DblN_ascend_se_FS11_EU_POR(7)	6.341	2	-4	12	6.339	0.443	Sel
Size_DblN_descend_se_FS11_EU_POR(7)	7.600	1	-15	15	7.592	1.007	Sel
Size_DblN_end_logit_FS11_EU_POR(7)	-3.906	1	-5	20	-3.879	16.126	Sel
Size_inflection_FS10_ELSE(8)	144.037	2	50	180	143.674	17.979	Sel
Size_95%width_FS10_ELSE(8)	66.042	3	0.01	100	65.824	23.941	Sel

Table 6. Benchmarks (SD) and relative stock status for the South Atlantic Blue shark final reference case model.

Benchmarks	Reference Model
SSB_unfished	90345.4 (4835.04)
Totbio_unfished	531378 (28437.9)
Recr_unfished	3306.45 (176.952)
SSB_MSY	21803.1 (1145.61)
SPR_MSY	0.288747 (0.00221843)
annF_MSY	0.304855 (0.0205132)
Dead_Catch_MSY	26209.6 (1255.71)
SSB_2022/SSB_MSY	1.19274 (0.189023)
F_2021/F_MSY	1.1618 (0.186331)

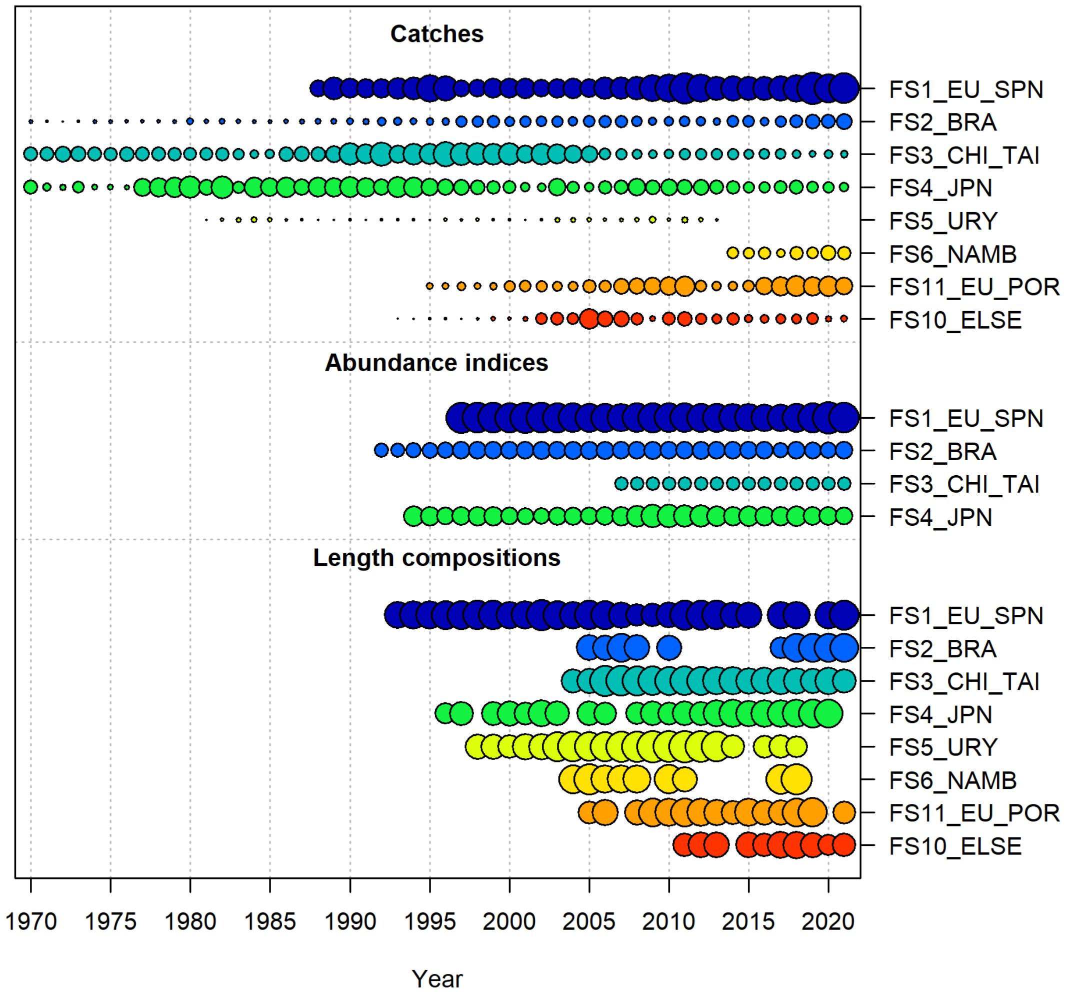

Figure 1. Time series of data inputs for the South Atlantic Blue Shark Stock Synthesis reference model.

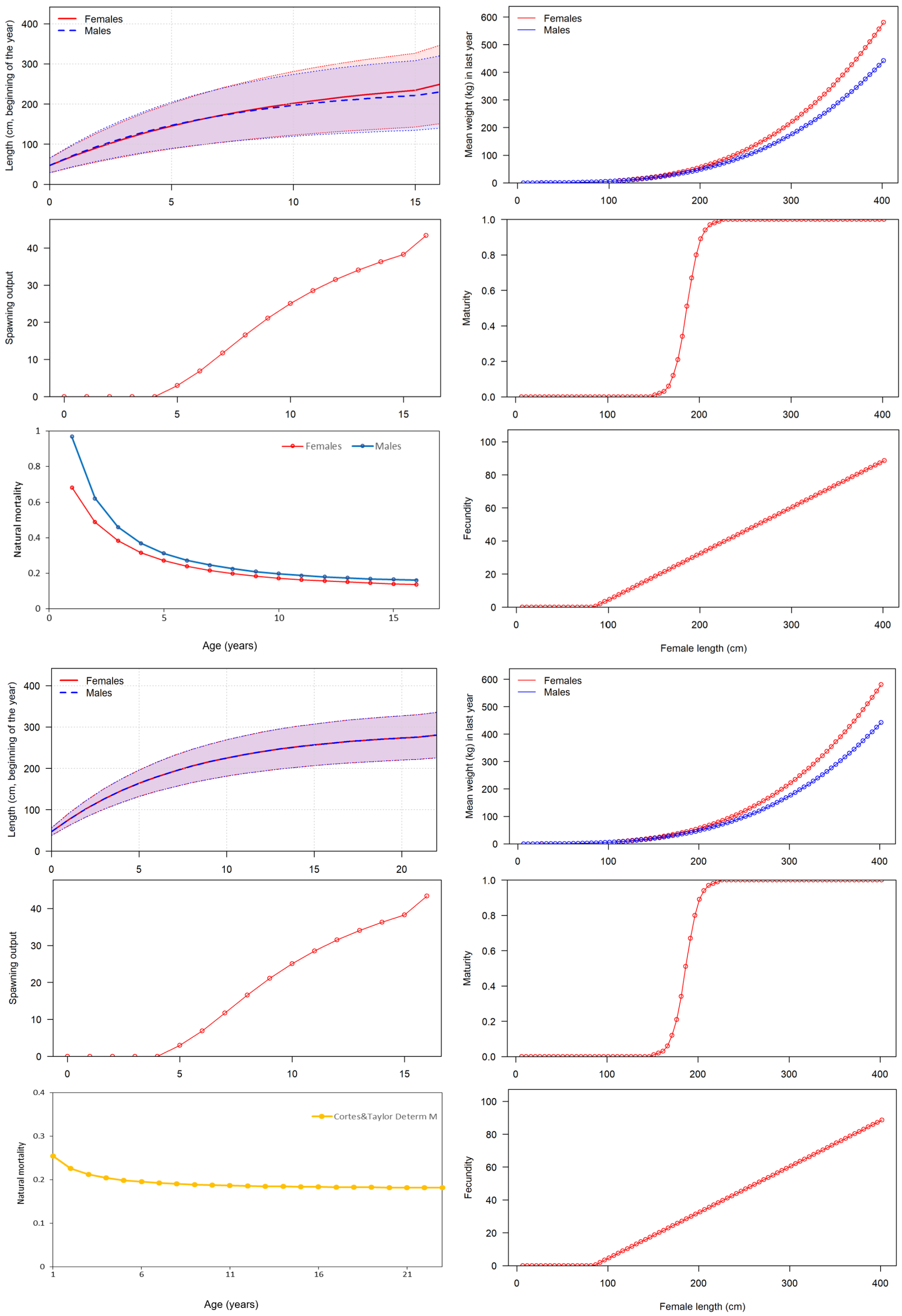

Figure 2. General biology description for the South Atlantic Blue Shark Stock Synthesis preliminary base case model (upper four panels) and the final reference model (lower four panels).

