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

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SUMMARY

Preliminary Stock Synthesis model runs were conducted for North Atlantic blue sharks based on the available catch, CPUE, length composition, and life history data compiled by the Shark Working Group. A combined sex model was implemented in order to reduce model complexity. Beverton-Holt stock-recruitment was assumed. The steepness of the stock recruitment relationship and natural mortality at age were fixed at independently estimated values. Several preliminary model runs resulted in unreasonable convergence diagnostics, and model results were sensitive to the sample sizes (weights) assigned in the model likelihood to length composition data. Two preliminary model runs which utilized multiplication factors to reduce the input sample size assigned to length composition data in the model likelihood resulted in reasonable convergence diagnostics. Model fits to CPUE and length composition data were similar for both models. Both models resulted in sustainable spawning stock size and fishing mortality rates relative to maximum sustainable yield. The model with a relatively lower sample size assigned to the length composition data resulted in a relatively more depleted stock size.

RÉSUMÉ

Des scénarios préliminaires du modèle Stock synthèse ont été réalisés 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 de sexe combiné a été mis en œuvre afin de réduire la complexité du modèle. 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. Plusieurs scénarios préliminaires du modèle ont donné lieu à des diagnostics de convergence déraisonnables, et les résultats du modèle étaient sensibles aux tailles de l'échantillon (pondérations) attribuées dans la vraisemblance du modèle aux données de composition par taille. Deux scénarios préliminaires du modèle qui utilisaient des facteurs de multiplication pour réduire la taille de l'échantillon saisi assignée aux données de composition par taille dans la vraisemblance du modèle ont donné des diagnostics de convergence raisonnables. Les ajustements du modèle aux données de CPUE et de composition par taille étaient similaires pour les deux modèles. Les deux modèles ont donné lieu à une taille du stock reproducteur et à des taux de mortalité par pêche soutenables par rapport à la production maximale équilibrée. Le modèle dont la taille de l'échantillon relativement plus faible était assignée aux données de composition par taille a entraîné une taille de stock relativement plus appauvrie.

RESUMEN

Se llevaron a cabo ensayos preliminares del modelo Stock Shynthesis para la tintorera del Atlántico norte basados en los datos disponibles de captura, CPUE, composición por tallas y ciclo vital recopilados por el Grupo de especies de tiburones. Se implementó un modelo de sexos combinados para reducir la complejidad del modelo. 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. Varios de los ensayos preliminares del modelo tuvieron como resultado un diagnóstico de convergencia irrazonable, y los resultados del modelo eran sensibles a los tamaños de la muestra (ponderaciones) asignadas en la verosimilitud del modelo a los datos de composición por tallas. Dos ensayos preliminares del modelo que utilizaban factores de multiplicación para reducir el tamaño de la muestra de entrada asignado a los datos de composición por tallas en

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la verosimilitud del modelo, tuvieron como resultado diagnósticos de convergencia razonables. Los ajustes de los modelos a los datos de composición por tallas y de CPUE fueron similares para ambos. Ambos modelos tuvieron como resultado un tamaño del stock reproductor y tasas de mortalidad por pesca sostenibles respecto al rendimiento máximo sostenible. El modelo con un tamaño de la muestra relativamente menor asignado a los datos de composición por tallas tuvo como resultado un tamaño del stock relativamente más mermado.

KEYWORDS

Stochastic models, Stock assessment, Shark fisheries, Pelagic fisheries, Blue shark

1. Introduction

A length-based age-structured statistical model was implemented with Stock Synthesis (Methot and Wetzel 2013) version 3.24U (SS3; e.g., Methot 2015) for the North Atlantic blue shark stock. Stock Synthesis is an integrated modeling approach (Maunder and Punt 2013) and was proposed to take advantage of the length composition data sources available for North Atlantic blue shark. 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. Because of the model complexity and because this is the first time that Stock Synthesis will be applied to sharks in ICCAT, its application was limited to the North Atlantic stock.

2. Materials and methods

The model was fitted to the available catch, CPUE, and length composition data compiled during the 2015 Blue Shark Data Preparatory meeting. Life history inputs were obtained from data first assembled at the 2014 Intersessional Meeting of the Shark Species Group (Anon. 2014), plus additional information provided during the 2015 Blue Shark Data Preparatory meeting and thereafter as summarized below and as reported in document SCRS/2015/142 (Cortés In prep.). A combined sex model was implemented in order to reduce model complexity.

2.1 Time series data

Time series of catch, abundance, and length composition data considered for use in the preliminary SS3 model runs are summarized in **Table 1** and **Figure 7**. Based on available time series of catch data, the start year of the model was 1971, and the end year was 2013.

2.1.1 Catch

Catch in metric tons (t) by major flag for North Atlantic blue shark was obtained from data compiled during the 2015 Blue Shark Data Preparatory meeting (**Table 2, Figure 1**) and assigned to "fleets" F1 – F9 for use in the SS3 preliminary model runs as described in **Table 1**. Equilibrium catch (Eq. catch = 17,077 t) at the beginning of the fishery (1970) was obtained from an average of 10 posterior years (1971 to 1980) for fleets F1 (EU España + EU Portugal) + F2 (Japan) + F3 (Chinese Taipei) (**Table 2**, **Figure 1**).

2.1.2 Indices of abundance

Indices of abundance for North Atlantic blue shark and their corresponding coefficients of variation (CV) were obtained from data compiled during the 2015 Blue Shark Data Preparatory meeting (**Tables 3 and 4**) except for updated Irish Recreational and Chinese Taipei time series which were submitted separately (**Tables 3 and 4)**. The available abundance indices and their associated CVs were assigned to "surveys" S1 – S10 for use in the SS3 preliminary model runs as described in **Table 1**.

2.1.3 Length composition

Length composition data for North Atlantic blue shark (35 – 390 cm FL, 5 cm FL bins) was obtained from data compiled during the 2015 Blue Shark Data Preparatory meeting, as reported in document SCRS/2015/039 (Coelho et al. In prep.), for EU (España + Portugal, 1993-2013), JPN (Japan, 1997-2013), TAI (Chinese Taipei, 2004-2013), USA (1992-2013), and VEN (Venezuela, 1994-2013) (**Figure 2**) and assigned to "fleets" F1 – F9 and "surveys" S1 – S10 for use in the SS3 preliminary model runs as described in **Table 1**. The bin width used in the SS3 preliminary model runs was increased to 10 cm FL because a jagged pattern in the length compositions of some data sources (TAI and VEN) indicated the lengths may not have been measured at a 5 cm FL resolution (**Figure 3**). Length composition data for males and females were then combined for use in the SS3 preliminary model runs in order to reduce preliminary model complexity.

2.2 Life history

Life history inputs were obtained from data first assembled at the 2014 Intersessional Meeting of the Shark Species Group (Anon. 2014) and additional information provided during the 2015 Blue Shark Data Preparatory meeting and thereafter as summarized below in **Table 5** and as reported in document SCRS/2015/142 (Cortés In prep.). The maximum age was fixed at 16 (**Table 5**). A combined sex model was implemented as described below.

2.2.1 Growth

Growth in length at age was assumed to follow a von Bertalanffy growth (VBG) relationship (**Table 5**). A total of 71 population length bins (35 – 385+ cm FL, 5 cm FL bins) were defined for use in SS3. A combined sex model was implemented by calculating the average sex specific VBG length at age-0 (Combined L_{Amin}, 62.3 cm FL), the average sex specific VBG L_inf (Combined L_{inf} = 296.0), and the average sex specific VBG growth coefficient (combined k = 0.16) (**Table 6, Figure 4)**. The distribution of mean length at each age was modeled as a normal distribution and the CV in mean length at age was modeled as a linear function of length. The CVs in length at age were fixed at 0.15 for L_{Amin} and 0.12 for L_{inf}, and linearly interpolated between LAmin and L_{inf} (**Figure 5**). A combined sex length-weight relationship was used (**Table 5**) to convert body length (cm FL) to body weight (kg).

2.2.2 Pup production

Annual pup production at each age (**Table 7**) was calculated as follows. Mean litter size was modeled as a constant 39 pups per litter beginning at age 5 (**Tables 5 and 7**). The proportion of females mature at age was modeled as 0% for ages ≤ 5(yr), 50% for age 6 (yr), and 100% for ages ≥ 7 (yr), based on an assumed female T50 of 6 (yr) (**Tables 5 and 7**). The proportion of females in a maternal condition at age a was modeled as the proportion of females mature at age a + 1, based on a gestation period of 9-12 months (**Tables 5 and 7**). Annual pup production at age was calculated as the mean litter size at each age multiplied by the proportion of females in a maternal condition at each age (**Table 7**).

2.2.3 Stock recruitment, steepness, and natural mortality

The steepness of the stock recruitment relationship (h) and natural mortality at age (M_a) were obtained from preliminary results based on life history invariant methods described separately in document SCRS/2015/142 (Cortés In prep.). A Beverton-Holt stock-recruitment relationship was assumed for the preliminary SS3 model runs. In Stock Synthesis, the Beverton-Holt stock-recruitment model is parameterized in terms of a steepness parameter, h, which describes the fraction of the unexploited recruits produced at 20% of the equilibrium spawning biomass level. For the preliminary SS3 model runs, the steepness parameter, h, was fixed at the mean of the distribution of steepness values obtained from the life history invariant methods (h = 0.73). Similarly, sex specific survival at each age was calculated here as the mean of the distribution in survival at age, $\bar{S}_a$, obtained from document SCRS/2015/142 (Cortés In prep.). Sex specific natural mortality at age was then obtained as $M_a = -\ln\left(\bar{S}_a\right)$. Combined sex natural mortality was then computed as the average mortality of males and females at each age (**Table 8, Figure 6**).

2.3 Model structure

2.3.1 Stock recruitment

A Beverton-Holt stock-recruitment relationship was assumed. 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).

Main recruitment deviations were estimated for the time period 1991 – 2010 based on the availability of length composition data in the stock assessment model. Main recruitment deviations were assumed to sum to zero on the log scale. Early recruitment deviations were estimated beginning in 1968 based on a minimum correlation threshold among estimated parameters of (cormin=0.01). An examination of SS3 output with the program r4ss also indicated that there was little information in the data to estimate recruitment deviations prior to 1968 and after 2010. Consequently, recruitment was set equal to the mean, R_y, for the years 2010 – 2013. Because recruitment deviations are estimated on the log scale in Stock Synthesis, the expected recruitments require a bias adjustment so that the resulting recruitment level on the standard scale is mean unbiased. The years chosen for bias adjustment, and the maximum bias adjustment parameter value were obtained from Stock Synthesis output with the program r4ss (Taylor *et al.* 2014).

Spawning stock size in the stock-recruitment relationship was calculated as the sum of female numbers at age multiplied by pup production (males and females) at age at the beginning of each calendar year and defined as spawning stock fecundity (SSF). SSF was input in the assessment with the assumed fraction female fixed at 0.5.

2.3.2 Parameters estimated conditionally

Only one stock-recruitment parameter, ln(R_0), was estimated in the preliminary SS3 Model runs. The remaining parameters of the Beverton-Holt stock-recruitment model (h and σ_R) were fixed, with recruitment estimated as deviations from mean recruitment. The steepness of the stock recruitment relationship, h, was fixed at the mean of the distribution of steepness values obtained in the analysis based on life history invariant methods, as described above. The parameter representing the standard deviation in recruitment, σ_R, was fixed at a value 0.4.

Parameter estimation for ln(R_0) and initial fishing mortality utilized a normal prior with a large standard deviation (Pr_SD) and independent minimum and maximum boundary conditions (Min, Max) for each parameter. Implementation of a normal prior is described in the manual for Stock Synthesis (Methot 2015).

Parameter estimation for 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 2015).

A simple logistic selectivity function (Stock Synthesis selectivity pattern 1; Methot 2015) was fit to the available length composition data (10 cm FL bin width) obtained for fleet F3 (Chinese Taipei-TAI, 2004-2013) (**Table 1 and Figure 3**). The simple logistic selectivity function in Stock Synthesis (Patterns 1 (size) and 12 (age); Methot 2015) is implemented as follows:

$$S(a) = \frac{1}{1+e^{\left(\frac{-\log(19)(a-p1)}{p2}\right)}},$$

where a is age (or size), $p1$ is age (or size) at inflection, and $p2$ is width for 95% selection; a negative width causes a descending curve.

A double logistic selectivity function (Stock Synthesis selectivity pattern 9; Methot 2015; e.g., Methot 1990) was implemented to fit the available length composition data (10 cm FL bin width) for fleets F1, F2, F4, and F5 (EU España + EU Portugal, 1993-2013; Japan, 1997-2013; USA, 1992-2013; and Venezuela, 1994-2013; respectively) (**Table 1 and Figure 3**). The double logistic selectivity function in Stock Synthesis (Patterns 9 (size) and 19 (age); Methot 2015; e.g., Methot 1990) is implemented as follows:

$$S(a) = \left[\left(\frac{1}{1+e^{\left(-p2(a-p1)\right)}} \right) \left(1 - \frac{1}{1+e^{\left(-p4(a-p3)\right)}} \right) \right] \Big/ Max \text{,}$$

where a is age (or size), $p1$ (INFL1) is the ascending inflection age (or size in cm), $p2$ (SLOPE1) is the ascending slope, $p3$ (INFL2) is the descending inflection age (or size in cm), and $p4$ (SLOPE2) is the descending slope. Two additional parameters are $p5$ (first BIN), the bin number for the first bin with non-zero selectivity (must be an integer bin number, not an age or size), and $p6$ (offset): which is fixed at a value of 0 in order to estimate $p3$ independently of $p1$; or fixed at a value of 1 in order to estimate $p3$ as an offset from $p1$. Examples of the resulting selectivity curves for model runs that converged, as described below, are provided in **Figure 8**.

2.3.3 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). 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.

2.3.4 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 Evaluation of stock status

Derived quantities and their associated asymptotic standard errors were obtained for time series of annual spawning stock size (calculated in fecundity; SSF) relative to spawning stock size at MSY (SSF/SSF_MSY) and for annual fishing mortality relative to fishing mortality at MSY (F/F_MSY).

2.5 Model sensitivity to input sample sizes and CVs

Several preliminary model runs were conducted in order to evaluate model sensitivity to the input sample sizes (weights) assigned in the model likelihood to length composition data and to the input CVs assigned to CPUE data (inverse CV weighting is used in the model likelihood for CPUE data in all model runs).

2.6 Preliminary model runs

2.6.1 Preliminary Run 1

For Preliminary Run 1, the observed sample sizes (the number of sharks measured) obtained from the available length compositions (fleets F1 – F5, **Table 1**) were used directly in the model likelihood variance calculations to "weight" the length composition data (**Table 9**). The observed CVs obtained from the available abundance indices (surveys S1 – S10, **Table 4**) were used in the model likelihood as inverse CV "weights" for the abundance indices. Main recruitment deviations were implemented from 1991 – 2010 based on years with length composition data. Early recruitment deviation began in 1957 in an attempt to explore the minimum correlation threshold (cormin = 0.01) in preliminary model runs.

2.6.2 Preliminary Run 2

Preliminary Run 2 was the same as Preliminary Run 1 except that a constant CV of 20% was applied as the inverse CV weighting to the abundance index obtained for survey S9 (ESP-LL-N) (**Tables 1** and **4**). Main recruitment deviations were implemented from 1991 – 2010 based on years with length composition data. Early recruitment deviation began in 1957 in an attempt to explore the minimum correlation threshold (cormin = 0.01) in preliminary model runs.

