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PRELIMINARY STOCK SYNTHESIS ASSESSMENT MODEL FOR NORTHERN ATLANTIC ALBACORE

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SUMMARY

The North Atlantic Albacore Management Strategy Evaluation (MSE) provided scientific support for adopting an interim harvest control rule by ICCAT in 2017. Within the new MSE process started for this stock, one of the first tasks is to develop a new assessment model that can serve as a benchmark to monitor the status of the stock and as the basis for developing a new set of Operating Models. In this document, we show a preliminary configuration of Stock Synthesis based on the model developed using Multifan-CL in 2013 with some modifications based on the discussions and recommendations by the North Atlantic Albacore species group. The assessment model is annual, covers the period 1930-2021, and integrates nominal catch data, length composition data, abundance indices of eight fleets, and age composition data estimated from reading spines. This document shows an overview of the data and standard diagnostics to analyse the fits to index and length compositions, jitter of starting parameters, randomness tests of model residuals, retrospective profiles of key estimated parameters, and hindcasting.

RÉSUMÉ

L'Évaluation de la stratégie de gestion (MSE) pour le germon de l'Atlantique Nord a fourni le soutien scientifique pour l'adoption d'une règle de contrôle de l'exploitation provisoire par l'ICCAT en 2017. Dans le cadre du nouveau processus de MSE lancé pour ce stock, l'une des premières tâches consiste à développer un nouveau modèle d'évaluation pouvant servir de référence pour surveiller l'état du stock et servir de base pour élaborer un nouvel ensemble de modèles opérationnels. Dans ce document, nous présentons une configuration préliminaire de Stock Synthesis, fondée sur le modèle développé à l'aide de Multifan-CL en 2013, incluant certaines modifications basées sur les discussions et les recommandations du Groupe d'espèce sur le germon de l'Atlantique Nord. Le modèle d'évaluation est annuel, couvre la période 1930-2021 et intègre des données de capture nominale, des données de composition par taille, des indices d'abondance de huit flottilles ainsi que des données de composition par âge estimées d'après la lecture des épines. Ce document présente un aperçu des données et des diagnostics standards pour analyser les ajustements à l'indice et aux compositions par taille, la fluctuation (« jitter ») des paramètres de départ, les tests du caractère aléatoire des valeurs résiduelles du modèle, les profils rétrospectifs des principaux paramètres estimés et la simulation rétrospective.

RESUMEN

La evaluación de estrategias de ordenación (MSE) del atún blanco del Atlántico norte proporcionó apoyo científico para la adopción de una norma provisional de control de capturas por parte de ICCAT en 2017. Dentro del nuevo proceso de MSE iniciado para este stock, una de las primeras tareas es desarrollar un nuevo modelo de evaluación que pueda servir como referencia para supervisar el estado del stock y como base para desarrollar un nuevo conjunto de modelos operativos. En este documento, mostramos una configuración preliminar de Stock Synthesis basada en el modelo desarrollado utilizando Multifan-CL en 2013 con algunas modificaciones basadas en las discusiones y recomendaciones del grupo de especies de atún blanco del Atlántico norte. El modelo de evaluación es anual, abarca el periodo 1930-2021 e integra datos de capturas nominales, datos de composición por tallas, índices de abundancia de ocho flotas y datos de composición por edades estimados a partir de la lectura de espinas. Este documento muestra una visión general de los datos y los diagnósticos estándar para analizar los ajustes los índices y composiciones por tallas, la fluctuación de los parámetros de partida, las pruebas de aleatoriedad de los residuos del modelo, los perfiles retrospectivos de los parámetros clave estimados y la simulación retrospectiva.

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KEYWORDS

North Atlantic albacore, Management Strategy Evaluation, Operating Model, stock assessment, stock synthesis, diagnostics.

1. Introduction

The Commission adopted Recommendation 21-04 para 18 (Anon., 2021a) and supported the continuation of the development of a new MSE framework by the SCRS to support the possible adoption of a new MP by the Commission no later than 2026 and the setting of a TAC for the management period 2027-2030. In 2020, the albacore group recommended that a new benchmark should be developed using Stock Synthesis, and that this configuration could also be used to build a new set of Operating Models (OM) for the North Atlantic albacore MSE (ICCAT 2020).

This document presents a preliminary model for a stock assessment of North Atlantic albacore (*Thunnus alalunga*), including fleet data available in 2023. The assessment model consists of an age-structured population model using Stock Synthesis (Methot Jr and Wetzel 2013). In 2013, another age-structure model was configured as a benchmark assessment for this stock, Multifan-CL (Kleiber, Hampton *et al.* 2012; Merino, De Bruyn *et al.* 2013). The Stock Synthesis model presented in this document has a similar structure as the runs done in 2013, and the assumptions are comparable to the Multifan-CL base run. However, there are some differences with the previous models based on discussions in the albacore working groups since 2021 and in the data preparatory meeting conducted in 2023 and intersessional meetings with the modelling subgroup.

The present document explains the preliminary Stock Synthesis model development for North Atlantic albacore.

2. Data and method

2.1 Definition of fleets

The current version of Stock Synthesis adopted equivalent fleet definitions used in the 2013 Multifan-CL model with modifications discussed in the albacore working group in 2020 and 2021. These fleets represent relatively homogeneous fishing units with similar selectivity and catchability characteristics that do not vary over time. Fifteen fleets were defined in the model, fourteen fleets based on location, time period, fishing gear, and country (**Table 1**) (SCRS/2022/065), and an additional fleet was added during the data preparatory meeting in 2023 by dividing baitboat islands fishing in season 2 and others in two different fleets. Length composition data indicated differences between seasons within baitboat island fleet, fishing smaller fish in season 2 than in the other seasons. Another important change relative to the 2013 model consists of the disaggregation of Chinese Taipei, Japanese and US longline fleet in North and South components, each one with its own selectivity.

2.2 Catch history

Catch data has been compiled based on the fleets definitions (**Figure 1**). Catch data start in 1930 with 12, 183 t from troll and in gillnets and start to increase around 1950s with the longline and baitboat fleet development reaching the peak in 1971 with a total catch of 56,820 tons. Since then, the catches start to decrease until 2009 with 15, 390 t. Since then, catches start to increase until 31,387 t in 2021.

The main fleet and gears that represent 96% of the catch are shown in **Figure 2**. The model is configured assuming that catch information is accurate (CV=0.01) and that the catches at the initial period were in equilibrium with 10 000 t catch by troll and gillnet fleet, similar to the observed catches of troll and gillnet in 1930 of around 12 000 t.

2.3 CPUE indices

Since 2016 the assessments of North Atlantic albacore were built using standardized CPUE data from the US, Japan, Chinese Taipei and Venezuelan longlines and Spanish baitboat. The CPUE estimates were done separately for the longline fishing in the north and south of 30ºN (**Table 1**). The CVs between the different CPUES are very different; for baitboat and Venezuelan longline CPUE is very large, while for the rest of longlines is very small and this could difficult the convergency of the model. Therefore, all the CPUEs were normalized with a CV of 0.2 to give the same weight to all the indices but considering the inter-annual variability of the uncertainty of each of the CPUE. All the indices show an overall increasing trend (**Figure 3**).

Some standardized CPUE values were not considered in the model for consistency with decisions taken in previous assessments (ICCAT 2020):

- The 2010 estimated CPUE value of Japanese longline operating north of 30ºN was not considered due to the change in the target species.
- The 2013 value from the fleet operating in the south of 30ºnorth because it was a very extreme value and the group decided it was biologically implausible.
- The Venezuelan LL CPUE data for 2018 were excluded due to low spatial and temporal sampling coverage in that year

2.4 Length frequency data

Available length-frequency data for each of the defined fleets were provided by the Secretariat after all CPC data updates were completed following the data preparatory meeting. The length composition was defined with a 2 cm bin size class from 26 to 158. However, the last 15 bin size classes were aggregated due to the few data of the largest fish available. In the case of baitboat, troll, and gillnet, the last 20 bins were aggregated.

The length composition was annual and compiled into 2-cm size classes as a weighted average with data by quarter and considering the number of samples per quarter. The month of the length frequency data was also calculated similarly. Due to the no availability of the number of independent samples, the number of samples was estimated as the logarithm of the total number of fish by year-quarter and fleet.

2.5 Age composition data

Two different sources of ageing data from reading spine sections were considered in the model: one collected in 1990 described by Santiago and Arrizabalaga (2005) and the other from 2008 to 2012 described by Ortiz de Zarate and Babcock (2015 , although only data from 2011-2012 were described in the study, similar procedure was followed for the data of the other years. The fish were sampled from baitboat and troll and gillnets although due to the lack of information, the data were assumed to be collected by baitboat, the fleet with the largest catch. The age distribution was introduced by bin size class of 2 cm. The number of samples were defined as the logarithm of the sum of the observations plus 1 to avoid 0 values, similar to the length composition data. These data were only considered in the likelihood if the number of observations were more than 3.

The ageing error matrix considered for all the data was the same. The standard deviation by age was estimated from 2 readers from data from 2011. The mean age was estimated assuming that the fish were born in June and that they were caught in season 3, the main fleet season (**Table 3**).

3. Model assumptions

3.1 Model temporal and spatial resolution

A single area model (also referred as reference case in the document) was developed for North Atlantic albacore including Atlantic waters north of Lat 5ºN but following the "fleets-as-areas" approach. The model was annual with four sub-seasons, and the period covered by the model is 1930-2021, representing the period for which catch data were available. Previous runs of Stock Synthesis were seasonal, with quarters defined as seasons. However, the model had difficulties fitting the length distribution of the fleet with the highest catches, fishing small and medium size fish, due to the observed differences in the length composition between seasons. These differences could be explained by differences in availability that could be related to the migratory behaviour of the species. These differences were complicated to model in a single area model and therefore, an annual resolution was considered a better approach with the actual knowledge and data available in 2023.

3.2 Biology

The model assumed a population comprised of 15 age classes. Some biological parameters were based on the values agreed upon by the albacore working group (ICCAT 2016):

- *Spawning* was set at the beginning of month 6.
- *Growth*: Fish grow following the Von Bertalanffy function. The growth rate *K* and the maximum mean size L_∞ were estimated within the model. The standard deviations for young and old fish were also estimated within the model.
- *Length weight* relationship parameters a=1.339x10^{-5} and b=3.1066, taken from (Santiago 1993). Both parameters were fixed.
- *Maturity*: Albacore was assumed to reach 50% maturity at age 5 (90 cm) (Bard 1981) and 100% at age 6.
- *Natural mortality* at age was estimated within the model following the Lorenzen curved, assuming natural mortality at age 6 of 0.36 based on the assumption of a maximum age of 15 and following the Hamel and Cope (2022) approach (SCRS/2023/032).
- *Stock recruitment* relationship was modelled by following a Beverton-Holt function with steepness estimated within the model, giving a prior of 0.75 with normal distribution sd=0.15, equivalent to the relationship assumed in the 2013 Multifan-CL reference case (Merino, De Bruyn *et al*. 2013).
- *Recruitment deviates* were estimated from 1972 to 2020 with a SigmaR of 0.4 based on FishLife package (Thorson *et al*. 2023) estimates for the species. In 1972 the length composition data from fleet fishing the smallest fish is available. The model assumes that recruitment deviates equal to 0 for 2021 because the model did not have information to estimate recruitment that year with indices and fleets fishing fish older than one year.
    - The advanced bias option for recruitment is parameterized following the advice from SS3, and assuming early recruitment deviates starting in the 60s. Japan longline North data started in 1964, and taking into account that the fleet catch 4-year-old fish, then is assumed that these data could inform estimations of early recruitment deviates starting in 1960.

3.3 Fleet Selectivity

US longline south and Venezuelan longline fleet, with catches of the largest fish, were assumed to follow a logistic selectivity. The selectivity of baitboat and midwater trawlers, due to the complex shape of the length distribution, were estimated with splines with 4 and 3 knots, respectively. Double-normal selectivity was assumed for the rest of the longlines, troll and gillnets, and baitboat island fleet. Other longlines, other surface fleet and the mixed Korea, Panama, and China were mirrored to the US longline South selectivity. The choice was made for simplicity, considering the homogeneous size distribution with time of the fleet.

Three time blocks were assumed for Japanese and Chinese Taipei longline North and South, as mentioned in SCRS/2022/065 (**Table 1**). The first block was assumed as offset as recommended by the SS3 manual. For midwater and troll and gillnet fleet, a random walk was assumed due to the differences in the length frequency distribution, which could be related to differences in the availability of fish between years.

3.4 Data re-weighting

The data are not re-weighted.

3.5 Model diagnostics

Standard model diagnostics included jitters of starting parameters, fits to data sources and model residuals, retrospective analyses, profiling of key estimated parameters (R0), data source residual run tests, hindcasting of abundance indices, and ASPM analysis. Analyses were conducted using SS built-in diagnostics and the ss3diags R package (Carvalho *et al.* 2021).

