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PRELIMINARY STOCK SYNTHESIS (SS3) MODEL RUNS CONDUCTED FOR NORTH ATLANTIC BLUE SHARK (1971-2021)

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SUMMARY

Stock Synthesis model runs were conducted for the North Atlantic blue shark based on the available catch, CPUE, length composition, and life history data compiled by the Shark Species Group. A sex-specific model was implemented in order to allow for observed differences in growth between sexes. Beverton-Holt stock-recruitment was assumed. The steepness of the stock recruitment relationship and natural mortality at age were fixed at independently estimated values. A two-stage data weighting approach was implemented. Model sensitivity was evaluated to CPUE groupings, to the steepness of the stock recruitment relationship, and to natural mortality at age compiled by the Shark Species Group. A wide range of model results were obtained from these preliminary structural uncertainty analyses that could be useful to inform a structural uncertainty grid for the 2023 blue shark stock assessment. A preliminary reference case model was identified that may be useful as a starting point for continued model development during the 2023 blue shark stock assessment.

RÉSUMÉ

*Des scénarios du modèle Stock synthèse ont été exécutés pour le requin peau bleue de l'Atlantique Nord basés sur les données disponibles de capture, CPUE, composition par taille et cycle vital qui ont été compilées par le Groupe d'espèces sur les requins. Un modèle spécifique au sexe a été mis en œuvre afin de tenir compte des différences de croissance observées entre les sexes. On a postulé une relation stock-recrutement de Beverton-Holt. La pente à l'origine de la relation stock-recrutement (*steepness*) et la mortalité naturelle par âge ont été fixées à des valeurs estimées de façon indépendante. Une approche de pondération des données en deux étapes a été mise en œuvre. La sensibilité du modèle a été évaluée en fonction des groupes de CPUE, de la pente à l'origine de la relation stock-recrutement et de la mortalité naturelle par âge compilée par le Groupe d'espèces sur les requins. Ces analyses préliminaires de l'incertitude structurelle ont permis d'obtenir un large éventail de résultats de modèles qui pourraient être utiles pour informer une grille d'incertitude structurelle pour l'évaluation des stocks de requin peau bleue de 2023. Un cas de base préliminaire du modèle a été identifié et celui-ci pourrait être utile comme point de départ pour la poursuite du développement du modèle au cours de l'évaluation des stocks du requin peau bleue de 2023.*

RESUMEN

Se realizaron ensayos del modelo Stock Synthesis para el tiburón azul del Atlántico norte basándose en los datos disponibles de capturas, CPUE, composición por tallas y ciclo vital recopilados por el Grupo de especies de tiburones. Se implementó un modelo específico por sexo con el fin de tener en cuenta las diferencias observadas en el crecimiento entre sexos. Se asumió una relación stock-reclutamiento de Beverton-Holt. La inclinación de la relación stock-reclutamiento y la mortalidad natural por edad se fijaron en valores estimados independientemente. Se implementó un enfoque de ponderación de datos en dos fases. Se evaluó la sensibilidad del modelo a las agrupaciones de CPUE, a la inclinación de la relación stock-reclutamiento y a la mortalidad natural por edad recopilada por el Grupo de especies de tiburones. A partir de estos análisis preliminares de incertidumbre estructural se obtuvo una amplia gama de resultados del modelo que podrían ser útiles para aportar información a

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una matriz de incertidumbre estructural para la evaluación de stock de tiburón azul de 2023. Se identificó un modelo de caso de referencia preliminar que podría ser útil como punto de partida para continuar el desarrollo del modelo durante la evaluación de stock de tiburón azul de 2023.

KEYWORDS

Stock assessment, Shark fisheries, Pelagic environment

1. Introduction

The analytical approach implemented in this assessment is a length-based age-structured statistical model implemented within Stock Synthesis (Methot and Wetzel 2013; e.g., Wetzel and Punt 2011a, 2011b). Stock Synthesis utilizes an integrated modeling approach (Maunder and Punt 2013; e.g., see Punt *et al*. 2020, 2023) to take advantage of the many data sources available.

An integrated modeling approach in Stock Synthesis was proposed by the Shark Working Group (Anon. 2023) for the North Atlantic blue shark stock to take advantage of available length composition data sources. An advantage of the integrated modeling approach is that the development of statistical methods which combine several sources of information into a single analysis allows for consistency in assumptions and permits the uncertainty associated with multiple data sources to be propagated to final model outputs (Maunder and Punt 2013). A disadvantage of the integrated modeling approach is the increased model complexity.

Stock Synthesis is implemented here using an area as fleets approach by including multiple fleets within a spatially-aggregated assessment model. See, for example, the multiple references in Fisheries Research volume 158, 2014, resulting from the 2013 Center for the Advancement of Population Assessment Methodology (CAPAM) workshop organized to address recent methodological advances in modeling selectivity, particularly, issues surrounding complications and potential confounding with related parameters in the assessment model (Maunder and Crone 2014; e.g., Hurtado-Ferro *et al*. 2014; Sampson 2014; Punt *et al*. 2014; Waterhouse *et al.* 2014). In the areas as fleets approach, each fleet is assigned its own size selectivity pattern. Size selectivity is the probability of a fleet capturing a shark of a given size relative to the probability of that fleet capturing a shark of a different size (here the size at which the probability of capture is highest). Size selectivity for each fleet is either fixed or estimated within the assessment model based on the available size composition data. The resulting size selectivity for each fleet is interpreted as the combined effect of availability to the fishing gear (i.e., a shark of a given size is in the fishing area when fishing occurs and is available to be captured) and size selectivity of the fishing gear. Previous examples of the areas as fleets approach implemented in Stock Synthesis are available for ICCAT North Atlantic pelagic shark stocks from previous assessments conducted within the ICCAT process (Anon. 2016, 2017c; e.g., Courtney 2016 and Courtney *et al*. 2017a, 2017b), and for northwest Atlantic coastal shark stocks assessed within the Southeast Data Assessment and Review (SEDAR) process (Anon. 2015, 2017a, 2018, 2020).

A sex-specific model is implemented to allow for observed differences in length at age between sexes. Length composition data are obtained from ICCAT and life history inputs are obtained from the Shark Working Group. Sex-specific natural mortality and growth are implemented, and sex-specific selectivity is implemented for fleets with sex-specific length composition data.

A two-stage Francis (2011; 2017) data weighting approach is 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. An example of this approach was previously investigated for North Atlantic blue shark and described in Courtney *et al.* (2017b). This approach was subsequently implemented for North Atlantic shortfin mako shark (Courtney *et al.* 2017a).

The continuity of Stock Synthesis model results presented here is evaluated relative to preliminary model runs conducted for the 2015 ICCAT blue shark stock assessment in the North Atlantic (Courtney 2016). The effects of modeling multiple data components simultaneously are evaluated here with model sensitivity analyses to CPUE groupings recommended by the Shark Working Group (Anon. 2023; SCRS/2023/061, Rice In Prep.) and to the steepness of the stock recruitment relationship and natural mortality at age provided in SCRS/2023/115 (Cortés and Taylor In Prep.).

Ending year (2021) stock status relative to maximum sustainable yield (MSY) reference points are not provided here because of the wide range of model results obtained from preliminary sensitivity analyses. The wide range of model results obtained here could, in the future, be grouped into a structural uncertainty grid and used to evaluate the effects of potential management actions relative to structural assessment uncertainty (e.g., SCRS/2023/051, Rice and Courtney In Prep.).

2. Methods

A length-based age-structured statistical model was implemented for the North Atlantic blue shark stock with Stock Synthesis version 3.30.15.00 (SS3; Methot *et al.* 2020). Preliminary North Atlantic blue shark stock assessment models were fit to the available catch, CPUE, length composition, and life history data compiled by the Shark Working Group during the 2023 Blue Shark Data Preparatory Meeting (Anon. 2023). A sex-specific model was implemented to allow for differences in von Bertalanffy growth (VBG) in length at age identified between sexes for the North Atlantic blue shark stock (Carlson *et al.* 2023). The preliminary steepness of the stock recruitment relationship and natural mortality at age were obtained from SCRS/2023/115 (Cortés and Taylor In Prep.; Pers. Comm. E. Cortés).

2.1 Time series data

Available time series of catch, abundance, and length composition data considered for use in the SS3 model runs were assigned to “fleets” and “surveys” as summarized in **Table 1**. The start year of the model was 1971, and the end year was 2021.

2.1.1 Catch

North Atlantic blue shark catch in metric tons (t) was obtained from data compiled during the 2023 Data Preparatory Meeting (**Table 2** and **Figure 1**) and assigned here to “fleets” F1 – F10 for use in preliminary 2023 North Atlantic blue shark SS3 model runs.

2.1.2 Indices of abundance

Indices of relative abundance for North Atlantic blue shark were obtained from data compiled during the 2023 Data Preparatory Meeting (**Table 3** and **Figure 2**) and assigned here to “surveys” S1 – S8 for use in preliminary 2023 North Atlantic blue shark SS3 model runs. Updated indices of relative abundance for North Atlantic blue shark were obtained from SCRS/2023/046 (Revised submission 5 May, 2023; their Table 3a; **Table 4**) and assigned here to “surveys” S4 and S5 for use in preliminary 2023 North Atlantic blue shark SS3 model runs.

2.1.3 Length composition

Available length composition for use in preliminary 2023 North Atlantic blue shark SS3 model runs were obtained from ICCAT (**Table 5** and **Figure 3**) and assigned to fishing “fleets” F1 – F10. Years with small sample size (total number of sharks measured < 100) were excluded from the preliminary models (see **Appendix B** for reference case model fits to annual length composition). Annual length composition sample size was entered in SS3 by fleet as the natural log of the number of sharks measured (where the annual number of sharks measured by fleet ≥ 100; **Table 5**). Sex-specific length composition data were used where available, otherwise combined sex data were used (**Table 5**).

Available length composition data were pooled into 10 cm fork length (FL) bins [35 – 380 cm FL]. A 10 cm FL data length bin width was chosen in order to remove a jagged pattern apparent at finer resolution (5 cm FL bin width). In Stock Synthesis, a finer bin width (e.g., 5 cm FL) can be established for internal calculation of numbers at length (population length bins) in contrast to those used to fit the available data (data length bins). However, for the purposes of this assessment, a 10 cm FL bin width was chosen for both population and data length bins. These modeling choices resulted in a total of 36 population and data length bins (a 20 cm lower bin :15 – 35 cm FL; followed by 10 cm bins: 35 – 380+ cm FL). The lower bin (15 - 35 cm FL) was included here to evaluate the effect of including a lower minimum size bin on the resulting fit to length composition data.

2.2 Life history

Life history inputs considered for use in preliminary 2023 North Atlantic blue shark SS3 model runs were obtained from data first assembled at the 2014 Intersessional Meeting of the Shark Species Group (Anon. 2015b), updated during the 2016 Intersessional Meeting of the Shark Species Group (Anon. 2017b) and updated again during the 2023 Blue Shark Data Preparatory Meeting (Anon. 2023). A sex-specific model was implemented in preliminary 2023 North Atlantic blue shark SS3 model runs to allow for differences in von Bertalanffy growth (VBG) in length at age identified between sexes for the North Atlantic blue shark stock (Carlson *et al*. 2023), as summarized in **Table 6**.

2.2.1 Growth

Growth in length at age was assumed to follow a von Bertalanffy two parameters (L1 and L2) growth (VBG) relationship, and sex-specific growth was implemented in SS3 by modeling female and male VBG with updated parameters provided in (**Tables 6** and **7** and **Figure 4**).

A normal distribution in mean length at each age was assumed and was implemented in SS3 separately for females and males (**Figure 5**). The CV in mean length at age was assumed to be a linear function of length. Values for the CVs in length at each age were obtained from a previous analysis conducted for North Atlantic shortfin mako (SCRS/2017/111; R. Coelho, Pers. Comm.; Anon 2017c). In the previous analysis, the sample standard deviation in observed length at each age for North Atlantic shortfin mako was divided by the mean in observed length at each age. The resulting CV for LAmin was computed as the average CV for ages <= 8 yr. The resulting CV for Linf was computed as the average CV for ages > 8 yr. The resulting CVs for LAmin were 0.093 and 0.097 for female and male North Atlantic blue shark, respectively. The resulting CVs for Linf were 0.090 and 0.082 for female male North Atlantic blue shark, respectively. CVs were linearly interpolated between LAmin and Linf. The break point at age (8 yr) was chosen because this was the approximate age after which male and female growth for North Atlantic shortfin mako began to differ noticeably.

A combined-sex length-weight relationship (**Table 6**) was implemented in SS3 to convert body length (cm FL) to body weight (kg) for both males and females.

2.2.2 Pup production

Annual pup production at each age was implemented in SS3 model runs as described in (**Table 8**).

2.3 Model structure

2.3.1 Natural mortality

For continuity analyses with the 2015 North Atlantic blue shark preliminary model run 6 (Courtney 2016), sex-specific natural mortality rates at each age (Ma) were fixed at values obtained independently with life history invariant methods, as described in the 2015 assessment document SCRS/2015/142 (Cortés 2016) and summarized here Section 2.4 below and in **Table 9.**

Structural uncertainty was then evaluated independently stock-recruit steepness parameter, *h*, and the sex-specific natural mortality at each age (M_a) obtained independently of the stock assessment model with life history invariant methods described in document SCRS/2023/115 (Cortés and Taylor In Prep.; Pers. Comm. E. Cortés 7/5/2023) and summarized below in Section 2.5, **Table 13** and in **Figure 6.**

2.3.2 Stock recruitment

A Beverton-Holt stock-recruitment relationship was assumed and implemented in SS3. In Stock Synthesis, the Beverton-Holt stock-recruitment model is parameterized with three parameters, the log of unexploited equilibrium recruitment (R_0), the steepness parameter, *h*, and a parameter representing the standard deviation in recruitment (σ_R) (Methot and Wetzel 2013; e.g., Wetzel and Punt 2011a, 2011b). Parameter estimation for ln(R_0) utilized a normal prior with a large standard deviation (Pr_SD) along with independent minimum and maximum boundary conditions (Min, Max). Implementation of a normal prior is described in the manual for Stock Synthesis (Methot *et al*. 2020). The steepness parameter, *h*, describes the fraction of the unexploited recruits produced at 20% of the equilibrium spawning biomass level.

For continuity analyses with the 2015 North Atlantic blue shark preliminary model run 6 (Courtney 2016), the stock-recruit steepness parameter was fixed at a value obtained analytically based on life history, h = 0.73, as described in the 2015 assessment document SCRS/2015/142 (Cortés 2016) and summarized here in Section 2.4 below and in **Table 9**. Structural uncertainty was then evaluated to the externally derived stock-recruit steepness parameter, *h*, as described above for natural mortality**.**

The parameter representing the standard deviation in recruitment, σ_R, was fixed at the value of 0.28, which was previously obtained from 2017 preliminary Stock Synthesis model runs conducted for North Atlantic shortfin mako (Courtney *et al.* 2017a) as follows. The parameter representing the standard deviation in recruitment, σ_R, for North Atlantic shortfin mako (Courtney *et al*. 2017a) was adjusted one time from an initial value of 0.4 to the value of 0.28 in order match the RMSE of recruitment variability obtained in SS3 during the main recruitment deviation period (1990 – 2012). Additional iterative adjustments for the standard deviation in recruitment, σ_R, based on the RMSE of recruitment variability obtained in SS3 were not attempted because the adjustments may tend to zero (Courtney, D. Pers. Observation from the CAPAM hosted technical workshop on data conflict and weighting, likelihood functions, and process error in La Jolla, CA, USA, October 19-23, 2015). In addition, lower values for the standard deviation in recruitment, evaluated in preliminary model runs for North Atlantic shortfin mako (Courtney *et al.* 2017a) resulted in a noticeable trend in recruitment (matching the trend in CPUE), which did not seem plausible. For example, a similar trend in recruitment, matching the CPUE trends, was observed in preliminary model runs for North Atlantic shortfin mako (Courtney *et al.* 2017a) when estimation of early recruitment deviations began in either 1951 (near start year of the model) or in 1966 (the first year for which early recruitment deviations were correlated with other data in the assessment).

Spawning stock size in the stock-recruitment relationship was modelled as spawning stock fecundity (SSF), and calculated here as the sum of female numbers at age (reported in 1,000s) multiplied by annual female pup production at age (male and female pups, assuming a 1:1 ratio of male to female pups) at the beginning of each calendar year.

An examination of preliminary SS3 output with the program r4ss (Taylor *et al.* 2021a, 2021b) indicated that there was little recruitment information in the data prior to about 1990, that there was a ramp up in recruitment information from about 1990 to 2000 consistent with availability of about 4 years of EU-ESP length composition data beginning in 1997 (**Figure 7**), and a ramp back down after about 2019 consistent with the decreasing influence of length composition data on recruitment with proximity (3 years) to the terminal year of the model (2021, e.g., see **Figure 11**). Consequently, a modeling decision was made to model main recruitment deviations in these SS3 model runs for the years 1995 – 2019, with early recruitment deviations beginning 5 years prior to the main recruitment in 1990. The estimation of main recruitment deviations in SS3 is zero centered. The estimation of early recruitment deviations and late recruitment deviations in SS3 are not zero centered. Consequently, the modeling decision to include early and late recruitment deviations allows for recruitment in in these periods to be estimated without biasing recruitment estimates in the main period.

Recruitment deviations are estimated on the log scale in Stock Synthesis. Consequently, the expected recruitments require a bias adjustment so that the resulting recruitment level on the standard scale is mean unbiased (Methot and Taylor 2011). The years chosen for bias adjustment, and the maximum bias adjustment parameter value were obtained from Stock Synthesis output with the program r4ss and implemented in SS3 (Taylor *et al*. 2021a, 2021b; e.g., **see Figure 11**):

```
1961      #_last_early_yr_nobias_adj_in_MPD
1999      #_first_yr_fullbias_adj_in_MPD
2019.4    #_last_yr_fullbias_adj_in_MPD
2021.3    #_first_recent_yr_nobias_adj_in_MPD
0.5164    #_max_bias_adj_in_MPD
```

2.3.3 Selectivity

A double normal selectivity function (Stock Synthesis selectivity pattern 24; Methot *et al*. 2020) was implemented in SS3 for fleets F1 – F10 (**Tables 1** and **5**) and fit to the available length composition data (10 cm FL bin width; **Figure 3**). The double normal selectivity function includes six parameters: p1 - Peak value, p2 - Top logistic, p3 - Ascending width, p4 - Descending width, p5 - Selectivity at initial size bin, and p6 - Selectivity at final size bin. Initial values for all parameters were obtained by fitting the selectivity curve by eye to the available length composition data separately for each fleet externally to the stock assessment model with a Microsoft Excel spreadsheet. Selectivity at the first bin (p5) was subsequently fixed at its value determined by eye, and the remaining parameters were estimated within SS3 with initial values set to those obtained by eye. This approach allowed for either asymptotic selectivity or dome-shaped selectivity depending upon the data. Parameter estimation for double normal selectivity parameters utilized a diffuse symmetric beta prior (Pr_SD = 0.05) scaled between parameter bounds. A diffuse symmetric beta prior imposed larger penalty near minimum and maximum boundary conditions (Min, Max) and is described in the manual for Stock Synthesis (Methot *et al.* 2020). Because there was no prior information, other than the fit by eye to available data, the prior means were set equal to the initial values obtained from the fit by eye.

Sex-specific selectivity was implemented in SS3 with the gender=3 option for fleets with sufficient sex-specific length composition data (**Table 5**). Sex-specific selectivity was implemented as a parameter offset to the double normal selectivity, which included the estimation of five additional parameters per fleet: p1-offset (peak), p3-offset (ascending width), p4-offset (descending width), p6-offset (selectivity at final size bin), and sex specific apical selectivity. Parameter offsets to double normal selectivity were estimated with a diffuse normal prior (SD = 1000) and minimum and maximum boundary conditions (Min, Max). For each fleet, the proportion of female and male the length composition was computed. The sex with the lower proportion was offset from the sex with the higher proportion. This approach resulted in maximum selectivity equal to one so that the resulting apical fishing mortality *F* (the *F* that would be obtained when multiplied by maximum selectivity) was comparable among fleets. Initial values for selectivity offset parameters were set equal to the difference in initial values obtained for the respective double normal parameters. The minimum and maximum boundary conditions for selectivity offset parameters were adjusted by trial and error in preliminary model runs to insure that parameter estimates were not hitting upper or lower bounds. The adjustment of minimum and maximum boundary conditions for offset parameters were also evaluated to ensure that initial values of the jitter diagnostic resulted in reasonable starting parameter values.

This approach resulted in asymptotic selectivity for some fleets (F2_JPN, F3_CTP, F8_BEL, F9_OTH) and dome shaped selectivity for other fleets (F1_EU_ESP, F4_USA and F6_CAN that mirrored F4_USA selectivity, F5_VEN, F7_CPR and F10_EU_POR). For example see **Figure 8**.

2.3.4 Data weighting

A two-stage (Francis 2011) data weighting approach was implemented. In stage one, a minimum average standard error (SE; on the natural log scale) was implemented in SS3 for each CPUE series. The minimum SE was based on fitting a simple smoother to each CPUE (on the natural log scale) external to the stock assessment and then calculating the residual variance of each CPUE relative to the smooth curve (e.g., Francis 2011; Lee *et al.* 2014a, 2014b; Courtney *et al.* 2017a, 2017b). In stage two, the effective sample size (Effn) of each length composition data set was obtained from the residuals of the Stock Synthesis model fit to each length composition data set using either the Francis (2011) method or the McAllister and Ianelli (1997) harmonic mean method. The Francis (2011) and McAllister and Ianelli (1997) data weighting methods are reviewed in Francis (2017) and Punt (2017). Data weighting philosophies in fisheries stock assessment models are discussed in Punt *et al*. (2014).

Stage 1

A LOESS smoother was fit to each CPUE data on the log scale (**Appendix A**). The square root of the residual variance was calculated for each CPUE series based on the fit of the simple smoother to the CPUE series on the log scale as

(Eq. 1)

$$\mathrm{RMSE}_{smoother} = \sqrt{\left(\tfrac{1}{N}\right)\sum_{t=1}^{N}\left(Y_t - \hat{Y}_t\right)^2} \; .$$

The value for Y_t is the observed CPUE in year *t* on the log scale, $\hat{Y}_t$ is the predicted CPUE in year *t* obtained from the smoother fit to the data on the log scale, and *N* is the number of CPUE observations (Francis 2011; Lee *et al.* 2014a, 2014b; e.g., Courtney *et al.* 2017a, 2017b). The average annual CV input (SE.in) for each CPUE series in the Stock Synthesis was assumed to be equal to the average SE on the log scale. The SE was then adjusted based on the expectation that the stock assessment model would fit each CPUE time series **at best** as well as a LOESS smoother (Francis 2011; Lee *et al.* 2014a, 2014b; e.g., Courtney *et al.* 2017a, 2017b).

On one hand, if SE.in for a CPUE series was less than $\mathrm{RMSE}_{smoother}$ for that CPUE series, then the input SE for the CPUE series was adjusted (SE.adj) in Stock Synthesis before running the model so that the new average SE was equal to $\mathrm{RMSE}_{smoother}$ (SE.in + SE.adj = $\mathrm{RMSE}_{smoother}$). On the other hand, if SE.in for a CPUE series was greater than or equal to the $\mathrm{RMSE}_{smoother}$ for that CPUE series, then the SE of the CPUE series was not adjusted in the Stock Synthesis model. All calculations were implemented in R (R Core Team 2021).

The resulting variance adjustments for surveys are provided below.

Survey	Mean of input CV	Variance adjustment	Mean of adjusted input CV
S1_ESP-LL-N	0.0284	0.051	0.0789
S2_JP-LL-N	0.1461	0.005	0.1510
S3_CTP-LL-N	0.0697	0.562	0.6320
S4_US-Obs-E	0.2971	0.000	0.2971
S5_US-Obs-L	0.2826	0.000	0.2826
S6_VEN-LL	1.3730	0.000	1.3730
S7_POR-LL-N	0.0782	0.007	0.0849
S8_MOR-LL-N	0.0617	0.140	0.2020

Stage 2

For length composition data sets with more than ten years of data, Effn was estimated using the Francis method (Punt 2017, his equation 1.C "Francis tuning method"). Otherwise, Effn was estimated using either the Francis method or the McAllister and Ianelli harmonic mean method (Punt 2017, his equation 1.B "McAllister-Ianelli-2 tuning method"), which resulted in the smaller Effn. Sample size for the Francis method is based on the number of years with length composition data (Punt 2017, his Table 2). In contrast, sample size for the McAllister and Ianelli harmonic mean method is based on the number of lengths measured each year (Punt 2017, his Table 2). Consequently, the Francis method may not be as robust for small sample sizes. The number of years (10) was chosen arbitrarily based on previous experience. Effn estimates were obtained from the R package r4ss (Taylor *et al.* 2021a, 2021b) for the Francis method, and from Stock Synthesis output (Methot and Wetzel 2013; Methot *et al.* 2020) for the McAllister and Ianelli harmonic mean method.

The resulting variance adjustments for length composition are provided below.

Length composition data source	Number of years with length composition	Adjustment method	Sample size adjustment
F1_EU_ESP	25	Francis Effn	3.781
F2_JPN	24	Francis Effn	1.127
F3_CTP	9	Francis Effn	1.908
F4_USA	15	Francis Effn	1.689
F5_VEN	15	Francis Effn	0.724
F7_CPR	3	Francis Effn	1.176
F8_BEL	5	Francis Effn	0.200
F9_OTH	5	Francis Effn	0.241
F10_EU_POR	17	Francis Effn	0.556

2.3.5 Initial fishing mortality

The population was assumed to be in a fished state of equilibrium at the start of the model (1971). The population age structure and overall size in the unfished equilibrium year (1970) was offset as a function of the parameter estimate of the first year recruitment on the natural log scale, ln(R_0), and the initial equilibrium catch for three fleets: F1_ EU-ESP (13,817 t), F2_ JPN (2,501 t), and F3_ CTP (760 t). Initial equilibrium catch was assumed to be equal to the average catch from 1971 – 1980 for each fleet (**Table 2**).

2.3.6 Model convergence and diagnostics

Model convergence was based on whether or not the Hessian inverted (i.e., the matrix of second derivatives of the likelihood with respect to the parameters, from which the asymptotic standard error of the parameter estimates is derived in ADMB; Fournier *et al.* 2011). Other convergence diagnostics were also evaluated. Excessive CVs on estimated quantities (>> 50%) or a large final gradient (>1.00E-05) were indicative of uncertainty in parameter estimates or assumed model structure. The correlation matrix was also examined for highly correlated (> 0.95) and non-informative (< 0.01) parameters. Parameters estimated at a bound were a diagnostic for possible problems with data or the assumed model structure. Fits to CPUE and patterns in Pearson's residuals of fits to length composition data were examined as diagnostics for problems with data or the assumed model structure.

2.3.7 Uncertainty and measures of precision

Uncertainty in estimated and derived parameters was obtained from asymptotic standard errors calculated from the maximum likelihood estimates of parameter variances at the converged solution. In SS3 asymptotic standard errors are obtained for derived quantities by including the derived parameters in the inverted Hessian matrix calculation.

2.4 Continuity analyses

Five continuity analyses scenarios were evaluated:

2015 Continuity Scenario 1: Ngenders "1", Fecundity "39" [female fecundity]
2015 Continuity Scenario 2: Ngenders "-1", Fecundity "39" [female fecundity]
2015 Continuity Scenario 3: Ngenders "1", Fecundity "19.5" [per capita fecundity]
2023 BSH-N Continuity: Ngenders "2", Fecundity "39"
2023 BSH-N Ref Case: Ngenders "2", Fecundity "39"

Stock Synthesis model continuity was evaluated relative to the 2015 ICCAT North Atlantic Preliminary Run 6 (Courtney 2016), which was implemented in Stock Synthesis version 3.24U (e.g., Methot 2015). In contrast, the 2015 Continuity Scenarios 1 – 3 implemented the same 2015 ICCAT North Atlantic Preliminary Run 6, but in an updated version of Stock Synthesis, 3.30.15.00 (Methot *et al.* 2020). The 2015 Continuity Scenarios 1 – 3 also evaluate the effect of implementing three alternative fecundity specifications, as described above.

The "2023 BSH-N Continuity" model run, implemented in Stock Synthesis version 3.30.15.00, included updated 2023 catch, CPUE, and length composition. However, the "2023 BSH-N Continuity" model used natural morality, *M*, and steepness, *h*, obtained from the 2015 ICCAT North Atlantic Preliminary Run 6 (Courtney 2016) as described in **Table 9.**

In contrast, the "2023 BSH-N Ref Case" model, implemented in Stock Synthesis version 3.30.15.00, included updated 2023 catch, CPUE, and length composition, as above, but also included updated median M (0.178) and median h (0.86) obtained from Monte Carlo simulation of updated vital rates with a Leslie matrix approach for the North Atlantic stock (SCRS/2023/115, their Table 5).

Continuity was evaluated with an index of average percent error developed to evaluate the precision of age determinations (Beamish and Fournier 1981). Two indices of precision were calculated. The Index_of_Average_Percent_Error_1 evaluated SSF (1,000s of pups) for unfished equilibrium (SSF_0), year 1971 (SSF_1971), and year 2013 (SSF_2013). In contrast, the Index_of_Average_Percent_Error_2 evaluated error in SSF/SSF_0 for year 1971 (SSF_1971/SSF_0), and year 2013 (SSF_2013/SSF_0).

Average percent error was calculated as described in the following pseudo code:

```
#New_1 <- c(SSF_0, SSF_1971,SSF_2013)
#New_2 <- c(SSF_1971/SSF_0,SSF_2013/SSF_0)

#Average_Error_1 <- abs(New_1-Ref_1)/Ref_1
#Average_Error_2 <- abs(New_2-Ref_2)/Ref_2

#Index_of_Average_Error_1 <- sum(Average_Error_1)/length(Average_Error_1)
#Index_of_Average_Error_2 <- sum(Average_Error_2)/length(Average_Error_2)

#Index_of_Average_Percent_Error_1 <- Index_of_Average_Error_1*100
#Index_of_Average_Percent_Error_2 <- Index_of_Average_Error_2*100
```

2.5 Structural uncertainty analyses

2.5.1 Structural uncertainty to CPUE

CPUE structural uncertainty scenarios used the 2015 North Atlantic blue shark model stock-recruit steepness parameter, h, and the sex-specific natural mortality at each age (M_a), obtained as described above in **Table 9**.

Structural uncertainty was then evaluated to North Atlantic blue shark CPUE groupings recommended by the Shark Working Group (Anon 2023; **Table 10**):

Grouping CPUE Scenario 1: All 2023 North Atlantic CPUE fleets (**Tables 3** and **4**);
Grouping CPUE Scenario 2: 2023 North Atlantic CPUE from fleets assumed to target blue shark;
Grouping CPUE Scenario 3: 2023 North Atlantic CPUE from fleets assumed not to target blue shark;
Grouping CPUE Scenario 4: Hierarchical cluster analysis alternative 1;
Grouping CPUE Scenario 5: Hierarchical cluster analysis alternative 2;
Grouping CPUE Scenario 6: Hierarchical cluster analysis alternative 3.

Structural uncertainty was evaluated to including each North Atlantic blue shark CPUE series (**Tables 3** and **4**) one at a time in the Stock Synthesis model (**Table 11**):

Including each CPUE Scenario 1: Include all 2023 North Atlantic CPUE fleets (**Tables 3** and **4**);
Including each CPUE Scenario 2: Include only S1 (ESP-LL-N);
Including each CPUE Scenario 3: Include only S2 (JPN-LL-N);
Including each CPUE Scenario 4: Include only S3 (CTP-LL-N);
Including each CPUE Scenario 5: Include only S4 (US-Obs-E) and S5 (US-Obs-L);
Including each CPUE Scenario 6: Include only S6 (VEN-LL);
Including each CPUE Scenario 7: Include only S7 (POR-LL-N);
Including each CPUE Scenario 8: Include only S8 (MOR-LL).

Structural uncertainty was evaluated to removing each North Atlantic blue shark CPUE series (**Tables 3** and **4**) one at a time from the Stock Synthesis model (**Table 12**):

Removing each CPUE Scenario 1: Include all 2023 North Atlantic CPUE fleets (**Tables 3** and **4**);
Removing each CPUE Scenario 2: Remove only S1 (ESP-LL-N);
Removing each CPUE Scenario 3: Remove only S2 (JPN-LL-N);
Removing each CPUE Scenario 4: Remove only S3 (CTP-LL-N);
Removing each CPUE Scenario 5: Remove only S4 (US-Obs-E) and SN5 (US-Obs-L);
Removing each CPUE Scenario 6: Remove only S6 (VEN-LL);
Removing each CPUE Scenario 7: Remove only S7 (POR-LL-N);
Removing each CPUE Scenario 8: Remove only S8 (MOR-LL).

2.5.2 Structural uncertainty to externally derived natural mortality and steepness

Structural uncertainty to externally derived natural mortality, *M*, and steepness, *h*, was evaluated with seven scenarios developed from SCRS/2023/115:

M and h Scenario 1: Median M and h obtained from Monte Carlo simulation.
M and h Scenario 2: LCL M and h obtained from Monte Carlo simulation.
M and h Scenario 3: UCL M and h obtained from Monte Carlo simulation.
M and h Scenario 4: Deterministic M at age obtained with 6 life-history invariant methods (separately for females and males) and corresponding deterministic h obtained for the North Atlantic stock.
M and *h* Scenario 5: Deterministic M at age obtained with 6 life-history invariant methods (average of females and males) and corresponding deterministic h obtained for the North Atlantic stock.
M and *h* Scenario 6: Deterministic M at age obtained with the Dureuil *et al.* (2021) method (separately for females and males) and corresponding deterministic h.
M and *h* Scenario 7: Deterministic M at age obtained with the Dureuil *et al.* (2021) method (average of females and males) and corresponding deterministic h.

Estimates of instantaneous natural mortality rates (yr-1) (female and male) were obtained with 6 life-history invariant methods used in the deterministic life tables SCRS/2023/115 (Pers. Comm. E. Cortés 7/5/2023; **Table 13 Panel A**). Estimates of instantaneous natural mortality rates (yr-1) (female and male) were obtained with the Dureuil *et al.* (2021) method SCRS/2023/115 (Pers. Comm. E. Cortés 7/5/2023; **Table 13 Panel B**).

M and h Scenario 1: Median M and h obtained from Monte Carlo simulation. Natural mortality (M): Median M obtained from Monte Carlo simulation of vital rates with a Leslie matrix approach for the North Atlantic stock (0.178; SCRS/2023/115, their Table 5). Steepness (h): Median h obtained from Monte Carlo simulation of vital rates with a Leslie matrix approach for the North Atlantic stock (0.86; SCRS/2023/115, their Table 5).

M	0.178
h	0.86

M and h Scenario 2: LCL M and h obtained from Monte Carlo simulation. Natural mortality (M): LCL M obtained from Monte Carlo simulation of vital rates with a Leslie matrix approach for the North Atlantic stock (0.148; SCRS/2023/115, their Table 5). Steepness (h): LCL h obtained from Monte Carlo simulation of vital rates with a Leslie matrix approach for the North Atlantic stock (0.57; SCRS/2023/115, their Table 5).

M	0.148
h	0.57

M and h Scenario 3: UCL M and h obtained from Monte Carlo simulation. Natural mortality (M): UCL M obtained from Monte Carlo simulation of vital rates with a Leslie matrix approach for the North Atlantic stock (0.210; SCRS/2023/115, their Table 5). Steepness (h): UCL h obtained from Monte Carlo simulation of vital rates with a Leslie matrix approach for the North Atlantic stock (0.96; SCRS/2023/115, their Table 5).

M	0.21
h	0.96

M and h Scenario 4: Deterministic M at age obtained with 6 life-history invariant methods (separately for females and males) and corresponding deterministic h obtained for the North Atlantic stock. Natural mortality (M): Separate female and male estimates of instantaneous natural mortality rates (yr-1) obtained with 6 life-history invariant methods used in the deterministic life tables SCRS/2023/115. Steepness (h): Corresponding deterministic h obtained for the North Atlantic stock (0.87; SCRS/2023/115, their Table 5).

M	**Table 13** Panel A (female and male)
h	0.87

M and h Scenario 5: Deterministic M at age obtained with 6 life-history invariant methods (average of females and males) and corresponding deterministic h obtained for the North Atlantic stock. Natural mortality (M): Average of female and male estimates of instantaneous natural mortality rates (yr-1) obtained with 6 life-history invariant methods used in the deterministic life tables SCRS/2023/115. Steepness (h): Corresponding deterministic h obtained for the North Atlantic stock (0.87; SCRS/2023/115, their Table 5).

M	**Table 13** Panel A (average of female and male)
h	0.87

M and h Scenario 6: Deterministic M at age obtained with the Dureuil et al. (2021) method (separately for females and males) and corresponding deterministic h. Natural mortality (M): Separate female and male estimates of instantaneous natural mortality rates (yr-1) obtained with the Dureuil *et al.* (2021) method used in the deterministic life tables SCRS/2023/115. Steepness (h): Corresponding deterministic h obtained for the North Atlantic stock (0.69; SCRS/2023/115, their Table 5).

M	**Table 13** Panel B (female and male)
h	0.69

M and h Scenario 7: Deterministic M at age obtained with the Dureuil et al. (2021) method (average of females and males) and corresponding deterministic h. Natural mortality (M): Average of female and male estimates of instantaneous natural mortality rates (yr-1) obtained with the Dureuil *et al.* (2021) method used in the deterministic life tables SCRS/2023/115. Steepness (h): Corresponding deterministic h obtained for the North Atlantic stock (0.69; SCRS/2023/115, their Table 5).

