PRELIMINARY WESTERN ATLANTIC SKIPJACK TUNA STOCK ASSESSMENT 1952-2020 USING STOCK SYNTHESIS

L. G. Cardoso[1], E. Kikuchi[1], R. Sant'Ana[2], M. Lauretta[3], A. Kimoto[4], B. Leite Mourato[5]

SUMMARY

This document describes the provisional and the final version of the stock assessment model using Stock Synthesis (SS) for the western Atlantic skipjack. The model runs from 1952 to 2020 and was fit to length composition data, 5 indices and 5 fishing fleets. Growth was fixed in the model, with three alternative growth scenarios considered based on a comprehensive meta-analysis of skipjack growth studies and recommendations from the stock assessment team. The associated natural mortality-at-age vectors were tested, along with three alternative values of growth quantiles to construct the model uncertainty grid. However, initial runs showed poor performance, an alternative parameterization within SS was applied using a Lorenzen function with the same assumed asymptotic natural mortality-at-age for each growth curve scenario. Model diagnostics demonstrated fast and stable convergence, acceptable retrospectives, informed estimation of population absolute scale (R0), and a robust solution across different starting values. A comprehensive set of model diagnostics are presented for the provisional and final reference case, as well as the model estimates of SSB, recruitment, SSB/SSBmsy and F/Fmsy across the entire uncertainty grid.

RÉSUMÉ

Le présent document décrit la version provisoire et la version finale du modèle d'évaluation des stocks utilisant Stock Synthesis (SS) pour le listao de l'Atlantique Ouest. Le modèle couvre la période allant de 1952 à 2020 et a été ajusté aux données de composition par taille, à 5 indices et à 5 flottilles de pêche. La croissance a été fixée dans le modèle, avec trois scénarios de croissance alternatifs considérés sur la base d'une méta-analyse complète des études de croissance du listao et des recommandations de l'équipe d'évaluation du stock. Les vecteurs de mortalité naturelle par âge associés ont été testés, ainsi que trois valeurs alternatives de quantiles de croissance pour construire la grille d'incertitude du modèle. Cependant, les premiers scénarios ont montré de mauvais résultats, une paramétrisation alternative au sein de SS a été appliquée en utilisant une fonction de Lorenzen avec la même mortalité naturelle asymptotique postulée par âge pour chaque scénario de courbe de croissance. Les diagnostics du modèle ont démontré une convergence rapide et stable, des schémas rétrospectifs acceptables, une estimation informée de l'échelle absolue de la population (R0) et une solution solide pour différentes valeurs de départ. Un ensemble complet de diagnostics du modèle est présenté pour le cas de référence provisoire et final, ainsi que les estimations du modèle de la SSB, du recrutement, de la SSB/SSB_{PME} et de F/F_{PME} dans toute la grille d'incertitude.

RESUMEN

Este documento describe la versión provisional y la versión final del modelo de evaluación de stock utilizando Stock Synthesis (SS) para el listado del Atlántico occidental. Los ensayos de modelo abarcan desde 1952 hasta 2020 y el modelo se ajustó a los datos de composición por tallas, cinco índices y cinco flotas pesqueras. El crecimiento se fijó en el modelo, con tres escenarios alternativos de crecimiento considerados sobre la base de un meta-análisis exhaustivo de los estudios de crecimiento del listado y las recomendaciones del equipo de

[1] FURG - Universidade Federal do Rio Grande, Rio Grande, BR
[2] UNIVALI - Universidade do Vale do Itajaí, Itajaí, BR
[3] NOAA - National Marine Fisheries Service, USA
[4] ICCAT Secretariat – International Commission for the Conservation of Atlantic Tunas, SP
[5] UNIFESP - Universidade Federal de São Paulo, Santos, SP, Brasil

evaluación de stock. Se probaron los vectores de mortalidad natural a la edad asociados, junto con tres valores alternativos de cuantiles de crecimiento para construir la cuadrícula de incertidumbre del modelo. Sin embargo, los ensayos iniciales mostraron un desempeño pobre, se aplicó una parametrización alternativa dentro de SS utilizando una función de Lorenzen con la misma mortalidad natural asintótica asumida a la edad para cada escenario de curva de crecimiento. Los diagnósticos del modelo demostraron una convergencia rápida y estable, retrospectivas aceptables, una estimación informada de la escala absoluta de la población (R0) y una solución robusta en los diferentes valores de partida. Se presenta un conjunto completo de diagnósticos del modelo para el caso de referencia provisional y final, así como las estimaciones del modelo de SSB, reclutamiento, SSB/SSB_{RMS} y F/F_{RMS} en toda la matriz de incertidumbre.

KEYWORDS

Stock assessment, Western Atlantic, skipjack tuna

INTRODUCTION

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

The Standing Committee on Research and Statistics (SCRS) of the International Commission for the Conservation of Atlantic Tunas (ICCAT) has historically considered the existence of two distinct stocks of skipjack tuna (*Katsuwonus pelamis*, SKJ) in the Atlantic Ocean (eastern and western). The western stock occurs from the US coast to the southern Brazilian coast. It has been mainly caught by the Brazilian and Venezuelan fleets, which together have accounted for 97% of the catches, on average, in the past ten years (2009-2018). Brazil has caught on average 90% (ranging from 82.6 to 94.4) of skipjack removals in the West Atlantic, and Venezuela 7% (4.5-10.5%). The last stock assessment for the western SKJ was conducted in 2014 using catch data available up to 2013 (Anon., 2015). The model based on catches and the non-equilibrium surplus biomass production model has estimated the MSY at 30,000 t - 32,000 t, and the fishing mortality vector is estimated by a method based on the development of the average size of individuals captured over time (mainly from Brazilian catches) shows a similar profile. According to the trajectory of B/B_{MSY} and F/F_{MSY} ratios, it was unlikely that the catch at the time of assessment was larger than the replacement yield.

This paper presents the provisional and final results of the Stock Synthesis analyses for the western skipjack tuna. The final results represent what was agreed upon by the stock assessment group in the 2022 Skipjack stock assessment meeting of ICCAT, which is presented in Appendix I. The model covered the period from 1952 to 2020 and includes size composition and indices from 5 fleets (**Figure 1**). At first, two model configurations were tested: Model 1: using the median associated growth parameters from the joint analysis considering all oceans and the respective M (natural mortality) at age vector recommended by the stock assessment team (Anon. 2022a) that was tasked by Tropical Tuna Species Group during the SKJ Data Preparatory Meeting in 2022 February (Anon. 2022b), with a fixed steepness value of 0.8 (central value of the uncertainty grid), and Model 2: using the median associated growth parameters but with the M vector estimated internally by the SS using a Lorenzen function and steepness of 0.8, and assuming the same reference M-at-age recommended (i.e. M at age 6 for each growth scenario) by the stock assessment team that was tasked for additional decisions by Tropical Tuna Species Group during the SKJ Data Preparatory Meeting (Anon. 2022b). After analyzing these two models and assessing diagnostics, it was decided that the Lorenzen scaling in SS was more appropriate, while retaining the M-at-age 6 values provided by the stock assessment team. Then ran each of the different model configurations considering the nine-model uncertainty grid for 3 sets of the growth parameters/M value and the three alternative steepness values (0.7, 0.8, 0.9) recommended by the stock assessment team (Anon. 2022a). Basic equations and technical specifications underlying Stock Synthesis can be found in Methot and Wetzel (2011). In these models, we use SS version 3.30.18.

MATHERIAL AND METHODS

Model Spatio/Temporal Structure

A one-area, combined sex, yearly structured model, was constructed for the Western Atlantic Skipjack. The fleet structure was designed as proposed by the stock assessment team (Anon. 2022a) (5 fleets and five indices) with a general spatial/temporal structure of fleets separated according to whether they occurred along the western Atlantic (**Table 1**). The functional assumption of the fleet selectivity curves (**Table 1**) was determined based on size composition distributions, and the selectivity parameters were freely estimated.

Temporal domain and initial conditions

The model starts in 1952 and runs to 2020. Conditions were assumed to be near-virgin in 1952 with one fleet (BB_West) operating in the initial period. An annual time step was considered for the model, with fishing assumed to occur throughout the year. Individual indices were adjusted to account for the timing within the year when the index occurred. A time block for the selectivity of the PS_West are imposed but no time block on catchability.

Biology

A combined-sex model was assumed, and spawning biomass was considered the summed mass of all mature fish. Recruitment was estimated as age 0 fish, and the model assumed a plus group age of 6. Size at 50% maturity was considered 42 cm (approx. 9.5 months old) and fully mature at 55 cm. Growth was modeled with a von Bertalanffy two parameters (L1 and L2) formulation and initially input as the central values of growth parameters obtained from studies from all oceans as proposed by the stock assessment team (Anon. 2022a, Table 5). Two natural mortality vectors were tested considering each growth quantile (**Table 2**), one using the Gaertner (2015) scaling (Anon. 2022a) and estimated internally by the SS using a Lorenzen scaling function. A large CV was set for the young (0.2) and old fish (0.2) was established due to the uncertainty within the growth parameters and to cover observations of larger fish. Fecundity was modeled as female stock spawning biomass (SSB) (i.e., weight-at-age multiplied by the maturity ogive), and proportional to length (eggs=a*Lb), with the overall western Atlantic length-weight relationship was used to convert the size to weight (7.48e-06* length^ 3.253).

Stock- recruitment relationship

A standard Beverton-Holt stock recruit relationship was assumed. The spawning biomass was considered equal to the mature population's biomass according to the maturity schedule outlined in the biology section. Parameters of the stock-recruitment relationship (steepness and sigmaR) were fixed at 0.8 and 0.3 for the reference case model. Equilibrium recruitment (R0) was estimated without a prior. Deviations from the stock-recruitment relationship were assumed to follow a lognormal distribution estimated on a log scale as N(0, sigmaR) variates with a min and max of -5 and 5, respectively. Zero recruitment deviations were assumed until the start of informative data on size structure (continuous length composition series from the main fleets), i.e., annual deviates were only estimated from 1980-to 2018.

Total catch (Task I)

The total catches were calculated by the ICCAT Secretariat (**Table 3**, **Figure 2**) for the fleets presented above. Catch in mass was used in the model for all fleets, and was assumed to be known essentially with a CV of 0.01.

Size frequency information

The ICCAT Secretariat provided size frequency data by fleet in the format of seasonal counts per size bin (**Figure 3**). Measurements were in cm straight fork length (SFL) and modeled with 2 cm length bins between 20 and 156 cm in the model. Length composition data were modeled assuming a multinomial distribution. The length compositions of the years previous from 2002 for the LL_OTH fleet were excluded from the analysis since they differed significantly from the most recent years, and considering that they are less representative due to the small participation of the LL_OTH fleet on the total landings, the expected effect on the model were considered negligible.

Catch per unit effort data

Indices were available for 4 of the 5 fleets (PS_West, BB_West, LL_USMX, LL_OTH, and HL_RR) (**Figure 4**). Two indices were available for the baitboat fleet, one from 1981 to 1999 (BRA_BB_hist and BB_West). The BRA_BB_hist index was set as a survey, and its selectivity mirrored the BB_West selectivity. CPUE indices were assumed to have a lognormal error structure. No time-blocks on indices were modeled as indices that required splits were input as separate indices.

Selectivity

Selectivity was parameterized as length-based for all fleets, with the selectivity parameters being freely estimated by the model (**Table 1**). It was assumed to a dome-shaped for the fleets PS_West, BB_West, and HL_RR and an asymptotic shape for the LL_USMX and LL_OTH as proposed by the stock assessment team (Anon. 2022a).

Model Diagnostics

Model convergence was assessed using the Carvalho *et al.* (2021) flow chart. The first diagnostic was whether the Hessian (i.e., the matrix of second derivatives of the likelihood concerning the parameters) inverts. The second measure observed the joint residuals plot and ensured that they were randomly distributed. The third measure was the retrospective analyses conducted on Model 2 with five-year retrospective peels. The fourth measure analyzed the model prediction skills by completing a model-based hindcasting. The fifth diagnostic was a jitter analysis of parameter starting values to evaluate whether the model has converged to a global solution rather than a local minimum. Starting values of all estimated parameters were randomly perturbed by 10%, and 50 trials were run.

Other diagnostics included likelihood profiling of critical parameters (steepness, sigmaR, Equilibrium recruitment (R0), Linf, and M at age 6). Likelihood profiles elucidate conflicting information among various data sources, determine asymmetry around the likelihood surface surrounding point estimates and evaluate the precision of parameter estimation.

Uncertainty Grid Analysis

The uncertainty grid comprised 9 models with all combinations of fixed alternative assumptions for growth parameters and the resulting M at age vectors for three steepness (h = 0.7, 0.8 and 0.9) values. These alternative runs of the uncertainty grid are listed in **Table 4**.

RESULTS AND DISCUSSION

Model diagnostics

Overall, the models showed relatively good diagnostic performance, showing good convergence properties. Model 1, considering the central values for growth studies from all and the resulting M vector calculated from the Gaertner (2015) scaling, presented a good fit to the length compositions as well to the index of all the fleets. However, the M for the age 0 was too high, and the model interpreted that just a few individuals survived to the ages one and on (**Table 2**, **Figure 5**). Using the same model configuration of the Model 1 but changing the growth parameters for the quantiles 0.25 and 0.75 and the respective M vectors still resulted in unrealistic numbers at age and length (**Figure 5**). With the growth parameters quantile 0.75 the model estimated that some individuals survived to the older ages, but few individuals survived to the larger lengths between 40 and 80 cm, which is not supported by the observations from the catches **(Figure 5**). These results were interpreted as being biologically unrealistic.

Model 2, using the internally estimated M vector considering the 0.5 quantile of the growth parameters with the Lorenzen scaling, also presented a good fit to the length compositions as well to the index of all the fleets (**Figure 6**). The M vector showed lower values for the first ages, and the model let some individuals survive to older ages resulting in reasonable and time-dynamic estimated of numbers at ages (**Table 2**, **Figure 7**).

The final gradient of Model 2 was notably small (0.00000786), and the Hessian matrix for the parameter estimates was positive definite. The models run relatively fast (~35 seconds) and show good convergence properties. Therefore the authors considered Model 2 as the provisional reference case for the W-SKJ SS model, and a comprehensive set of model diagnostics are presented for the reference case, as well as the model estimates of SSB and recruitment across the entire uncertainty grid.

The joint residual plots for the reference case (Model 2) showed a random pattern for the residuals of the fits to the index for all fleets with some outliers for the HL_RR and LL_USMX fleets (>1 or < -1) but without a significant impact on the overall pattern (**Figure 8**). The residuals of the length composition fits also showed a random pattern for all fleets with no evident outliers (**Figure 8**).

The retrospective performance of the reference set (Model 2) is overall good (**Figure 9**), all falling within the confidence intervals of the different runs. The scale of SSB and recruitments increased as the analysis removed -4 and -5 years but without changing the overall pattern. The scale of F/F_{MSY} decreased as -4 and -5 years were removed, but also without changing the overall pattern. Retrospective fits of the indices were overall good (**Figure 10**), except for the fits to the years between 2013 and 2017 for the BB_West index that fits higher values than the observed ones. The overall fits to the indices change very little retrospectively.

When analyzing the reference case (Model 2) prediction skills, all five fitted CPUE indices and length compositions included at least one observation that fell within the hindcast evaluation period 2015–2019 (**Figure 11**). However, the MASE scores > 1 for the index of the two main fleets indicate that they have lower prediction skills than the length compositions of all fleets, except for LL_USMX, which presented MASE scores <1, i.e., BB_West, HL_RR, and LL_OTH (**Figure 11**).

The model shows high stability in the log-likelihood with different starting values (**Figure 12**). All 50 jitter model runs converged, with 45 model runs at the total negative likelihood estimate value of the base case model run (349 likelihood units), and 5 model runs had larger total negative likelihood values (**Figure 12**). The jittered model was robust to the initial values of the parameters and gave no evidence that the base case model converged to a local minimum of the objective function instead of the global minimum.

Model results

Estimated selectivities at length generally reflected assumed patterns of the fisheries (**Figure 13**, **Table 5**). The doming of the PS_West, BB_West, and BRA_BB_hist is pretty steep but seems determined by the fact that the longline fleets (LL_USMX and LL_OTH) have asymptotic selectivity and capture much larger fish. This steep dome-shaped selectivity follows the size composition observed from these fleets (Cardoso *et al.*, 2022). The selectivity for the HL_RR fleet also follows the observed size composition since fishes above 80 cm can be observed in its catches.

The estimated stock-recruitment relationship indicates no distinct positive relationship between SSB and recruitment (**Figure 14**). High recruitments were predicted with small SSB and low recruitment events with high SSB with high interannual variability in estimated recruitment deviations (**Figure 14**). The steepness was fixed at 0.8 for the reference case (Model 2), and the likelihood profiles (**Figure 26**) do not significantly influence this parameter in the results.

Overall the length composition data reasonably fit with few systematic departures (**Figure 6**). The size composition of the LL_OTH fleet presented some heterogeneity among years, which helps to explain the poor mode fits. Fits for each year and each fleet (**Figure 15-19**) indicate that while most fits are reasonable, there are some years with departures. Problematic departures can be seen in the Pearson residuals, where one would look for solid patterned trends (**Figure 20**).

The time series of SSB and depletion (B/B0) indicate stock decreasing from the late 1970s to the early 1980s, remaining relatively low during the mid-1980 and mid-1990 period and showing a pattern of steady population growth from mid-1990 until 2015, when it presented a new decrease (**Figure 21**, **Table 6**). The recruitment time series shows a highly variable pattern with a dynamic deviation from zero through time (**Figure 21**). Fishing mortality increased significantly in the early 1980s, reaching its all-time high in the mid-1980s and decreasing fast until the late 1980s. Since then, it presented a dynamic pattern but with a steady decline until 2016, when it had a slight increase (**Figure 22**). Estimates of F_{MSY} ranged 4. 428 to 4.82 (**Table 6**) (exploitation in biomass), with the highest F_{MSY} estimated under the high natural mortality (max age =6) and steepness assumptions h=0.8.

