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# WESTERN ATLANTIC BLUEFIN TUNA STOCK ASSESSMENT 1950-2018 USING STOCK SYNTHESIS: PART II. MODEL DIAGNOSTICS AND RESULTS

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*SUMMARY*

*This document describes a stock assessment model using Stock Synthesis (version 3.30.14) for the Western Atlantic population of bluefin tuna. This document describes model diagnostics and initial results derived from settings agreed at the Atlantic bluefin tuna Species Group in May 2020, which were only slightly changed from those used in 2017, commensurate with this being a strict update. The diagnostics result showed relatively good performance with some negative signs, while those problems similarly occurred in last assessment. The two model runs showed very similar behavior with the stock decreasing during the 1970s, remaining relatively low during the 1980-2000 period and showing a pattern of steady population growth since 2000. The addition of three years of data (2016-2018) indicates a relatively stable population trend. This paper represents the second in a series of three papers that will describe the update assessment process.*

*RÉSUMÉ*

*Ce document décrit un modèle d'évaluation des stocks utilisant Stock Synthesis (version 3.30) pour la population de thon rouge de l'Atlantique Ouest. Ce document décrit les diagnostics du modèle et les premiers résultats obtenus à partir des paramètres convenus en mai 2020 au sein du Groupe d'espèces sur le thon rouge de l'Atlantique, qui n'ont été que légèrement modifiés par rapport à ceux utilisés en 2017, dans la mesure où il s'agit d'une mise à jour stricte. Le résultat des diagnostics a montré une performance relativement bonne avec quelques signes négatifs, alors que ces problèmes se sont produits de la même manière lors de la dernière évaluation. Les deux scénarios du modèle ont montré un comportement très similaire, le stock diminuant dans les années 70, demeurant relativement faible durant la période 1980-2000 et faisant apparaître un schéma de croissance constante de la population depuis 2000. L'ajout de trois années de données (2016-2018) indique une tendance relativement stable de la population. Ce document est le deuxième d'une série de trois documents qui décriront le processus d'actualisation de l'évaluation.*

*RESUMEN*

*Este documento describe un modelo de evaluación de stock que utiliza Stock Synthesis (versión 3.30.14) para la población de atún rojo del Atlántico occidental. Este documento describe los diagnósticos del modelo y los resultados iniciales derivados de las especificaciones acordadas en el Grupo de especies de atún rojo del Atlántico en mayo de 2020, que fueron ligeramente cambiadas respecto a las usadas en 2017, de acuerdo con ser una estricta actualización. El resultado de los diagnósticos mostró un desempeño relativamente bueno, con algunos signos negativos, aunque estos problemas ocurrieron igual en la última evaluación. Los dos ensayos del modelo mostraban un comportamiento similar, con el stock descendiendo durante los 70, permaneciendo relativamente bajo durante el periodo 1980-2000 y mostrando un patrón constante de crecimiento de la población desde 2000. El añadido de tres años de datos (2016-2018) indica una tendencia relativamente estable de la población. Este documento representa el segundo de una serie de tres documentos que describirán el proceso de actualización de la evaluación.*

*KEYWORDS*

*Stock assessment, bluefin tuna, Stock Synthesis*

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## Introduction

Stock Synthesis 3 (SS3) is an integrated statistical catch-at-age model which is widely used for many stock assessments in the United States and throughout the world (Methot and Wetzel 2013 http:// https://vlab.ncep.noaa.gov/web/stock-synthesis). SS3 takes relatively unprocessed input data and incorporates many of the important processes (mortality, selectivity, growth, etc.) that operate in conjunction to produce observed catch, size and age composition and CPUE indices. Because many of these inputs are correlated, the concept behind SS3 is that they should be modeled together, which helps to ensure that uncertainties in the input data are properly accounted for in the assessment. SS3 is comprised of three subcomponents: 1) a population subcomponent that recreates an estimate of the numbers/biomass at age using estimates of natural mortality, growth, fecundity, etc.; 2) an observational sub-component that consists of observed (measured) quantities such as CPUE or proportion at length/age; and 3) a statistical sub-component that uses likelihoods to quantify the fit of the observations to the recreated population.

According to the terms of reference outlined in the 2019 SCRS report (Anon 2020, Appendix 5) the stock assessment in 2020 represents as strict of an update of the 2017 stock assessment as possible. The 2017 assessment terminal year of data was 2015 and for this assessment we update with data up until 2018. Input data and model settings agreed in SCRS ABTWG in May 2020 were used (SCRS/2020/072) with SS 3.30.14. There were two models by maturity schedules; model 1 was assumed to be a late maturity schedule (100% maturity at age 13) and model 2 was assumed to be earlier maturity schedule (100% maturity at age 5). This paper describes the model diagnostics and assessment results derived from agreed final model settings at the first BFT intersessional meeting in May 2020. A subsequent paper (Part III) will describe projections on the results shown in this document.

## Model Diagnostics

*Model diagnostics*

The appropriateness of model convergence was assessed using several means (SCRS/2020/072).

1. Whether the Hessian, (i.e., the matrix of second derivatives of the likelihood with respect to the parameters) inverts.
2. The maximum gradient component which, ideally, should be low.
3. 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 according to a normal distribution defined where the pr(par min)=0.01 and pr(par max)=0.99).
4. Parameter coefficients of variation where the CV of the parameter estimate comes from the model estimated variance from the variance-covariance matrix.
5. Likelihood profiles were completed for three key model parameters: steepness of the stock-recruit relationship ($h$) and the log of unexploited equilibrium recruitment ($R_0$) and sigma R.
6. Evaluation of fits to the indices and length composition.
7. Retrospective analyses. Retrospective analyses are also standard diagnostic practice and were conducted on models 1-2 with 5 year retrospective peels.
8. Sensitivity to sets of different indices (index jackknife evaluation)
9. Parametric bootstrapping to evaluate observation error in parameter estimates and derived quantities.

Both models show nearly identical diagnostic performance and very similar log-likelihoods and thus can be discussed as a single model with regard to the diagnostics. The Hessian matrices were defined positive for the both models and the standard deviations for every parameter could be estimated (**Table 1** and **2**).

No parameters hit bounds and most parameters showed relatively low standard deviations relative to the estimated values, indicating good estimation. The models show relatively good diagnostic performance though the maximum gradient components are slightly higher than desired (usually less than 0.0001) (**Table 3**). Derived quantities, benchmarks and standard errors indicate relatively well determined values (**Table 4**).

Some runs for both models in the jitter analysis had much higher log-likelihood than the global solution, which seems not to achieve good convergence (**Figures 1a** and **1b**), however global solutions were found for both models and the practical result of this instability is negligible (**Figures 2a** and **2b**).

Both models converge on particular solution of steepness, sigmaR and R0 (**Figures 3 and 4**), though there is some conflict among data sources for steepness and sigmaR. Notably the length composition data diverges from other data sources.

Fits to indices are generally fairly poor for both models (**Figures 5 and 6**). A fit to index from the Canadian acoustic survey looks relatively better than the other indices, though a decline in the acoustic index in 2017 could not be fit even when the acoustic data point in 2018 was removed.

Overall the length composition data are fairly well fit with few systematic departures (**Figures 7 and 8**). Fits for each year and each fleet indicate that while most fits are good, there are many years with departures, which also appeared in the result of last assessment. Problematic departures can be seen in the Pearson residuals where one would look for strong patterned trends. Of particular note is the recent residual pattern in the length composition of the JAPAN_LL where there remain strong positive residuals along a diagonal and a near absence of fish below this diagonal from about 2000 onward. This pattern is somewhat evident in the OTHER_ATL_LL and the CAN_HL residuals and can be seen in the raw data (**Figures 9 and 10**).

Retrospective performance of the models is good (**Figure 11**) with no perceptible pattern in SSB. There are some patterns in the terminal year estimate of recruitment. This is due to the bias adjustment ramping, which is assumed for recruitment deviation to be 0 at terminal year. The values of Mohn's rho of SSB are 0.17 and 0.01, and those of recruitment are -0.01 and -0.01 for model 1 and model 2, respectively. All Mohn's rho values are less than 0.2, hence the retrospective patterns could be negligible.

The performance evaluations of each index by jackknife analysis indicate that every index does not have strong impacts on over all trajectories of SSB and recruitment, while there were differences of the SSB in the recent years due to the instability of recruitment estimation, especially for the model without a US_RR_66_114 index (**Figure 12**). This index represents stock trend for the youngest life stage among indices, which means this is most informative for recruitment estimation. The difference in recruitment between the model without US_RR_66_114 index and the other jackknife models may suggest the conflict of the indices themselves. Further investigation of the index for this younger life stage will be important for achieving robust assessment for this species.