3.6 Parameter estimation and uncertainty.

The estimated parameters included four growth parameters (Length-at-age 0.5, *K*, L_∞, *sd young*, *sd old*), steepness, R0, initial F, 60 selectivity parameters, and annual recruitment deviations. Model parameter standard deviations were derived from the variance-covariance matrix.

3.7 Sensitivity analysis

Re-weighting of the length composition data with the Dirichlet method.

Re-weighting of the length composition data with the Francis method.

Considering data until 2011 as in the assessment of Northern Atlantic Albacore in 2013.

Considering the natural mortality at age estimated from Lorenzen (1996) equation but assuming natural mortality of 0.415 at age 6 (SCRS/2023/032)

Considering size-dependent mortality at age following the Chen and Watanabe (1989) equation

4. Results

4.1 Growth

The model estimated K=0.19 y^{-1} and $L\infty$= 125.8 cm (**Table 4**). These estimates were similar to growth parameters estimated in other studies (Santiago and Arrizabalaga (2005), Ortiz de Zarate and Babcock (2015)). The estimated standard deviation in growth for young was 3.32 and for old fish 5.57, very narrow values but similar to those estimated by Santiago and Arrizabalaga (4.7 cm, **Figure 4**).

4.2 Fleet selectivity

Fleet selectivity patterns were estimated based on length data. Splines functions for baitboat and mid-water trawlers, logistic shape for Venezuelan and US South longlines and the rest with double-normal shape (**Figure 5**). Baitboat island was split into two fleets due to the differences in selectivity in season 2 and the rest of the seasons (**Figure 5**). Random walks were used to improve the fits of the fleet fishing the small and medium size of fish (**Figure 6**). These fleets showed some differences in the fishing pattern with time, probably related to the differences in availability and migration pattern between years (**Figure 7**). In the case of Japanese and Chinese Taipei, time blocks were used to fit the differences in selectivity in the 3 periods mentioned previously (**Figure 8**).

4.3 Fishing mortality

The model assumed an equilibrium state of 10 000 t fished by troll and gillnets at the beginning of the time series, and thus, the model estimated an initial F of 0.05 (**Table 4**). Fishing mortality (reported as exploitation rate in biomass) estimated in the reference case showed an increase of F with time until 1986 to values of 0.21. Since then, it decreased until 2010, when it became quite stable (**Figure 8**).

4.4 Recruitment

The reference case estimated a steepness (h) value of 0.67 of the Beverton-Holt curve, SD of 0.067 (**Table 4**) and an average level of age-0 recruitment at un-fished equilibrium spawning biomass (R0) of 11.49 (natural log scale), equivalent to approximately 91.1 million age-0 fish.

Main recruitment deviations were estimated since 1972 and the early recruitment deviates from 1960 (**Figure 9**). The estimated deviations around 2000 were negative, with deviations lower than -0.5 in 1999. Instead, the estimated deviations since 2015 were positive and values higher than 0.5 in 2016 and 2017. Nevertheless, the confidence intervals since 2017 were very high, with a 0 value within the interval.

4.5 Stock biomass

The virgin biomass estimated in the model was higher than the biomass at the beginning of the time series due to the assumption of an equilibrium catch of 10 000 t. Overall, the model showed a decrease in biomass until 1965 and an increasing trend since then. It was difficult to compare the results of the reference case with the assessment model developed in 2013 with Multifan-CL (the model used to condition the operating models of the MSE). Some of the assumptions between both models were very different. In the model of 2013, the fleet considered in the model and fleets selectivity was different, the mortality-at-age was assumed to be 0.3 constant, the age composition data were not considered, growth was not estimated within the model and the indices were not normalized with a CV of 0.2. However, the reference case with the model only with data until 2011 was compared. When only data until 2011 is considered, the estimated steepness was 0.83, the same estimated value in the Multifan-CL model in 2013 (**Figure 10**).

5. Model diagnostics

Convergence

The reference case converged to a stable solution at the minimum negative log-likelihood and can estimate the matrix with the inverse of the Hessian (i.e., estimates of covariance across parameters were obtained). The reference case converged with a gradient of 0.000847942, close to the target of 0.0001 (lower is better), so the model had an acceptable convergence. However, the jitter analysis showed some instability in the model; depending on the starting values, the model did not converge to the global minimum (**Figure 11**).

Growth

Profiling of the L_∞ and K parameter showed that the model follows the age composition data but with some conflicts in estimating this parameter between length composition and age composition data (**Figure 12**). The mean age composition data were between 2 and 4 years (**Figure 13**), so the estimated growth parameters could be biased to fit the growth of the youngest fish. However, the model fits to length-at-age data were within the confidence interval until age 9 (**Figure 14**), but not in 1990, here the model underestimated the size at age for the fish older than 6 years. However, in 1990 the fits of the standard deviation of length at age were better than in comparison to other years data.

Stock recruitment

Likelihood profiles for unfished recruitment (**Figure 15**) (assuming steepness fixed at the estimated steepness in the reference case $h=0.67$, **Table 4**) (the estimated value by the base case) showed that R0 with the minimum likelihood were quite similar for all the components. However, for the steepness profile, the indices showed a minimum at larger steepness value (around 0.85) compared to the other components or total likelihood.

The standard deviation of recruitment deviates, *sigmaR*, was fixed in the reference case with a value of 0.4 following the FishLife package (Thorson *et al.* 2023). Profiling of *sigmaR* showed that recruitment had a lower likelihood at low levels of *sigmaR* while the length composition had higher.

A comparison of an age-structured production model ASPM and the reference case was performed to evaluate the influence of the recruitment deviations in the trends. The ASPM model only estimated the *ln(R0)* parameter by fixing the rest of the parameters at the estimated value in the reference case and without considering any deviation in recruitment. The results showed that the increase rate of SSB after 1980 is higher in the ASPM model due to the lack of recruitment deviates (**Figure 16**).

Analysis of the residual patterns of the indices and length composition data

Runs test analysis from *ss3diags* package in R was performed to analyze the randomness of the residual patterns of the indices (**Figure 17**). The results suggested that the model could fit 4 of 8 indices considered in the model: Japanese longline and Chinese Taipei longline North and South CPUEs.

Overall, the reference model demonstrated an acceptable fit to the aggregated length composition data of all fleets (**Figure 18**). However, the model failed the run test of baitboat, troll and gillnets, Chinese Taipei longline North and South and US longline North (**Figure 19**) length composition data.

Hindcasting of the indices

The hindcasting cross-validation technique is used to evaluate if the model can predict the index or not. A MASE score >1 indicates that the average model forecasts are worse than a random walk (Carvalho *et al.* 2021). The results showed that the reference case could predict Chinese Taipei longline North and US longline North indices. But baitboat and USLL_N had very close values to 1, 1.02 (**Figure 20**). The Venezuelan longline index only had data until 2017, so it was not possible to evaluate the prediction skills of this index by only pealing the last five years.

Retrospective pattern

The retrospective pattern of SSB and F showed some consistency with estimates of Mohn's rho values within the acceptable range for long-live species (-0.15, 0.2) (**Figure 21**). However, in the case of recruitment, Mohn's rho values were not within that interval, and the confidence interval of the last years was quite large.

6. Sensitivity analysis

When the Dirichlet method (Thorson *et al*. 2017) was analysed as a sensitivity analysis in the model to re-weight the length and age composition data, the model did not have good convergence.

Francis (2011) method was also analysed by re-weighting the length composition data with lambda values estimated after multiplying the suggested values in 2 iterations and assuming a maximum lambda value of 2 (**Table 5**). Troll and gillnets and mid water trollers were up-weighted and some of the longlines length composition data, while all the other length composition data were down-weighted. Age composition was also downweighted by 0.09. Therefore, the estimated $L\infty$= 115.7and K=0.23 changed compared to the reference case driven by the length composition of the longline fleet. The estimated steepness increased to h=0.7. The initial SSB values were within the confidence interval of the reference case until 1980, when the SSB started to increase at higher rates than in the reference case with a higher final SSB value. The SSB final values were very similar to the initial SSB value.

Assuming natural mortality values higher than in the reference case, with an M-at-age 6 of 0.415 (estimated assuming maximum age of 13) instead of 0.36 (assuming maximum age of 15), the estimated steepness was lower and R0 higher. However, the biomass trends were similar, and the biomass at the end of the time series the same. In the case of assuming an M-at-age vector estimated from Chen and Watanabe (1989) equation based on length, with a lower M than in the reference case, then the estimated steepness was h=0.74 and *ln(R0)* lower with a value of 10.64. However, the natural mortality at age estimated from Chen and Watanabe (1989) assumed growth parameters estimated by Santiago and Arrizabalaga (2005) and the values estimated in this model were slightly different ($L\infty$=122 and K=0.2 y^{-1}).

In the data preparatory meeting, it was agreed to use the Japanese longline North index only from 1988 due to possible issues in the standardization of the CPUE from 1975 to 1987 caused by differences in target species. However, it was also suggested to do a sensitivity analysis also considering that period. In this case, the steepness was the same value as in the reference case 0.67, and R0 very similar but a bit lower 11.4. So, due to the similarities in the estimated parameters, the initial values were very similar until 1980 where the increase rate of SSB is much lower than in the reference case (**Figure 22**). The differences were explained by the differences in trends of the estimated recruitment deviates (**Figure 22**).

7. Discussion

The time resolution of the model was annual, and a single area was considered as spatial distribution so the seasonal differences in the length distribution of some fleet as baitboat, troll gillnets, baitboat islands and mid-water trawlers were very difficult to fit for the model. So due to the lack of knowledge in migration and, therefore, the difficulty of modeling a spatially disaggregated model, it was decided better to use a single area model with annual resolution.

The model showed conflicts between age composition, length composition and indices to estimate growth and steepness. Age composition data, which was mainly based on fish aged between 2 and 4, converged at higher $L\infty$ values than length composition data. In terms of steepness, indices also showed different trends in the profiling likelihood to the length composition data. The reference case follows the length composition, age composition and recruitment, estimating a steepness value of 0.67, while the indices showed a minimum likelihood at higher steepness values of around 0.85. Even when the Japanese longline North index is considered since 1975 the model estimated a very similar steepness value but with differences in the trends of recruitment deviates.

The model estimated a different steepness value when the assumption of natural mortality changed. However, the estimated steepness values were between 0.67 and 0.74, relatively low values in comparison to what is considered in other tropical tuna species assessment models, which usually are considered between 0.7 and 1 and compared to the value estimated in the previous North Atlantic Albacore benchmark assessment using Multifan-CL in 2013 (estimated value of 0.83). The estimated steepness, based on FishLife package (Thorson *et al*. 2023), suggests that steepness could be between 0.4 and 0.95, depending on the growth rate. In this case, the estimated growth rate by the reference case was around 0.2; therefore, the steepness value would be around 0.6 and 0.8 (**Figure 23**).

This document presents a preliminary stock synthesis model for Atlantic Northern Albacore (*Thunnus alalunga*) that will be discussed in the next Atlantic Albacore Stock Assessment meeting (Madrid, 26-29th June 2023).

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Table 1. Definition of fleets for North Atlantic albacore Stock Synthesis model configuration.