2.6.3 Preliminary Run 3

Preliminary Run 3 was the same as Preliminary Run 2 except that the input length composition sample size (**Table 9**) was fixed at a maximum of 200. Main recruitment deviations were implemented from 1991 – 2010 based on years with length composition data. Early recruitment deviation began in 1968 based on the earliest recruitment deviation estimated within the minimum correlation threshold (cormin = 0.01) in preliminary model runs. The years chosen for bias adjustment, and the maximum bias adjustment parameter value were obtained from Stock Synthesis output with the program r4ss (Taylor et al. 2014) in preliminary model runs as follows:

1968	#_recdev_early_start
1967.0648	#_last_early_yr_nobias_adj_in_MPD
1997.391	#_first_yr_fullbias_adj_in_MPD
2010	#_last_yr_fullbias_adj_in_MPD
2012.3068	#_first_recent_yr_nobias_adj_in_MPD
0.8868	# Max bias adj

2.6.4 Preliminary Run 4

Preliminary Run 4 was the same as Preliminary Run 2 except that the input sample sizes for the length composition data for fleets F1 – F5 (**Table 9**) were adjusted with variance adjustment multiplication factors (0.01, 0.01, 0.1, 0.1, 0.1, respectively) so that the effective sample sizes for fleets F1 – F5 were approximately equal to 50-200. Main recruitment deviations were implemented from 1991 – 2010 based on years with length composition data. Early recruitment deviation began in 1968 based on the earliest recruitment deviation estimated within the minimum correlation threshold (cormin = 0.01) in preliminary model runs. The years chosen for bias adjustment, and the maximum bias adjustment parameter value were obtained from Stock Synthesis output with the program r4ss in preliminary model runs as follows:

1968	#_recdev_early_start
1964.5807	#_last_early_yr_nobias_adj_in_MPD
1980.2039	#_first_yr_fullbias_adj_in_MPD
2010	#_last_yr_fullbias_adj_in_MPD
2016.9809	#_first_recent_yr_nobias_adj_in_MPD
0.5661	# Max bias adj, use value of 1 for compatibility with earlier versions

2.6.5 Preliminary Run 5

Preliminary Run 5 was the same as Preliminary Run 2 except that the input sample sizes for the length composition data for fleets F1 – F5 (**Table 9**) were adjusted with variance adjustment multiplication factors (0.0184, 0.0478, 0.0261, 0.1373, 0.2236, respectively) so that the effective sample sizes for fleets F1 – F5 were approximately equal to the effective sample size obtained from Stock Synthesis output, presumably based on McAllister and Ianelli (1997) as described in Punt et al. (2014). Main recruitment deviations were implemented from 1991 – 2010 based on years with length composition data. Early recruitment deviation began in 1968 based on the earliest recruitment deviation estimated within the minimum correlation threshold (cormin = 0.01) in preliminary model runs. The years chosen for bias adjustment, and the maximum bias adjustment parameter value were obtained from Stock Synthesis output with the program r4ss in preliminary model runs as follows:

1968	#_recdev_early_start
1958.9484	#_last_early_yr_nobias_adj_in_MPD
1997.7019	#_first_yr_fullbias_adj_in_MPD
2010	#_last_yr_fullbias_adj_in_MPD
2014.9151	#_first_recent_yr_nobias_adj_in_MPD
0.7393	# Max bias adj, use value of 1 for compatibility with earlier versions

2.6.6 Preliminary Run 6

Preliminary Run 6 was the same as Preliminary Run 2 except that the input sample sizes for the length composition data for fleets F1 – F5 (**Table 9**) were adjusted with variance adjustment multiplication factors (0.0019, 0.0047, 0.0046, 0.0573, 0.0403, respectively) so that the effective sample sizes for fleets F1 – F5 were approximately equal to the effective sample size obtained from the program r4ss (Francis Weights) presumably based on Francis (2011), as described in Punt et al. (2014). Main recruitment deviations were implemented from

1991 – 2010 based on years with length composition data. Early recruitment deviation began in 1968 based on the earliest recruitment deviation estimated within the minimum correlation threshold (cormin = 0.01) in preliminary model runs. The years chosen for bias adjustment, and the maximum bias adjustment parameter value were obtained from Stock Synthesis output with the program r4ss in preliminary model runs as follows:

1968	#_recdev_early_start
1964.3397	#_last_early_yr_nobias_adj_in_MPD
1978.775	#_first_yr_fullbias_adj_in_MPD
2010	#_last_yr_fullbias_adj_in_MPD
2013.0992	#_first_recent_yr_nobias_adj_in_MPD
0.4654	# Max bias adj, use value of 1 for compatibility with earlier versions

3. Results

Convergence diagnostics are presented below for Preliminary Runs 1 – 6. Model fits are presented for the preliminary models with the best convergence diagnostics (Preliminary Runs 4 and 6).

3.1 Convergence diagnostics

3.1.1 Preliminary Runs 1 – 3 and 5

For Preliminary Runs 1 – 3 and 5, the Hessian matrix inverted and was presumably positive definite. However, the final gradient was relatively large (5.26E-04, 4.57E-03, and 3.97E-03, respectively) and the parameter estimate for the natural log of equilibrium recruitment (SR_LN(R0)), which represents the absolute scale of the population size, was below the minimum correlation threshold (cormin = 0.01) and at an upper boundary condition. The parameter estimate for initial fishing mortality (InitF1) was also at a lower boundary condition. These results were interpreted as a diagnostic for possible problems with data or the assumed model structure. As a result, Preliminary Runs 1 – 3 and 5 were not pursued any farther.

3.1.2 Preliminary Run 4

For Preliminary Run 4, the Hessian matrix inverted and was presumably positive definite. The final gradient was relatively small (5.30E-06) and no parameters were estimated below the minimum correlation threshold (cormin=0.01). However, the parameters InitF_1 and SR_LN(R0) (cor = -1.00) were estimated above the maximum correlation threshold (cormax=0.95), the parameter InitF_1 was estimated at a lower bound, and the CV of the one of the selectivity parameters for fleet 4 (USA, SizeSel_4P_3_F4, 355%) was >> 50% (**Table 10**).

3.1.3 Preliminary Run 6

For Preliminary Run 6, the Hessian matrix inverted and was presumably positive definite. The final gradient was relatively small (9.03E-06) and no parameters were estimated above the maximum correlation threshold *(cormax = 0.95)* or below the minimum correlation threshold (*cormin* = 0.01), and no parameters were estimated at boundary conditions. The CV of the parameter SizeSel_4P_3_F4 (360%) was >> 50%. However, Preliminary Run 6 model results did not appear to be sensitive to the value estimated for this parameter (**Table 11**).

3.2 Model Fits

Model fits were similar for Preliminary Runs 4 and 6 and are presented together below.

3.2.1 Indices of abundance

Model predicted and observed standardized indices of relative abundance are provided in **Figures 9 – 18** for Preliminary Runs 4 and 6. See **Tables 1 and 3** for a description of each index of relative abundance and **Table 4** for the coefficients of variation (CV) corresponding to each index of relative abundance. Index S1 (US-Log) used the same data as S2 (US-Obs). Index S5 (IRL-Rec) was preliminary. Consequently, the indices S1 (US-Log, **Figure 9**) and S5 (IRL-Rec, **Figure 13**) were only included in the model for exploratory purposes, were not fit in the model likelihood (lambda = 0), and had no influence on model results or predicted values. The index S6 (US-Obs_cru, **Figure 14**) used the same data as S2 (US-Obs, **Figure 10**) during the years 1992 – 2000. Consequently, index S6 (US-Obs_cru) was only fit in the model likelihood for years 1971 – 1991. Index S10 (CTP-LL-N, **Figure 18**) was preliminary, but was fit in the model likelihood because of its presumed extensive geographic coverage.

3.2.2 Length compositions

Model predicted and observed aggregated annual length compositions (female + male) are provided in **Figure 19** for Preliminary Runs 4 and 6. See **Table 1 and Figures 2 and 3** for a description of each length composition data source.

3.3 Estimated Time Series

3.3.1 Recruitment

Expected recruitment from the stock-recruitment relationship (**Figure 20**), estimated log recruitment deviations (**Figure 21**), estimated annual recruitment (**Figure 22**), and the bias adjustment applied to the stock-recruitment relationship (**Figure 23**) are provided for Preliminary Runs 4 and 6.

3.3.2 Fishing mortality

Two estimates of exploitation rates were obtained from Stock Synthesis model output for Preliminary Runs 4 and 6. First, instantaneous fishing mortality rates (Continuous F) were estimated for each fleet (F1 – F9) (**Figure 24**). Second, total annual fishing mortality for all fleets combined was estimated as the total exploitation rate in numbers relative to total annual fishing mortality at MSY (F/F_MSY) (**Figure 25**). Fleet definitions are provided in **Table 1**, and catch data are described in **Tables 1 and 2, and Figure 1**.

3.3.3 Spawning stock biomass

Estimated **s**pawning stock size (spawning stock fecundity, SSF) along with approximate 95% asymptotic standard errors (± 2*s.e.) relative to spawning stock size at MSY (SSF_MSY) are provided for Preliminary Runs 4 and 6 (**Figure 26)**.

3.3.4 Evaluation of uncertainty

The expected recruitment from the stock-recruitment relationship differed substantially between Preliminary Run 4 and Preliminary Run 6 (**Figures 20-22**). However, the maximum bias adjustment applied to the stock-recruitment relationship for Preliminary Runs 4 and 6 were relatively low (0.5661, and 0.4654, respectively; **Figure 22**) indicating that there was very little information in the data to estimate recruitment. Maximum bias adjustment recommendations range from 0 – 1, and values near 0 indicate that there is very little information in the data to estimate recruitment deviations (Taylor *et al.* 2014).

Preliminary Run 6 (the model run with relatively less weight applied to the length composition data in the model likelihood) resulted in relatively more precise estimates of age-0 recruitment (**Figure 22**) and spawning stock size (spawning stock fecundity, SSF; **Figure 26**), compared to Preliminary Run 4.

The expected recruitment from the stock-recruitment relationship (**Figure 20**), the estimated total annual fishing mortality relative to fishing mortality at MSY (F/F_MSY) (**Figure 25**), and spawning stock size (spawning stock fecundity, SSF) relative to spawning stock size at MSY (SSF_MSY) (**Figure 26**) differed substantially between Preliminary Run 4 and Preliminary Run 6.

3.4 Stock Status

Both Preliminary Run 4 and Preliminary Run 6 resulted in sustainable spawning stock size and fishing mortality rates relative to maximum sustainable yield (**Figures 25 and 26**). However, Preliminary Run 6 (the model run with relatively less weight applied to the length composition data in the model likelihood) resulted in a relatively more depleted stock size, compared to Preliminary Run 4 (**Figures 25 and 26**).

However, the stock status results obtained from Preliminary Runs 4 and 6 should be considered preliminary, because the model was sensitive to the weight given to length composition data in the model likelihood and the choice of weights applied to length data in Preliminary Runs 4 and 6 was ad-hoc. Other weights could lead to different model results.

4. Discussion

Preliminary model run results were sensitive to the sample sizes (weights) assigned in the model likelihood to length composition data. Several of the preliminary model runs resulted in unreasonable convergence diagnostics. Two preliminary model runs which utilized multiplication factors to reduce the input sample size assigned to length composition data in the model likelihood resulted in reasonable convergence diagnostics. Model fits to CPUE and length composition data were similar for both models and both models resulted in sustainable spawning stock size and fishing mortality rates relative to maximum sustainable yield. The model with a relatively lower sample size assigned to the length composition data resulted in a relatively more depleted stock size.

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Table 1. Time series of catch, abundance, and length composition data considered for use in the preliminary 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	EU España + Portugal (1971-2013)	EU España + Portugal (1993-2013)
2	F2	Catch (t)	JPN	Japan (1971-2013)	Japan (1997-2013)
3	F3	Catch (t)	CTP	Chinese Taipei (1971-2013)	Chinese Taipei (2004-2013)
4	F4	Catch (t)	USA	USA (1981-2013)	USA (1992-2013)
5	F5	Catch (t)	VEN	Venezuela (1986-2013)	Venezuela (1994-2013)
6	F6	Catch (t)	CAN	Canada (1974-2007)	Mirror USA (F4)
7	F7	Catch (t)	CPR	China PR (1993-2013)	Mirror CTP (F3)
8	F8	Catch (t)	BEL	Belize (2009-2013)	Mirror VEN (F5)
9	F9	Catch (t)	OTH	Other (1978-2013)	Mirror CTP (F3)
10	S1	Relative abundance (numbers)	US-Log	US logbook (1986-2013) [1]	Mirror USA (F4)
11	S2	Relative abundance (numbers)	US-Obs	US observer (1992-2013)	Mirror USA (F4)
12	S3	Relative abundance (numbers)	JPLL-N-e	Japan (1971-1993)	Mirror JPN (F2)
13	S4	Relative abundance (numbers)	JPLL-N-l	Japan (1994-2013)	Mirror JPN (F2)
14	S5	Relative abundance (numbers)	IRL-Rec	Irish Rec. (1980-2006) [2]	Mirror CTP (F3)
15	S6	Relative abundance (numbers)	US-Obs-cru	[1957-1970] (1971-1991) [1992-2000] [3]	Mirror USA (F4)
16	S7	Relative abundance (biomass)	POR-LL	EU Portugal (1997-2013)	Mirror EU (F1)
17	S8	Relative abundance (numbers)	VEN-LL	Venezuela (1994-2013)	Mirror VEN (F5)
18	S9	Relative abundance (biomass)	ESP-LL-N	EU España (1997-2013)	Mirror EU (F1)
19	S10	Relative abundance (numbers)	CTP-LL-N	Chinese Taipei (2004-2013) [4]	Mirror CTP (F3)

1. Index S1 (US-Log) used the same data as S2 (US-Obs) and was not fit in model likelihood (lambda = 0).
2. Index S5 (IRL-Rec) was preliminary and was not fit in model likelihood (lambda = 0).
3. Index S6 (US-Obs_cru) overlapped with S2 (US-Obs) during the years 1992 – 2000; Consequently, data from 1992 – 200 were excluded from S6 in the model.
4. Index S10 (CTP-LL-N) was preliminary, but was fit in the model likelihood because of its presumed extensive geographic coverage.

Table 2. North Atlantic blue shark (BSH-N) catch in metric tons (t) was obtained from data compiled during the 2015 Blue Shark Data Preparatory meeting and assigned to "fleets" F1 – F9 for use in the SS3 preliminary model runs as defined below; Equilibrium catch (Eq. catch = 17,077 t) at the beginning of the fishery (1970) was obtained from an average of 10 posterior years (1971 to 1980) for fleets F1 (EU España + Portugal) + F2 (Japan) + F3(Chinese Taipei).

Region	**BSH-N**										
Major flag	**Belize**	**Canada**	**China PR**	**Chinese Taipei**	**EU(España)**	**EU(Portugal)**	**Japan**	**USA**	**Venezuela**	**Others**	**TOTAL**
Name (SS3)	**BEL**	**CAN**	**CPR**	**CTP**	**EU**	**EU**	**JPN**	**USA**	**VEN**	**OTH**	
Fleet (SS3)	**F8**	**F6**	**F7**	**F3**	**F1**	**F1**	**F2**	**F4**	**F5**	**F9**	
Eq. catch				**760**	**13817**		**2501**				**17077**
1971				738	14085		1258				16081
1972				932	13361		1675				15968
1973				901	15954		654				17509
1974		2		740	12042		3422				16205
1975		16		659	15596		4380				20652
1976		11		800	11721		1130				13663
1977		86		742	13773		3295				17896
1978		1754		734	15030		3368			4	20891
1979		2252		702	10747		924			12	14637
1980		1360		649	15858		4902			12	22782
1981		411		404	16703		6342	204		10	24075
1982		411		880	18955		5331	156		9	25742
1983		728		919	29552		3461	605		8	35273
1984		353		970	26285	29	2455	107		14	30213
1985		417		868	30930	62	3650	341		39	36308
1986		320		1175	40424	1865	2928	1112	11	50	47885
1987		147		440	46343	4096	2975	1400	15	67	55483
1988		968		248	39958	2547	2388	776	8	91	46985
1989		978		165	23708	1215	4533	751	9	81	31440
1990		680		1174	23875	1387	3599	829	9	133	31686
1991		774		2675	27080	2257	3580	1080	7	188	37641
1992		1277		2025	26435	1583	4509	399	24	277	36529
1993		1702	22	1428	26605	5726	5942	1816	23	322	43587
1994		1260	46	2684	25086	4669	2526	601	18	351	37242
1995		1494	68	1569	28920	4722	2813	641	16	283	40525
1996		528	66	2004	22972	4843	4179	987	6	282	35866
1997		831	23	1479	24497	2630	4191	391	27	215	34285
1998		612	73	893	22504	2440	3461	447	7	166	30604
1999		547	128	1177	21811	2227	3150	317	47	482	29886
2000		624	136	1157	24112	2081	2838	429	43	447	31867
2001		1162	300	906	17362	2110	2724	145	47	289	25045
2002		836	168	1108	15666	2265	1890	68	29	713	22742
2003		346	240	1449	15975	5643	3098	0	40	71	26861
2004		965	192	1378	17314	2025	3195	72	10	116	25266
2005		1134	232	857	15006	4027	3531	68	28	127	25009
2006		977	256	364	15464	4338	2824	47	12	358	24639
2007		843	367	292	17038	5283	2271	54	19	1108	27277
2008			109	110	20788	6167	3187	137	8	874	31379
2009	114		88	73	24465	6252	2942	107	73	2021	36135
2010	461		53	99	26094	8261	2755	176	75	198	38172
2011	1039		109	148	27988	6509	2148	271	118	676	39007
2012	903		98	115	28666	3768	2256	162	98	539	36605
2013	1216		327	135	28562	3694	1354	264	52	1145	36748

Table 3. Indices of relative abundance for North Atlantic blue shark were obtained from data compiled during the 2015 Blue Shark Data Preparatory meeting, except for updated Irish (IRL-Rec) and Chinese Taipei (CTP-LL-N) time series which were submitted separately; The available abundance indices were assigned to "surveys" S1 – S10 for use in SS3 as described **Table 1**.