M	**Table 13** Panel B (average of female and male)
h	0.69

2.6 Preliminary reference case model

M and h Scenario 1 is identified here as a 2023 Reference Case model that may be useful as a starting point for continued model development during the 2023 blue shark stock assessment. The 2023 Reference Case model used 2023 catch, CPUE, and length composition along with 2023 median *M* (0.178) and median *h* (0.86) obtained from Monte Carlo simulation of vital rates with a Leslie matrix approach for the North Atlantic stock (SCRS/2023/115, their Table 5).

3. Results

Model results are presented below for the 2023 Reference Case model, identified as described above, along with the continuity analyses and the structural uncertainty analyses.

3.1 Convergence diagnostics

The Hessian matrix inverted and was presumably positive definite for the 2023 Reference Case model, identified as described above, along with the continuity analyses and the structural uncertainty analyses described above. The final gradient was reasonably small (< 1.00E-05) for the 2023 Reference Case model, identified as described above, along with the continuity analyses and the structural uncertainty analyses described above. Some parameters, depending upon the model run, were estimated above the maximum correlation threshold *(cormax = 0.95)* or below the minimum correlation threshold (*cormin* = 0.01). Some parameters, depending upon the model run, were also estimated very near parameter boundaries. However, in each of these cases the boundary condition was deemed to not be informative. For example, initial *F* was estimated for F3_ CTP at very small values, near the lower bound of the estimate. Similarly, some selectivity parameters were also estimated near a bound in some model runs, but, in contrast, not estimated near the bound in other runs. Individual parameter CVs and gradients were not evaluated because of the large number of model runs evaluated and their preliminary nature.

3.2 Model fits

3.2.1 Indices of abundance

Predicted and observed standardized indices of relative abundance obtained for the 2023 Reference Case model, identified as described above, are provided in **Figure 9** for each standardized index of relative abundance as defined in **Tables 1**, **3**, and **4**. Fits on the nominal scale and on the log scale are provided. In many cases, e.g., S1_ESP-LL-N, the model fits to CPUE are very poor. This result indicates that additional diagnostics may be required to evaluate the possibility of data conflict among the many data sources included in the SS3 model (Hurtado-Ferro *et al.* 2014; Maunder and Piner 2015, 2017; Carvalho *et al.* 2017, 2021; Maunder *et al.* 2020; Minte-Vera *et al.* 2017, 2021; e.g., Courtney *et al.* 2020 and Karp *et al.* 2022).

3.2.2 Length compositions

Model predicted and observed aggregated length compositions (as defined in **Tables 1** and **5)** are provided in **Figure 10.** Fits to aggregate length compositions appeared to be reasonably accurate for some fleets (e.g., F1_EU_ESP) – indicating that the estimated selectivity curves removed sharks from the modelled population in aggregate at comparable length to that observed in the data. However, model fits to aggregate length compositions for some other fleets resulted in poor fit at some sizes. This result indicates that additional model structure may be needed to address the poor fits to some fleets, e.g., time blocks in selectivity or alternative more flexible selectivity model formulations such as a random walk in selectivity e.g., F2_JPN **(Figure B.2)** as discussed below. However, before additional model structure is added to selectivity, another possibility is that the length data itself may require further evaluation and refinement to insure that the data are representative, both in aggregate and annually, of the size distribution of sharks encountered by each fleet. For example, F4_USA exhibited spikes in size distribution that were not present in the data used for the previous assessment (Courtney 2016 his Figures 2 and 3). In contrast, F10_EU_POR exhibited a bimodal distribution that was identified during the previous assessment as resulting from geographic differences in size of blue sharks encountered by the fleet at about 30ºN within the North Atlantic (north of 5ºN) (Anon. 2016, their Figures 1 and 2). However, further evaluation and refinement of input length composition data here was beyond the scope of the current assessment due to time constraints.

Fits to annual length compositions by fleet are provided in **Appendix B**. Fits to the annual length compositions by fleet were generally poorer than fits to aggregate length composition. In some cases, e.g., F2_JPN **(Figure B.2),** as discussed above**,** there were obvious systematic patterns observed in the residuals (trends in patterns of positive or negative residuals) suggesting that the addition of time blocks to selectivity may improve fit for those fleets. However, in other cases, there were not obvious systematic patterns observed in the residuals making it more difficult to objectively determine how to improve the fits. However, as mentioned above, further evaluation and refinement of input length composition data here was beyond the scope of the current assessment due to time constraints.

The diameter of Pearson residuals was relatively small (≤ 2) for all fleets (**Appendix B**). Consequently, our assumption was that the relatively poor fit to annual length composition may not have had a large effect on the model results. However, this assumption was not tested. In addition, diagnostics should be evaluated for fits to length (e.g., Carvalho *et al*. 2021).

3.3 Estimated time series

3.3.1 Recruitment

Expected recruitment from the stock-recruitment relationship and the bias adjustment applied to the stock-recruitment relationship (**Figure 11**) along with estimated log recruitment deviations and estimated annual recruitment (**Figure 12**) are provided for the 2023 Reference Case model run. Estimation of early recruitment deviations was limited to 5 years before the start of main recruitment because preliminary model runs which allowed earlier recruitment deviations resulted in increasing trend in the early recruitment pattern (not shown).

3.3.2 Fishing mortality

Two calculations of exploitation rate were obtained from Stock Synthesis model output for the 2023 Reference Case model run. First, instantaneous annual fishing mortality rates (Continuous *F*) were estimated for each fleet F1 – F10 (**Figure 13,** upper panel). Second, the estimated total annual fishing mortality for all fleets combined (*F*) was calculated with SS3 option 4 = true *F* for range of ages (0-28), relative to the fishing mortality obtained by SS3 at equilibrium MSY in the same units (**Figure 13,** lower panel).

3.4 Continuity analysis

Stock Synthesis model continuity was evaluated relative to the 2015 ICCAT North Atlantic Preliminary Run 6 (Courtney 2016) as described above in Section 2.4 and summarized in **Table 14** and **Figure 14.** The index of average percent error for Model 1 (Continuity Scenario 1, as described in Section 2.4) was less than 1% for both SSF and SSF/SSF_MSY indicating good agreement between the 2015 ICCAT North Atlantic Preliminary Run 6 (Courtney 2016) implemented in Stock Synthesis version 324U (e.g., Methot 2015) and the same model implemented again here in Stock Synthesis version 3.30.15 (Methot *et al*. 2020).

In contrast, the index of average percent error for Models 2 and 3 (Continuity Scenarios 2 and 3, as described in Section 2.4) was 50% for SSF, but less than 1% SSF/SSF_MSY. This result indicated poor agreement in SSF between the 2015 ICCAT North Atlantic Preliminary Run 6 implemented here in Stock Synthesis version 3.30.15, and the same model implemented with alternative formulations for "Ngenders" and "Fecundity" as described in Section 2.4.

In comparison, the index of average percent error for Models 4 and 5 (2023 BSH-N Continuity and 2023 BSH-N Ref Case), as described in Section 2.4 was about 40% and 10% for SSF and SSF/SSF_MSY, respectively. This result also indicated poor agreement in SSF between the 2015 ICCAT North Atlantic Preliminary Run 6 implemented here in Stock Synthesis version 3.30.15, and the same model with alternative formulations for "Ngenders" and "Fecundity" in a two sex model as described in Section 2.4 (2023 BSH-N Continuity) and the same model with updated M and h obtained as described in Sections 2.5 and 2.6 (2023 BSH-N Ref Case).

3.5 Structural uncertainty analysis

3.5.1 Structural uncertainty to CPUE

Structural uncertainty was evaluated to North Atlantic blue shark CPUE groupings recommended by the Shark Working Group (Anon 2023) as described in Section 2.5.1 and **Table 10**. There was a wide range in resulting SSF (10^6 pups) for unfished equilibrium SSF (SSF_0), SSF in year 2013 (SSF_2013), and SSF at equilibrium MSY (SSF_MSY) as well as annual fishing mortality rate, *F*, for year 2013 (F_2013) and *F* at equilibrium MSY (F_MSY) **Table 15** and **Figure 15**.

Structural uncertainty was evaluated to including each North Atlantic blue shark CPUE series (**Tables 3** and **4**) one at a time in the Stock Synthesis model as described in Section 2.5.1 and **Table 11**. There was a wide range in resulting SSF (10^6 pups) for unfished equilibrium (SSF_0), year 2013 (SSF_2013), and at equilibrium MSY (SSF_MSY) as well as annual fishing mortality rate for year 2013 (F_2013) and at equilibrium MSY (F_MSY) **Table 16** and **Figure 16**.

Structural uncertainty was evaluated to removing each North Atlantic blue shark CPUE series (**Tables 3** and **4**) one at a time from the Stock Synthesis model as described in Section 2.5.1 and **Table 12.** There was a wide range in resulting SSF (10^6 pups) for unfished equilibrium (SSF_0), year 2013 (SSF_2013), and at equilibrium MSY (SSF_MSY) as well as annual fishing mortality rate for year 2013 (F_2013) and at equilibrium MSY (F_MSY) **Table 17** and **Figure 17**. However, the range of uncertainty was smaller than that from CPUE groupings recommended by the Shark Working Group (Anon 2023) and from including each North Atlantic blue shark CPUE series one at a time.

3.5.2 Structural uncertainty to externally derived natural mortality and steepness

Structural uncertainty to externally derived natural mortality, *M*, and steepness, *h*, was evaluated with seven scenarios developed from SCRS/2023/115 as described in Section 2.5.2 and **Table 13.** There was a very wide range in resulting SSF (10^6 pups) for unfished equilibrium (SSF_0), year 2013 (SSF_2013), and at equilibrium MSY (SSF_MSY) as well as annual fishing mortality rate for year 2013 (F_2013) and at equilibrium MSY (F_MSY) **Table 18** and **Figure 18**. The range of uncertainty was larger than that from CPUE groupings recommended by the Shark Working Group (Anon 2023) and including each North Atlantic blue shark CPUE series one at a time. The range of uncertainty was also larger than that obtained from continuity analysis exploring alternative formulations of Ngenders and Fecundity. Consequently highest priority in ongoing model development for North Atlantic blue shark Stock Synthesis model may be to reduce uncertainty in the range of externally estimate steepness and natural mortality.

4. Discussion

Model development is ongoing pending feedback from Shark Working Group.

Results of the continuity analysis indicated that updating the North Atlantic blue shark Stock Synthesis model from Stock Synthesis version 324U to version 3.30.15 had little effect. The index of average percent error for Model 1 (Continuity Scenario 1) was less than 1% for both SSF and SSF/SSF_MSY. In contrast, results of the continuity analysis indicated that alternative implementations for "Ngenders" and "Fecundity" in a single sex model (Continuity Scenarios 2 and 3, as described in Section 2.4) had a large effect on model results. In particular, the index of average percent error for Models 2 and 3 (Continuity Scenarios 2 and 3) was 50% for SSF

Results of structural uncertainty to North Atlantic blue shark CPUE groupings recommended by the Shark Working Group (Anon 2023) and to including each North Atlantic blue shark CPUE series (**Tables 3** and **4**) one at a time in the Stock Synthesis model as described in Section 2.5.1 had a large effect on estimates of stock size and fishing mortality. This result indicated that it may be useful to include both CPUE groupings and including CPUE one at a time within a structural uncertainty grid, in order to capture the range of uncertainty in CPUE within the assessment results.

Results of structural uncertainty to externally derived natural mortality, *M*, and steepness, *h*, had the largest effect on resulting estimates of stock size and fishing mortality. Consequently highest priority in ongoing model development for North Atlantic blue shark Stock Synthesis model may be to reduce uncertainty in the range of externally estimated steepness and natural mortality before including them within a structural uncertainty grid.

Other sources of structural uncertainty could also be explored. For example implementation of a stock–recruitment relationship based on pre-recruit survival was implemented in a recent shortfin mako assessment (Taylor *et al* 2013; Anon. 2017c), which was not evaluated in this assessment document. Similarly some historical North Atlantic blue shark CPUE series included in preliminary Stock Synthesis model runs for the previous blue shark assessment including JPLL-N-e Japan (1971-1993) and US-Obs_cru (1971-1991) (Courtney 2016) were not evaluated in this assessment document. In addition model sensitivity runs could be developed to explore improving fits to larger size sharks by assigning asymptotic selectivity to US length composition and fitting final selectivity for other fleets and increasing the CV in Linf to 0.2.

Once a final model or a structural uncertainty grid has been agreed upon by the Shark Working Group, additional evaluation of the model(s) could be conducted, for example implementation of a range of model diagnostics (e.g., Hurtado-Ferro *et al.* 2014; Carvalho *et al.* 2017, 2021; Maunder and Piner 2015, 2017, 2020; Minte-Vera *et al*. 2017, 2021; also see Courtney *et al.* 2020 and Karp *et al.* 2022).

If the final model or models included within a structural uncertainty grid reasonably pass a range of model diagnostics, then they could also be recommended for use in projections (e.g., Courtney and Rice 2020; Walter and Winker 2020; Winker *et al*. 2019).

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Table 1. Time series of catch, relative abundance, and length composition data considered for use in preliminary 2023 North Atlantic blue shark SS3 model runs.

Time series #	Symbol	Catch (t) and abundance (numbers or biomass)	Name	Definition	Length composition (10 cm FL bins)
1	F1	Catch (t)	EU-ESP	EU España (1971-2021)	EU España (1997-2021)
2	F2	Catch (t)	JPN	Japan (1971-2021)	Japan (1997-2020)
3	F3	Catch (t)	CTP	Chinese Taipei (1971-2021)	Chinese Taipei (2007-2021)
4	F4	Catch (t)	USA	USA (1981-2021)	USA (1992-2016)
5	F5	Catch (t)	VEN	Venezuela (1986-2021)	Venezuela (1994-2015)
6	F6	Catch (t)	CAN	Canada (1974-2021)	Mirror USA (F4)
7	F7	Catch (t)	CPR	China PR (1993-2021)	China PR (2015-2021)
8	F8	Catch (t)	BEL	Belize (2009-2021)	Belize (2010-2021)
9	F9	Catch (t)	OTH	Other (1978-2021)	Other (1994-2021)
10	F10	Catch (t)	EU-POR	EU Portugal (1984-2021)	EU Portugal (2003-2021)
11	S1	Relative abundance (biomass)	ESP-LL-N	EU España longline North Atlantic (1997-2021)	Mirror F1 EU_ESP
12	S2	Relative abundance (numbers)	JP-LL-N	Japan longline North Atlantic (1994-2021)	Mirror F2 JPN
13	S3	Relative abundance (numbers)	CTP-LL-N	Chinese Taipei longline North Atl. (2004-2021)	Mirror F3 CTP
14	S4	Relative abundance (numbers)	US-Obs-E	US Observer early time series (1992-2014)	Mirror F4 USA
15	S5	Relative abundance (numbers)	US-Obs-L	US Observer late time series (2015-2021)	Mirror F4 USA
16	S6	Relative abundance (numbers)	VEN-LL	Venezuela longline (1994-2013)	Mirror F5 VEN
17	S7	Relative abundance (biomass)	POR-LL-N	EU Portugal longline North Atl. (1997-2021)	Mirror F10_EU_POR
18	S8	Relative abundance (biomass)	MOR-LL	Morocco longline (2010-2021)	Mirror F3 CTP

Table 2. North Atlantic blue shark catch in metric tons (t) obtained from data compiled during the 2023 Data Preparatory Meeting and assigned here to "fleets" F1 – F10 for use in preliminary 2023 North Atlantic blue shark SS3 model runs as described in **Table 1**.

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	
Year	EU-ESP	JPN	CTP	USA	VEN	CAN	CPR	BEL	OTH	EU-POR	Grand Total
1971	14,085.24	1,257.87	737.79	-	-	-	-	-	-	0	16,080.90
1972	13,360.99	1,674.82	932.29	-	-	-	-	-	-	0	15,968.10
1973	15,954.11	653.64	901.07	-	-	-	-	-	-	0	17,508.82
1974	12,041.54	3,421.98	740.45	-	-	1.52	-	-	-	0	16,205.49
1975	15,596.15	4,380.45	658.98	-	-	15.92	-	-	-	0	20,651.50
1976	11,721.05	1,130.01	800.47	-	-	11.37	-	-	-	0	13,662.90
1977	13,773.06	3,295.02	742.17	-	-	85.67	-	-	-	0	17,895.93
1978	15,030.08	3,368.29	734.21	-	-	1,754.40	-	-	4.00	0	20,890.99
1979	10,747.07	924.00	701.74	-	-	2,251.76	-	-	12.00	0	14,636.56
1980	15,858.38	4,902.49	648.92	-	-	1,360.15	-	-	12.00	0	22,781.94
1981	16,703.32	6,342.45	404.00	204.27	-	410.93	-	-	10.00	0	24,074.97
1982	18,955.13	5,331.14	880.00	155.62	-	410.93	-	-	8.80	0	25,741.62
1983	29,552.35	3,460.67	919.00	605.27	-	727.84	-	-	8.00	0	35,273.14
1984	26,284.95	2,455.01	970.00	106.97	-	352.55	-	-	14.00	29.13612	30,212.61
1985	30,930.08	3,650.34	868.00	340.98	-	416.99	-	-	39.00	62.43455	36,307.82
1986	40,424.29	2,928.40	1,175.00	1,112.34	10.61	320.00	-	-	50.00	1864.712	47,885.36
1987	46,343.09	2,975.08	440.00	1,400.47	14.78	147.00	-	-	67.00	4095.707	55,483.13
1988	39,958.11	2,388.19	248.00	776.09	8.19	968.00	-	-	91.00	2547.33	46,984.91
1989	23,708.48	4,532.70	165.00	750.52	8.62	978.00	-	-	81.00	1215.393	31,439.71
1990	23,874.97	3,599.22	1,174.00	828.68	9.16	680.00	-	-	132.60	1387	31,685.64
1991	27,079.95	3,579.60	2,675.00	1,080.14	7.14	774.00	-	-	188.00	2257	37,640.82
1992	26,434.79	4,509.07	2,025.00	399.20	23.94	1,277.00	-	-	277.00	1583	36,528.99
1993	26,605.44	5,942.43	1,428.00	1,816.37	22.83	1,702.00	22.00	-	322.00	5726	43,587.07
1994	25,086.20	2,526.12	2,684.00	601.09	18.30	1,260.00	46.00	-	351.34	4669	37,242.05
1995	28,919.68	2,813.01	1,569.00	641.04	15.62	1,494.00	68.00	-	282.82	4722	40,525.17
1996	22,971.75	4,179.26	2,004.00	986.75	5.51	528.00	65.60	-	282.00	4843	35,865.86
1997	24,497.43	4,191.43	1,479.00	391.12	27.34	831.00	23.20	-	214.50	2630	34,285.02
1998	22,504.26	3,460.87	893.00	446.96	7.31	612.00	73.20	-	166.30	2440.401	30,604.30
1999	21,811.27	3,149.59	1,177.00	316.77	47.40	547.00	128.00	-	481.88	2226.59	29,885.50

Table 2. Continued.

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	
Year	EU-ESP	JPN	CTP	USA	VEN	CAN	CPR	BEL	OTH	EU-POR	Grand Total
2000	24,111.92	2,838.40	1,157.00	428.52	43.34	624.00	136.00	-	446.80	2081	31,866.97
2001	17,361.73	2,723.72	906.00	145.24	47.11	1,162.00	300.00	-	289.37	2109.9	25,045.08
2002	15,665.91	1,890.03	1,108.00	67.87	29.04	836.00	168.00	-	712.72	2264.6	22,742.17
2003	15,974.54	3,097.72	1,449.00	-	39.55	346.00	240.00	-	70.96	5642.796	26,860.58
2004	17,313.89	3,194.83	1,378.00	71.57	9.95	965.00	192.00	-	115.65	2024.645	25,265.52
2005	15,006.08	3,530.98	857.00	67.90	27.73	1,134.00	232.00	-	126.72	4027.016	25,009.43
2006	15,463.63	2,824.18	364.00	46.98	11.63	977.00	256.00	-	358.03	4337.882	24,639.33
2007	17,038.47	2,270.99	292.00	54.32	19.25	843.00	367.00	-	1,108.46	5283.258	27,276.75
2008	20,787.81	3,186.59	109.57	137.32	8.14	-	109.00	-	873.77	6166.767	31,378.98
2009	24,465.47	2,942.14	72.94	107.11	72.77	-	88.00	113.82	2,020.99	6251.56	36,134.81
2010	26,094.31	2,755.04	98.51	176.11	75.04	-	52.84	460.53	198.29	8261.083	38,171.76
2011	27,988.17	2,147.89	148.30	271.31	117.80	-	108.83	1,039.17	676.35	6509.127	39,006.94
2012	28,665.76	2,256.35	115.12	162.27	98.39	-	97.62	902.52	538.96	3767.776	36,604.76
2013	28,562.01	1,353.72	135.02	263.77	51.61	-	326.72	1,216.15	1,144.52	3694.375	36,747.90
2014	29,041.14	3,286.88	83.14	165.79	115.68	0.64	177.72	391.86	1,810.85	3059.526	38,133.22
2015	30,078.30	4,011.13	238.07	114.15	130.42	5.54	1.24	4.28	1,748.49	3859.15	40,190.77
2016	29,018.73	4,217.09	286.56	74.05	117.47	16.03	27.28	5.74	2,503.53	7819.014	44,085.49
2017	27,316.48	4,443.85	75.63	66.68	107.68	32.01	2.44	201.09	2,094.35	5664.246	40,004.46
2018	21,684.72	4,111.12	153.10	30.14	112.44	70.91	5.69	316.60	2,299.44	5194.573	33,978.73
2019	16,314.20	3,855.22	38.49	36.27	55.96	3.91	17.93	368.90	2,014.08	4507.329	27,212.29
2020	12,324.85	2,289.79	73.60	32.17	59.01	193.31	65.44	300.68	1,972.23	3836.275	21,147.36
2021	13,124.58	1,985.26	53.37	34.45	10.97	173.18	2.21	349.43	1,814.70	4299.984	21,848.13

Table 3. Indices of relative abundance for North Atlantic blue shark were obtained from data compiled during the 2023 Data Preparatory Meeting and assigned here to “surveys” S1 – S8 for use in preliminary 2023 North Atlantic blue shark SS3 model runs.

	Venezuela LL		Spain LL		Portugal LL		Japan LL		Chinese-Taipei LL		Morocco LL	
	SCRS/2015/022		SCRS/2023/040		SCRS/2023/045		SCRS/2023/050		SCRS/2023/059		SCRS/2023/058	
	S6 (VEN-LL)		S1 (ESP-LL-N)		S7 (POR-LL-N)		S2 (JPN-LL-N)		S3 (CTP-LL-N)		S8 (MOR-LL)	
Year	CPUE	CV	CPUE	CV	CPUE	CV	CPUE	CV	CPUE	CV	CPUE	CV
1990												
1991												
1992												
1993												
1994	0.047	1.08					1.03	0.12				
1995	0.073	0.87					1.17	0.11				
1996	0.017	1.90					1.01	0.11				
1997	0.154	0.69	186.37	0.0226	160.89	0.079	1.06	0.12				
1998	0.216	0.67	180.36	0.0227	163.87	0.071	0.93	0.11				
1999	0.117	0.84	212.08	0.0248	141.54	0.072	0.64	0.12				
2000	0.151	0.74	285.83	0.0240	189.44	0.077	0.71	0.14				
2001	0.133	0.77	259.30	0.0236	215.57	0.083	0.74	0.11				
2002	0.074	1.03	222.91	0.0240	191.07	0.080	0.53	0.11				
2003	0.044	1.26	258.79	0.0273	229.91	0.077	0.77	0.10				
2004	0.034	1.53	233.39	0.0278	262.03	0.079	0.53	0.09				
2005	0.006	3.88	223.52	0.0293	217.76	0.082	0.69	0.07				
2006	0.013	2.24	221.88	0.0324	213.06	0.079	0.87	0.08				
2007	0.060	1.35	250.51	0.0335	235.13	0.080	1.02	0.09	0.546	0.071		
2008	0.088	1.16	289.60	0.0336	223.60	0.080	1.49	0.08	0.464	0.068		
2009	0.045	1.56	274.86	0.0320	233.14	0.081	1.24	0.11	0.524	0.069		
2010	0.040	1.54	269.23	0.0313	274.04	0.084	1.44	0.16	0.888	0.044	94	0.11
2011	0.044	1.51	279.63	0.0315	244.96	0.074	1.15	0.18	0.771	0.055	233	0.08
2012	0.107	1.00	275.01	0.0309	310.08	0.076	1.63	0.20	0.678	0.060	248	0.04
2013	0.044	1.84	288.31	0.0319	309.59	0.076	1.26	0.23	0.953	0.056	165	0.04
2014			272.34	0.0300	288.26	0.071	1.36	0.22	0.877	0.077	261	0.08
2015			281.97	0.0283	383.11	0.078	1.37	0.18	0.072	0.179	304	0.06
2016			257.40	0.0279	373.44	0.083	1.17	0.20	1.663	0.035	385	0.05
2017			244.98	0.0289	344.19	0.082	1.13	0.21	0.928	0.059	333	0.03
2018			241.42	0.0315	330.21	0.081	0.74	0.21	0.812	0.057	267	0.09
2019			239.11	0.0312	340.89	0.080	0.91	0.21	0.709	0.065	383	0.05
2020			260.78	0.0202	373.14	0.073	0.64	0.21	0.668	0.057	262	0.06
2021			263.46	0.0282	345.71	0.080	0.77	0.21	0.243	0.095	340	0.05

Table 4. Updated indices of relative abundance for North Atlantic blue shark obtained from SCRS/2023/046 (Revised submission 5 May, 2023; their Table 3a) and assigned here to "surveys" S4 and S5 for use in preliminary 2023 North Atlantic blue shark SS3 model runs.

	US pelagic LL SCRS/2023/046 S4 (US-Obs-E)		US pelagic LL SCRS/2023/046 S5 (US-Obs-E)	
Year	CPUE	CV	CPUE	CV
1990				
1991				
1992	6.509	0.275		
1993	10.04	0.254		
1994	8.375	0.254		
1995	8.532	0.258		
1996	6.528	0.444		
1997	12.53	0.289		
1998	14.826	0.300		
1999	6.997	0.282		
2000	9.037	0.273		
2001	4.588	0.330		
2002	5.172	0.327		
2003	3.619	0.302		
2004	9.079	0.292		
2005	3.228	0.302		
2006	3.651	0.300		
2007	6.357	0.321		
2008	6.252	0.302		
2009	5.961	0.301		
2010	7.565	0.294		
2011	13.688	0.279		
2012	7.229	0.287		
2013	6.882	0.285		
2014	6.939	0.283		
2015			5.196	0.286
2016			7.748	0.254
2017			6.978	0.250
2018			4.581	0.299
2019			3.596	0.289
2020			3.308	0.292
2021			4.081	0.308

Table 5. Available length composition for us in preliminary 2023 North Atlantic blue shark SS3 model runs were obtained from ICCAT (sample sizes, number of sharks measured, provided below) and assigned to fishing “fleets” F1 – F10 (**Table 1**); Years with small sample size (total number of sharks measured < 100) were excluded from the preliminary models (see **Appendix B** for reference case model fits to annual length composition).

	F1		F2		F3		F4		F5	
	EU-ESP		JPN		CTP		USA		VEN	
Year	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male
1992							31	0		
1993							0	634		
1994							466	507	23	34
1995							118	134	49	45
1996							0	0	5	8
1997	7110	6096	660	2153			0	169	58	67
1998	5216	8444	415	793			0	30	93	54
1999	10633	9897	155	146			37	55	35	48
2000	6445	7939	225	129			58	85	78	19
2001	10130	11532	500	423			0	44	33	41
2002	6335	7312	699	95			0	0	22	23
2003	5898	6505	1578	329			0	0	10	16
2004	5455	7305	1133	258			130	95	24	16
2005	4438	5894	1874	627			0	0	3	1
2006	5386	7010	1578	498			129	96	4	10
2007	5384	5747	1583	661	37	26	238	142	0	7
2008	2529	3668	2208	1530	38	57	151	130	19	7
2009	3283	4338	1122	694	50	108	155	191	16	8
2010	3827	5796	2289	551	126	152	593	348	23	21
2011	5230	6891	1418	1073	189	173	554	342	128	36
2012	6140	7204	1919	1082	224	284	0	36	112	57
2013	8055	9666	2571	1042	250	22	110	135	52	38
2014	18090	15377	5456	2458	134	130	0	0	0	57
2015	14620	13720	5983	1416	4	16	0	110	33	0
2016	14649	15094	2039	1427	185	46	41	109		
2017	7919	12750	4089	2010	155	119				
2018	6220	6592	2272	1027	112	69				
2019	5077	5856	3364	1899	34	43				
2020	3075	7132	280	135	18	25				
2021	5896	10234			22	25				

Table 5. Continued.

	F7		F8	F9	F10		
	CPR		BEL	OTH	EU-POR		
Year	Female	Male	Combined sex	Combined sex	Female	Male	Total
1992							31
1993							634
1994				23			1053
1995				49			395
1996				5			18
1997				58			16371
1998				93			15138
1999				35			21041
2000				78			15056
2001				33			22736
2002				22			14508
2003				10	559	2469	17374
2004				24	108	445	14993
2005				3	55	940	13835
2006				4	42	92	14849
2007				0	0	0	13825
2008				19	2672	1037	14065
2009				16	855	615	11451
2010			1295	23	2831	3442	21317
2011			5588	128	2203	436	24389
2012			2521	112	6157	4792	30640
2013				52	1664	942	24599
2014				2673	2492	1031	47898
2015	0	0		0	965	972	37839
2016	0	0		31	2169	2841	38631
2017	0	0		77	2806	3263	33188
2018	224	283		650	1081	1807	20337
2019	610	577	5912	1790	979	2469	28610
2020	955	553		0	48	38	12259
2021	0	31	1749	64	2793	2756	23570

Table 6. Life history inputs considered for use in preliminary 2023 North Atlantic blue shark SS3 model runs were obtained from data first assembled at the 2014 Intersessional Meeting of the Shark Species Group (Anon. 2015b), plus updated information provided during the 2016 Intersessional Meeting of the Shark Species Group (Anon. 2017b) and updated during the 2023 Blue Shark Data Preparatory Meeting (green highlight; Anon. 2023). A sex-specific model was implemented in preliminary 2023 North Atlantic blue shark SS3 model runs to allow for differences in von Bertalanffy growth (VBG) in length at age identified between sexes for the North Atlantic blue shark stock (Carlson *et al*. 2023), as summarized below.

	North Atlantic (2015)	North Atlantic (2023)
Reproduction		
L_{mat} (♂)	192-208 FL	a=-72.94 (+/-41.46); b=0.37 (+/-0.21)
L_{50} (♂)	200 FL	197 cm FL
T_{mat} (♂)	5	a=-7.58 (+/-1.96); b=1.53 (+/-0.42)
T_{50} (♂)		4.9
L_{mat} (♀)	185 FL	a=-21.36 (+/-7.42); b=0.11 (+/-0.38)
L_{50} (♀)		190.7 cm FL (west)
T_{mat} (♀)	5	a=-10.81 (+/-3.45); b=2.02 (+/-0.65)
T_{50} (♀)	**6**	5.3
Cycle	1	
GP (months)	9-12	
L_0	47 FL	
Mean LS	**39**	
Min LS	1	
Max LS	96	
Litter size vs Maternal size		
Age & Growth		
L_{inf} (♀)	**310 FL**	337.3 cm FL
k (♀)	**0.13**	0.107
T_o / L_o (♀)	**-1.77**	**-2.43**
T_{max} (♀)	**15**	**15**
L_{inf} (♂)	282 FL	282.4
k (♂)	0.18	0.179
T_o / L_o (♂)	-1.35	-1.59
T_{max} (♂)	16	16
Reproduction		
L_{mat} (sex combined)		a=-30.03 (+/-8.36); b=0.15 (+/-0.04)
L_{50} (sex combined)		197 FL
T_{mat} (sex combined)		a=-8.57 (+/-1.67); b=1.66 (+/-0.33)
T_{50} (sex combined)		5.1
Age & Growth		
L_{inf} (sex combined)		292.4 FL
k (sex combined)		0.157
T_o / L_o (sex combined)		**-1.8**
T_{max} (sex combined)		**16**
Conversion Factors		
Length-length [cm]	FL=0.8313TL+1.3908	
Length-weight (b) [cm,kg]	**W=3.18E-06FL^3.1313**	
Length-weight (♀) [cm,kg]	W=1.30E-06TL^3.2	
Length-weight (♂) [cm,kg]	W=3.90E-07TL^3.41	

Table 7. Sex-specific von Bertalanffy growth (VBG) in length at age used in preliminary 2023 North Atlantic blue shark SS3 model runs (Carlson *et al*. 2023 as summarized in **Table 6)** and the assumed CV implemented for L_{Amin} and L_{inf} along with observed and theoretical maximum age (t_{max}).

Age (yr)	Female cm FL predicted from VBG parameters below	Male cm FL predicted from VBG parameters below
0	77.2	69.9
1	103.6	104.8
2	127.3	133.9
3	148.6	158.2
4	167.8	178.6
5	185.0	195.6
6	200.4	209.8
7	214.3	221.7
8	226.8	231.7
9	238.0	240.0
10	248.1	246.9
11	257.1	252.7
12	265.3	257.6
13	272.6	261.7
14	279.2	265.1
15[1]	285.1	267.9
16[1]	290.4	270.3
17	295.1	272.3
18	299.4	273.9
19	303.2	275.3
20	306.7	276.5
21	309.8	277.4
22	312.6	278.3
23	315.1	278.9
24	317.4	279.5
25	319.4	280.0
26[2]	321.2	280.4
27	322.8	280.7
28	324.3	281.0
29	325.6	281.2
30	326.8	281.4

VBG parameters	Female	Male
L_{inf}	337.3	282.4
k	0.107	0.179
t_0	-2.43	-1.59
CV implemented for L_{Amin}	0.093	0.097
CV implemented for L_{inf}	0.090	0.082

Maximum age	Female	Male
[1]Observed t_{max} (**Table 6**)	15	16
[2]Theoretical t_{max} (SCRS/2023/115)	26	

Table 8. Annual pup production at age used in preliminary 2023 North Atlantic blue shark SS3 model runs.

Age (yr)	Step 1: Litter Size (LS)	Step 2: Fraction mature (Mat)	Step 3: Fraction Maternal	Step 4: Female pup production (LS) * (Maternal)	Step 5: Annual female pup production
0	39.00	0.00	0.00	0.0	0.00
1	39.00	0.00	0.00	0.0	0.00
2	39.00	0.00	0.00	0.0	0.01
3	39.00	0.01	0.00	0.0	0.04
4	39.00	0.06	0.01	0.3	0.33
5	39.00	0.33	0.06	2.4	2.39
6	39.00	0.79	0.33	12.9	12.85
7	39.00	0.97	0.79	30.7	30.71
8	39.00	1.00	0.97	37.7	37.65
9	39.00	1.00	1.00	38.8	38.82
10	39.00	1.00	1.00	39.0	38.98
11	39.00	1.00	1.00	39.0	39.00
12	39.00	1.00	1.00	39.0	39.00
13	39.00	1.00	1.00	39.0	39.00
14	39.00	1.00	1.00	39.0	39.00
15	39.00	1.00	1.00	39.0	39.00
16	39.00	1.00	1.00	39.0	39.00
17	39.00	1.00	1.00	39.0	39.00
18	39.00	1.00	1.00	39.0	39.00
19	39.00	1.00	1.00	39.0	39.00
20	39.00	1.00	1.00	39.0	39.00
21	39.00	1.00	1.00	39.0	39.00
22	39.00	1.00	1.00	39.0	39.00
23	39.00	1.00	1.00	39.0	39.00
24	39.00	1.00	1.00	39.0	39.00
25	39.00	1.00	1.00	39.0	39.00
26	39.00	1.00	1.00	39.0	39.00
27	39.00	1.00	1.00	39.0	39.00
28	39.00	1.00	1.00	39.0	39.00
29	39.00	1.00	1.00	39.0	39.00
30	39.00	1.00	1.00	39.0	39.00

Step 1. Mean litter size (LS) is 39 (**Table 6**).

Step 2. Fraction mature at age, Tmat (♀) as a proportion, 1/(1+exp-(-10.81 + 2.02 * age)) (**Table 6**).

Step 3. The fraction of females in a maternal condition (Maternal) assumes a one year gestation period (9-12 months, **Table 6**).

Step 4. Female pup production at age is calculated as (LS) * (Maternal)

Step 5. Annual female pup production was obtained by assuming an annual reproductive cycle (**Table 6**).

Table 9. Continuity analyses relative to the 2015 North Atlantic blue shark model stock-recruit steepness parameter, *h*, and the sex-specific natural mortality at each age (M_a), were obtained here from preliminary model runs conducted for the 2015 North Atlantic blue shark stock assessment (Courtney 2016).