FL	Fishery ID	Description	Time	Gear	Catch (FlagName* or FleetCode*)	Size (FleetCode*)
1	1 BB	Baitboat (Spain, France)	1953-2021	BB	EU.ESP-ES-CANT_ALB, EU.FRA-FR	EU.ESP-ES-CANT_ALB, EU.FRA-FR
2	2 BB isl	Baitboat islands (Portugal Madeira/Azores, Spain Canary)	1958-2021 Quarters 1,3,4	BB	EU.PRT-PT-AZORES, EU.PRT-PT-MADEIRA, EU.ESP-ES-CANARY, EU.ESP-ES-CANT_ALBaz, EU.ESP-ES-CANT_ALBcd	EU.PRT-PT-AZORES, EU.PRT-PT-MADEIRA, EU.ESP-ES-CANARY
3	3 TR+GN	Troll (Spain, France) + Gillnets (France, Ireland)	1930-2021	TR+GN	TR: EU.ESP-ES-CANT_ALB, EU.FRA-FR, EU.IRL. GN: EU.FRA-FR, EU.IRL, GBR	TR: EU.ESP-ES-CANT_ALB, EU.FRA GN: EU.IRL
4	4 MWT	Mid water trawl (France, Ireland)	1987-2021	TW	EU.FRA-FR, EU.IRL, GBR	EU.FRA, EU.IRL
5	5 JP LL T N	Japan LL target north30	1961-1969			
5	5 JP LL t N	Japan LL transition north30	1970-1975	LL	Japan (North of 30N)	JPN (North of 30N)
5	5 JP LL b N	Japan LL late north30	1976-2021			
6	6 JP LL T S	Japan LL target south30	1956-1969			
6	6 JP LL t S	Japan LL transition south30	1970-1975	LL	Japan (South of 30N)	JPN (South of 30N)
6	6 JP LL b S	Japan LL late south30	1976-2021			
7	7 TWLL e N	Taiwan LL early north30	1968-1986			
7	7 TWLL t N	Taiwan LL transition north30	1987-1998	LL	Chinese Taipei (North of 30N)	CTP (North of 30N)
7	7 TWLL 1 N	Taiwan LL late north30	1999-2021			
8	8 TWLL e S	Taiwan LL early south30	1962-1986			
8	8 TWLL t S	Taiwan LL transition south30	1987-1998	LL	Chinese Taipei (South of 30N)	CTP (South of 30N)
8	8 TWLL 1 S	Taiwan LL late south30	1999-2021			
9	9 US CAN LL N	US and Canada LL north30	1981-2021	LL	USA and Canada (North of 30N)	USA-US-Com, USA, Canada (North of 30N)
10	10 US LL S	US LL south30	1981-2021	LL	USA (South of 30N)	USA-US-Com, USA (South of 30N)
11	11 Ven LL	Venezuela LL	1960-2021	LL	Venezuela	VEN
12	12 MIX KR+PA	Mixed flags (KR+PA+CHN) LL	1964-2021	LL	Mixed flags (KR+PA), China PR, Korea Rep., Panama	Not included
13	13 Oth LL	Other LL	1965-2021	LL	all others	Not included
14	14 Oth Surf	Other surface	1978-2021		all others	Not included
15	15 BB isl Qt2	Baitboat islands (Portugal Madeira/Azores, Spain Canary)	1965-2021 Quarter 2	BB	EU.PRT-PT-AZORES, EU.PRT-PT-MADEIRA, EU.ESP-ES-CANARY, EU.ESP-ES-CANT_ALBaz, EU.ESP-ES-CANT_ALBcd	EU.PRT-PT-AZORES, EU.PRT-PT-MADEIRA, EU.ESP-ES-CANARY

Table 2. Abundance indices used in this stock assessment.

Index	First year	Final year	Reference
Spanish baitboat	1981	2021	SCRS/P/2023/012
Japan bycatch longline- North	1988	2009	SCRS/2023/029
Japan bycatch longline - South	1988	2021	SCRS/2023/029
Chinese Taipei longline late – North	1999	2021	SCRS/2023/035
Chinese Taipei longline late – South	1999	2021	SCRS/2023/035
US longline – North	1987	2021	SCRS/2023/036
US longline – South	1987	2021	SCRS/2023/036
Venezuelan longline	1991	2017	SCRS/2020/089

Table 3. Ageing error matrix for the data from 2008 to 2012.For each age bin is defined the mean age and standard deviation (SD).

Bin age	age0	age1	age2	age3	age4	age5	age6	age7	age8	age9	age10	age11	age12
Age mean	0.25	1.25	2.25	3.25	4.25	5.25	6.25	7.25	8.25	9.25	10.25	11.25	12.25
SD	0.1	0.5	0.43	0.32	0.76	0.38	0.5	0.79	1.41	0.96	0.96	0.96	0.96

Table 4. The estimated parameter by the base case.

Parameter	*Value*	*Phase*	*Min*	*Max*	*Init*	*Status*	*Parm_StDev*	*Gradient*	*Pr_type*	*Prior*
L_at_Amin_Fem_GP_1	41.9949	2	1.00E+01	60	41.7956	OK	0.535283	0.000247694	No_prior	NA
L_at_Amax_Fem_GP_1	125.446	2	7.00E+01	150	124.51	OK	2.2617	7.02E-05	No_prior	NA
VonBert_K_Fem_GP_1	0.193582	3	1.00E-02	1	0.200271	OK	0.0096646	0.000378793	No_prior	NA
SD_young_Fem_GP_1	3.32707	3	1.00E-03	20	3.34583	OK	0.161705	1.16E-05	No_prior	NA
SD_old_Fem_GP_1	5.57733	3	1.00E-06	20	5.7947	OK	0.714613	5.81E-07	No_prior	NA
SR_LN(R0)	11.4255	1	8.00E+00	12	11.4962	OK	0.127329	0.000254811	No_prior	NA
SR_BH_steep	0.671032	2	2.00E-01	1	0.629824	OK	0.0670499	8.95E-05	Normal	0.75
InitF_seas_1_flt_33_TR_GN	0.0601424	1	1.00E-02	0.3	0.0507465	OK	0.0135506	0.000158533	No_prior	NA
SizeSpline_GradLo_1_BB(1)	0.466869	5	-1.00E-03	1	0.473662	OK	0.11985	8.31E-07	No_prior	NA
SizeSpline_GradHi_1_BB(1)	-0.363607	5	-1.00E+00	0.001	-0.366203	OK	0.060149	-1.55E-06	No_prior	NA
SizeSpline_Val_1_1_BB(1)	-3.64137	4	-9.00E+00	7	-3.64179	OK	0.323554	2.76E-06	No_prior	NA
SizeSpline_Val_2_1_BB(1)	-1.49351	4	-9.00E+00	7	-1.48322	OK	0.170208	-1.48E-05	No_prior	NA
SizeSpline_Val_4_1_BB(1)	-1.80881	4	-9.00E+00	7	-1.82816	OK	0.197067	5.84E-06	No_prior	NA
Size_DblN_peak_2_BB_isl(2)	104.45	4	2.70E+01	120	104.619	OK	5.56091	5.28E-06	No_prior	NA
Size_DblN_ascend_se_2_BB_isl(2)	5.34848	4	0.00E+00	10	5.34403	OK	0.162297	-5.15E-06	No_prior	NA
Size_DblN_descend_se_2_BB_isl(2)	4.94424	5	0.00E+00	10	4.94603	OK	0.557327	-7.54E-07	No_prior	NA
Size_DblN_peak_3_TR_GN(3)	63.8702	4	2.70E+01	120	63.673	OK	3.03423	-6.89E-05	No_prior	NA
Size_DblN_top_logit_3_TR_GN(3)	-3.73247	5	-2.50E+01	0	-3.45615	OK	1.92742	9.50E-05	No_prior	NA
Size_DblN_ascend_se_3_TR_GN(3)	3.56702	4	0.00E+00	10	4.31542	OK	1.40193	0.000178806	No_prior	NA
Size_DblN_descend_se_3_TR_GN(3)	5.19697	5	0.00E+00	10	5.1741	OK	0.388136	0.000168934	No_prior	NA
SizeSpline_GradLo_4_MWT(4)	0.418192	3	-1.00E-03	1	0.423272	OK	0.0921502	4.75E-06	Sym_Beta	0
SizeSpline_GradHi_4_MWT(4)	-0.230347	3	-1.00E+00	0.001	-0.233793	OK	0.0673618	2.15E-06	Sym_Beta	0
SizeSpline_Val_1_4_MWT(4)	-3.97128	2	-9.00E+00	7	-3.8665	OK	2.39713	2.21E-05	Sym_Beta	0
SizeSpline_Val_3_4_MWT(4)	-3.95544	2	-9.00E+00	7	-3.917	OK	1.96703	-4.15E-06	Sym_Beta	0
Size_DblN_peak_5_JPLL_N(5)	93.4383	4	3.50E+01	120	93.9005	OK	3.00472	-2.22E-06	No_prior	NA
Size_DblN_top_logit_5_JPLL_N(5)	-13.4938	5	-2.50E+01	0	-13.5454	OK	196.387	1.57E-06	No_prior	NA
Size_DblN_ascend_se_5_JPLL_N(5)	4.17814	4	0.00E+00	10	4.37148	OK	0.531645	1.54E-06	No_prior	NA
Size_DblN_descend_se_5_JPLL_N(5)	5.34334	5	0.00E+00	10	5.43204	OK	0.526706	9.71E-07	No_prior	NA
Size_DblN_peak_6_JPLL_S(6)	102.158	4	3.50E+01	120	102.522	OK	2.37875	2.10E-06	No_prior	NA
Size_DblN_top_logit_6_JPLL_S(6)	-13.5785	5	-2.50E+01	0	-13.6243	OK	192.24	1.19E-06	No_prior	NA
Size_DblN_ascend_se_6_JPLL_S(6)	4.16449	4	0.00E+00	10	4.28495	OK	0.428425	-4.74E-07	No_prior	NA
Size_DblN_descend_se_6_JPLL_S(6)	5.1376	5	0.00E+00	10	5.25922	OK	0.495407	2.75E-06	No_prior	NA
Size_DblN_peak_7_TAILL_N(7)	100.6	4	3.50E+01	156	100.021	OK	3.75923	2.41E-06	No_prior	NA
Size_DblN_top_logit_7_TAILL_N(7)	-14.0467	5	-2.50E+01	0	-14.057	OK	172.816	-5.05E-07	No_prior	NA
Size_DblN_ascend_se_7_TAILL_N(7)	5.7772	4	0.00E+00	10	5.74706	OK	0.250976	-3.23E-06	No_prior	NA
Size_DblN_descend_se_7_TAILL_N(7)	5.20286	5	0.00E+00	10	5.23627	OK	0.513187	1.46E-06	No_prior	NA
Size_DblN_peak_8_TAILL_S(8)	120.869	4	3.50E+01	156	118.036	OK	8.25729	4.13E-07	No_prior	NA
Size_DblN_top_logit_8_TAILL_S(8)	-13.8705	5	-2.50E+01	0	-13.816	OK	179.413	7.67E-07	No_prior	NA
Size_DblN_ascend_se_8_TAILL_S(8)	6.15817	4	0.00E+00	10	6.06927	OK	0.300205	-3.54E-06	No_prior	NA
Size_DblN_descend_se_8_TAILL_S(8)	4.96601	5	0.00E+00	10	5.05631	OK	0.557761	2.81E-07	No_prior	NA
Size_DblN_peak_9_USLL_N(9)	104.172	4	3.50E+01	120	104.065	OK	1.98116	1.88E-05	No_prior	NA
Size_DblN_top_logit_9_USLL_N(9)	-12.3886	5	-2.50E+01	0	-12.3503	OK	295.488	1.48E-06	No_prior	NA
Size_DblN_ascend_se_9_USLL_N(9)	5.2321	4	0.00E+00	10	5.23386	OK	0.185477	-2.70E-05	No_prior	NA
Size_DblN_descend_se_9_USLL_N(9)	4.49768	5	0.00E+00	10	4.53384	OK	0.572389	1.67E-06	No_prior	NA

Size_inflection_10_USLL_S(10)	107.231	4	1.00E+01	130	107.415	OK	2.04991	1.13E-05	No_prior	NA
Size_95%width_10_USLL_S(10)	12.6638	5	-1.50E+01	60	12.7404	OK	1.4057	-9.71E-06	No_prior	NA
Size_inflection_11_VENLL(11)	97.3427	4	1.00E+01	130	97.3747	OK	1.73076	2.43E-06	No_prior	NA
Size_95%width_11_VENLL(11)	10.3633	5	-1.50E+01	60	10.4644	OK	1.68935	-2.25E-06	No_prior	NA
Size_DblN_peak_15_BBisl_s2(15)	83.775	4	3.50E+01	120	83.9126	OK	4.32935	-0.000356381	No_prior	NA
Size_DblN_top_logit_15_BBisl_s2(15)	-14.1088	5	-2.50E+01	0	-14.1301	OK	170.691	-1.38E-06	No_prior	NA
Size_DblN_ascend_se_15_BBisl_s2(15)	5.10408	4	0.00E+00	10	5.02471	OK	1.65001	0.00028258	No_prior	NA
Size_DblN_descend_se_15_BBisl_s2(15)	5.70764	5	0.00E+00	10	5.69381	OK	0.343099	-3.29E-05	No_prior	NA
Size_DblN_peak_5_JPLL_N(5)_BLK1repl_1970	101.993	6	3.50E+01	156	98.5469	OK	5.66269	1.49E-05	No_prior	NA
Size_DblN_peak_5_JPLL_N(5)_BLK1repl_1976	105.542	6	3.50E+01	156	105.09	OK	2.85865	1.64E-05	No_prior	NA
Size_DblN_ascend_se_5_JPLL_N(5)_BLK1repl_1970	5.6669	6	0.00E+00	10	5.55622	OK	0.381589	-1.65E-05	No_prior	NA
Size_DblN_ascend_se_5_JPLL_N(5)_BLK1repl_1976	6.19255	6	0.00E+00	10	6.18216	OK	0.139548	-2.96E-05	No_prior	NA
Size_DblN_peak_6_JPLL_S(6)_BLK1repl_1970	102.388	6	3.50E+01	156	98.2598	OK	7.43774	1.70E-07	No_prior	NA
Size_DblN_peak_6_JPLL_S(6)_BLK1repl_1976	106.173	6	3.50E+01	156	105.691	OK	2.11208	3.06E-05	No_prior	NA
Size_DblN_ascend_se_6_JPLL_S(6)_BLK1repl_1970	5.23418	6	0.00E+00	10	4.9783	OK	0.709563	2.97E-07	No_prior	NA
Size_DblN_ascend_se_6_JPLL_S(6)_BLK1repl_1976	5.16607	6	0.00E+00	10	5.13685	OK	0.201055	-2.12E-05	No_prior	NA
Size_DblN_peak_7_TAILL_N(7)_BLK2repl_1987	93.7191	6	3.50E+01	156	93.5537	OK	3.51429	3.19E-06	No_prior	NA
Size_DblN_peak_7_TAILL_N(7)_BLK2repl_1999	104.475	6	3.50E+01	156	104.49	OK	1.71749	2.71E-05	No_prior	NA
Size_DblN_ascend_se_7_TAILL_N(7)_BLK2repl_1987	5.38535	6	0.00E+00	10	5.3786	OK	0.343435	-1.56E-06	No_prior	NA
Size_DblN_ascend_se_7_TAILL_N(7)_BLK2repl_1999	5.24968	6	0.00E+00	10	5.25821	OK	0.160692	-2.11E-05	No_prior	NA
Size_DblN_peak_8_TAILL_S(8)_BLK2repl_1987	127.528	6	3.50E+01	156	127.624	OK	12.0037	3.11E-06	No_prior	NA
Size_DblN_peak_8_TAILL_S(8)_BLK2repl_1999	108.455	6	3.50E+01	156	108.489	OK	1.72292	3.96E-05	No_prior	NA
Size_DblN_ascend_se_8_TAILL_S(8)_BLK2repl_1987	6.54277	6	0.00E+00	10	6.5516	OK	0.340277	-1.19E-05	No_prior	NA
Size_DblN_ascend_se_8_TAILL_S(8)_BLK2repl_1999	5.14611	6	0.00E+00	10	5.155	OK	0.170864	-3.04E-05	No_prior	NA