INDICES	1	2	3	4	5	6	7	8	9	10
Units	Numbers	Numbers	Numbers	Numbers	Numbers	Numbers	Biomass	Numbers	Biomass	Numbers
Type	Logbook	observer			nominal					
Name (SS3)	US-Log[1]	US-Obs	JPLL-N-e	JPLL-N-l	IRL-Rec[2]	US-Obs-cru[3]	POR-LL	VEN-LL	ESP-LL-N	CTP-LL-N[4]
Survey (SS3)	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
1957						0.98				
1958						0.48				
1959						1.11				
1960						1.18				
1961						1.13				
1962						1.5				
1963						0.7				
1964						0.87				
1965						1.55				
1966						1.27				
1967						1.43				
1968						1.31				
1969						1.96				
1970						0.97				
1971			0.87			1.08				
1972			1.46			1.93				
1973			1.12							
1974			2.62							
1975			1.85			0.88				
1976			1.07			0.75				
1977			1.89			1.82				
1978			1.58			1.06				
1979			1.30			0.86				
1980			2.21			0.83				
1981			2.19			1.05				
1982			2.08			0.78				
1983			1.81			1.01				
1984			1.22			0.68				
1985			1.51			0.74				
1986	19.622		1.52			0.48				
1987	13.362		2.13			0.5				
1988	9.011		1.21			0.44				
1989	7.273		1.51		2.83	0.8				
1990	7.586		1.34		3.25	0.94				
1991	9.098		1.26		2.28	1.22				
1992	8.842	7.455	1.90		2.81	0.63				
1993	9.519	11.076	2.43		4.16	0.95				
1994	7.980	9.717		2.33	3.06	0.98		0.047		
1995	7.167	10.170		2.10	3.33	0.73		0.073		
1996	7.700	8.208		2.05	3.76	0.47		0.017		
1997	7.662	14.439		2.05	3.38	1.25	158.137	0.154	156.828	
1998	6.076	18.408		1.72	2.45	1.16	169.020	0.216	154.453	
1999	4.259	6.663		1.89	1.93	0.76	149.831	0.117	179.914	
2000	3.903	9.541		1.58	2.11	0.78	201.435	0.151	213.046	
2001	3.202	2.306		1.71	2.09		222.138	0.133	215.631	
2002	3.044	2.277		1.37	0.88		200.859	0.074	183.944	
2003	2.802	1.876		1.97	1.93		238.767	0.044	222.877	
2004	3.364	9.503		1.79	0.79		266.155	0.034	177.270	0.749
2005	2.298	3.193		1.90	1.57		218.555	0.006	166.824	2.195
2006	2.540	4.674		2.16	1.52		212.626	0.013	177.107	1.308
2007	2.992	9.645		2.18	1.44		241.319	0.060	187.056	0.561
2008	3.383	8.512		2.48	0.97		225.675	0.088	215.796	0.495
2009	4.445	8.322		2.46	2.01		228.300	0.045	196.083	0.570
2010	5.829	13.545		2.45	1.77		276.760	0.040	209.027	0.877
2011	5.628	21.806		2.37	2.69		233.287	0.044	221.132	0.765
2012	3.691	8.128		2.60	1.11		305.530	0.107	238.003	0.668
2013	4.700	7.374		2.09	3.17		304.081	0.044	203.485	1.045

1. Index S1 (US-Log) used the same data as S2 (US-Obs) and was not fit in model likelihood (lambda = 0).
2. Index S5 (IRL-Rec) was preliminary and was not fit in model likelihood (lambda = 0).
3. Index S6 (US-Obs_cru) overlapped with S2 (US-Obs) during the years 1992 – 2000, and data from those years from S6 were excluded.
4. Index S10 (CTP-LL-N) was preliminary, but was fit in the model likelihood because of its presumed extensive geographic coverage.

Table 4. Coefficients of variation (CV) corresponding to indices of relative abundance for North Atlantic blue shark were obtained from data compiled during the 2015 Blue Shark Data Preparatory meeting, except for updated Irish and Chinese Taipei time series which were submitted separately.

CVs	1	2	3	4	5	6	7	8	9	10
Units	**Numbers**	**Numbers**	**Numbers**	**Numbers**	**Numbers**	**Numbers**	**Biomass**	**Numbers**	**Biomass**	**Numbers**
Type	**Logbook**	**observer**			**nominal**					
Name (SS3)	**US-Log**	**US-Obs**	**JPLL-N-e**	**JPLL-N-l**	**IRL-Rec**	**US-Obs-cru**	**POR-LL**	**VEN-LL**	**ESP-LL-N**	**CTP-LL-N**
Survey (SS3)	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
1957						0.17				
1958						0.16				
1959						0.25				
1960						0.38				
1961						0.35				
1962						0.27				
1963						0.25				
1964						0.17				
1965						0.17				
1966						0.23				
1967						0.21				
1968						0.21				
1969						0.22				
1970						0.32				
1971			0.534			0.23				
1972			0.386			0.21				
1973			0.452							
1974			0.316							
1975			0.335			0.19				
1976			0.470			0.29				
1977			0.267			0.2				
1978			0.316			0.11				
1979			0.242			0.11				
1980			0.290			0.09				
1981			0.357			0.09				
1982			0.362			0.09				
1983			0.368			0.1				
1984			0.499			0.1				
1985			0.444			0.1				
1986	0.221		0.393			0.09				
1987	0.169		0.346			0.1				
1988	0.168		0.489			0.12				
1989	0.168		0.444		0.179	0.39				
1990	0.167		0.489		0.195	0.17				
1991	0.167		0.470		0.078	0.11				
1992	0.167	0.314	0.428		0.188	0.1				
1993	0.167	0.291	0.399		0.242	0.09				
1994	0.166	0.289		0.499	0.171	0.1		1.075		
1995	0.166	0.292		0.546	0.094	0.1		0.867		
1996	0.166	0.503		0.510	0.082	0.3		1.898		
1997	0.167	0.330		0.522	0.095	0.13	0.084	0.685	0.008	
1998	0.168	0.346		0.534	0.103	0.15	0.076	0.666	0.008	
1999	0.170	0.342		0.489	0.118	0.13	0.077	0.843	0.008	
2000	0.172	0.319		0.282	0.122	0.12	0.083	0.737	0.008	
2001	0.172	0.393		0.560	0.087		0.089	0.771	0.008	
2002	0.174	0.394		0.623	0.182		0.086	1.034	0.008	
2003	0.177	0.366		0.589	0.111		0.082	1.262	0.009	
2004	0.175	0.297		0.687	0.171		0.084	1.525	0.009	0.120
2005	0.179	0.345		0.713	0.195		0.087	3.881	0.010	0.185
2006	0.181	0.310		0.687	0.203		0.084	2.244	0.010	0.062
2007	0.182	0.324		0.606	0.253		0.085	1.353	0.011	0.220
2008	0.174	0.321		0.687	0.453		0.085	1.164	0.011	0.275
2009	0.174	0.312		0.643	0.190		0.086	1.559	0.012	0.171
2010	0.175	0.308		0.643	0.406		0.089	1.543	0.010	0.101
2011	0.175	0.294		0.510	0.464		0.079	1.514	0.010	0.119
2012	0.176	0.336		0.510	0.483		0.081	1.000	0.010	0.109
2013	0.174	0.305		0.206	0.553		0.085	1.842	0.011	0.138

Table 5. Life history inputs were obtained from data first assembled at the 2014 Intersessional Meeting of the Shark Species Group (Anon. 2014), plus additional information provided during the 2015 Blue Shark Data Preparatory meeting and thereafter as summarized below; Cited references in the table are provided separately in Anon. (2014), except where identified.

Reproduction	North Atlantic Blue Shark (Anon. 2014 Appendix 5)	Cited Reference
L_{mat} (♂)	230-249 TL	Campana et al. (2005) [2]
L_{50} (♂)	239 TL	Campana et al. (2005) [2]
T_{mat} (♂)	5	Skomal & Natanson (2005) [2]
T_{50} (♂)		
L_{mat} (♀)	221 TL	Pratt (1979) [2]
L_{50} (♀)		
T_{mat} (♀)	5	Skomal & Natanson (2005) [2]
T_{50} (♀) [1]	6	Cortes et al. (2012) [2]
Cycle[1]	1	Pratt (1979) [2]
GP (months) [1]	9-12	Pratt (1979) [2]
L_0	55 TL	Pratt (1979) [2]
Mean LS [1]	39	Mejuto & García-Cortés (2005) [2]
Min LS	1	Mejuto & García-Cortés (2005) [2]
Max LS	96	Mejuto & García-Cortés (2005) [2]
LS at length [3]	-91.97+0.6052*TL	Castro and Mejuto (1995) [3]

Age & Growth		
L_{inf} (♀) [cm] [1]	371 TL [310 FL]	Skomal and Natanson (2003) [2]
k (♀)[1]	0.13	Skomal and Natanson (2003) [2]
T_o / L_o (♀) [1]	-1.77	Skomal and Natanson (2003) [2]
T_{max} (♀) [yr] [1]	15	Skomal and Natanson (2003) [2]
L_{inf} (♂) [cm] [1]	338 TL [282 FL]	Skomal and Natanson (2003) [2]
k (♂)[1]	0.18	Skomal and Natanson (2003) [2]
T_o / L_o (♂) [1]	-1.35	Skomal and Natanson (2003) [2]
T_{max} (♂) [yr] [1]	16	Skomal and Natanson (2003) [2]

Conversion Factors		
Length-length [cm]	FL=0.8313TL+1.3908	Kohler et al. (1995) [2]
Length-weight (both) [cm,kg] [1]	W=3.18E-06FL^3.1313	Kohler et al. (1995) [2]
Length-weight (♀) [cm,kg]	W=1.30E-06TL^3.2	Stevens (1975) [2]
Length-weight (♂) [cm,kg]	W=3.90E-07TL^3.41	Stevens (1975) [2]

1. Parameters used in the preliminary North Atlantic blue shark Stock Synthesis model runs.
2. Cited references provided separately in Anon. (2014).
3. Cited references are provided in this report (Section 6. References).

Table 6. The average sex specific VBG length at age-0 (combined L_{Amin}, 62.3 cm FL), the average sex specific VBG L_inf (combined L_{inf} = 296.0), and the average sex specific VBG growth coefficient (combined k = 0.16) to define combined sex VBG growth at age for use in preliminary SS3 model runs.

Age Class (yr)	Male cm FL predicted from VBG (**Table 5**)	Female cm FL predicted from VBG (**Table 5**)	Average of male and female VBG (cm FL)
0	60.8	63.7	62.3
1	97.3	93.7	95.5
2	127.7	120.1	123.9
3	153.1	143.3	148.2
4	174.3	163.6	169.0
5	192.1	181.4	186.8
6	206.9	197.1	202.0
7	219.3	210.9	215.1
8	229.6	223.0	226.3
9	238.2	233.6	235.9
10	245.4	242.9	244.2
11	251.5	251.1	251.3
12	256.5	258.2	257.4
13	260.7	264.6	262.6
14	264.2	270.1	267.2
15	267.1	275.0	271.0
16	269.6	279.2	274.4

VBG parameters	Male cm FL predicted from VBG (**Table 5**)	Female cm FL predicted from VBG (**Table 5**)	Average of male and female VBG (cm FL)
L_{inf}	282.0	310.0	296.0
k	0.18	0.13	0.16
t_0	-1.4	-1.8	-1.6

Table 7. Annual pup production at age was calculated as the mean litter size at each age multiplied by the proportion of females in a maternal condition at each age

Age (yr)	Mean litter size	Proportion mature	Proportion in a maternal condition	(Mean litter size) * (proportion in a maternal condition)
0	0	0.00	0.00	0
1	0	0.00	0.00	0
2	0	0.00	0.00	0
3	0	0.00	0.00	0
4	0	0.00	0.00	0
5	39	0.00	0.00	0
6	39	0.50	0.00	0
7	39	1.00	0.50	19.5
8	39	1.00	1.00	39
9	39	1.00	1.00	39
10	39	1.00	1.00	39
11	39	1.00	1.00	39
12	39	1.00	1.00	39
13	39	1.00	1.00	39
14	39	1.00	1.00	39
15	39	1.00	1.00	39
16	39	1.00	1.00	39
17	39	1.00	1.00	39
18	39	1.00	1.00	39
19	39	1.00	1.00	39
20	39	1.00	1.00	39

Table 8. Sex specific survival at each age was calculated here as the mean of the distribution in survival at age, $\bar{S}_a$, obtained from document SCRS/2015/142 (Cortés In prep.). Sex specific natural mortality at age was then obtained as $M_a = -\ln\left(\bar{S}_a\right)$. Combined sex natural mortality was then computed as the average mortality of males and females at each age.

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

Table 9. Observed sample size (number of sharks measured) for available length composition (fleets F1 – F5, **Table 1**) used in preliminary model run 1.

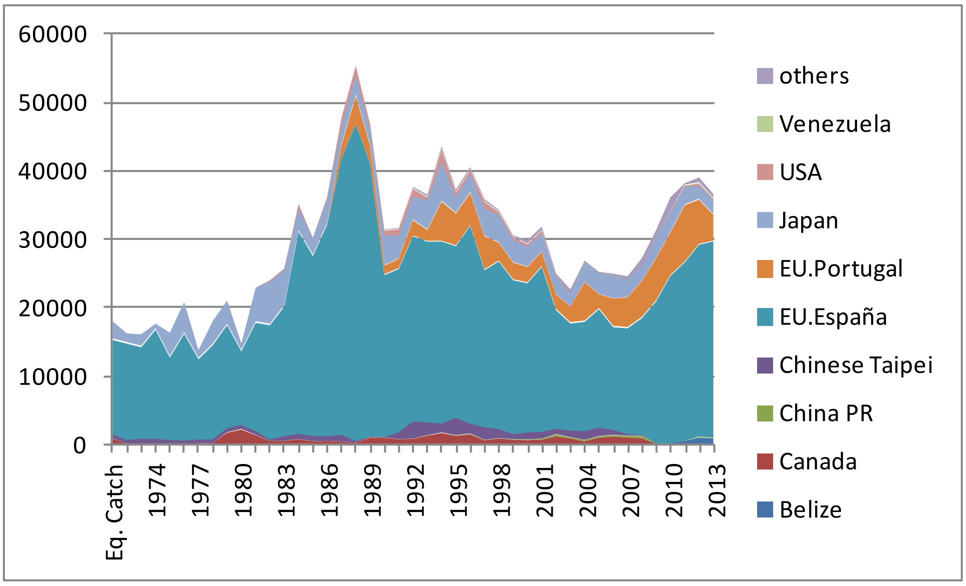
Year	F1 (EU)	F2 (JPN)	F3 (CTP)	F4 (USA)	F5 (VEN)
1992	0	0	0	35	0
1993	2025	0	0	363	0
1994	0	0	0	319	57
1995	0	0	0	105	94
1996	0	0	0	10	13
1997	914	2813	0	146	125
1998	562	1208	0	13	147
1999	2142	301	0	21	83
2000	2325	354	0	84	97
2001	4643	923	0	5	74
2002	1127	794	0	2	45
2003	5096	1907	0	9	26
2004	2455	1386	413	98	40
2005	3153	2488	289	39	4
2006	7242	2076	7373	85	14
2007	3359	2244	159	125	7
2008	4828	3729	192	129	26
2009	2754	1786	595	98	24
2010	7345	2226	287	511	44
2011	2639	1751	444	393	164
2012	10949	1970	359	10	169
2013	2606	1799	236	17	90

Table 10. Preliminary Run 4 non-recruitment parameter estimates. Parameters with a negative phase were fixed at their initial value. CV is calculated as the asymptotic standard error (Parm_StDev) divided by the estimated value (Value).

Num	Label	Value	Active_Cnt	Phase	Min	Max	Init	Status	Parm_StDev	PR_type	Prior	Pr_SD	CV (%)
16	SR_LN(R0)	9.978	1	1	2.3	13.82	7.04	OK	0.892	Normal	7.04	1000	8.9
65	InitF_1F1	0.010	45	1	0	1.9	0.1	LO	0.009	Normal	0.38	1000	91.3
74	SizeSel_1P_1_F1	100.660	46	2	1	500	100	OK	2.823	Sym_Beta	100.00	0.05	2.8
75	SizeSel_1P_2_F1	0.147	47	3	0	1	0.15	OK	0.032	Sym_Beta	0.15	0.05	21.6
76	SizeSel_1P_3_F1	262.059	48	2	1	500	243	OK	4.537	Sym_Beta	243.00	0.05	1.7
77	SizeSel_1P_4_F1	0.131	49	3	0	1	0.08	OK	0.033	Sym_Beta	0.08	0.05	25.5
78	SizeSel_1P_5_F1	1.000	_	-88	1	24	1	NA	_	Sym_Beta	1.00	0.05	NA
79	SizeSel_1P_6_F1	0.000	_	-88	0	1	0	NA	_	Sym_Beta	0.00	0.05	NA
80	SizeSel_2P_1_F2	127.221	50	2	1	500	120	OK	6.038	Sym_Beta	120.00	0.05	4.7
81	SizeSel_2P_2_F2	0.085	51	3	0	1	0.15	OK	0.016	Sym_Beta	0.15	0.05	19.0
82	SizeSel_2P_3_F2	219.498	52	2	1	500	220	OK	9.238	Sym_Beta	220.00	0.05	4.2
83	SizeSel_2P_4_F2	0.056	53	3	0	1	0.07	OK	0.013	Sym_Beta	0.07	0.05	24.1
84	SizeSel_2P_5_F2	1.000	_	-88	1	24	1	NA	_	Sym_Beta	1.00	0.05	NA
85	SizeSel_2P_6_F2	0.000	_	-88	0	1	0	NA	_	Sym_Beta	0.00	0.05	NA
86	SizeSel_3P_1_F3	206.335	54	2	5	500	200	OK	4.338	Sym_Beta	200.00	0.05	2.1
87	SizeSel_3P_2_F3	55.517	55	3	0.01	60	25	OK	2.961	Sym_Beta	25.00	0.05	5.3
88	SizeSel_4P_1_F4	109.074	56	2	1	500	110	OK	3.087	Sym_Beta	110.00	0.05	2.8
89	SizeSel_4P_2_F4	0.127	57	3	0	1	0.09	OK	0.012	Sym_Beta	0.09	0.05	9.8
90	SizeSel_4P_3_F4	7.344	58	2	1	500	120	OK	26.060	Sym_Beta	120.00	0.05	354.8
91	SizeSel_4P_4_F4	0.038	59	3	0	1	0.05	OK	0.004	Sym_Beta	0.05	0.05	10.9
92	SizeSel_4P_5_F4	1.000	_	-88	1	24	1	NA	_	Sym_Beta	1.00	0.05	NA
93	SizeSel_4P_6_F4	0.000	_	-88	0	1	0	NA	_	Sym_Beta	0.00	0.05	NA
94	SizeSel_5P_1_F5	214.228	60	2	1	500	210	OK	16.849	Sym_Beta	210.00	0.05	7.9
95	SizeSel_5P_2_F5	0.064	61	3	0	1	0.05	OK	0.011	Sym_Beta	0.05	0.05	17.8
96	SizeSel_5P_3_F5	110.312	62	2	1	500	210	OK	48.701	Sym_Beta	210.00	0.05	44.1
97	SizeSel_5P_4_F5	0.035	63	3	0	1	0.05	OK	0.014	Sym_Beta	0.05	0.05	39.3
98	SizeSel_5P_5_F5	1.000	_	-88	1	24	1	NA	_	Sym_Beta	1.00	0.05	NA
99	SizeSel_5P_6_F5	0.000	_	-88	0	1	0	NA	_	Sym_Beta	0.00	0.05	NA

Table 11. Preliminary Run 6 non-recruitment parameter estimates. Parameters with a negative phase were fixed at their initial value. CV is calculated as the asymptotic standard error (Parm_StDev) divided by the estimated value (Value).