Likelihood profiles

Likelihood profiles were conducted to assess the information content in the model with regards to estimation of the main parameters, primarily those associated with stock recruitment assumptions (R0, h, and sigma R). Overall the model contained some information to estimate sigma R, and with a minimum observed near 0.4, although higher estimates were more likely than values lower than 0.4 (**Figure 23**). Estimates were not sensitive to the sigma R assumption in general. Unfished recruitment was relatively well-determined with both the length composition and index data providing a consistent minimum R0 near 11.2. The profile of steepness indicated a

minimum near the upper limit (**Figure 24**). The model showed moderate sensitivity over a range of Linf values mainly for the estimated scales at the end of the time series with larger Linf (>85 cm) estimating lower spawning biomass and recruitments in recent years (**Figure 25**). The length composition of the LL_USMX was very informative, since it regularly caught the larger individuals (**Figure 25**). The model showed a moderate sensitivity for a range of steepness values with recruitment being very informative (**Figure 26**).

Sensitivities

The 9 uncertainty grid model runs based on Model 2 were conducted to evaluate different parameter combinations, mainly between growth, the resulting M vector, and steepness, to address the issues raised at the data preparatory workshop. Overall there were significant differences across model runs regarding mainly the scale of the estimates (**Figure 27**). The steepness value doesn't show an important influence, with the model being more sensitive to the growth parameters and the resulting M vectors. Overall, 0.25 quantile for the growth parameters resulted in smaller SSB at the beginning but larger SSB at the end of the time series. In contrast, the opposite was observed as the growth quantiles increased. Regarding the recruitment, the scale of the age-0 recruits decreased as the quantile of the growth parameters increased. However, the overall trend was similar among uncertainty grid model runs.

Depending on the assumptions of growth parameter quantiles, the respective natural mortality vector and steepness, the stock may have reached an overfished status or may have an ongoing overfishing (**Figure 28**). In general, a combination of higher Linf (0.75 quantile), the respective M vector and the steepness value of 0.7 and 0.9 lead the stock as being overfished and suffering from an ongoing overfishing (**Figure 29**). Smaller L*inf* (0.25 and 0.75 quantiles), the respective M vectors led to a more optimistic perception of stock status.

Final reference case

After the provisional model configuration (described above) was presented, the growth/M-at-age of the uncertainty grid was maintained. But, because the yield curve was not well determined at a steepness level of 0.9, the steepness level values in the uncertainty grid were modified to h = 0.6, 0.7, and 0.8. It was noted that this is consistent with a hypothesis that the overall productivity of the western SKJ stock is lower in comparison with the eastern SKJ stock at least based on the historical catches (Evans *et al.*, 1981). Some alternatives of different years for estimating the recruitment deviations were tested and the estimations of the recruitment deviations were restricted to start in 1993 (originally estimated from 1980 onwards) when size compositions for all the major fishing fleets become available. The restriction of estimating the recruitment deviations (between 1993 and 2018) resulted in a less steep decline in the spawning biomass in early 1980, which addressed a concern raised by the group in the original model configuration. The final reference case configuration, diagnostics and results are presented in **Appendix I**.

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Table 1. Fleet ID, selectivity pattern, and fishery definitions of the fleets used in the SS model.

Fleet ID.	Fleet/Index	Selectivity (all length based)	Sel time-block	use	start	end
1	PS_West	Double Normal	Y (1966-2014;2015-2020)	Y	1962	2020
2	BB_West	Double Normal	N	Y	1952	2020
3	LL_USMX	Logistic	N	Y	1971	2020
4	LL_OTH*	Logistic	N	Y	1966	2020
5	HL_RR	Double Normal	N	Y	1975	2020
6	BRA_BB_hist	Mirror BB_West	N	Y	1981	1999

* renamed from LL_JPNCTP in Table 2 of Anon. 2022

Table 2. Growth parameters and mortality at age vectors estimated from three quantiles of the simulated distributions in length at age. M vectors at age using the Gaertner (2015) scaling function and an internally estimated age vector with a Lorenzen scaling function.

M scaling	quantile	L_{inf}	*K*	*t0*	M0	M1	M2	M3	M4	M5	M6
Gaertner scaling	0.25	67	0.54	-0.09	11.0	1.72	0.9	0.68	0.61	0.57	0.55
	0.5	76	0.53	-0.31	6.91	1.19	0.7	0.57	0.53	0.51	0.5
	0.75	86	0.49	-0.49	3.29	0.92	0.59	0.51	0.49	0.49	0.49
Internally estimated Lorenzen scaling	0.25	67	0.54	-0.09	1.29	0.81	0.67	0.61	0.58	0.56	0.55
	0.5	76	0.53	-0.31	1.02	0.71	0.60	0.55	0.53	0.51	0.50
	0.75	86	0.49	-0.49	0.96	0.69	0.59	0.54	0.52	0.50	0.49

Table 3. Task I landings input for the W- SKJ SS3 model.

Year	PS_West	BB_West	LL_USMX	LL_OTH	HL_RR
1952	0	1229	0	0	0
1953	0	1281	0	0	0
1954	0	1370	0	0	0
1955	0	1396	0	0	0
1956	0	1503	0	0	0
1957	0	1955	0	0	0
1958	0	1650	0	0	0
1959	0	1830	0	0	0
1960	0	3263	0	0	0
1961	0	3295	0	0	0
1962	463	1549	0	0	0
1963	2995	968	0	0	0
1964	3980	1071	0	0	0
1965	64	1481	0	0	0
1966	40	1651	0	100	0
1967	32	2655	0	103.069	0
1968	135	2407	0	102.148	0
1969	102	1655	0	101.228	0
1970	0	2200	0	277.394	0

1971	0	1700	16.898	273.212	0
1972	245	1400	16.179	279.28	0
1973	29	1921	42	575.301	0
1974	28	2972	41.707	389.55	0
1975	196	2836	91.488	258.719	2
1976	700	2883	13.38	177.569	0
1977	334	2588	7.769	141	19
1978	1722	2464	26.24	209.685	63
1979	737	4225	2.112	176.334	292
1980	2887	9351	3.217	149.946	1.1
1981	4654	17999	23.018	236	180
1982	9705	22402	11.789	386	22
1983	9845	20057	202.572	525	109.07
1984	10924.9	16810	49	743	36
1985	9270	28506	69.18	444	62.13
1986	4954	25885	18.18	897	143.06
1987	4964	18805	17.31	280	97.24
1988	2315.01	21146	12	212	51.31
1989	2466	23492	19.56	373	31.82
1990	3241	22350	27.42	416	75.87
1991	6935	24096	10.36	662.785	107.74
1992	7389	21112	11.23	459.298	63.03
1993	12397	19902	11.709	421	92.09
1994	5712	22855	8.57	1296	77.52
1995	2059	17744	33.71	1941.9	81
1996	3349	23741	11.31	374.788	85.5
1997	4347	27045	6.147	232.305	81.31
1998	3826	24727	18.802	411.706	103.53
1999	2936	23881	56.594	331.875	150.06
2000	3063.34	25641	22.281	424.5	42.28
2001	5297.1	25142.3	59.454	886.63	65.28
2002	2116.05	18736.9	318.012	344.089	84.49
2003	2296.3	21990.3	81.162	303.212	77.56
2004	2769.12	24081.6	179.399	329.533	101.835
2005	1966.57	26027.6	178.841	314.121	29.445
2006	2045.01	23766.1	256.359	324.215	60.806
2007	1209.25	23897.9	50.52	210.467	71.332
2008	901.277	20701.9	40.665	303.703	65.57
2009	2034.57	23518.1	19.578	78.831	123.208
2010	1943.16	22803.5	851.878	210.339	97.782
2011	1859.49	29468.1	351.712	227.048	481.309
2012	1582.03	30692.8	49.872	167.453	342.581
2013	907.743	32187.1	639.95	245.925	547.544
2014	1081.25	24814	433.605	287.754	551.523
2015	2243.09	17537.8	187.413	190.315	558.567
2016	1912.29	16810.4	788.614	203.455	1347.31

2017	2150.27	14646.5	258.65	244.674	5490.89
2018	1226.3	14926.5	290.306	209.613	4618.91
2019	876.459	15409.5	388.69	181.706	2240.82
2020	1008.94	14593.5	174.364	61.395	2344.38

Table 4. Uncertainty grid used for sensitivity analysis.

Parameter	**Value 1**	**Value 2**	**Value 3**	**Value 4**	**Value 5**	**Value 6**	**Value 7**	**Value 8**	**Value 9**
Steepness	0.7	0.7	0.7	0.8	0.8	0.8	0.9	0.9	0.9
Growth param quantile	0.25	0.5	0.75	0.25	0.5	0.75	0.25	0.5	0.75

Table 5. Parameter estimates, phases initial values and standard deviations for Model 2.

Label	Value	Phase	Min	Max	Init	Status	SD	Prior	Afterbound	Type
SR_LN(R0)	11.13	1	0.0001	20	11.13	OK	0.09	No_prior	OK	SRR
Size_DblN_peak_PS_West(1)	49.17	2	20	90	49.16	OK	0.94	No_prior	OK	Sel
Size_DblN_top_logit_PS_West(1)	-12.17	2	-15	15	-12.17	OK	47.55	No_prior	OK	Sel
Size_DblN_ascend_se_PS_West(1)	4.43	3	-4	12	4.43	OK	0.18	No_prior	OK	Sel
Size_DblN_descend_se_PS_West(1)	4.78	3	-10	6	4.78	OK	0.30	No_prior	OK	Sel
Size_DblN_end_logit_PS_West(1)	-2.28	3	-20	20	-2.28	OK	0.50	No_prior	OK	Sel
Size_DblN_peak_BB_West(2)	55.94	2	20	90	55.94	OK	1.08	No_prior	OK	Sel
Size_DblN_top_logit_BB_West(2)	-11.89	2	-15	15	-11.89	OK	50.66	No_prior	OK	Sel
Size_DblN_ascend_se_BB_West(2)	4.90	3	-4	12	4.90	OK	0.18	No_prior	OK	Sel
Size_DblN_descend_se_BB_West(2)	4.73	3	-10	6	4.73	OK	0.32	No_prior	OK	Sel
Size_DblN_end_logit_BB_West(2)	-4.59	3	-20	20	-4.59	OK	4.20	No_prior	OK	Sel
Size_inflection_LL_USMX(3)	48.81	2	20	126	48.80	OK	1.75	No_prior	OK	Sel
Size_95%width_LL_USMX(3)	9.31	3	0.01	100	9.30	OK	2.53	No_prior	OK	Sel
Size_inflection_LL_OTH(4)	77.87	2	20	126	77.85	OK	9.37	No_prior	OK	Sel
Size_95%width_LL_OTH(4)	13.43	3	0.01	100	13.43	OK	7.28	No_prior	OK	Sel
Size_DblN_peak_HL_RR(5)	53.21	2	20	90	53.20	OK	2.01	No_prior	OK	Sel
Size_DblN_top_logit_HL_RR(5)	-10.80	2	-15	15	-10.80	OK	62.28	No_prior	OK	Sel
Size_DblN_ascend_se_HL_RR(5)	4.95	3	-10	15	4.95	OK	0.32	No_prior	OK	Sel
Size_DblN_descend_se_HL_RR(5)	2.98	3	-10	15	2.98	OK	1.45	No_prior	OK	Sel
Size_DblN_end_logit_HL_RR(5)	-0.60	3	-20	20	-0.60	OK	0.50	No_prior	OK	Sel
Size_DblN_peak_PS_West(1)_BLK1repl_2015	57.63	2	20	90	57.63	OK	1.70	No_prior	OK	Sel
Size_DblN_top_logit_PS_West(1)_BLK1repl_2015	-2.98	2	-15	15	-2.98	OK	1.07	No_prior	OK	Sel
Size_DblN_ascend_se_PS_West(1)_BLK1repl_2015	4.37	3	-4	12	4.37	OK	0.36	No_prior	OK	Sel
Size_DblN_descend_se_PS_West(1)_BLK1repl_2015	3.62	3	-10	6	3.62	OK	1.55	No_prior	OK	Sel
Size_DblN_end_logit_PS_West(1)_BLK1repl_2015	-0.89	3	-20	20	-0.90	OK	0.91	No_prior	OK	Sel

Table 6. Benchmarks (SD) and relative stock status for Model 2.

Benchmarks	Model 2
SSB_unfished	150621 (12917.9)
Totbio_unfished	166421 (14272.9)
SmryBio_unfished	106006 (9091.56)
Recr_unfished	67896.4 (5823.08)
SSB_Btgt	60248.4 (5167.16)
SPR_Btgt	0.4375 (2.41223E-18)
annF_Btgt	0.872567 (0.0240883)
Dead_Catch_Btgt	24612.3 (1756.48)
SSB_SPR	54223.6 (4650.44)
annF_SPR	1.09478 (0.0313325)
Dead_Catch_SPR	25942.4 (1860.08)
SSB_MSY	27207.9 (2200.67)
SPR_MSY	0.231848 (0.00220018)
annF_MSY	0.794938 (0.0136573)
Dead_Catch_MSY	29424.1 (2038.56)
Ret_Catch_MSY	29625.2 (2038.56)
B_MSY/SSB_unfished	0.180638 (0.00234685)

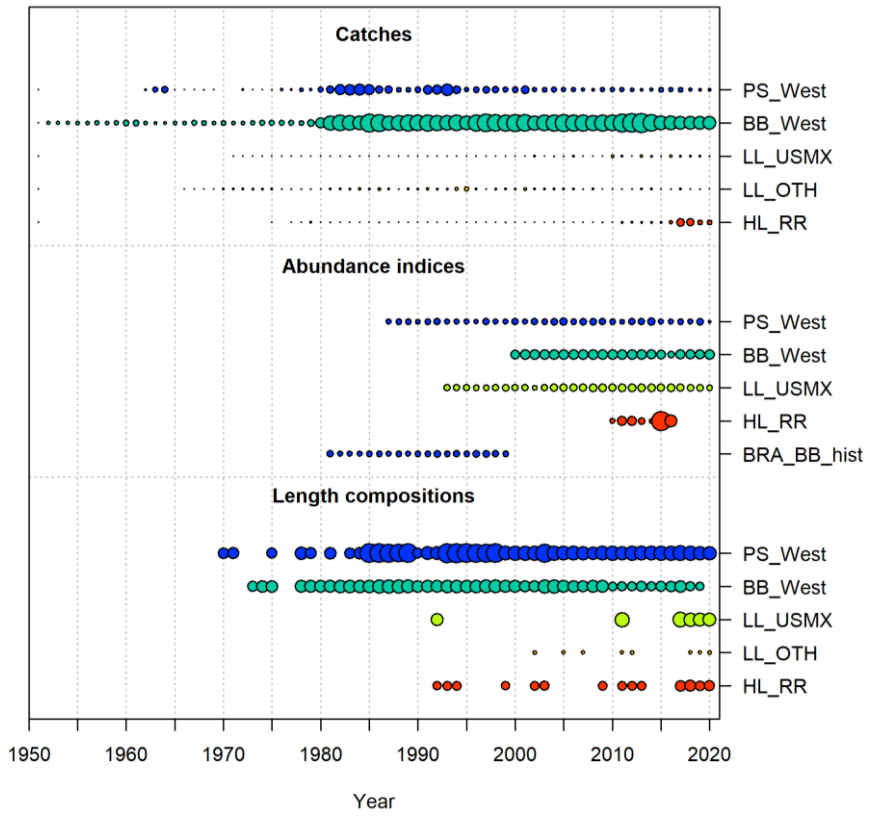


Figure 1. Time series of data inputs to the WSKJ SS model.

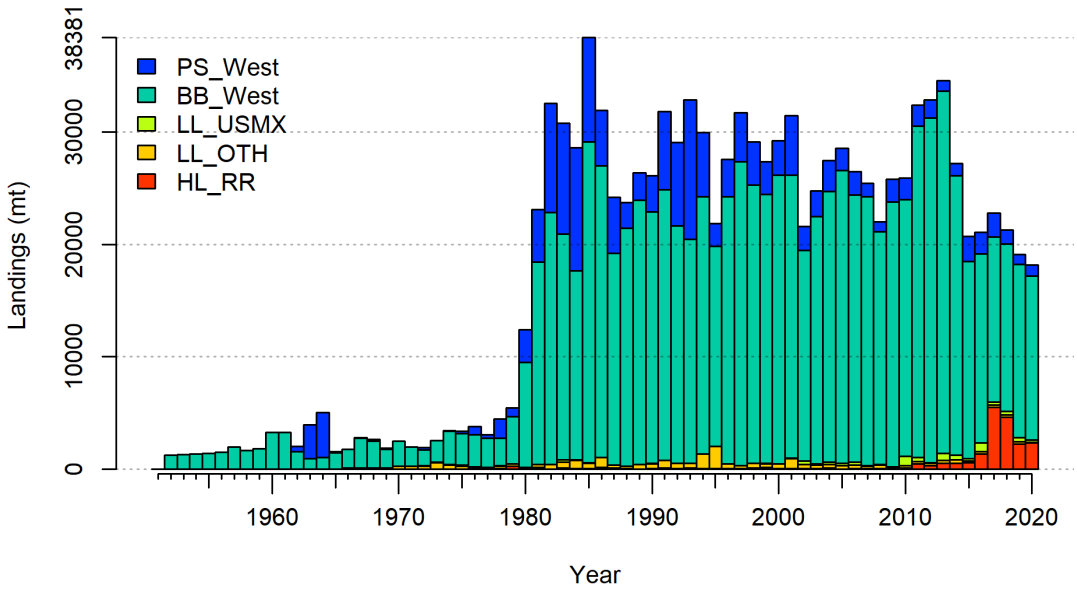


Figure 2. Task I landings input for the W-SKJ SS3 model.