Bootstrapping results indicate that the base models which are without data perturbation are relatively well aligned with and mostly centered on the 100 bootstrap replicates for both SSB and recruitment (**Figure 13**). The estimates from the original run for two of three stock-recruitment relationships ($R_0$ and steepness) were generally near the center of the histogram of estimates from the bootstrap replicates (**Figure 14**). However, for sigmaR, the estimate from the original run was higher than those from every bootstrap replicate for both models. This may be a product of the bootstraps being created from an assumed multinomial distribution and resampling in accordance with input sample size for the length composition information. Hence the composition data may be far less noisy then the real data, resulting in reduced estimates of recruitment variability, though this does not appear to affect the SSB and recruitment trends.

*Model results*

Estimated selectivities generally reflected assumed patterns of the actual fisheries (**Figures 15 and 16**). The doming of the Japan_LL is fairly steep but seems rather well determined by the fact that several fleets have asymptotic selectivity and capture much larger fish on average. The size composition is extremely sharp, indicating that it could be a product of several cohorts and that due to the short time period of data the lack of fit may be due to the effect of a transient cohort. Given that this represents some of the earliest length composition in the model this could be one of the factors influencing some of the initial model instability in estimating the earliest recruitment deviations.

Overall, the times series of SSB and recruitment and other derived parameters are extremely similar between the two model runs indicating a relatively limited effect of changing the age at maturity on model fit or model performance (**Figure 17**). While SSB is scaled higher or lower the resulting total biomass estimates and relative levels of depletion from virgin are very similar. Both models indicate stock decline during the 1970s, remaining relatively low during the 1980-2000 period, and showing a pattern of steady population growth since 2000. Fishing mortality has generally decreased in the most recent 20 years. While levels of fishing mortality for both models were relatively stable since 2010, the SSB trends, especially for model 2, shows peaking out since 2015. The time series of SSB and recruitment also show less evidence of a 'regime change' in the longer time series and more an indication of recruitment declining due to a decline in SSB.

**Acknowledgements**

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**References**

Anonymous (2020) Report of the 2019 Standing Committee on Research and Statistics (SCRS).

Methot, R.D. (2000) Technical description of the stock synthesis assessment program. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-43, 46 p.

Methot, R.D. and Wetzel C.R. (2013) Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management, Fisheries Research 142: 86-99.

Tsukahara, Y., Walter, J., Kimoto, A., Ortiz, M., (2020) Western Atlantic Bluefin Tuna Stock Assessment 1950-2018 using stock synthesis: Part i. Model Specification and Data, ICCAT - SCRS/2020/072.