Num	Label	Value	Active_Cnt	Phase	Min	Max	Init	Status	Parm_StDev	PR_type	Prior	Pr_SD	CV (%)
16	SR_LN(R0)	8.789	1	1	2.3	13.82	7.04	OK	0.146	Normal	7.04	1000	1.7
65	InitF_1F1	0.046	45	1	0	1.9	0.1	OK	0.012	Normal	0.38	1000	26.1
74	SizeSel_1P_1_F1	171.635	46	2	1	500	100	OK	51.767	Sym_Beta	100.00	0.05	30.2
75	SizeSel_1P_2_F1	0.029	47	3	0	1	0.15	OK	0.011	Sym_Beta	0.15	0.05	37.7
76	SizeSel_1P_3_F1	251.752	48	2	1	500	243	OK	13.177	Sym_Beta	243.00	0.05	5.2
77	SizeSel_1P_4_F1	0.098	49	3	0	1	0.08	OK	0.051	Sym_Beta	0.08	0.05	52.0
78	SizeSel_1P_5_F1	1.000	_	-88	1	24	1	NA	_	Sym_Beta	1.00	0.05	NA
79	SizeSel_1P_6_F1	0.000	_	-88	0	1	0	NA	_	Sym_Beta	0.00	0.05	NA
80	SizeSel_2P_1_F2	130.939	50	2	1	500	120	OK	9.218	Sym_Beta	120.00	0.05	7.0
81	SizeSel_2P_2_F2	0.079	51	3	0	1	0.15	OK	0.020	Sym_Beta	0.15	0.05	26.0
82	SizeSel_2P_3_F2	230.031	52	2	1	500	220	OK	14.903	Sym_Beta	220.00	0.05	6.5
83	SizeSel_2P_4_F2	0.057	53	3	0	1	0.07	OK	0.026	Sym_Beta	0.07	0.05	45.8
84	SizeSel_2P_5_F2	1.000	_	-88	1	24	1	NA	_	Sym_Beta	1.00	0.05	NA
85	SizeSel_2P_6_F2	0.000	_	-88	0	1	0	NA	_	Sym_Beta	0.00	0.05	NA
86	SizeSel_3P_1_F3	224.418	54	2	5	500	200	OK	12.015	Sym_Beta	200.00	0.05	5.4
87	SizeSel_3P_2_F3	52.088	55	3	0.01	60	25	OK	9.247	Sym_Beta	25.00	0.05	17.8
88	SizeSel_4P_1_F4	108.567	56	2	1	500	110	OK	3.872	Sym_Beta	110.00	0.05	3.6
89	SizeSel_4P_2_F4	0.131	57	3	0	1	0.09	OK	0.017	Sym_Beta	0.09	0.05	12.8
90	SizeSel_4P_3_F4	10.746	58	2	1	500	120	OK	38.707	Sym_Beta	120.00	0.05	360.2
91	SizeSel_4P_4_F4	0.036	59	3	0	1	0.05	OK	0.005	Sym_Beta	0.05	0.05	14.7
92	SizeSel_4P_5_F4	1.000	_	-88	1	24	1	NA	_	Sym_Beta	1.00	0.05	NA
93	SizeSel_4P_6_F4	0.000	_	-88	0	1	0	NA	_	Sym_Beta	0.00	0.05	NA
94	SizeSel_5P_1_F5	215.389	60	2	1	500	210	OK	25.063	Sym_Beta	210.00	0.05	11.6
95	SizeSel_5P_2_F5	0.064	61	3	0	1	0.05	OK	0.018	Sym_Beta	0.05	0.05	28.3
96	SizeSel_5P_3_F5	104.847	62	2	1	500	210	OK	101.137	Sym_Beta	210.00	0.05	96.5
97	SizeSel_5P_4_F5	0.030	63	3	0	1	0.05	OK	0.021	Sym_Beta	0.05	0.05	69.2
98	SizeSel_5P_5_F5	1.000	_	-88	1	24	1	NA	_	Sym_Beta	1.00	0.05	NA
99	SizeSel_5P_6_F5	0.000	_	-88	0	1	0	NA	_	Sym_Beta	0.00	0.05	NA



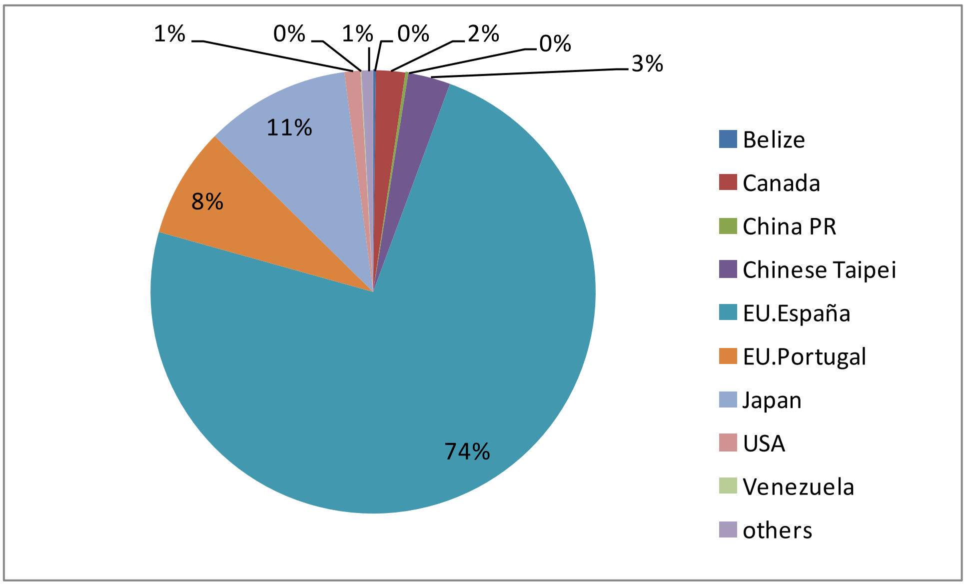


Figure 1. Catch in metric tons (t) by major flag obtained from data compiled during the 2015 Blue Shark Data Preparatory meeting and presented here as annual time series (Top Panel) and as the proportion of the total catch (Bottom Panel).

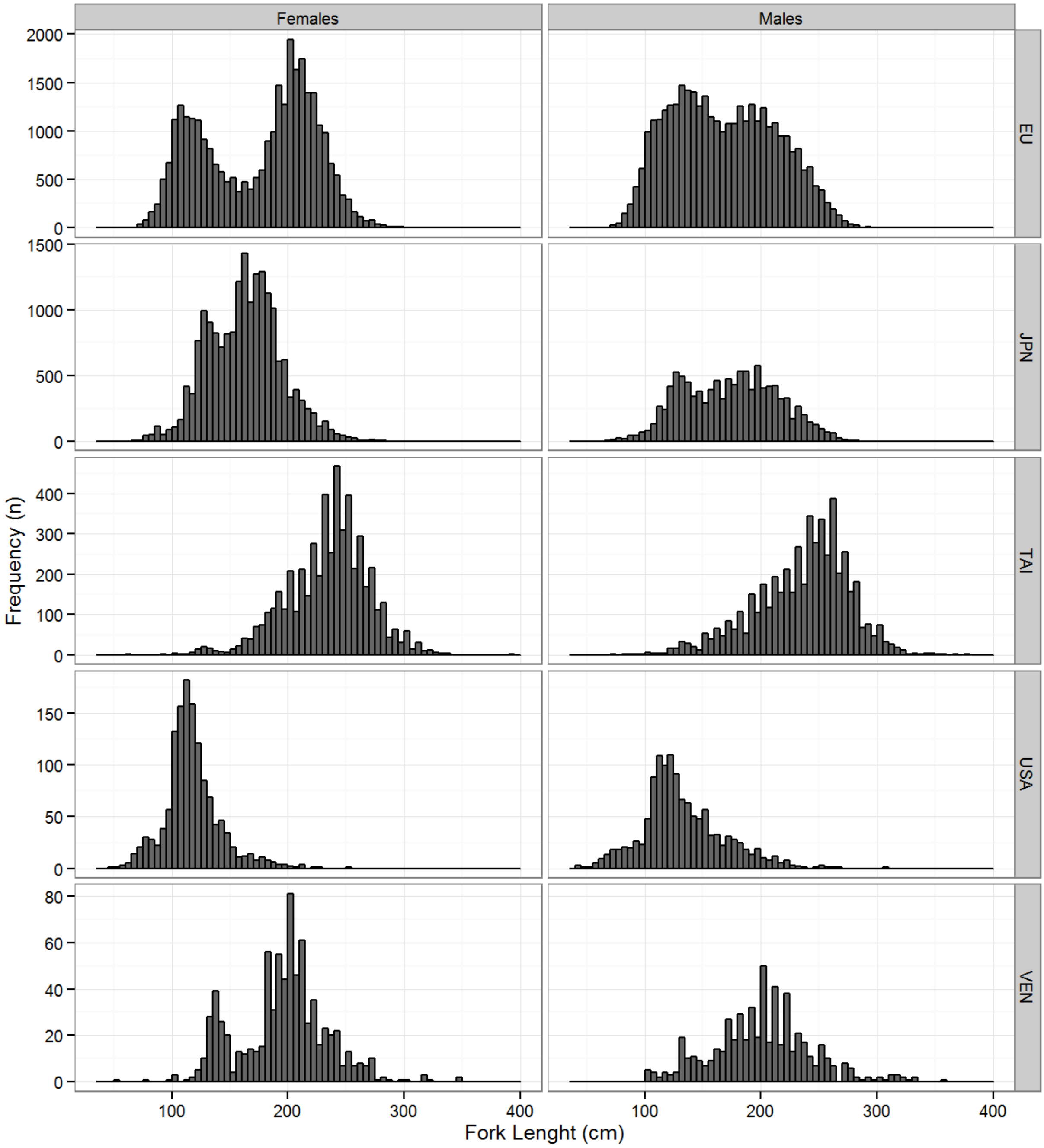


Figure 2. Length composition data for North Atlantic blue shark (35 – 390 cm FL, 5 cm bins) obtained from data compiled during the 2015 Blue Shark Data Preparatory meeting, as described in document SCRS/2015/039 (Coelho et al. In prep.), for EU (España + Portugal, 1993-2013), JPN (Japan, 1997-2013), TAI (Chinese Taipei, 2004-2013), USA (1992-2013), and VEN (Venezuela, 1994-2013).

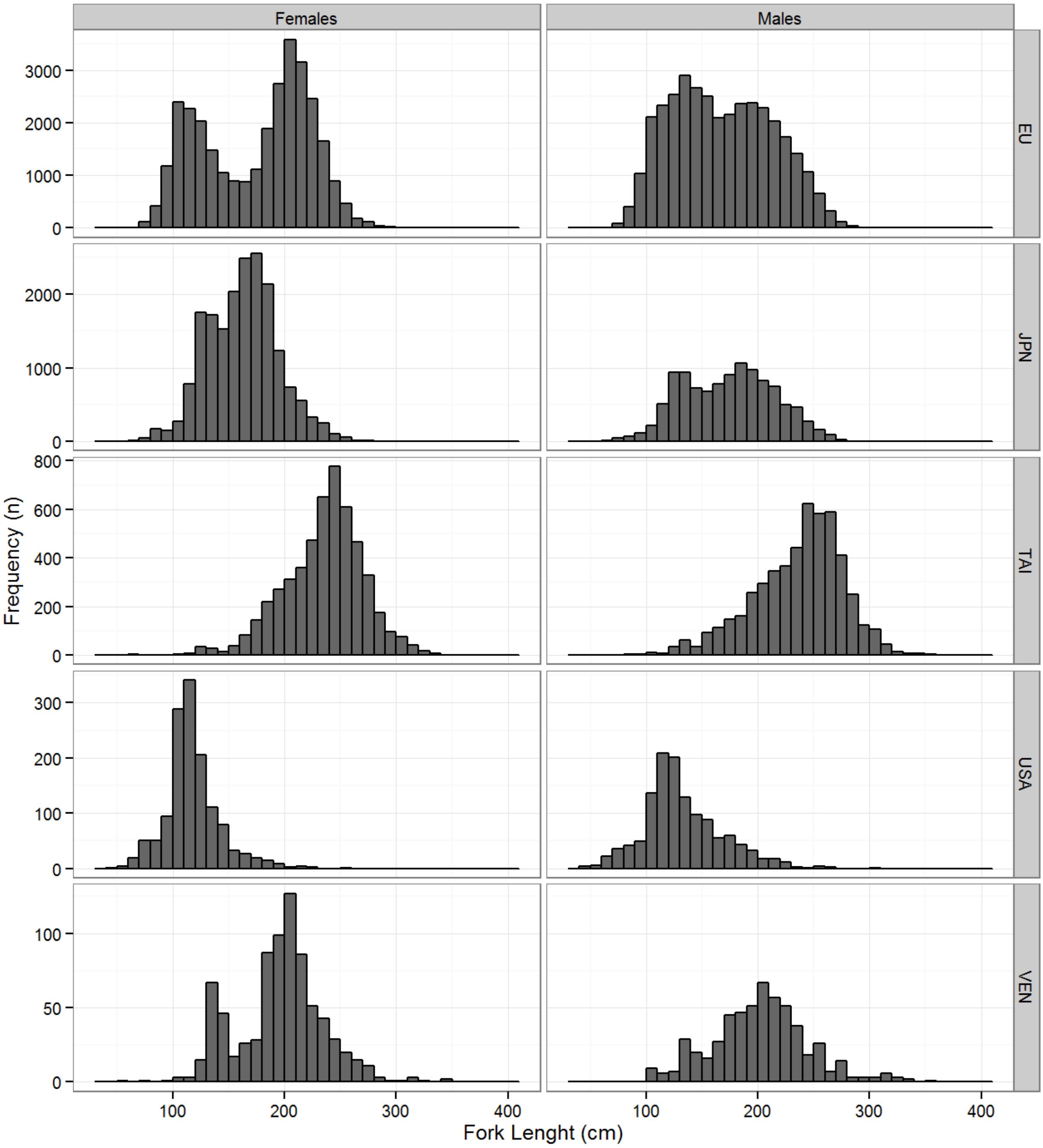


Figure 3. Length composition data for North Atlantic blue shark (35 – 390 cm FL, 10 cm bins) obtained from data compiled during the 2015 Blue Shark Data Preparatory meeting, as described in document SCRS/2015/039 (Coelho et al. In prep.), for EU (España + Portugal, 1993-2013), JPN (Japan, 1997-2013), TAI (Chinese Taipei, 2004-2013), USA (1992-2013), and VEN (Venezuela, 1994-2013).