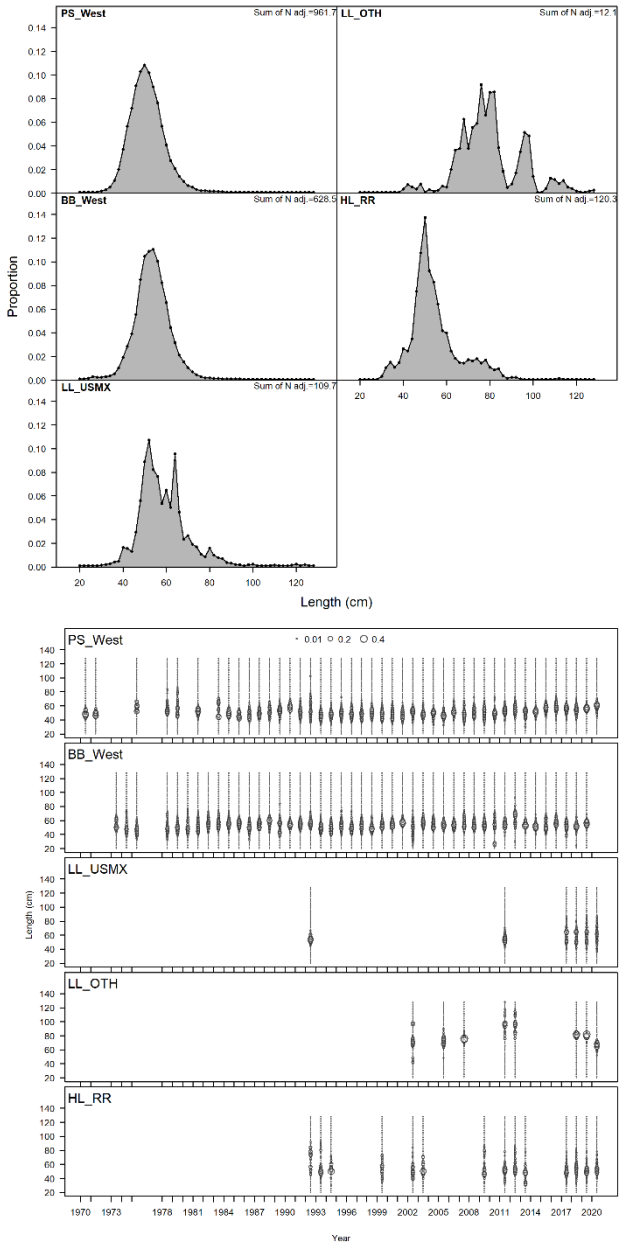


Figure 3. Size frequency input for the W-SKJ SS3 model.

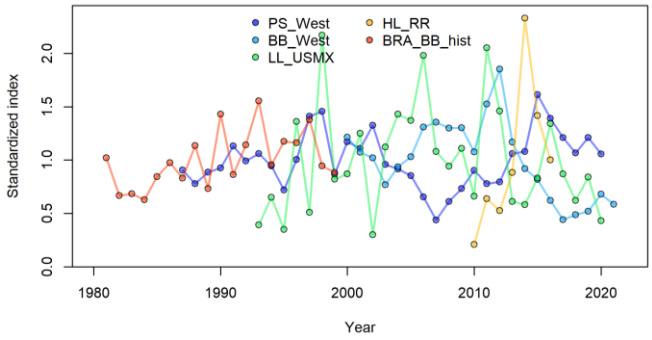


Figure 4. Index time series input for the W-SKJ SS3 model.

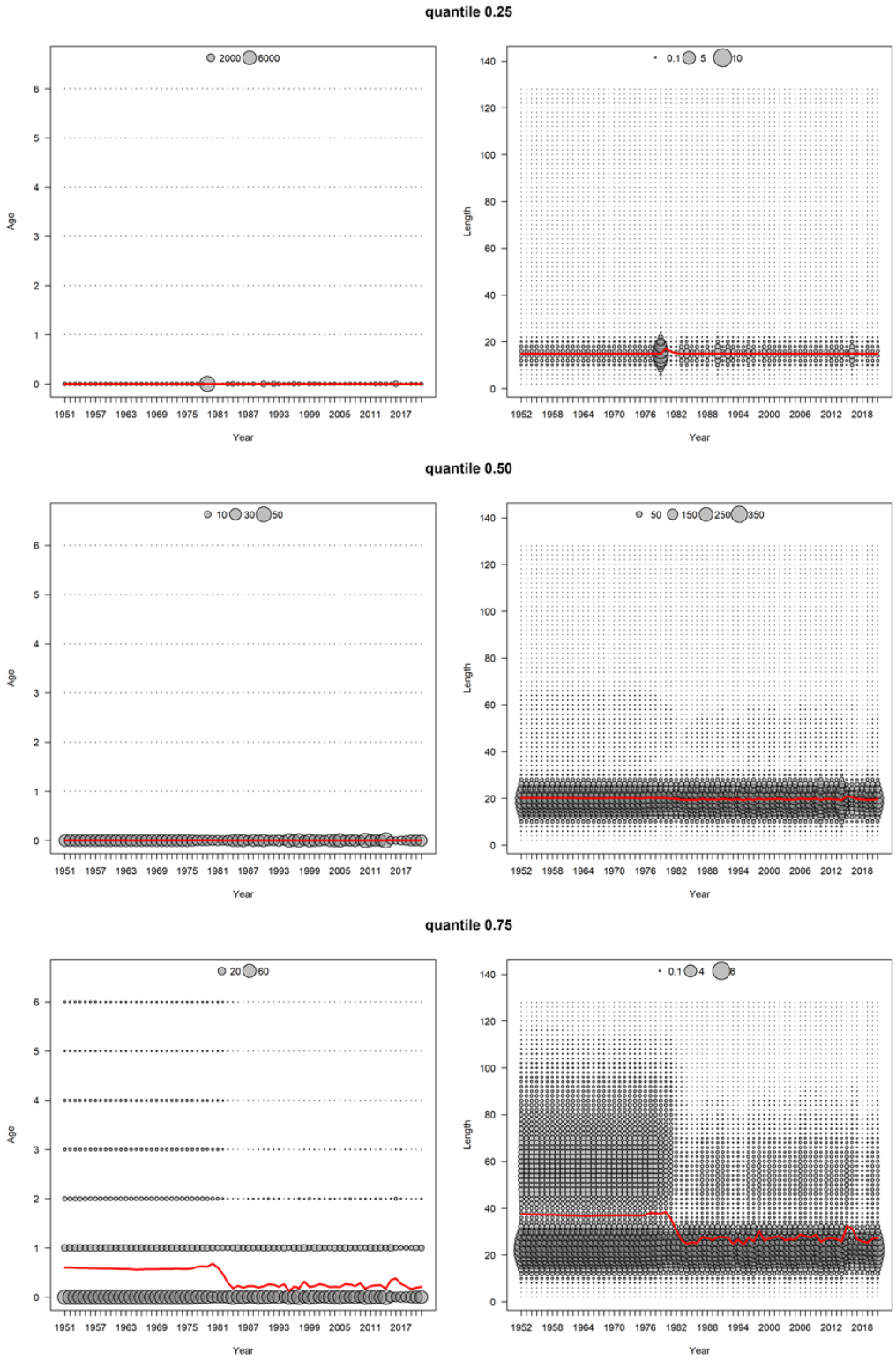


Figure 5. Numbers at age (left panel) and numbers at length (right panel) estimated by the Model 1 (quantile 0.5) and for the 0.25 and 0.75 quantiles for the W SKJ. Red lines indicate mean numbers at age and length.

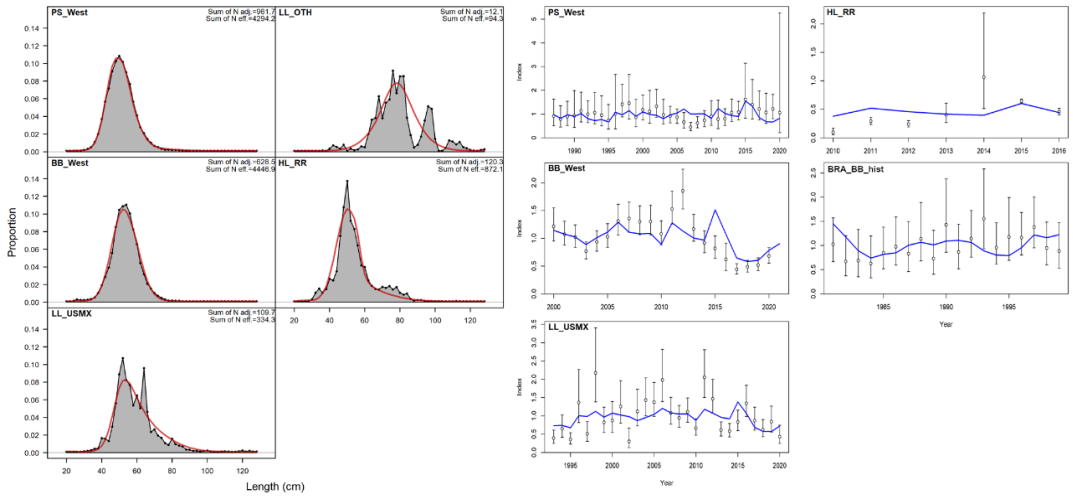


Figure 6. Model 2 fits to the aggregated length compositions for each fleet (left panels) and for the index (right panels) for the W-SKJ SS3 model.

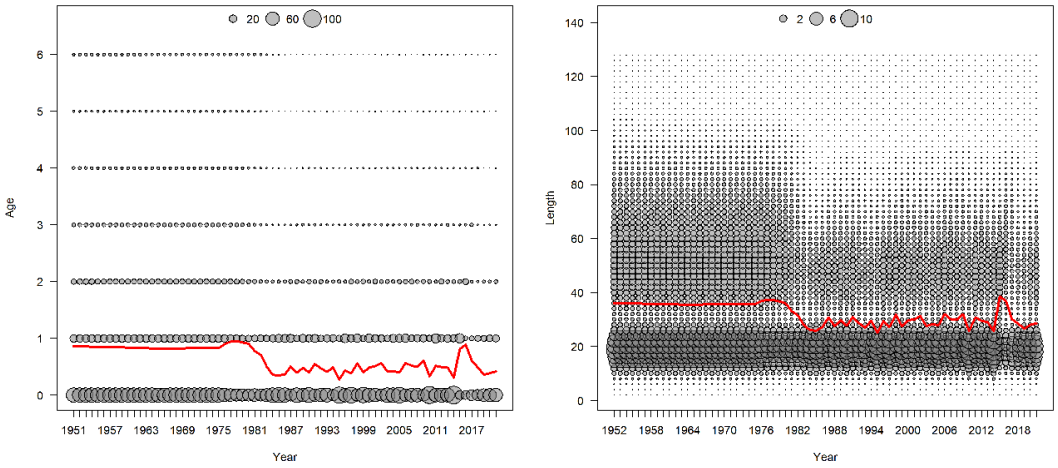


Figure 7. Numbers at age and numbers at length estimated by the Model 2 for the W-SKJ SS3 model.

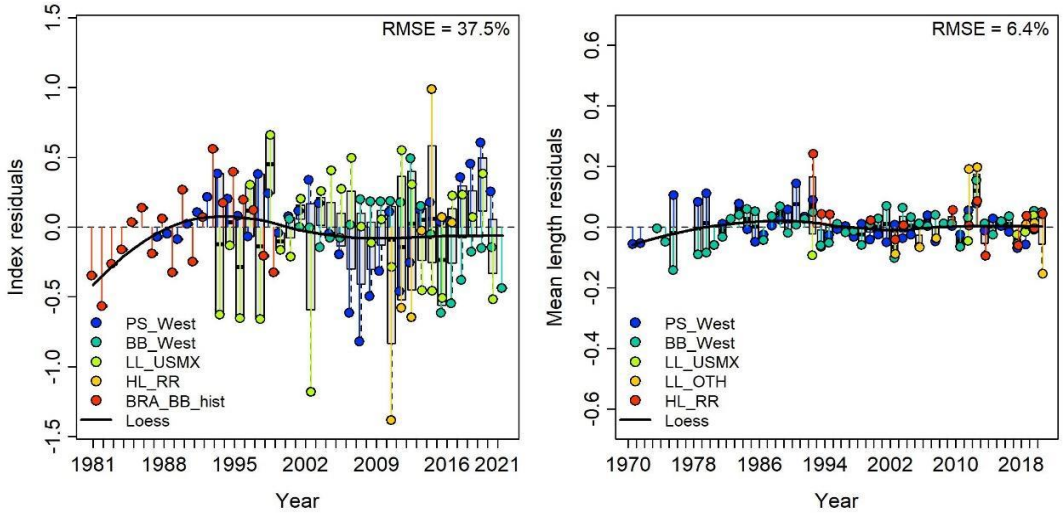


Figure 8. Joint residuals plot for the index and length composition fits (Model 2).

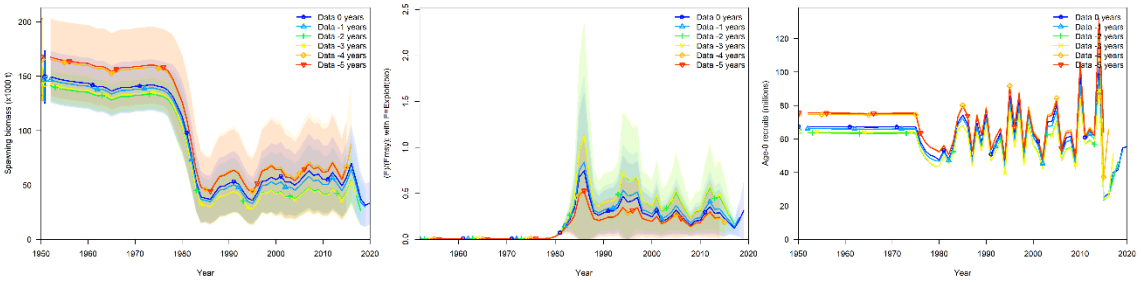


Figure 9. Retrospective plots of spawning biomass, F/F_{MSY} and age-o recruitment for Model 2.

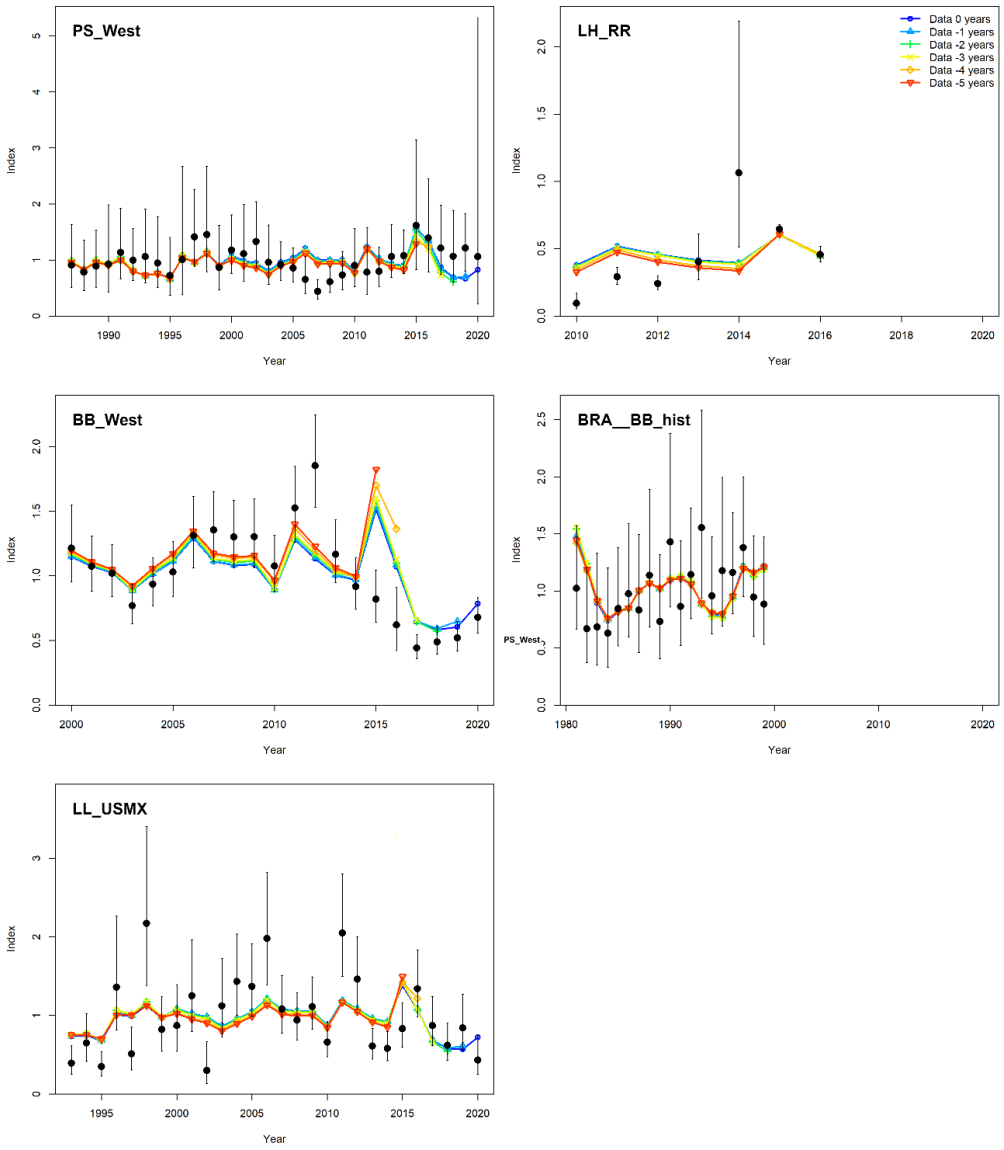


Figure 10. Retrospective plots of fits to the index for each fleet in Model 2.