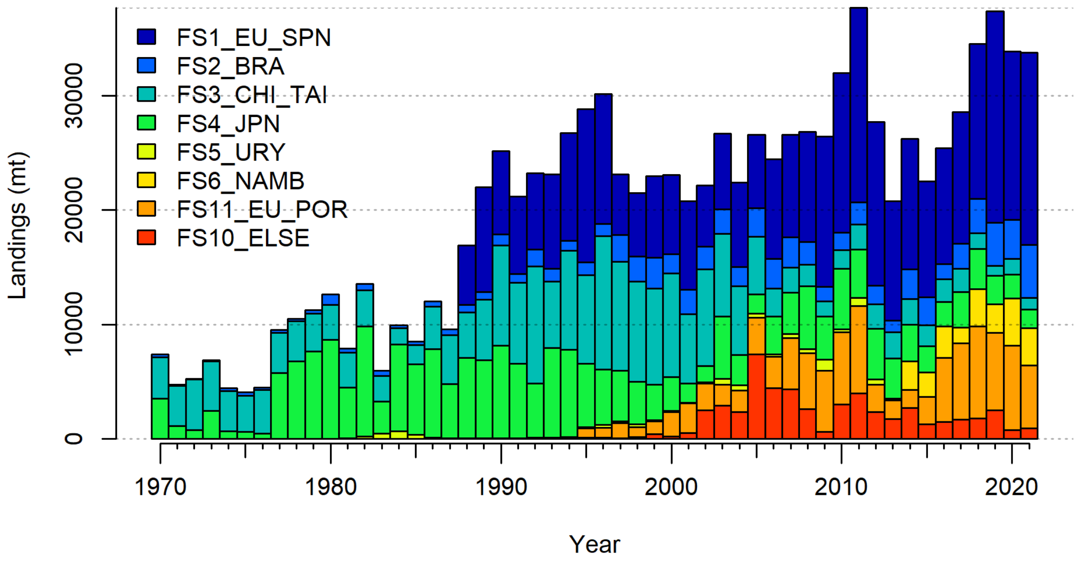

Figure 3. Task 1 landings input for the South Atlantic Blue Shark Stock Synthesis model.

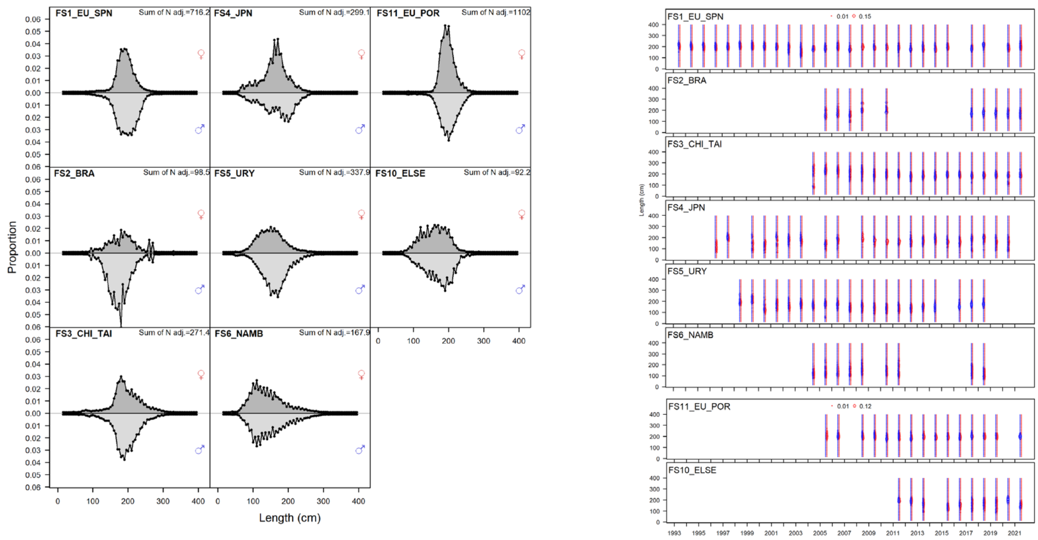

Figure 4. Size frequency input for the South Atlantic Blue Shark Stock Synthesis model for aggregated years (left panel) and by year (right panel).

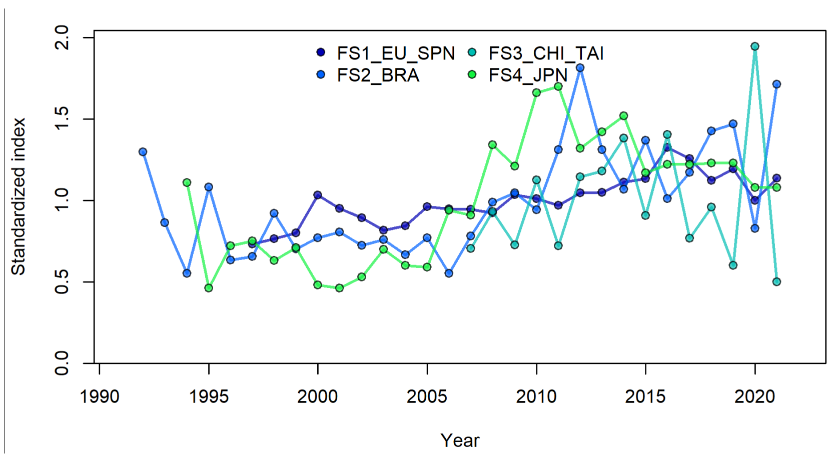

Figure 5. Index time series input for the South Atlantic Blue Shark Stock Synthesis model.

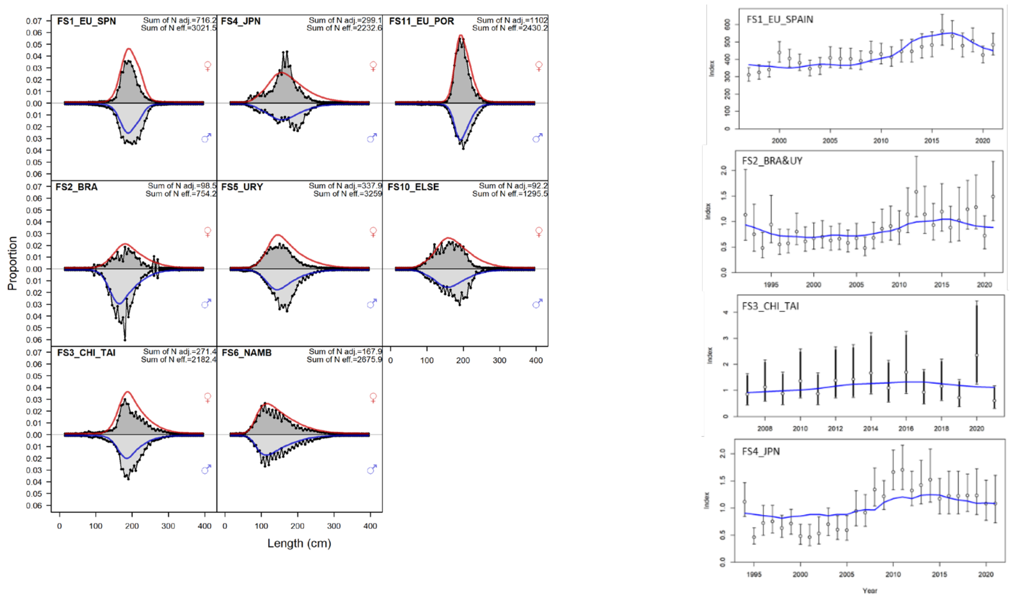

Figure 6. Preliminary base case model fits to the aggregated length compositions for each fleet (left panels) and for the index (blue lines, right panels) for the South Atlantic Blue Shark Stock Synthesis model.