**Table 1.** Parameter estimates, phases initial values and standard deviations for model 1. Rec devs not shown.

| Label | Value | Phase | Min | Max | Init | StDev | Gradient |
|---|---|---|---|---|---|---|---|
| NatM_p_1_Fem_GP_1 | 0.10 | -3 | 0.05 | 0.3 | 0.10 | – | – |
| L_at_Amin_Fem_GP_1 | 42.98 | -2 | 0 | 50 | 42.98 | – | – |
| L_at_Amax_Fem_GP_1 | 264.07 | 4 | 200 | 400 | 264.07 | 0.75 | -9.7E-04 |
| VonBert_K_Fem_GP_1 | 0.30 | 4 | 0.05 | 0.4 | 0.30 | 0.01 | 7.4E-03 |
| Richards_Fem_GP_1 | -0.95 | 4 | -3 | 3 | -0.95 | 0.08 | 1.7E-02 |
| CV_young_Fem_GP_1 | 0.09 | 3 | 0.05 | 0.25 | 0.09 | 0.01 | 2.9E-04 |
| CV_old_Fem_GP_1 | 0.07 | 3 | 0.02 | 0.25 | 0.07 | 0.00 | 8.0E-05 |
| Wtlen_1_Fem_GP_1 | 0.00 | -3 | 1.00E-08 | 0.01 | 0.00 | – | – |
| Wtlen_2_Fem_GP_1 | 3.00 | -3 | 2 | 4 | 3.00 | – | – |
| Mat50%_Fem_GP_1 | 8.80 | -3 | 4 | 15 | 8.80 | – | – |
| Mat_slope_Fem_GP_1 | -50 | -3 | -100 | -1 | -50 | – | – |
| Eggs_scalar_Fem_GP_1 | 1.00 | -3 | 1 | 1 | 1.00 | – | – |
| Eggs_exp_wt_Fem_GP_1 | 1.00 | -3 | 1 | 1 | 1.00 | – | – |
| RecrDist_GP_1 | 0.00 | -4 | 0 | 0 | 0.00 | – | – |
| RecrDist_Area_1 | 0.00 | -4 | 0 | 0 | 0.00 | – | – |
| RecrDist_month_1 | 0.00 | -4 | 0 | 0 | 0.00 | – | – |
| CohortGrowDev | 1.00 | -1 | 0.1 | 10 | 1.00 | – | – |
| FracFemale_GP_1 | 0.50 | -99 | 1.00E-06 | 0.99999 | 0.50 | – | – |
| SR_LN(R0) | 6.38 | 1 | 5 | 10 | 7.00 | 0.04 | 2.3E-02 |
| SR_BH_steep | 0.63 | 2 | 0.2 | 0.99 | 0.62 | 0.03 | 2.0E-03 |
| SR_sigmaR | 0.79 | 6 | 0.2 | 2 | 0.78 | 0.09 | -3.1E-03 |
| SR_regime | 0.00 | -4 | -5 | 5 | 0.00 | – | – |
| SR_autocorr | 0.00 | -99 | 0 | 0 | 0.00 | – | – |
| InitF_seas_1_flt_4USA_TRAP | 0.02 | 5 | 1.00E-05 | 0.03 | 0.02 | 0.00 | -1.3E-04 |
| InitF_seas_1_flt_5USA_CAN_HARPOON | 0.00 | -5 | 1.00E-05 | 1 | 0.00 | – | – |
| LnQ_base_IDX1_JAPAN_LL | -4.92 | -1 | -25 | -2 | -4.90 | – | – |
| LnQ_base_IDX2_US_RR_66_114 | -5.24 | -1 | -25 | -2 | -5.19 | – | – |
| LnQ_base_IDX3_US_RR_115_144 | -4.06 | -1 | -25 | -2 | -4.01 | – | – |
| LnQ_base_IDX4_US_RR_LT145 | -5.40 | -1 | -25 | -2 | -5.39 | – | – |
| LnQ_base_IDX5_US_RR_GT177 | -4.51 | 1 | -10 | -2 | -4.43 | 0.07 | 8.9E-05 |
| LnQ_base_IDX6_US_RR_GT195 | -4.35 | -1 | -25 | -2 | -4.34 | – | – |
| LnQ_base_IDX7_USPLL_GOM | -3.56 | -1 | -25 | -1 | -3.57 | – | – |
| LnQ_base_IDX8_JLL_GOM | -5.01 | -1 | -25 | -2 | -5.01 | – | – |
| LnQ_base_IDX9_CAN_GSLNS | -4.40 | 1 | -10 | -2 | -4.38 | 0.06 | 8.8E-05 |
| LnQ_base_IDX10_GOMlarval | -4.38 | -1 | -25 | -2 | -4.35 | – | – |
| LnQ_base_IDX12_CAN_ACOUSTIC | -5.60 | 1 | -10 | -2 | -5.78 | 0.11 | 1.0E-04 |
| LnQ_base_IDX13_oceanographic | -1.62 | -1 | -25 | -0.001 | -1.61 | – | – |
| LnQ_base_IDX14_JAPAN_LL2 | -3.55 | -1 | -25 | -1 | -3.46 | – | – |
| LnQ_base_IDX15_USPLL_GOM_LL2 | -3.84 | -1 | -25 | -1 | -3.80 | – | – |
| LnQ_base_IDX5_US_RR_GT177_ENV_mult | 0.13 | 3 | -5 | 5 | 0.00 | 0.05 | -1.3E-04 |
| LnQ_base_IDX9_CAN_GSLNS_ENV_mult | -0.28 | 3 | -5 | 5 | 0.00 | 0.04 | -1.3E-04 |
| LnQ_base_IDX12_CAN_ACOUSTIC_ENV_mult | -0.08 | 3 | -5 | 5 | 0.00 | 0.04 | -2.0E-04 |
| Size_DblN_peak_JAPAN_LL | 211.71 | 2 | 120 | 230 | 211.96 | 2.89 | 9.5E-07 |
| Size_DblN_top_logit_JAPAN_LL | -9.72 | 2 | -10 | 3 | -9.72 | 7.89 | 2.1E-07 |
| Size_DblN_ascend_se_JAPAN_LL | 6.84 | 3 | -5 | 9 | 6.84 | 0.16 | 2.4E-06 |
| Label | Value | Phase | Min | Max | Init | StDev | Gradient |
| Size_DblN_descend_se_JAPAN_LL | 7.74 | -2 | -5.00 | 9.00 | 7.74 | _ | _ |
| Size_DblN_start_logit_JAPAN_LL | -999.00 | -3 | -999.00 | 15.00 | -999.00 | _ | _ |
| Size_DblN_end_logit_JAPAN_LL | -12.02 | 4 | -20.00 | 10.00 | -12.04 | 101.13 | -2.0E-07 |
| Size_DblN_peak_USA_CAN_PSFS | 68.50 | -2 | 50.00 | 80.00 | 68.50 | _ | _ |
| Size_DblN_top_logit_USA_CAN_PSFS | -1.00 | -3 | -5.00 | 3.00 | -1.00 | _ | _ |
| Size_DblN_ascend_se_USA_CAN_PSFS | 3.72 | 4 | -4.00 | 12.00 | 3.72 | 0.44 | -1.5E-03 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Size_DblN_descend_se_USA_CAN_PSFS | -5.00 | -3 | -5.00 | 6.00 | -5.00 | _ | _ |
| Size_DblN_start_logit_USA_CAN_PSFS | -999.00 | -2 | -15.00 | 5.00 | -999.00 | _ | _ |
| Size_DblN_end_logit_USA_CAN_PSFS | -999.00 | -2 | -15.00 | 10.00 | -999.00 | _ | _ |
| Size_DblN_peak_USA_CAN_PSFB | 213.67 | -1 | 150.00 | 250.00 | 213.67 | _ | _ |
| Size_DblN_top_logit_USA_CAN_PSFB | -2.39 | 2 | -5.00 | 3.00 | -2.42 | 0.33 | 3.2E-05 |
| Size_DblN_ascend_se_USA_CAN_PSFB | 6.92 | 3 | -4.00 | 8.00 | 6.92 | 0.07 | -3.8E-05 |
| Size_DblN_descend_se_USA_CAN_PSFB | 6.00 | -3 | -2.00 | 6.00 | 6.00 | _ | _ |
| Size_DblN_start_logit_USA_CAN_PSFB | -999.00 | -2 | -15.00 | 5.00 | -999.00 | _ | _ |
| Size_DblN_end_logit_USA_CAN_PSFB | -2.32 | 4 | -15.00 | 5.00 | -2.31 | 0.51 | 8.6E-05 |
| Size_DblN_peak_USA_TRAP | 114.23 | 1 | 80.00 | 150.00 | 114.23 | 11.30 | 2.0E-04 |
| Size_DblN_top_logit_USA_TRAP | -1.89 | 3 | -5.00 | 3.00 | -1.89 | 0.63 | 1.5E-04 |
| Size_DblN_ascend_se_USA_TRAP | 7.16 | 3 | -4.00 | 8.00 | 7.16 | 0.48 | -2.4E-04 |
| Size_DblN_descend_se_USA_TRAP | 7.25 | 3 | -2.00 | 10.00 | 7.25 | 0.51 | 2.0E-04 |
| Size_DblN_start_logit_USA_TRAP | -999.00 | -2 | -15.00 | 5.00 | -999.00 | _ | _ |
| Size_DblN_end_logit_USA_TRAP | -999.00 | -2 | -15.00 | 10.00 | -999.00 | _ | _ |