A. The 2015 North Atlantic blue shark preliminary sex specific survival at each age was calculated as the mean of the distribution in survival at age, $\overline{S}_a$, obtained from document SCRS/2015/142 (Cortés 2016); Sex specific natural mortality at age was then obtained as $M_a = -\ln\left(\overline{S}_a\right)$; Combined sex natural mortality was then computed as the average mortality of males and females at each age (Adapted from Courtney 2016, his Table 10)

Age (yr)	Female	Male	Average
0	0.36	0.40	0.38
1	0.30	0.31	0.30
2	0.26	0.28	0.27
3	0.24	0.25	0.25
4	0.23	0.24	0.24
5	0.22	0.23	0.23
6	0.22	0.23	0.22
7	0.21	0.22	0.22
8	0.21	0.22	0.21
9	0.20	0.22	0.21
10	0.20	0.21	0.21
11	0.20	0.21	0.21
12	0.20	0.21	0.20
13	0.20	0.21	0.20
14	0.20	0.21	0.20
15	0.20	0.21	0.20
16	0.20	0.21	0.20

(Adapted from Courtney 2016, his Table 10)

B. The 2015 North Atlantic blue shark preliminary steepness, *h*, was obtained from life history invariant methods described separately in the 2015 assessment document SCRS/2015/142 (Cortés 2016). The 2015 North Atlantic blue shark preliminary steepness parameter, *h*, was fixed at the mean of the distribution of steepness values obtained from the life history invariant methods ($h = 0.73$; Adapted from Courtney 2016).

C. The resulting 2015 North Atlantic blue shark steepness, *h*, and natural mortality, *M*, scenario was used here for preliminary 2023 North Atlantic blue shark SS3 model runs and for the continuity analysis relative to the 2015 North Atlantic blue shark SS3 preliminary model runs.

M (female and male M_a obtained from above; Adapted from Courtney 2016, his Table 10)

h ($h = 0.73$ obtained from above; Adapted from Courtney 2016)

Table 10. Structural uncertainty was evaluated to North Atlantic blue shark CPUE groupings recommended by the Shark Working Group (Anon 2023); CPUE scenarios used the 2015 North Atlantic blue shark model stock-recruit steepness parameter, *h*, and the sex-specific natural mortality at each age (M_a), obtained as described above in **Table 9**.

CPUE	Group CPUE Scenario 1	Group CPUE Scenario 2	Group CPUE Scenario 3	Group CPUE Scenario 4	Group CPUE Scenario 5	Group CPUE Scenario 6
SN1 (ESP-LL-N)	1	1	0	0	1	0
SN2 (JPN-LL-N)	1	0	1	0	1	0
SN3 (CTP-LL-N)	1	0	1	0	1	0
SN4 (US-Obs-E)	1	0	1	0	0	1
SN5 (US-Obs-L)	1	0	1	0	0	1
SN6 (VEN-LL)	1	0	1	0	0	1
SN7 (POR-LL-N)	1	1	0	1	0	0
SN8 (MOR-LL)	1	1	0	1	0	0

The value “1” indicates CPUE index was fit in the SS3 model likelihood.
The value “0” indicates CPUE index was not fit in the SS3 model likelihood.

Table 11. Structural uncertainty was evaluated to including each North Atlantic blue shark CPUE series (**Tables 3 and 4**) one at a time in the Stock Synthesis model; All CPUE scenarios used the 2015 North Atlantic blue shark model stock-recruit steepness parameter, *h*, and the sex-specific natural mortality at each age (M_a), obtained as described above in **Table 10**.

CPUE	Each CPUE Scenario 1	Each CPUE Scenario 2	Each CPUE Scenario 3	Each CPUE Scenario 4	Each CPUE Scenario 5	Each CPUE Scenario 6	Each CPUE Scenario 7	Each CPUE Scenario 8
SN1 (ESP-LL-N)	1	1	0	0	0	0	0	0
SN2 (JPN-LL-N)	1	0	1	0	0	0	0	0
SN3 (CTP-LL-N)	1	0	0	1	0	0	0	0
SN4 (US-Obs-E)	1	0	0	0	1	0	0	0
SN5 (US-Obs-L)	1	0	0	0	1	0	0	0
SN6 (VEN-LL)	1	0	0	0	0	1	0	0
SN7 (POR-LL-N)	1	0	0	0	0	0	1	0
SN8 (MOR-LL)	1	0	0	0	0	0	0	1

The value “1” indicates CPUE index was fit in the SS3 model likelihood.
The value “0” indicates CPUE index was not fit in the SS3 model likelihood.

Table 12. Structural uncertainty was evaluated to removing each North Atlantic blue shark CPUE series (**Tables 3 and 4**) one at a time from the Stock Synthesis model; All CPUE scenarios used the 2015 North Atlantic blue shark model stock-recruit steepness parameter, *h*, and the sex-specific natural mortality at each age (M_a), obtained as described above in **Table 10**.

CPUE	Remove CPUE Scenario 1	Remove CPUE Scenario 2	Remove CPUE Scenario 3	Remove CPUE Scenario 4	Remove CPUE Scenario 5	Remove CPUE Scenario 6	Remove CPUE Scenario 7	Remove CPUE Scenario 8
SN1 (ESP-LL-N)	1	0	1	1	1	1	1	1
SN2 (JPN-LL-N)	1	1	0	1	1	1	1	1
SN3 (CTP-LL-N)	1	1	1	0	1	1	1	1
SN4 (US-Obs-E)	1	1	1	1	0	1	1	1
SN5 (US-Obs-L)	1	1	1	1	0	1	1	1
SN6 (VEN-LL)	1	1	1	1	1	0	1	1
SN7 (POR-LL-N)	1	1	1	1	1	1	0	1
SN8 (MOR-LL)	1	1	1	1	1	1	1	0

The value “1” indicates CPUE index was fit in the SS3 model likelihood.
The value “0” indicates CPUE index was not fit in the SS3 model likelihood.

Table 13. Structural uncertainty was evaluated to externally derived stock-recruit steepness parameter, *h*, and the sex-specific natural mortality at each age (M_a) obtained independently of the stock assessment model with life history invariant methods as described in document SCRS/2023/115 (Cortés and Taylor In Prep.).

A. Estimates of instantaneous natural mortality rates (yr-1) (female and male, grey highlight) obtained with 6 life-history invariant methods used in the deterministic life tables SCRS/2023/115 (Pers. Comm. E. Cortés 7/5/2023).

Blue shark North Atlantic			
Age	Female	Male	Average of female and male
0	0.212	0.239	0.226
1	0.200	0.222	0.211
2	0.193	0.213	0.203
3	0.188	0.208	0.198
4	0.185	0.205	0.195
5	0.182	0.202	0.192
6	0.180	0.201	0.190
7	0.179	0.199	0.189
8	0.177	0.198	0.188
9	0.176	0.197	0.187
10	0.175	0.197	0.186
11	0.175	0.196	0.185
12	0.174	0.196	0.185
13	0.173	0.196	0.185
14	0.173	0.195	0.184
15	0.173	0.195	0.184
16	0.172	0.195	0.184
17	0.172	0.195	0.183
18	0.172	0.195	0.183
19	0.171	0.195	0.183
20	0.171	0.194	0.183
21	0.171	0.194	0.183
22	0.171	0.194	0.183
23	0.171	0.194	0.182
24	0.171	0.194	0.182
25	0.170	0.194	0.182
26	0.170	0.194	0.182

Table 13. Continued.

B. Estimates of instantaneous natural mortality rates (yr-1) (female and male, grey highlight) obtained with the Dureuil *et al*. (2021) method SCRS/2023/115 (Pers. Comm. E. Cortés 7/5/2023).

Blue shark North Atlantic			
Age	Female	Male	Average of female and male
0	0.524	0.827	0.676
1	0.391	0.552	0.471
2	0.318	0.432	0.375
3	0.272	0.366	0.319
4	0.241	0.324	0.283
5	0.219	0.296	0.257
6	0.202	0.276	0.239
7	0.189	0.261	0.225
8	0.178	0.250	0.214
9	0.170	0.241	0.206
10	0.163	0.234	0.199
11	0.157	0.229	0.193
12	0.153	0.225	0.189
13	0.148	0.221	0.185
14	0.145	0.218	0.182
15	0.142	0.216	0.179
16	0.139	0.214	0.177
17	0.137	0.212	0.175
18	0.135	0.211	0.173
19	0.133	0.210	0.172
20	0.132	0.209	0.171
21	0.131	0.209	0.170
22	0.129	0.208	0.169
23	0.128	0.207	0.168
24	0.128	0.207	0.167
25	0.127	0.207	0.167
26	0.126	0.206	0.166

Table 14. Stock Synthesis model continuity was evaluated relative to the 2015 ICCAT North Atlantic Preliminary Run 6 (Courtney 2016). Five continuity analyses scenarios were evaluated as described above in Section 2.4. Continuity was evaluated with an index of average percent error developed to evaluate the precision of age determinations (Beamish and Fournier 1981). Two indices of precision were evaluated. Index_of_Average_Percent_Error_1 evaluated absolute error in SSF (1,000s of pups) for unfished equilibrium (SSF_0), year 1971 (SSF_1971), and year 2013 (SSF_2013). Index_of_Average_Percent_Error_2 evaluated relative error in SSF year 1971 relative to unfished equilibrium (SSF_1971/SSF_0), and year 2013 relative to unfished equilibrium (SSF_2013/SSF_0).

Index of absolute error in SSF (1,000s of pups)	Model 1	Model 2	Model 3	Model 4	Model 5
SSF_0	186609	93304	93304	110310	120318
SSF_1971	141533	70766	70766	80719	82411
SSF_2013	62148	31074	31074	42877	36035
Index_of_Average_Percent_Error_1	0.31	50.16	50.16	38.48	39.96

Index of relative error in SSF	Model 1	Model 2	Model 3	Model 4	Model 5
SSF_1971/SSF_0	0.758	0.758	0.758	0.732	0.685
SSF_2013/SSF_0	0.333	0.333	0.333	0.389	0.299
Index_of_Average_Percent_Error_2	0.16	0.16	0.16	10.06	10.02

Table 15. Structural uncertainty was evaluated to North Atlantic blue shark CPUE groupings recommended by the Shark Working Group (Anon 2023) as described in Section 2.5.1 and **Table 10**; Annual SSF (10^6 pups) for unfished equilibrium (SSF_0), year 2013 (SSF_2013), and at equilibrium MSY (SSF_MSY); Annual fishing mortality rate for year 2013 (F_2013) and at equilibrium MSY (F_MSY).

	Scen 1	Scen 2	Scen 3	Scen 4	Scen 5	Scen 6	2023 Ref Case
TOTAL_like	276.49	272.08	302.72	294.68	277.75	313.62	277.06
Survey_like	-66.20	-73.83	-28.44	-49.93	-49.67	-7.13	-66.30
Length_comp_like	347.11	351.19	336.15	346.49	337.02	333.35	349.11
Parm_priors_like	0.60	0.65	0.62	0.63	0.61	0.65	0.71
SSF_2013/SSF_MSY	1.18	1.37	0.95	1.19	1.06	0.73	1.14
SSF_2013	42.88	54.32	29.43	45.58	34.90	21.45	36.04
F_2013	0.90	0.73	1.24	0.74	1.11	1.50	0.92
SSF_MSY	36.49	39.77	30.93	38.39	32.84	29.55	31.54
SSF_0	110.31	131.12	98.76	130.19	104.33	95.99	120.32
F_MSY	0.09	0.09	0.08	0.09	0.08	0.08	0.12

Table 16. Structural uncertainty was evaluated to including each North Atlantic blue shark CPUE series (**Tables 3 and 4**) one at a time in the Stock Synthesis model as described in Section 2.5.1 and **Table 11**; Annual SSF (10^6 pups) for unfished equilibrium (SSF_0), year 2013 (SSF_2013), and at equilibrium MSY (SSF_MSY); Annual fishing mortality rate for year 2013 (F_2013) and at equilibrium MSY (F_MSY).

	Scen 1	Scen 2	Scen 3	Scen 4	Scen 5	Scen 6	Scen 7	Scen 8	2023 Ref Case
TOTAL_like	276.49	280.21	301.92	318.93	301.76	324.60	302.50	318.29	277.06
Survey_like	-66.20	-45.64	-29.40	1.25	-14.81	8.33	-41.10	-3.88	-66.30
Length_comp_like	347.11	338.04	335.85	329.76	329.67	329.27	345.99	331.98	349.11
Parm_priors_like	0.60	0.70	0.57	0.60	0.60	0.62	0.63	0.55	0.71
SSF_2013/SSF_MSY	1.18	1.03	0.95	0.74	0.65	0.74	1.20	0.84	1.14
SSF_2013	42.88	34.73	29.67	21.75	18.77	22.09	46.30	27.71	36.04
F_2013	0.90	1.07	1.24	1.50	1.58	1.49	0.74	1.16	0.92
SSF_MSY	36.49	33.78	31.16	29.28	28.90	29.70	38.42	32.82	31.54
SSF_0	110.31	107.92	97.75	92.39	96.62	94.71	130.38	103.50	120.32
F_MSY	0.09	0.09	0.08	0.08	0.08	0.08	0.09	0.08	0.12

Table 17. Structural uncertainty was evaluated to removing each North Atlantic blue shark CPUE series (**Tables 3 and 4**) one at a time from the Stock Synthesis model as described in Section 2.5.1 and **Table 12**; Annual SSF (10^6 pups) for unfished equilibrium (SSF_0), year 2013 (SSF_2013), and at equilibrium MSY (SSF_MSY); Annual fishing mortality rate for year 2013 (F_2013) and at equilibrium MSY (F_MSY).

	Scen 1	Scen 2	Scen 3	Scen 4	Scen 5	Scen 6	Scen 7	Scen 8	2023 Ref Case
TOTAL_like	276.49	297.94	274.23	275.88	285.82	267.36	274.64	282.88	277.06
Survey_like	-66.20	-42.26	-70.74	-66.69	-56.16	-74.83	-53.18	-57.36	-66.30
Length_comp_like	347.11	343.09	350.69	347.03	346.33	346.58	337.08	345.66	349.11
Parm_priors_like	0.60	0.62	0.66	0.60	0.67	0.56	0.58	0.66	0.71
SSF_2013/SSF_MSY	1.18	1.16	1.30	1.17	1.18	1.17	1.06	1.18	1.14
SSF_2013	42.88	40.86	50.46	42.77	42.96	42.65	34.80	40.73	36.04
F_2013	0.90	0.84	0.77	0.90	0.90	0.90	1.07	0.91	0.92
SSF_MSY	36.49	35.33	38.82	36.50	36.51	36.39	32.96	34.63	31.54
SSF_0	110.31	118.09	125.88	110.41	111.08	110.47	104.45	113.34	120.32
F_MSY	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.12

Table 18. Structural uncertainty to externally derived natural mortality, *M*, and steepness, *h*, was evaluated with seven scenarios developed from SCRS/2023/115 as described in Section 2.5.2 and **Table 13**; Annual SSF (10^6 pups) for unfished equilibrium (SSF_0), year 2013 (SSF_2013), and at equilibrium MSY (SSF_MSY); Annual fishing mortality rate for year 2013 (F_2013) and at equilibrium MSY (F_MSY).

	Scen 1	Scen 2	Scen 3	Scen 4	Scen 5	Scen 6	Scen 7	2023 Ref Case
TOTAL_like	277.06	328.30	243.43	275.56	270.57	315.32	282.88	277.06
Survey_like	-66.30	-59.13	-76.69	-70.75	-64.56	-71.47	-64.07	-66.30
Length_comp_like	349.11	390.29	326.91	351.82	340.54	393.44	350.87	349.11
Parm_priors_like	0.71	0.58	0.64	0.59	0.54	0.64	0.66	0.71
SSF_2013/SSF_MSY	1.14	1.37	1.17	1.15	1.06	1.62	1.17	1.14
SSF_2013	36.04	135.03	17.92	38.55	27.52	106.07	37.54	36.04
F_2013	0.92	0.74	0.93	0.92	0.97	0.62	0.88	0.92
SSF_MSY	31.54	98.20	15.33	33.43	25.93	65.35	31.97	31.54
SSF_0	120.32	274.39	81.49	119.51	105.86	196.41	100.12	120.32
F_MSY	0.12	0.07	0.13	0.11	0.11	0.08	0.07	0.12

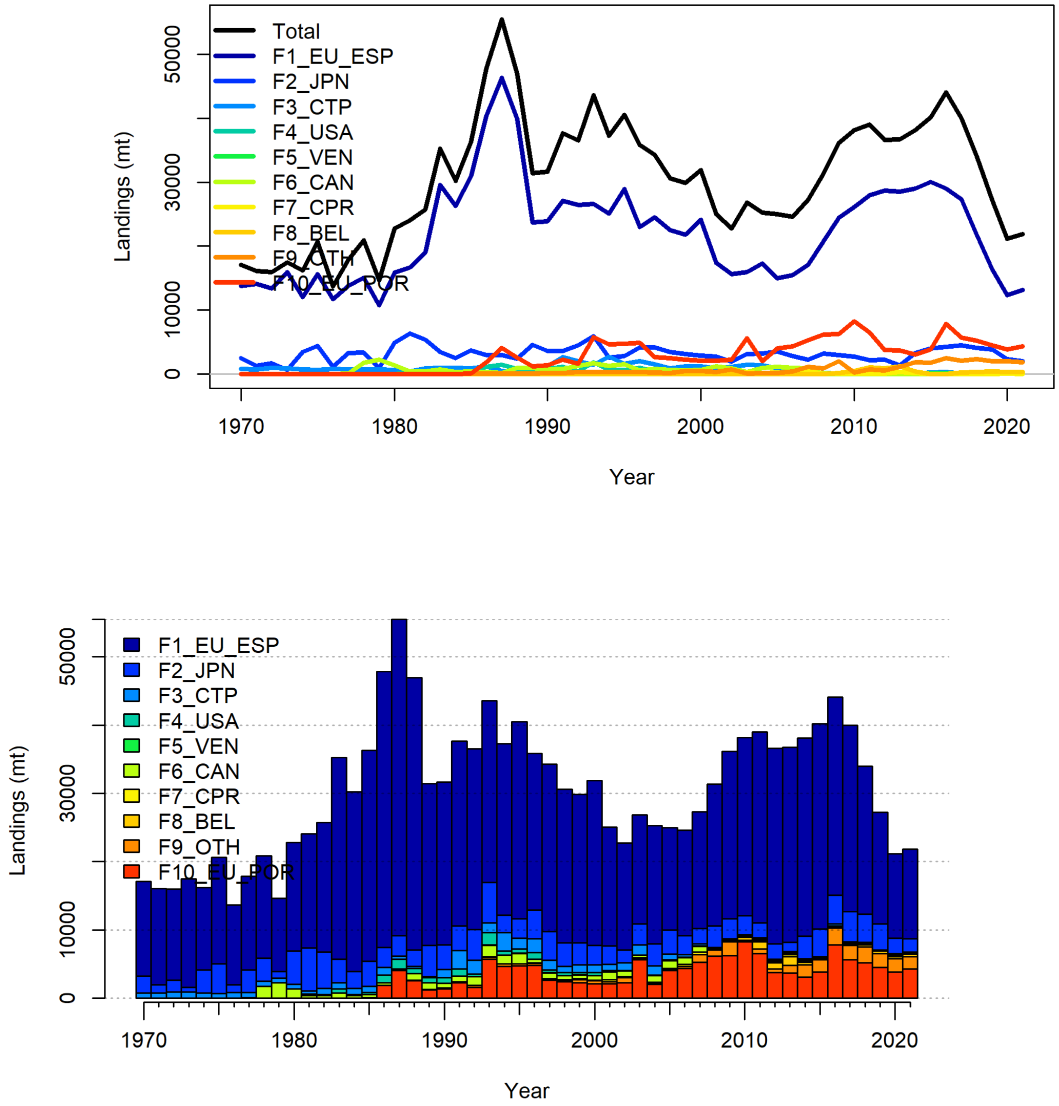


Figure 1. Catch in metric tons (t) by major flag obtained from data compiled during the 2023 Blue Shark Data Preparatory meeting (**Table 2**) and presented here as annual time series (upper panel) and as stacked total catch (lower panel).

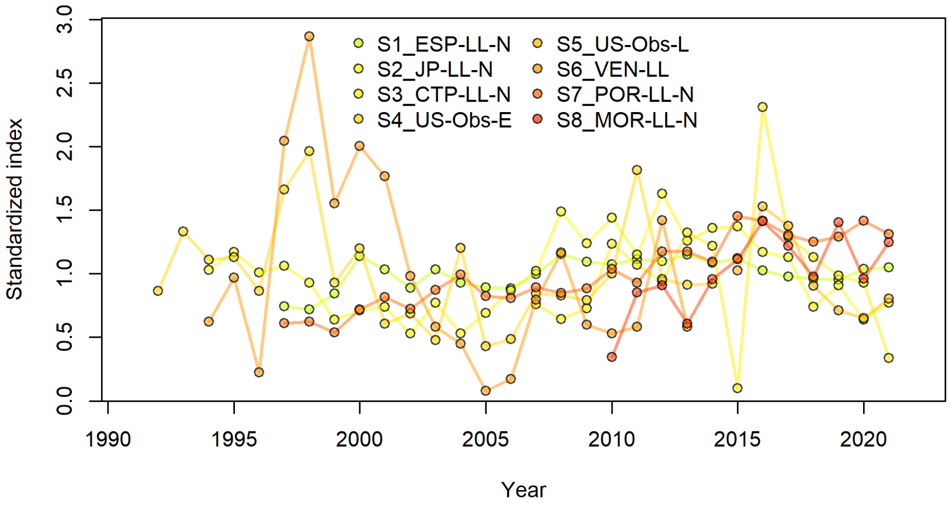


Figure 2. Indices of relative abundance for North Atlantic blue shark compiled during the 2023 Blue Shark Data Preparatory meeting (**Tables 3 and 4**) [standardized in r4ss output for plotting purposes].

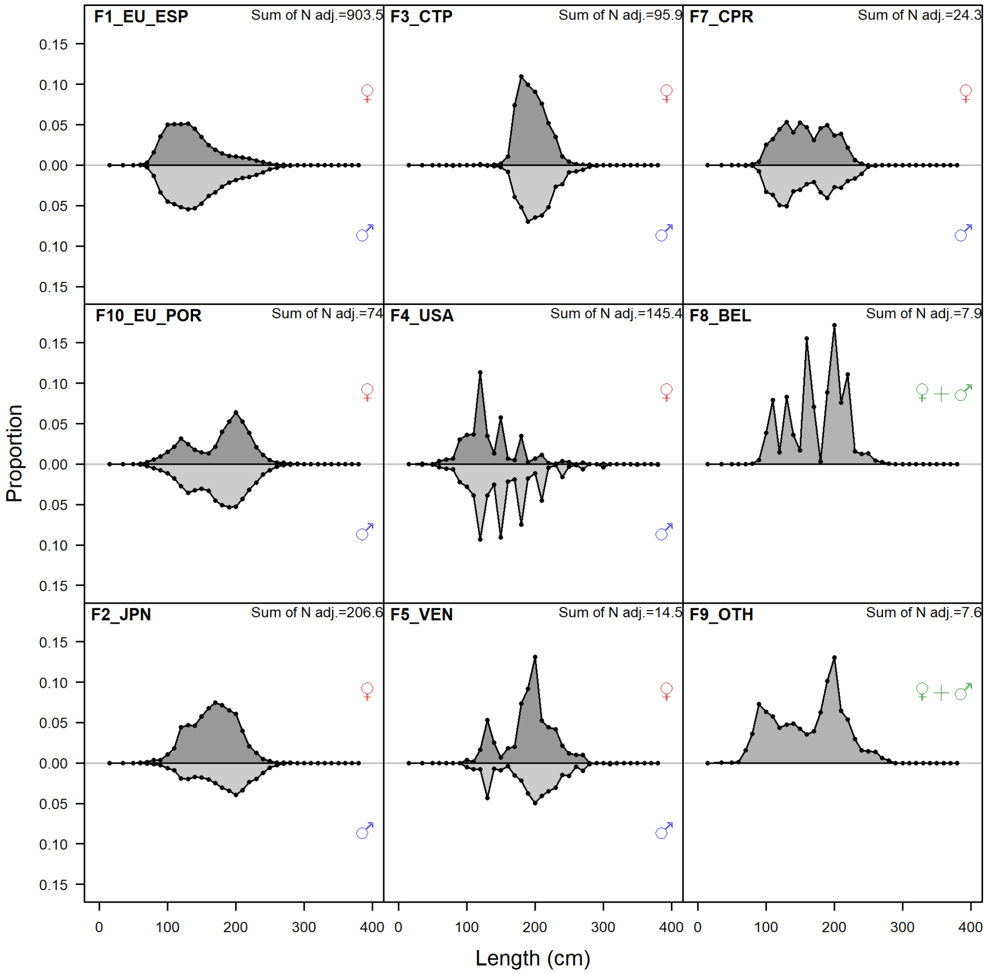


Figure 3. Available length composition data for North Atlantic blue shark compiled by ICCAT secretariat following the 2023 Blue Shark Data Preparatory meeting (**Table 5**). The "Sum of N adj." is the sum of input effective sample size provided by the R package r4ss using the Francis method (Stage 2) as described in the text of the main document above. Plots of fits to annual length composition by fleet are provided in **Appendix B**).

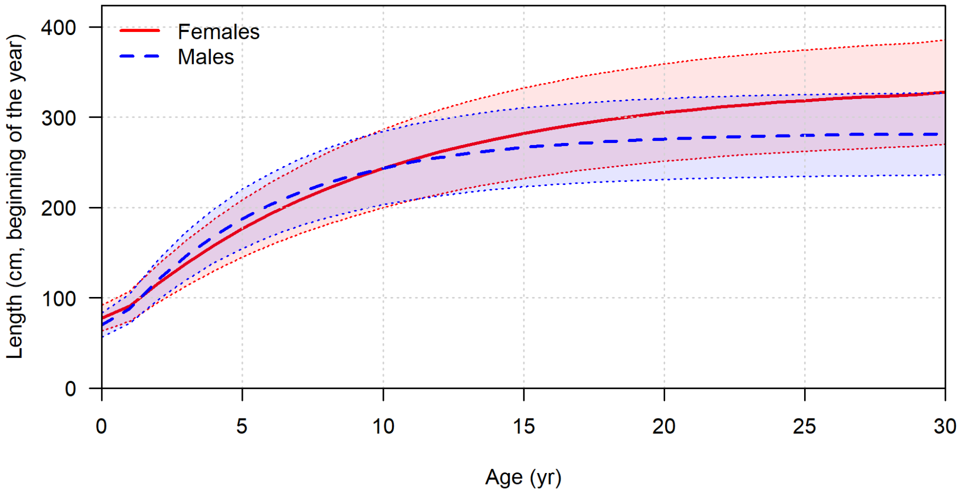


Figure 4. Sex-specific von Bertalanffy growth (VBG) in length at age used in preliminary 2023 North Atlantic blue shark SS3 model runs (Carlson *et al.* 2023 as summarized in **Table 6)** and the assumed CV implemented for L_{Amin} and L_{inf} along with observed and theoretical maximum age (t_{max}) as described in **Table 7**.

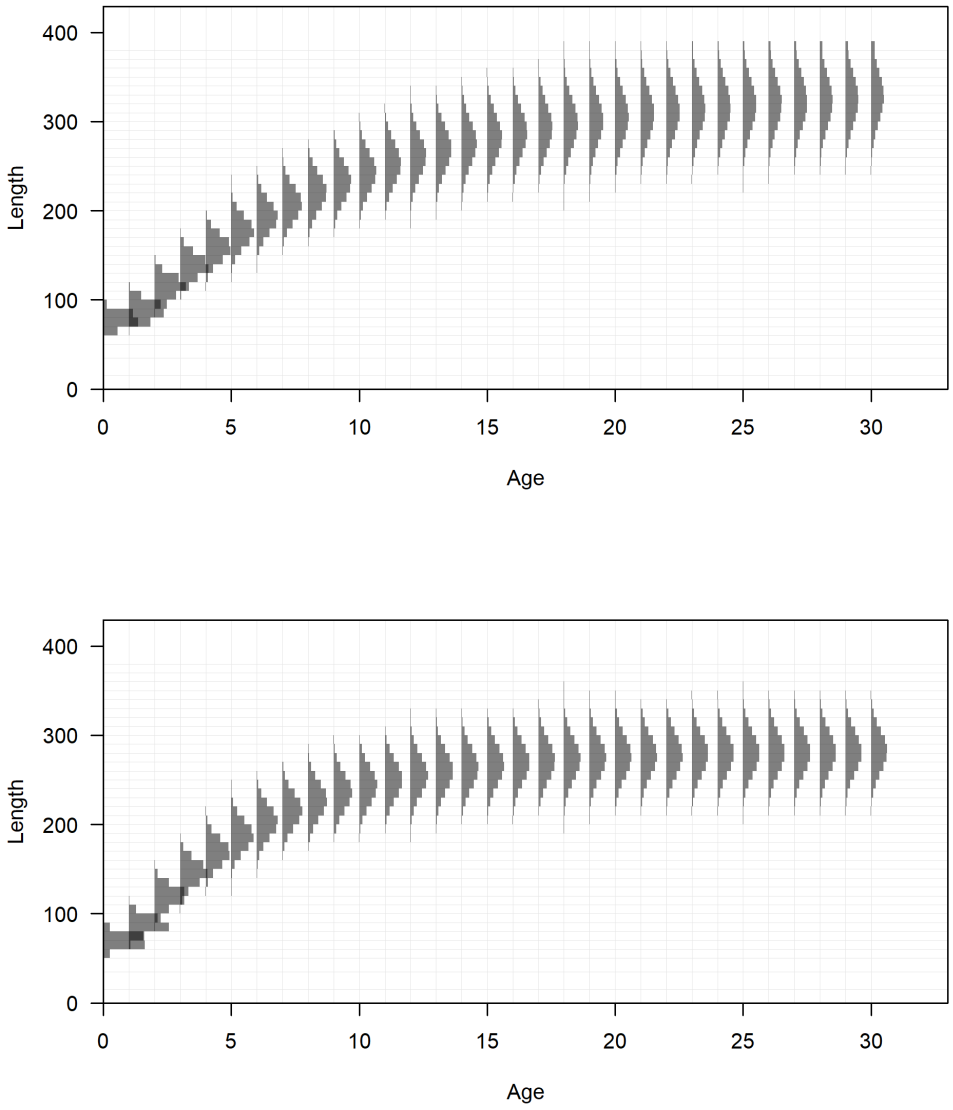
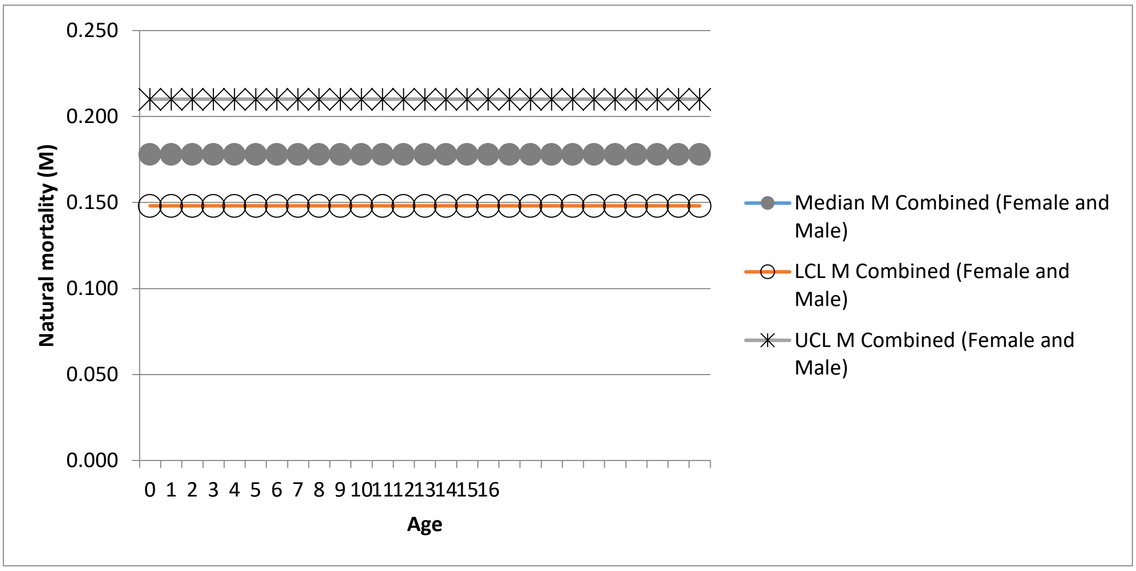


Figure 5. The assumed distribution of mean length at each age implemented in SS3 separately for females (upper panel) and males (lower panel) as described in the text of the main document and in **Table 7**.

A. *M* and *h* Scenarios 1-3 as described in Section 2.5.2



B. *M* and *h* Scenarios 4-6 as described in Section 2.5.2

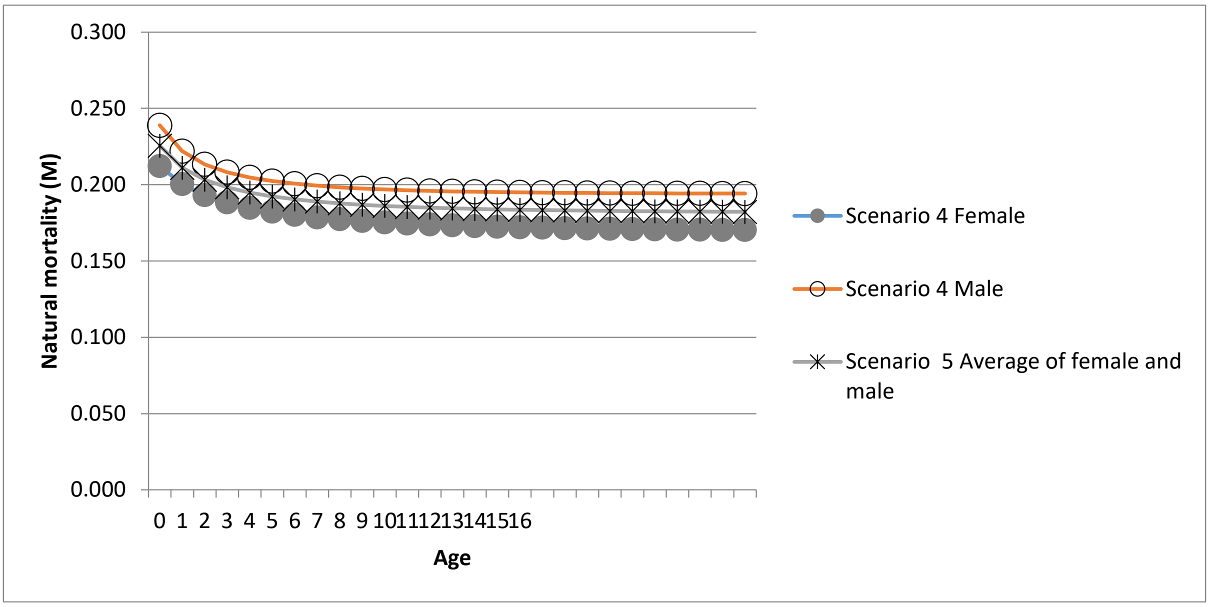


Figure 6. Sex-specific natural mortality at each age was evaluated for externally derived stock-recruit steepness parameter, *h*, and the sex-specific natural mortality at each age (M_a) obtained independently of the stock assessment model with life history invariant methods as described in document SCRS/2023/115 (Cortés and Taylor In Prep.) as described in Section 2.5.2 and **Table 13**.

C**.** *M* and *h* Scenarios 4-6 as described in Section 2.5.2

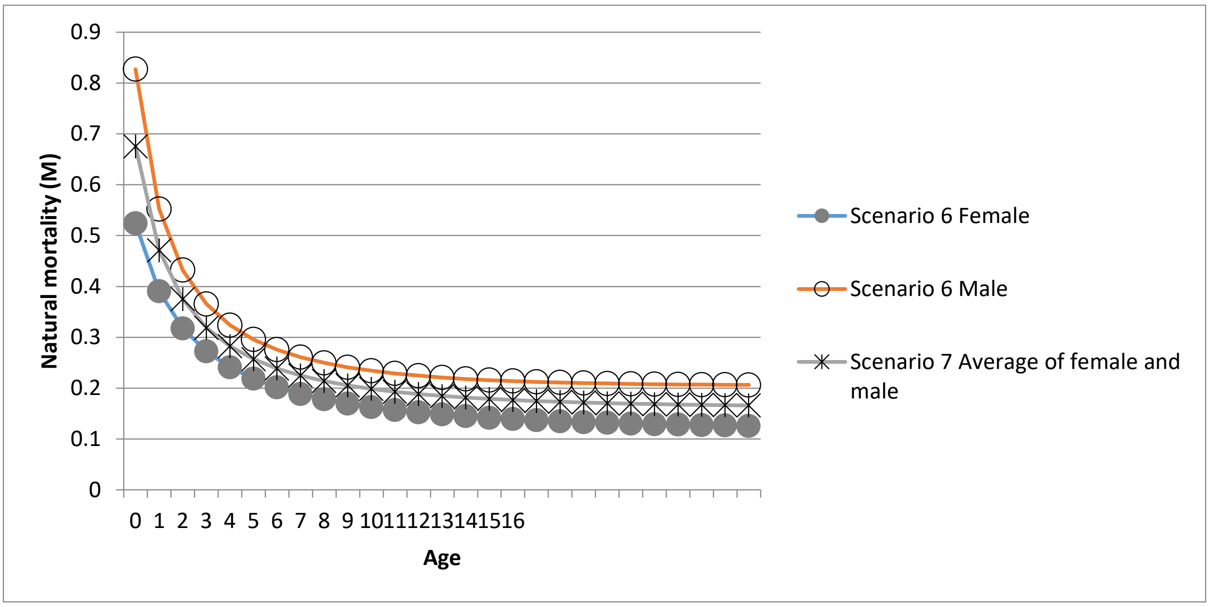


Figure 6. Continued.