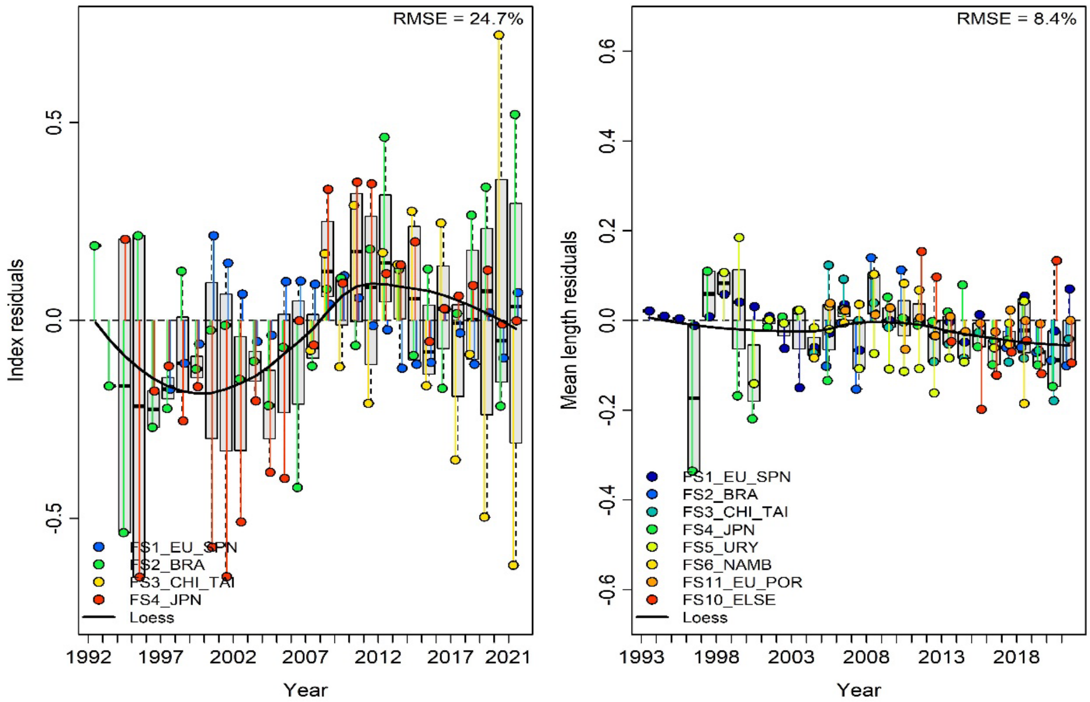

Figure 7. Joint residuals plot for the index and length composition fits for the South Atlantic Blue Shark Stock Synthesis preliminary base case model.

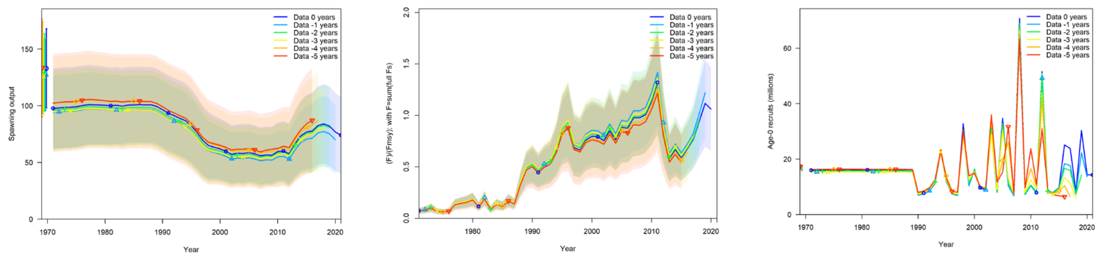

Figure 8. Retrospective plots of spawning output, F/F_{MSY} and age-0 recruitment for the South Atlantic Blue Shark Stock Synthesis preliminary base case model.

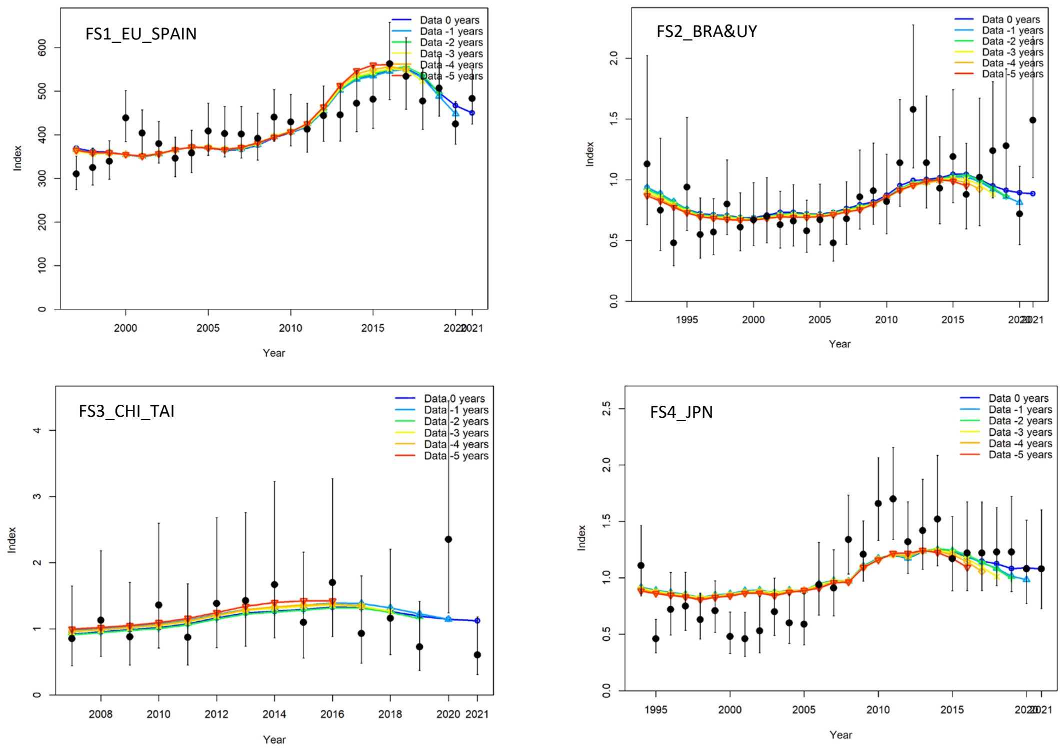

Figure 9. Retrospective plots of fits to the index for each fleet for the South Atlantic Blue Shark Stock Synthesis preliminary base case model.