| Size_inflection_USA_CAN_HARPOON | 177.04 | 2 | 100.00 | 220.00 | 177.02 | 0.81 | 4.1E-05 |
| Size_95%width_USA_CAN_HARPOON | 17.05 | 2 | 10.00 | 60.00 | 17.05 | 1.14 | -2.0E-06 |
| Size_DblN_peak_USA_RRFB | 192.76 | 1 | 140.00 | 220.00 | 192.86 | 0.82 | 4.9E-05 |
| Size_DblN_top_logit_USA_RRFB | -0.55 | -3 | -5.00 | 1.00 | -0.55 | _ | _ |
| Size_DblN_ascend_se_USA_RRFB | 6.57 | -3 | -4.00 | 8.00 | 6.57 | _ | _ |
| Size_DblN_descend_se_USA_RRFB | 6.00 | -3 | -2.00 | 8.00 | 6.00 | _ | _ |
| Size_DblN_start_logit_USA_RRFB | -999.00 | -2 | -15.00 | 5.00 | -999.00 | _ | _ |
| Size_DblN_end_logit_USA_RRFB | -0.87 | 2 | -15.00 | 5.00 | -0.90 | 0.31 | 7.9E-05 |
| Size_DblN_peak_USA_RRFS | 106.40 | 1 | 80.00 | 120.00 | 106.41 | 0.61 | 6.9E-06 |
| Size_DblN_top_logit_USA_RRFS | -1.50 | -2 | -5.00 | 3.00 | -1.50 | _ | _ |
| Size_DblN_ascend_se_USA_RRFS | 6.49 | -3 | -4.00 | 8.00 | 6.49 | _ | _ |
| Size_DblN_descend_se_USA_RRFS | 0.97 | -3 | -2.00 | 4.00 | 0.97 | _ | _ |
| Size_DblN_start_logit_USA_RRFS | -999.00 | -2 | -15.00 | 5.00 | -999.00 | _ | _ |
| Size_DblN_end_logit_USA_RRFS | -5.00 | -2 | -15.00 | 10.00 | -5.00 | _ | _ |
| Size_inflection_OTHER_ATL_LL | 157.08 | 2 | 100.00 | 200.00 | 157.01 | 2.11 | 2.4E-05 |
| Size_95%width_OTHER_ATL_LL | 46.20 | 2 | 10.00 | 100.00 | 46.19 | 2.07 | -8.3E-06 |
| Size_inflection_CAN_HOOKLINE | 194.69 | 2 | 150.00 | 250.00 | 194.54 | 1.37 | -4.5E-06 |
| Size_95%width_CAN_HOOKLINE | 32.81 | 2 | 30.00 | 50.00 | 32.70 | 1.53 | 3.3E-07 |
| Size_inflection_GOM_LL_US_MEX | 213.83 | 2 | 150.00 | 250.00 | 213.50 | 2.14 | 4.6E-07 |
| Size_95%width_GOM_LL_US_MEX | 38.84 | 2 | 20.00 | 50.00 | 38.56 | 2.28 | -3.9E-07 |
| Size_inflection_JLL_GOM | 200.13 | 2 | 150.00 | 250.00 | 200.06 | 3.98 | 2.3E-05 |
| Size_95%width_JLL_GOM | 22.37 | 2 | 10.00 | 50.00 | 22.34 | 4.86 | -1.4E-06 |
| Size_inflection_CAN_TRAP | 253.09 | 2 | 230.00 | 300.00 | 252.91 | 3.90 | 3.4E-06 |
| Size_95%width_CAN_TRAP | 55.12 | 2 | 40.00 | 80.00 | 55.21 | 2.72 | -1.1E-06 |
| Size_inflection_CAN_GSL1 | 255.52 | 2 | 200.00 | 300.00 | 255.40 | 1.73 | -4.5E-05 |
| Size_95%width_CAN_GSL1 | 19.13 | 2 | 10.00 | 50.00 | 19.46 | 2.24 | 1.7E-06 |
| Size_DblN_peak_IDX2_US_RR_66_114 | 65.00 | -3 | 40.00 | 200.00 | 65.00 | _ | _ |
| Size_DblN_top_logit_IDX2_US_RR_66_114 | -1.70 | -3 | -5.00 | 3.00 | -1.70 | _ | _ |
| Label | Value | Phase | Min | Max | Init | StDev | Gradient |
| Size_DblN_ascend_se_IDX2_US_RR_66_114 | -4.00 | -3 | -4.00 | 12.00 | -4.00 | _ | _ |
| Size_DblN_descend_se_IDX2_US_RR_66_114 | -2.00 | -3 | -2.50 | 6.00 | -2.00 | _ | _ |
| Size_DblN_start_logit_IDX2_US_RR_66_114 | -999.00 | -2 | -15.00 | 5.00 | -999.00 | _ | _ |
| Size_DblN_end_logit_IDX2_US_RR_66_114 | -5.00 | -2 | -15.00 | 10.00 | -5.00 | _ | _ |
| Size_DblN_peak_IDX3_US_RR_115_144 | 115.00 | -3 | 40.00 | 200.00 | 115.00 | _ | _ |
| Size_DblN_top_logit_IDX3_US_RR_115_144 | -2.10 | -3 | -5.00 | 3.00 | -2.10 | _ | _ |
| Size_DblN_ascend_se_IDX3_US_RR_115_144 | -4.00 | -3 | -4.00 | 12.00 | -4.00 | _ | _ |
| Size_DblN_descend_se_IDX3_US_RR_115_144 | -2.00 | -3 | -2.50 | 6.00 | -2.00 | _ | _ |
| Size_DblN_start_logit_IDX3_US_RR_115_144 | -999.00 | -2 | -15.00 | 5.00 | -999.00 | _ | _ |
| Size_DblN_end_logit_IDX3_US_RR_115_144 | -5.00 | -2 | -15.00 | 10.00 | -5.00 | _ | _ |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Size_DblN_peak_JAPAN_LL_BLK1repl_1950 | 162.00 | -5 | 120.00 | 230.00 | 162.00 | _ | _ |
| Size_DblN_peak_JAPAN_LL_dev_se | 50.00 | -5 | 0.00 | 100.00 | 50.00 | _ | _ |
| Size_DblN_peak_JAPAN_LL_dev_autocorr | 0.00 | -6 | -0.99 | 0.99 | 0.00 | _ | _ |
| Size_DblN_top_logit_JAPAN_LL_BLK1repl_1950 | -4.13 | 5 | -10.00 | 1.00 | -4.19 | 0.75 | 2.2E-04 |
| Size_DblN_ascend_se_JAPAN_LL_BLK1repl_1950 | 7.60 | 5 | -1.00 | 9.00 | 7.60 | 0.03 | -1.1E-03 |
| Size_DblN_descend_se_JAPAN_LL_BLK1repl_1950 | 7.74 | -2 | -1.00 | 9.00 | 7.74 | _ | _ |
| Size_DblN_start_logit_JAPAN_LL_BLK1repl_1950 | -999.00 | -3 | -5.00 | 15.00 | -999.00 | _ | _ |
| Size_DblN_end_logit_JAPAN_LL_BLK1repl_1950 | -4.61 | 5 | -20.00 | 1.00 | -4.63 | 0.78 | 3.5E-04 |
| Size_DblN_peak_USA_RRFS_BLK3repl_1950 | 88.46 | 4 | 60.00 | 110.00 | 88.46 | 0.80 | 3.1E-04 |
| Size_DblN_top_logit_USA_RRFS_BLK3repl_1950 | -1.50 | -2 | -5.00 | 3.00 | -1.50 | _ | _ |
| Size_DblN_ascend_se_USA_RRFS_BLK3repl_1950 | 6.49 | -3 | -4.00 | 10.00 | 6.49 | _ | _ |
| Size_DblN_descend_se_USA_RRFS_BLK3repl_1950 | 0.97 | -3 | -2.00 | 4.00 | 0.97 | _ | _ |
| Size_DblN_start_logit_USA_RRFS_BLK3repl_1950 | -999.00 | -2 | -15.00 | 5.00 | -999.00 | _ | _ |
| Size_DblN_end_logit_USA_RRFS_BLK3repl_1950 | -5.00 | -2 | -15.00 | 10.00 | -5.00 | _ | _ |
| Size_DblN_peak_JAPAN_LL_DEVrwalk_2011 | -0.81 | 6 | -10.00 | 10.00 | 0.00 | 0.11 | 3.7E-06 |
| Size_DblN_peak_JAPAN_LL_DEVrwalk_2012 | 0.31 | 6 | -10.00 | 10.00 | 0.00 | 0.13 | 7.3E-06 |
| Size_DblN_peak_JAPAN_LL_DEVrwalk_2013 | 0.64 | 6 | -10.00 | 10.00 | 0.00 | 0.14 | 1.4E-05 |
| Size_DblN_peak_JAPAN_LL_DEVrwalk_2014 | 0.04 | 6 | -10.00 | 10.00 | 0.00 | 0.14 | 4.3E-06 |
| Size_DblN_peak_JAPAN_LL_DEVrwalk_2015 | 0.16 | 6 | -10.00 | 10.00 | 0.00 | 0.14 | -3.4E-06 |