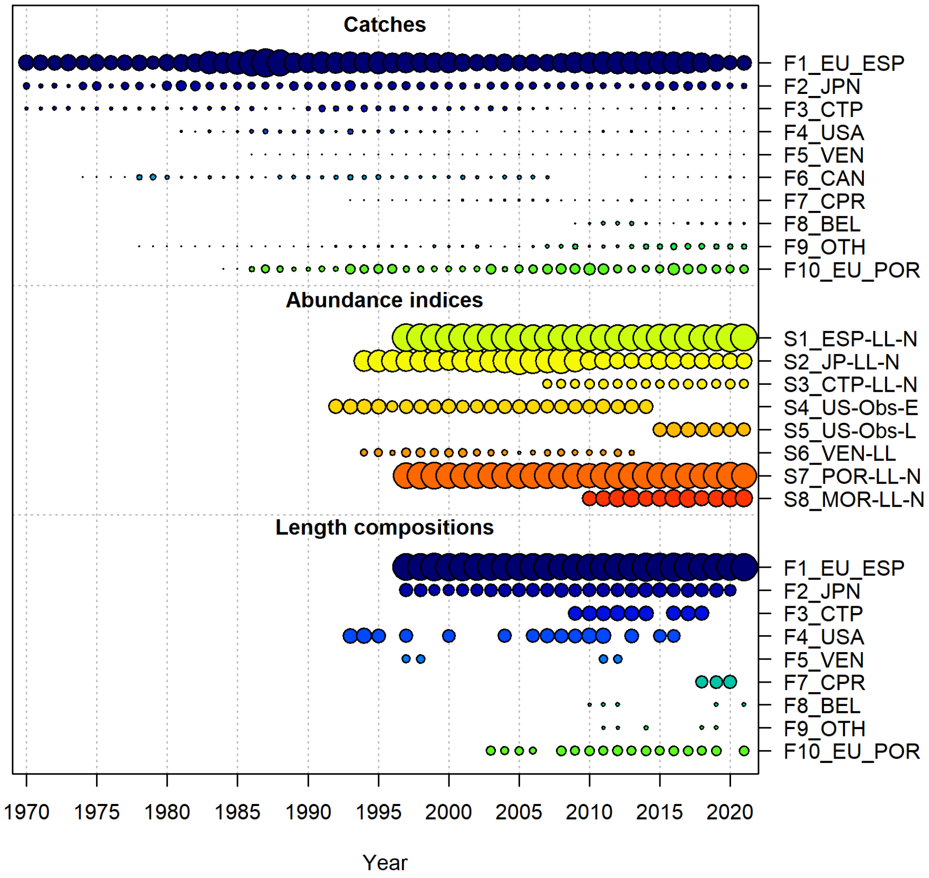


Figure 7. North Atlantic blue shark time series of catch, relative abundance, and length composition data used in the preliminary SS3 model runs, as described in **Table 1**.

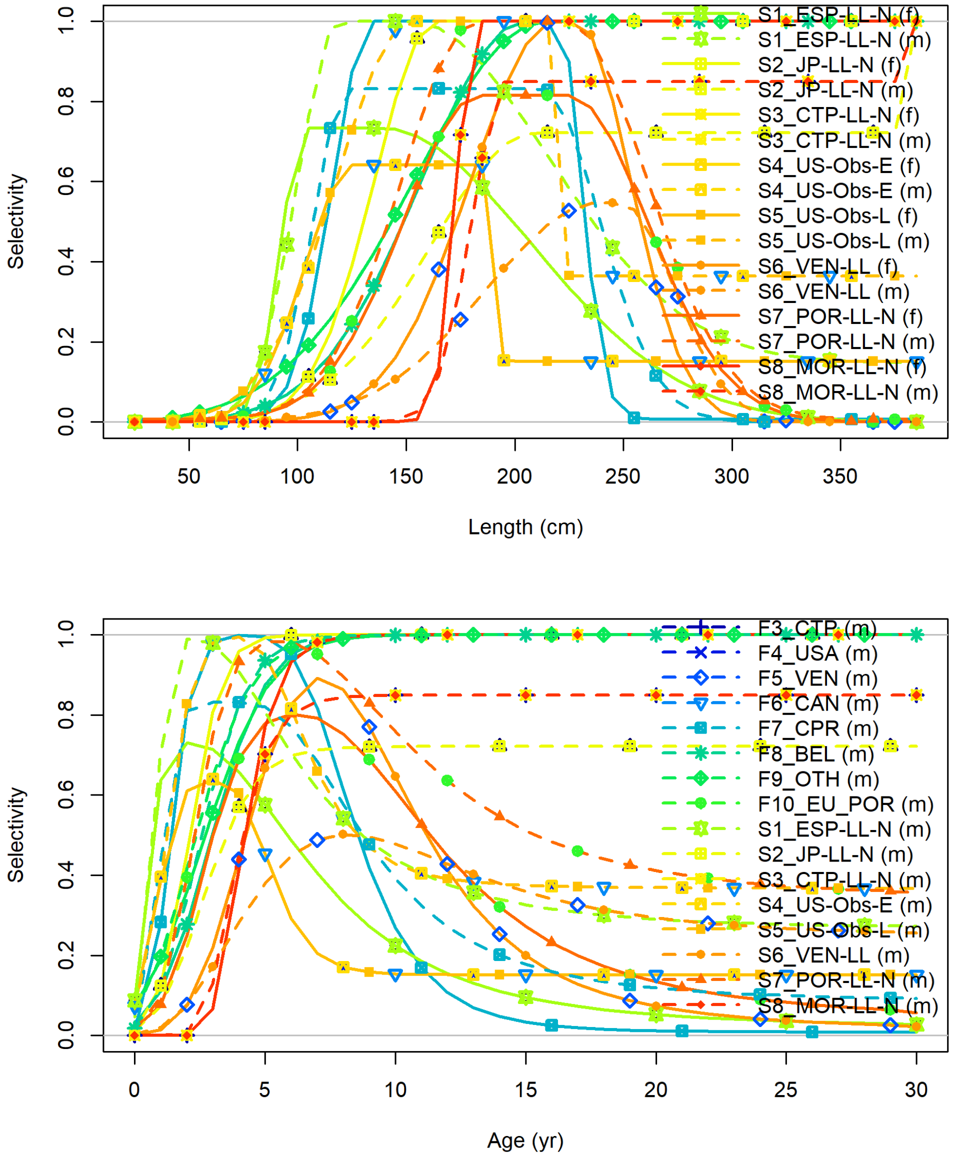


Figure 8. 2023 Reference Case model selectivity at length (cm FL; upper panel) and corresponding derived selectivity at age (lower panel). Fleets as defined in **Table 1** and available length composition as described in **Table 5** and **Figure 3**.

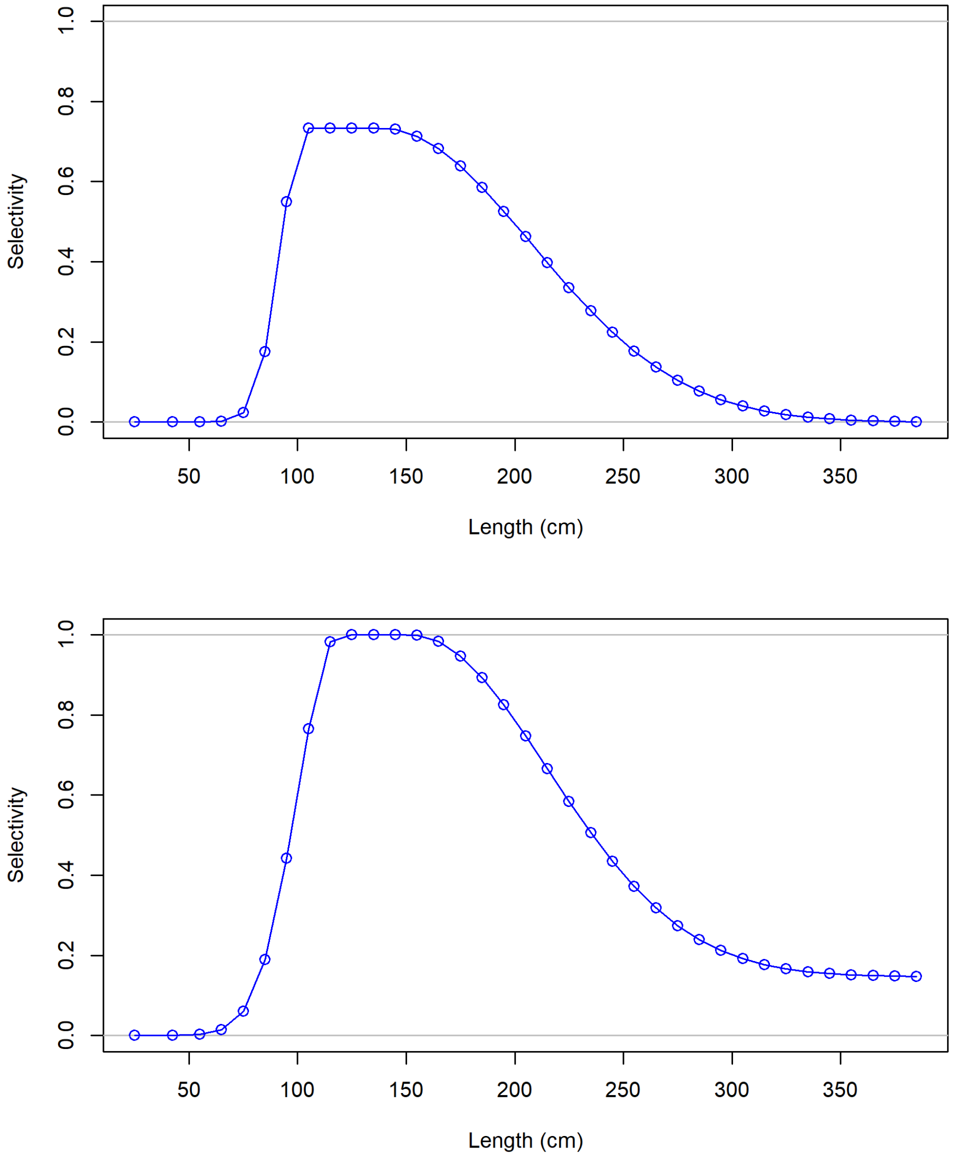
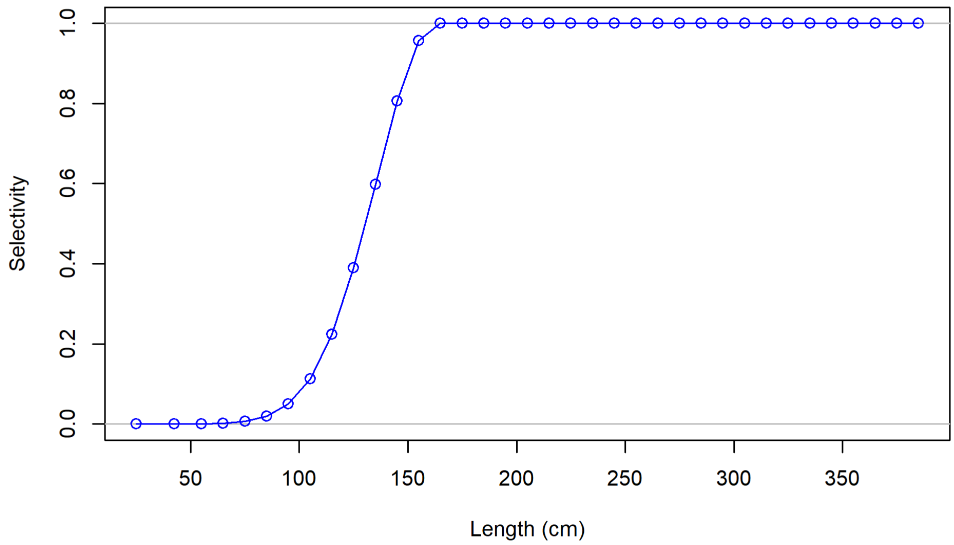


Figure 8. Continued; 2023 Reference Case model F1_EU_ESP selectivity, female upper panel and male (if different from female) in lower panel.



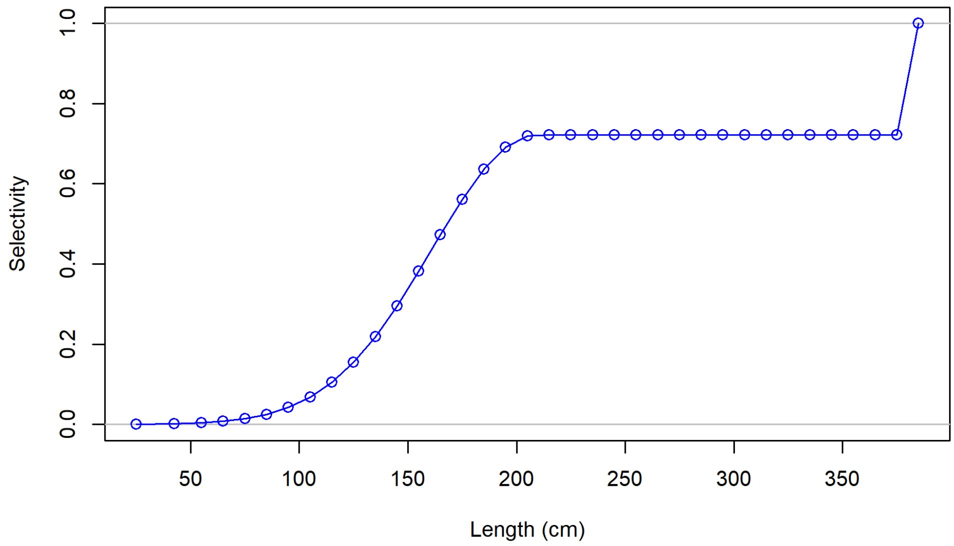


Figure 8. Continued; 2023 Reference Case model F2_JPN selectivity, female upper panel and male (if different from female) in lower panel.

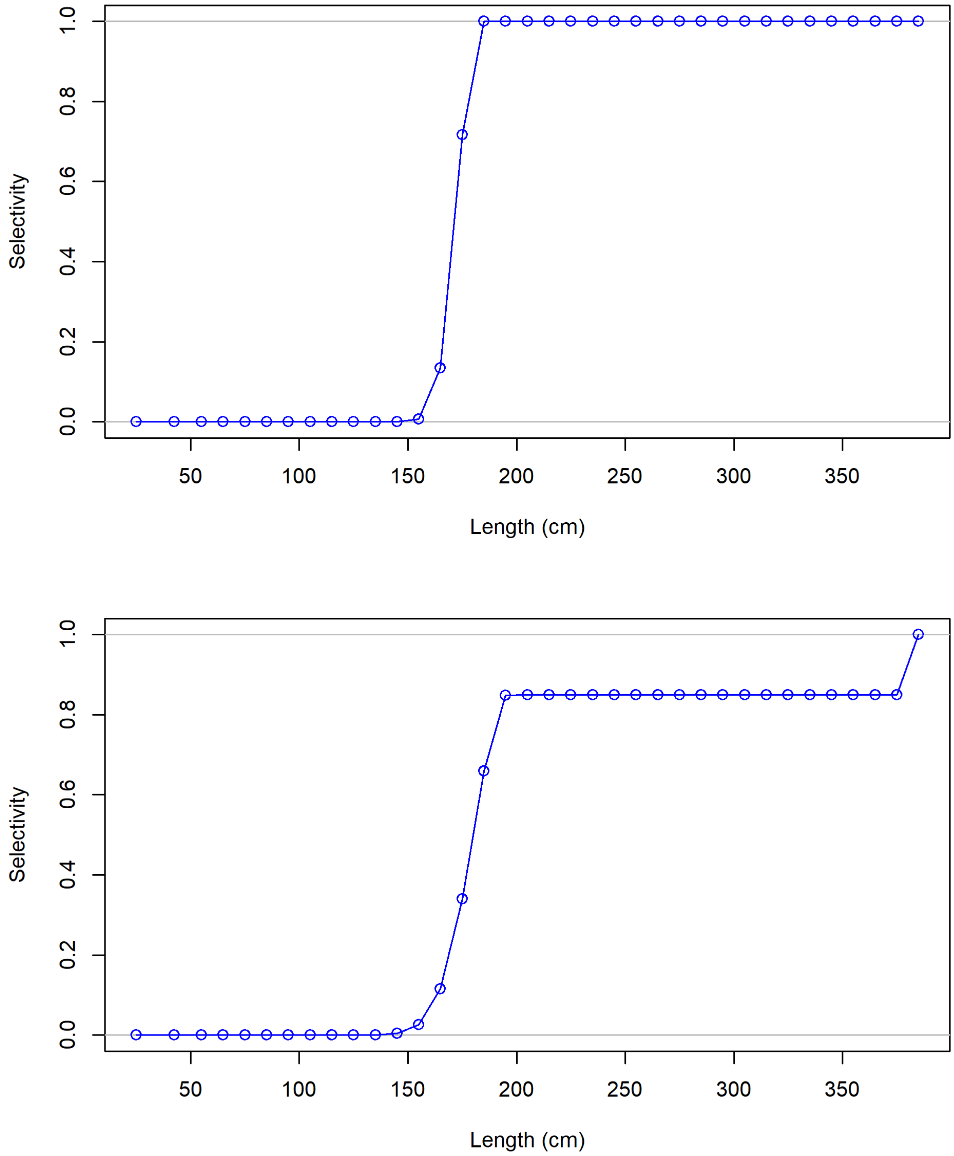


Figure 8. Continued; 2023 Reference Case model F3_CTP selectivity, female upper panel and male (if different from female) in lower panel.

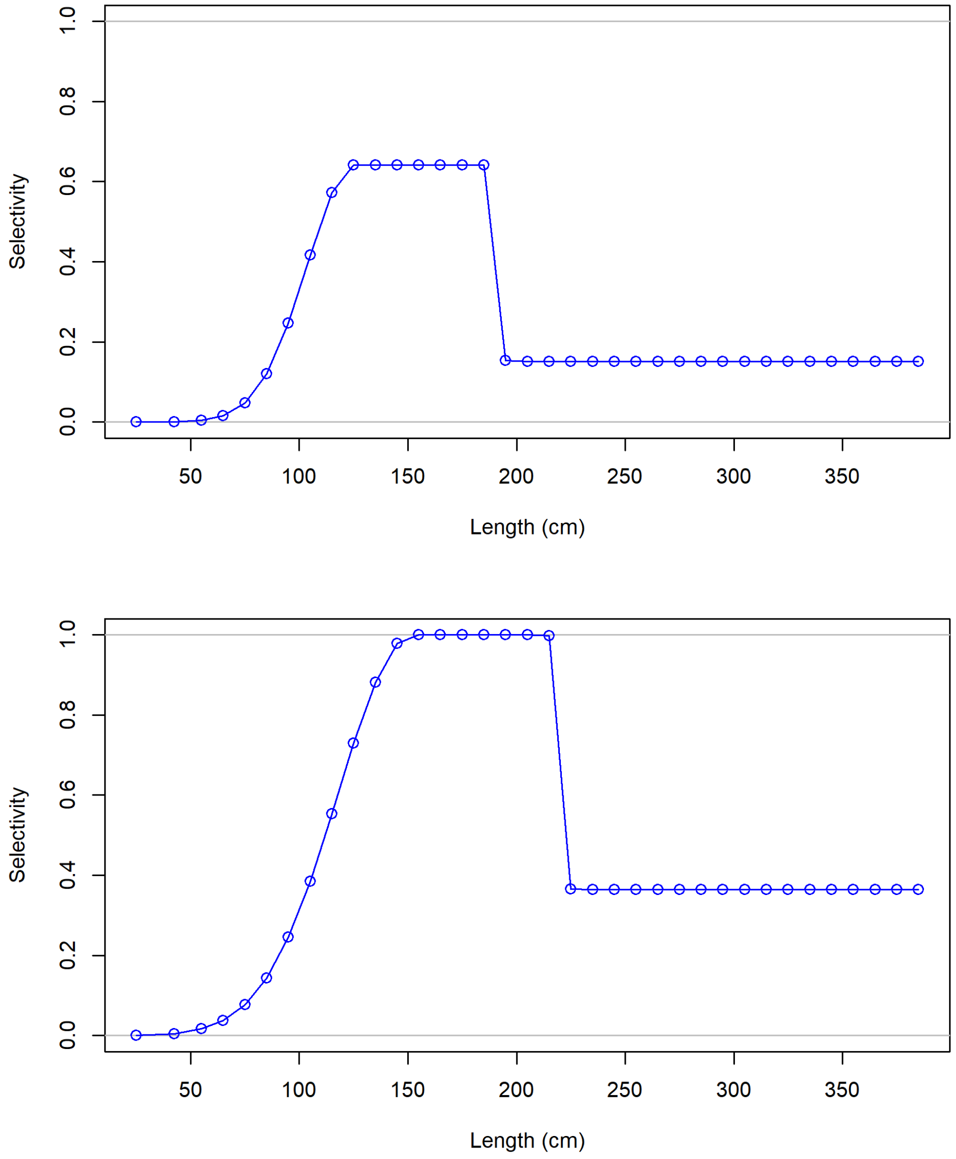


Figure 8. Continued; 2023 Reference Case model F4_USA selectivity, female upper panel and male (if different from female) in lower panel; [F6 CAN mirrored F4_USA selectivity]

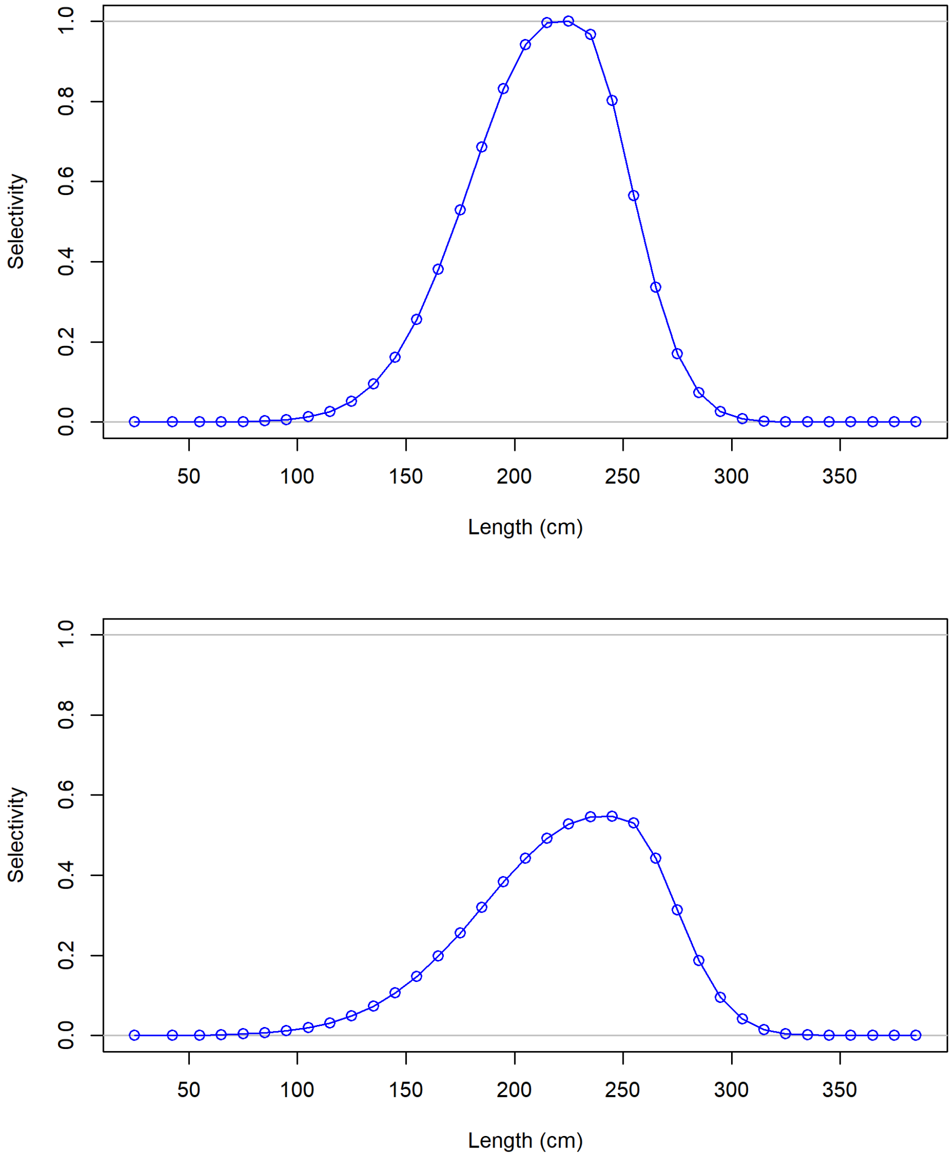


Figure 8. Continued; 2023 Reference Case model F5_VEN selectivity, female upper panel and male (if different from female) in lower panel.

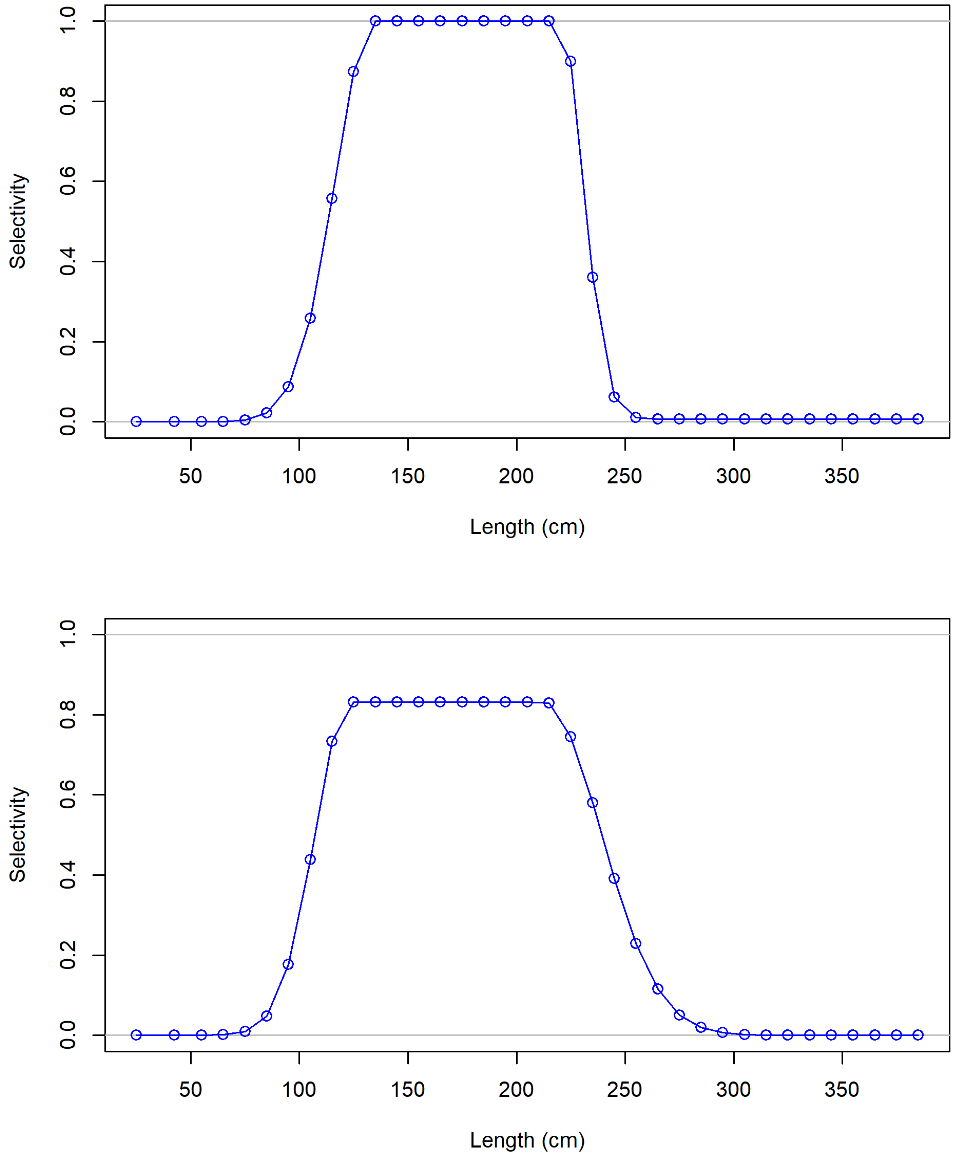


Figure 8. Continued; 2023 Reference Case model F7_CPR selectivity, female upper panel and male (if different from female) in lower panel.

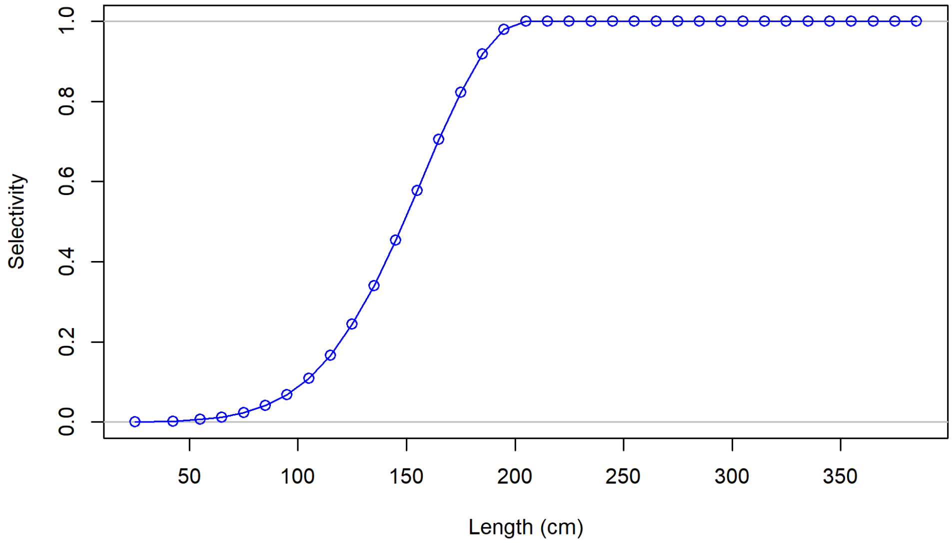


Figure 8. Continued; F8_BEL selectivity, combined female and male.

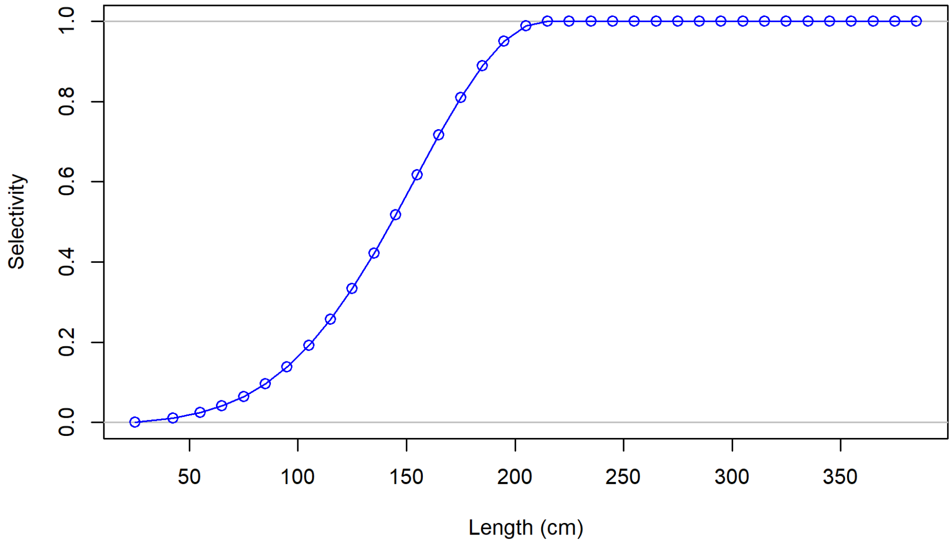


Figure 8. Continued; 2023 Reference Case model F9_OTH selectivity, combined female and male.

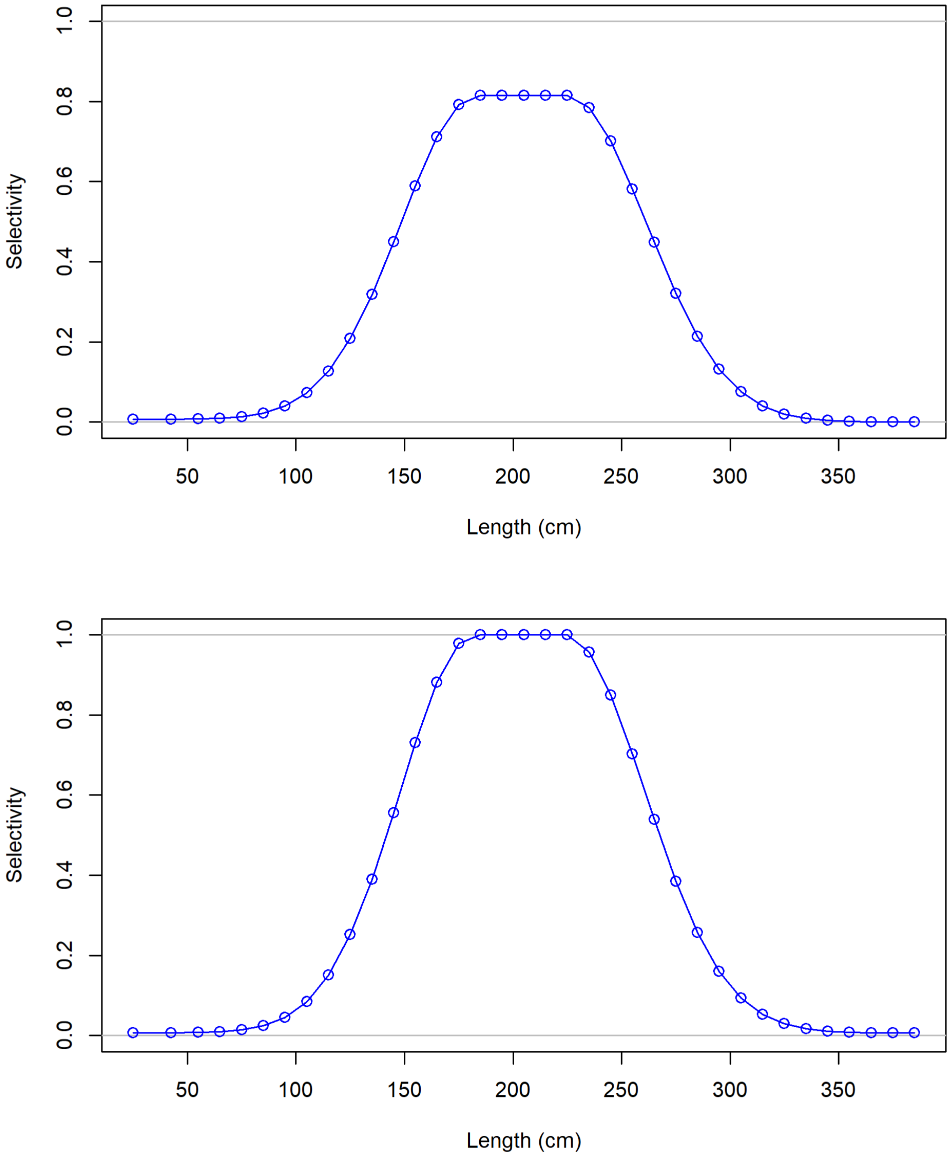


Figure 8. Continued; 2023 Reference Case model F10_EU_POR selectivity, female upper panel and male (if different from female) in lower panel.

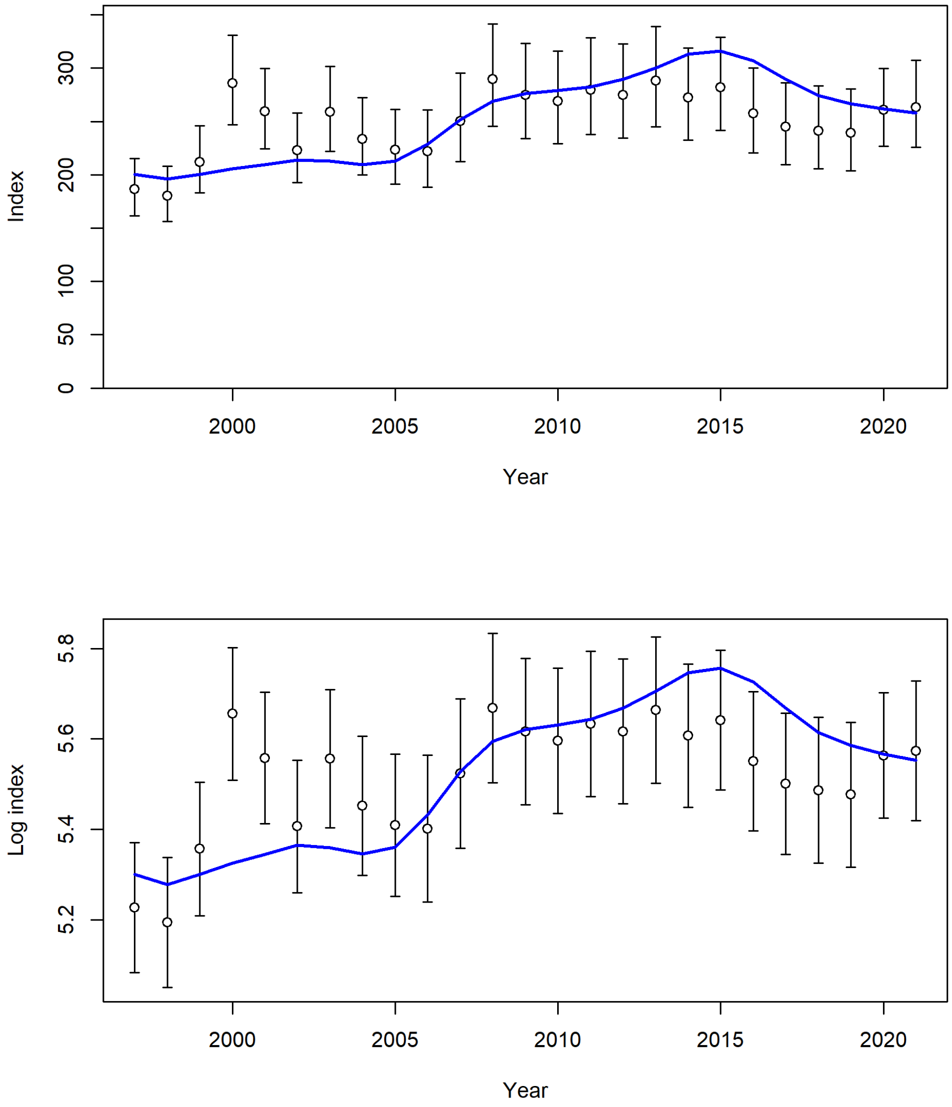


Figure 9. 2023 Reference Case model fit to Index data for S1_ESP-LL-N. Predicted (blue line) and observed (open circles with 95% confidence intervals assuming lognormal error) are provided for each standardized index of relative abundance as described **Tables 1, 3** and **4**. Fits on the nominal scale are provided in the upper panel and fits on the log scale are provided in the lower panel.