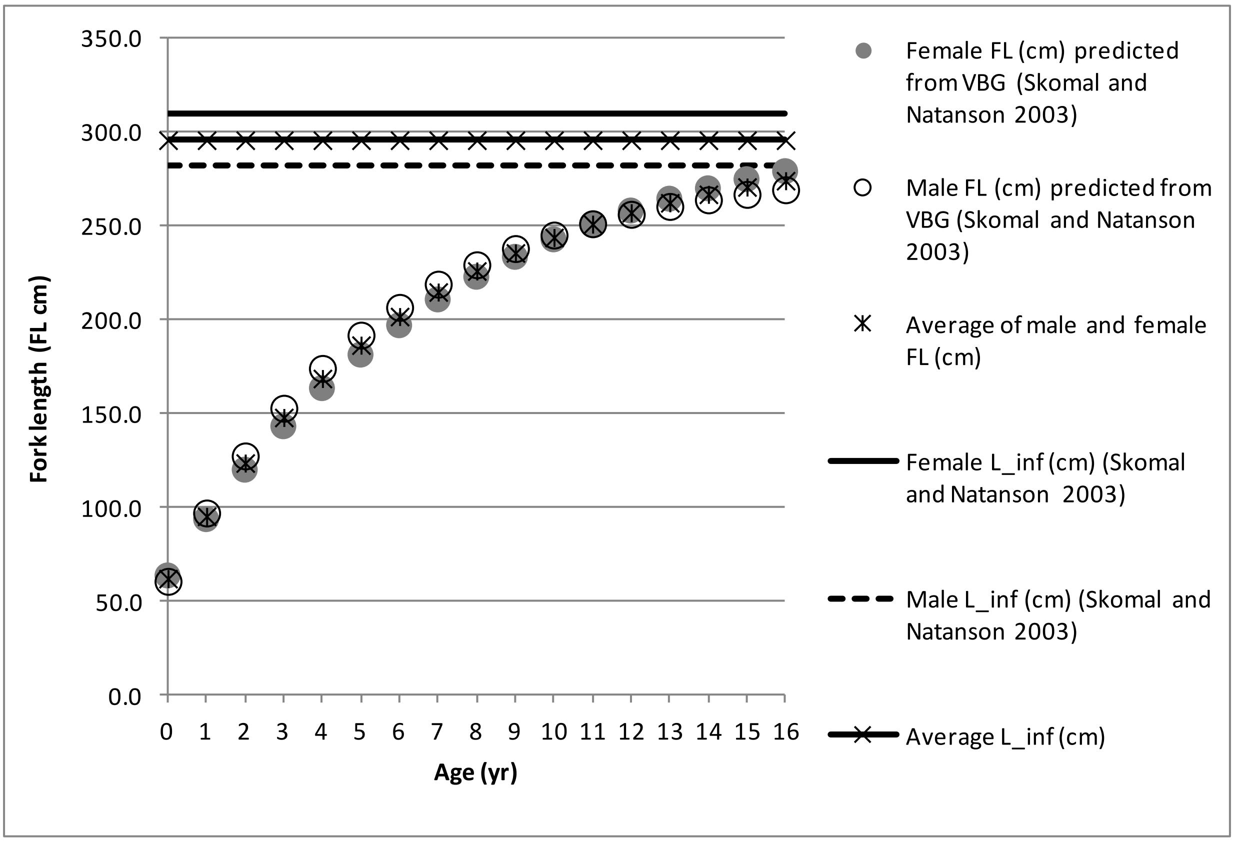


Figure 4. Growth in length at age was assumed to follow von Bertalanffy growth (VBG); References can be found in Anon. (2014) as identified in **Table 5**. A combined sex model was implemented by using the average sex specific VBG length at age-0 (combined L_{Amin}, 62.3 cm FL), the average sex specific VBG L_inf (combined L_{inf} = 296.0), and the average sex specific VBG growth coefficient (combined k = 0.16) to define combined sex VBG growth at age for use in preliminary SS3 model runs (**Table 6**).

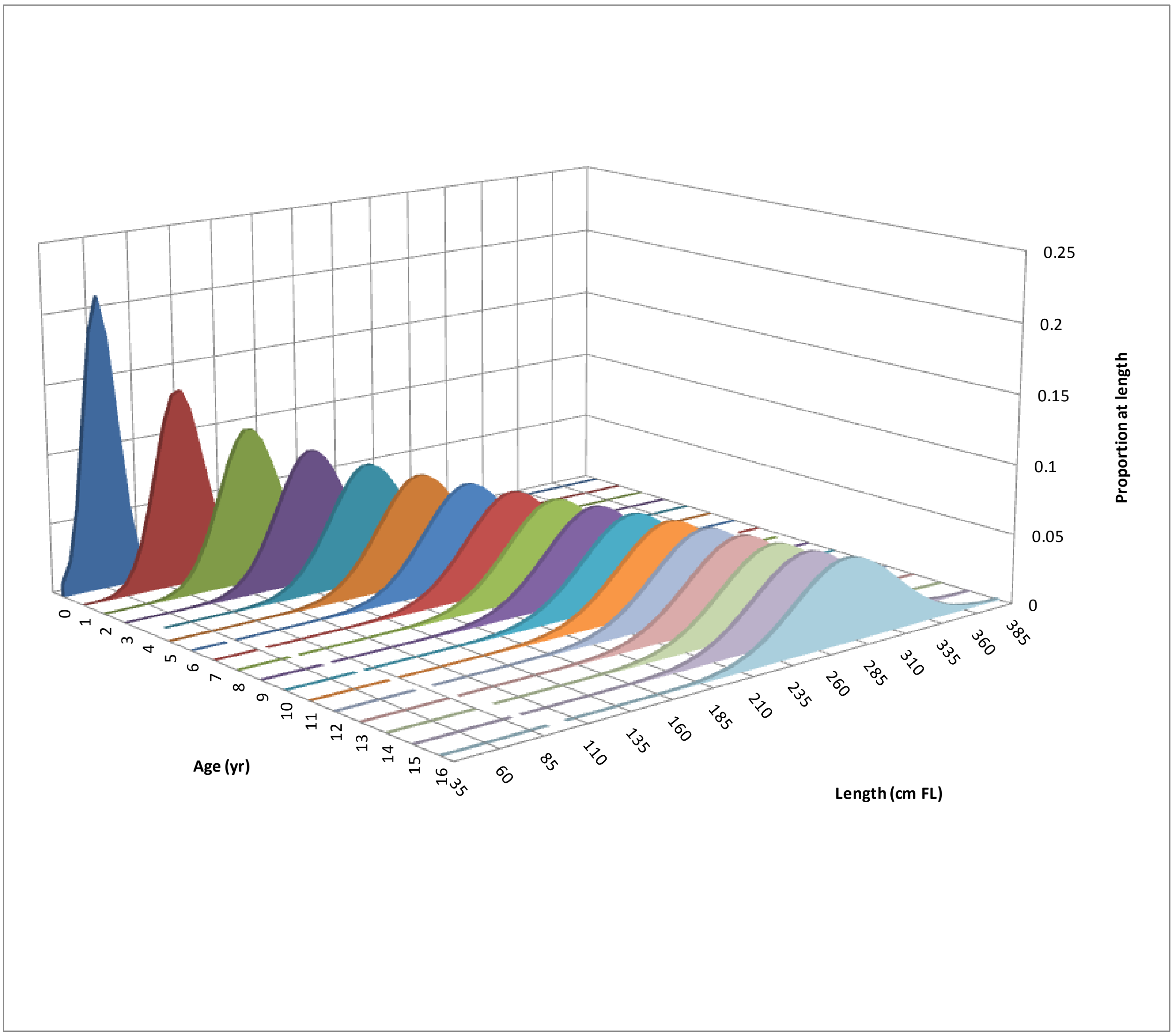


Figure 5. The distribution of mean length at each age was modeled as a normal distribution and the CV in mean length at age was modeled as a linear function of length. The CVs in length at age were fixed at 0.15 for L_{Amin} and 0.12 for L_{inf}, and linearly interpolated between L_{Amin} and L_{inf}.

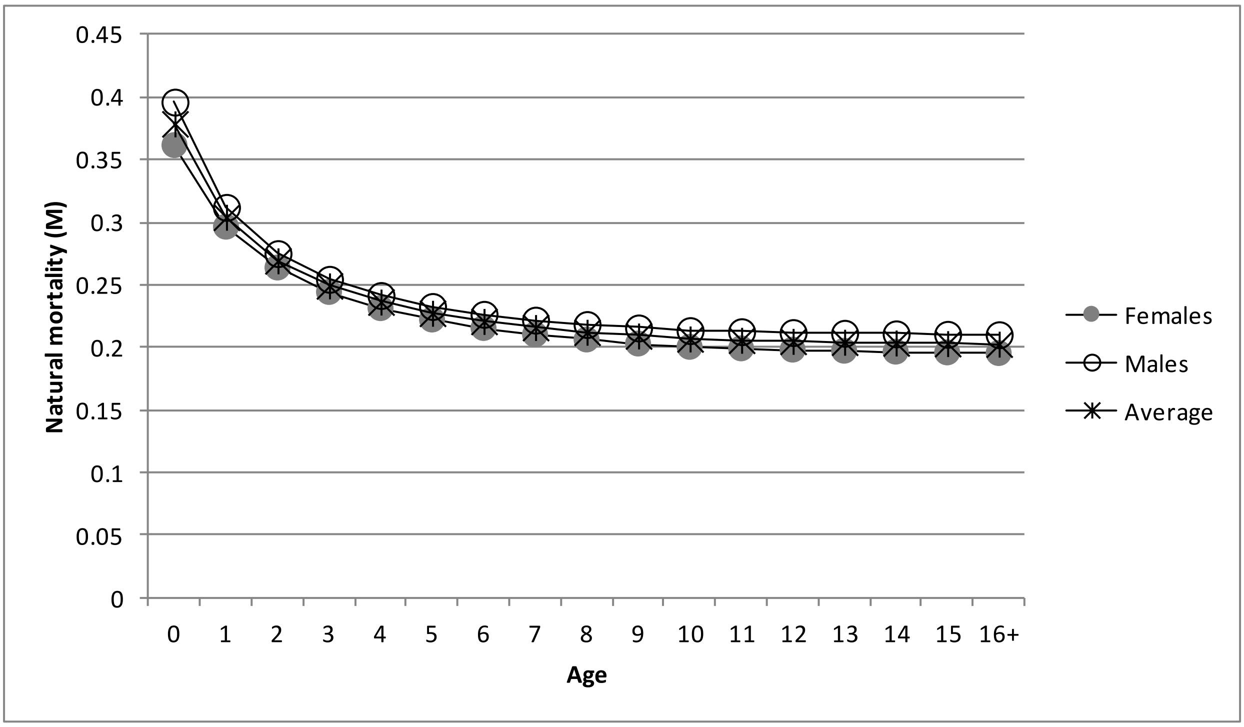


Figure 6. Combined sex natural mortality at age for use in preliminary SS3 model runs was computed as the average natural mortality at age of males and females obtained from life history invariant methods as described above (**Table 8**). References can be found in Anon. (2014) as identified in **Table 5**, and in document SCRS/2015/142 (Cortés In prep.).

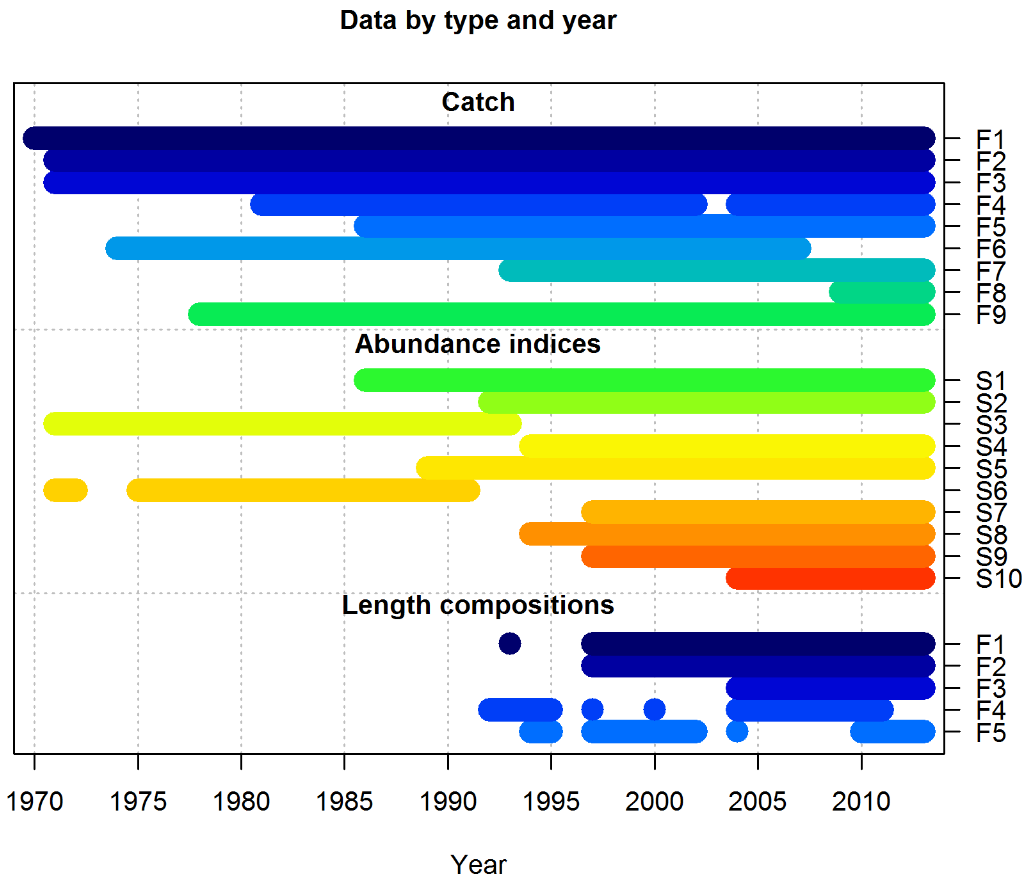


Figure 7. Final time series of catch, abundance, and length composition data considered for use in the preliminary SS3 model runs.

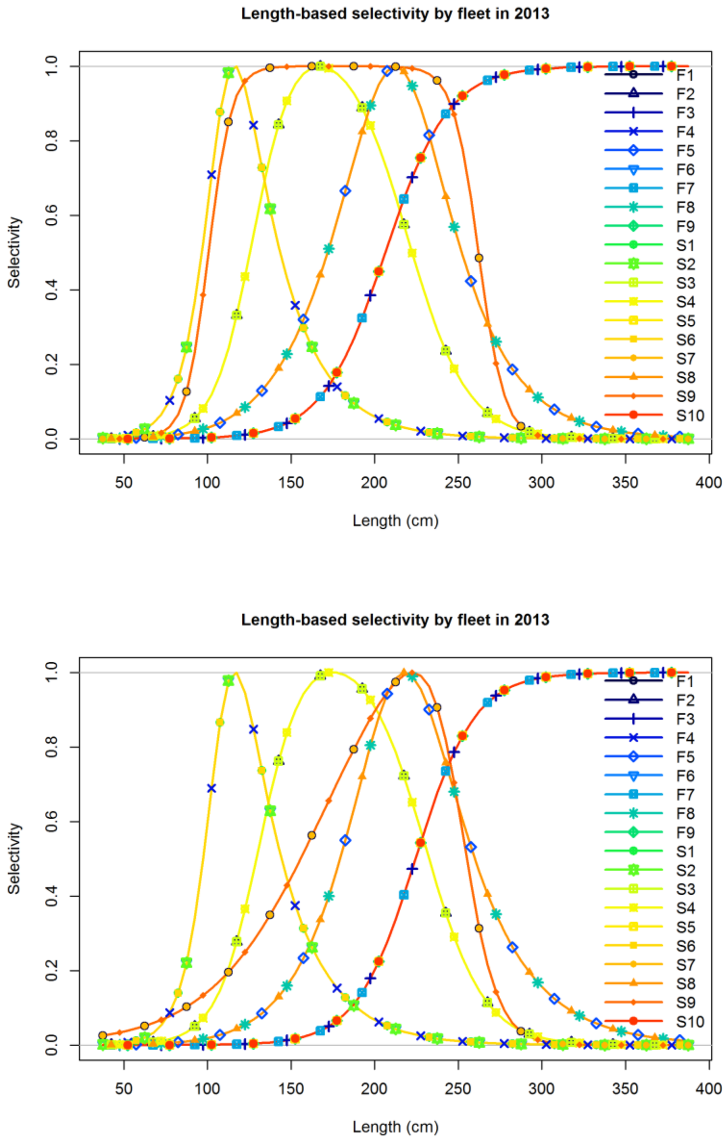
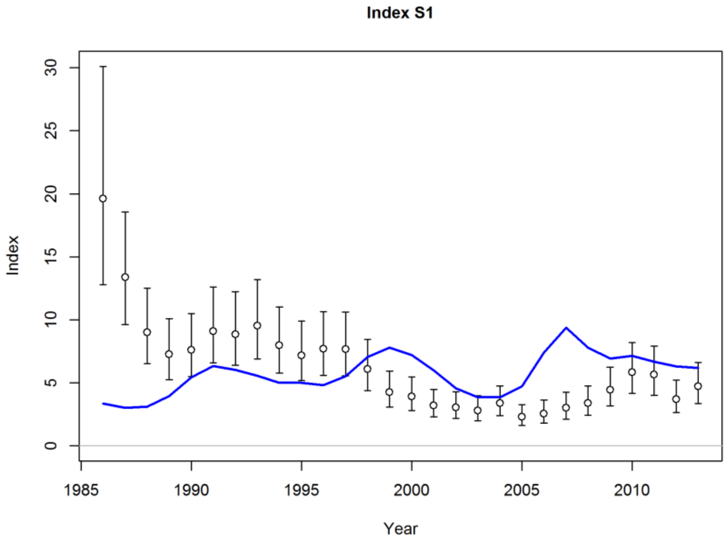


Figure 8. Selectivity at length (cm FL) obtained for Preliminary Run 4 (upper panel) and Preliminary Run 6 (lower panel).



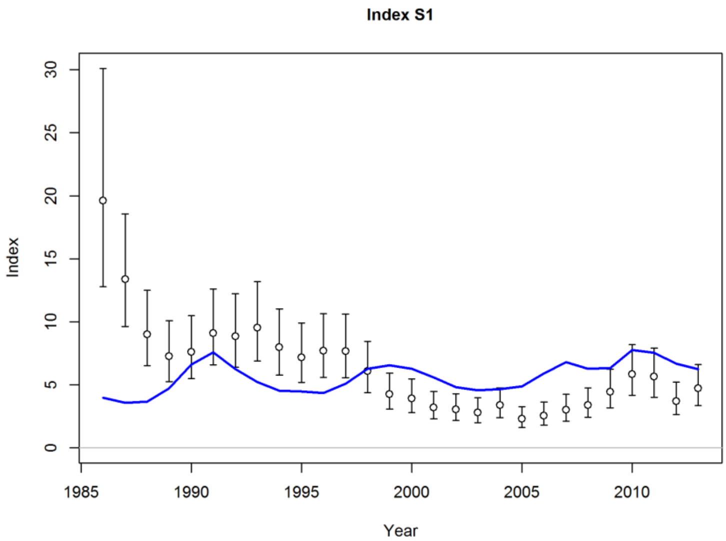


Figure 9. Index S1 (US-Log) predicted (blue line) and observed (open circles with 95% confidence intervals assuming lognormal error) standardized index of relative abundance for Preliminary Run 4 (upper panel) and Preliminary Run 6 (lower panel). Note that index S1 (US-Log) was only included in the model for exploratory purposes, was not fit in the model likelihood (lambda = 0), and had no influence on model results or predicted values.