**Table 2.** Parameter estimates, phases initial values and standard deviations for model 2. Rec devs not shown.

| Label | Value | Phase | Min | Max | Init | StDev | Gradient |
|---|---|---|---|---|---|---|---|
| NatM_p_1_Fem_GP_1 | 0.10 | -3 | 0.05 | 0.30 | 0.10 | _ | _ |
| L_at_Amin_Fem_GP_1 | 42.98 | -2 | 0.00 | 50.00 | 42.98 | _ | _ |
| L_at_Amax_Fem_GP_1 | 264.05 | 4 | 200.00 | 400.00 | 264.07 | 0.75 | -9.1E-04 |
| VonBert_K_Fem_GP_1 | 0.30 | 4 | 0.05 | 0.40 | 0.30 | 0.01 | 4.9E-03 |
| Richards_Fem_GP_1 | -0.94 | 4 | -3.00 | 3.00 | -0.95 | 0.08 | 1.1E-02 |
| CV_young_Fem_GP_1 | 0.09 | 3 | 0.05 | 0.25 | 0.09 | 0.01 | 2.0E-04 |
| CV_old_Fem_GP_1 | 0.07 | 3 | 0.02 | 0.25 | 0.07 | 0.00 | 8.5E-05 |
| Wtlen_1_Fem_GP_1 | 0.00 | -3 | 0.00 | 0.01 | 0.00 | _ | _ |
| Wtlen_2_Fem_GP_1 | 3.00 | -3 | 2.00 | 4.00 | 3.00 | _ | _ |
| Mat50%_Fem_GP_1 | 8.80 | -3 | 4.00 | 15.00 | 8.80 | _ | _ |
| Mat_slope_Fem_GP_1 | -50.00 | -3 | -100.00 | -1.00 | -50.00 | _ | _ |
| Eggs_scalar_Fem_GP_1 | 1.00 | -3 | 1.00 | 1.00 | 1.00 | _ | _ |
| Eggs_exp_wt_Fem_GP_1 | 1.00 | -3 | 1.00 | 1.00 | 1.00 | _ | _ |
| RecrDist_GP_1 | 0.00 | -4 | 0.00 | 0.00 | 0.00 | _ | _ |
| RecrDist_Area_1 | 0.00 | -4 | 0.00 | 0.00 | 0.00 | _ | _ |
| RecrDist_month_1 | 0.00 | -4 | 0.00 | 0.00 | 0.00 | _ | _ |
| CohortGrowDev | 1.00 | -1 | 0.10 | 10.00 | 1.00 | _ | _ |
| FracFemale_GP_1 | 0.50 | -99 | 0.00 | 1.00 | 0.50 | _ | _ |
| SR_LN(R0) | 6.38 | 1 | 5.00 | 10.00 | 7.00 | 0.04 | 1.5E-02 |
| SR_BH_steep | 0.54 | 2 | 0.20 | 0.99 | 0.62 | 0.03 | 1.8E-03 |
| SR_sigmaR | 0.77 | 6 | 0.20 | 2.00 | 0.78 | 0.09 | -2.1E-03 |
| SR_regime | 0.00 | -4 | -5.00 | 5.00 | 0.00 | _ | _ |
| SR_autocorr | 0.00 | -99 | 0.00 | 0.00 | 0.00 | _ | _ |
| InitF_seas_1_flt_4USA_TRAP | 0.02 | 5 | 0.00 | 0.03 | 0.02 | 0.00 | -9.3E-05 |
| InitF_seas_1_flt_5USA_CAN_HARPOON | 0.00 | -5 | 0.00 | 1.00 | 0.00 | _ | _ |
| LnQ_base_IDX1_JAPAN_LL | -4.92 | -1 | -25.00 | -2.00 | -4.90 | _ | _ |
| LnQ_base_IDX2_US_RR_66_114 | -5.24 | -1 | -25.00 | -2.00 | -5.19 | _ | _ |
| LnQ_base_IDX3_US_RR_115_144 | -4.06 | -1 | -25.00 | -2.00 | -4.01 | _ | _ |
| LnQ_base_IDX4_US_RR_LT145 | -5.39 | -1 | -25.00 | -2.00 | -5.39 | _ | _ |
| LnQ_base_IDX5_US_RR_GT177 | -4.51 | 1 | -10.00 | -2.00 | -4.43 | 0.07 | 6.6E-05 |
| LnQ_base_IDX6_US_RR_GT195 | -4.35 | -1 | -25.00 | -2.00 | -4.34 | _ | _ |
| LnQ_base_IDX7_USPLL_GOM | -3.56 | -1 | -25.00 | -1.00 | -3.57 | _ | _ |
| LnQ_base_IDX8_JLL_GOM | -5.01 | -1 | -25.00 | -2.00 | -5.01 | _ | _ |
| LnQ_base_IDX9_CAN_GSLNS | -4.40 | 1 | -10.00 | -2.00 | -4.38 | 0.06 | 4.2E-05 |
| LnQ_base_IDX10_GOMlarval | -4.38 | -1 | -25.00 | -2.00 | -4.35 | _ | _ |
| LnQ_base_IDX12_CAN_ACOUSTIC | -5.60 | 1 | -10.00 | -2.00 | -5.78 | 0.11 | 6.7E-05 |
| LnQ_base_IDX13_oceanographic | -1.52 | -1 | -25.00 | 0.00 | -1.61 | _ | _ |
| LnQ_base_IDX14_JAPAN_LL2 | -3.55 | -1 | -25.00 | -1.00 | -3.46 | _ | _ |
| LnQ_base_IDX15_USPLL_GOM_LL2 | -3.84 | -1 | -25.00 | -1.00 | -3.80 | _ | _ |
| LnQ_base_IDX5_US_RR_GT177_ENV_mult | 0.13 | 3 | -5.00 | 5.00 | 0.00 | 0.05 | -1.2E-04 |
| LnQ_base_IDX9_CAN_GSLNS_ENV_mult | -0.28 | 3 | -5.00 | 5.00 | 0.00 | 0.04 | -1.1E-04 |
| LnQ_base_IDX12_CAN_ACOUSTIC_ENV_mult | -0.08 | 3 | -5.00 | 5.00 | 0.00 | 0.04 | -1.5E-04 |
| Size_DblN_peak_JAPAN_LL | 211.71 | 2 | 120.00 | 230.00 | 211.96 | 2.89 | 1.9E-06 |
| Size_DblN_top_logit_JAPAN_LL | -9.72 | 2 | -10.00 | 3.00 | -9.72 | 7.90 | -1.4E-07 |
| Size_DblN_ascend_se_JAPAN_LL | 6.84 | 3 | -5.00 | 9.00 | 6.84 | 0.16 | -1.8E-05 |
| Label | Value | Phase | Min | Max | Init | StDev | Gradient |
| Size_DblN_descend_se_JAPAN_LL | 7.74 | -2 | -5.00 | 9.00 | 7.74 | _ | _ |
| Size_DblN_start_logit_JAPAN_LL | -999.00 | -3 | -999.00 | 15.00 | -999.00 | _ | _ |
| Size_DblN_end_logit_JAPAN_LL | -12.02 | 4 | -20.00 | 10.00 | -12.04 | 101.21 | 9.2E-08 |
| Size_DblN_peak_USA_CAN_PSFS | 68.50 | -2 | 50.00 | 80.00 | 68.50 | _ | _ |
| Size_DblN_top_logit_USA_CAN_PSFS | -1.00 | -3 | -5.00 | 3.00 | -1.00 | _ | _ |
| Size_DblN_ascend_se_USA_CAN_PSFS | 3.70 | 4 | -4.00 | 12.00 | 3.72 | 0.44 | -1.1E-03 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Size_DblN_descend_se_USA_CAN_PSFS | -5.00 | -3 | -5.00 | 6.00 | -5.00 | _ | _ |
| Size_DblN_start_logit_USA_CAN_PSFS | -999.00 | -2 | -15.00 | 5.00 | -999.00 | _ | _ |
| Size_DblN_end_logit_USA_CAN_PSFS | -999.00 | -2 | -15.00 | 10.00 | -999.00 | _ | _ |
| Size_DblN_peak_USA_CAN_PSFB | 213.67 | -1 | 150.00 | 250.00 | 213.67 | _ | _ |
| Size_DblN_top_logit_USA_CAN_PSFB | -2.39 | 2 | -5.00 | 3.00 | -2.42 | 0.33 | 2.2E-05 |
| Size_DblN_ascend_se_USA_CAN_PSFB | 6.92 | 3 | -4.00 | 8.00 | 6.92 | 0.07 | -2.3E-05 |
| Size_DblN_descend_se_USA_CAN_PSFB | 6.00 | -3 | -2.00 | 6.00 | 6.00 | _ | _ |
| Size_DblN_start_logit_USA_CAN_PSFB | -999.00 | -2 | -15.00 | 5.00 | -999.00 | _ | _ |
| Size_DblN_end_logit_USA_CAN_PSFB | -2.32 | 4 | -15.00 | 5.00 | -2.31 | 0.51 | 5.5E-05 |
| Size_DblN_peak_USA_TRAP | 114.20 | 1 | 80.00 | 150.00 | 114.23 | 11.29 | 1.5E-04 |
| Size_DblN_top_logit_USA_TRAP | -1.89 | 3 | -5.00 | 3.00 | -1.89 | 0.63 | 1.3E-04 |
| Size_DblN_ascend_se_USA_TRAP | 7.16 | 3 | -4.00 | 8.00 | 7.16 | 0.48 | -1.7E-04 |
| Size_DblN_descend_se_USA_TRAP | 7.25 | 3 | -2.00 | 10.00 | 7.25 | 0.51 | 1.7E-04 |
| Size_DblN_start_logit_USA_TRAP | -999.00 | -2 | -15.00 | 5.00 | -999.00 | _ | _ |
| Size_DblN_end_logit_USA_TRAP | -999.00 | -2 | -15.00 | 10.00 | -999.00 | _ | _ |
| Size_inflection_USA_CAN_HARPOON | 177.05 | 2 | 100.00 | 220.00 | 177.02 | 0.81 | 5.5E-06 |
| Size_95%width_USA_CAN_HARPOON | 17.06 | 2 | 10.00 | 60.00 | 17.05 | 1.14 | 3.7E-06 |
| Size_DblN_peak_USA_RRFB | 192.76 | 1 | 140.00 | 220.00 | 192.86 | 0.82 | 1.7E-05 |
| Size_DblN_top_logit_USA_RRFB | -0.55 | -3 | -5.00 | 1.00 | -0.55 | _ | _ |
| Size_DblN_ascend_se_USA_RRFB | 6.57 | -3 | -4.00 | 8.00 | 6.57 | _ | _ |
| Size_DblN_descend_se_USA_RRFB | 6.00 | -3 | -2.00 | 8.00 | 6.00 | _ | _ |
| Size_DblN_start_logit_USA_RRFB | -999.00 | -2 | -15.00 | 5.00 | -999.00 | _ | _ |
| Size_DblN_end_logit_USA_RRFB | -0.87 | 2 | -15.00 | 5.00 | -0.90 | 0.31 | 4.4E-05 |
| Size_DblN_peak_USA_RRFS | 106.40 | 1 | 80.00 | 120.00 | 106.41 | 0.61 | 7.8E-06 |
| Size_DblN_top_logit_USA_RRFS | -1.50 | -2 | -5.00 | 3.00 | -1.50 | _ | _ |
| Size_DblN_ascend_se_USA_RRFS | 6.49 | -3 | -4.00 | 8.00 | 6.49 | _ | _ |
| Size_DblN_descend_se_USA_RRFS | 0.97 | -3 | -2.00 | 4.00 | 0.97 | _ | _ |
| Size_DblN_start_logit_USA_RRFS | -999.00 | -2 | -15.00 | 5.00 | -999.00 | _ | _ |
| Size_DblN_end_logit_USA_RRFS | -5.00 | -2 | -15.00 | 10.00 | -5.00 | _ | _ |
| Size_inflection_OTHER_ATL_LL | 157.08 | 2 | 100.00 | 200.00 | 157.01 | 2.11 | 1.1E-05 |
| Size_95%width_OTHER_ATL_LL | 46.21 | 2 | 10.00 | 100.00 | 46.19 | 2.07 | 3.0E-06 |
| Size_inflection_CAN_HOOKLINE | 194.71 | 2 | 150.00 | 250.00 | 194.54 | 1.37 | -2.2E-05 |
| Size_95%width_CAN_HOOKLINE | 32.83 | 2 | 30.00 | 50.00 | 32.70 | 1.53 | 3.4E-06 |
| Size_inflection_GOM_LL_US_MEX | 213.83 | 2 | 150.00 | 250.00 | 213.50 | 2.14 | -2.6E-06 |
| Size_95%width_GOM_LL_US_MEX | 38.84 | 2 | 20.00 | 50.00 | 38.56 | 2.28 | -5.8E-07 |
| Size_inflection_JLL_GOM | 200.10 | 2 | 150.00 | 250.00 | 200.06 | 3.98 | 1.1E-05 |
| Size_95%width_JLL_GOM | 22.36 | 2 | 10.00 | 50.00 | 22.34 | 4.87 | -5.4E-07 |
| Size_inflection_CAN_TRAP | 253.09 | 2 | 230.00 | 300.00 | 252.91 | 3.89 | -2.0E-06 |
| Size_95%width_CAN_TRAP | 55.11 | 2 | 40.00 | 80.00 | 55.21 | 2.72 | 1.4E-06 |
| Size_inflection_CAN_GSL1 | 255.51 | 2 | 200.00 | 300.00 | 255.40 | 1.73 | -3.2E-05 |
| Size_95%width_CAN_GSL1 | 19.13 | 2 | 10.00 | 50.00 | 19.46 | 2.24 | 4.1E-06 |
| Size_DblN_peak_IDX2_US_RR_66_114 | 65.00 | -3 | 40.00 | 200.00 | 65.00 | _ | _ |
| Size_DblN_top_logit_IDX2_US_RR_66_114 | -1.70 | -3 | -5.00 | 3.00 | -1.70 | _ | _ |
| Label | Value | Phase | Min | Max | Init | StDev | Gradient |
| Size_DblN_ascend_se_IDX2_US_RR_66_114 | -4.00 | -3 | -4.00 | 12.00 | -4.00 | _ | _ |
| Size_DblN_descend_se_IDX2_US_RR_66_114 | -2.00 | -3 | -2.50 | 6.00 | -2.00 | _ | _ |
| Size_DblN_start_logit_IDX2_US_RR_66_114 | -999.00 | -2 | -15.00 | 5.00 | -999.00 | _ | _ |
| Size_DblN_end_logit_IDX2_US_RR_66_114 | -5.00 | -2 | -15.00 | 10.00 | -5.00 | _ | _ |
| Size_DblN_peak_IDX3_US_RR_115_144 | 115.00 | -3 | 40.00 | 200.00 | 115.00 | _ | _ |
| Size_DblN_top_logit_IDX3_US_RR_115_144 | -2.10 | -3 | -5.00 | 3.00 | -2.10 | _ | _ |
| Size_DblN_ascend_se_IDX3_US_RR_115_144 | -4.00 | -3 | -4.00 | 12.00 | -4.00 | _ | _ |
| Size_DblN_descend_se_IDX3_US_RR_115_144 | -2.00 | -3 | -2.50 | 6.00 | -2.00 | _ | _ |
| Size_DblN_start_logit_IDX3_US_RR_115_144 | -999.00 | -2 | -15.00 | 5.00 | -999.00 | _ | _ |
| Size_DblN_end_logit_IDX3_US_RR_115_144 | -5.00 | -2 | -15.00 | 10.00 | -5.00 | _ | _ |