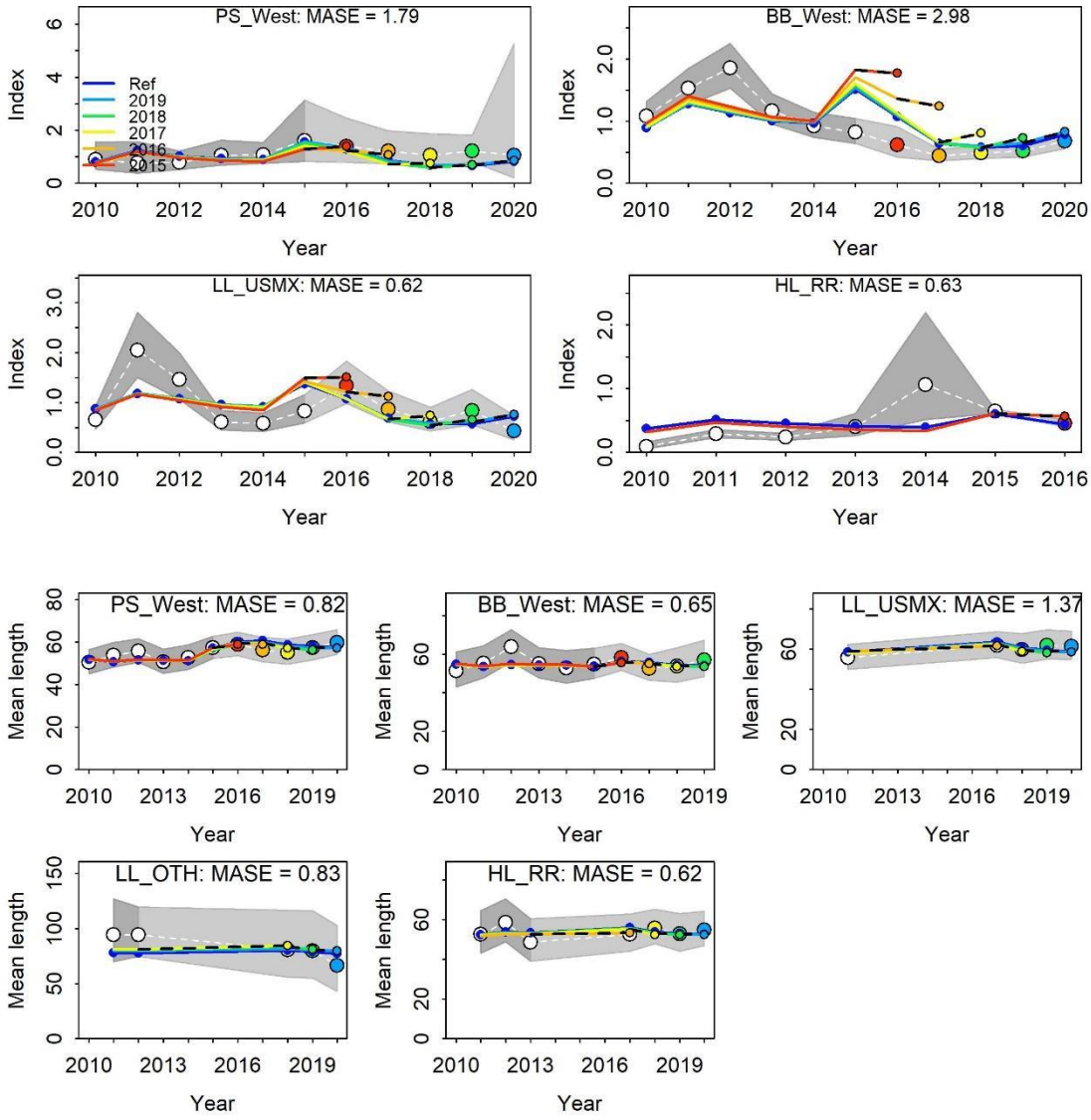


Figure 11. Hindcasting plots for the index and length composition fits in Model 2.

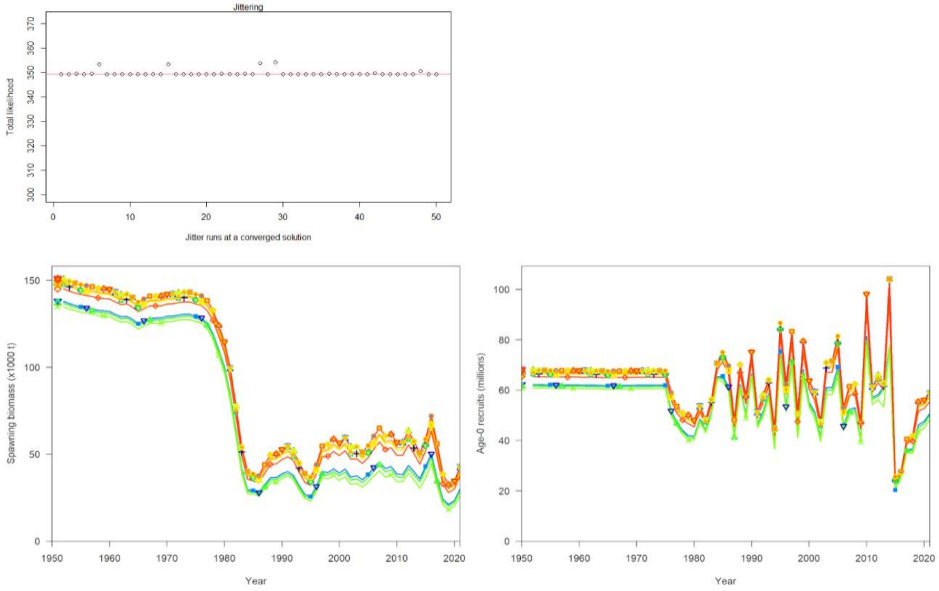


Figure 12. Jitter results for Model 2.

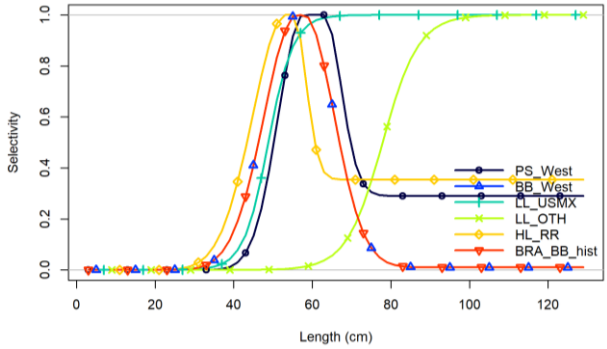


Figure 13. Selectivities at length shapes for Model 2.

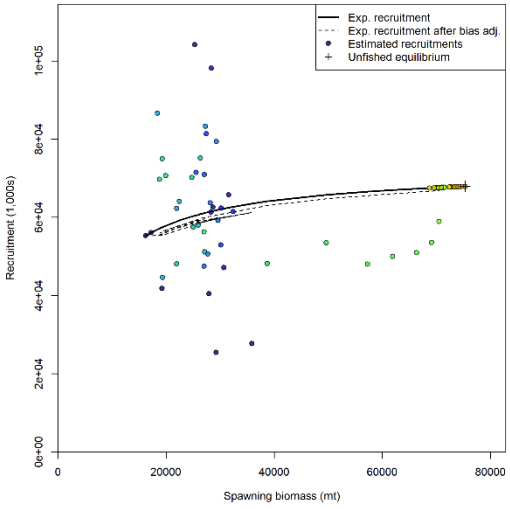
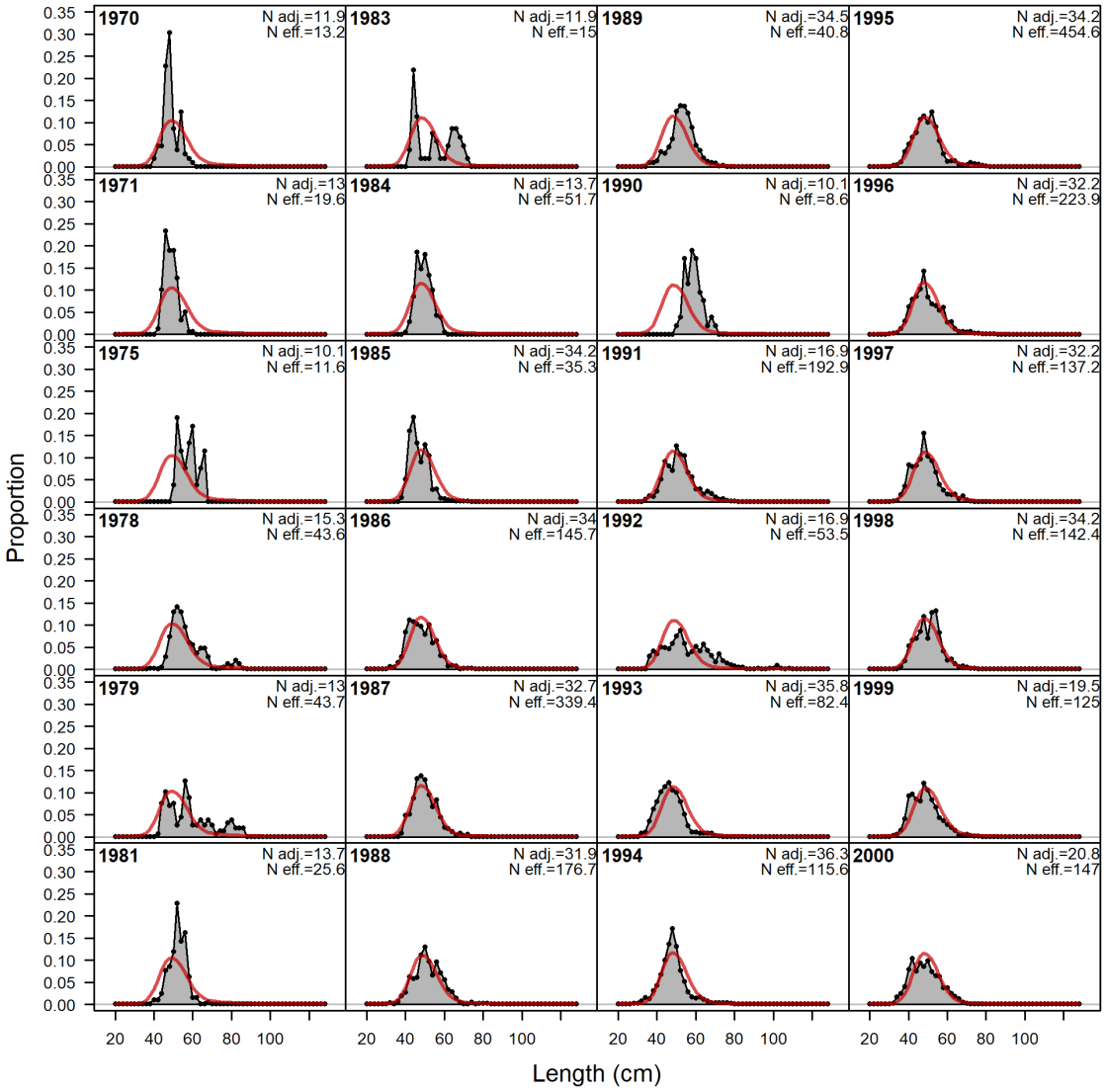


Figure 14. Stock-recruit curve for Model 2. Point colors indicate year, with warmer colors indicating earlier years and cooler colors in showing later years.


1970 N adj.=11.9 N eff.=13.2
1983 N adj.=11.9 N eff.=15
1989 N adj.=34.5 N eff.=40.8
1995 N adj.=34.2 N eff.=454.6
1971 N adj.=13 N eff.=19.6
1984 N adj.=13.7 N eff.=51.7
1990 N adj.=10.1 N eff.=8.6
1996 N adj.=32.2 N eff.=223.9
1975 N adj.=10.1 N eff.=11.6
1985 N adj.=34.2 N eff.=35.3
1991 N adj.=16.9 N eff.=192.9
1997 N adj.=32.2 N eff.=137.2
1978 N adj.=15.3 N eff.=43.6
1986 N adj.=34 N eff.=145.7
1992 N adj.=16.9 N eff.=53.5
1998 N adj.=34.2 N eff.=142.4
1979 N adj.=13 N eff.=43.7
1987 N adj.=32.7 N eff.=339.4
1993 N adj.=35.8 N eff.=82.4
1999 N adj.=19.5 N eff.=125
1981 N adj.=13.7 N eff.=25.6
1988 N adj.=31.9 N eff.=176.7
1994 N adj.=36.3 N eff.=115.6
2000 N adj.=20.8 N eff.=147
Proportion
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35
20 40 60 80 100
Length (cm)

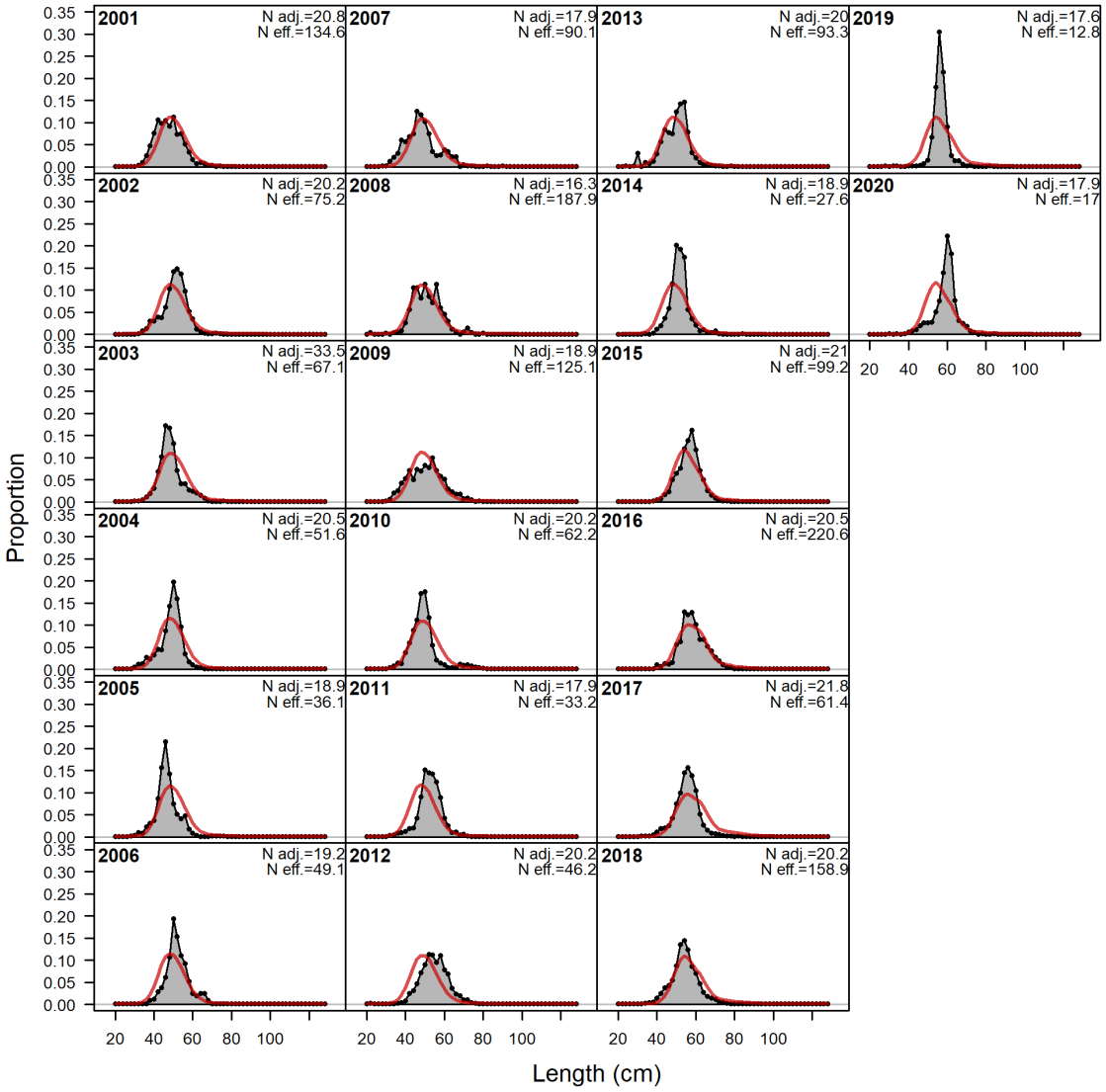
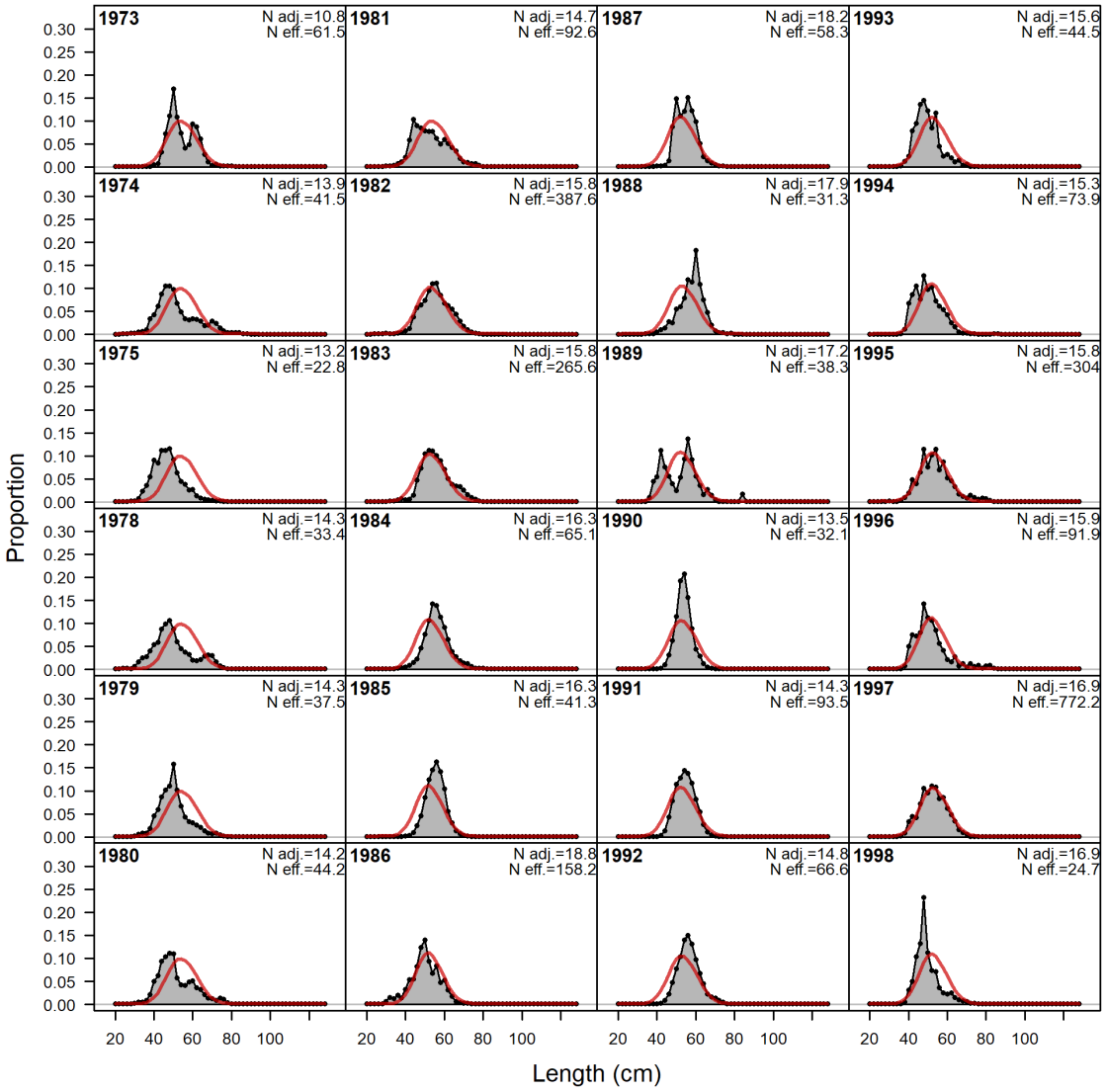


Figure 15. Fits to yearly length composition for the PS_WEST fleet in Model 2.