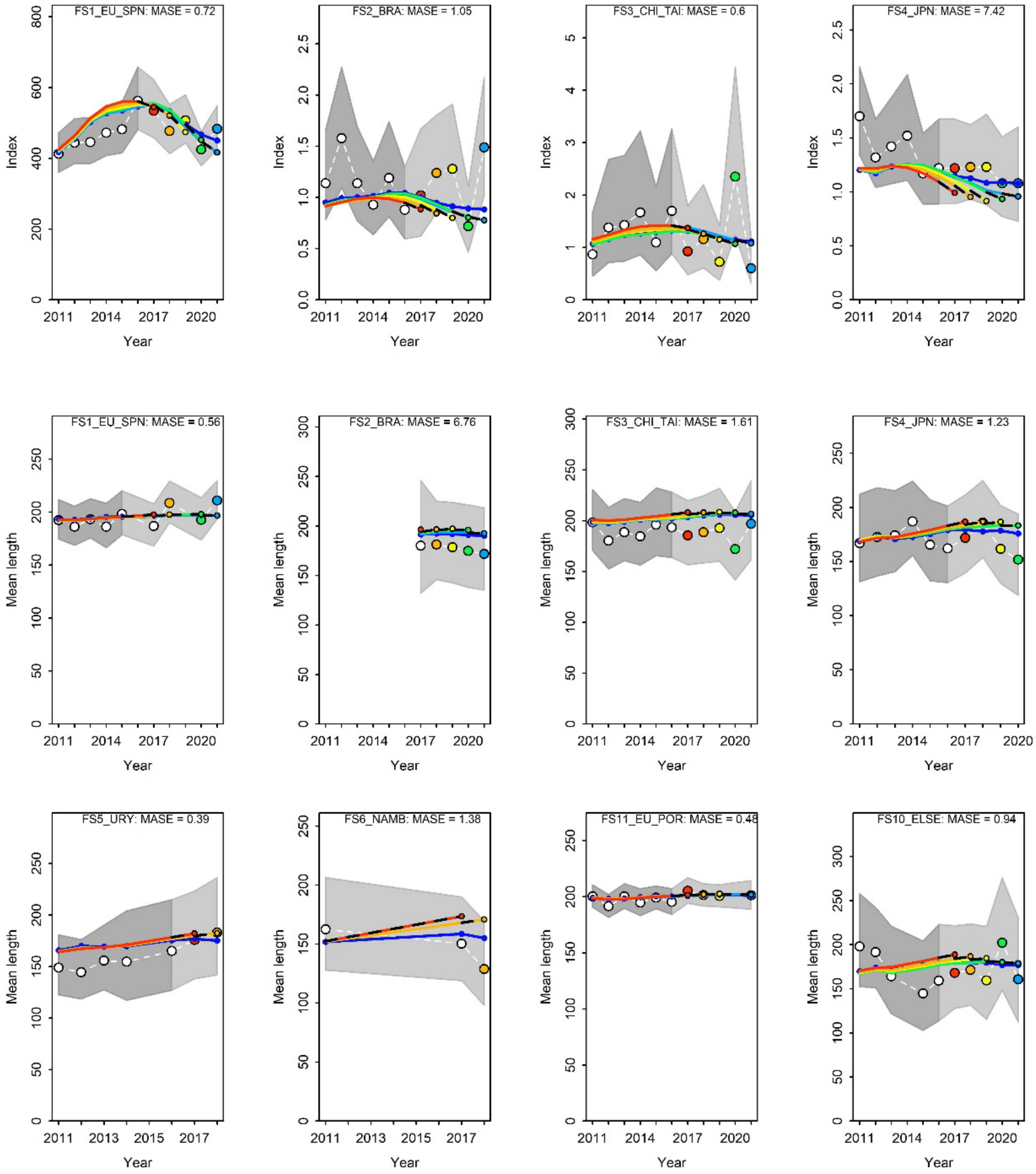

Figure 10. Hindcasting plots for the index (upper panels) and length composition (lower panels) fits for the South Atlantic Blue Shark Stock Synthesis preliminary base case model.

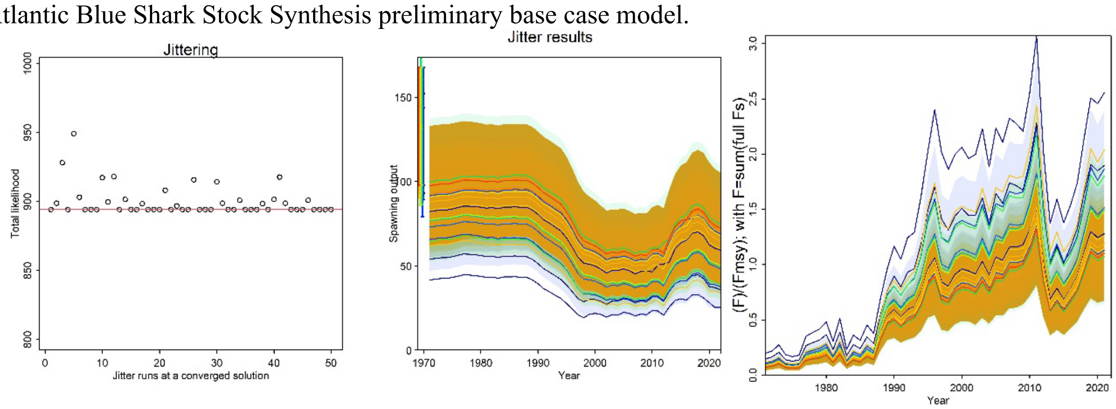

Figure 11. Jitter results for the South Atlantic Blue Shark Stock Synthesis preliminary base case model.

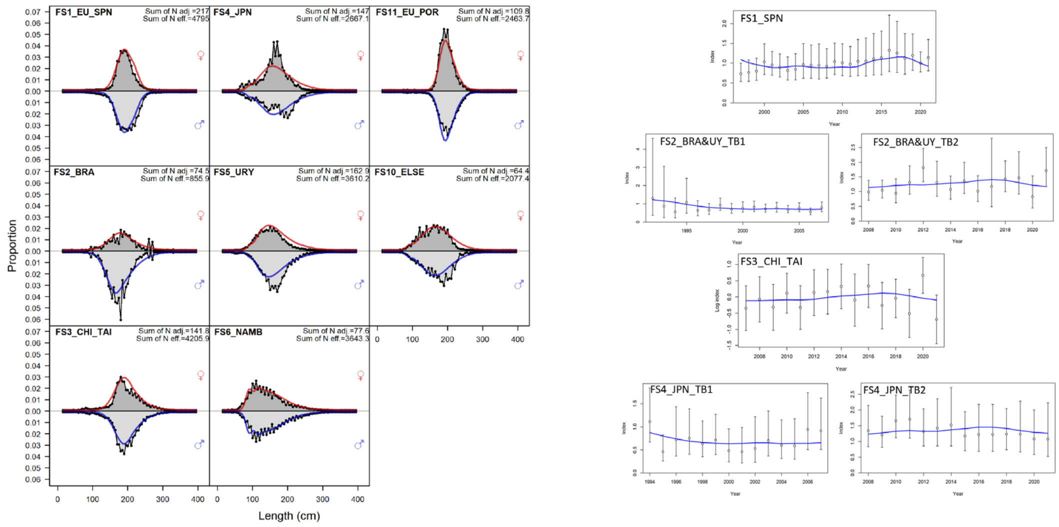

Figure 12. Final reference case model fits to the aggregated length compositions for each fleet (left panels) and for the index (blue lines, right panels) for the South Atlantic Blue Shark Stock Synthesis model.