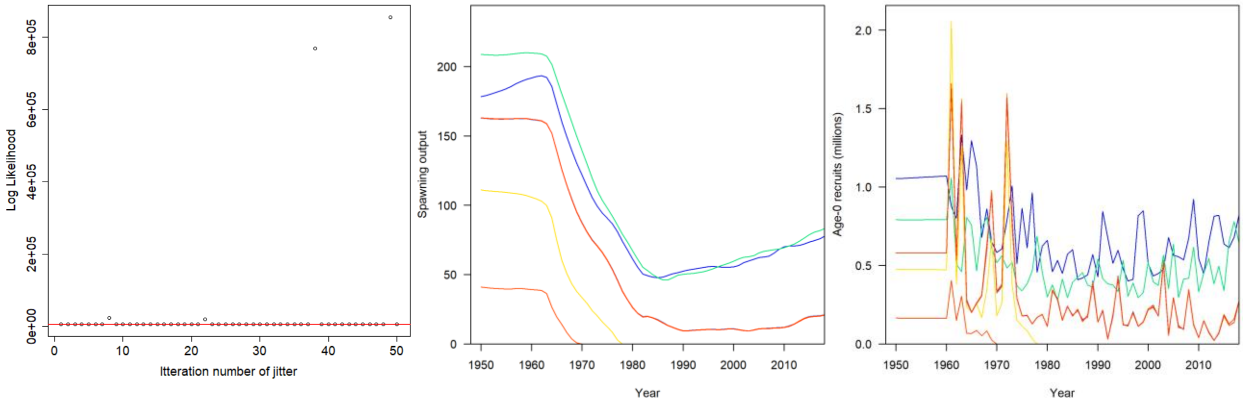
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Size_DblN_peak_JAPAN_LL_BLK1repl_1950 | 162.00 | -5 | 120.00 | 230.00 | 162.00 | _ | _ |
| Size_DblN_peak_JAPAN_LL_dev_se | 50.00 | -5 | 0.00 | 100.00 | 50.00 | _ | _ |
| Size_DblN_peak_JAPAN_LL_dev_autocorr | 0.00 | -6 | -0.99 | 0.99 | 0.00 | _ | _ |
| Size_DblN_top_logit_JAPAN_LL_BLK1repl_1950 | -4.12 | 5 | -10.00 | 1.00 | -4.19 | 0.74 | 1.8E-04 |
| Size_DblN_ascend_se_JAPAN_LL_BLK1repl_1950 | 7.60 | 5 | -1.00 | 9.00 | 7.60 | 0.03 | -8.6E-04 |
| Size_DblN_descend_se_JAPAN_LL_BLK1repl_1950 | 7.74 | -2 | -1.00 | 9.00 | 7.74 | _ | _ |
| Size_DblN_start_logit_JAPAN_LL_BLK1repl_1950 | -999.00 | -3 | -5.00 | 15.00 | -999.00 | _ | _ |
| Size_DblN_end_logit_JAPAN_LL_BLK1repl_1950 | -4.61 | 5 | -20.00 | 1.00 | -4.63 | 0.78 | 2.5E-04 |
| Size_DblN_peak_USA_RRFS_BLK3repl_1950 | 88.46 | 4 | 60.00 | 110.00 | 88.46 | 0.80 | 2.2E-04 |
| Size_DblN_top_logit_USA_RRFS_BLK3repl_1950 | -1.50 | -2 | -5.00 | 3.00 | -1.50 | _ | _ |
| Size_DblN_ascend_se_USA_RRFS_BLK3repl_1950 | 6.49 | -3 | -4.00 | 10.00 | 6.49 | _ | _ |
| Size_DblN_descend_se_USA_RRFS_BLK3repl_1950 | 0.97 | -3 | -2.00 | 4.00 | 0.97 | _ | _ |
| Size_DblN_start_logit_USA_RRFS_BLK3repl_1950 | -999.00 | -2 | -15.00 | 5.00 | -999.00 | _ | _ |
| Size_DblN_end_logit_USA_RRFS_BLK3repl_1950 | -5.00 | -2 | -15.00 | 10.00 | -5.00 | _ | _ |
| Size_DblN_peak_JAPAN_LL_DEVrwalk_2011 | -0.81 | 6 | -10.00 | 10.00 | 0.00 | 0.11 | 7.9E-05 |
| Size_DblN_peak_JAPAN_LL_DEVrwalk_2012 | 0.31 | 6 | -10.00 | 10.00 | 0.00 | 0.13 | 4.5E-05 |
| Size_DblN_peak_JAPAN_LL_DEVrwalk_2013 | 0.64 | 6 | -10.00 | 10.00 | 0.00 | 0.14 | 1.8E-05 |
| Size_DblN_peak_JAPAN_LL_DEVrwalk_2014 | 0.04 | 6 | -10.00 | 10.00 | 0.00 | 0.14 | 2.8E-05 |
| Size_DblN_peak_JAPAN_LL_DEVrwalk_2015 | 0.17 | 6 | -10.00 | 10.00 | 0.00 | 0.14 | 3.0E-05 |

**Table 3**. Table of key information for models 1 and 2, noting the specifications, log-likelihoods, run time, and parameters that hit bounds.

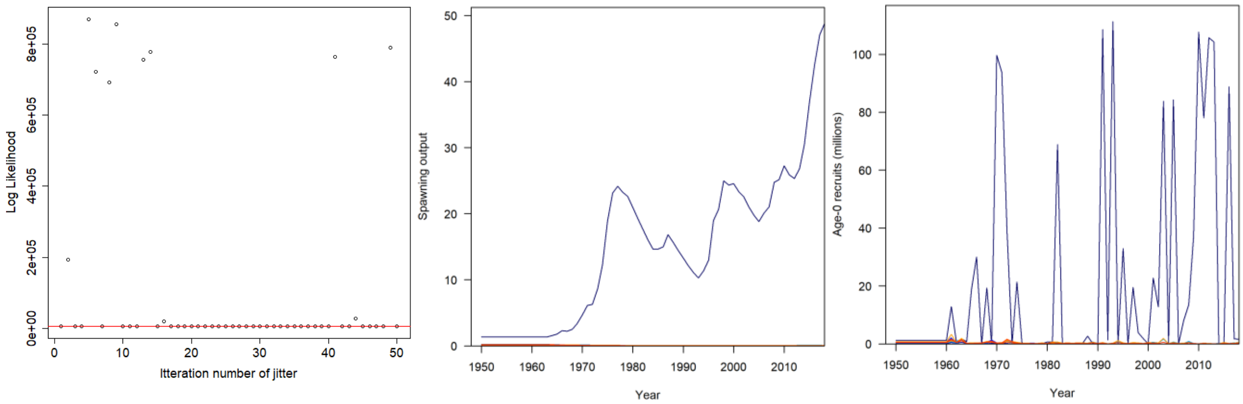
| model | Model 1<br>later spawning schedule | Model 2<br>later spawning schedule |
|---|---|---|
| max gradient component | LN(R0): 0.0225167 | LN(R0): 0.0151621 |
| run time | 13 min | 14 min |
| total loglikelihood | 6613.32 | 6612.96 |
| Catch | 1.78642e-011 | 1.78706e-011 |
| Equil_catch | 4.40544 | 4.09017 |
| Survey | 661.258 | 660.973 |
| Length_comp | 4094.37 | 4095.22 |
| Age_comp | 1840.09 | 1840.21 |
| Recruitment | 12.327 | 11.6033 |
| InitEQ_Regime | 0 | 0 |
| Forecast_Recruitment | 0 | 0 |
| Parm_priors | 0.254872 | 0.254878 |
| Parm_softbounds | 0.0108751 | 0.0108677 |
| Parm_devs | 0.597617 | 0.599129 |
| Crash_Pen | 0 | 0 |
| bounded parms | 0 | 0 |

**Table 4.** Benchmarks (SE) and relative stock status for model 1 and model 2.

| | Model 1<br>late spawning | Model 2<br>early spawning |
|---|---|---|
| SSB Unfished | 180935 (6279) | 222990 (8118) |
| Total Biomass Unfished | 226808 (7888) | 228089 (7965) |
| Recruitment Unfished | 588.4 (20.7) | 591.6 (20.8) |
| F current (geomean F of age 10-20 in 2016-18) | 0.0756 | 0.0756 |
| F0.1(geomean F of age 10-20) from YPR curve | 0.0896 | 0.0900 |
| SSB at F0.1 | 0.584 | 0.512 |
| Total Yield at F0.1 | 4537 | 4402 |
| F current / F0.1 | 0.843 | 0.840 |
| SSB at terminal year / SSB at F0.1 | 0.584 | 0.512 |