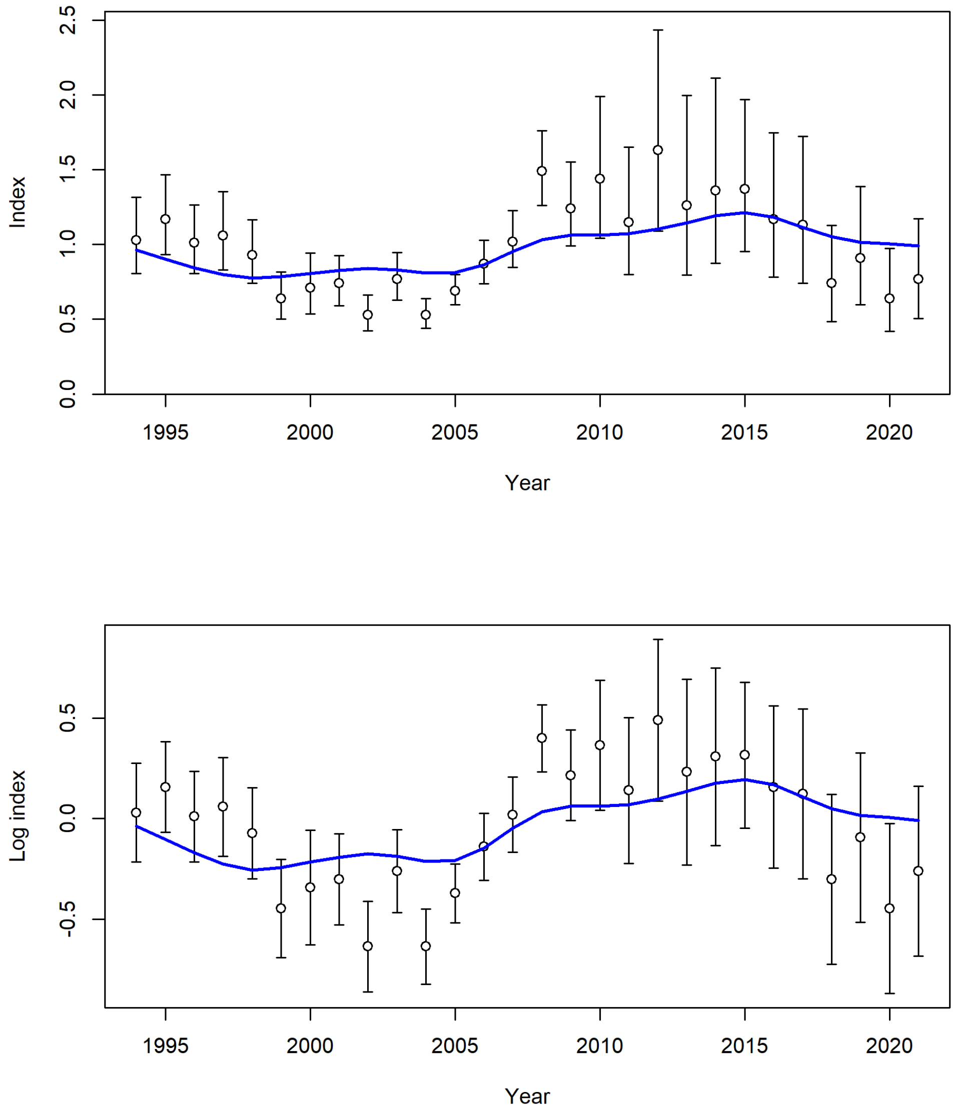
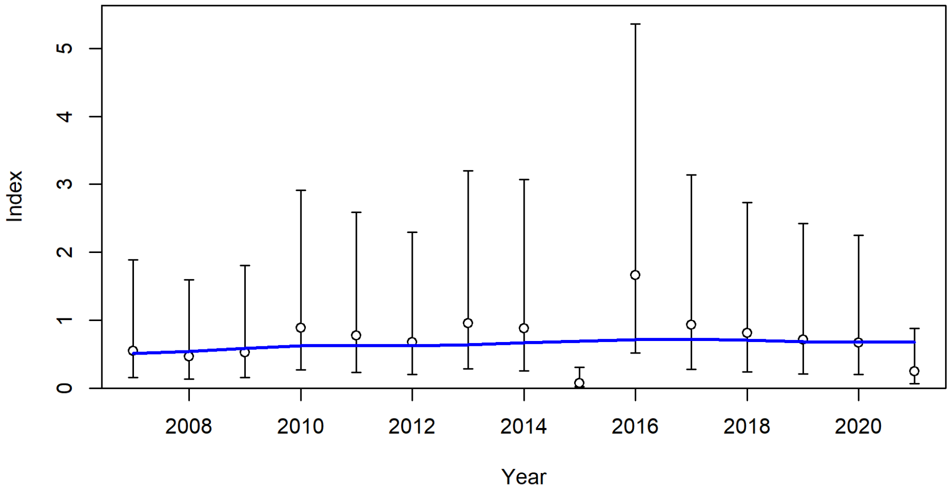


Figure 9. Continued; 2023 Reference Case model fit to Index data for S2_JP-LL-N.



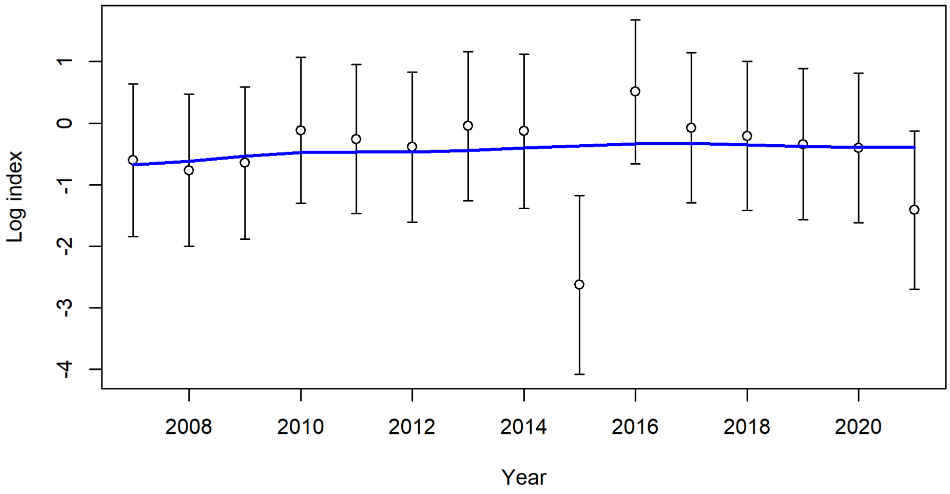
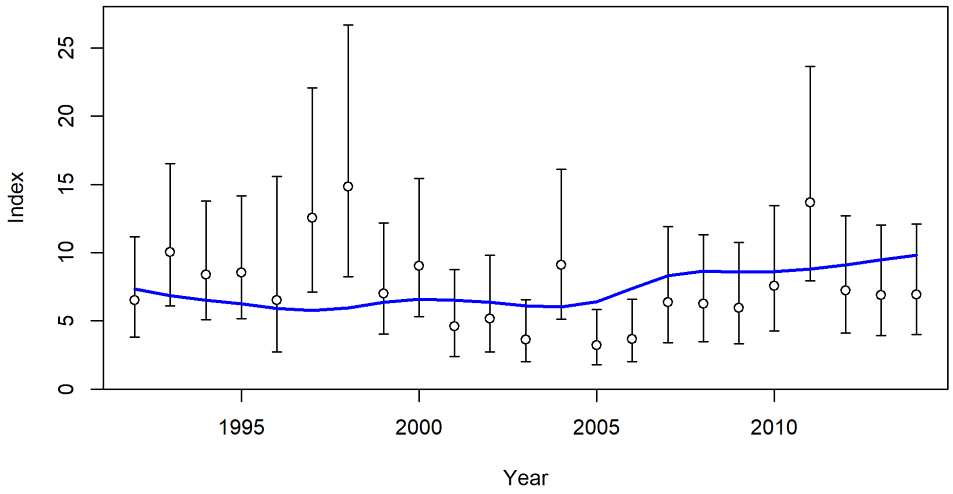


Figure 9. Continued; 2023 Reference Case model fit to Index data for S3_CTP-LL-N.



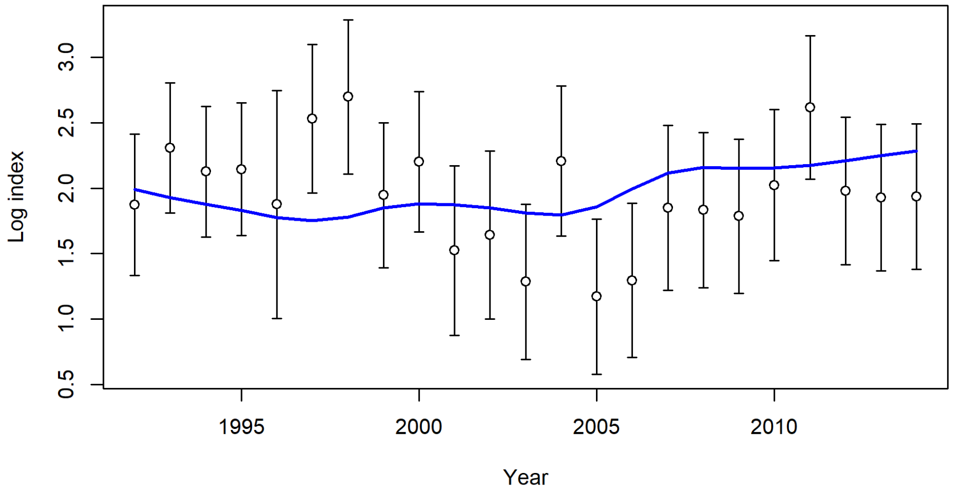
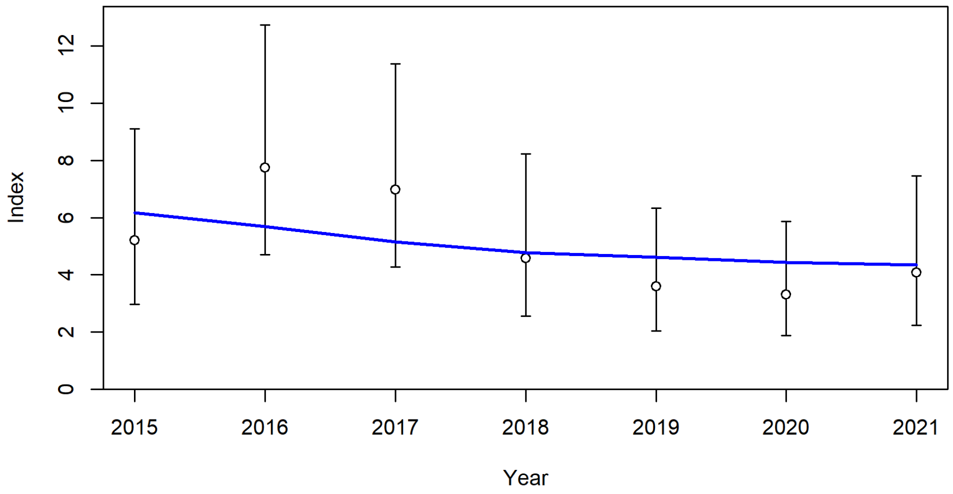


Figure 9. Continued; 2023 Reference Case model fit to Index data for S4_US-Obs-E.



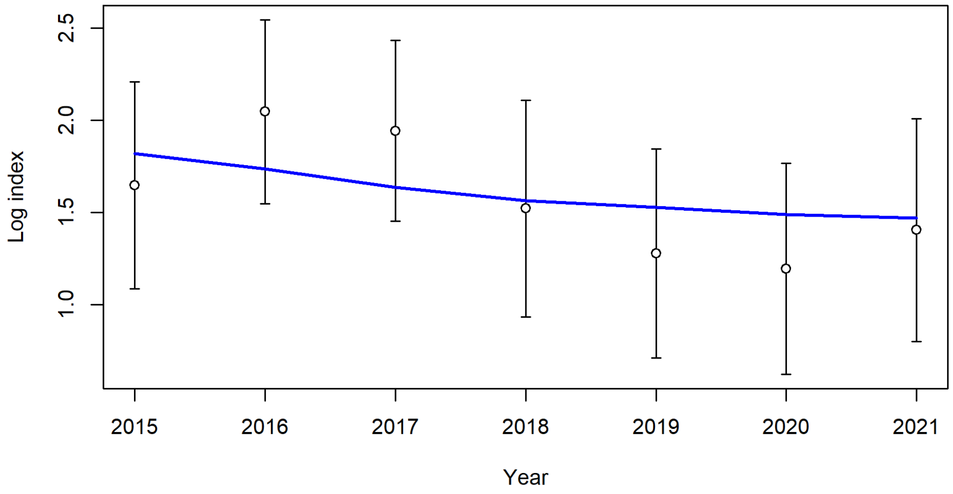
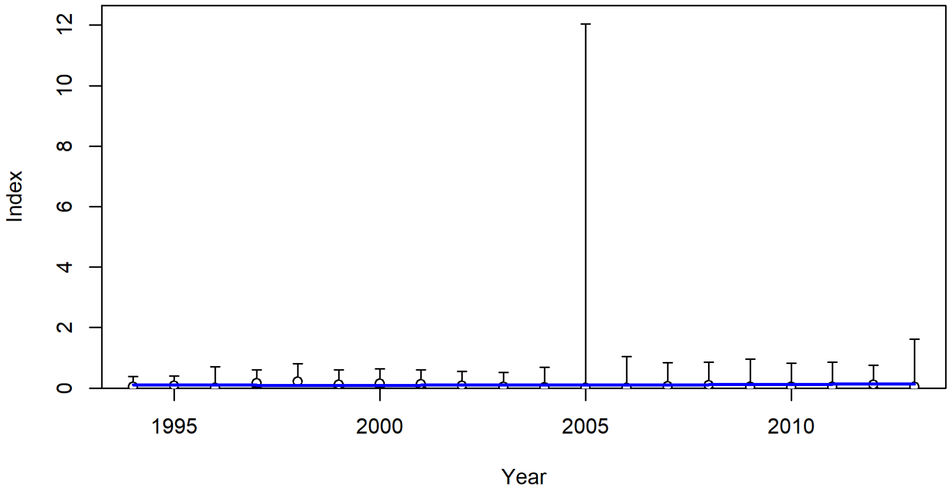


Figure 9. Continued; 2023 Reference Case model fit to Index data for S5_US-Obs-L.



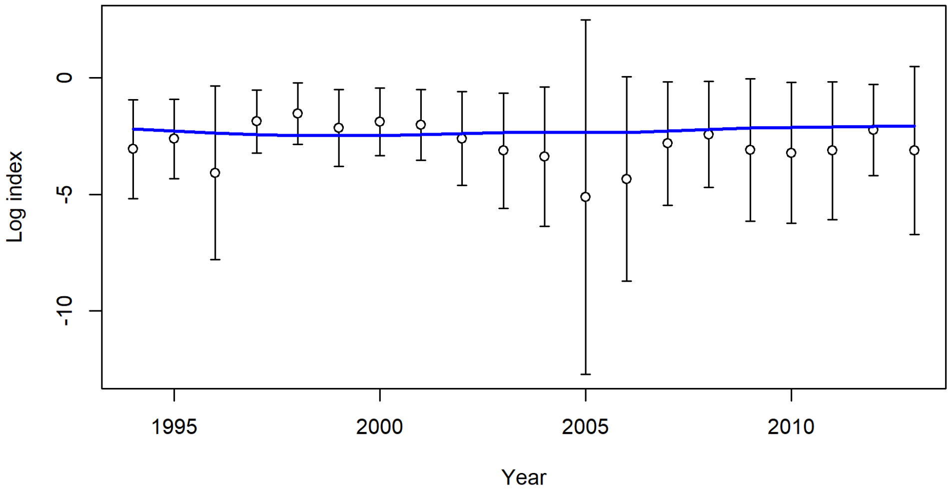
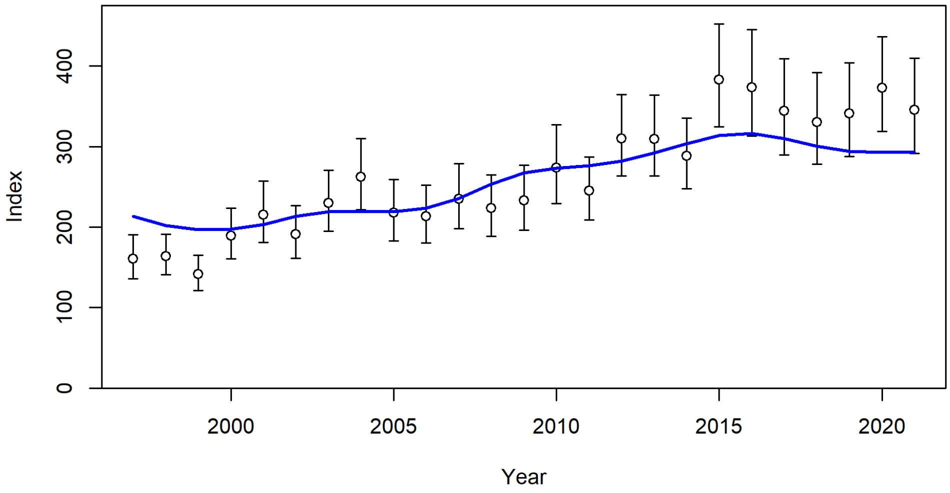


Figure 9. Continued; 2023 Reference Case model fit to Index data for S6_VEN-LL.



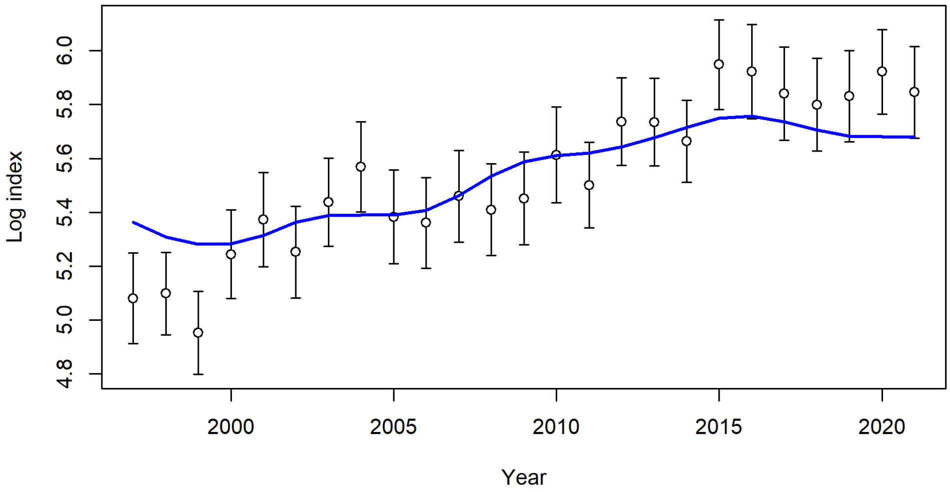


Figure 9. Continued; 2023 Reference Case model fit to Index data for S7_POR-LL-N.

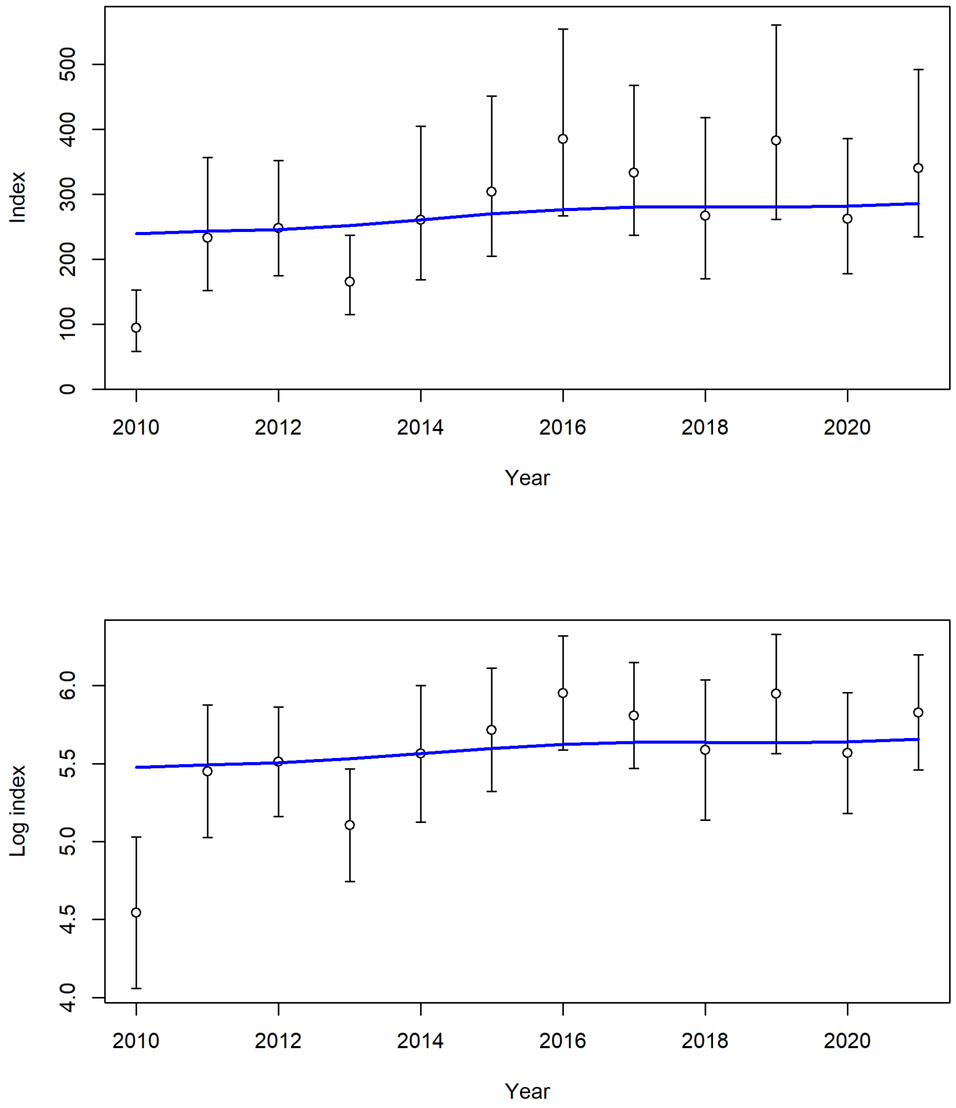


Figure 9. Continued; 2023 Reference Case model fit to Index data for S8_MOR-LL-N.

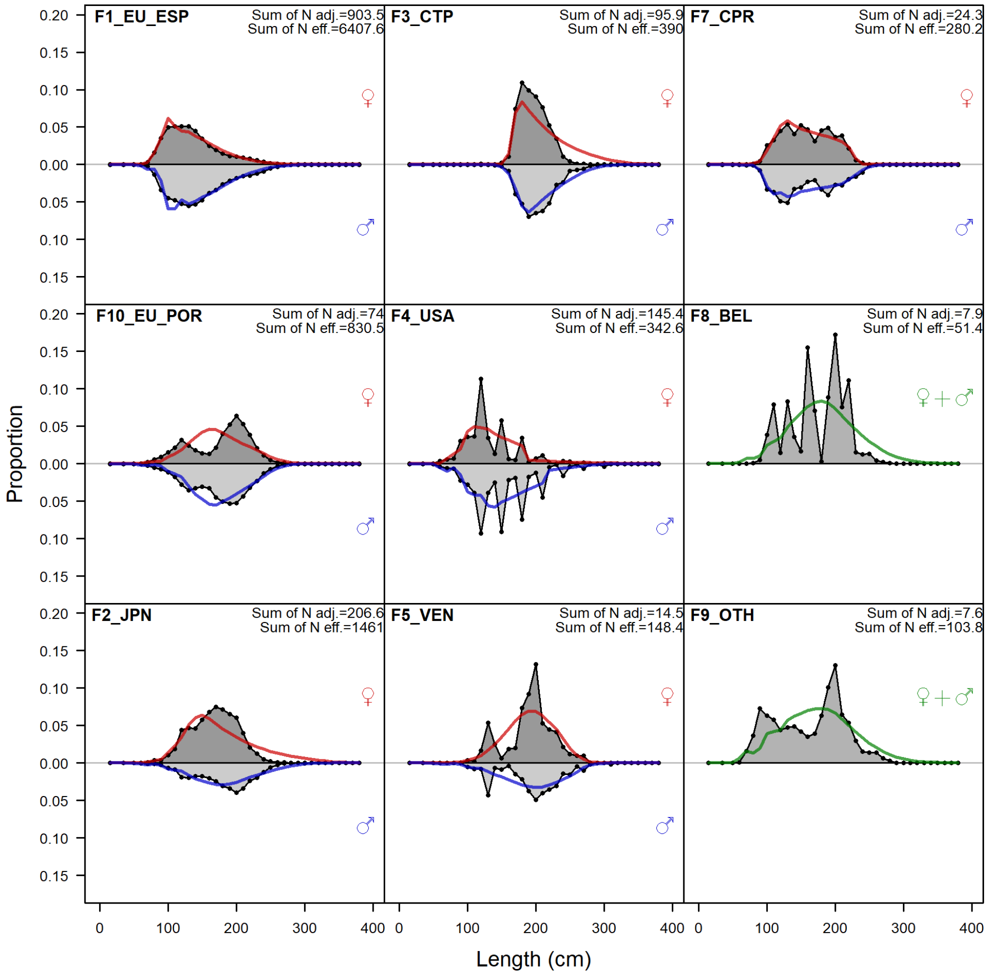


Figure 10. 2023 Reference Case model fit to length composition. Model predicted (line) and observed (shaded) aggregated length compositions. The "Sum of N adj." is the sum of input effective sample size provided by the R package r4ss using the Francis method (Stage 2) as described in the text of the main document above. The "Sum of N eff." is an alternative effective sample size provided by Stock Synthesis output (Report.ss) using the McAllister and Ianelli (1997) method (using the harmonic mean). Plots of annual fits to length composition data by fleet along with plots of Francis method (Stage 2) length composition variance adjustments are provided in **Appendix B**.

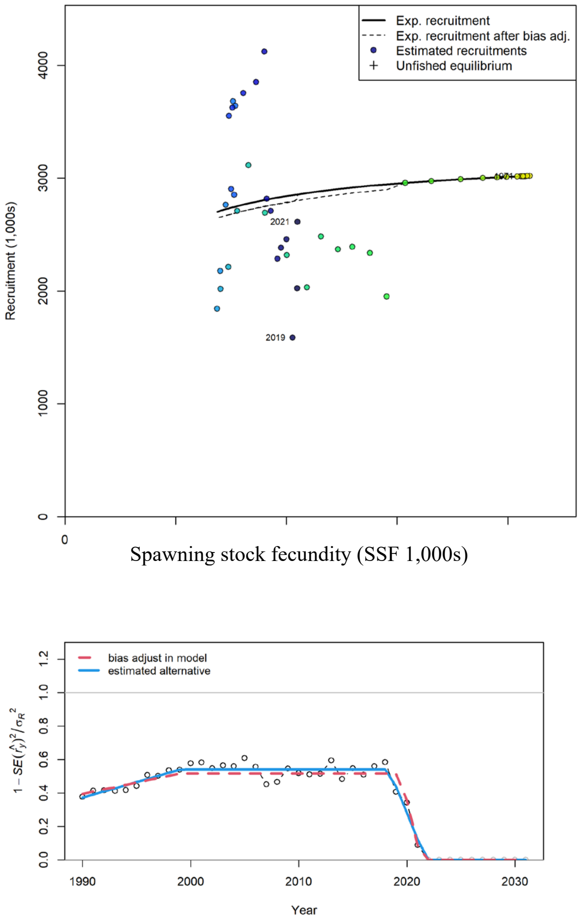


Figure 11. 2023 Reference Case model expected recruitment. Upper panel is the expected recruitment from the stock-recruitment relationship (black line), expected recruitment after implementing the bias adjustment correction (green line), estimated annual recruitments (circles), unfished equilibrium (plus), and first (1971) and last (2021) years along with years with log deviations > 0.5. Note the different scales on the Y-axis (number of recruits in 1,000s) and X-axis (spawning stock fecundity, SSF, in 1,000s). Lower panel is bias adjustment applied to the stock-recruitment relationship (red stippled line) and the estimated alternative (blue line) obtained from the r4ss output.

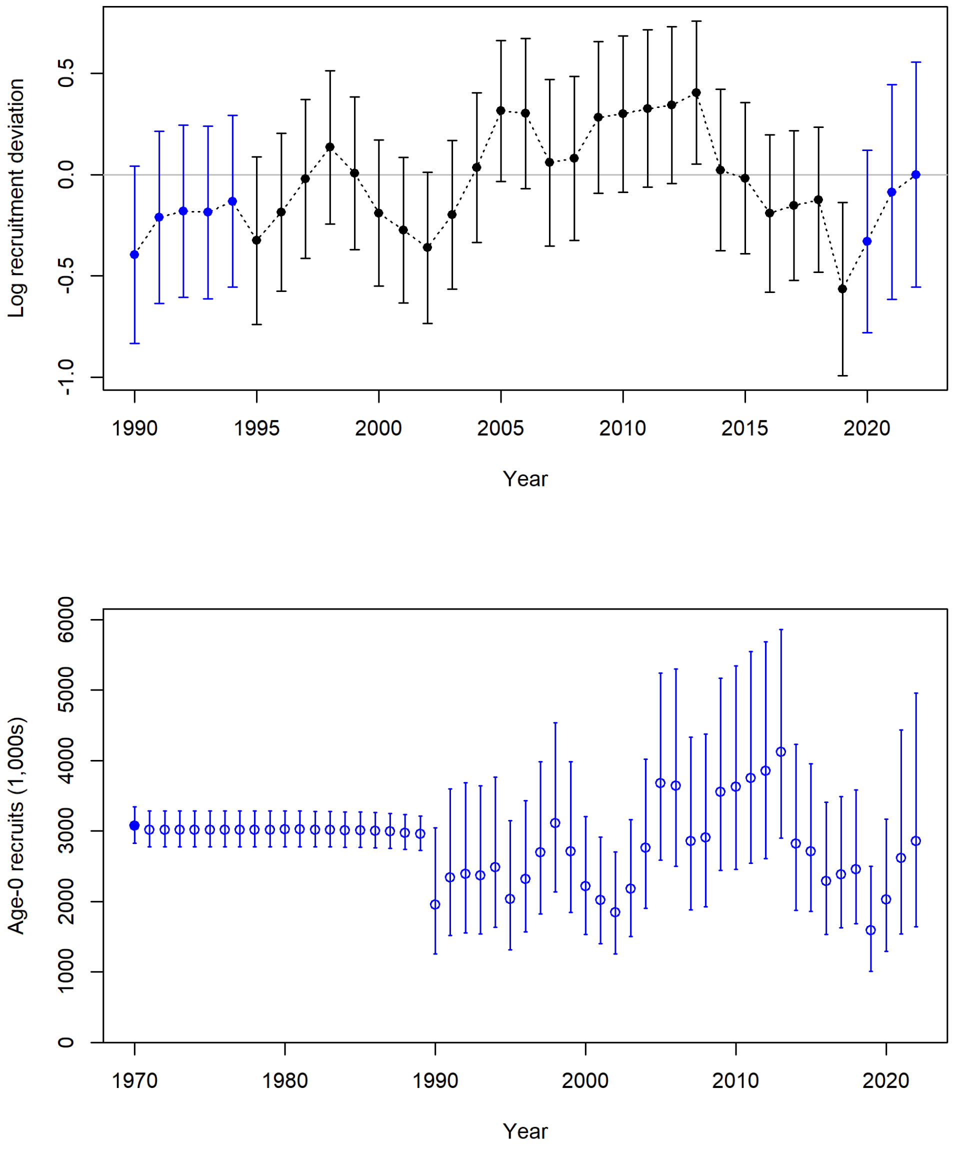


Figure 12. 2023 Reference Case model estimated recruitment. Upper panel is the estimated log recruitment deviations for the early (1990 – 1994, blue), main (1995 – 2019, black) recent (2020 – 2021, blue) and forecast (2022 blue) recruitment periods with associated 95% asymptotic confidence intervals. Lower panel is the estimated annual age-0 recruitment (circles) with 95% asymptotic confidence intervals; recruitment in years prior to 1990 and after 2021 follows the stock recruitment relationship exactly.

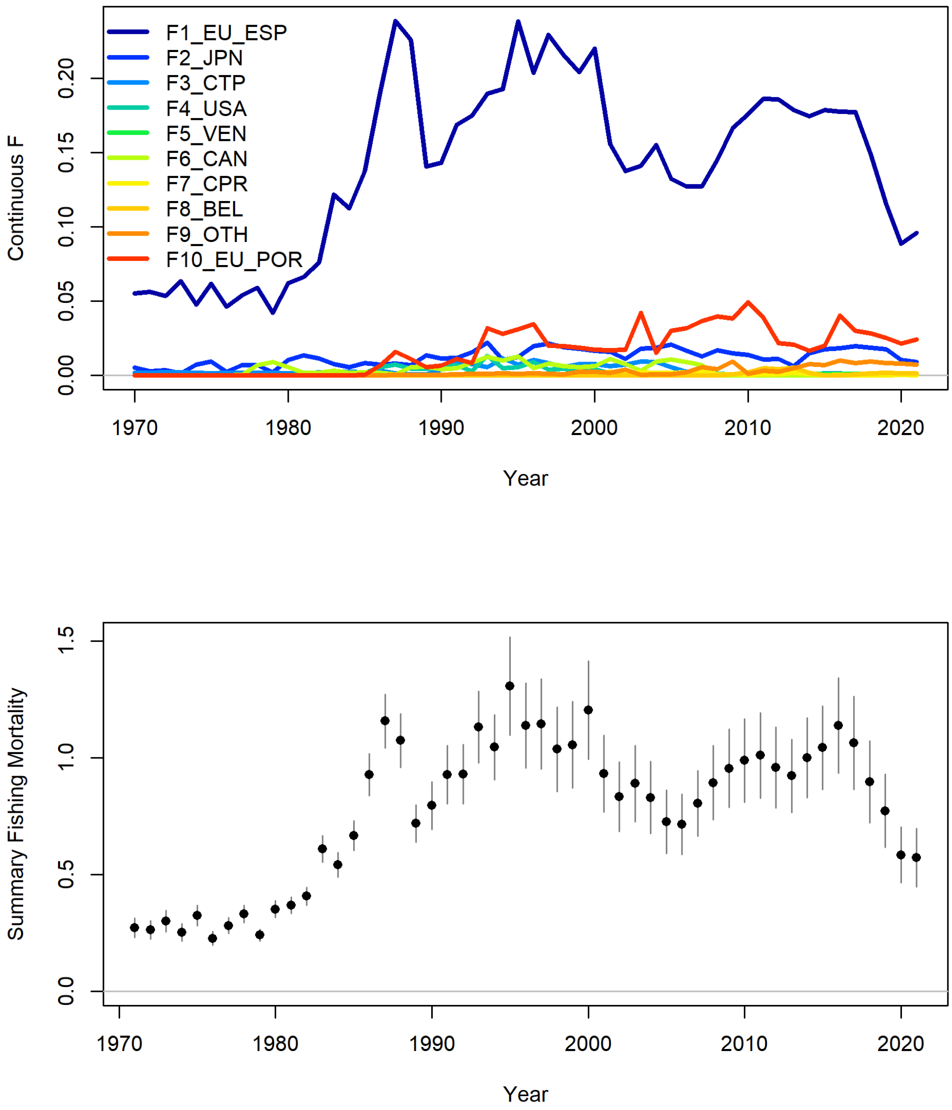


Figure 13. 2023 Reference Case model estimated instantaneous fishing mortality rates (Continuous *F*). Upper panel is *F* for each fleet (F1 – F10). Lower panel is the estimated total annual fishing mortality for all fleets combined, calculated with SS3 option 4=true F for range of ages (0-28), relative to the fishing mortality obtained by SS3 at equilibrium MSY in the same units.