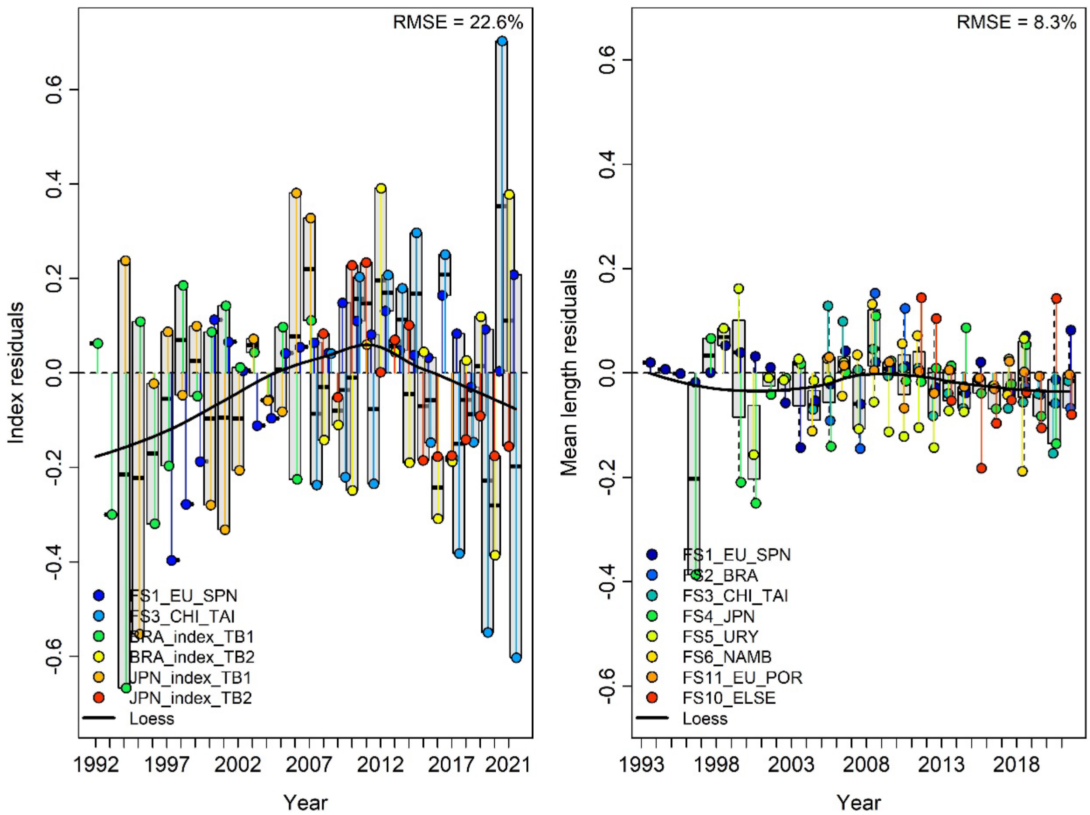

Figure 13. Joint residuals plot for the index and length composition fits for the South Atlantic Blue Shark Stock Synthesis final reference case model.

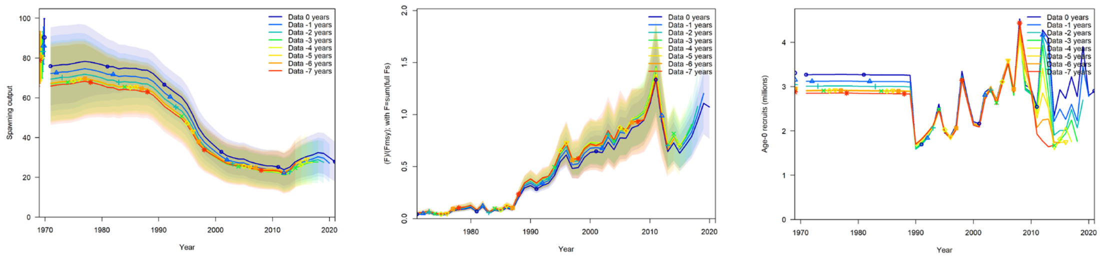

Figure 14. Retrospective plots of spawning output, F/F_{MSY} and age-0 recruitment for the South Atlantic Blue Shark Stock Synthesis final reference case model.

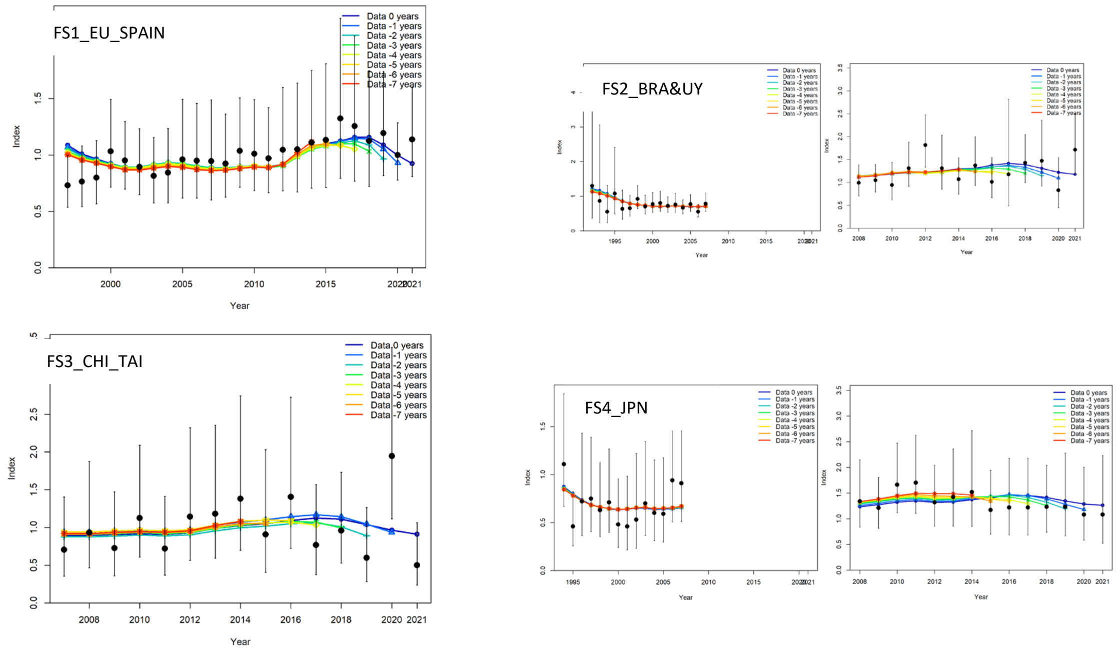

Figure 15. Retrospective plots of fits to the index for each fleet for the South Atlantic Blue Shark Stock Synthesis for the final reference model.

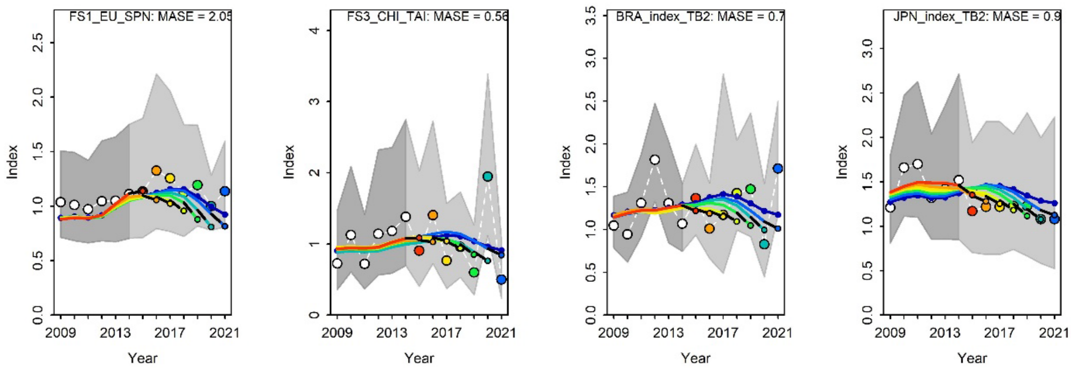

Figure 16. Hindcasting plots for the index fits for the South Atlantic Blue Shark Stock Synthesis final reference case model.