Table 5. The estimated re-weighting parameters after 2 iterations for the length and age components.

Composition	Fleet	Lambda
Length	1_BB	0.21
Length	2_BB_isl	0.19
Length	3_TR_GN	2
Length	4_MWT	2
Length	5_JPLL_N	0.43
Length	6_JPLL_S	1.53
Length	7_TAILL_N	0.36
Length	8_TAILL_S	0.2
Length	9_USLL_N	1.41
Length	10_USLL_S	1.43
Length	11_VENLL	0.09
Length	15_BBisl_s2	0.34
Age	1_BB	0.09

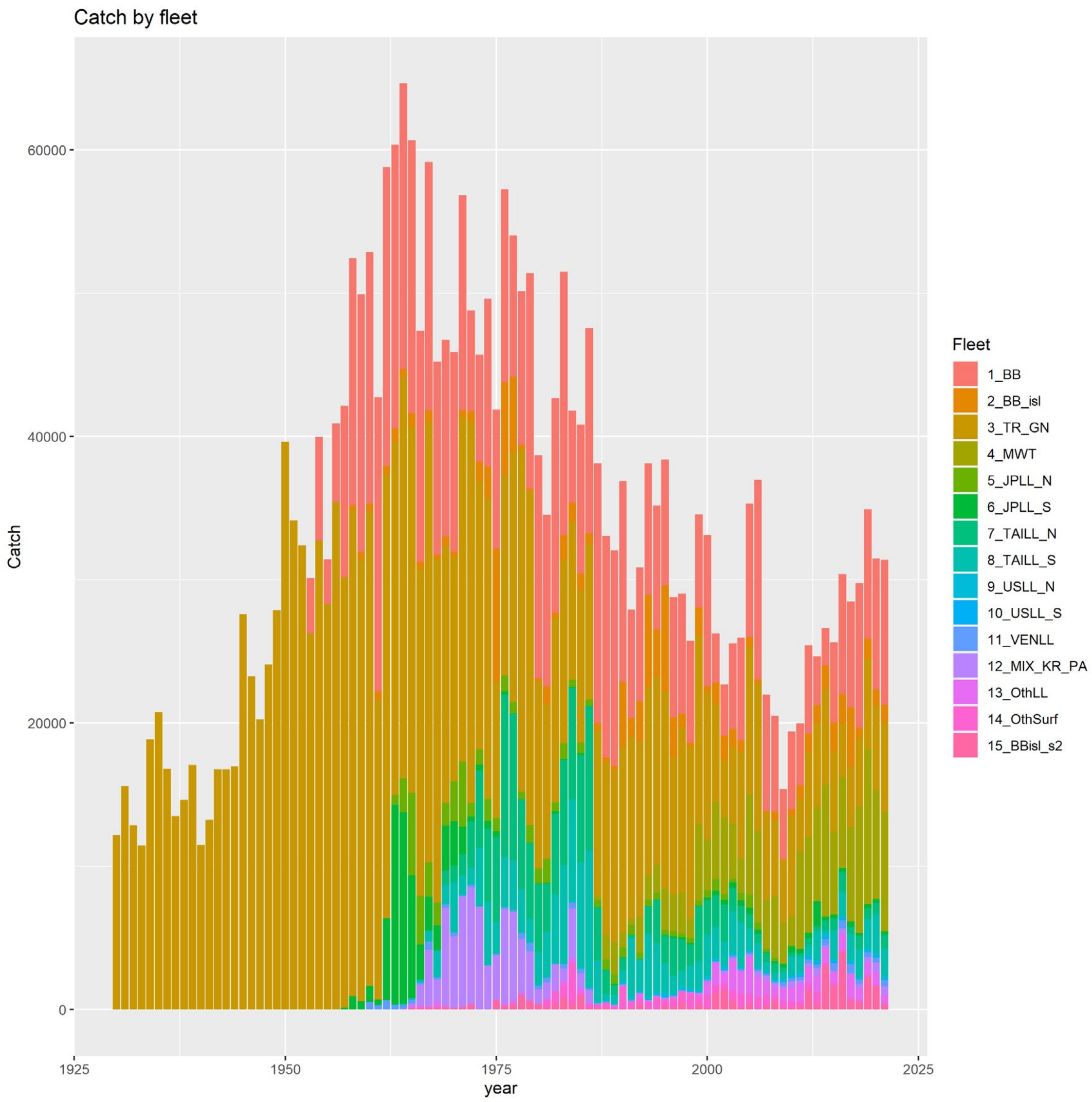


Figure 1. Total annual catch of North Atlantic albacore by main gear types from 1930 to 2021.

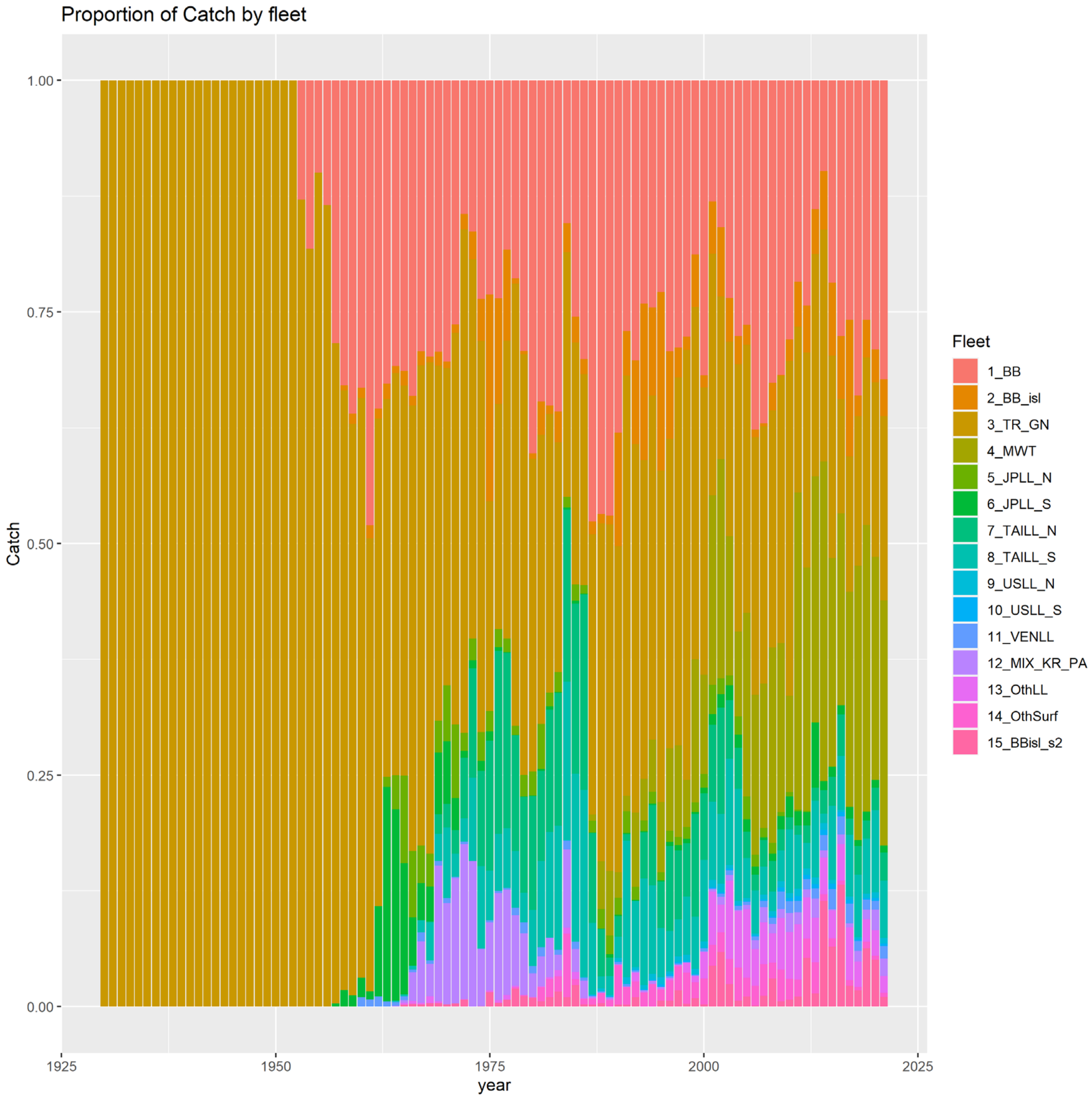


Figure 2. Catch proportion by gear.

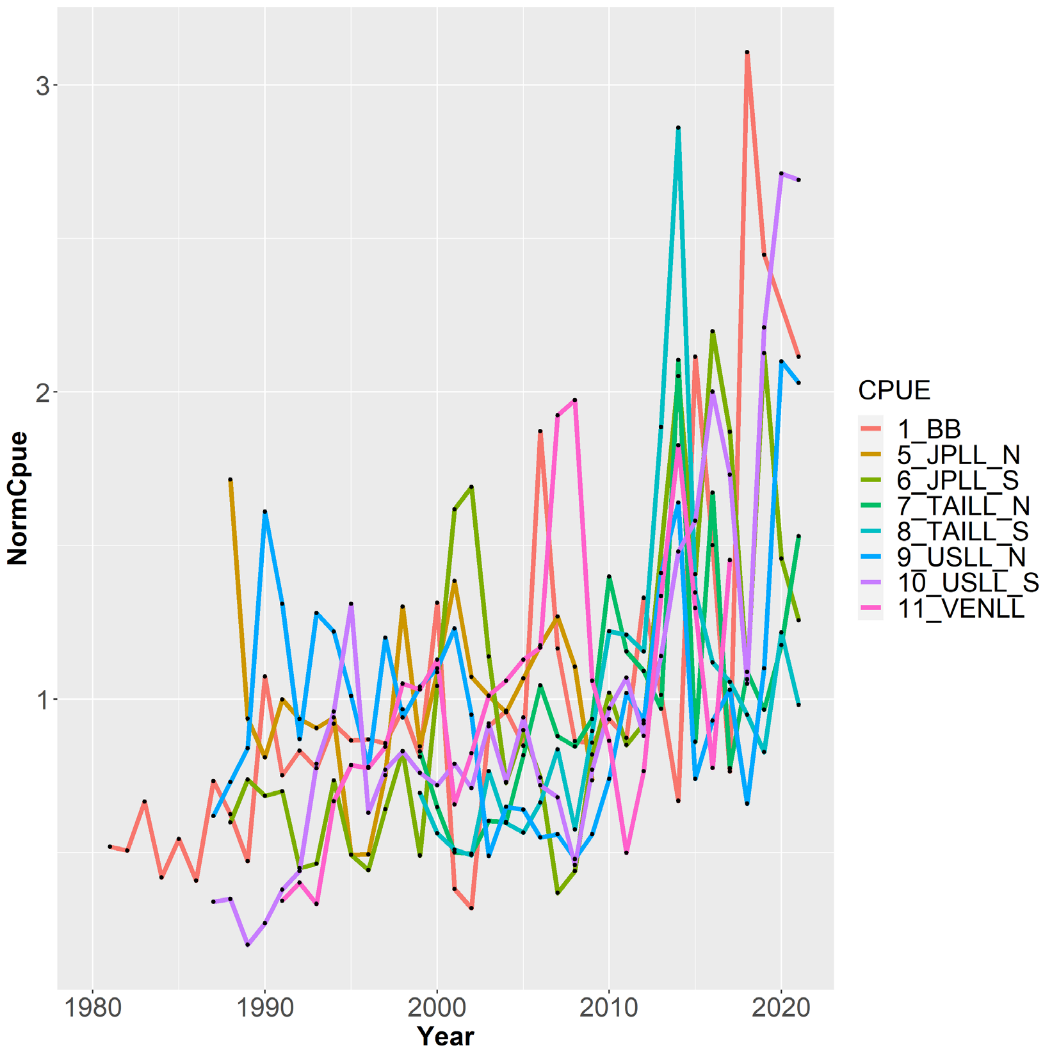


Figure 3. Normalized CPUE with a CV of 0.2.