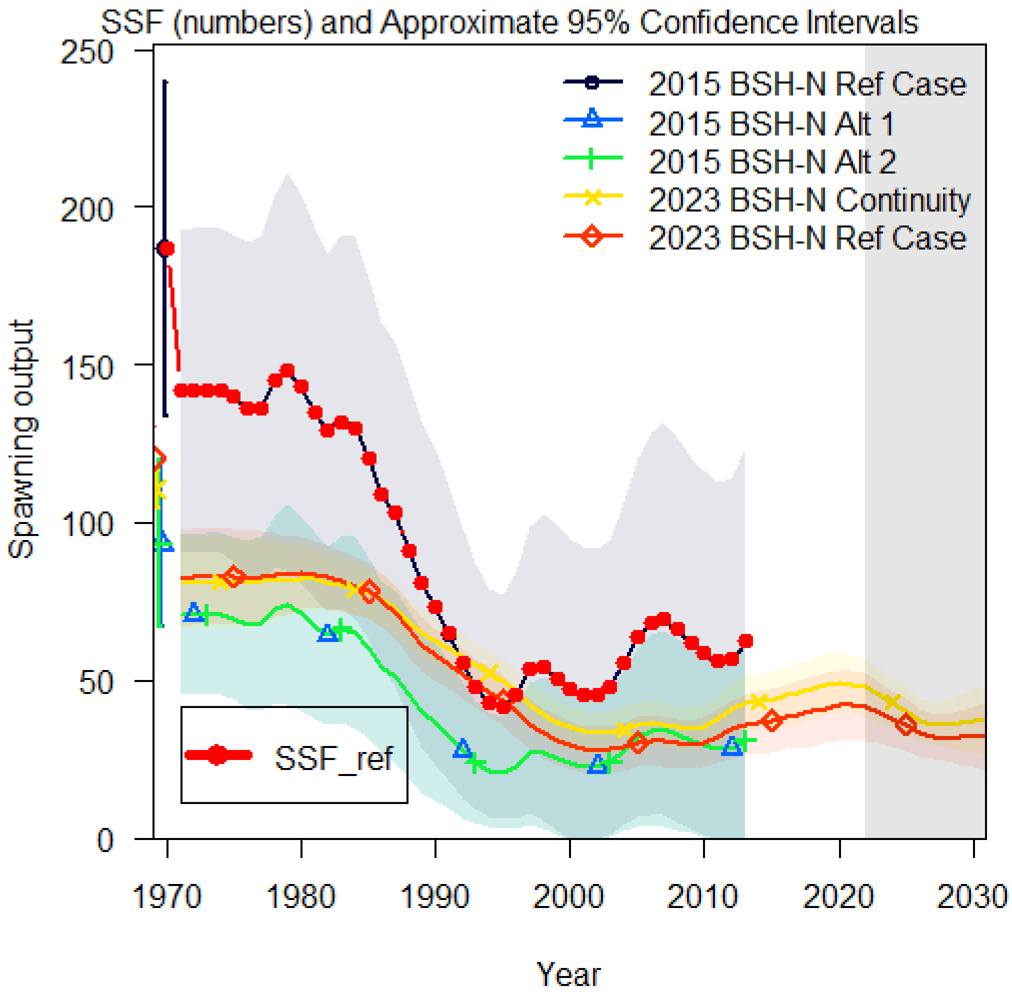


Figure 14. Stock Synthesis model continuity evaluated relative to the 2015 ICCAT North Atlantic Preliminary Run 6 (Courtney 2016) as described above in Section 2.4 and summarized in **Table 14.**

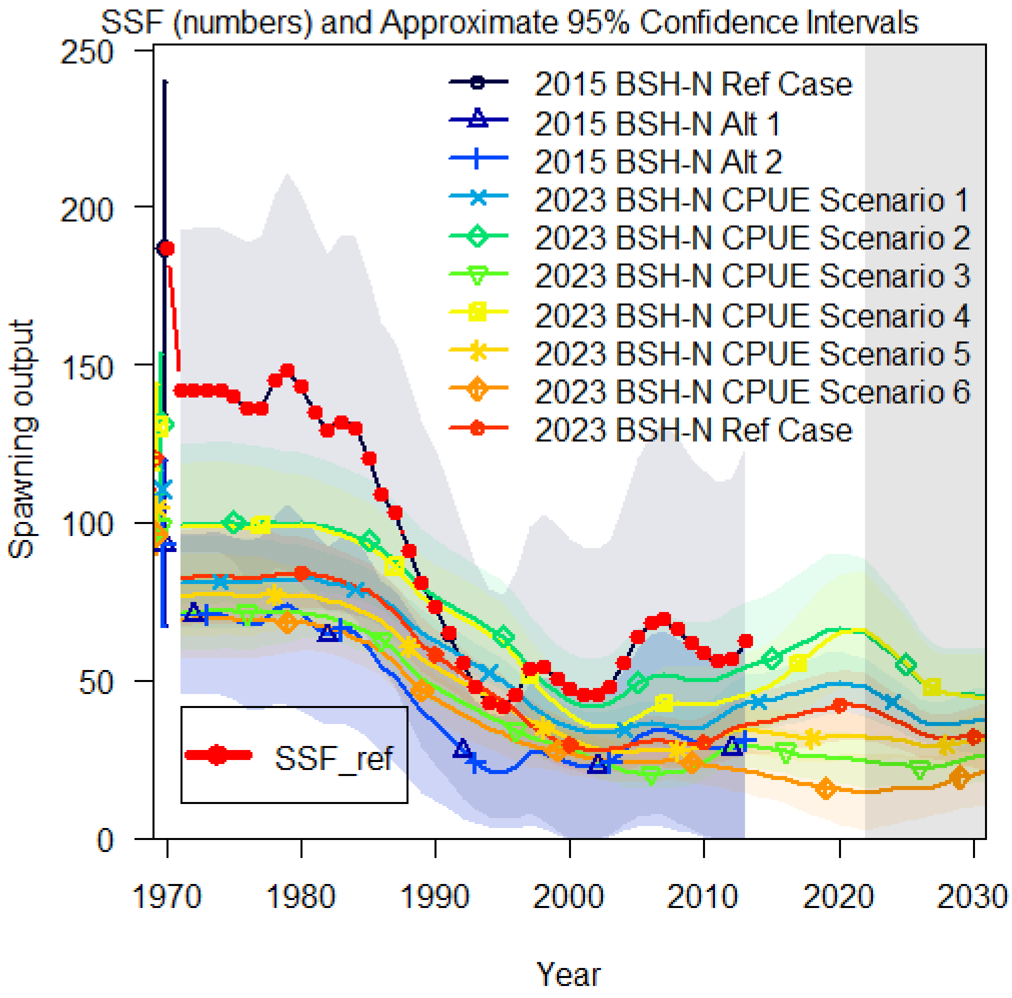


Figure 15. Structural uncertainty evaluated to North Atlantic blue shark CPUE groupings recommended by the Shark Working Group (Anon 2023) as described in Section 2.5.1 and **Table 10** and summarized in **Table 15.**

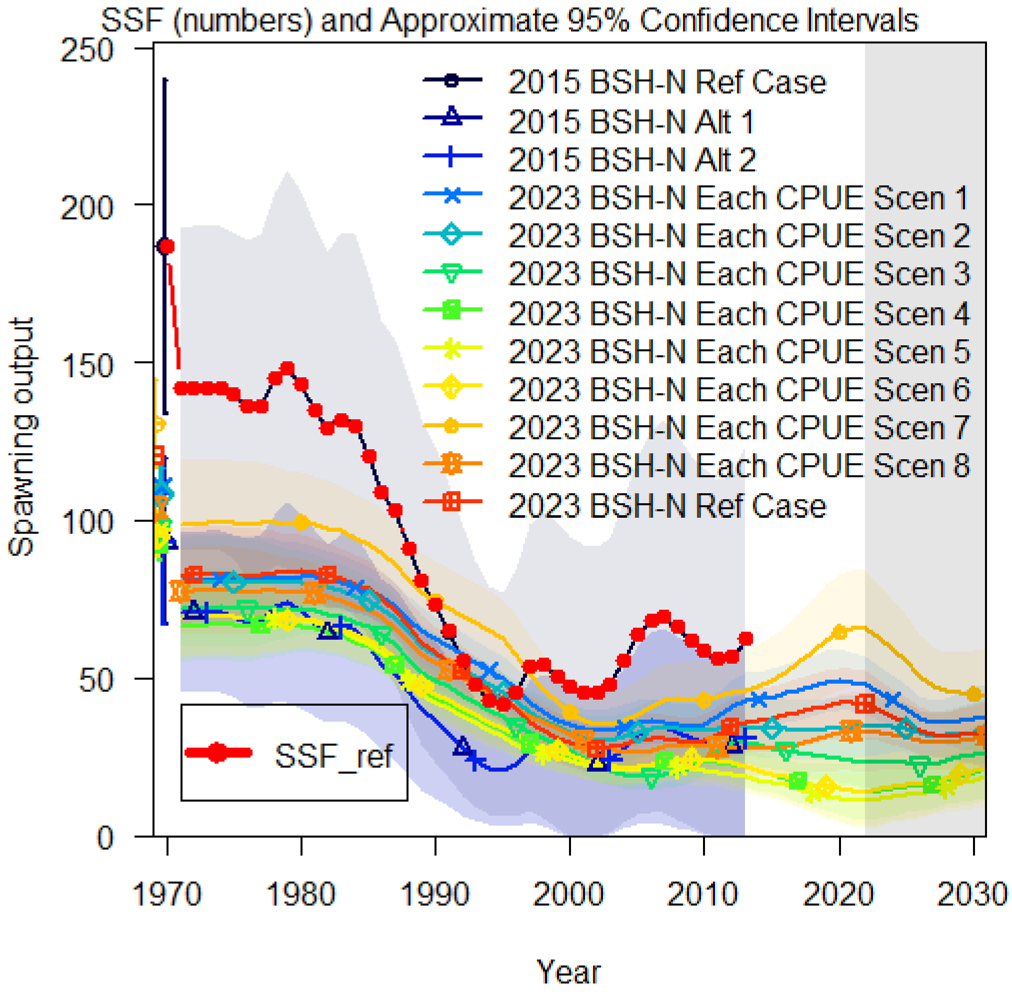


Figure 16. Structural uncertainty evaluated to including each North Atlantic blue shark CPUE series (**Tables 3 and 4**) one at a time in the Stock Synthesis model as described in Section 2.5.1 and **Table 11** and summarized in **Table 16.**

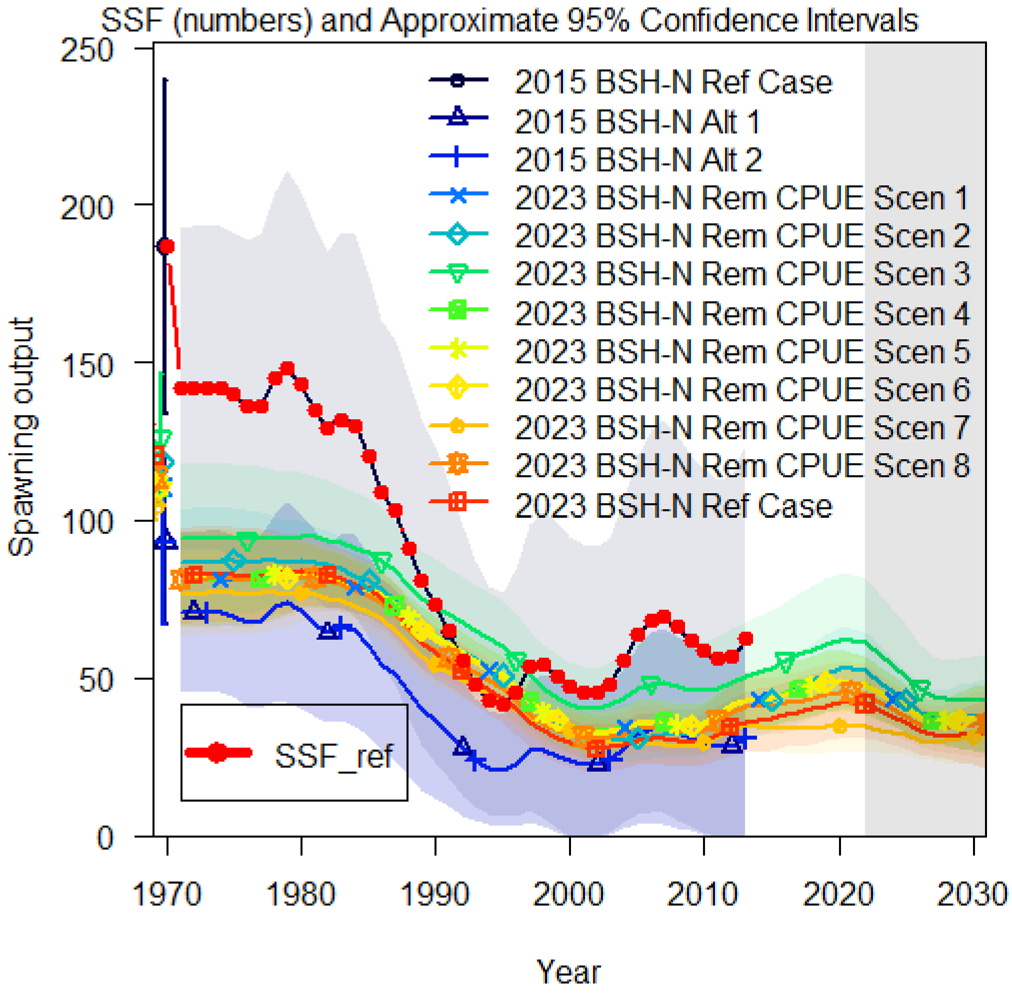


Figure 17. Structural uncertainty evaluated to removing each North Atlantic blue shark CPUE series (**Tables 3 and 4**) one at a time from the Stock Synthesis model as described in Section 2.5.1 and **Table 12** and summarized in **Table 17.**

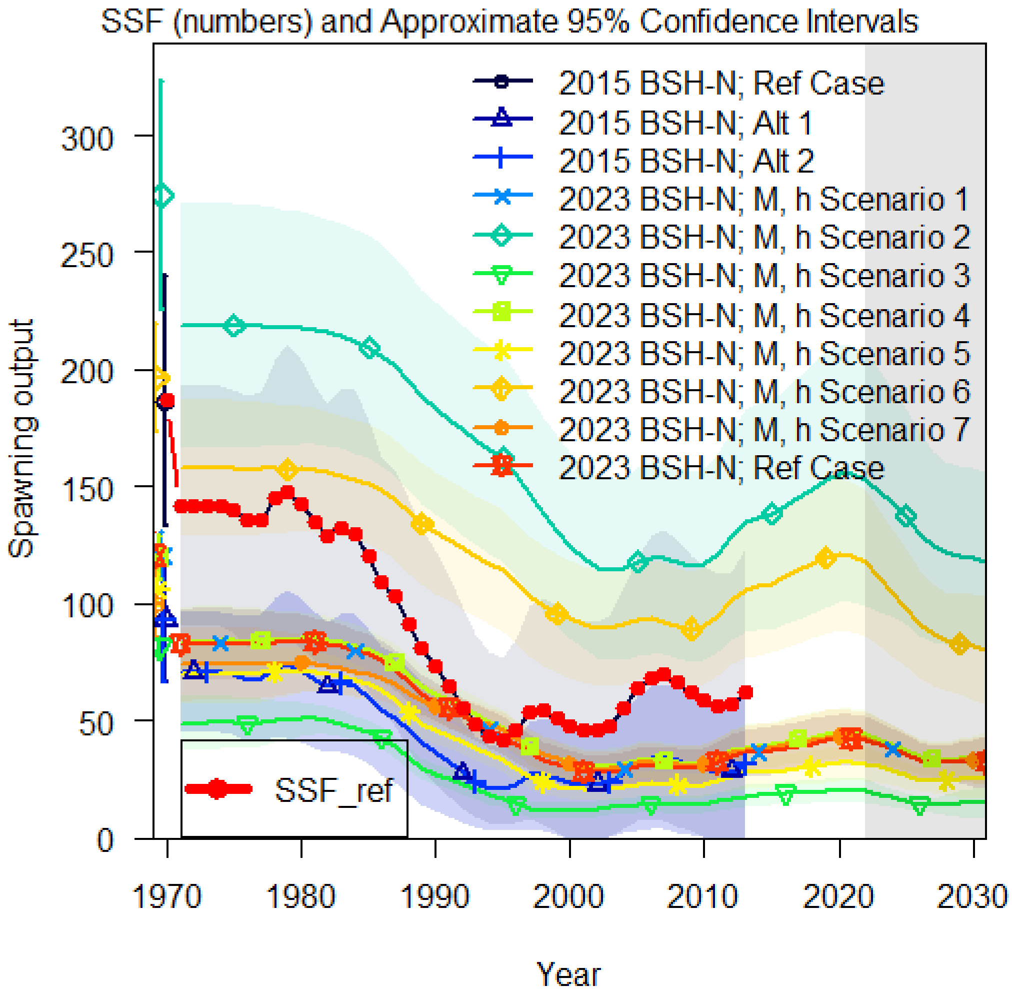


Figure 18. Structural uncertainty to externally derived natural mortality, *M*, and steepness, *h*, evaluated with seven scenarios developed from SCRS/2023/115 as described in Section 2.5.2 and **Table 13** and summarized in **Table 18.**

Appendix A

CPUE Variance Adjustments (Francis Method Stage 1).

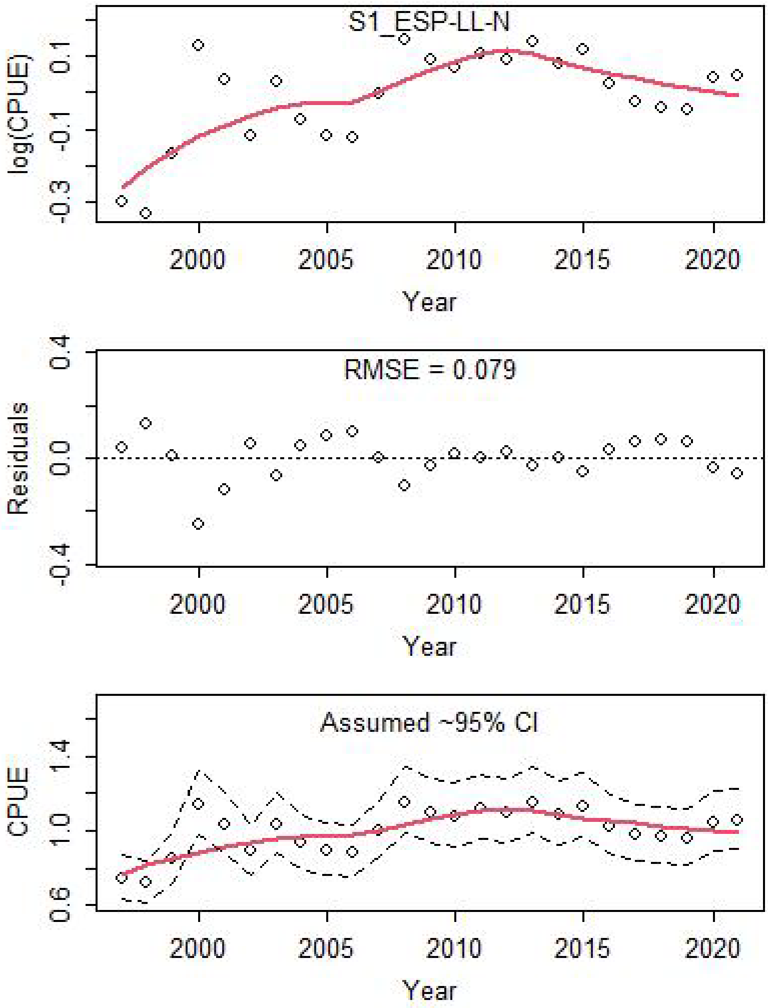


Figure A.1. Preliminary 2023 reference case SS3 CPUE variance adjustments for S1_ESP-LL-N. LOESS smoother fits were used to estimate the RMSEsmoother for each CPUE series; Upper panel: LOESS smoother fits to log (CPUE) data; Middle panel: Residual plots and estimated RMSE for each CPUE series; Lower panel: LOESS smoother fits illustrated for each CPUE index along with approximate 95% confidence intervals after applying the variance adjustment.

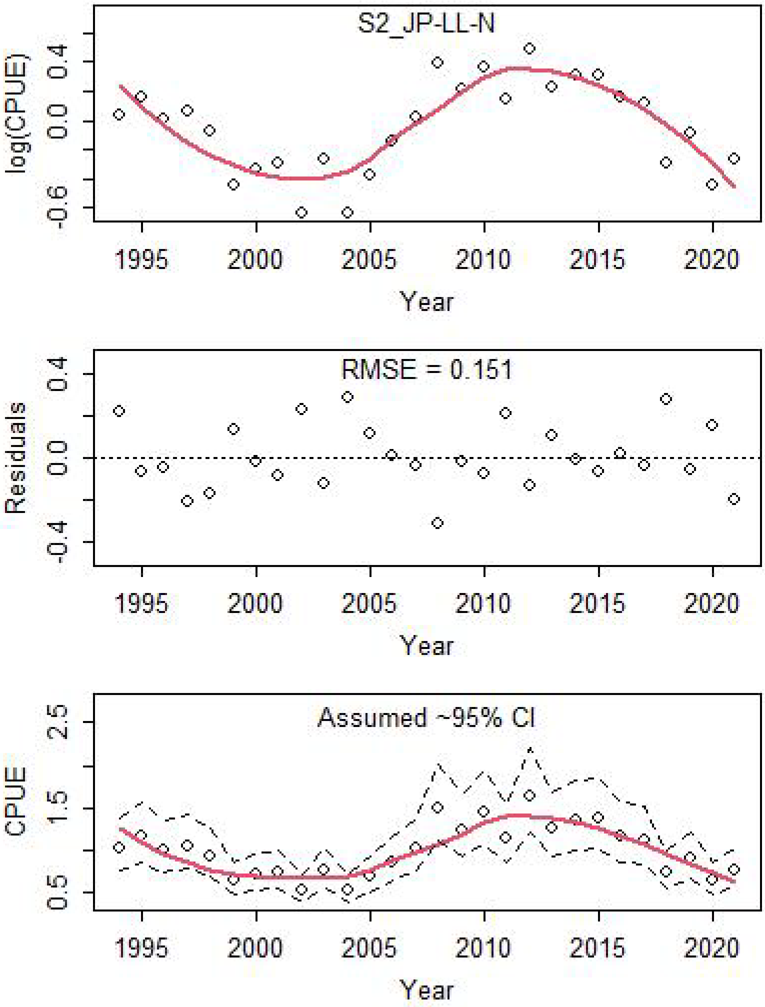


Figure A.2. Preliminary 2023 reference case SS3 CPUE variance adjustments for S2_JP-LL-N.

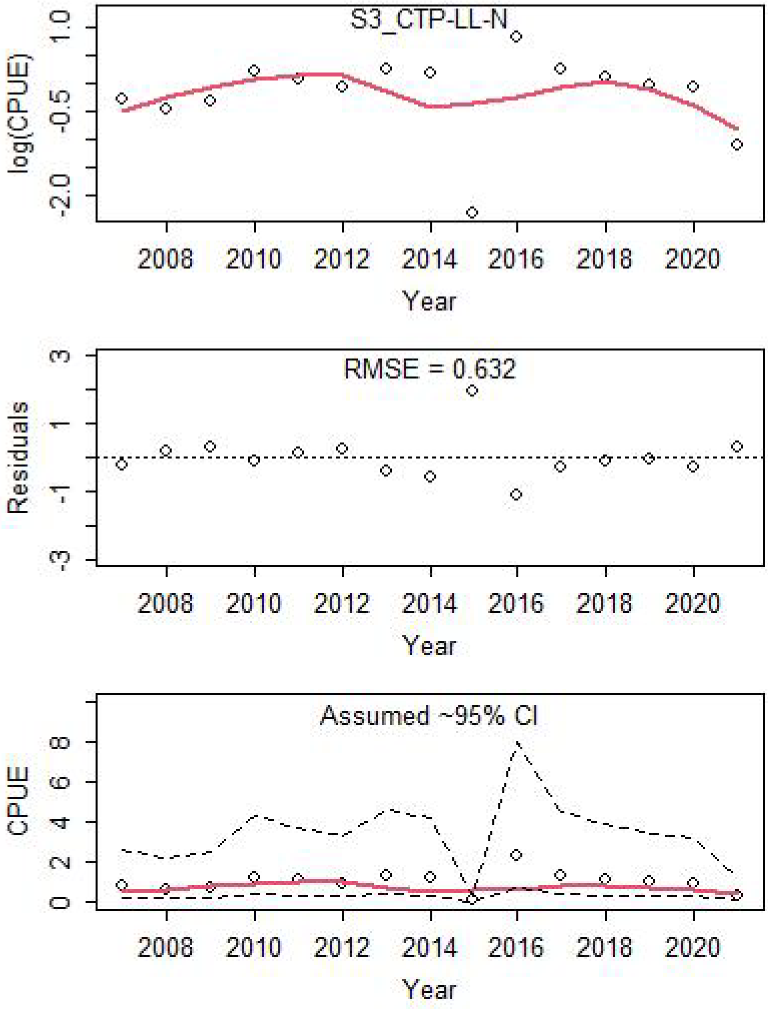


Figure A.3. Preliminary 2023 reference case SS3 CPUE variance adjustments for S3_CTP-LL-N.

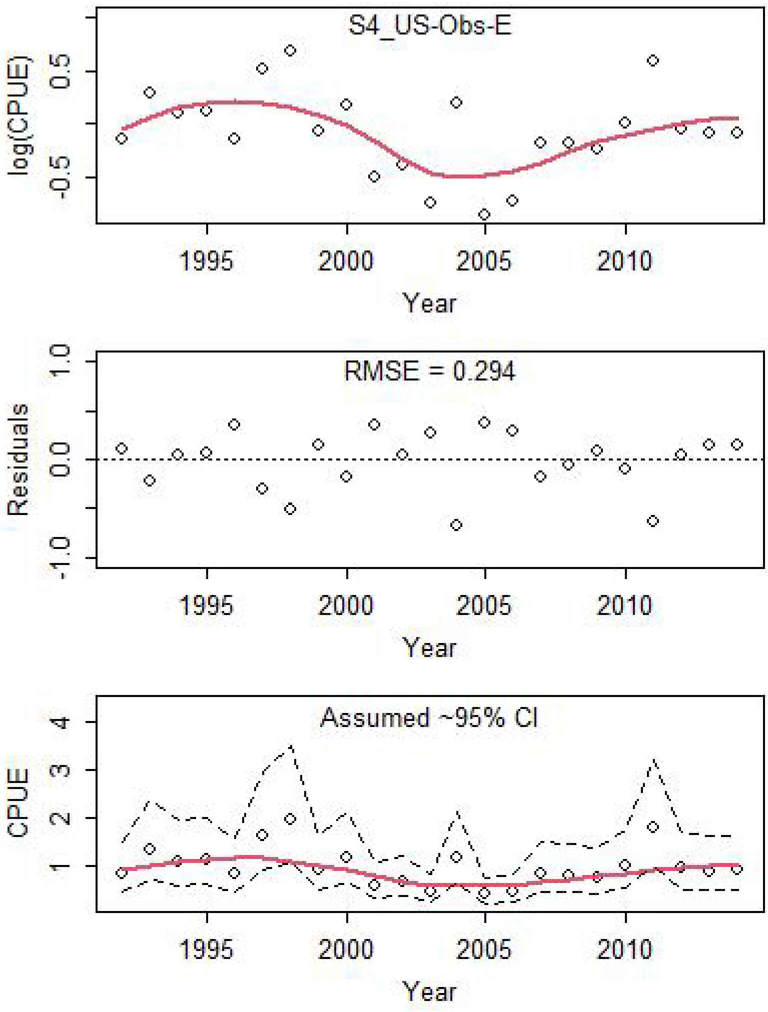


Figure A.4. Preliminary 2023 reference case SS3 CPUE variance adjustments for S4_US-Obs-E.

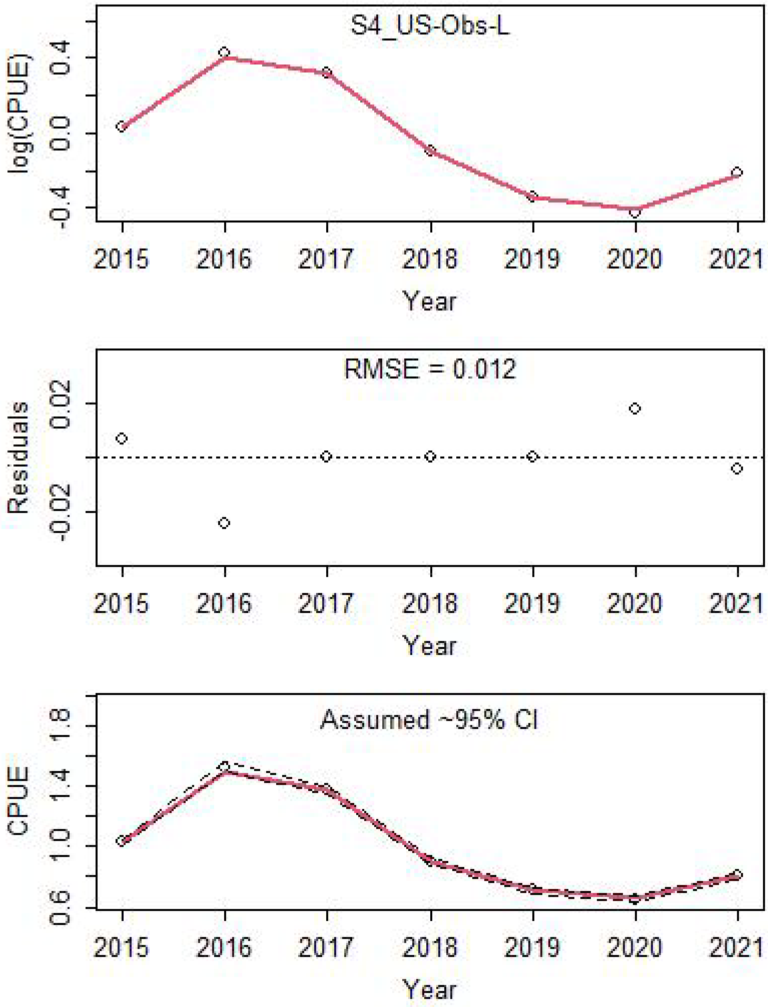


Figure A.5. Preliminary 2023 reference case SS3 CPUE variance adjustments for S5_US-Obs-L.

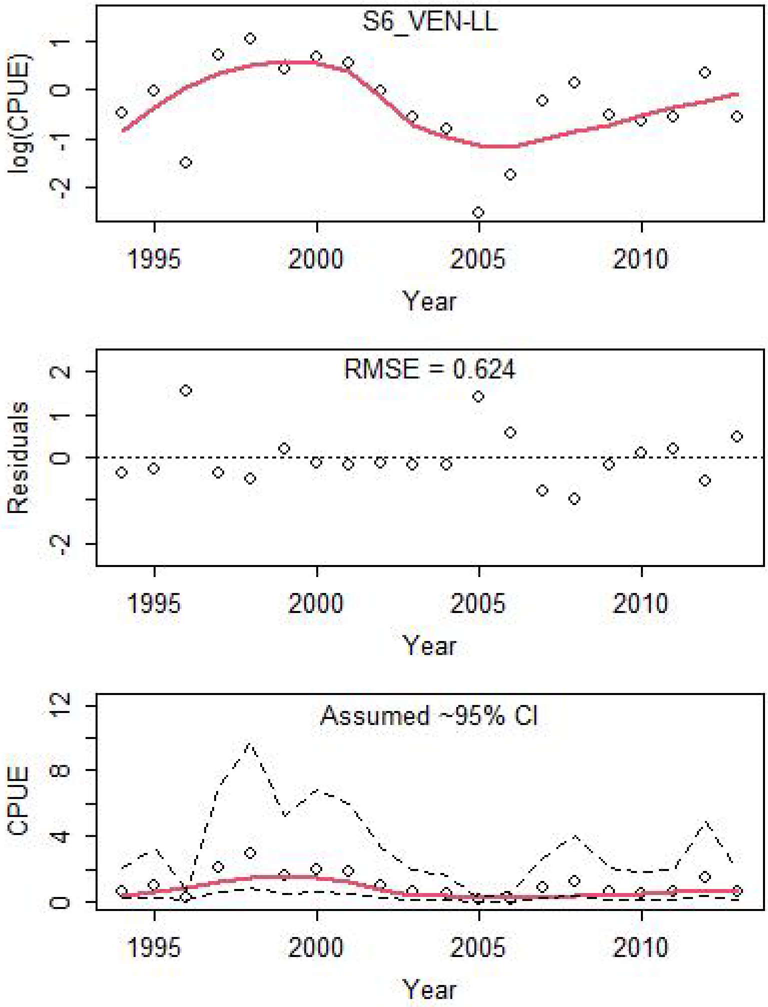


Figure A.6. Preliminary 2023 reference case SS3 CPUE variance adjustments for S6_VEN-LL.

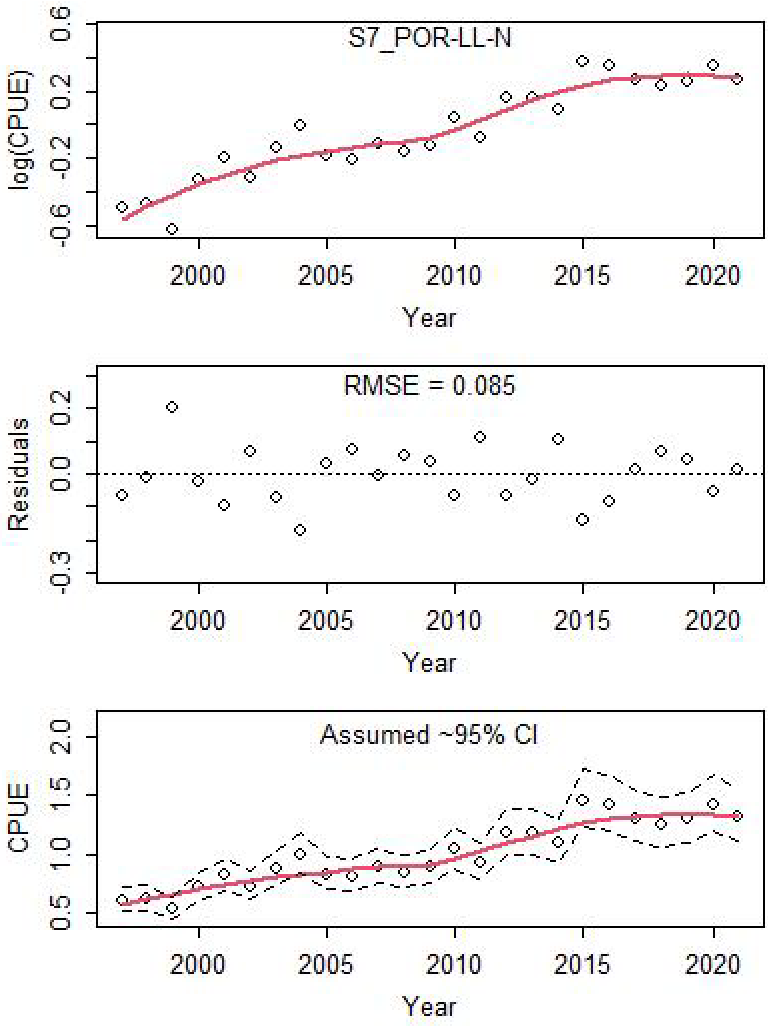


Figure A.7. Preliminary 2023 reference case SS3 CPUE variance adjustments for S7_POR-LL-N.

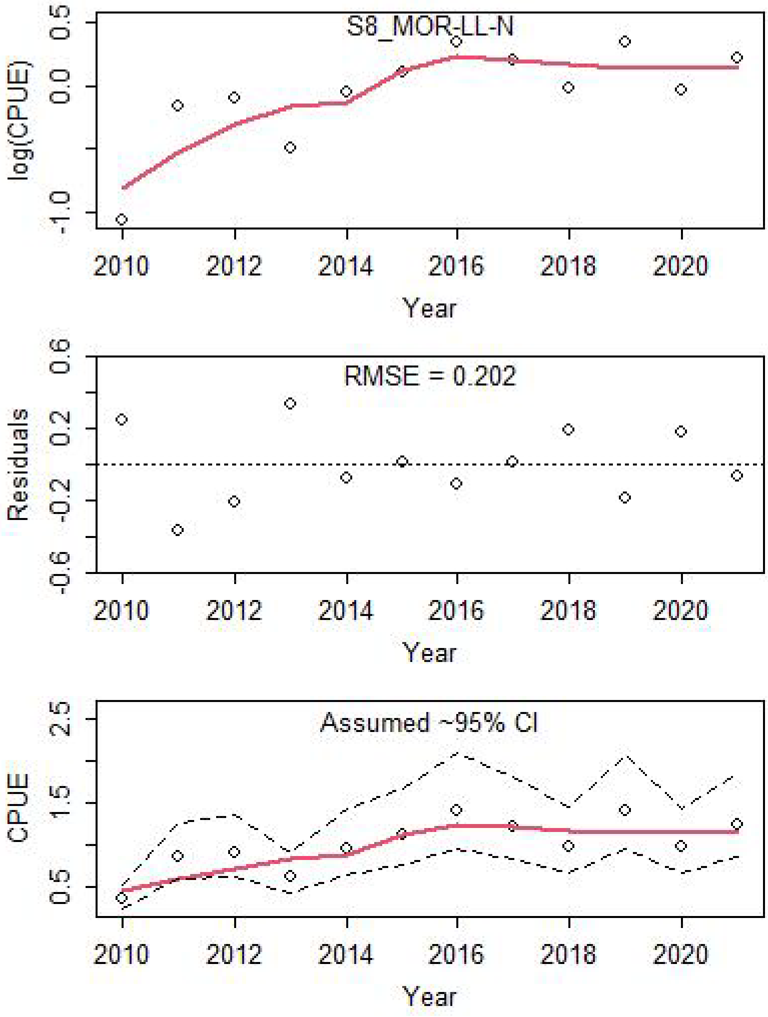


Figure A.8. Preliminary 2023 reference case SS3 CPUE variance adjustments for S8_MOR-LL-N.