1973 N adj.=10.8 N eff.=61.5
1981 N adj.=14.7 N eff.=92.6
1987 N adj.=18.2 N eff.=58.3
1993 N adj.=15.6 N eff.=44.5
1974 N adj.=13.9 N eff.=41.5
1982 N adj.=15.8 N eff.=387.6
1988 N adj.=17.9 N eff.=31.3
1994 N adj.=15.3 N eff.=73.9
1975 N adj.=13.2 N eff.=22.8
1983 N adj.=15.8 N eff.=265.6
1989 N adj.=17.2 N eff.=38.3
1995 N adj.=15.8 N eff.=304
1978 N adj.=14.3 N eff.=33.4
1984 N adj.=16.3 N eff.=65.1
1990 N adj.=13.5 N eff.=32.1
1996 N adj.=15.9 N eff.=91.9
1979 N adj.=14.3 N eff.=37.5
1985 N adj.=16.3 N eff.=41.3
1991 N adj.=14.3 N eff.=93.5
1997 N adj.=16.9 N eff.=772.2
1980 N adj.=14.2 N eff.=44.2
1986 N adj.=18.8 N eff.=158.2
1992 N adj.=14.8 N eff.=66.6
1998 N adj.=16.9 N eff.=24.7
Proportion
0.00 0.05 0.10 0.15 0.20 0.25 0.30
20 40 60 80 100
Length (cm)

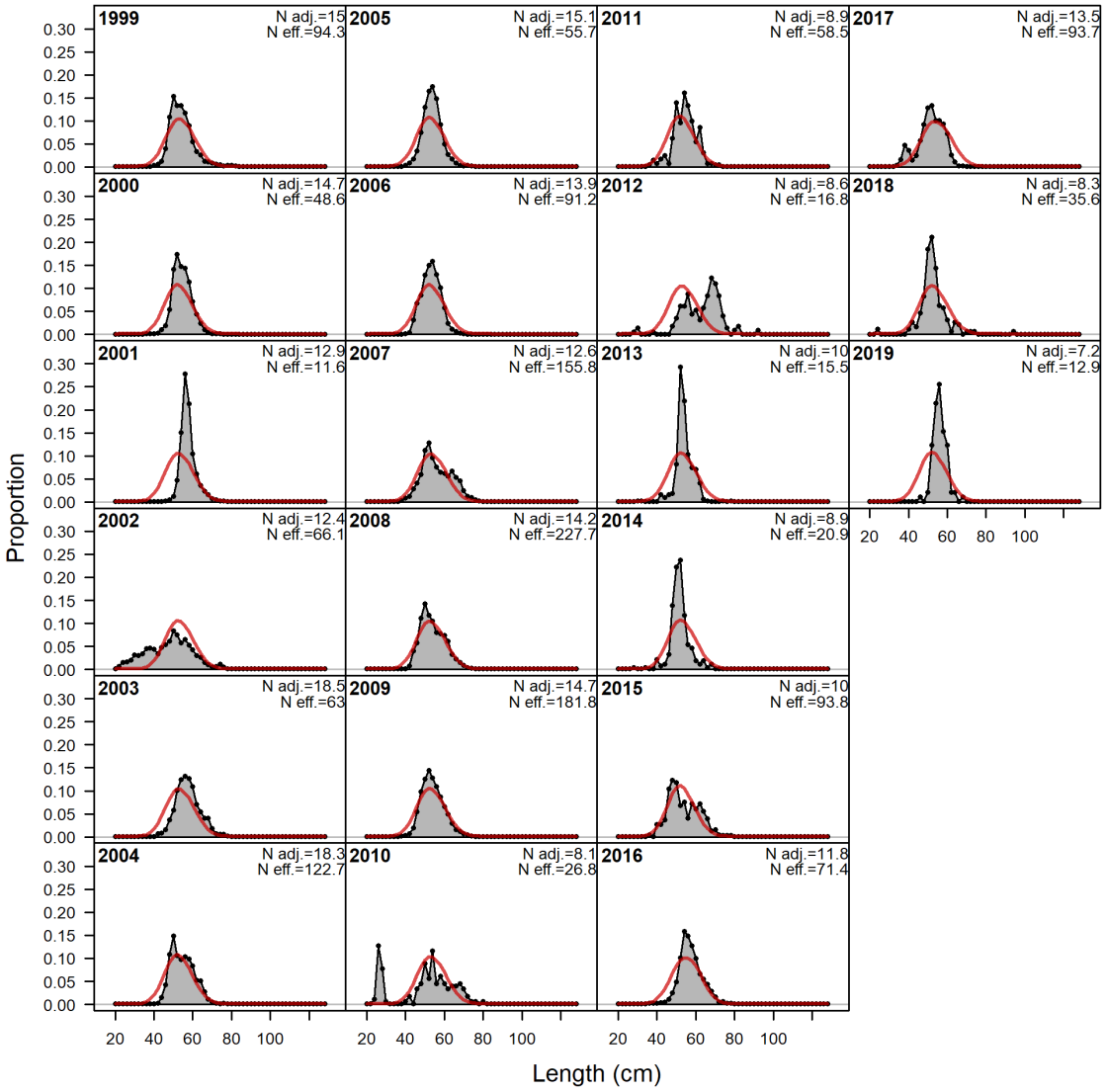


Figure 16. Fits to yearly length composition for the BB_West fleet in Model 2.

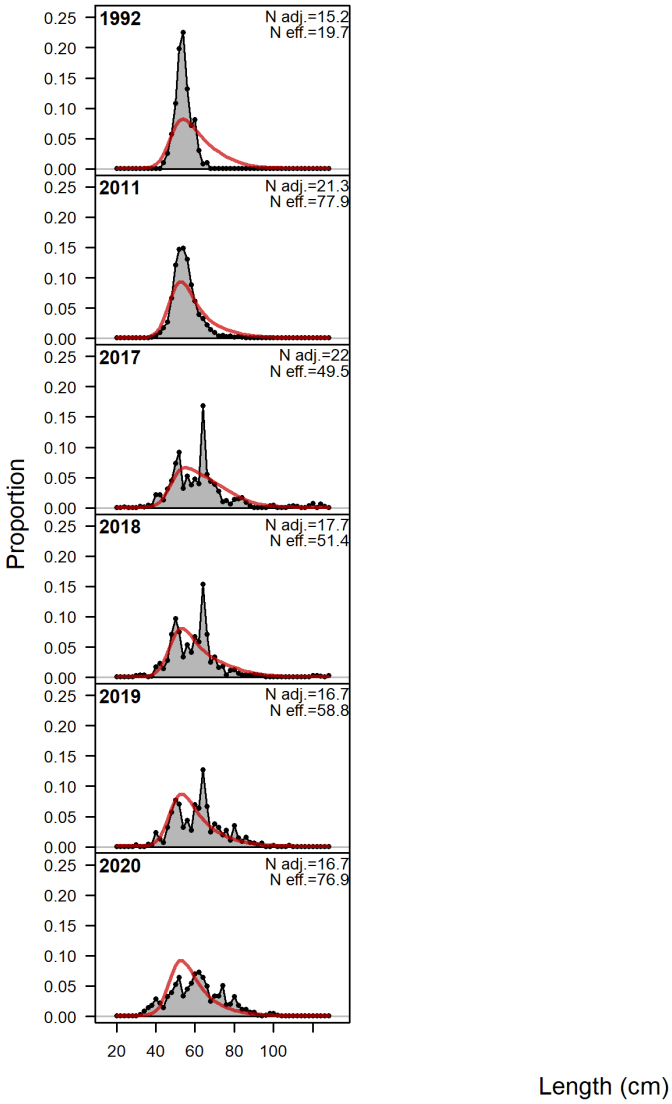


Figure 17. Fits to yearly length composition for the LL_USMX fleet in Model 2.

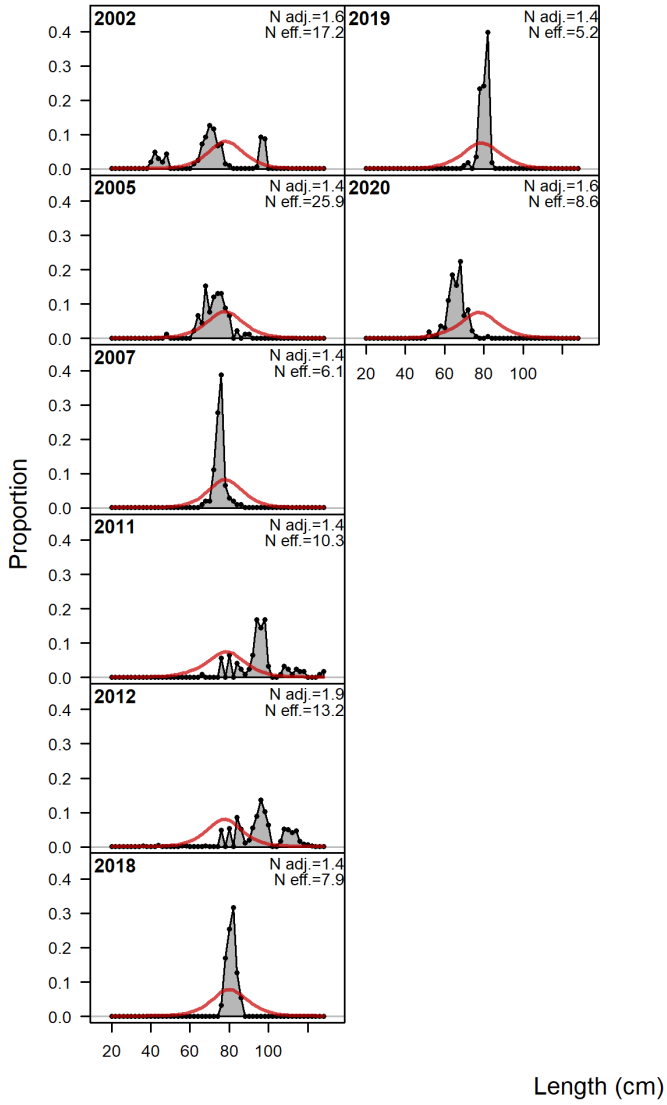


Figure 18. Fits to yearly length composition for the LL_OTH fleet in Model 2.

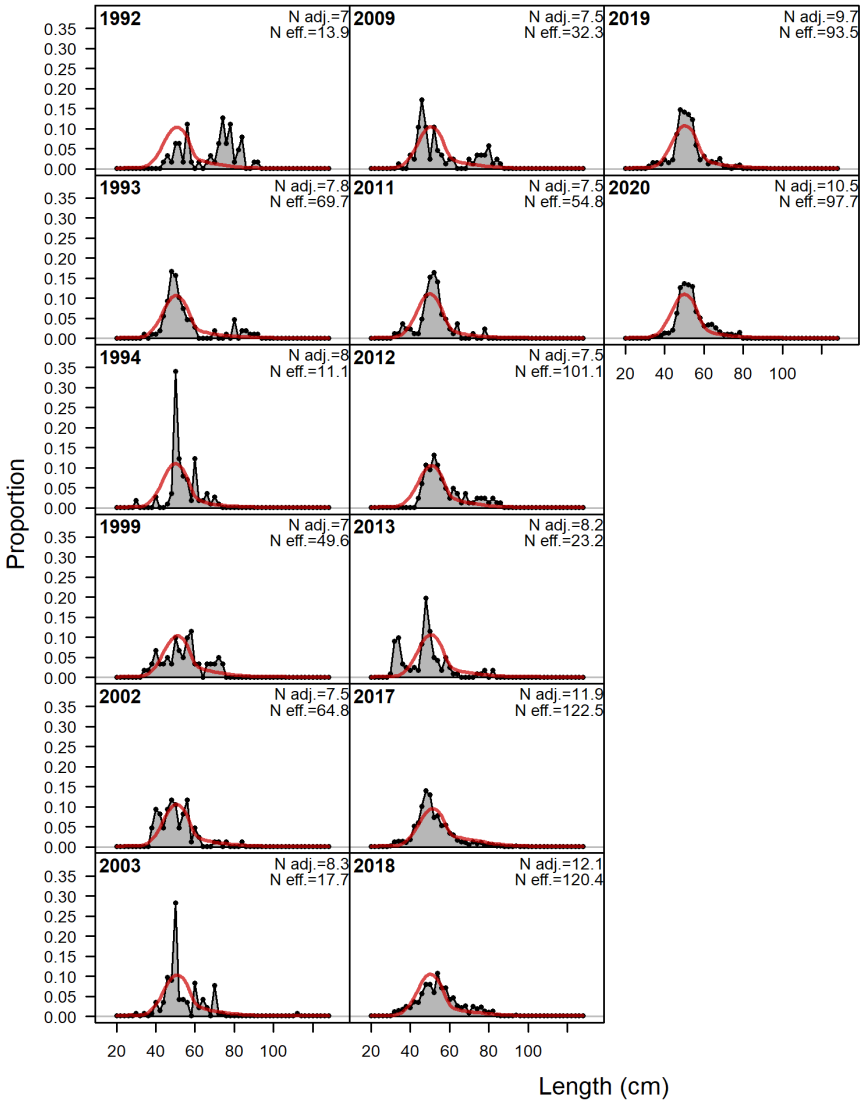


Figure 19. Fits to yearly length composition for the HL_RR fleet in Model 2.

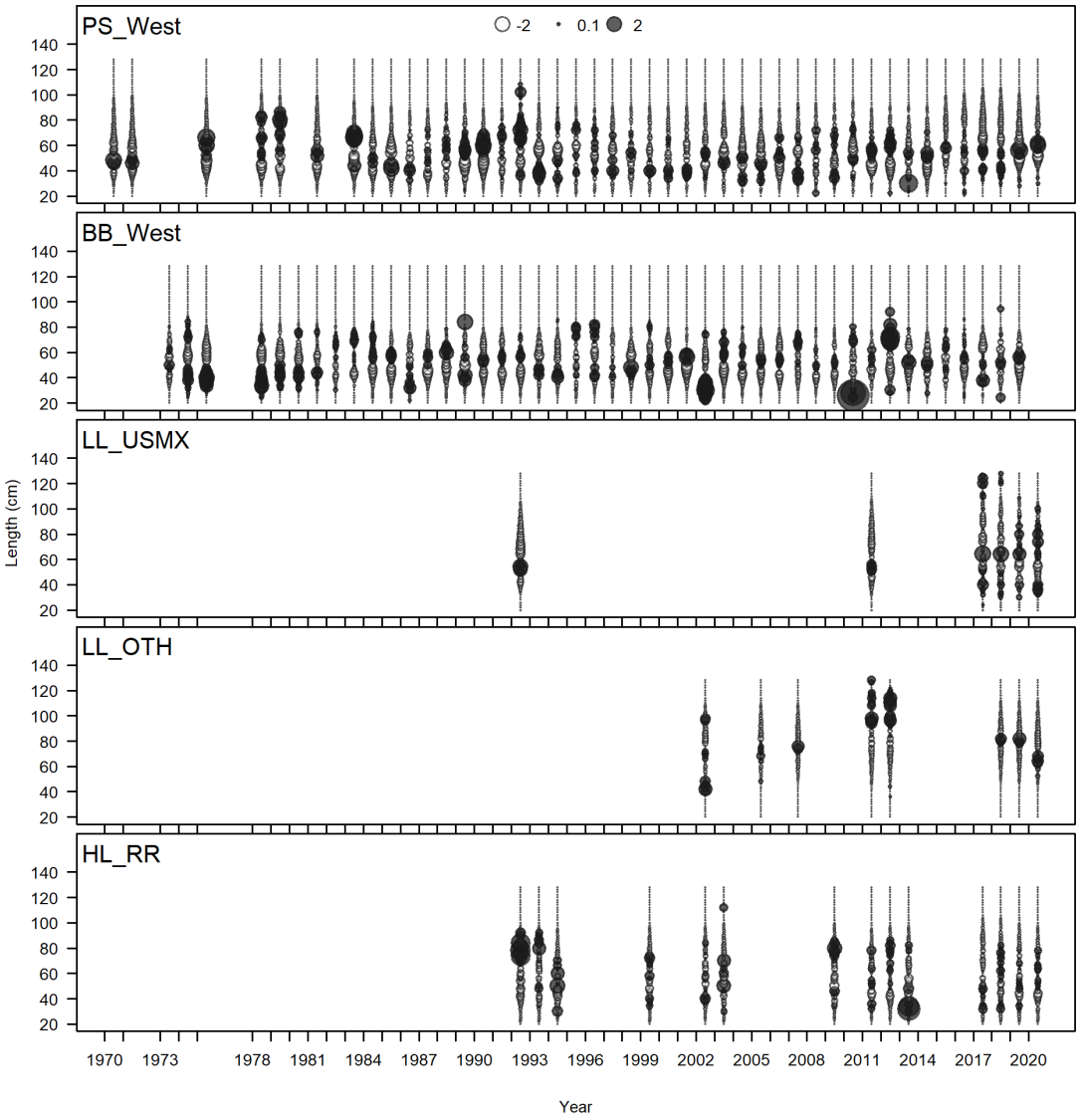


Figure 20. Pearson residuals to length composition fits for Model 2. Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected).