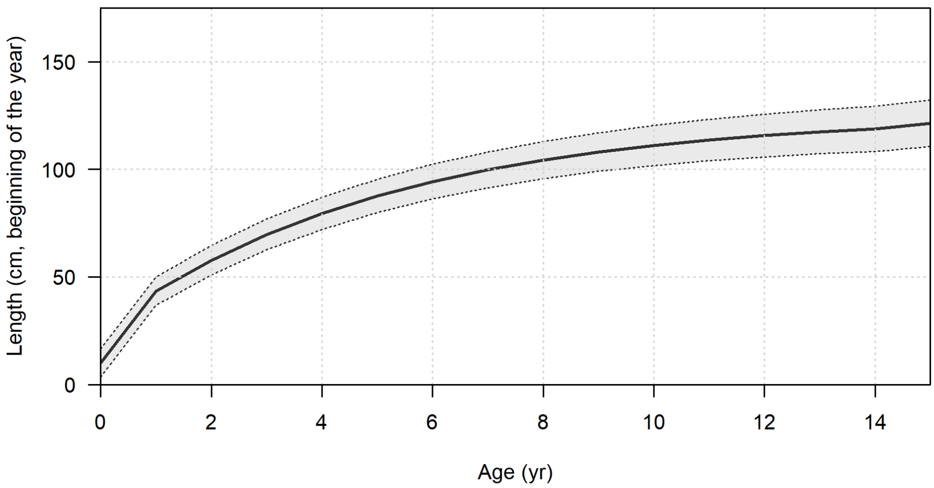
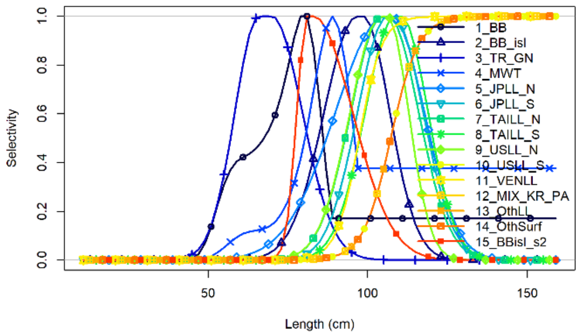


Figure 4. Length at age in the beginning of the year. Shared area indicates 95% distribution of length at age around the estimated growth curve.



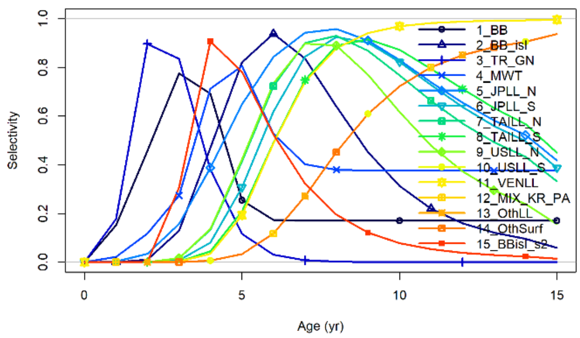


Figure 5. Estimated selectivity-at-length (left) and age (right) for the fleets.

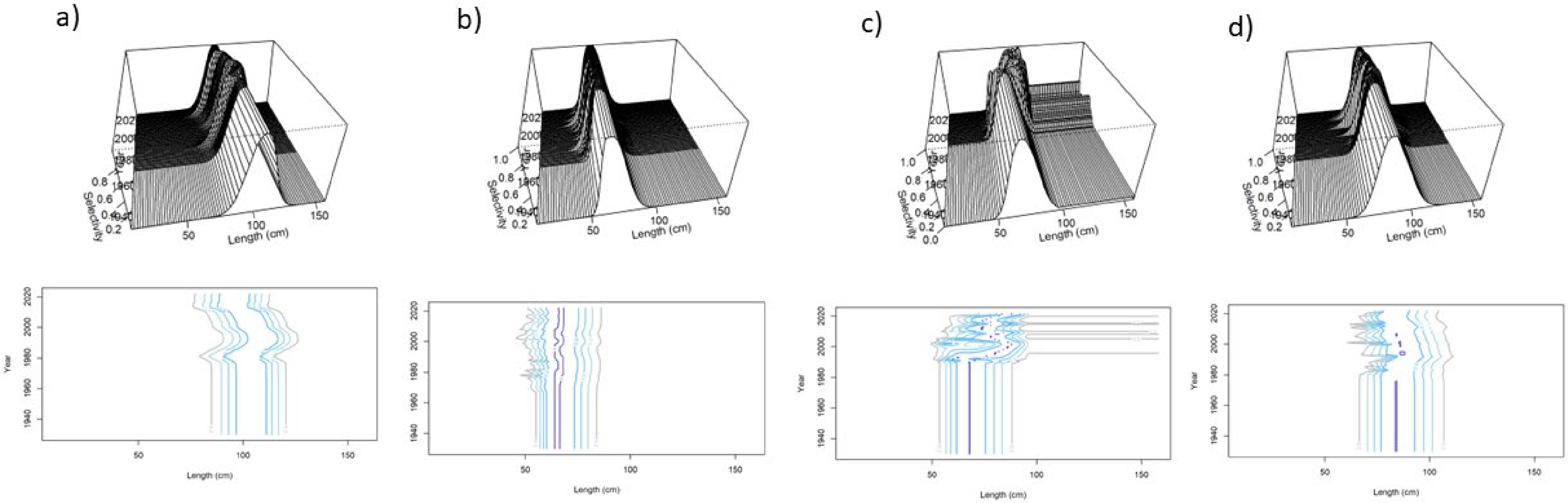


Figure 6. Random walk on selectivity of a) Baitboat islands (not season 2) b) troll and gillnets c) mid water trawlers d) Baitboat islands fishing in season2 and at the bottom the contour plots of the corresponding fleet on the top.

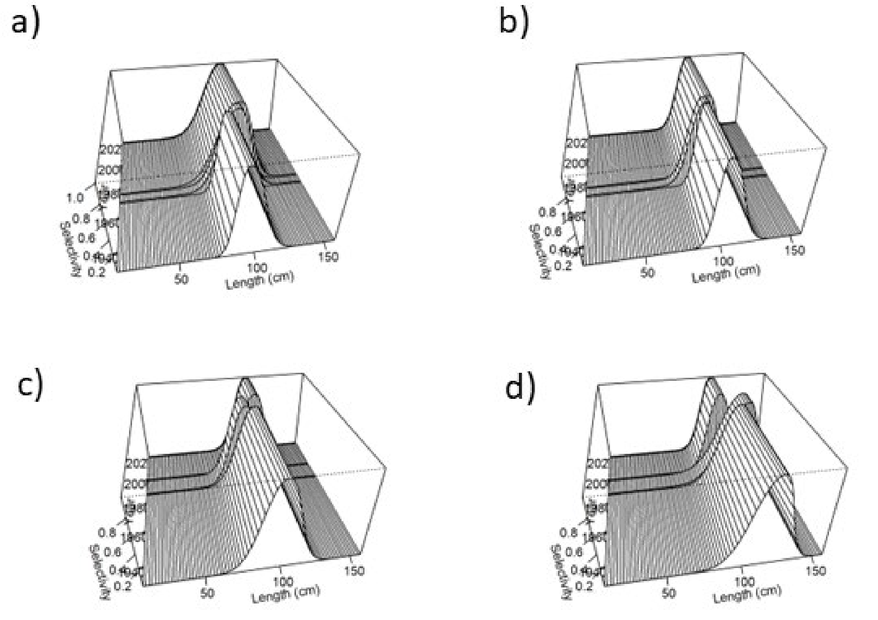


Figure 7. Time blocks of a) Japan longline north b) Japan longline south c) Chinese Taipei longline north and d) Chinese Taipei longline south.

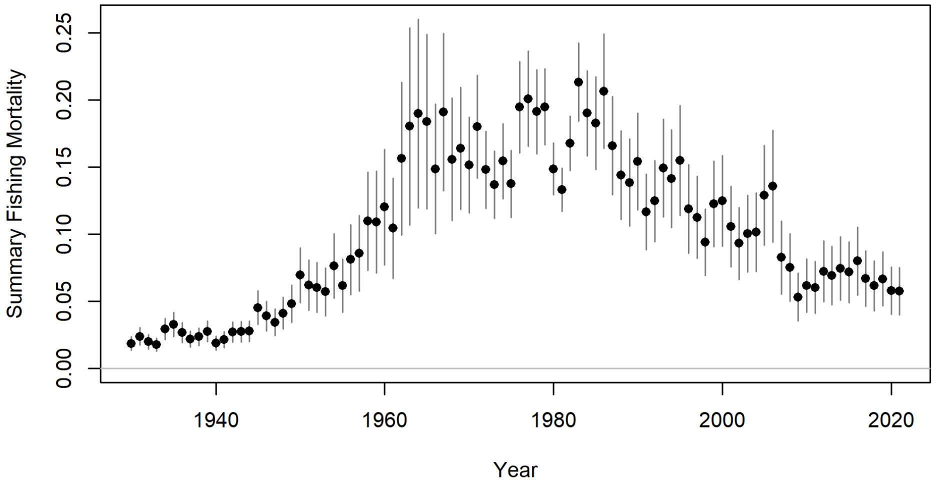


Figure 8. Fishing mortality (exploitation rate in biomass) estimates from the reference case model.

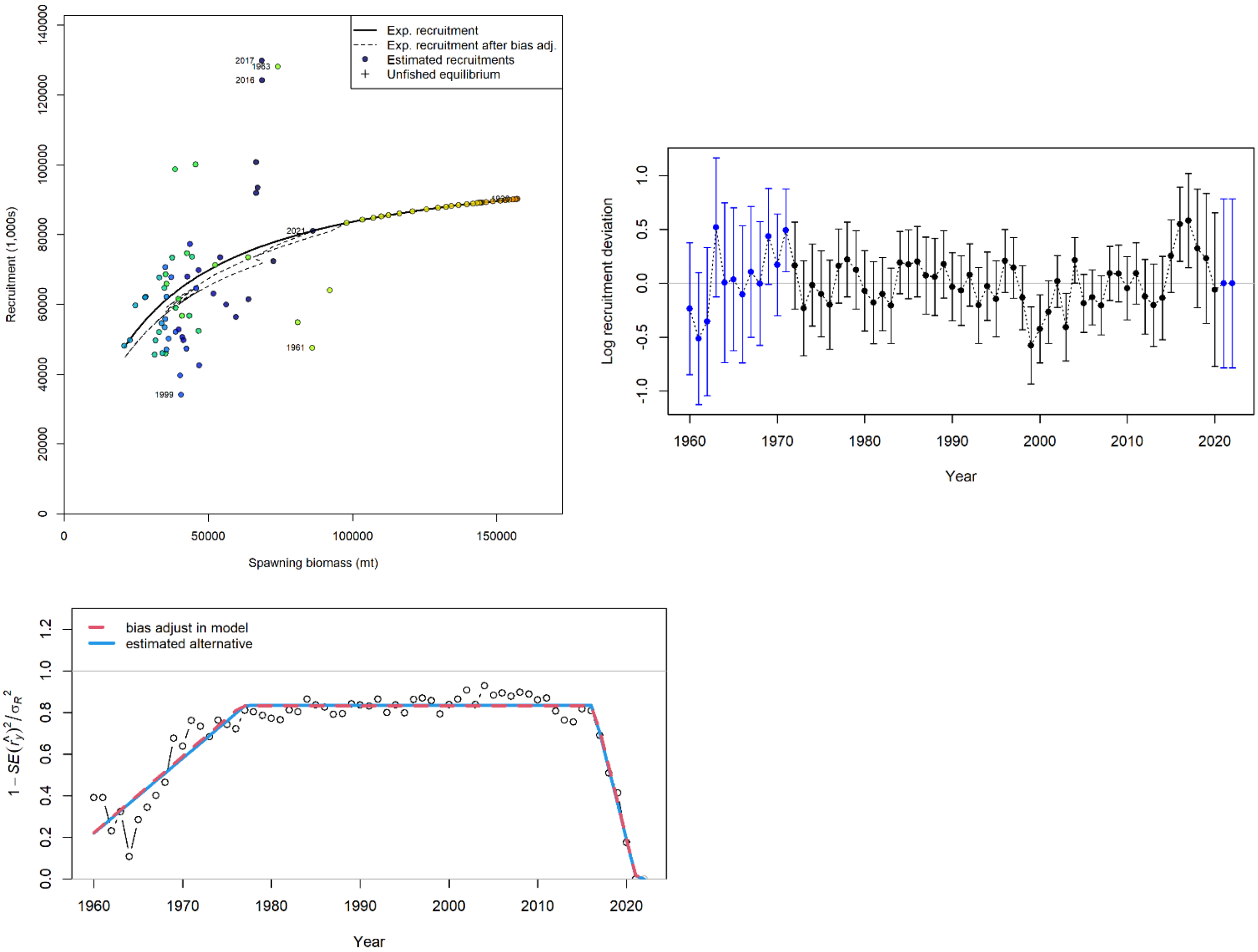


Figure 9. The figure in the top shows the stock-recruit curve with labels on first, last, and years with (log) deviations > 0.5. Point colours indicate year, with warmer colours indicating earlier years and cooler colors in showing later years. The figure in the top right shows the recruitment deviates and the 95% confidence interval. The figure at the bottom shows adjustment specified in control file (red line). Blue line shows least squares estimate of alternative bias adjustment relationship for recruitment deviations. Points are transformed variances.