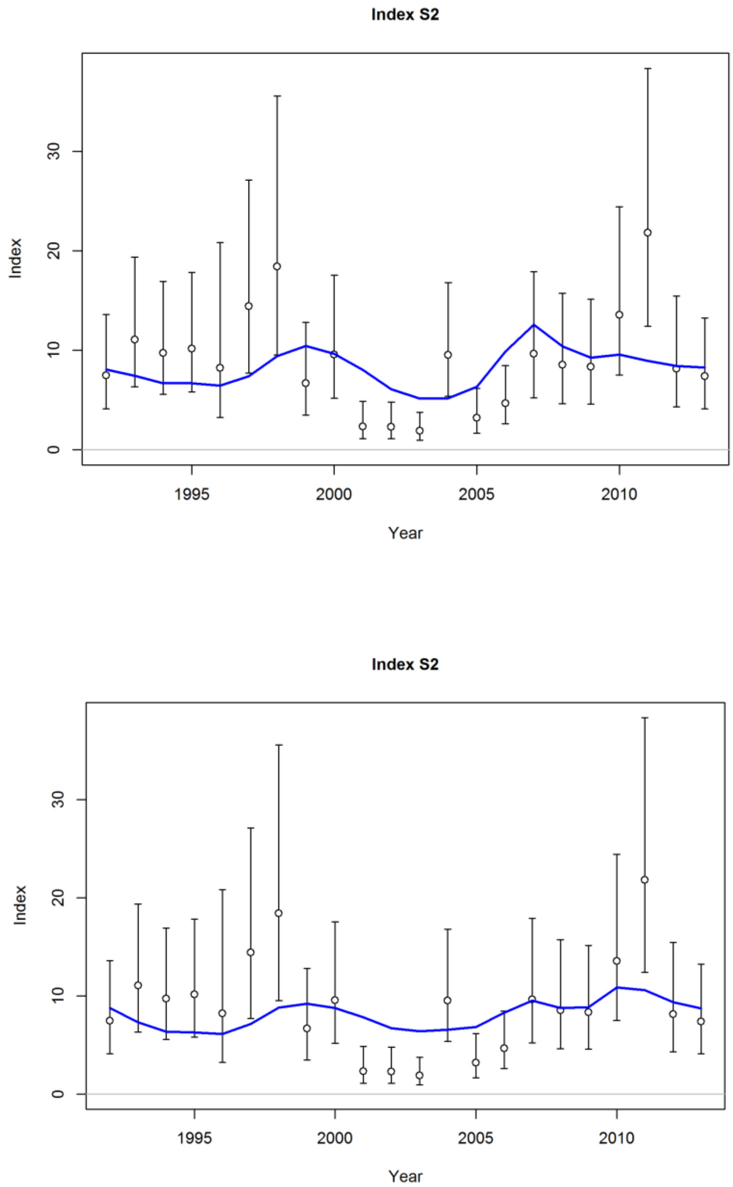


Figure 10. Index S2 (US-Obs) predicted (blue line) and observed (open circles with 95% confidence intervals assuming lognormal error) standardized index of relative abundance for Preliminary Run 4 (upper panel) and Preliminary Run 6 (lower panel).

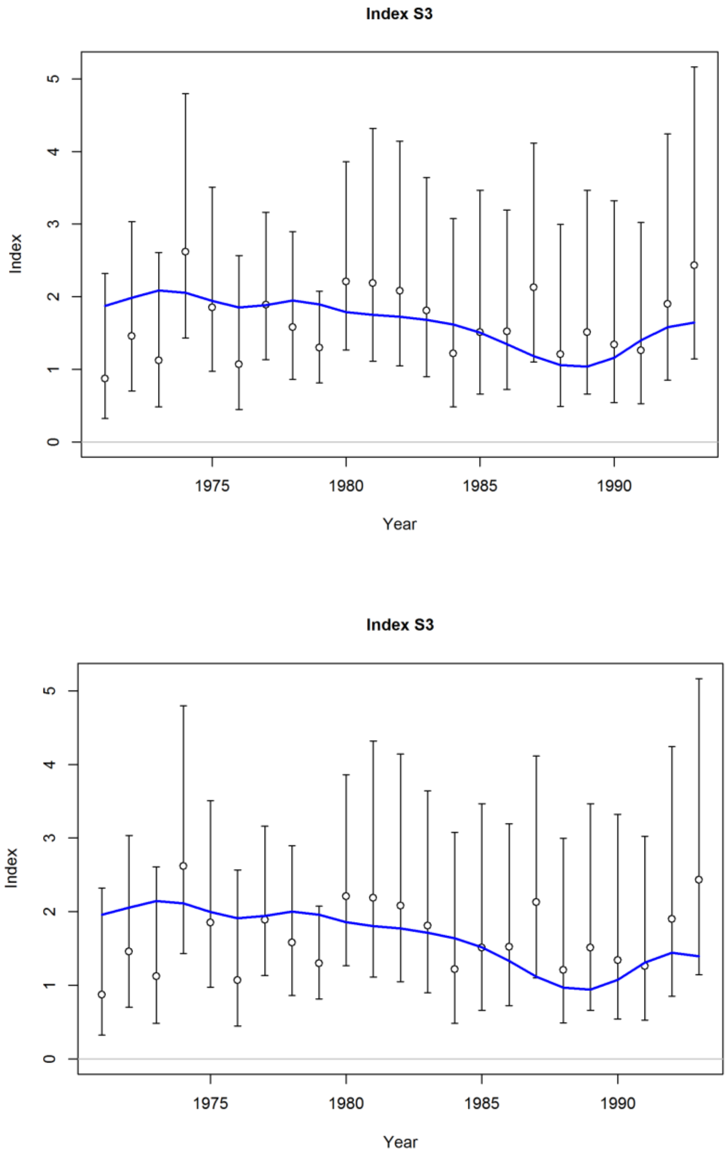


Figure 11. Index S3 (JPLL-N-e) predicted (blue line) and observed (open circles with 95% confidence intervals assuming lognormal error) standardized index of relative abundance for Preliminary Run 4 (upper panel) and Preliminary Run 6 (lower panel).

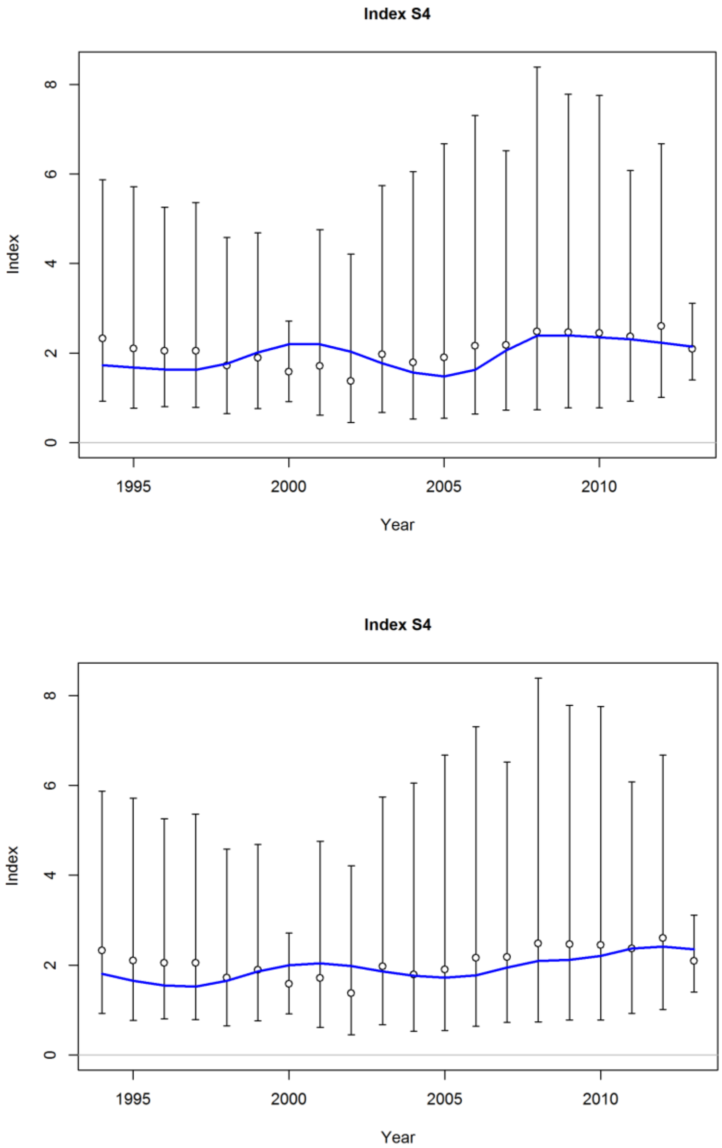


Figure 12. Index S4 (JPLL-N-l) predicted (blue line) and observed (open circles with 95% confidence intervals assuming lognormal error) standardized index of relative abundance for Preliminary Run 4 (upper panel) and Preliminary Run 6 (lower panel).

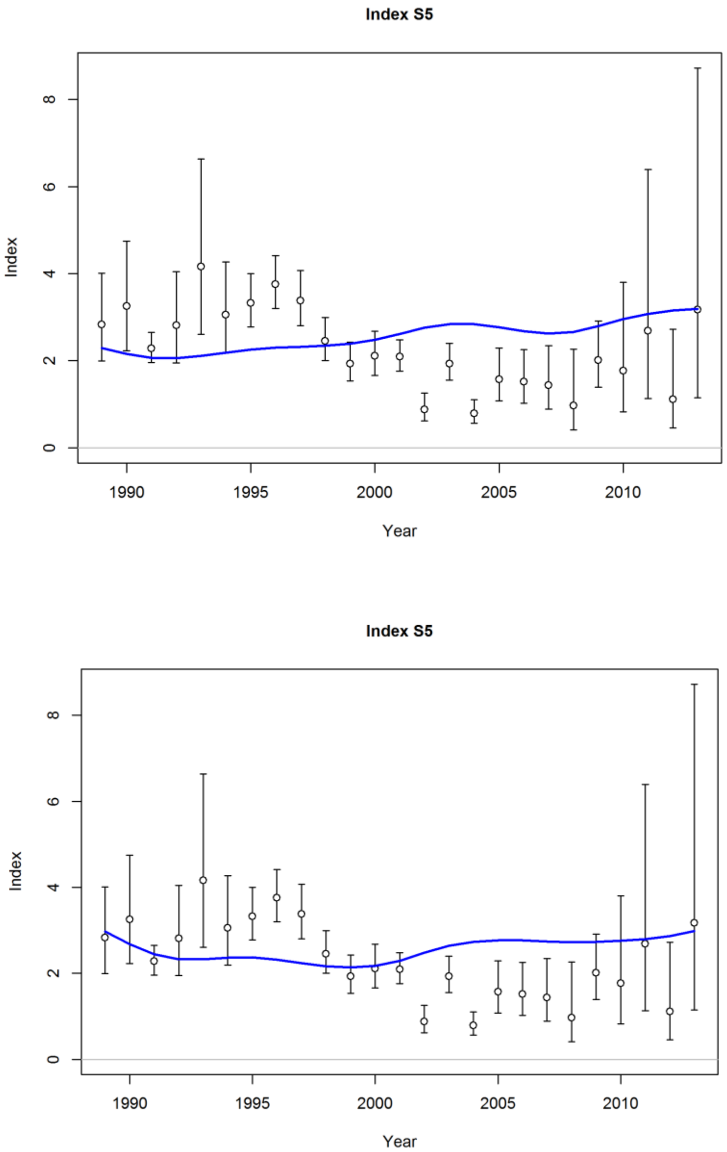


Figure 13. Index S5 (IRL-Rec) predicted (blue line) and observed (open circles with 95% confidence intervals assuming lognormal error) standardized index of relative abundance for Preliminary Run 4 (upper panel) and Preliminary Run 6 (lower panel). Note that index S5 (IRL-Rec) was only included in the model for exploratory purposes, was not fit in the model likelihood (lambda = 0), and had no influence on model results or predicted values.

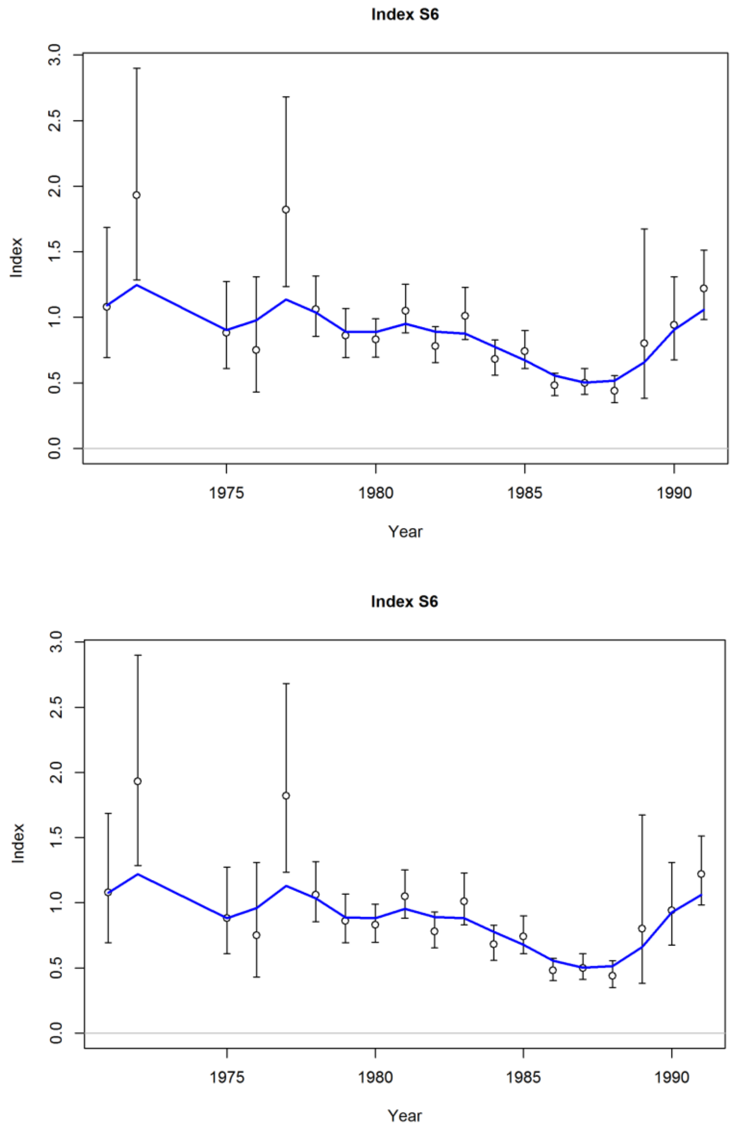


Figure 14. Index S6 (US-Obs-cru) predicted (blue line) and observed (open circles with 95% confidence intervals assuming lognormal error) standardized index of relative abundance for Preliminary Run 4 (upper panel) and Preliminary Run 6 (lower panel). Index S6 (US-Obs_cru) overlapped with S2 (US-Obs) during the years 1992 – 2000, and data from those years from S6 were excluded.

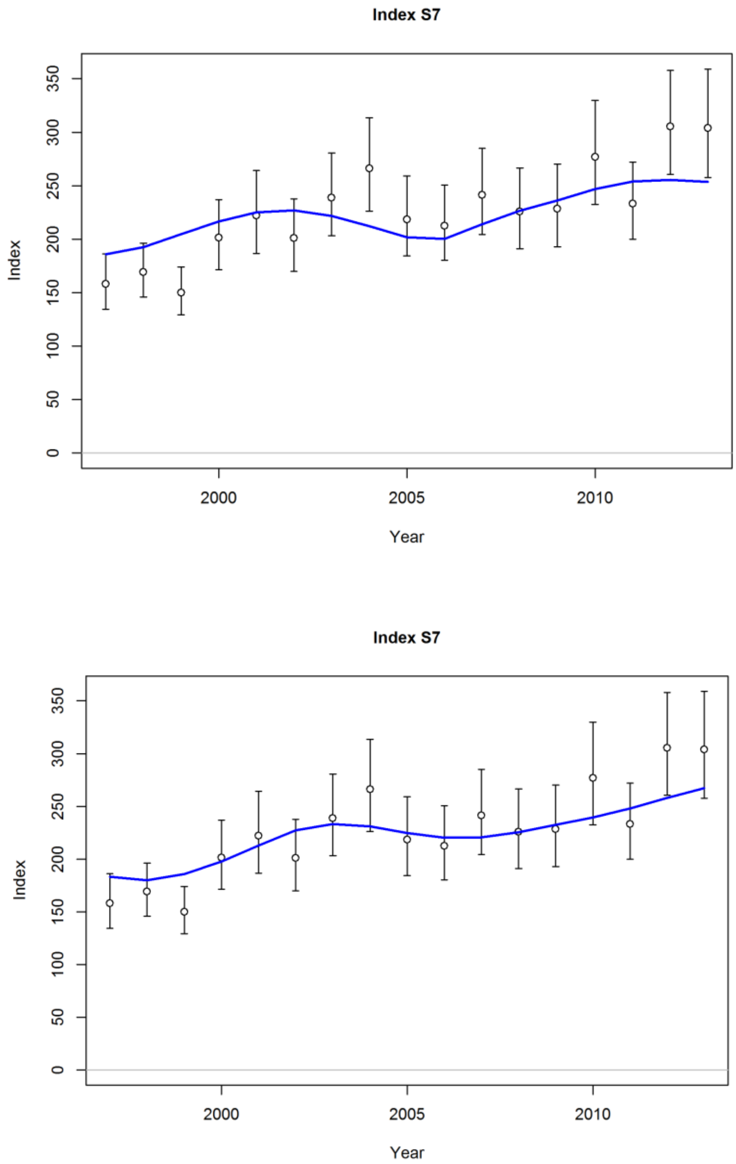


Figure 15. Index S7 (POR-LL) predicted (blue line) and observed (open circles with 95% confidence intervals assuming lognormal error) standardized index of relative abundance for Preliminary Run 4 (upper panel) and Preliminary Run 6 (lower panel).