Appendix B

Annual Length Composition Fits and Length Composition Variance Adjustments (Francis Method Stage 2).

Upper panels: Observed and predicted annual length compositions by fleet (as defined in **Tables 1 and 5** of the main document).

Middle panels: Diameter of Pearson residuals (lower panel, circles) indicates relative error; predicted < observed (solid), predicted > observed (transparent). The maximum diameter width of the plot for Pearson residuals (max) is an indication of relative fit. The "Sum of N adj." is the sum of input effective sample size provided by the R package r4ss using the Francis method (Stage 2) as described in the text of the main document above. The "Sum of N eff." is an alternative effective sample size provided by Stock Synthesis output (Report.ss) using the McAllister and Ianelli (1997) method (using the harmonic mean). Years with small sample size (total number of sharks measured < 100) were excluded from the fit.

Lower panels: Observed mean length (cm FL, open circle and 95% confidence intervals) and predicted mean length (blue line) by fleet (as defined in **Tables 1 and 5** of the main document); Confidence intervals are calculated using the input effective sample size (N) obtained from the Francis Method (Stage 2) as described in the main document and should include the predicted (blue line) mean annual length composition in about 95% of the observations (years). Years with small sample size (total number of sharks measured < 100) were excluded from the fit.

file:///C:/000/1001_ICCAT_BSH_2023/SS3/2023_Model_1/2023_09_Ref_Case/v1(7_8_2023)/Run_03/Plots_01_MODEL_OUTPUT_Check_Xeon/plots/_SS_output_LenComp.html

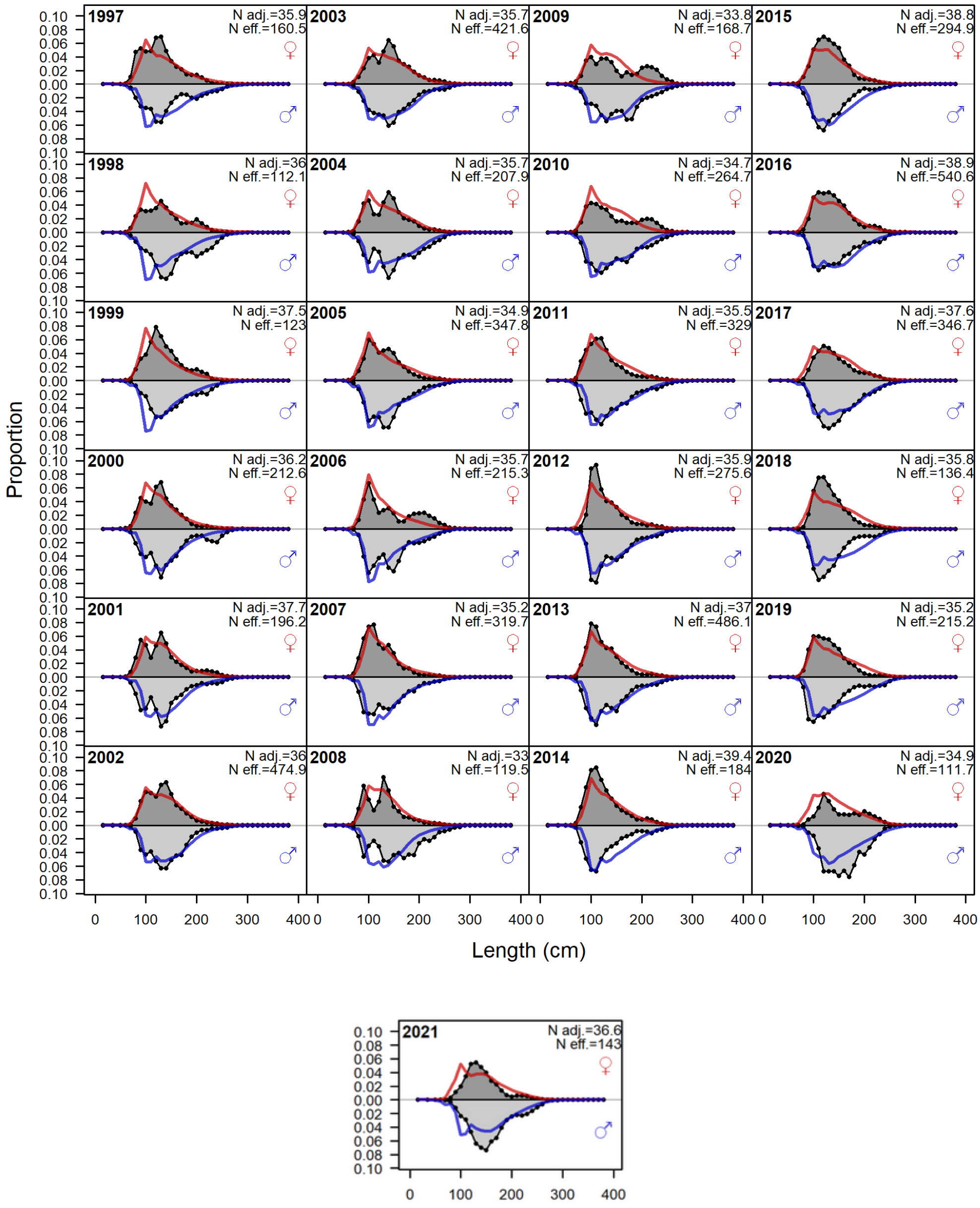


Figure B.1. Preliminary 2023 reference case SS3 model fit to F1_EU_ESP annual length composition.

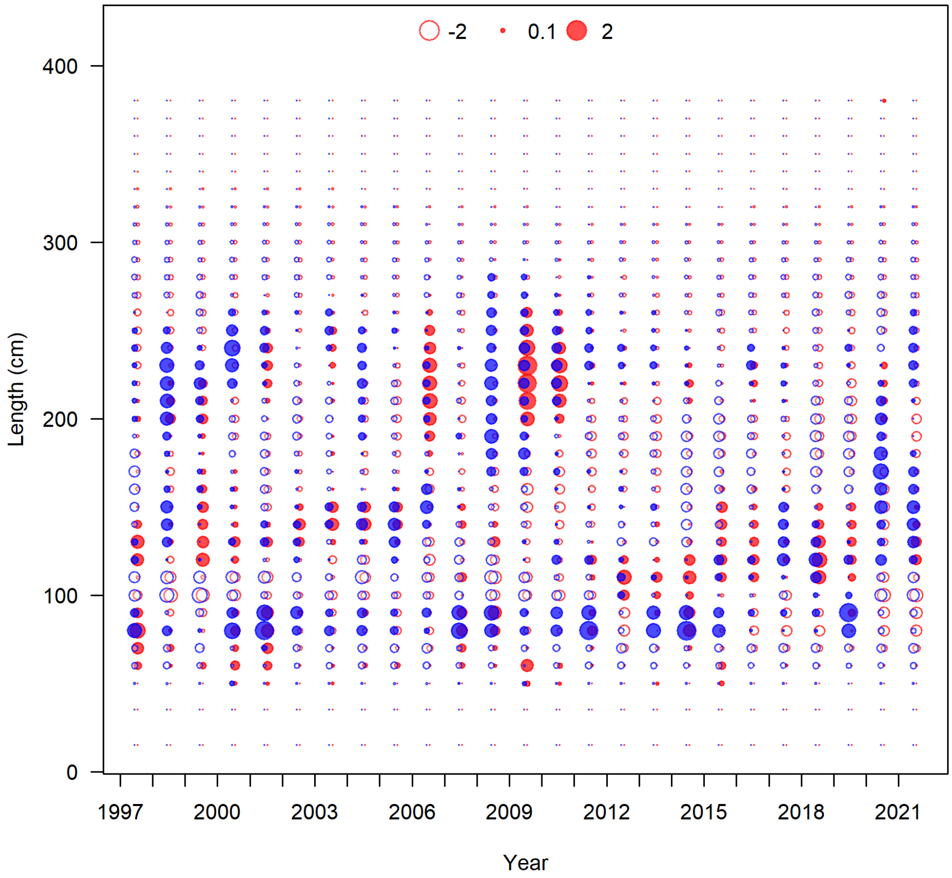


Figure B.1. Continued.

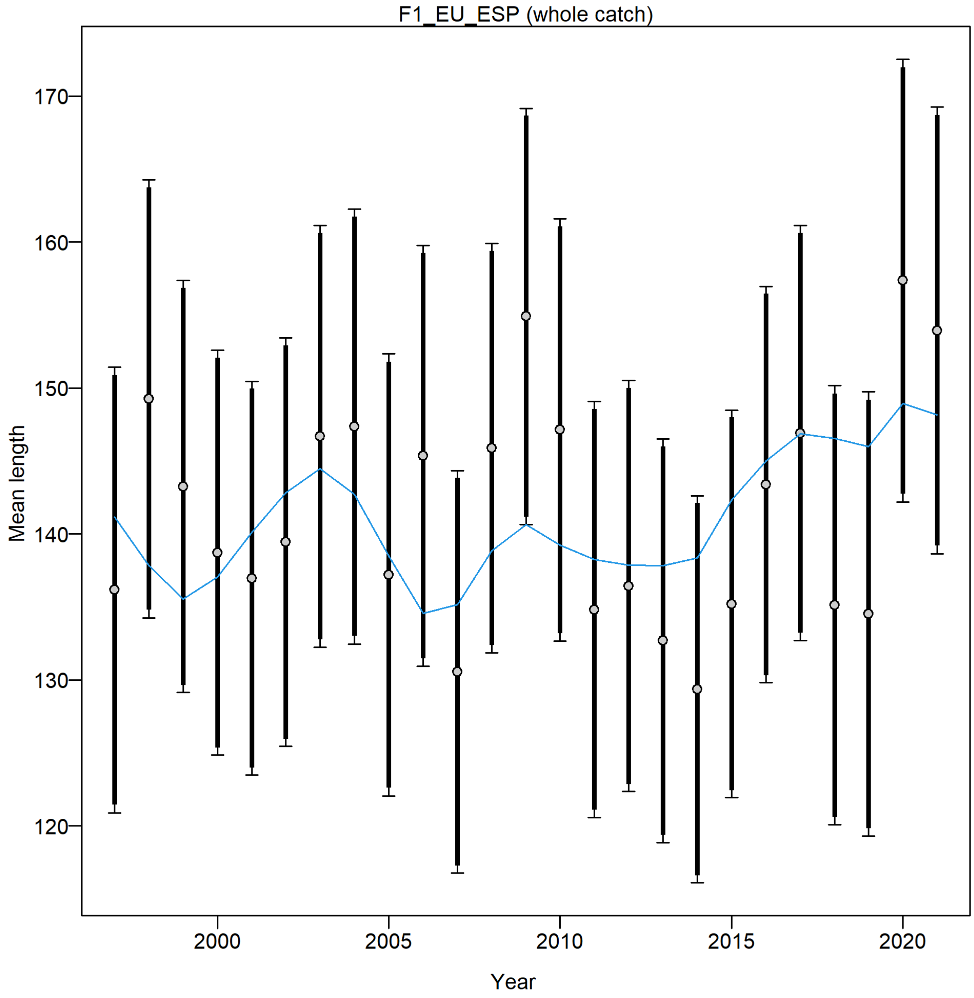


Figure B.1. Continued.

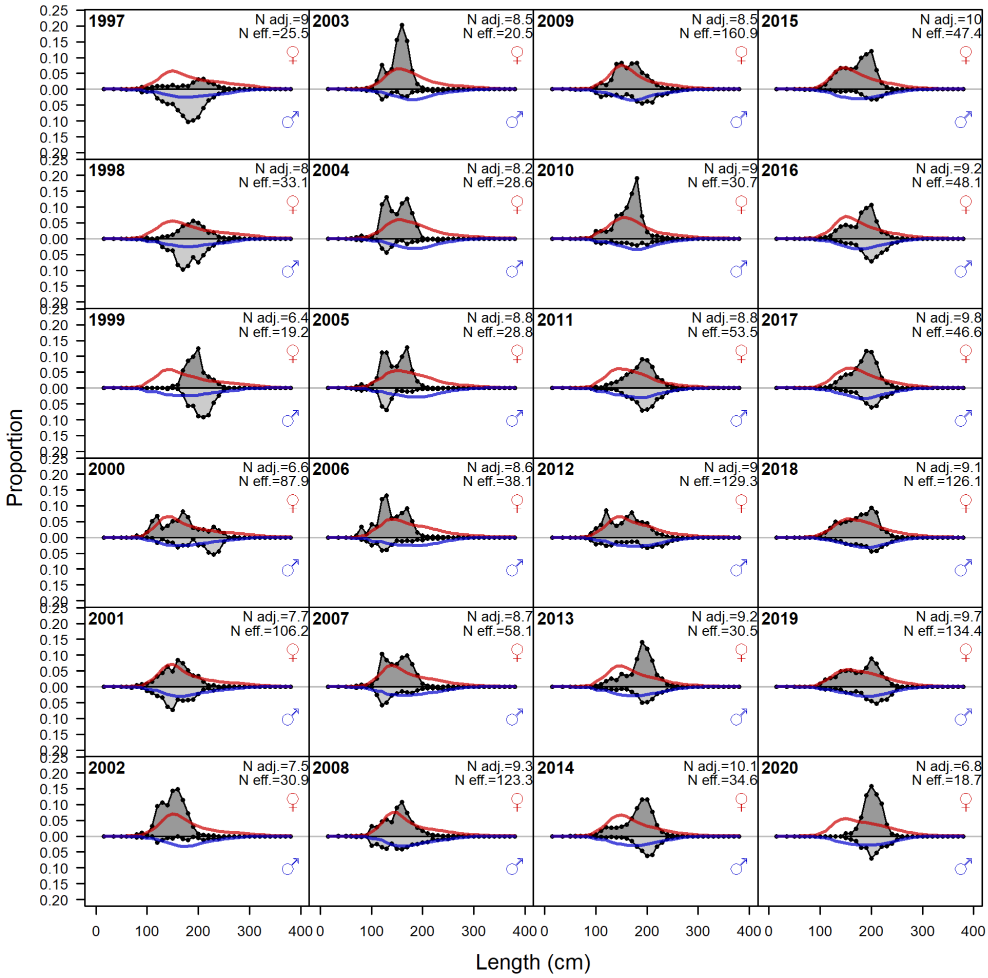


Figure B.2. Preliminary 2023 reference case SS3 model fit to F2_JPN annual length composition.

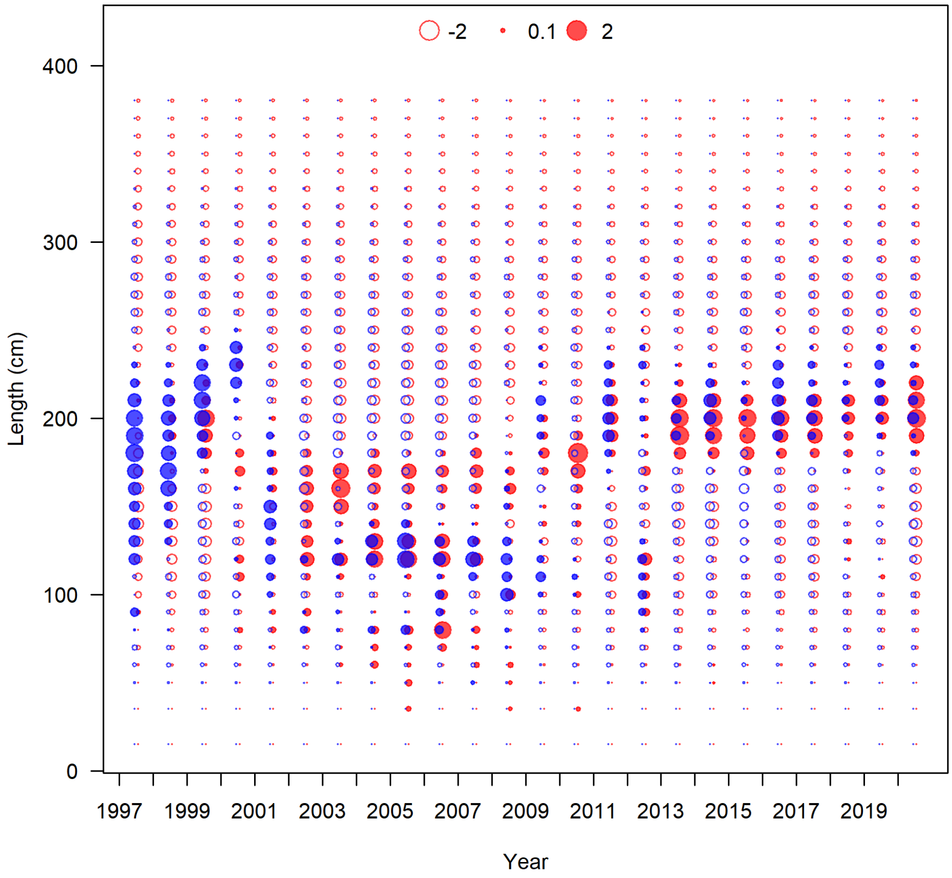


Figure B.2. Continued.

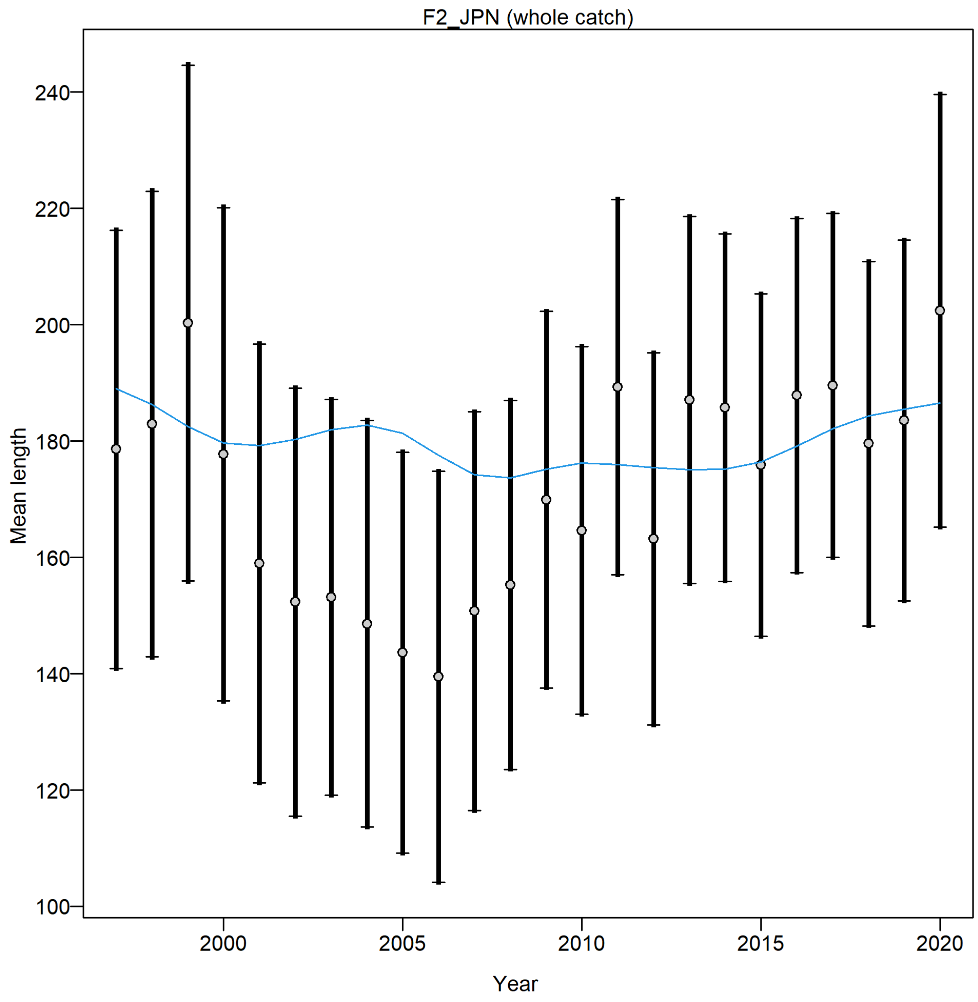


Figure B.2. Continued.

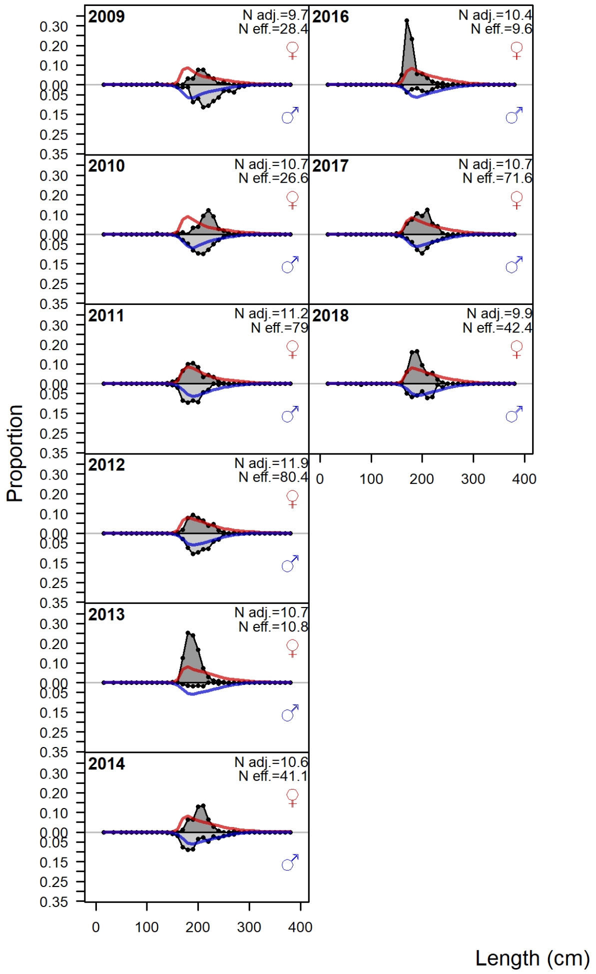


Figure B.3. Preliminary 2023 reference case SS3 model fit to F3_CTP annual length composition.

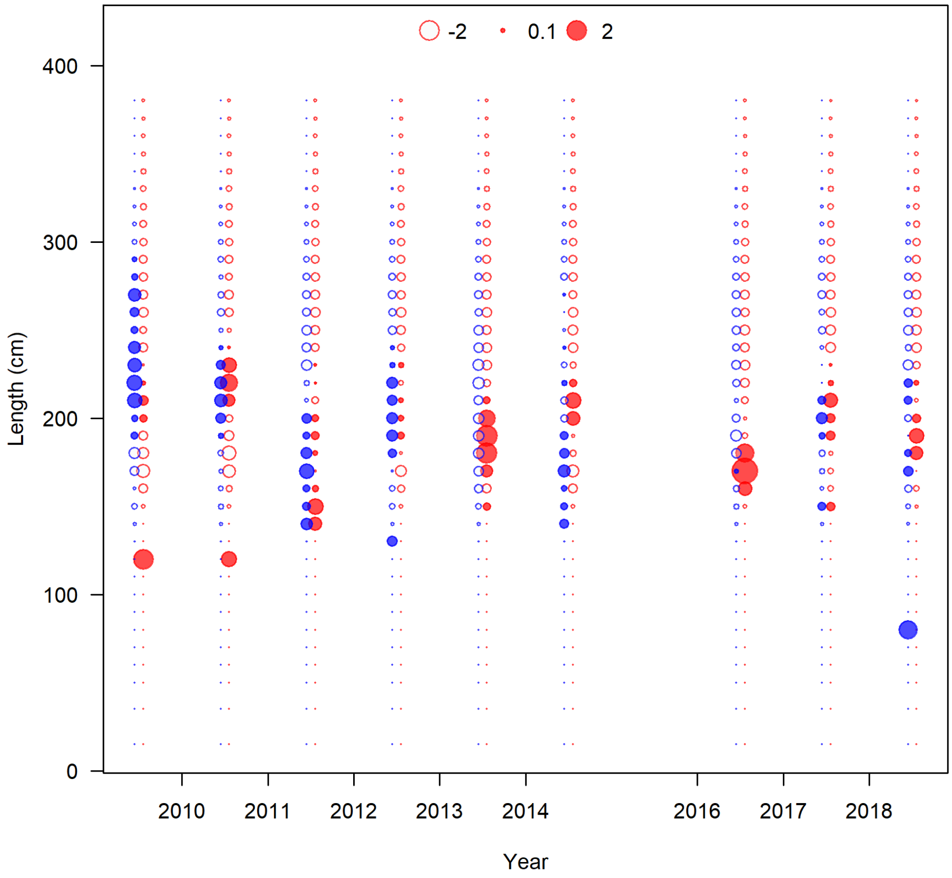


Figure B.3. Continued.

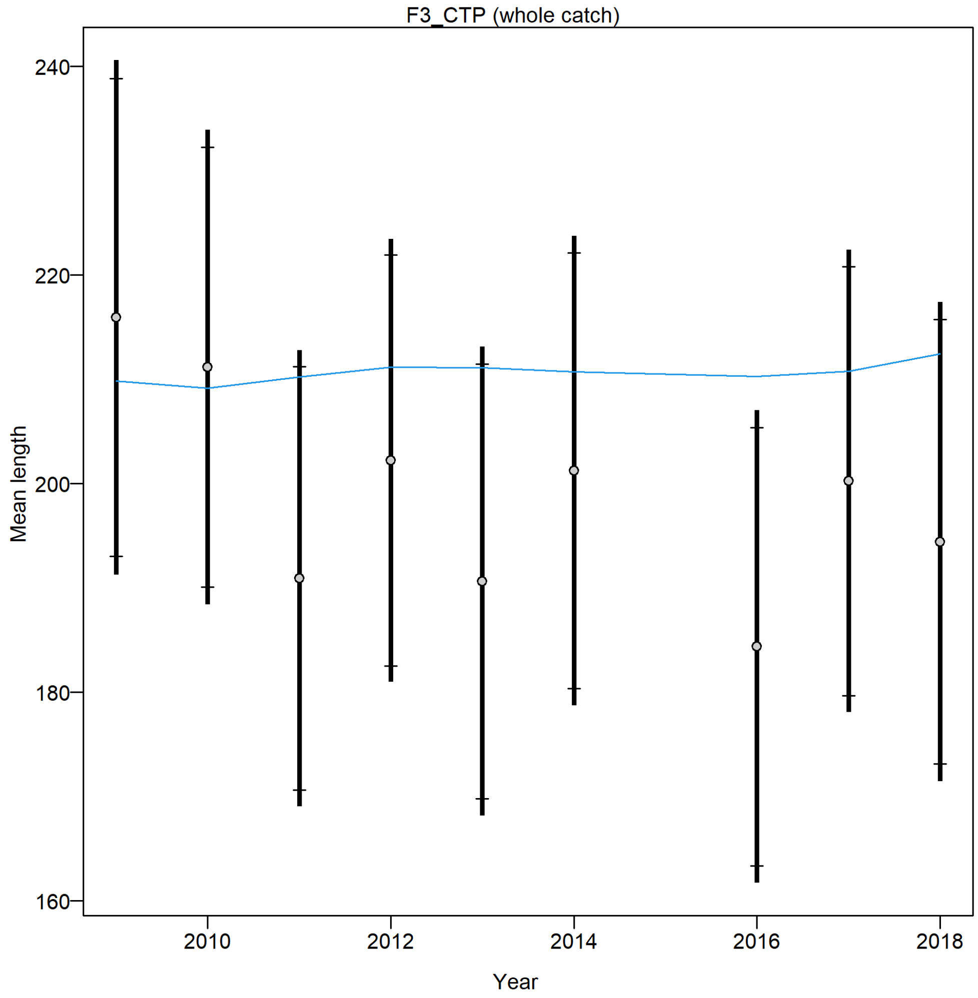


Figure B.3. Continued.

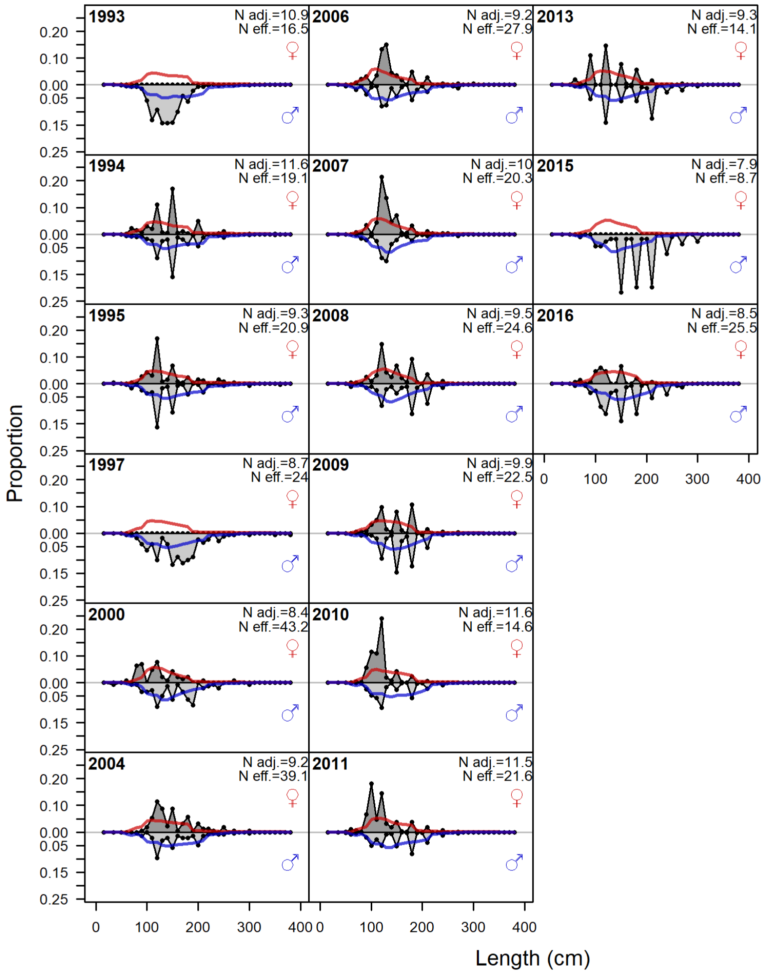
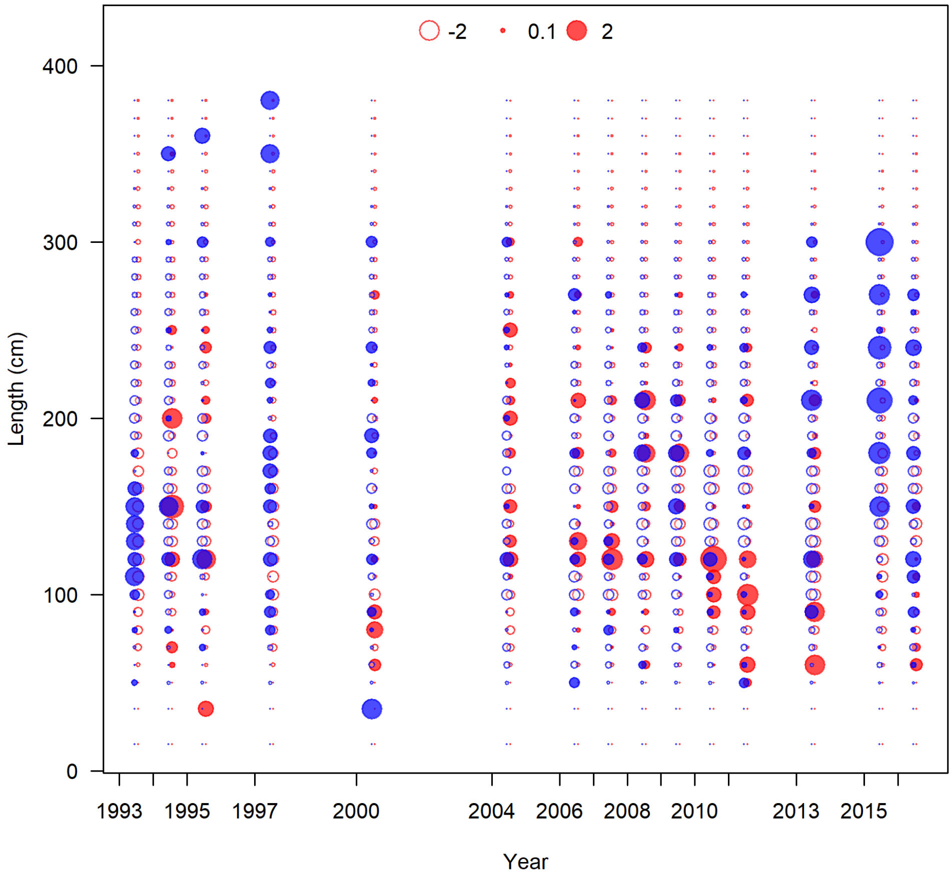


Figure B.4. Preliminary 2023 reference case SS3 model fit to F4_USA annual length composition.



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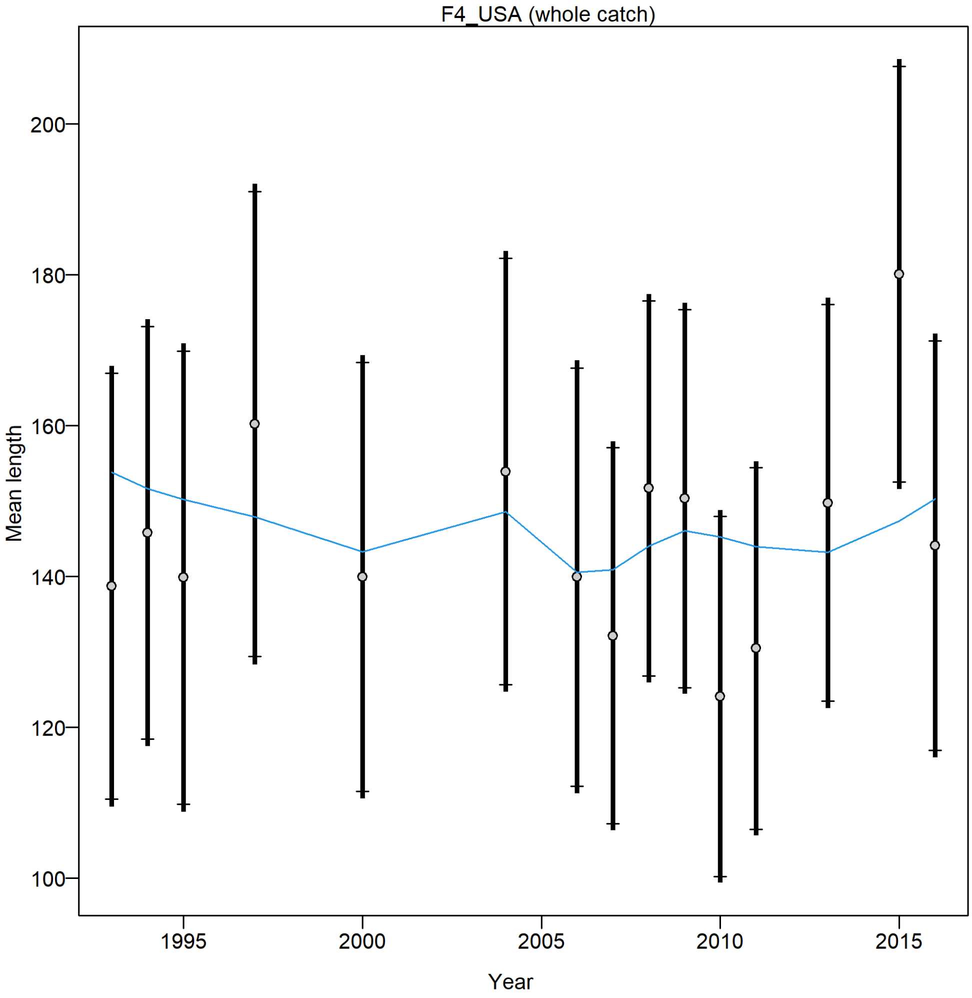


Figure B.4. Continued.