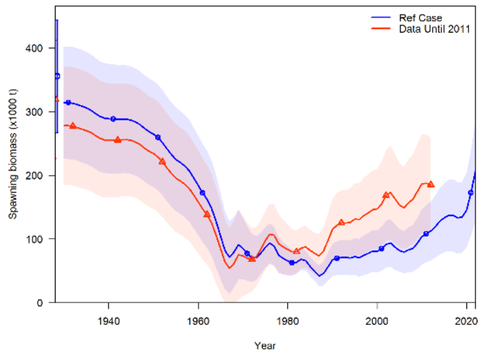


Figure 10. Spawning stock biomass estimates from the reference case SS3 model and 95% of confidence interval.

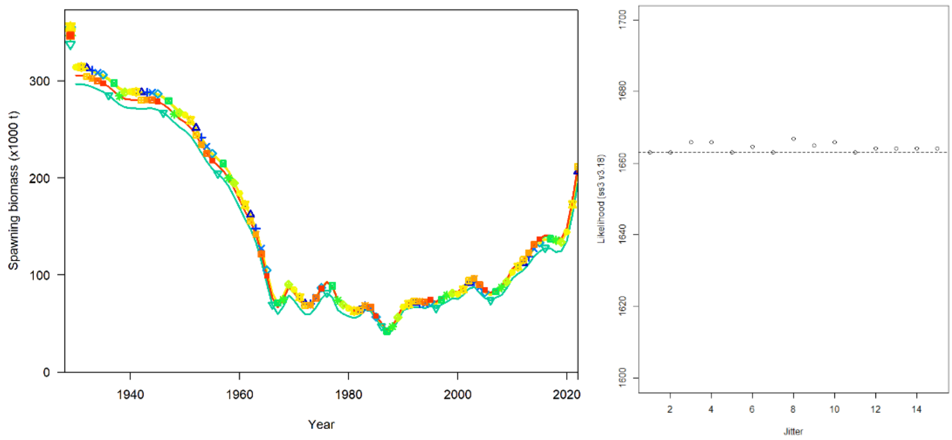


Figure 11. The SSB and likelihood of the 15 jitters that converged from 30. The jitters were run with version v3.30.18, while the rest of the analysis were done with v3.30.21. So total likelihood is different, but the values of the estimated parameters were the same.

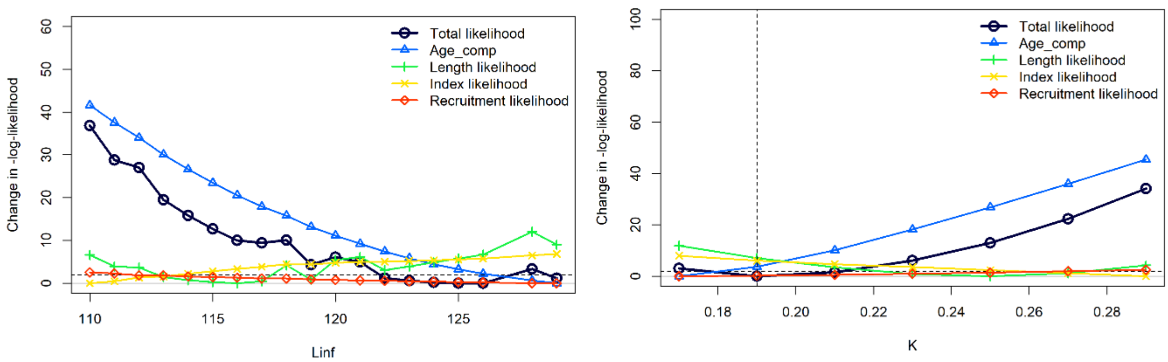


Figure 12. Profiling of the growth parameters Linf (left) and K (right).. The lines of different colour show the changes on likelihood of different components and in black the total likelihood. The vertical discontinuous line shows the initial value and the horizontal the confidence interval.

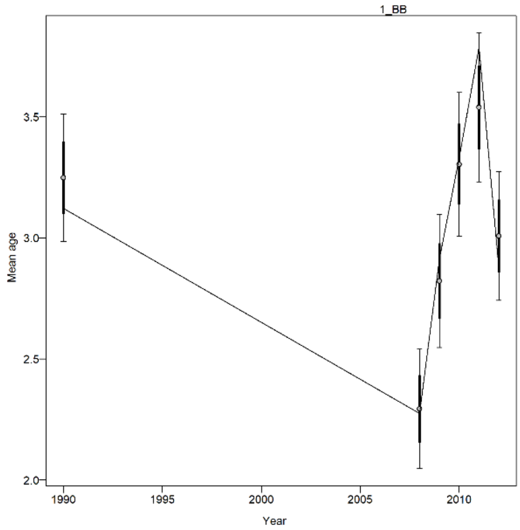


Figure 13. Mean age from conditional data (aggregated across length bins) for 1_BB with 95% confidence intervals based on current samples sizes

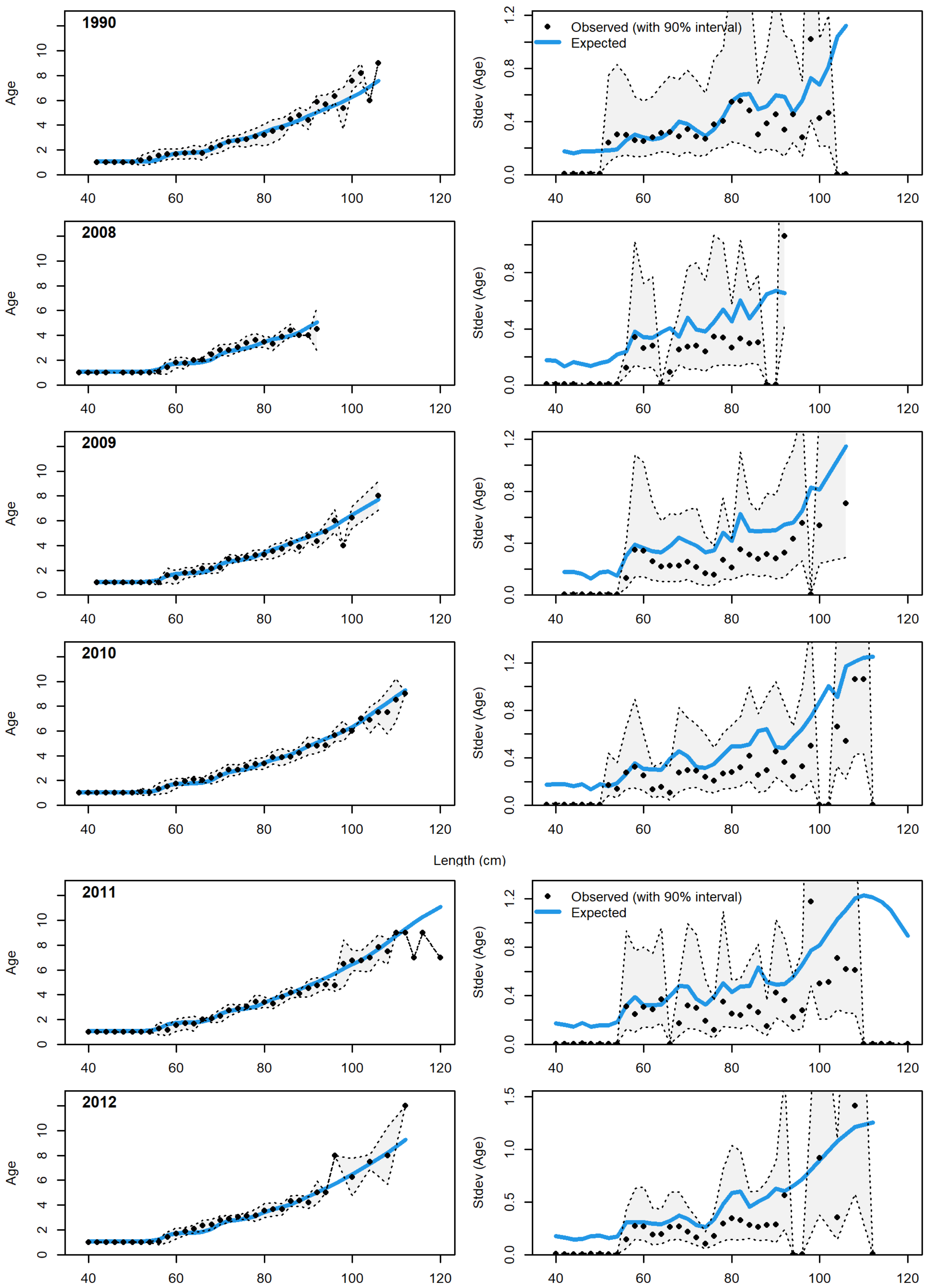


Figure 14. Left plots are mean age at length by size-class (obs. and exp.) with 90% CIs. Right plots in each pair are SE of mean age at length (obs. and exp.) with 90% CIs based on the chi-square distribution

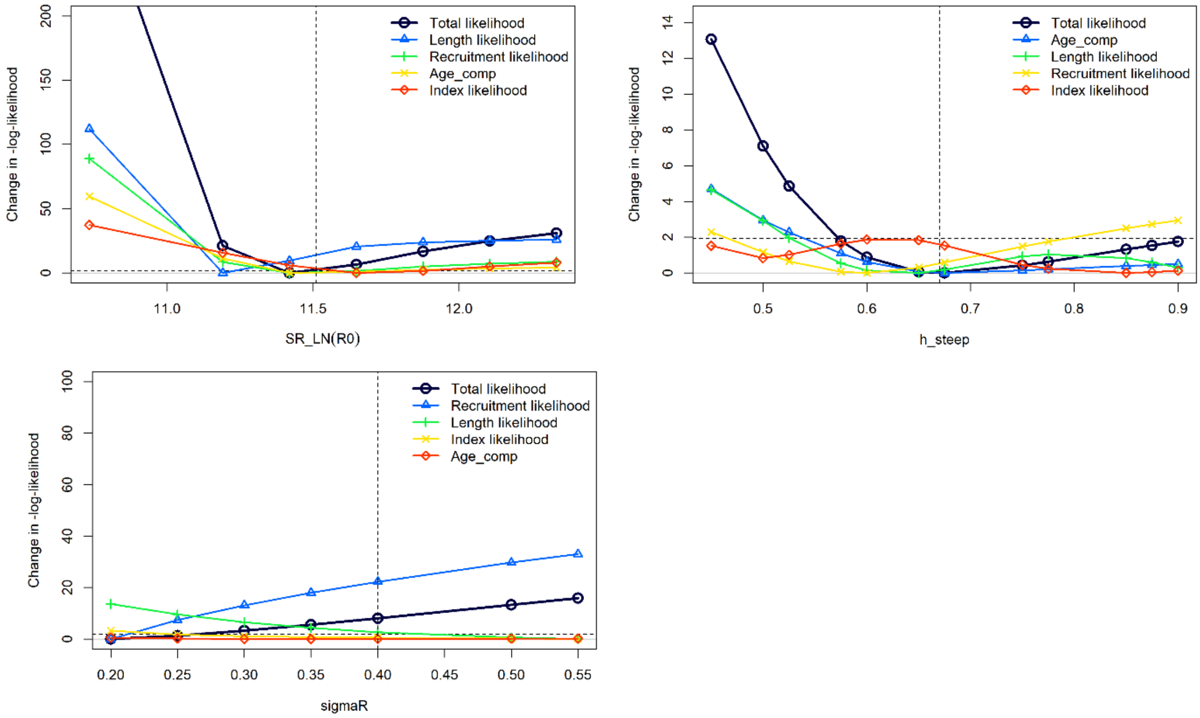


Figure 15. Profiling of the ln(R0) (assuming fixed steepness at 0.63)and steepness. The lines of different colour show the changes on likelihood of different components and in black the total likelihood. The vertical discontinuous line shows the initial value and the horizontal the confidence interval.