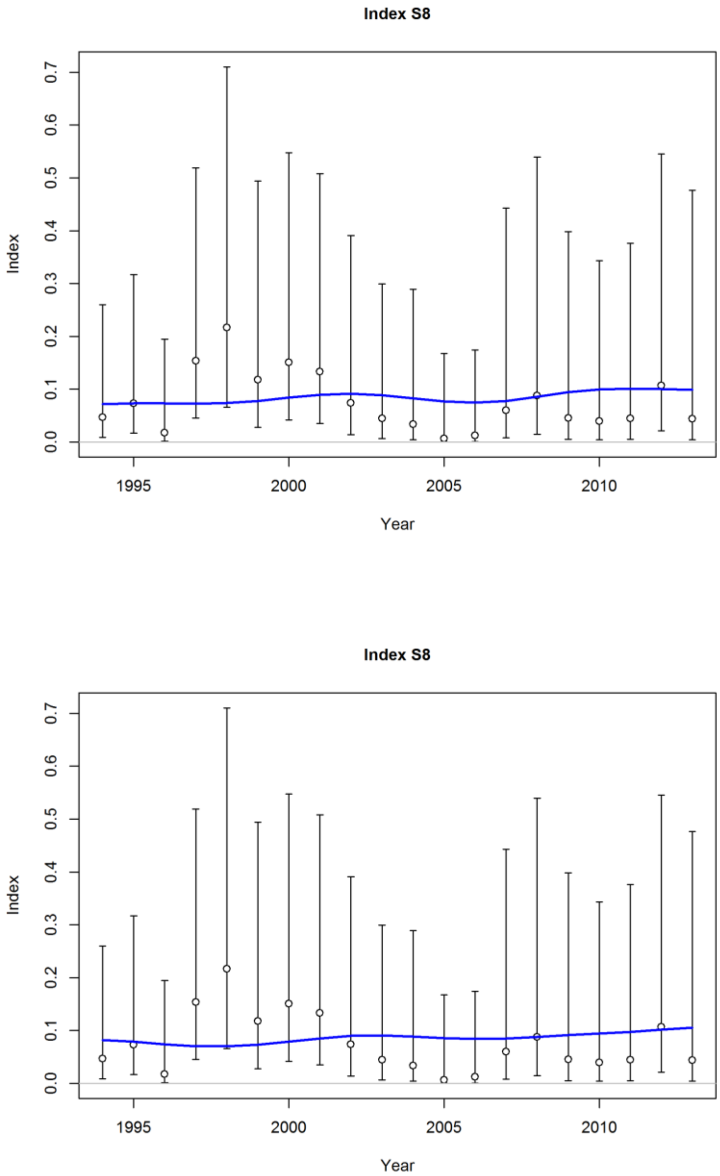


Figure 16. Index S8 (VEN-LL) predicted (blue line) and observed (open circles with 95% confidence intervals assuming lognormal error) standardized index of relative abundance for Preliminary Run 4 (upper panel) and Preliminary Run 6 (lower panel).

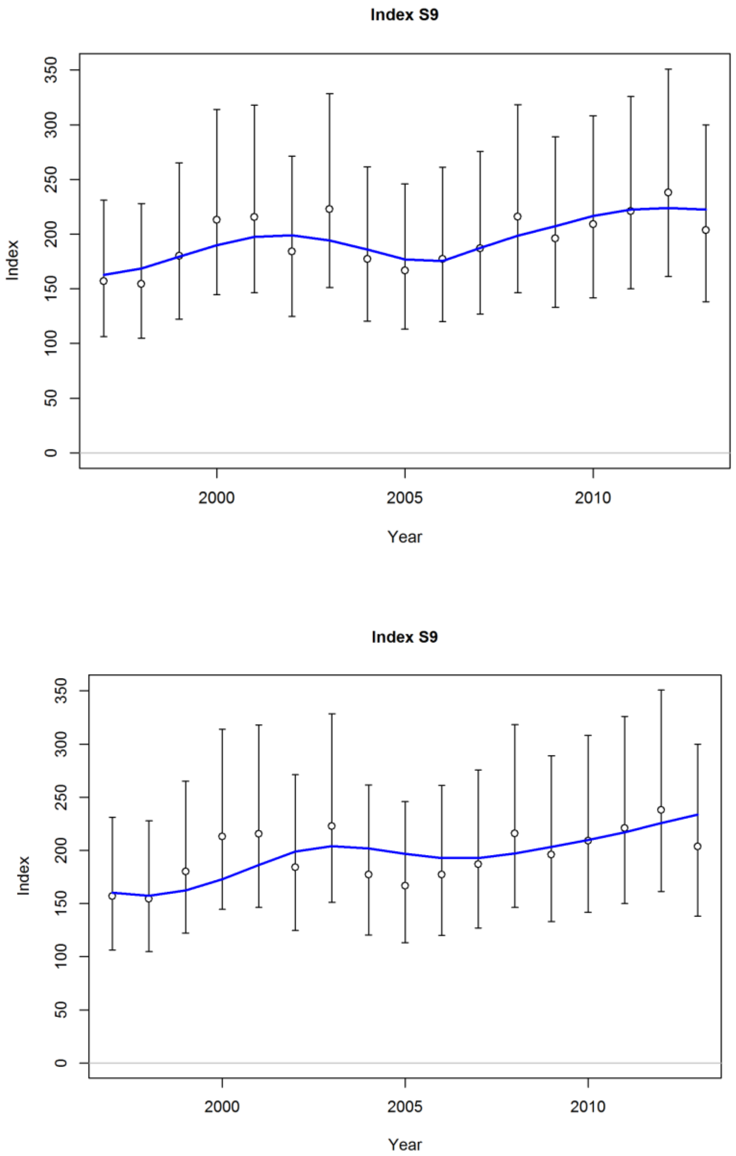
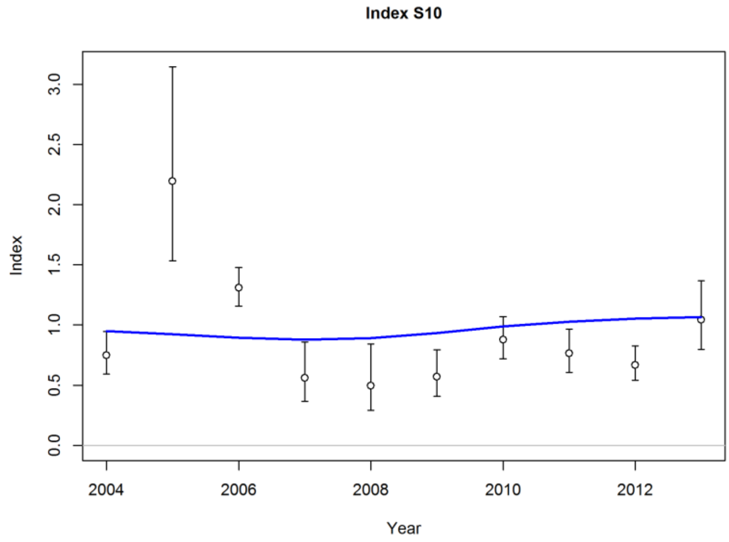


Figure 17. Index S9 (ESP-LL-N) predicted (blue line) and observed (open circles with 95% confidence intervals assuming lognormal error) standardized index of relative abundance for Preliminary Run 4 (upper panel) and Preliminary Run 6 (lower panel).



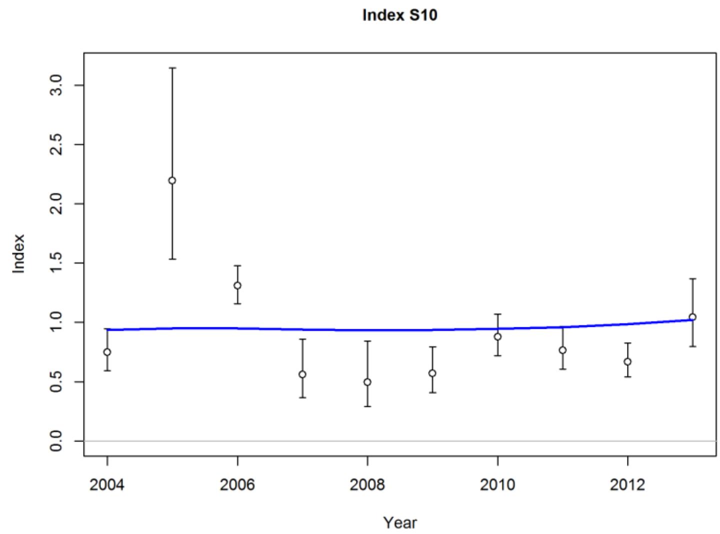


Figure 18. Index S10 (CTP-LL-N) predicted (blue line) and observed (open circles with 95% confidence intervals assuming lognormal error) standardized index of relative abundance for Preliminary Run 4 (upper panel) and Preliminary Run 6 (lower panel).

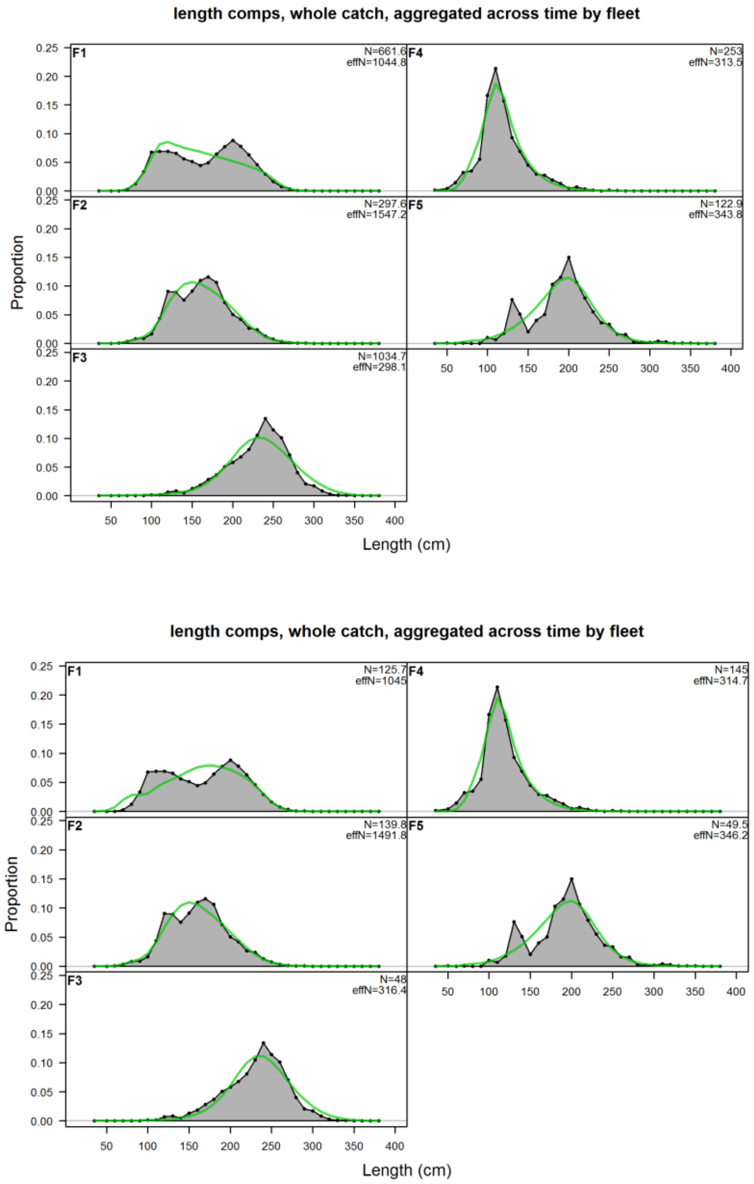


Figure 19. Model predicted (line) and observed (shaded) aggregated annual length compositions (female + male) for Preliminary Run 4 (upper panel) and Preliminary Run 6 (lower panel).

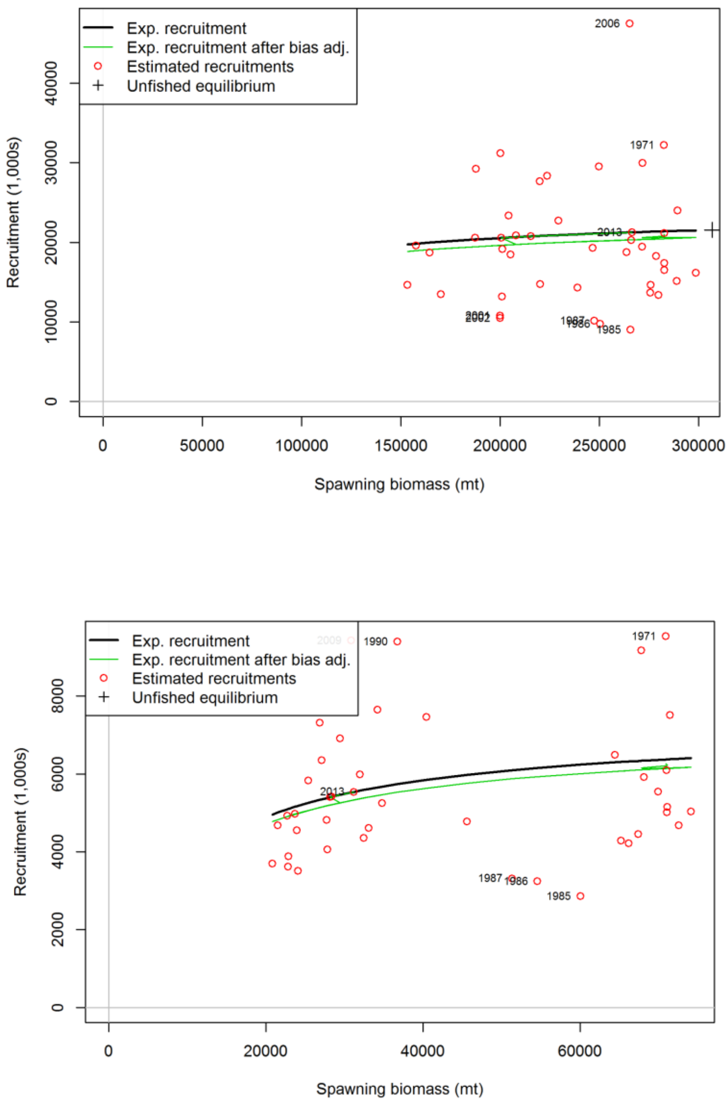


Figure 20. Expected recruitment from the stock-recruitment relationship (black line), expected recruitment after implementing the bias adjustment correction (green line), estimated annual recruitments (circles), unfished equilibrium (plus), and first (1971) and last (2013) years along with years with log deviations > 0.5 for Preliminary Run 4 (upper panel) and Preliminary Run 6 (lower panel). Note the different scales on the Y-axis (number of recruits in 1,000s) and X-axes (spawning biomass in metric tons-mt).