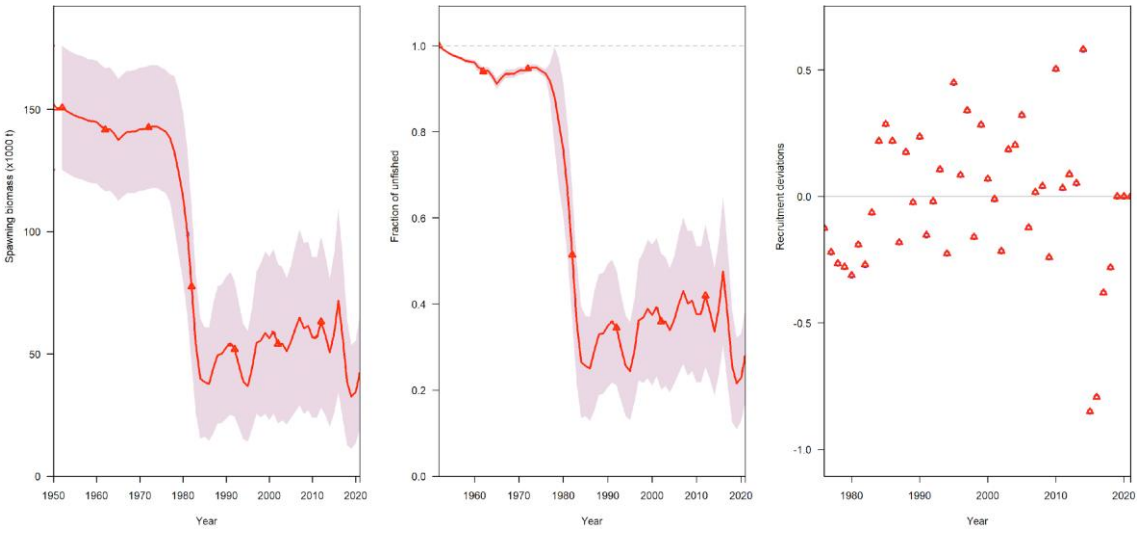


Figure 21. Spawning biomass, fraction of unfished total biomass and recruitment deviations time series for Model 2.

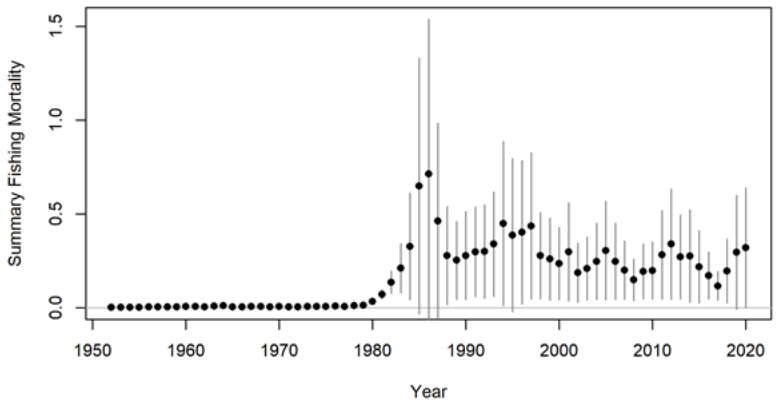


Figure 22. Summary of fishing mortality for the Model 2.

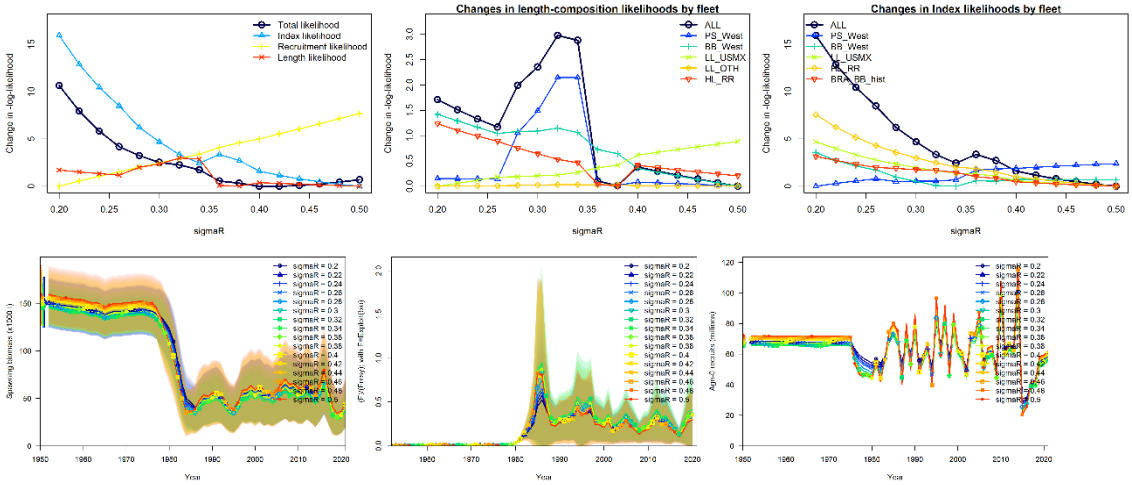


Figure 23. Likelihood profiles for sigma R for Model 2.

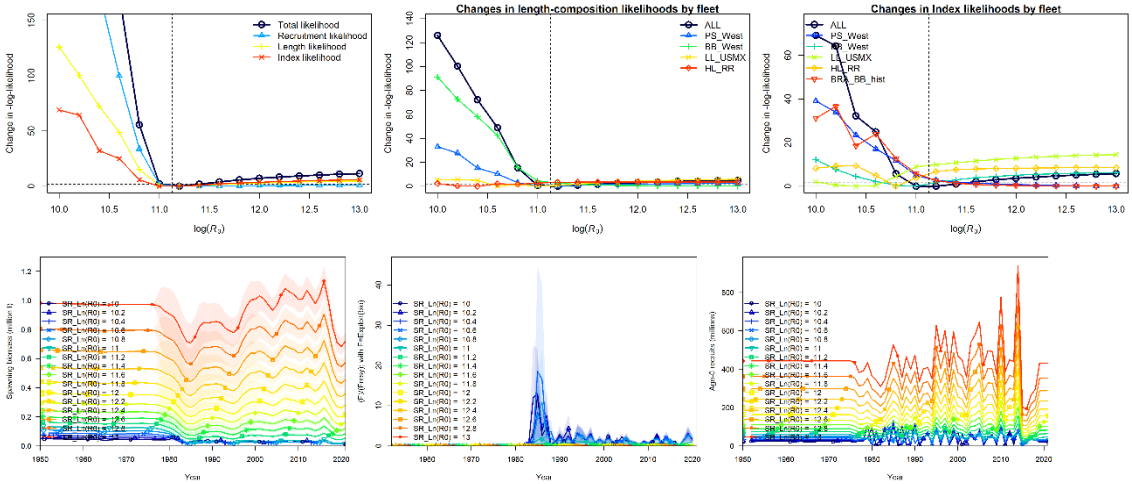


Figure 24. Likelihood profiles for R0 for Model 2.

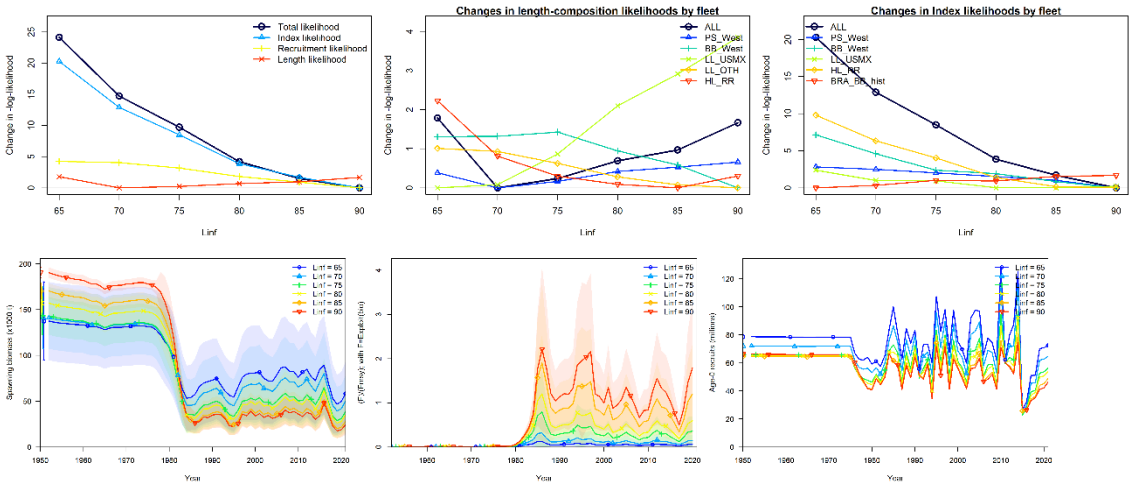


Figure 25. Likelihood profiles for Linf for Model 2.

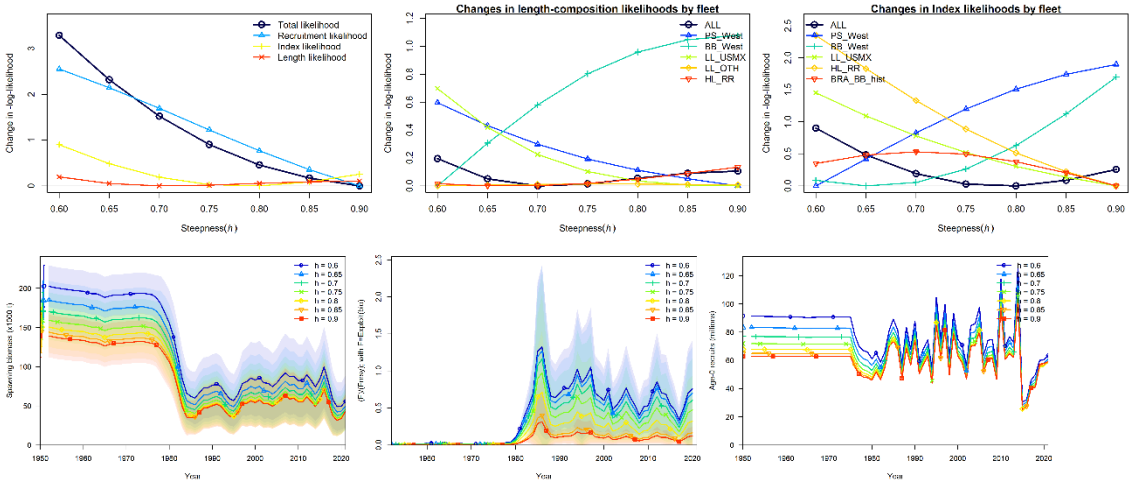


Figure 26. Likelihood profiles for Steepness (h) for Model 2.

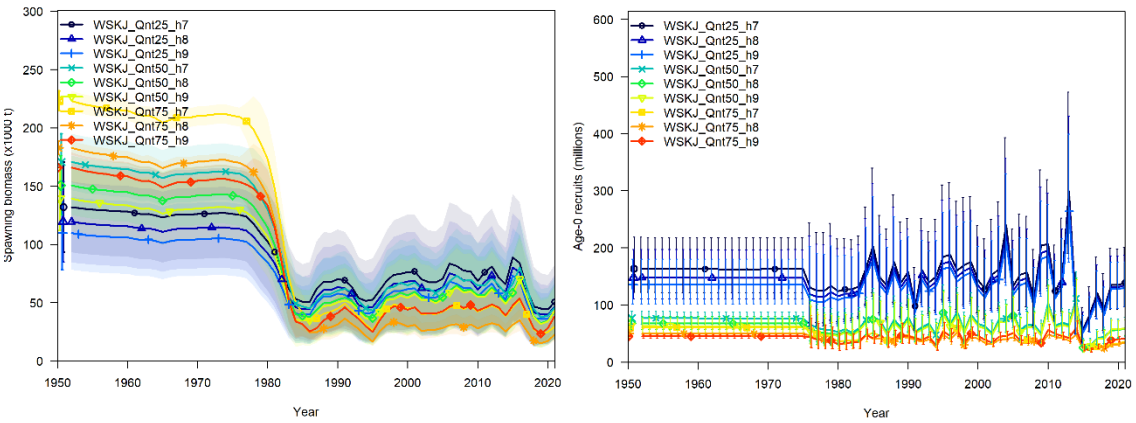


Figure 27. Spawning biomass and age-0 recruits trajectories through the uncertainty grid.

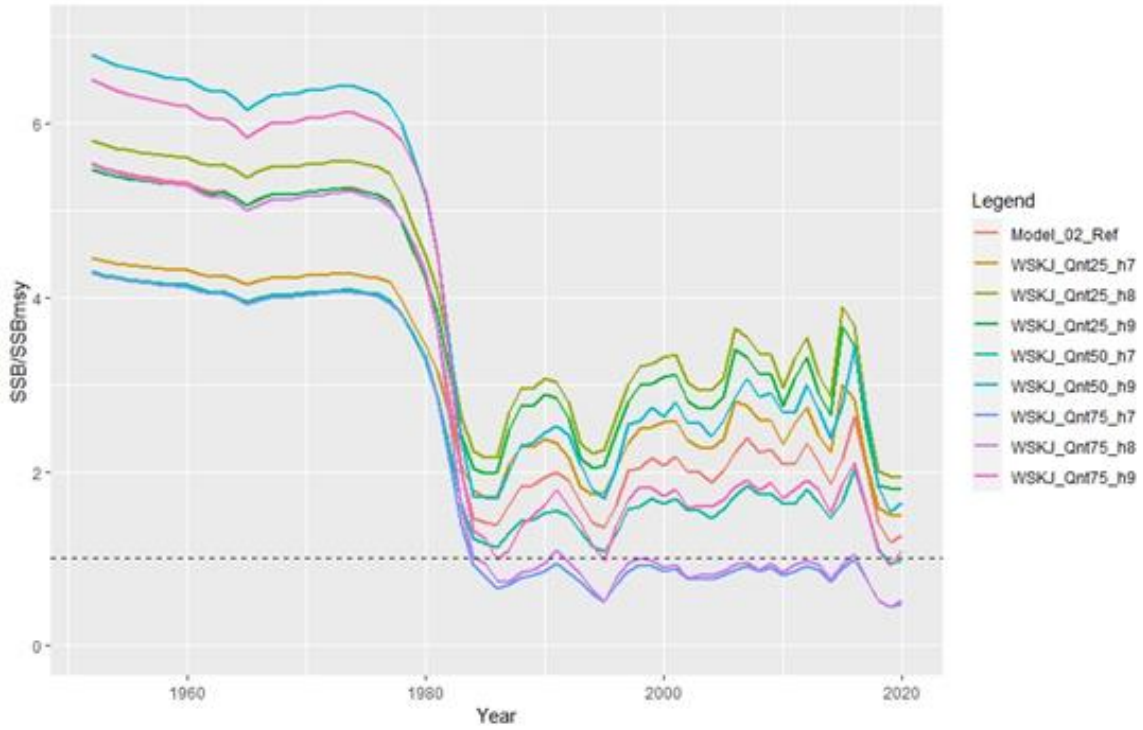


Figure 28. Time series of stock status trends (SSB/SSB_{MSY}) across the 9 uncertainty grid model runs.

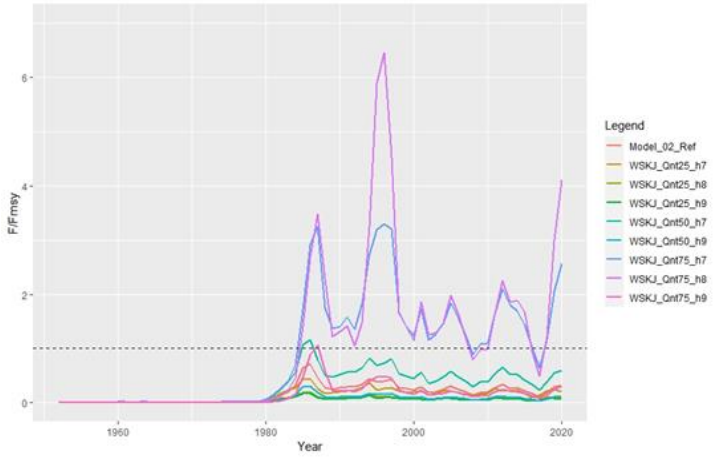


Figure 29. Time series of stock status trends (F/F_{MSY}) across the 9 uncertainty grid model runs.

Appendix I

Appendix 1 presents the modifications to the provisional reference case model requested by the group of the 2022 SKIPJACK tuna stock assessment meeting of ICCAT.

The agreed final reference model case used the growth/M-at-age level of the 0.5 quantile, steepness 0.7, and the recruitment deviations estimated from 1993 to 2018 (**Table 1.a**).

The final reference case of the Stock Synthesis model shows stability in the log-likelihood with different starting values (**Figure 1.a**). The final model gradient was 4.7e-05, lower than a target of 0.0001, and considered acceptable for model convergence, particularly since the solution was stable across different starting parameter values. All 50 jitter model runs converged, with 42 model runs at the total negative likelihood estimate value of the base case model run (365 likelihood units), and 8 model runs had larger total negative likelihood values (**Figure 1.a**). The jittered model was robust to the initial values of the parameters and gave no evidence that the model converged at the local minima of the objective function instead of the global minimum.

The model showed a generally good fit to the indices and showed acceptable fits to the length composition for all fishing fleets, except for the years between 2010 and 2016 for the BB_West fishing fleet (**Figure 2.a**). The residual patterns of the indices and the length fits were overall good. Deviations from the stock-recruitment curve estimated (e.g. recruitment deviates) indicated high variability in year-to-year recruitment (**Figure 3.a**), with positive deviations from 1994 to 1999 and a dynamic increase and decrease from 2000 to 2013 followed by a significant decrease in 2014 and 2015, followed by negative but closer to the mean in 2016 and 2017.

In general, the joint residual plots for the reference case showed a random pattern for the residuals of the fits to the indices for all fleets with some outliers for the HL_RR and LL_USMX fleets (>1 or < -1) but without a significant impact on the overall pattern (**Figure 4.a**). A negative trend in the residuals was observed at the beginning of the BRA_BB_hist index time series. The residuals of the length composition fits also showed a random pattern for all fleets with no evident outliers (**Figure 4.a**).