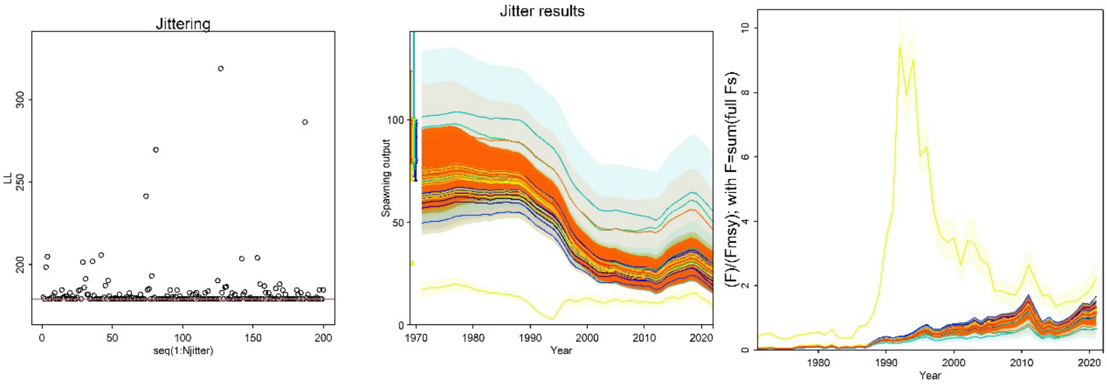

Figure 17. Jitter results for the South Atlantic Blue Shark Stock Synthesis final reference case model.

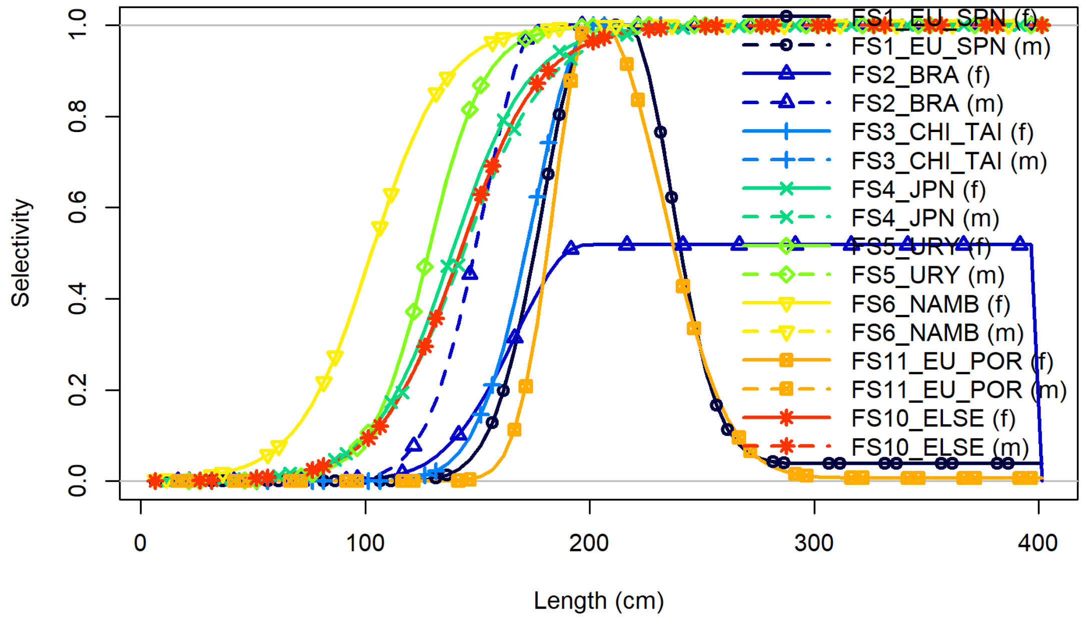

Figure 18. Selectivity at length shapes for the South Atlantic Blue Shark Stock Synthesis preliminary base case model.

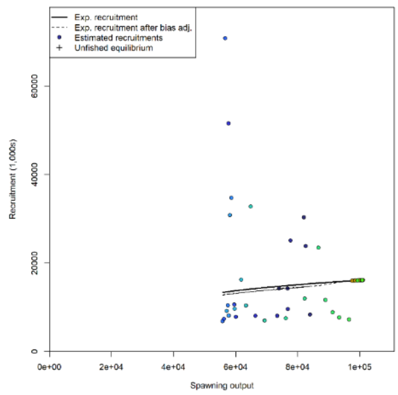

Figure 19. Stock-recruitment curve for the South Atlantic Blue Shark Stock Synthesis preliminary base case model. Point colors indicate year, with warmer colors indicating earlier years and cooler colors in showing later years.

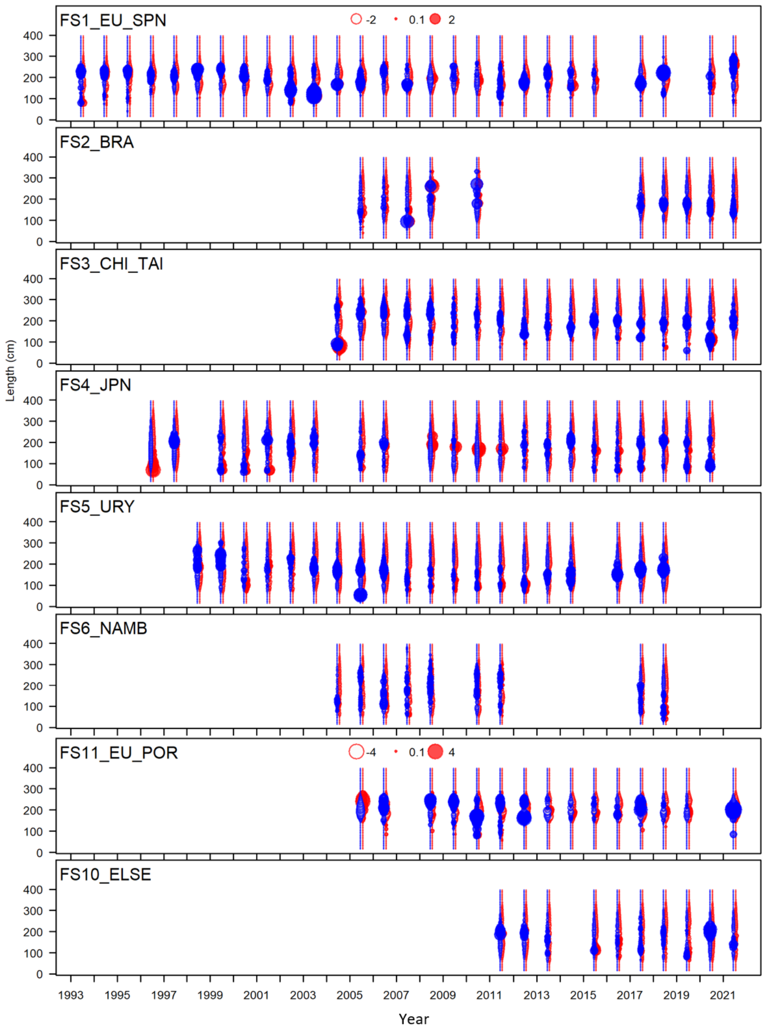

Figure 20. Pearson residuals to length composition fits for the preliminary base case model. Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected). Red=females, blue=males.