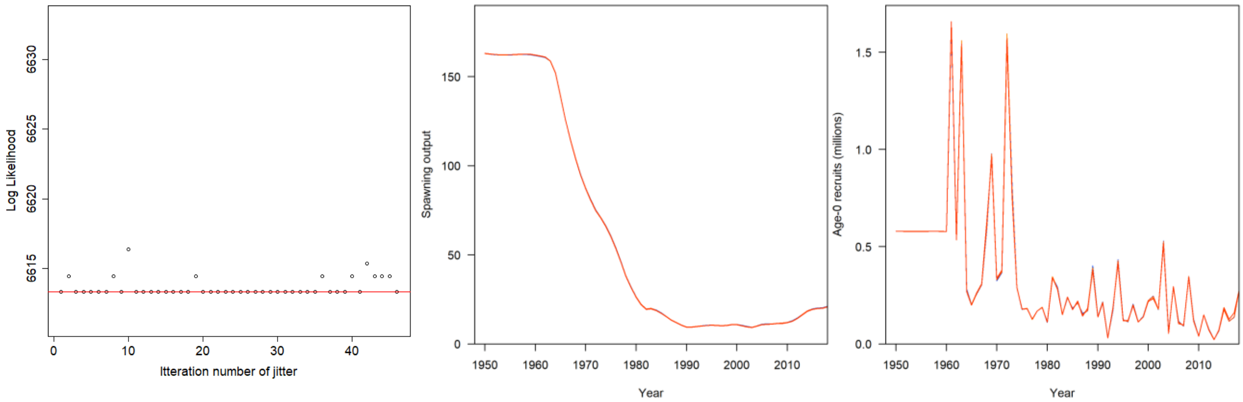



(a) Model 1

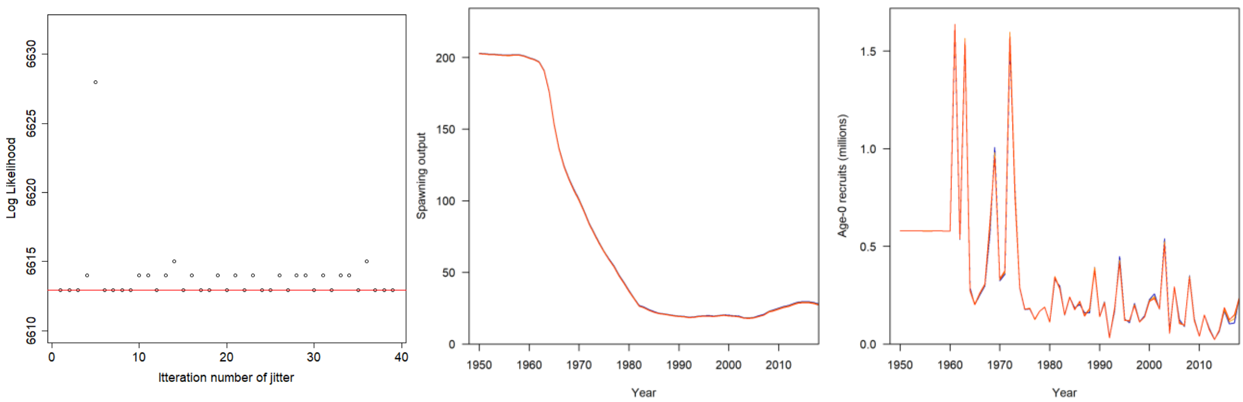



(b) Model 2

**Figure 1**. All results of the jitter analysis for (a) model 1 and (b) model 2.




(a) Model 1




(b) Model 2

**Figure 2**. The results of the jitter analysis excepting runs with extremely far from global solution for (a) model 1 and (b) model 2.

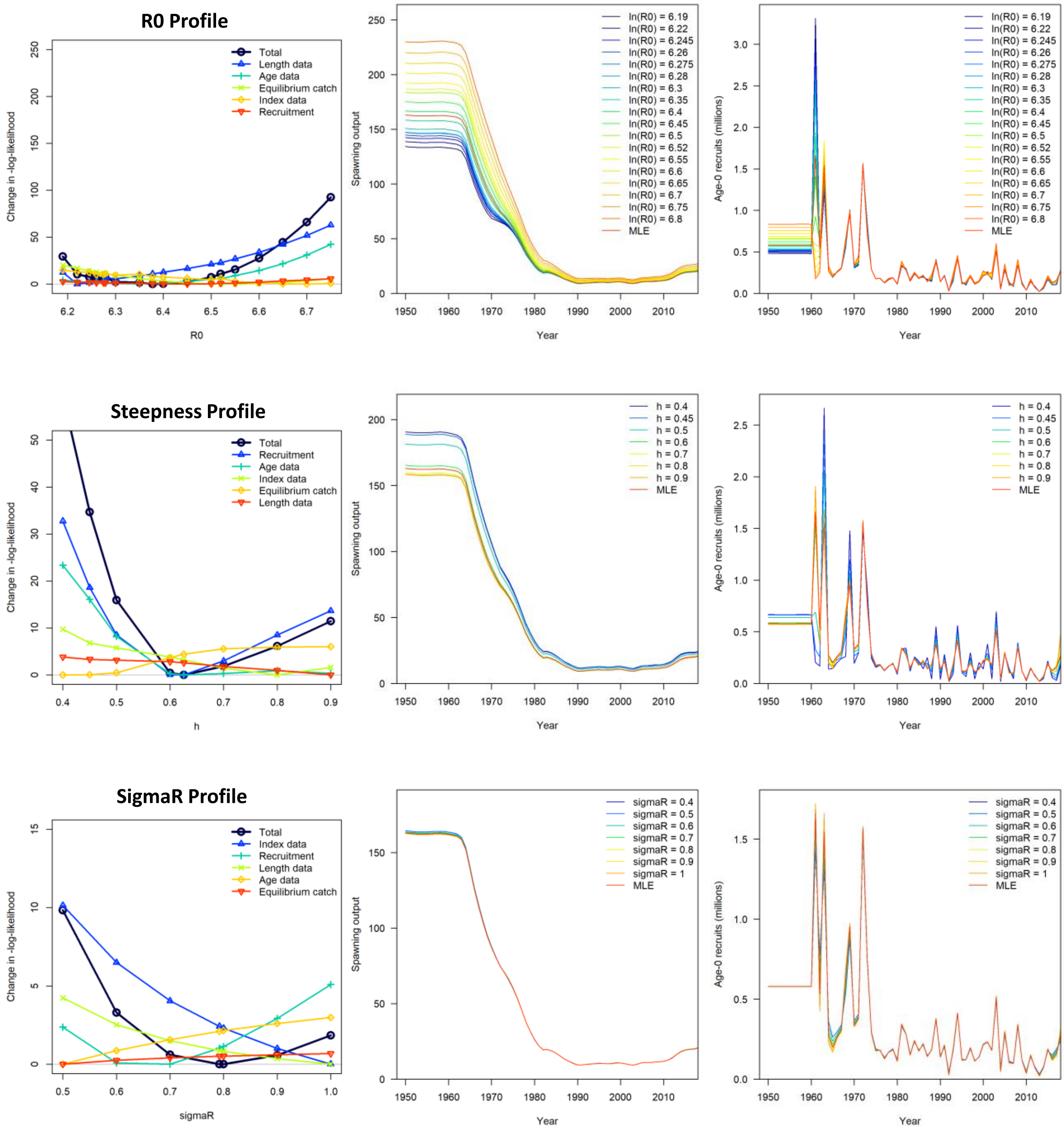



**Figure 3**. Likelihood profiles (Left) by R0 (Upper), steepness (Middle) and sigmaR (Bottom) and resulting SSB (Center) and recruitment (Right) trends for model 1.