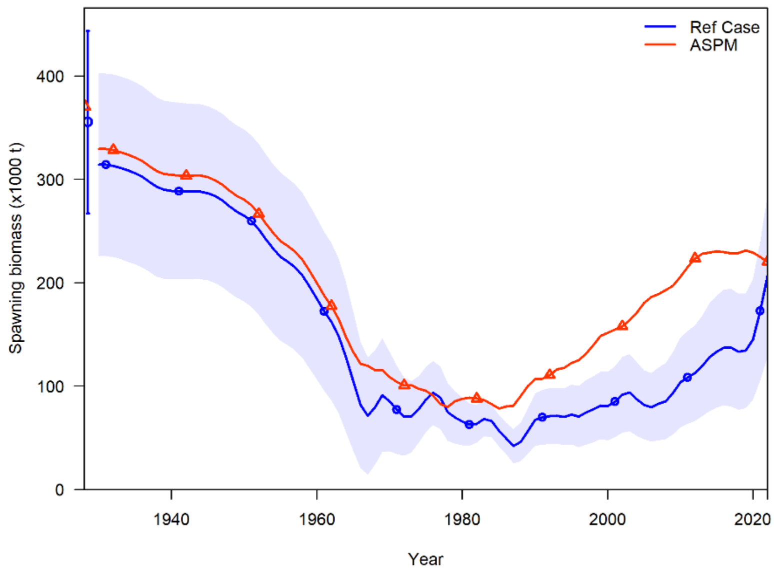


Figure 16. Comparison of the estimated SSB in the reference case and in the age structure production model (ASPM). This analysis indicates the influence of the recruitment deviates in the trend of SSB.

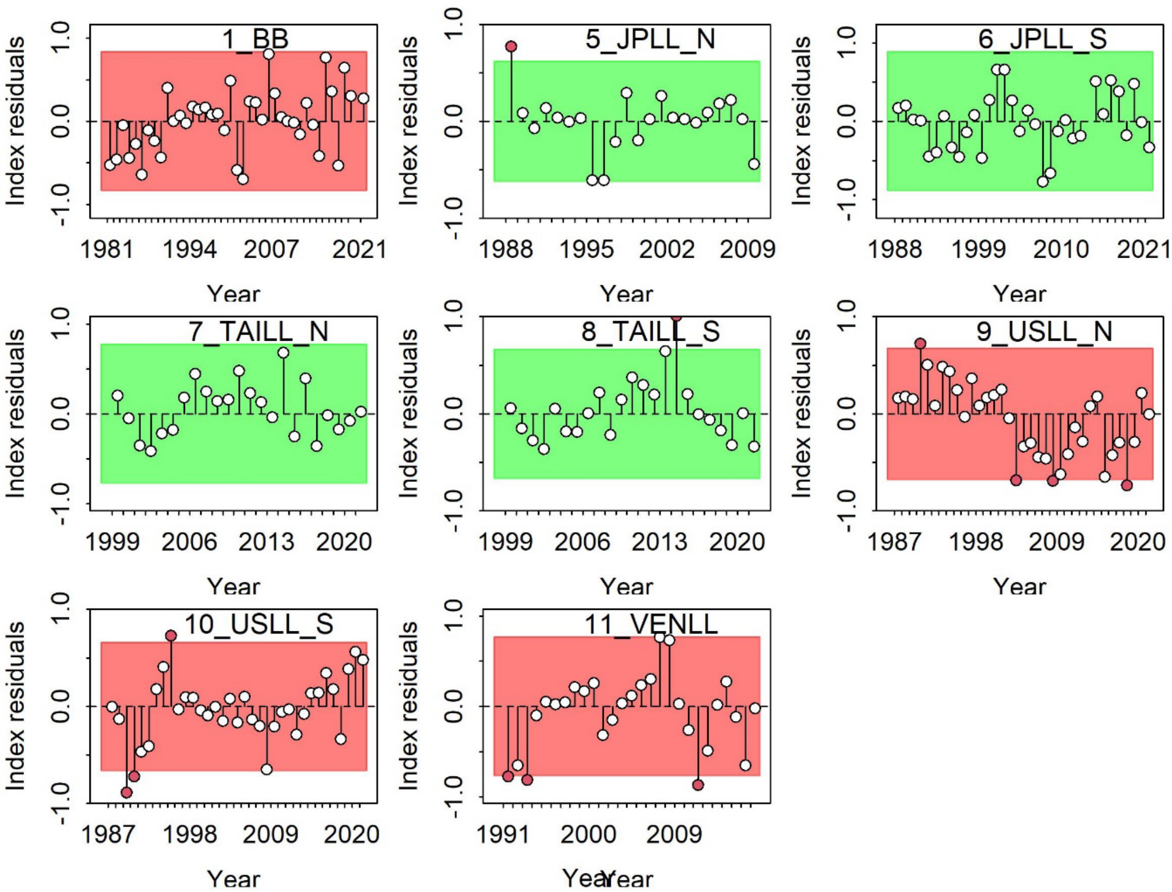


Figure 17. The runs test of each index indicates 4 of 8 indices failed the runs test (red shading), due to non-randomness in the sign of the residuals. Observations outside the red area can be considered outliers.

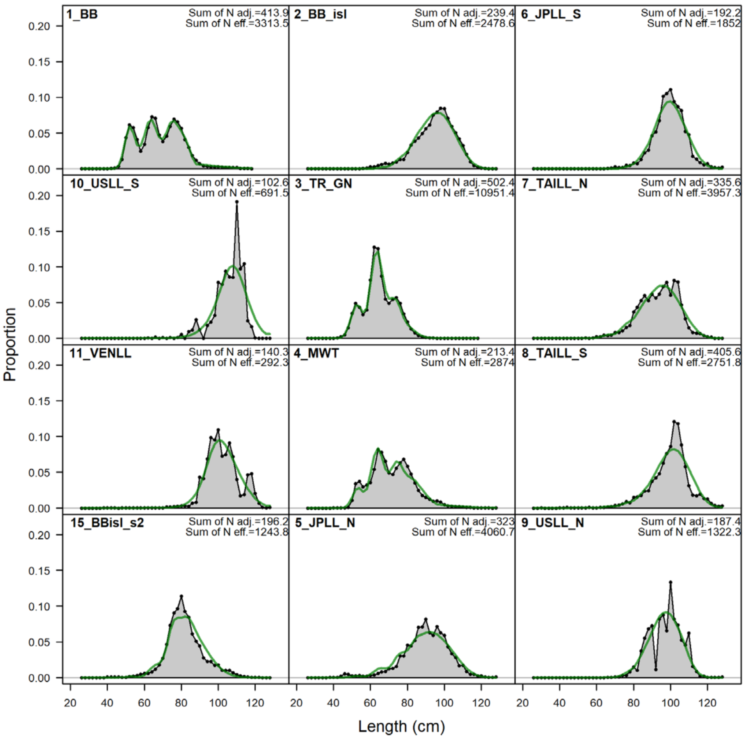


Figure 18. SS3 fits to each of the fleet aggregated length composition of the reference case. Grey histograms represent observed length data aggregated across all years by fleet. Green lines represent the fits by the SS3 model**.**

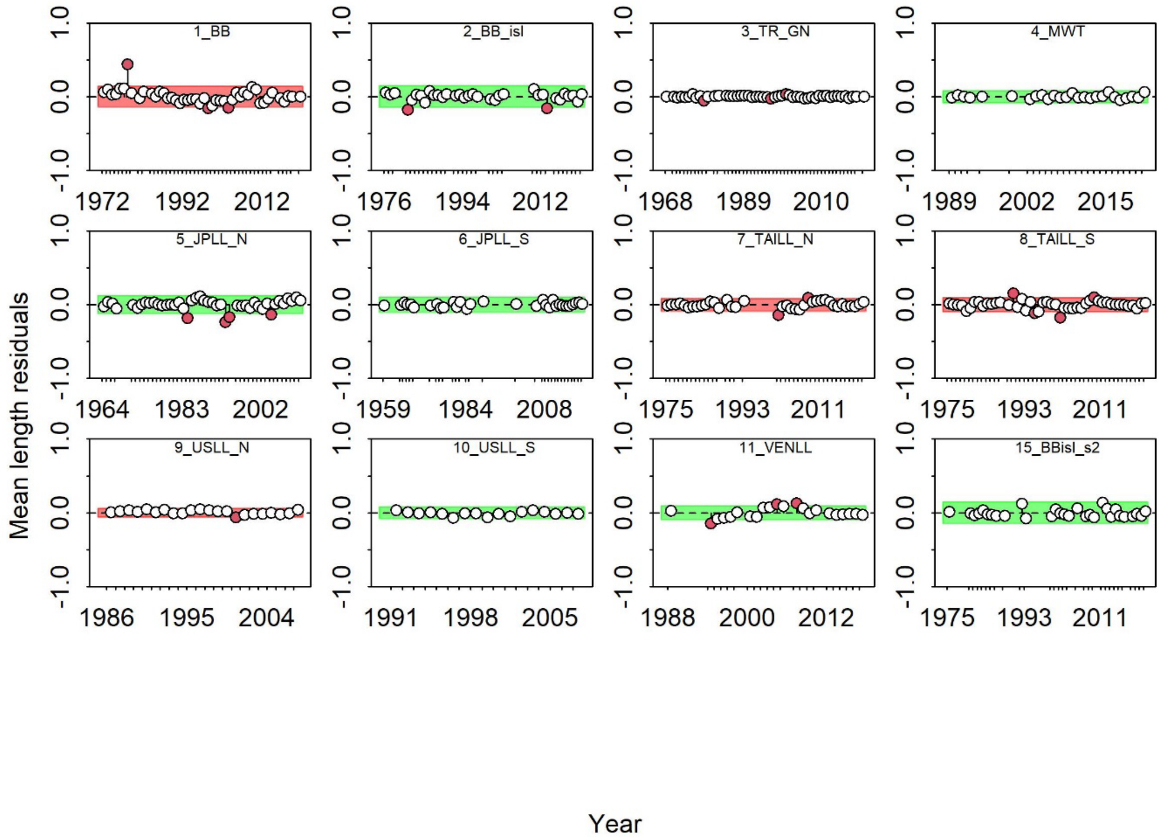


Figure 19. The runs test of the length composition indicates 5 of 11 fleets failed the runs test (red shading), due to non-randomness in the sign of the residuals. Observations outside the red area can be considered outliers.