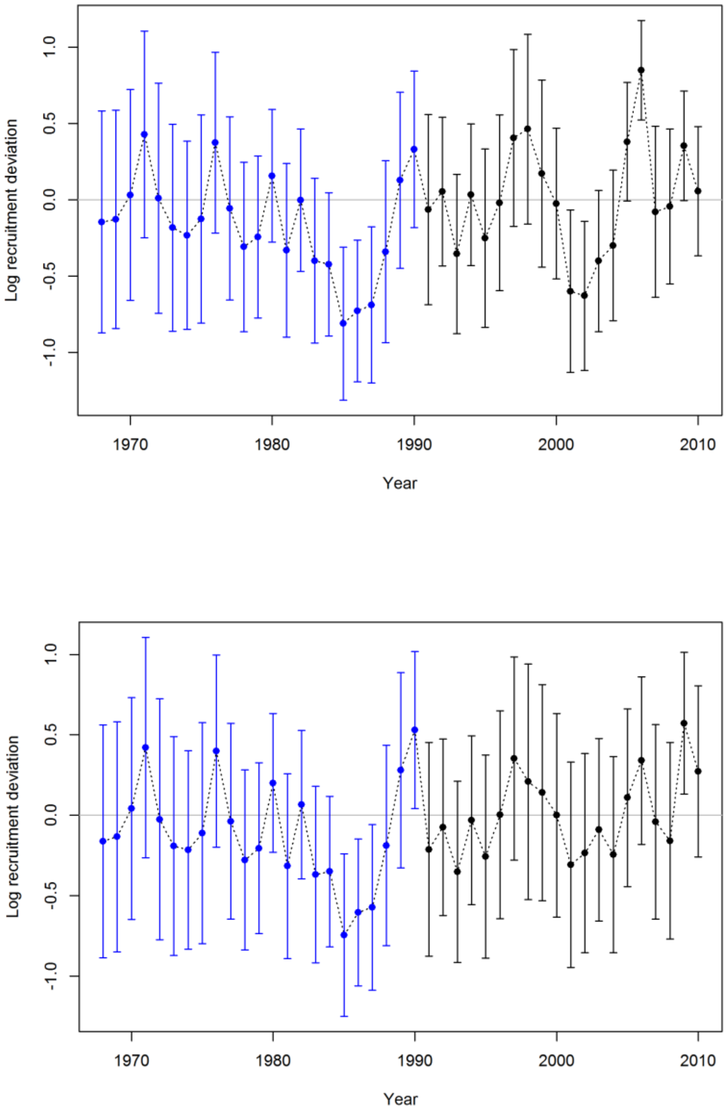
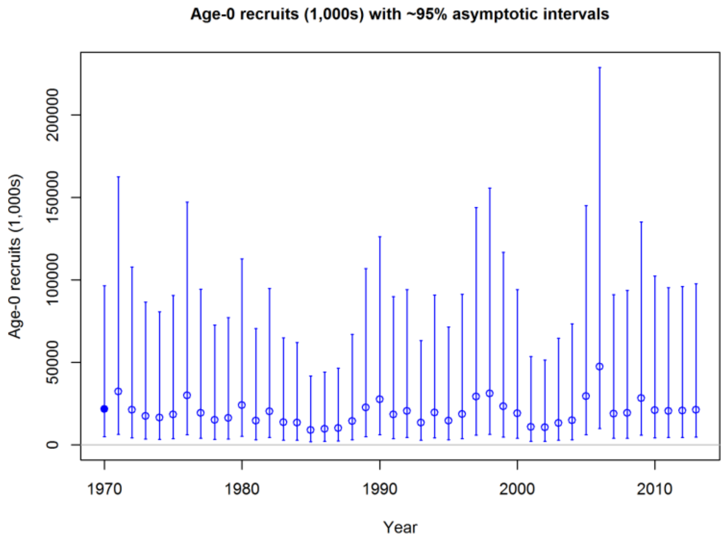


Figure 21. Estimated log recruitment deviations for the early (1968 – 1990, blue) and main (1991 – 2010, black) recruitment periods with associated 95% asymptotic intervals for Preliminary Run 4 (upper panel) and Preliminary Run 6 (lower panel).



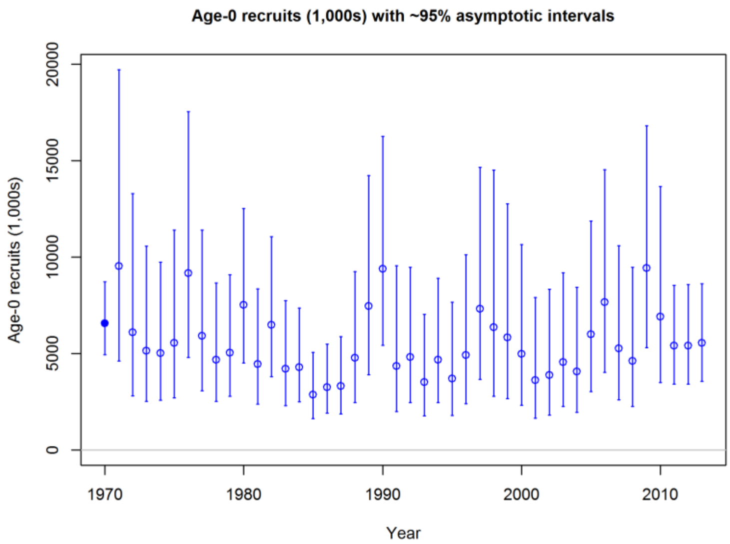


Figure 22. Estimated annual age-0 recruitment (circles) with approximate asymptotic 95% confidence intervals for Preliminary Run 4 (upper panel) and Preliminary Run 6 (lower panel). Note the different scale on the Y-axis.

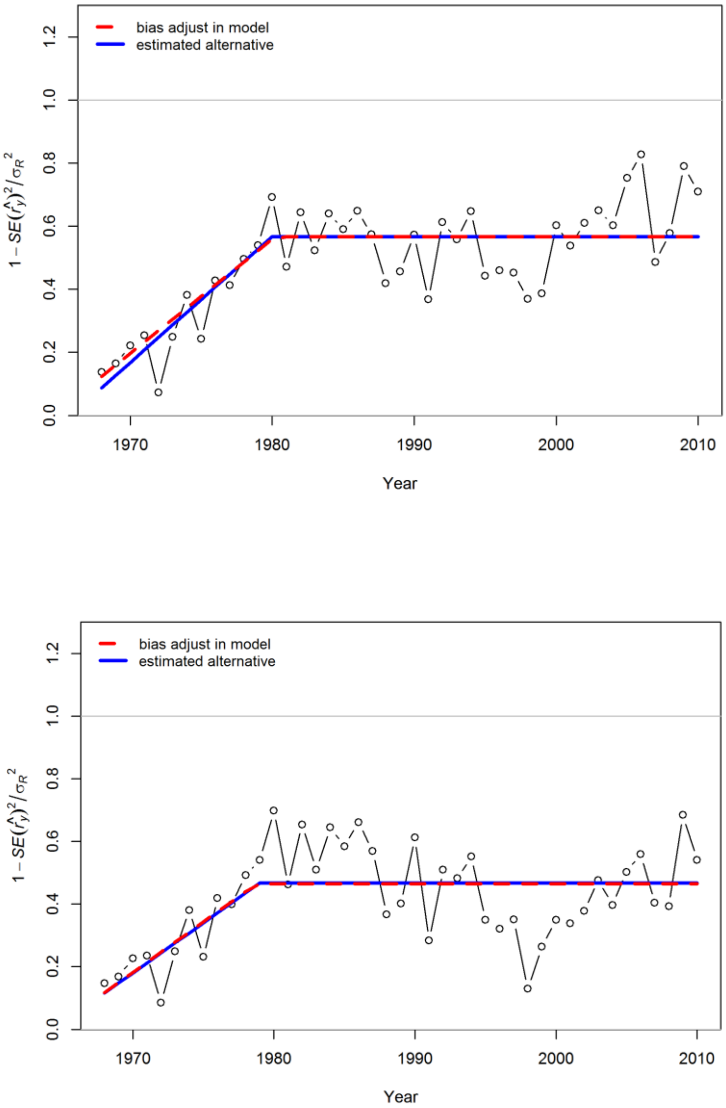


Figure 23. Bias adjustment applied to the stock-recruitment relationship for Preliminary Run 4 (upper panel) and Preliminary Run 6 (lower panel).

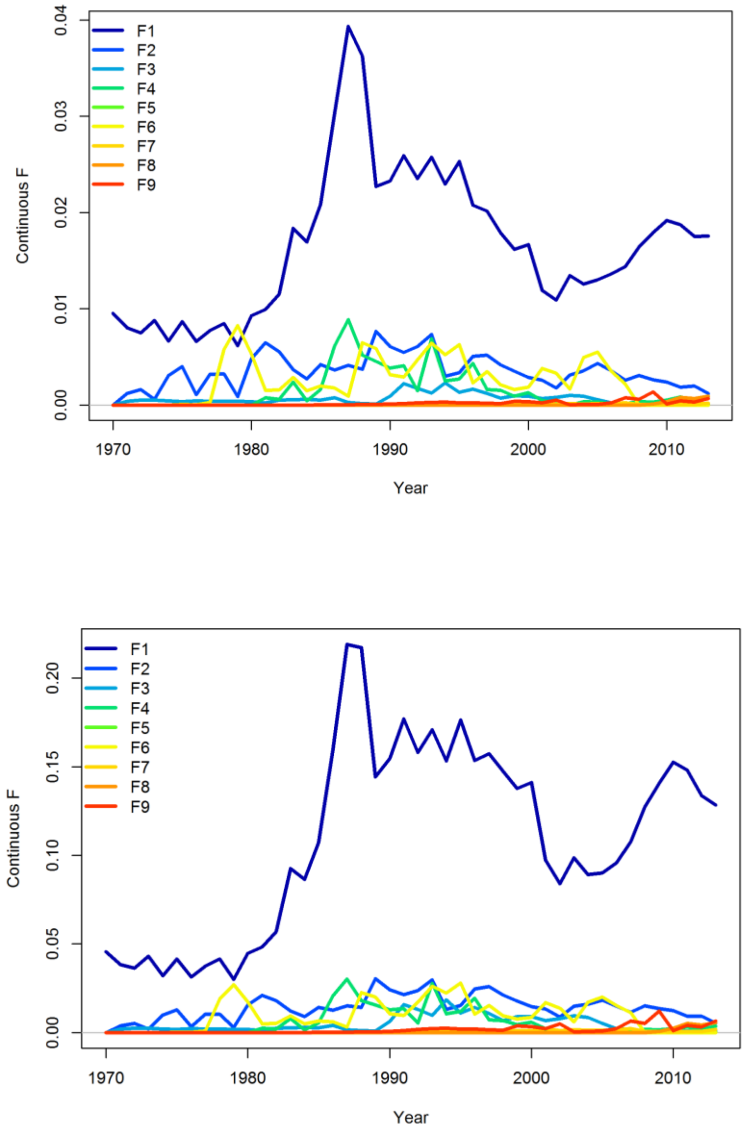


Figure 24. Estimated instantaneous fishing mortality rates (Continuous F) for each fleet (F1 – F9) obtained from Stock Synthesis output for Preliminary Run 4 (upper panel) and Preliminary Run 6 (lower panel).

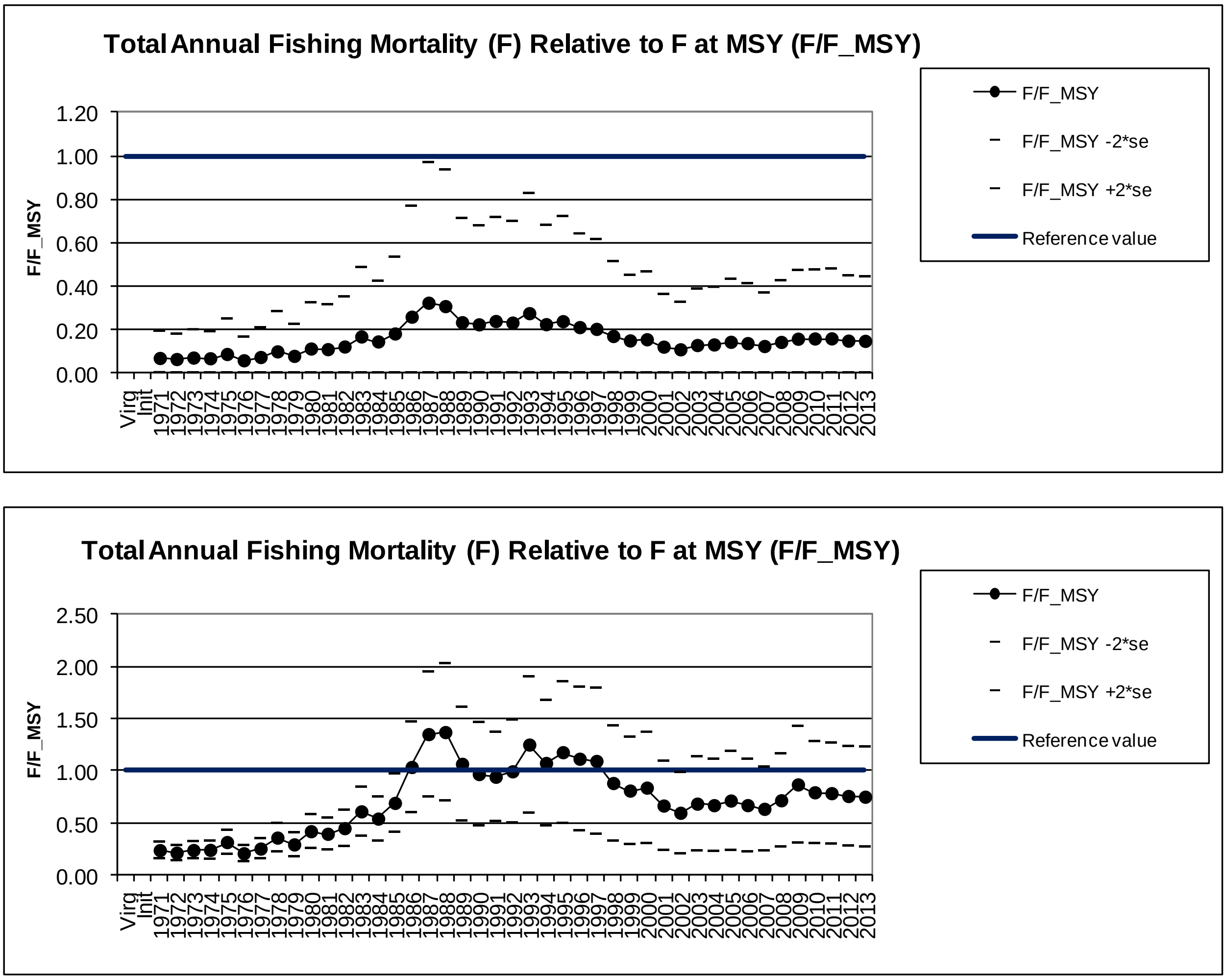


Figure 25. Estimated total annual fishing mortality for all fleets combined, estimated as the total exploitation rate in numbers relative to total annual fishing mortality at MSY (F/F_MSY), obtained from Stock Synthesis output for Preliminary Run 4 (upper panel) and Preliminary Run 6 (lower panel).

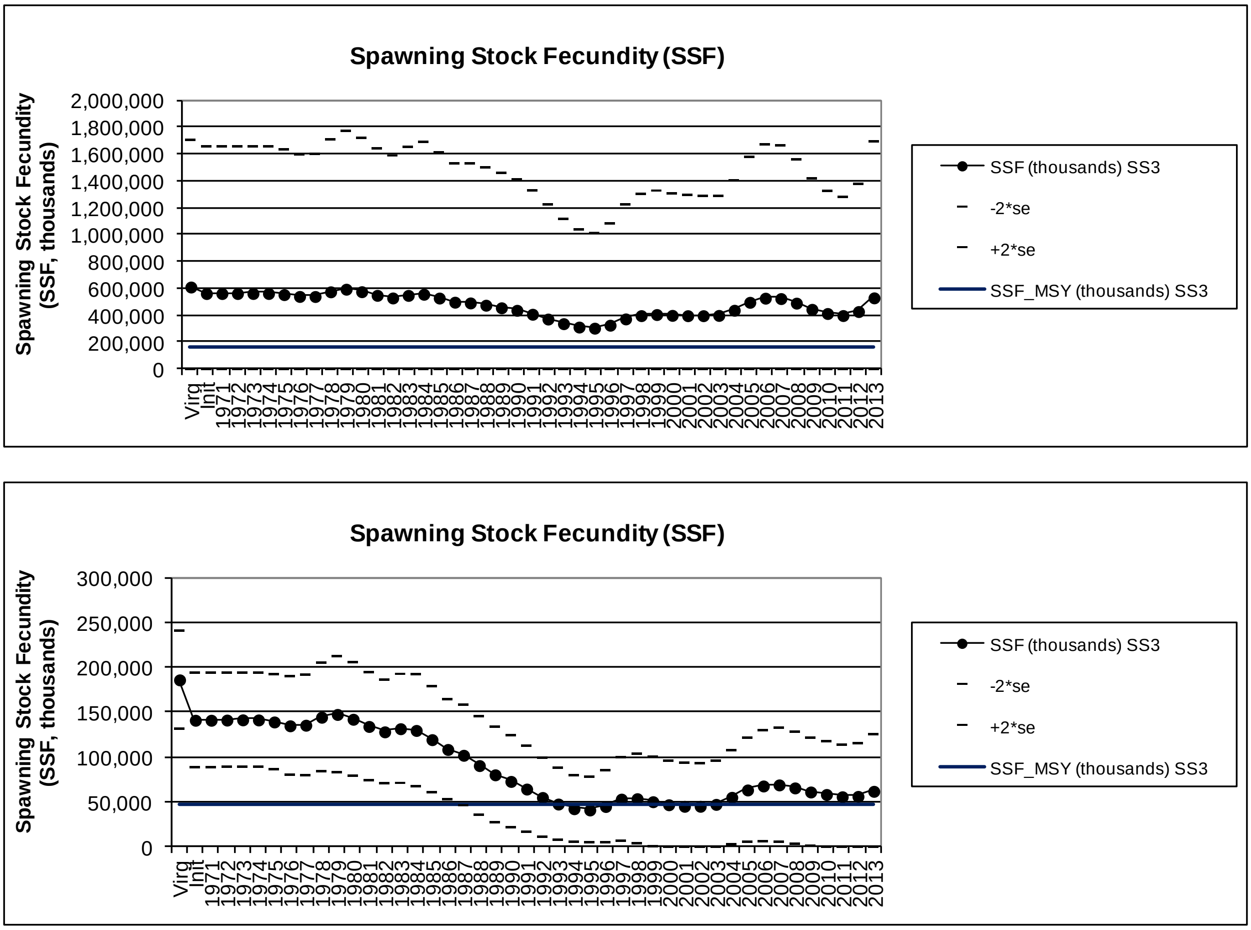


Figure 26. Estimated **s**pawning stock size (spawning stock fecundity, SSF) along with approximate 95% asymptotic standard errors (+- 2*s.e.) relative to spawning stock size at MSY (SSF_MSY) for Preliminary Run 4 (upper panel) and Preliminary Run 6 (lower panel).