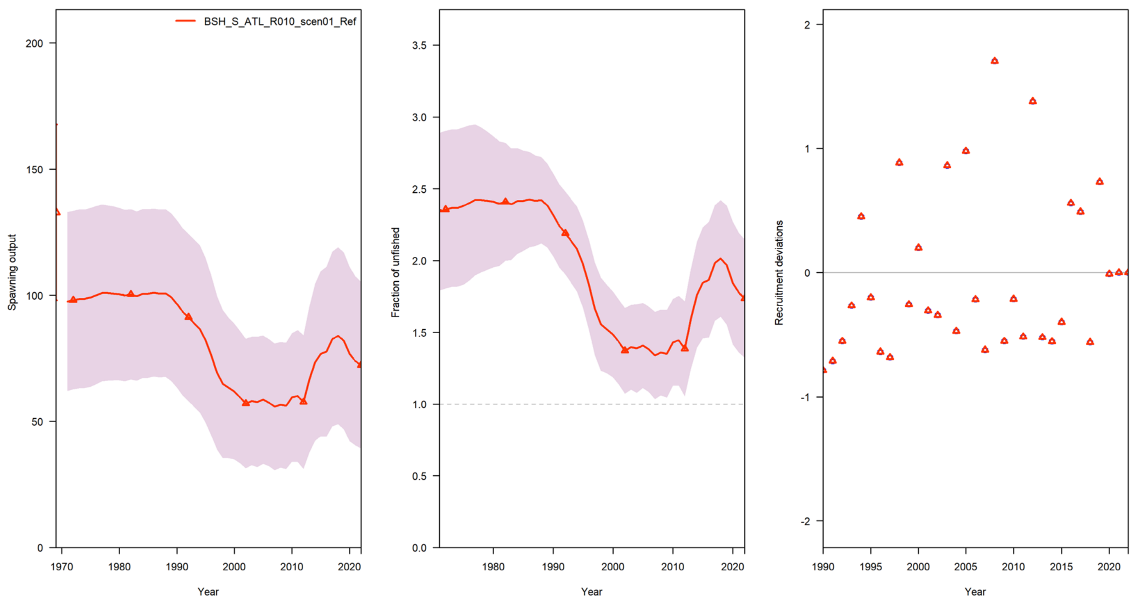

Figure 21. Spawning output relative, depletion in spawning output relative to MSY, and recruitment deviations (upper panel) time series for the South Atlantic Blue Shark Stock Synthesis preliminary base case model.

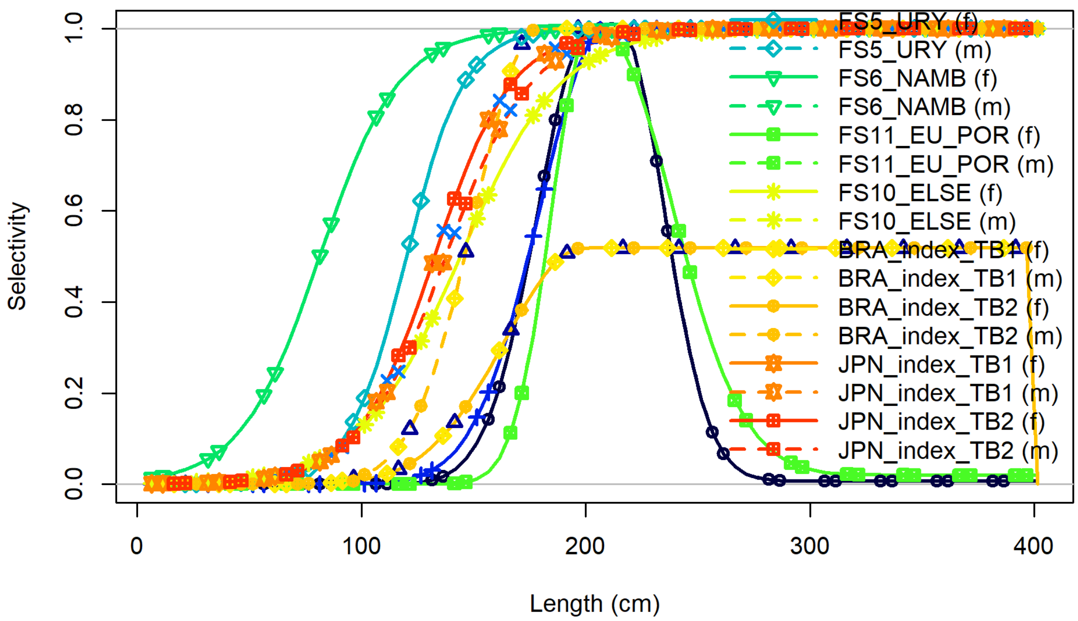

Figure 22. Selectivities at length shapes for the South Atlantic Blue Shark Stock Synthesis final reference case model.

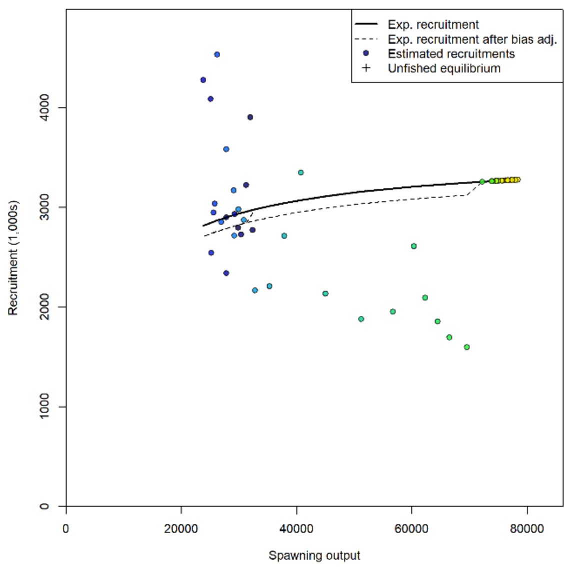

Figure 23. Stock-recruitment curve for the South Atlantic Blue Shark Stock Synthesis final reference case model. Point colors indicate year, with warmer colors indicating earlier years and cooler colors in showing later years.

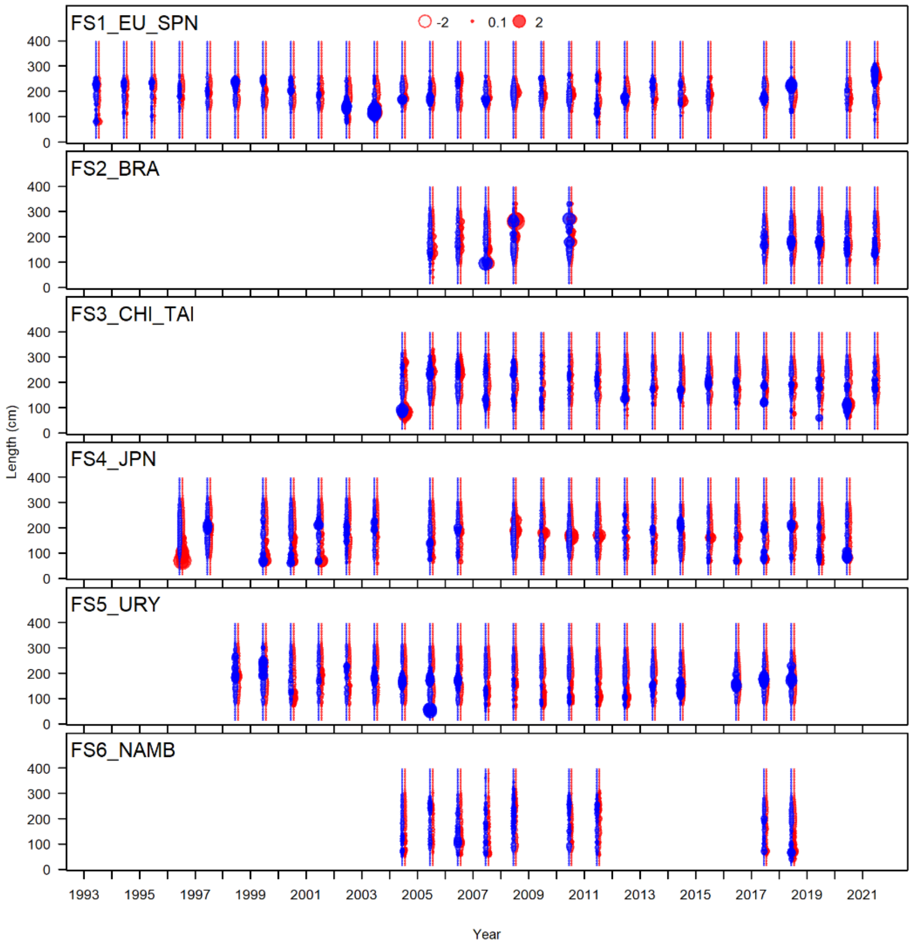

Figure 24. Pearson residuals to length composition fits for the final reference case model. Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected). Red=females, blue=males.