The retrospective analysis for the reference model performed relatively well (**Figure 5.a**), all falling within the confidence intervals of the different runs and showing no discernable trend. The scale of SSB increased but the overall trend remained when 4 and 5 years data were removed (Mohn's rho = 0.01 (0.07)) (**Figure 5a**).

The prediction skill analysis for the reference case showed that all recent CPUE indices and length compositions included at least one observation that fell within the hindcast evaluation period 2015–2019 (**Figures 6.a and 7.a**). The MASE scores > 1 for the index of the two main fleets PS_West and BB_West indicated lower prediction skills. In general, the length compositions have better prediction skills than the indices.

A list of model parameters is provided in **Table 2.a**, including estimated values and their associated asymptotic standard errors, initial parameter values, minimum and maximum values, priors if used, and whether the parameter was fixed or estimated. Since steepness (*h*) and the sigmaR of the Beverton-Holt curve were fixed, the main productivity parameter estimated in Stock Synthesis was the average level of age-0 recruitment at unfished equilibrium spawning biomass (R0).

The estimated time series of SSB for the reference case indicated that stock decreased from the late 1970s to the early 1980s, and remained at relatively low levels during the mid-1980 and mid-1990 period. After some immediate increase in the mid-1990s, the stock remained at around 100 to 130 thousand tons until 2015. A steep decrease was observed in SSB since 2015 to the historical lowest level in 2019 and 2020 (**Figure 8.a**).

Overall, throughout the uncertainty grid results, the higher growth/M (G/M) vectors quantiles (0.75) estimated the most drastic spawning biomass declines since the early years of the time series (warmer colors in **Figure 9.a**) and the lower spawning biomass in the recent periods. In contrast, the smaller G/M quantiles (0.25) estimated the lower SSB declines and the larger spawning biomass in recent periods. Inside each G/M quantile, the larger the steepness values, the lower the spawning biomass scales (**Figure 9.a**). Regarding the recruits at age 0 (**Figure 10.a**), the larger G/M quantile estimated lower recruits numbers and a more minor variation across the time series. The larger G/M quantile estimated larger numbers of age 0 recruits (almost double) and larger variation across the time series.

When considering only the 0.75th quantile level of growth/M vector of the uncertainty grid, the stock would have reached an overfished status (SSB/SSB_{MSY} <1) for the three steepness values (**Figure 11.a**, **Table 3.a**), driven in part by estimates of recent low recruitments. For the other axes of the uncertainty grid, the stock would have never been overfished (**Figure 11.a, Table 3.a)**. On the other hand, the stock would not have ongoing overfishing across the uncertainty grid (**Figure 12.a, Table 3.a**). The highest values of F/F_{MSY} were estimated for the 0.75th quantile of the growth/M vector (**Figure 12.a, Table 3.a**).

Appendix tables

Table 1 appendix. Uncertainty grid used for sensitivity analysis for the W-SKJ reference case of the stock synthesis model.

Parameter	Value 1	Value 2	Value 3	Value 4	Value 5	Value 6	Value 7	Value 8	Value 9
Steepness	0.6	0.6	0.6	0.7	0.7	0.7	0.8	0.8	0.8
Growth param quantile	0.25	0.5	0.75	0.25	0.5	0.75	0.25	0.5	0.75

Table 2 appendix. A list of model parameters for the W-SKJ reference case of the stock synthesis model. No priors were used in this model, and no parameter was estimated at the bounds.

Label	Value	Phase	Min	Max	Init	SD	Type
SR_LN(R0)	11.4604	1	0.0001	20	11.13	0.09	SRR
Size_DblN_peak_PS_West(1)	48.6286	2	20	90	49.16	0.94	Sel
Size_DblN_top_logit_PS_West(1)	-12.1995	2	-15	15	-12.17	47.55	Sel
Size_DblN_ascend_se_PS_West(1)	4.37675	3	-4	12	4.43	0.18	Sel
Size_DblN_descend_se_PS_West(1)	4.79913	3	-10	6	4.78	0.3	Sel
Size_DblN_end_logit_PS_West(1)	-2.69686	3	-20	20	-2.28	0.5	Sel
Size_DblN_peak_BB_West(2)	55.3124	2	20	90	55.94	1.08	Sel
Size_DblN_top_logit_BB_West(2)	-11.9822	2	-15	15	-11.89	50.66	Sel
Size_DblN_ascend_se_BB_West(2)	4.87641	3	-4	12	4.9	0.18	Sel
Size_DblN_descend_se_BB_West(2)	4.67589	3	-10	6	4.73	0.32	Sel
Size_DblN_end_logit_BB_West(2)	-4.15657	3	-20	20	-4.59	4.2	Sel
Size_inflection_LL_USMX(3)	47.35	2	20	126	48.8	1.75	Sel
Size_95%width_LL_USMX(3)	8.46853	3	0.01	100	9.3	2.53	Sel
Size_inflection_LL_OTH(4)	76.1612	2	20	126	77.85	9.37	Sel
Size_95%width_LL_OTH(4)	13.601	3	0.01	100	13.43	7.28	Sel
Size_DblN_peak_HL_RR(5)	52.676	2	20	90	53.2	2.01	Sel
Size_DblN_top_logit_HL_RR(5)	-10.932	2	-15	15	-10.8	62.28	Sel
Size_DblN_ascend_se_HL_RR(5)	4.93594	3	-10	15	4.95	0.32	Sel
Size_DblN_descend_se_HL_RR(5)	3.26863	3	-10	15	2.98	1.45	Sel
Size_DblN_end_logit_HL_RR(5)	-0.99757	3	-20	20	-0.6	0.5	Sel
Size_DblN_peak_PS_West(1)_BLK1repl_2015	57.6126	2	20	90	57.63	1.7	Sel
Size_DblN_top_logit_PS_West(1)_BLK1repl_2015	-3.2507	2	-15	15	-2.98	1.07	Sel
Size_DblN_ascend_se_PS_West(1)_BLK1repl_2015	4.40235	3	-4	12	4.37	0.36	Sel
Size_DblN_descend_se_PS_West(1)_BLK1repl_2015	3.63638	3	-10	6	3.62	1.55	Sel
Size_DblN_end_logit_PS_West(1)_BLK1repl_2015	-1.39099	3	-20	20	-0.9	0.91	Sel

Table 3 appendix. Benchmarks (SD) and relative stock status for W-SKJ reference case of the stock synthesis model.

Benchmarks	Model 2
SSB_unfished	203492 (24786.5)
Totbio_unfished	224838 (27386.5)
SmryBio_unfished	143217 (174446)
Recr_unfished	91729.6 (11173.2)
SSB_Btgt	81397.0 (9914.59)
SPR_Btgt	0.464286 (5.43526e-18)
annF_Btgt	0.7266714 (0.0158299)
Dead_Catch_Btgt	29104.8 (3259.4)
SSB_SPR	66745.5 (8129.96)
annF_SPR	1.05966 (0.02459)
Dead_Catch_SPR	31234.7 (3508.28)
SSB_MSY	47362.4 (5666.87)
SPR_MSY	0.314953 (0.001639)
annF_MSY	1.92971 (0.0514836)
Dead_Catch_MSY	32536.9 (3671.47)
Ret_Catch_MSY	32536.9 (36714.7)
B_MSY/SSB_unfished	0.23274 (0.001836)

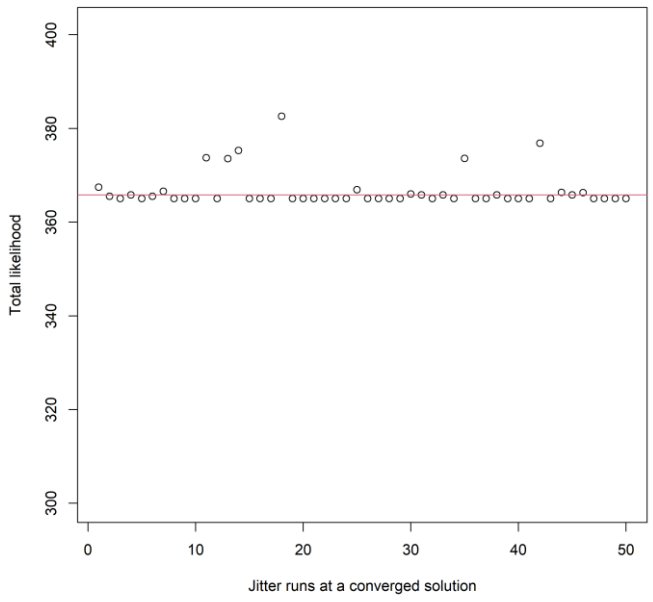


Figure 1 appendix. Jitter results for the reference case.

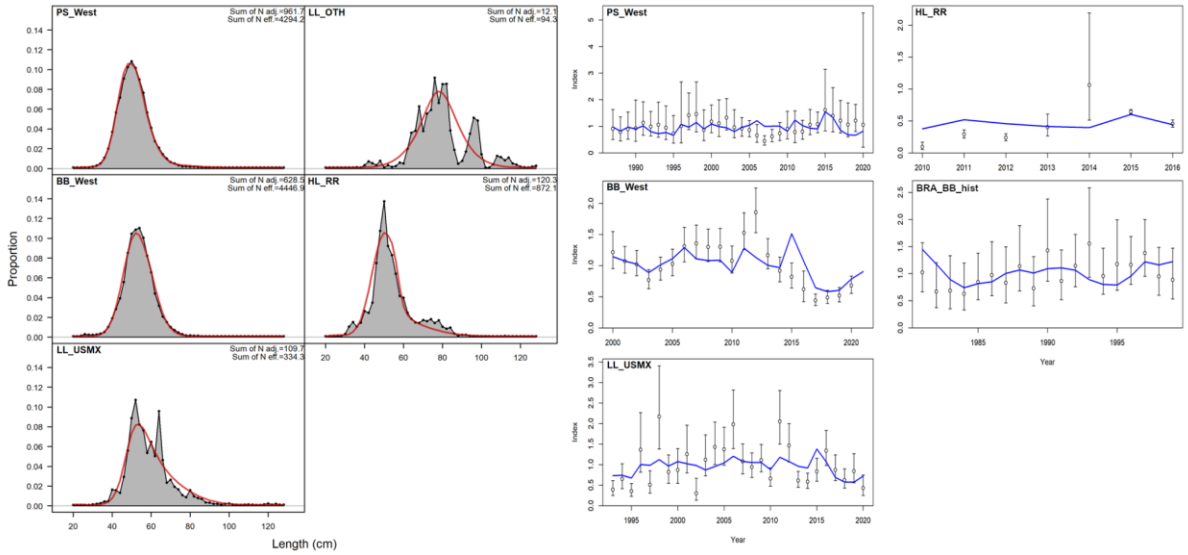


Figure 2 appendix. The model fits to the aggregated length compositions for each fleet (left panels) and for the index (right panels) for the reference case.

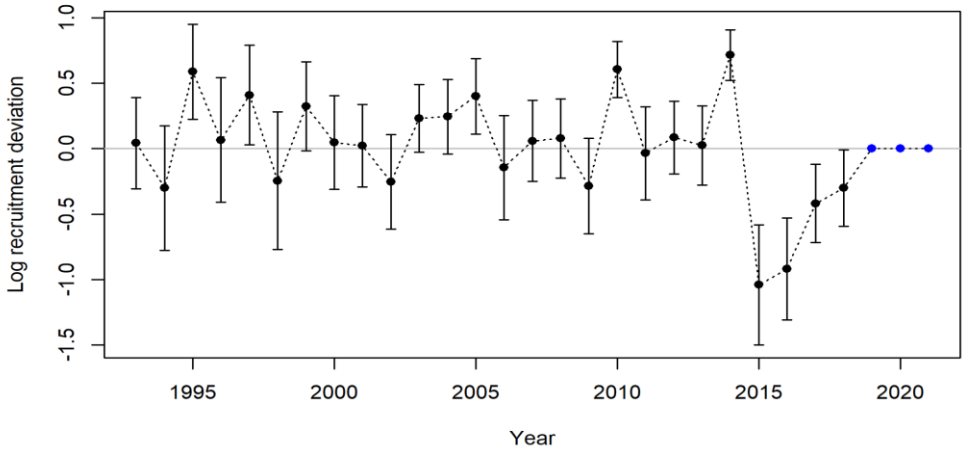


Figure 3 appendix. Recruitment deviations for the W-SKJ Stock synthesis model reference case.

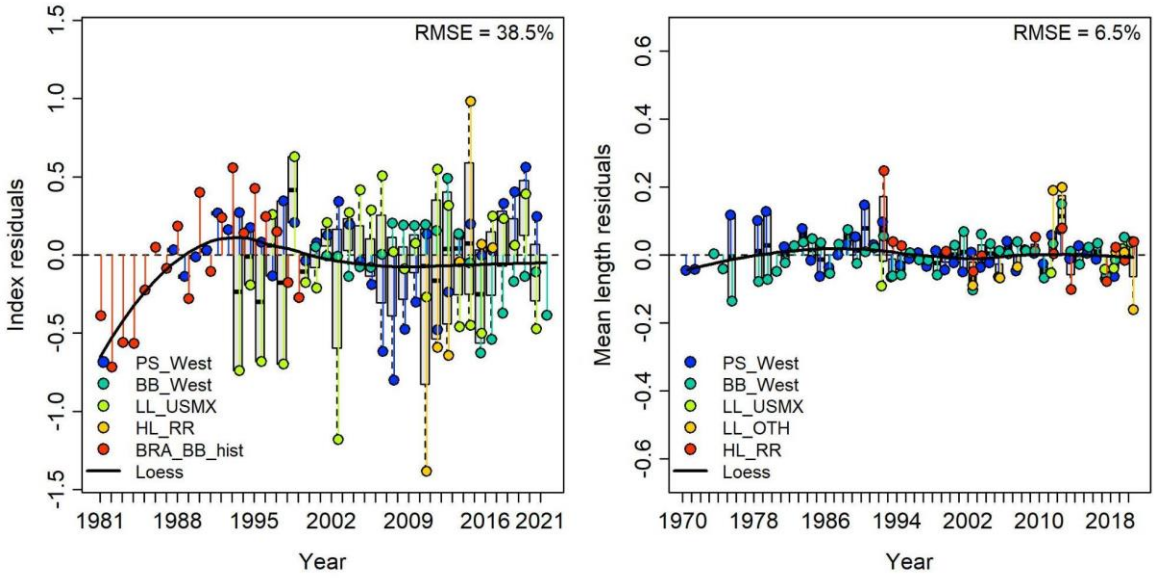


Figure 4 appendix. Joint residuals plot for the index (left panel) and length composition (right panel) fits for the W-SKJ Stock synthesis model reference case.

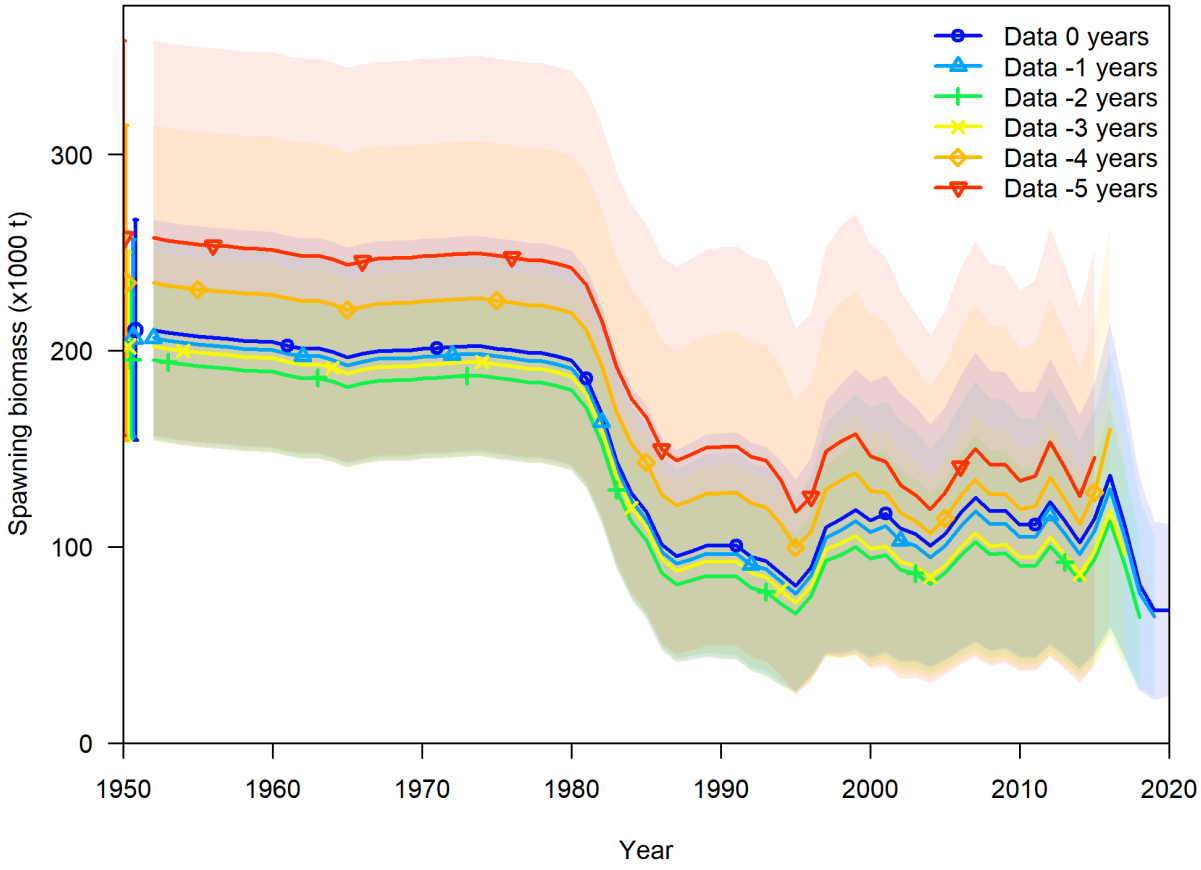


Figure 5 appendix. Retrospective plots of spawning biomass, for the W-SKJ Stock synthesis model reference case.