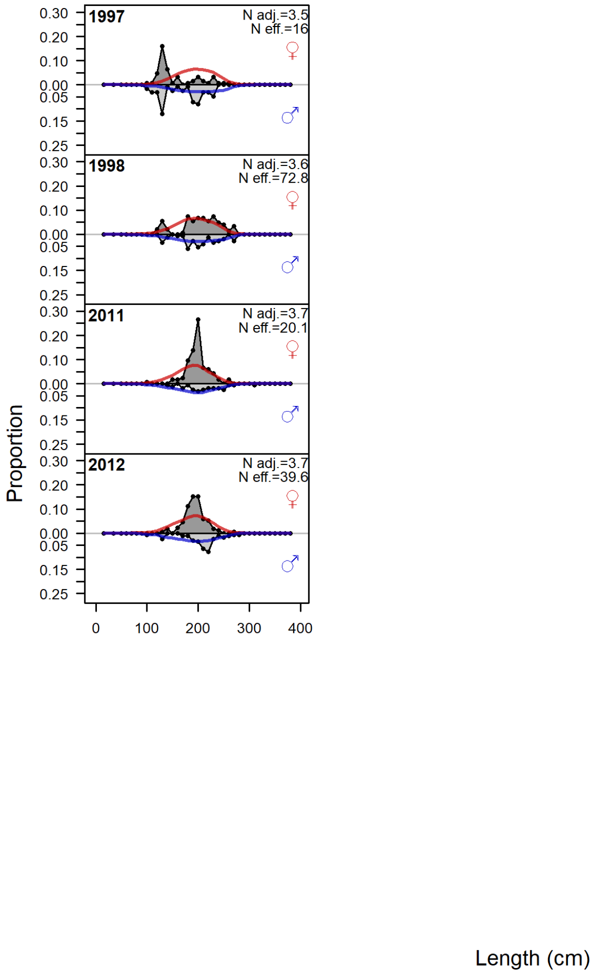


Figure B.5. Preliminary 2023 reference case SS3 model fit to F5_VEN annual length composition.

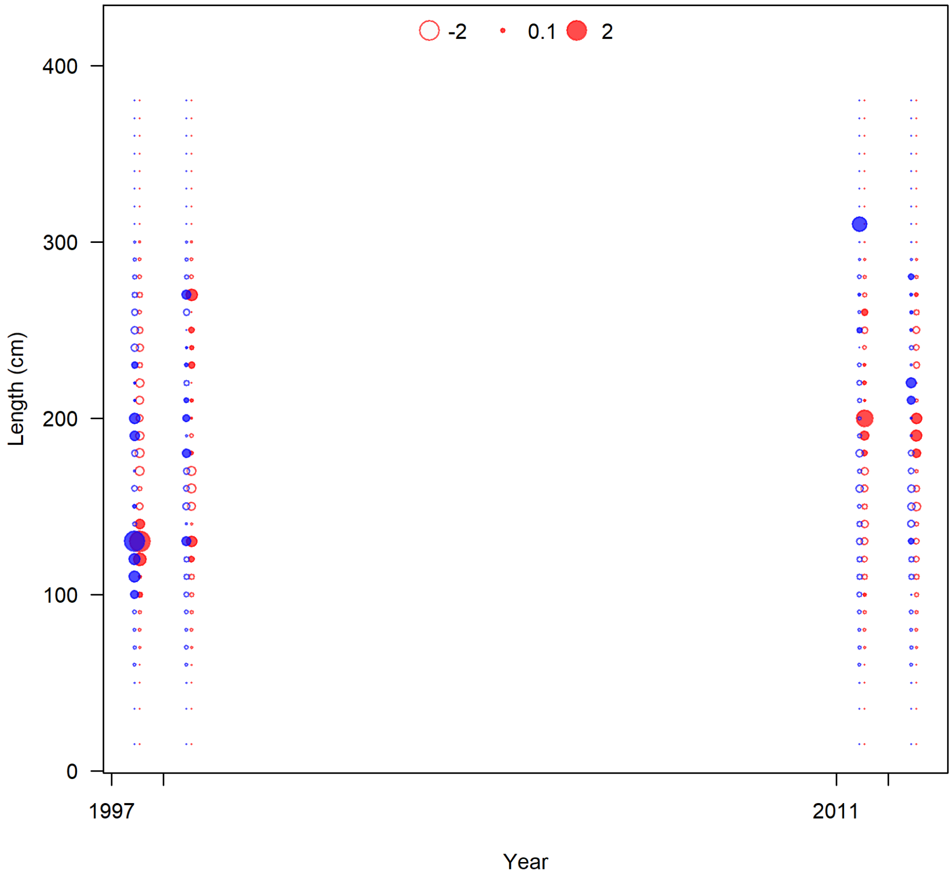


Figure B.5. Continued.

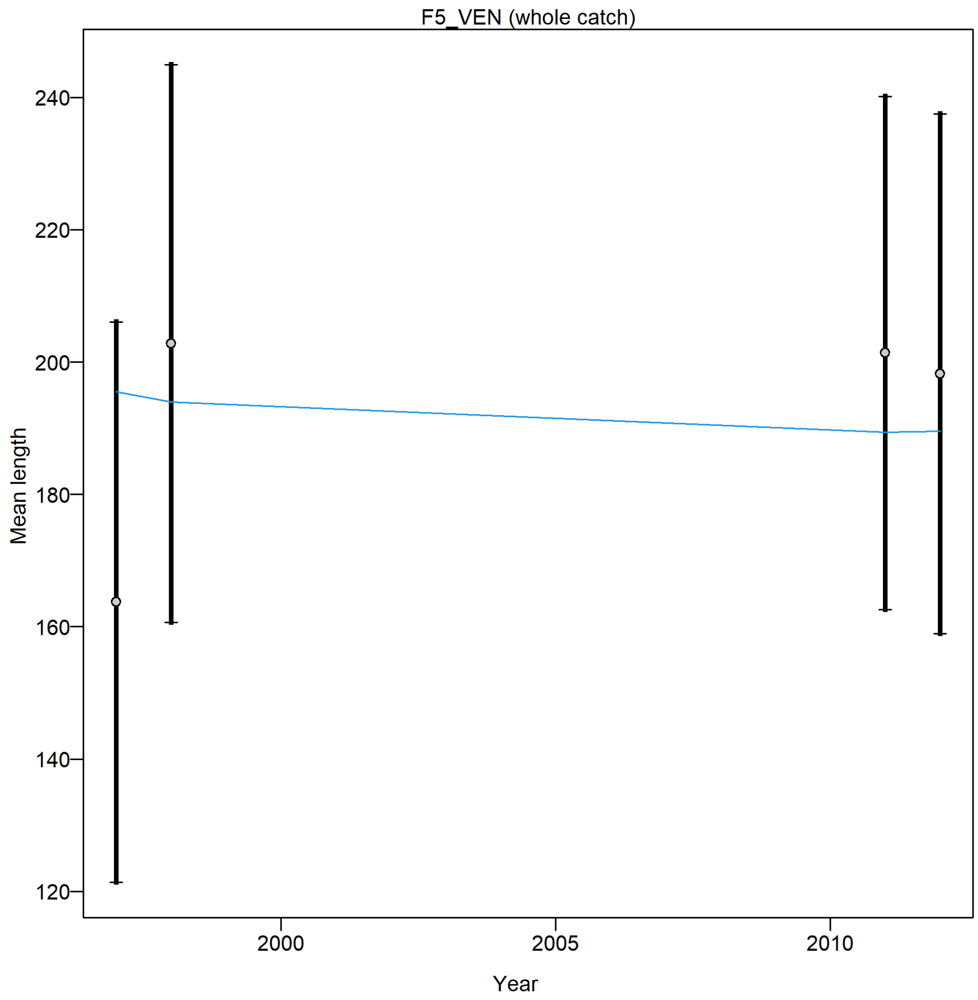


Figure B.5. Continued.

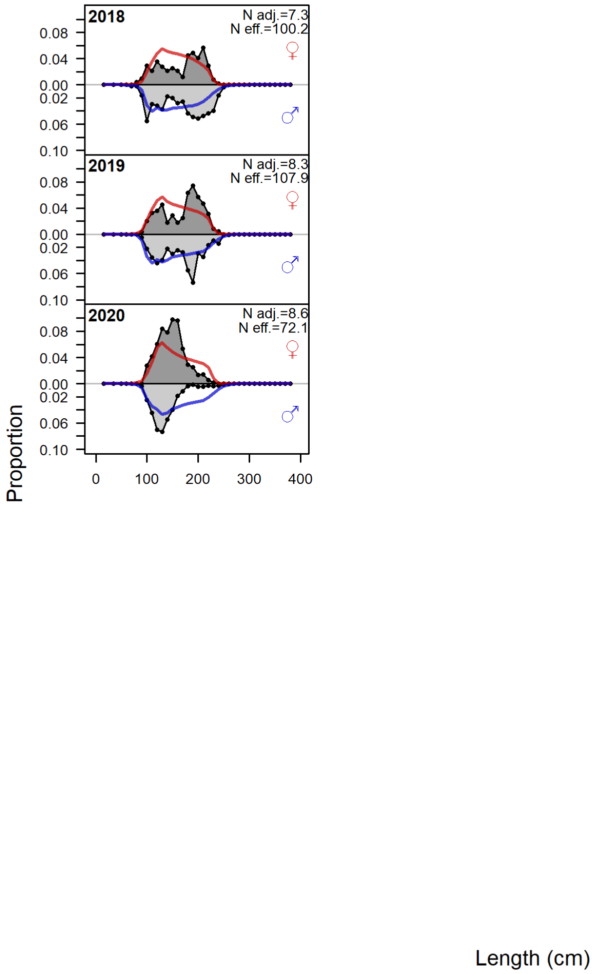


Figure B.6. Preliminary 2023 reference case SS3 model fit to F7_CPR annual length composition.

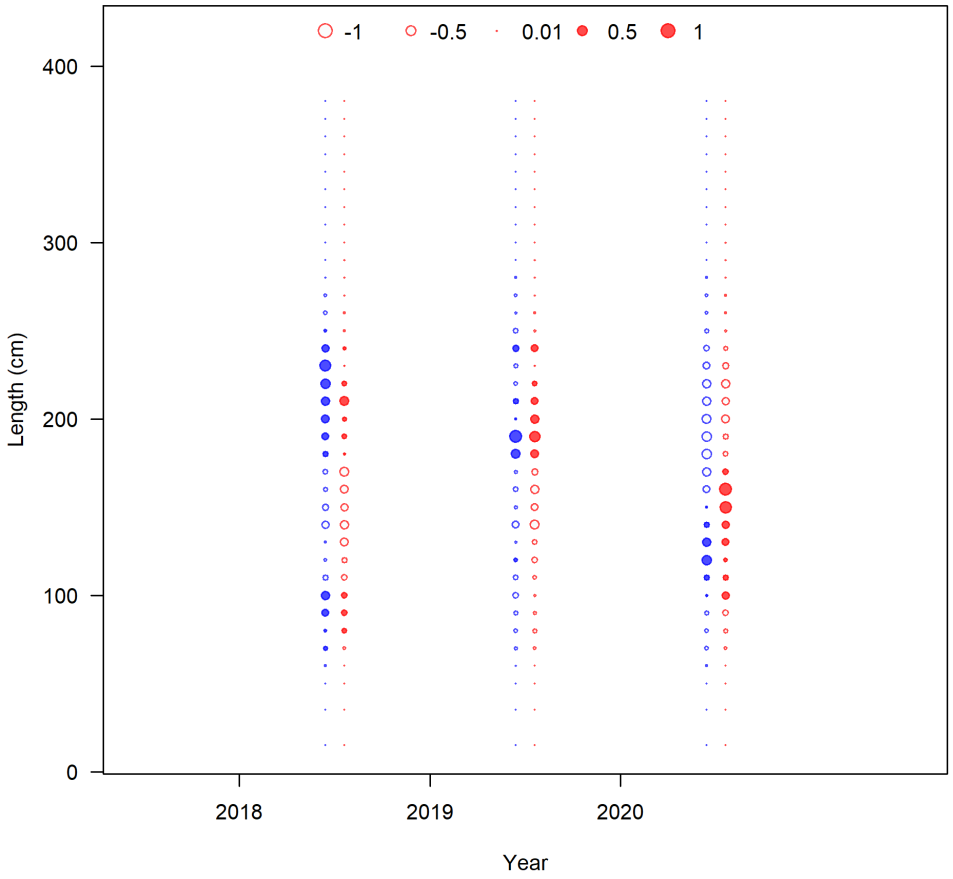


Figure B.6. Continued.

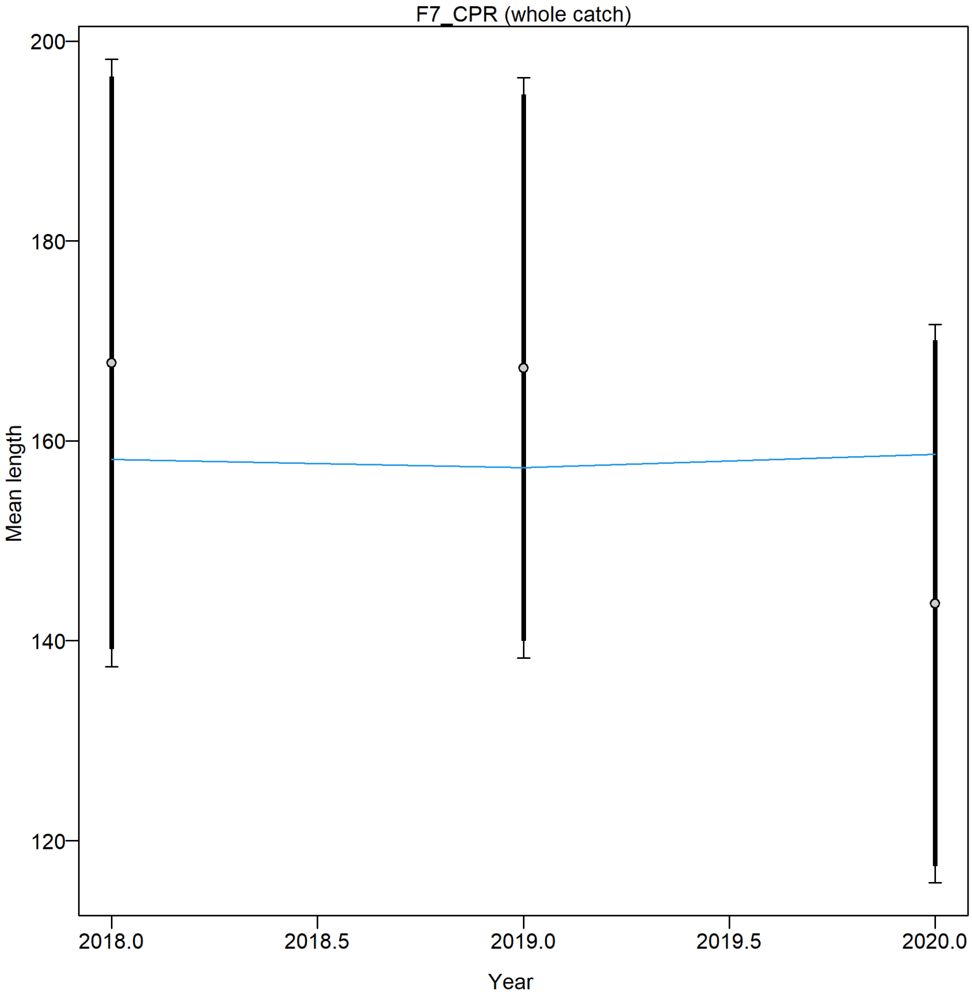


Figure B.6. Continued.

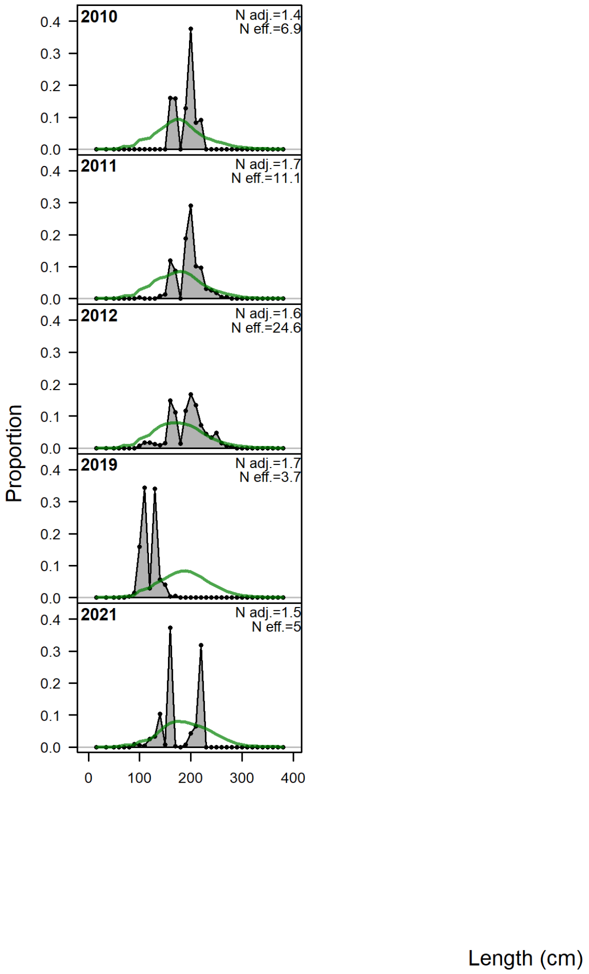
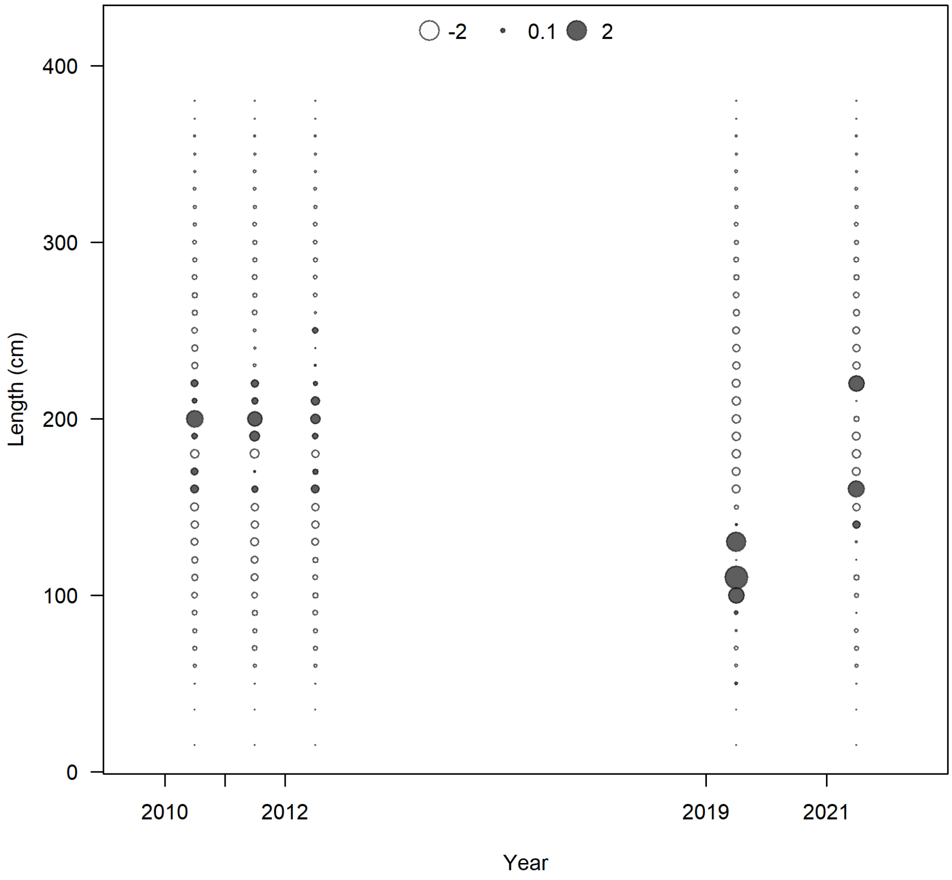


Figure B.7. Preliminary 2023 reference case SS3 model fit to F8_BEL annual length composition.



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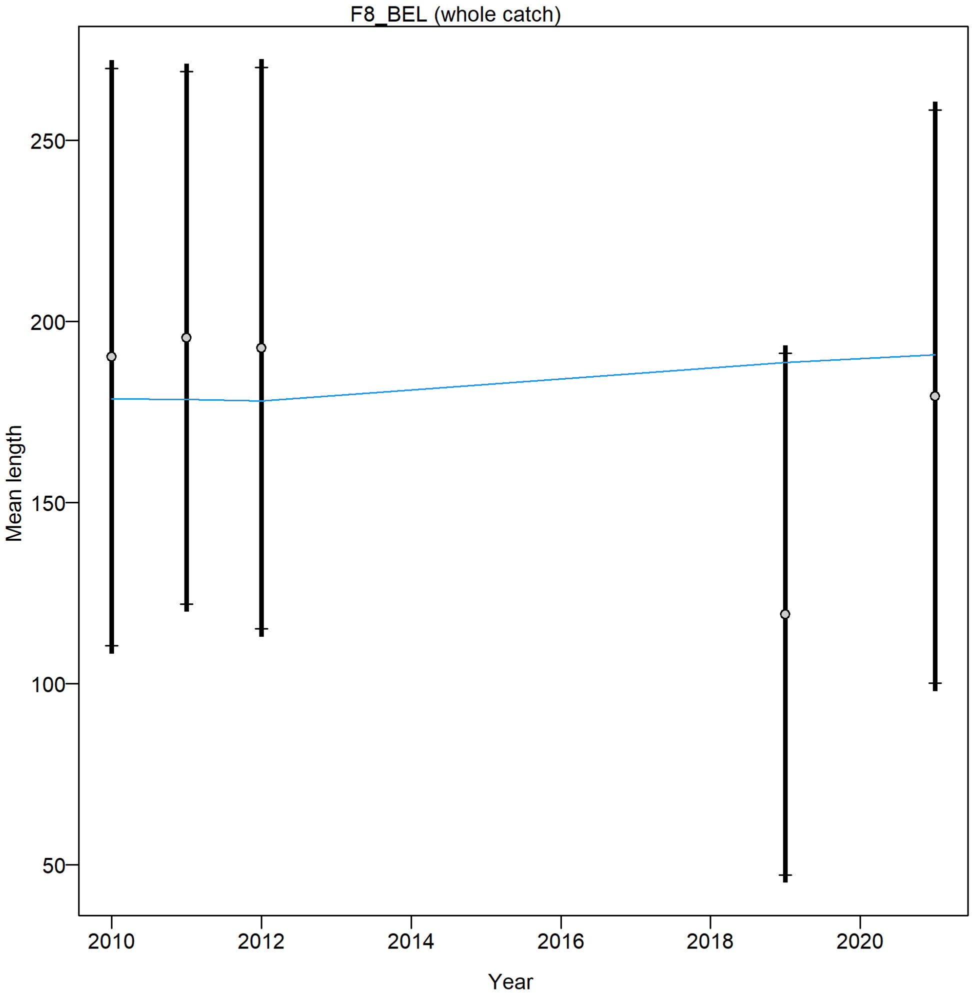


Figure B.7. Continued.

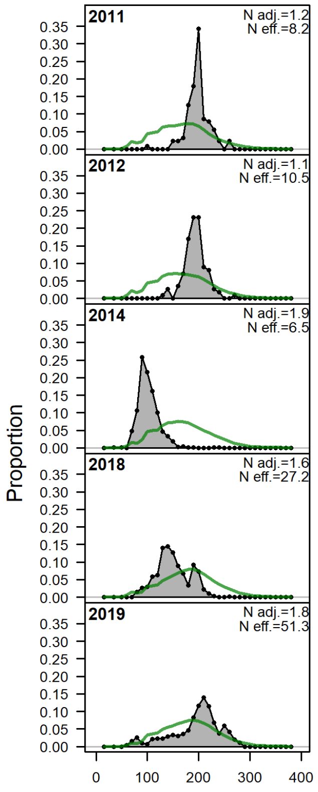


Figure B.8. Preliminary 2023 reference case SS3 model fit to F9_OTH annual length composition.

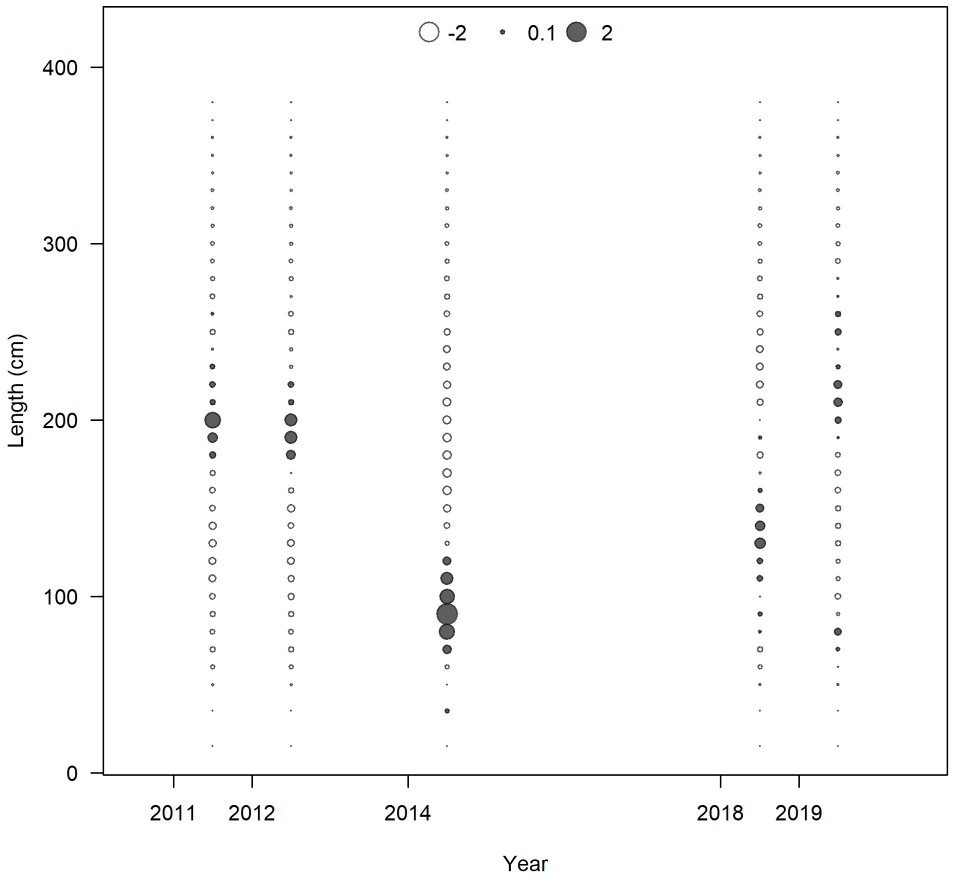
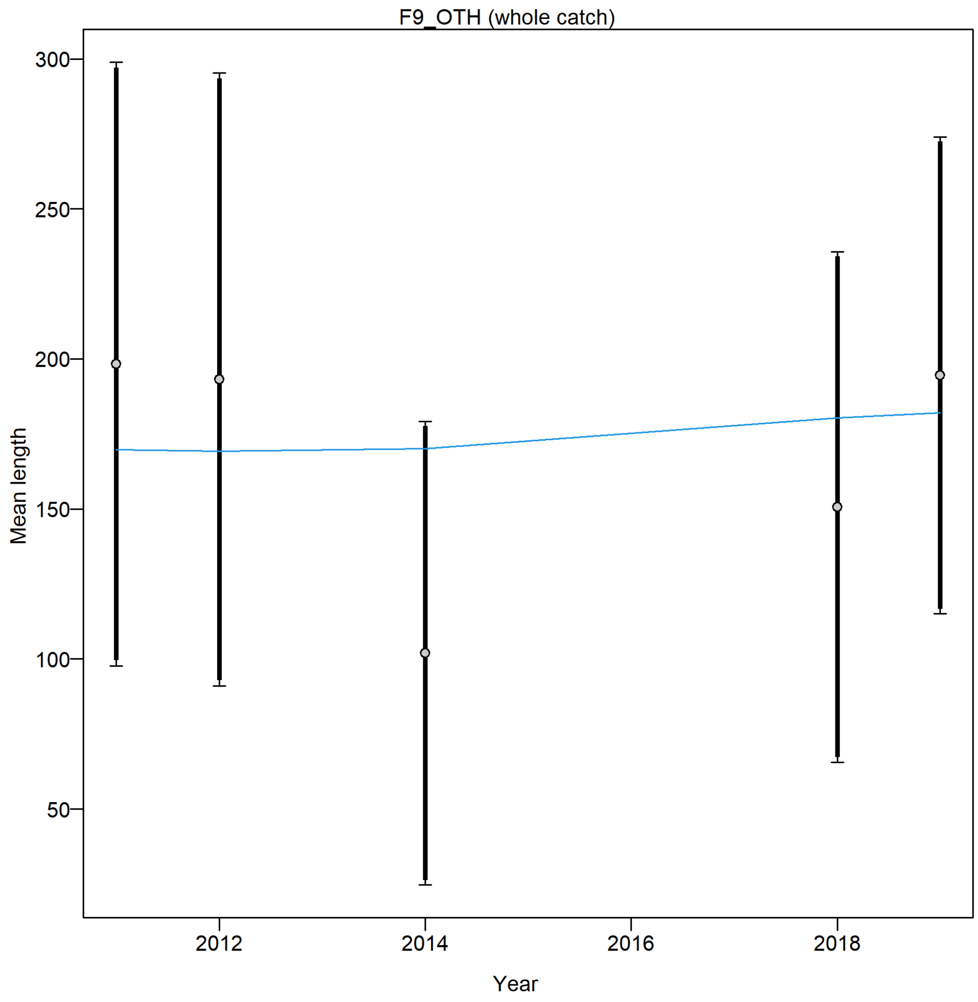


Figure B.8. Continued.



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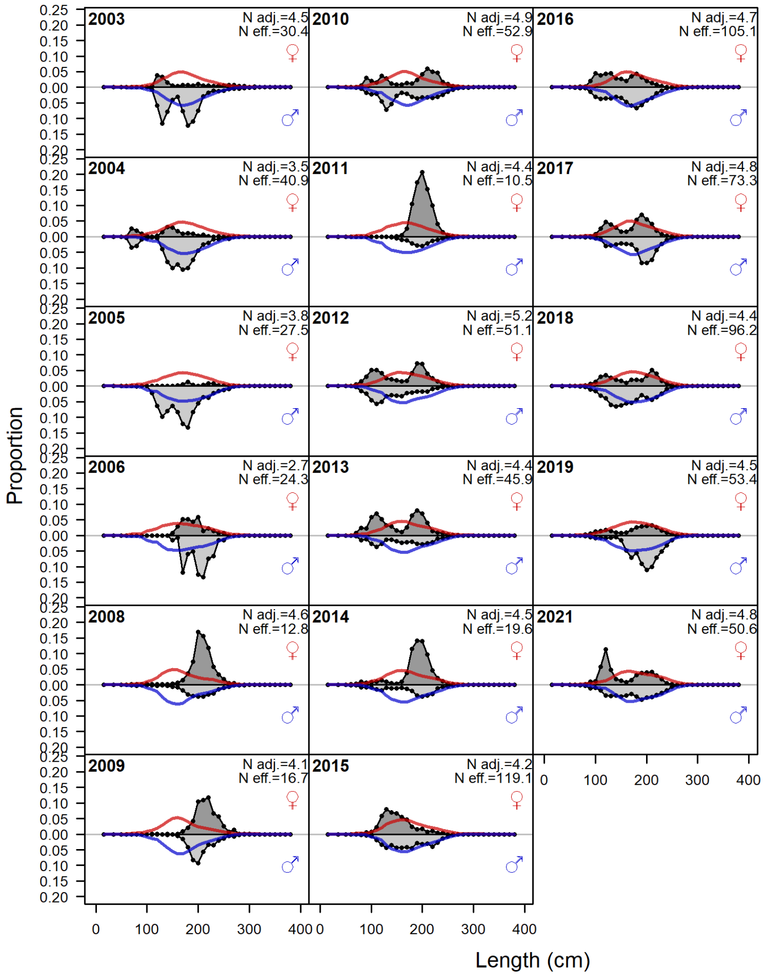

Figure B.9. Preliminary 2023 reference case SS3 model fit to F10_EU_POR annual length composition.

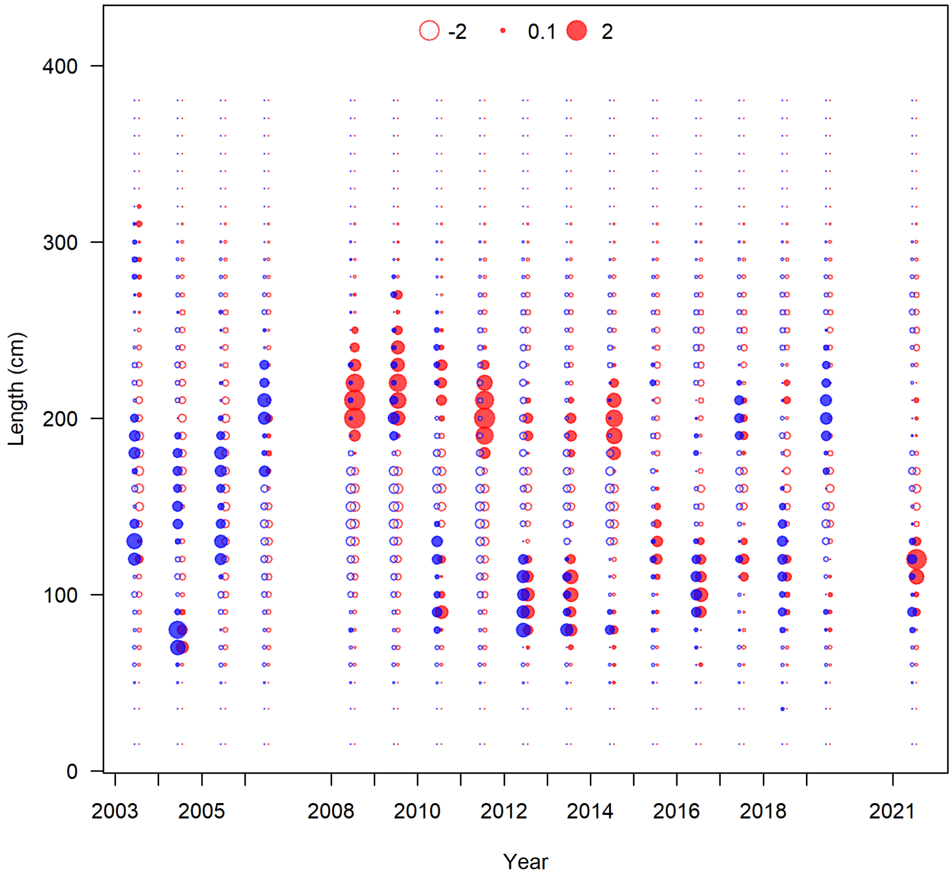

Figure B.9. Continued.

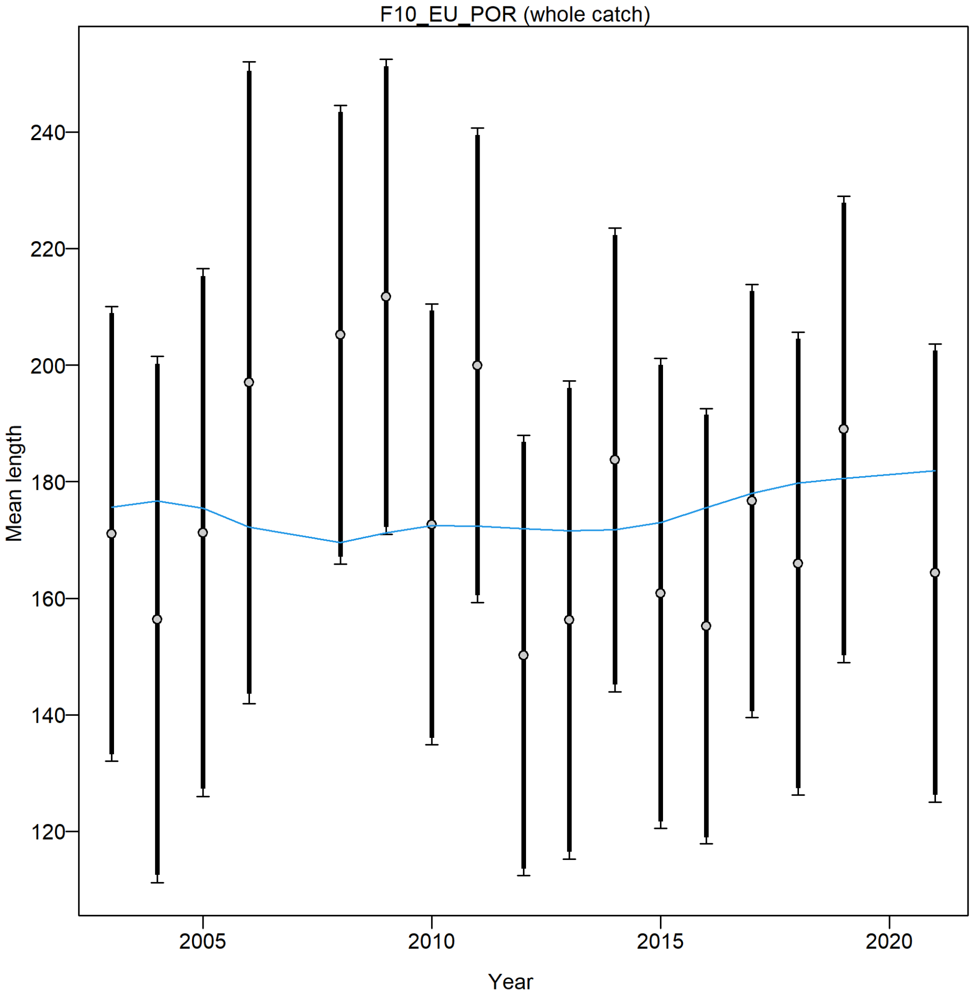

Figure B.9. Continued.