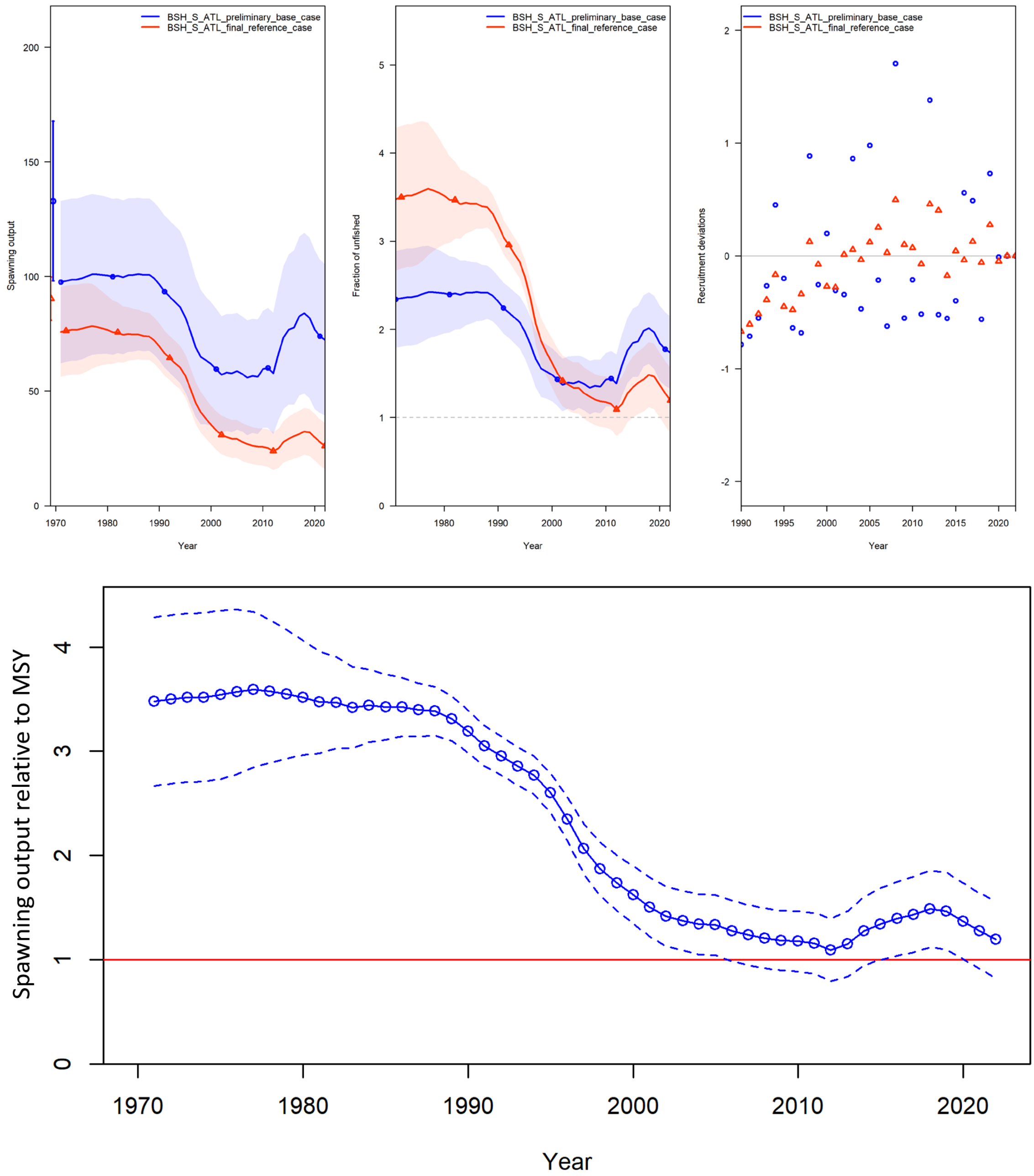

Figure 25. Spawning output, depletion in spawning output relative to MSY, recruitment deviations (upper panel) from the preliminary (blue circle) and final reference case models (red triangle) (upper panel) and the final spawning output relative to MSY (lower panel) time series for the South Atlantic Blue Shark Stock Synthesis final reference case model. Dashed lines indicate ~95% asymptotic confidence intervals.

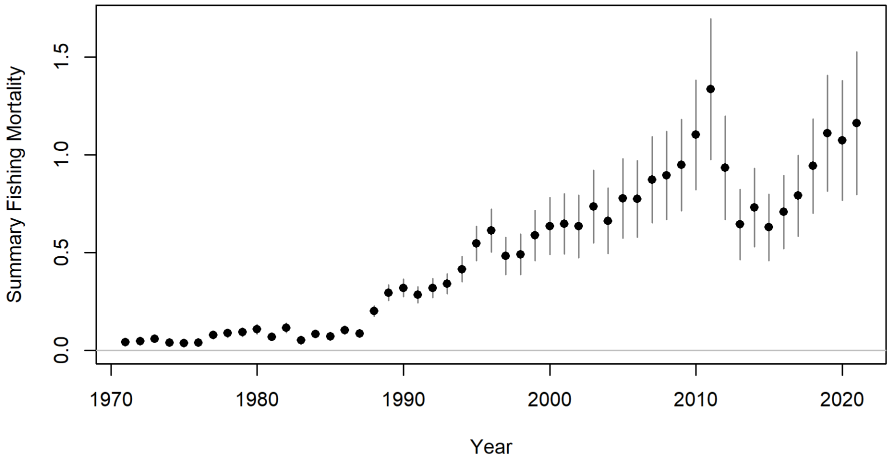

Figure 26. Stock Synthesis estimated time series of fishing mortality on South Atlantic blue shark final reference case. Vertical bars indicate ~ 95% asymptotic confidence intervals.

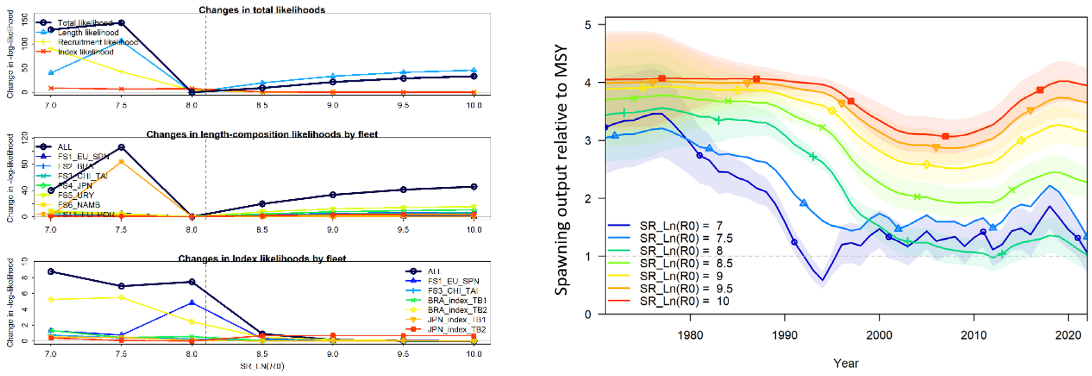

Figure 27. Likelihood profiles for R0 (left panels) and depletion in spawning output relative to MSY (right panel) for the South Atlantic Blue Shark Stock Synthesis final reference case model.