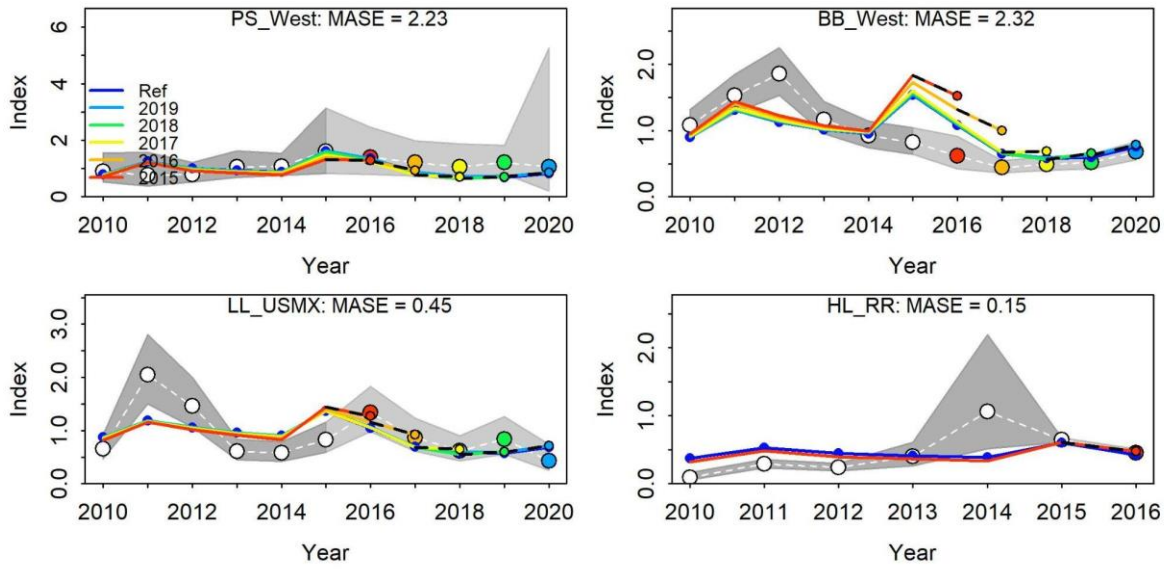


Figure 6 appendix. Hindcasting plots for the index fit for the W-SKJ Stock synthesis model reference case.

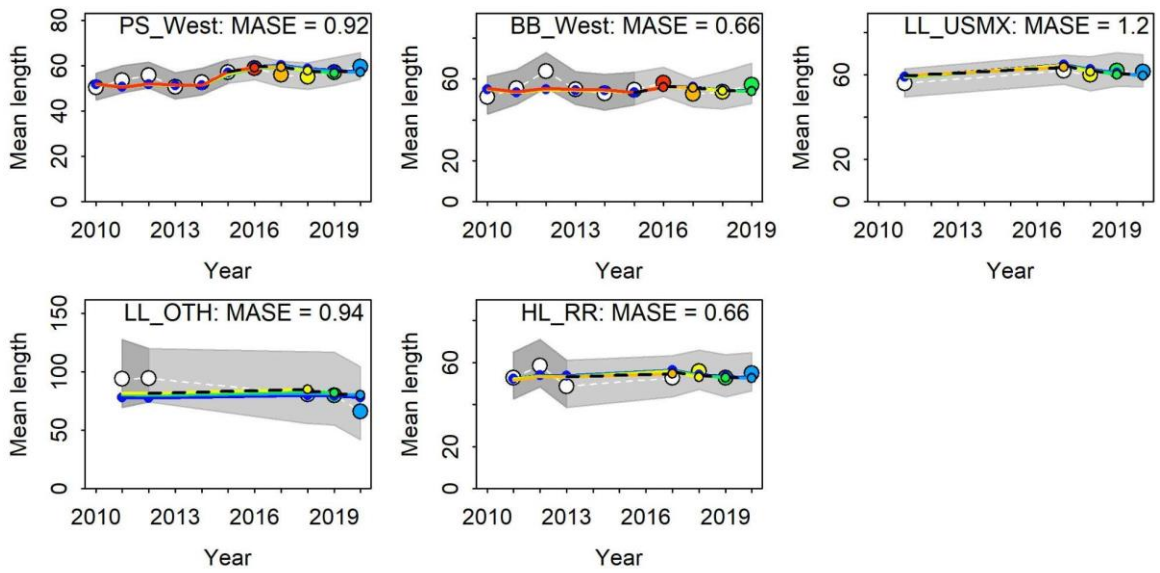


Figure 7 appendix. Hindcasting plots for the length composition fit in the W-SKJ Stock synthesis model reference case.

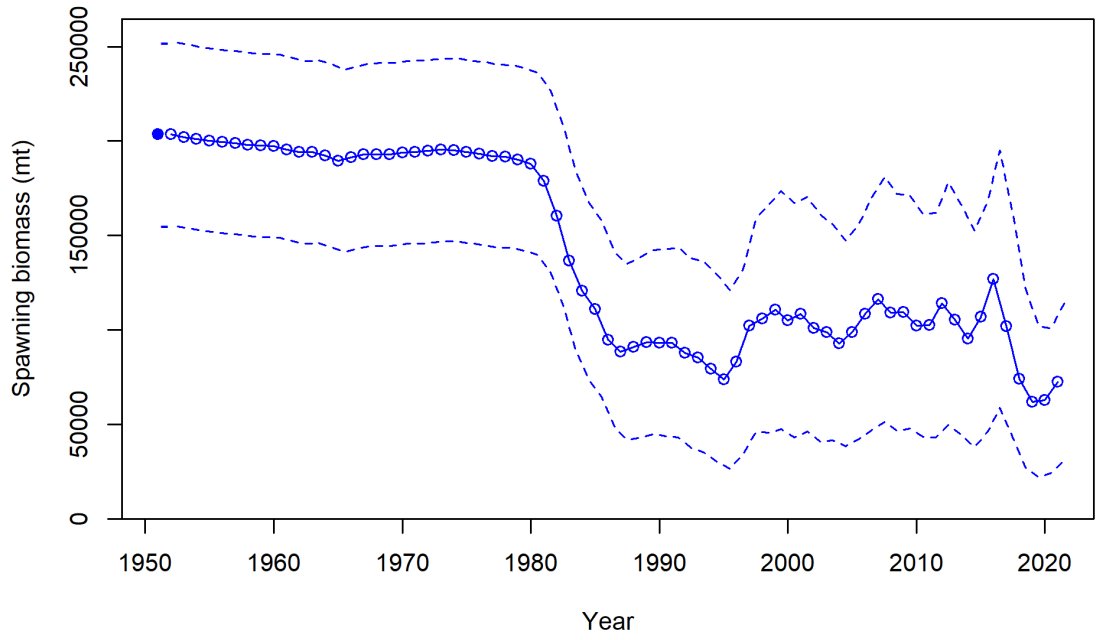


Figure 8 appendix. Spawning stock biomass estimates for the Stock Synthesis reference case of the western skipjack stock.

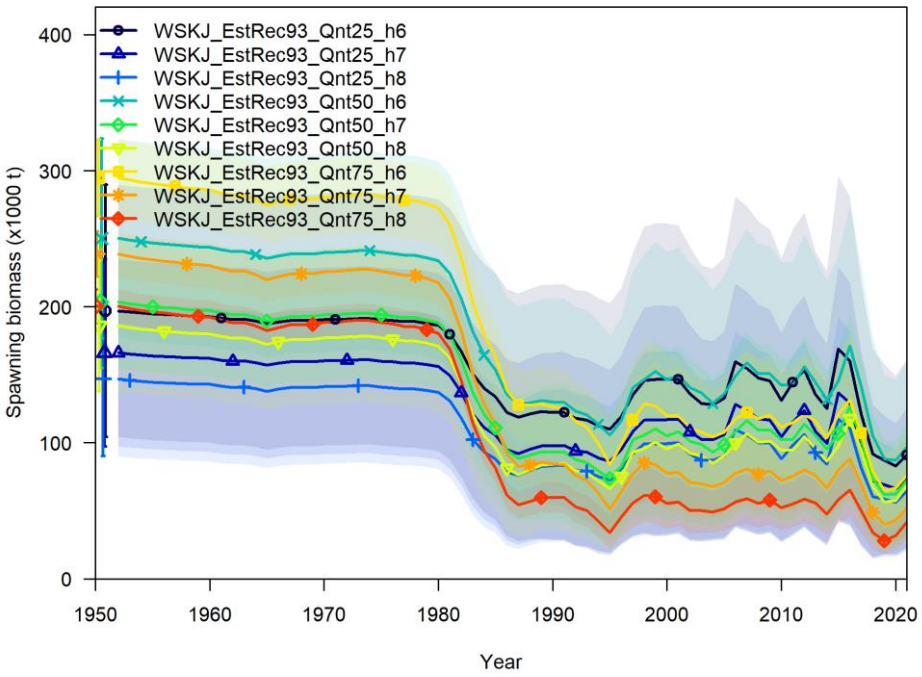


Figure 9 appendix. Spawning biomass trajectories across the Stock Synthesis uncertainty grid of the western skipjack stock.

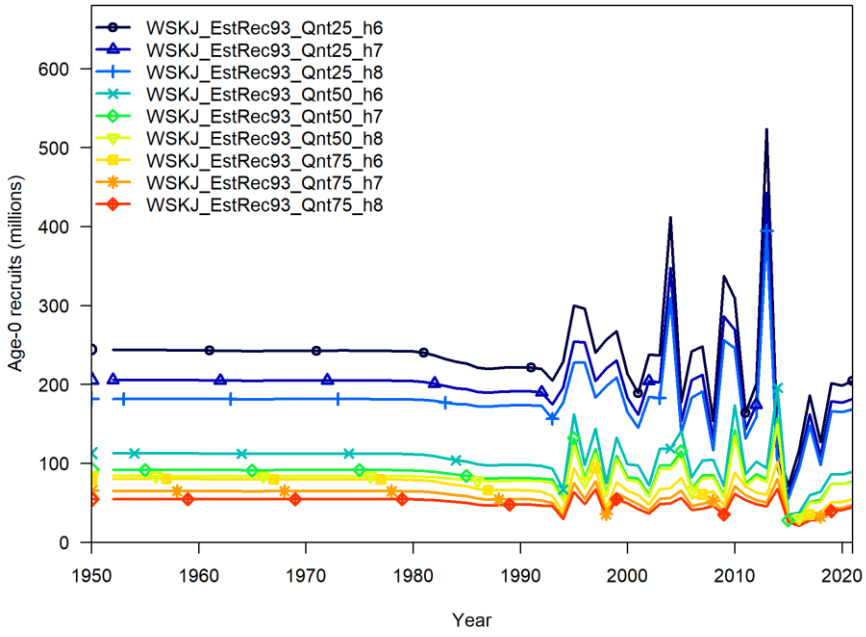


Figure 10 appendix. Age-0 recruits trajectories across the Stock Synthesis uncertainty grid of the western skipjack stock.

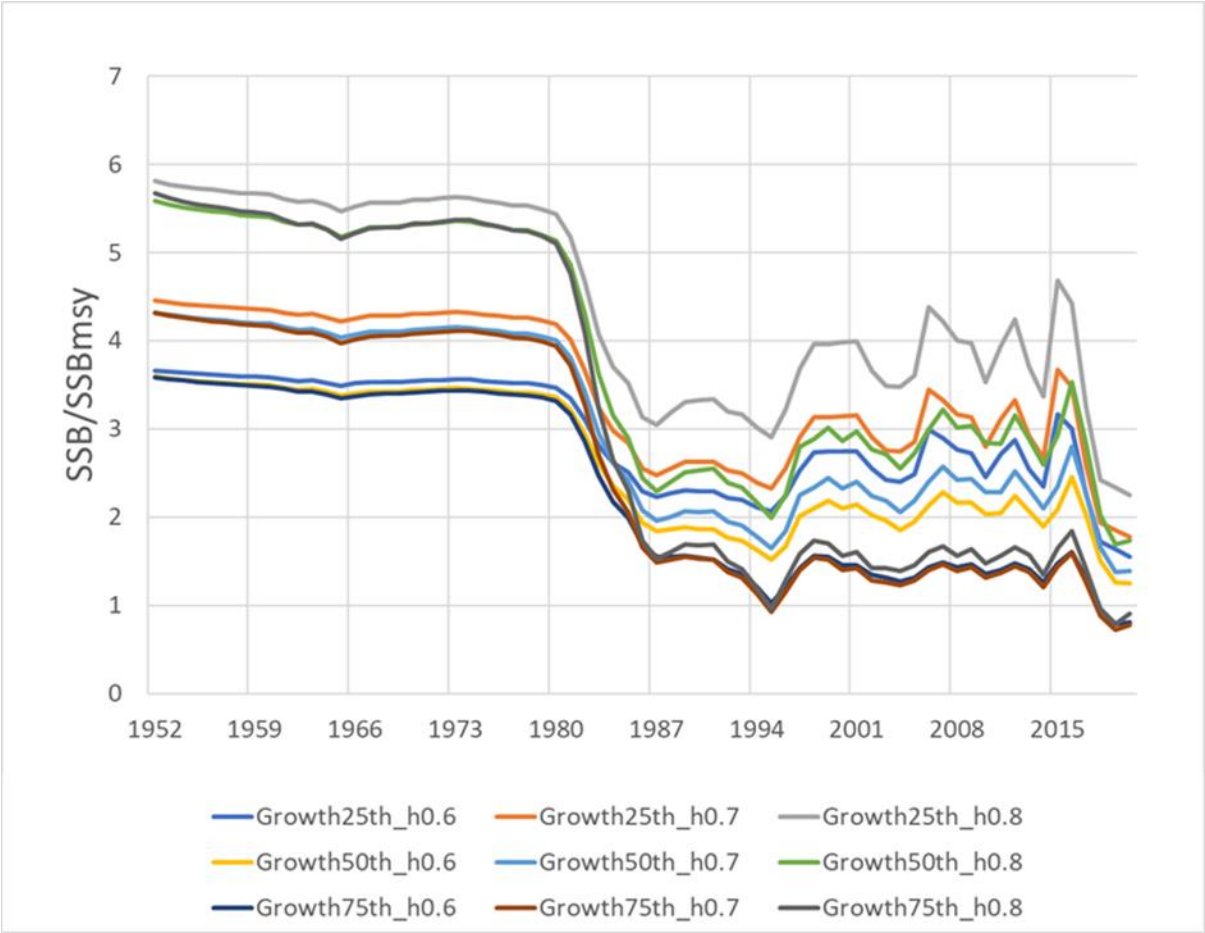


Figure 11 appendix. SSB/SSBM$_{SY}$ trajectories across the Stock Synthesis uncertainty grid of the western skipjack stock.

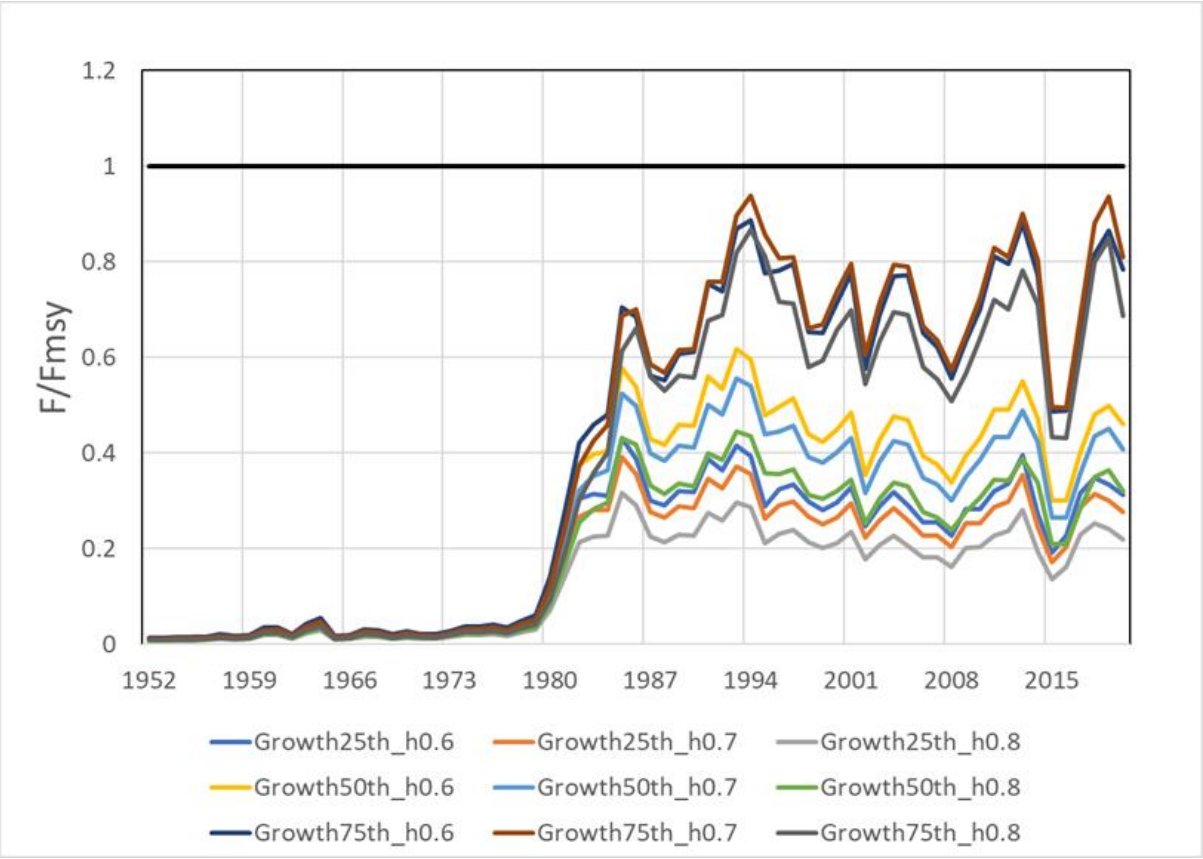


Figure 12 appendix. F/F_{MSY} trajectories across the Stock Synthesis uncertainty grid of the western skipjack stock.