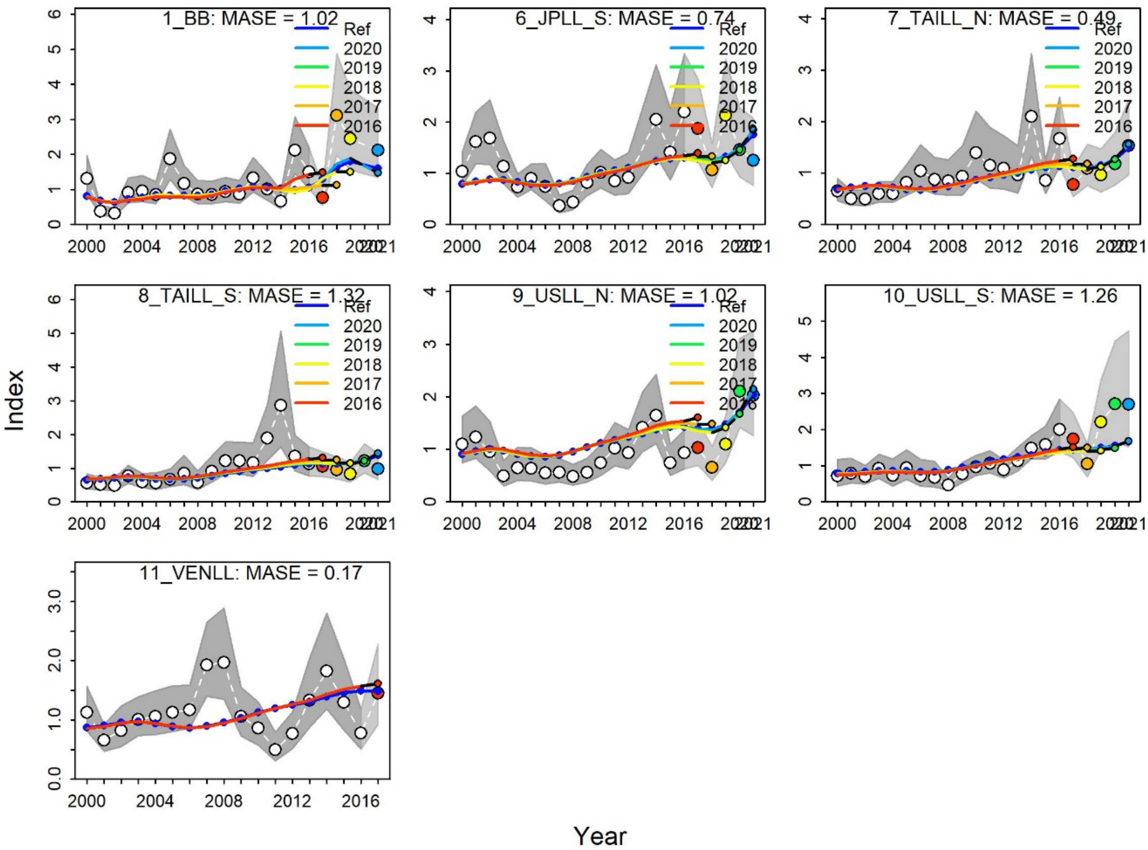


Figure 20. Hindcasting cross validation results to evaluate the indices prediction skill of the model.5 year hindcasting runs were used to estimate the MASE value. MASE <=1 indicates that the model has predictive skills. The observations used for cross validation are highlighted as color-coded solid circles with associated 95 % confidence intervals (light-grey shading). The model reference year refers to the endpoints of each one-year-ahead forecast and the corresponding observation (i.e., year of peel + 1

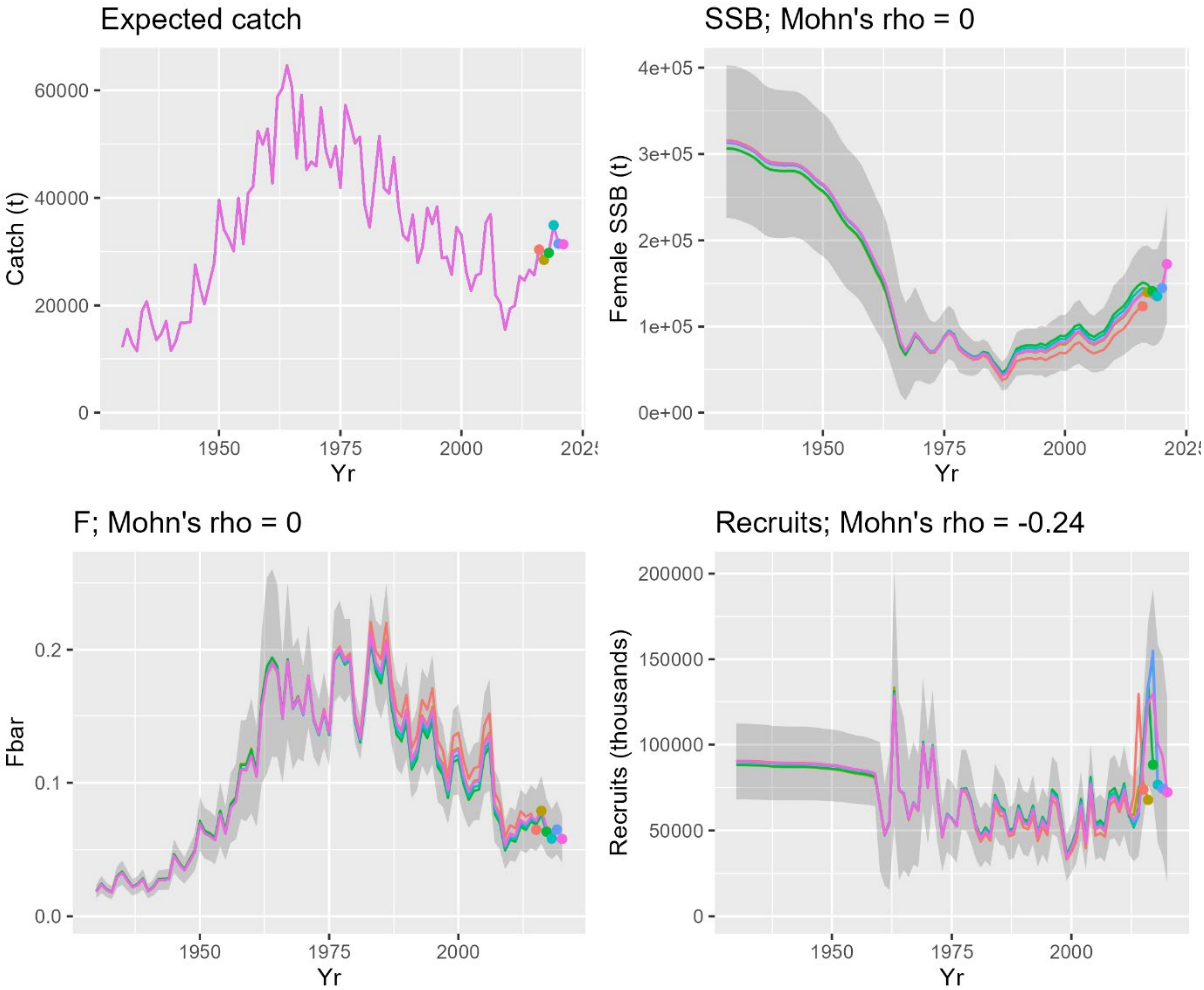


Figure 21. Retrospective pattern in catches, SSB, F and recruitments by re-fitting the reference model after removing five years of observations. One-year-ahead projections denoted by color-coded dashed lines with terminal points are shown for each model. Grey shaded areas are the 95 % confidence intervals from the reference model. Mohn's rho values were estimated for each of the variables.

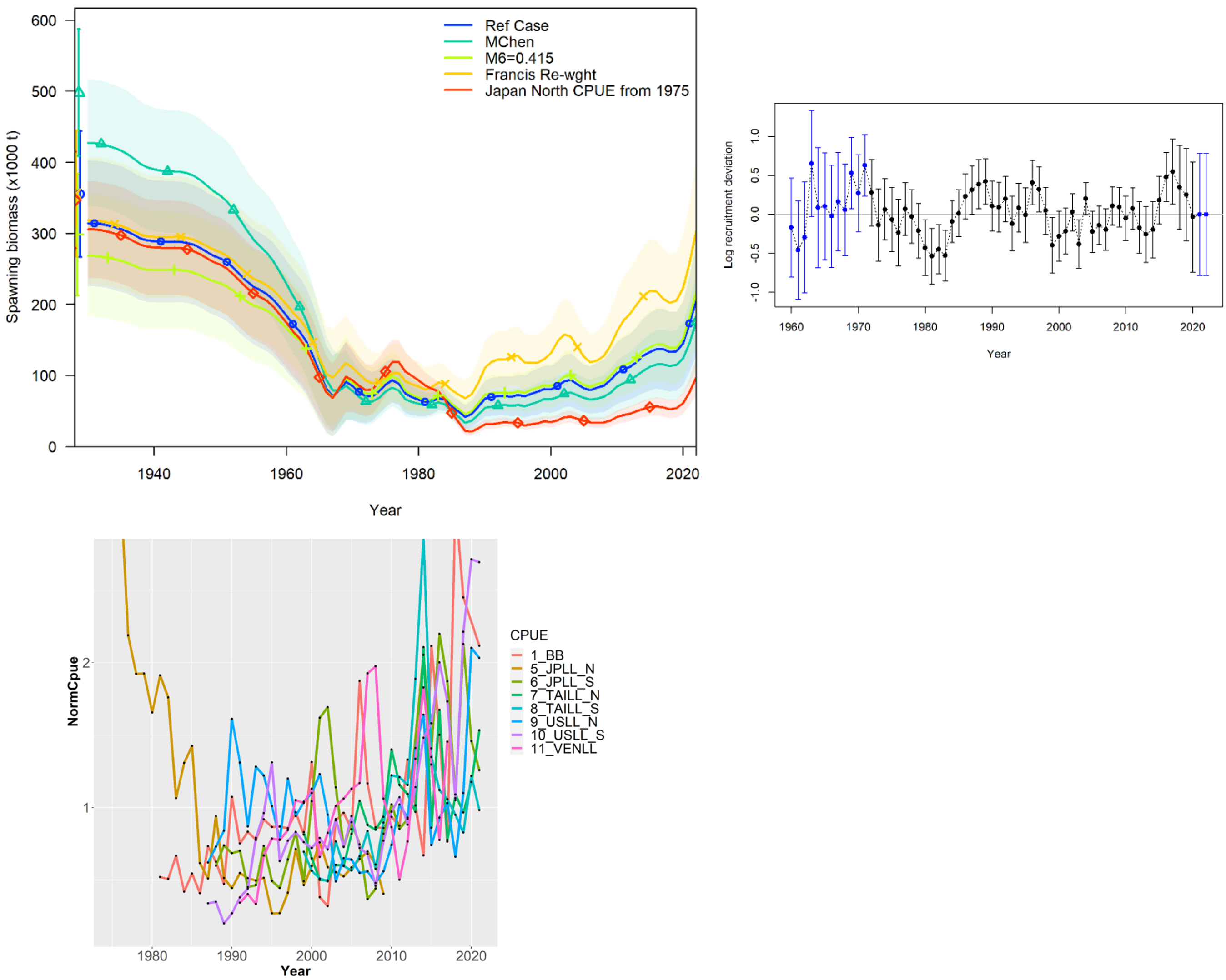


Figure 22. In the top the estimated SSB time series in the reference case and comparison with other sensitivity analysis scenarios: assuming an M at age 6 of 0.415, assuming the M at age estimated from Chen and Watanabe (1989) equation, Re-weighting the length composition data with Francis (2011) method and considering the Japan LL North index from 1975. In the bottom the normalized index considering the Japan LL North index from 1975.

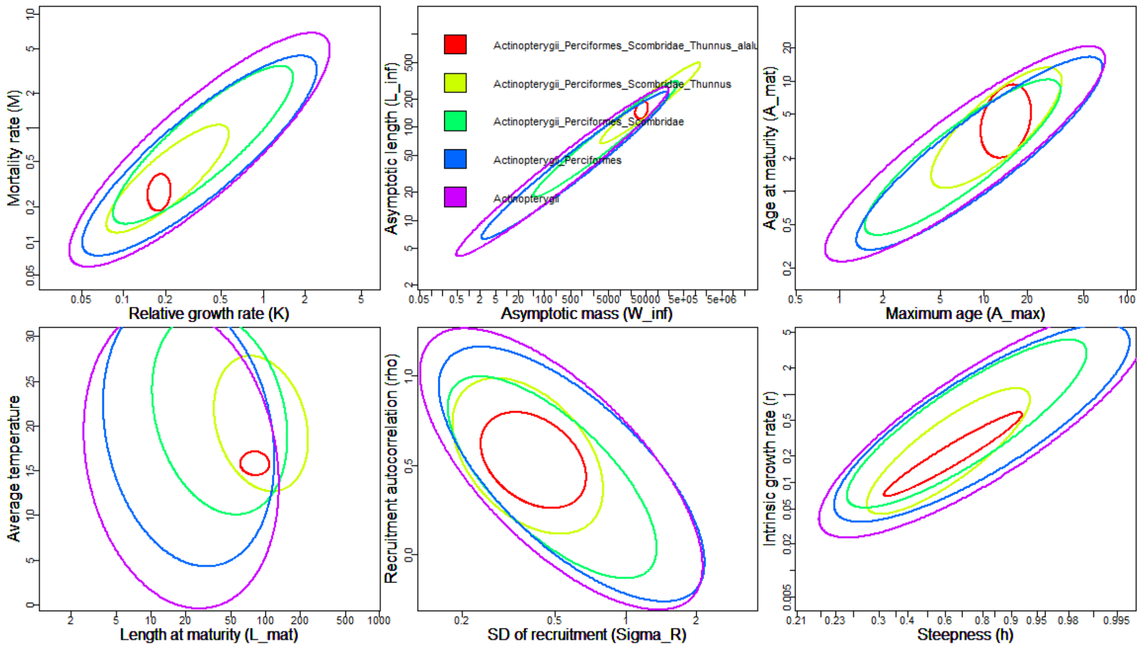


Figure 23. Estimates of biological parameter from FishLife package (Thorson 2023).