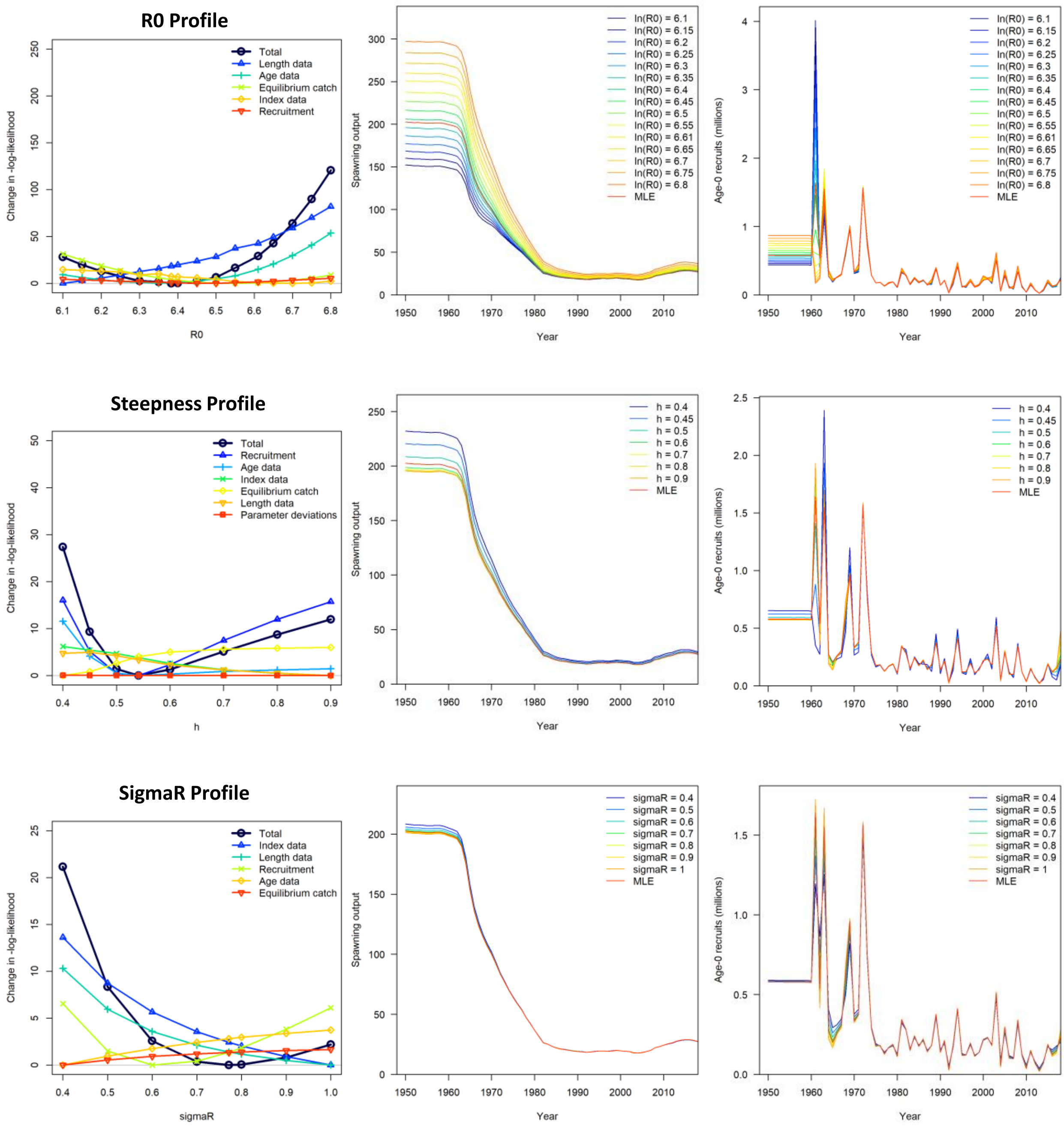
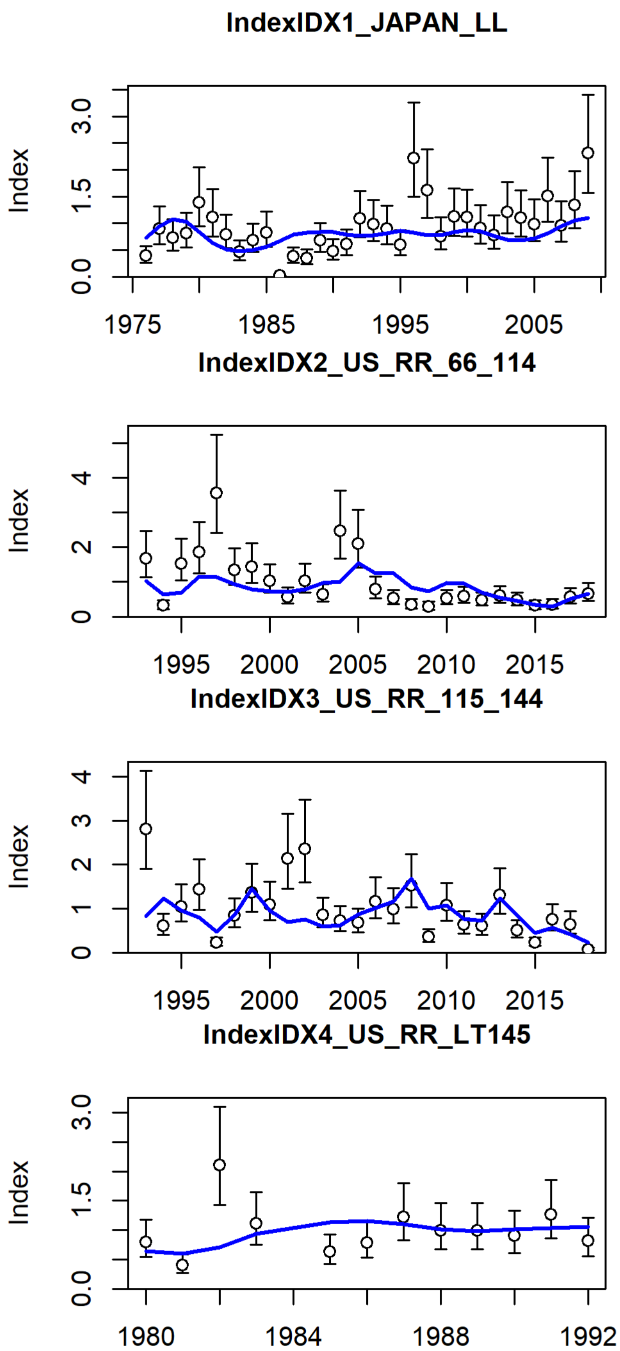



**Figure 4**. Likelihood profiles (Left) by R0 (Upper), steepness (Middle) and sigmaR (Bottom) and resulting SSB (Center) and recruitment (Right) trends for model 2.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1.5
3.0
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1985
1995
2005
IndexIDX2_US_RR_66_114
Index
0
2
4
1995
2000
2005
2010
2015
IndexIDX3_US_RR_115_144
Index
0
1
2
3
4
1995
2000
2005
2010
2015
IndexIDX4_US_RR_LT145
Index
0.0
1.5
3.0
1980
1984
1988
1992

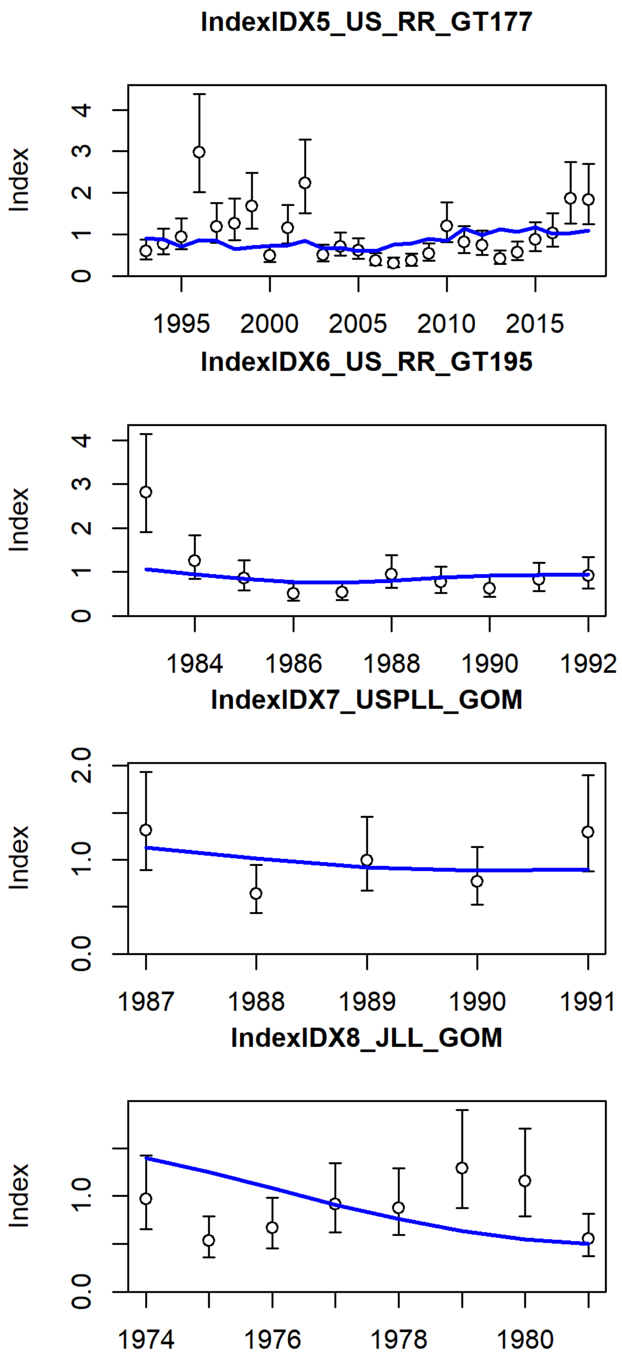
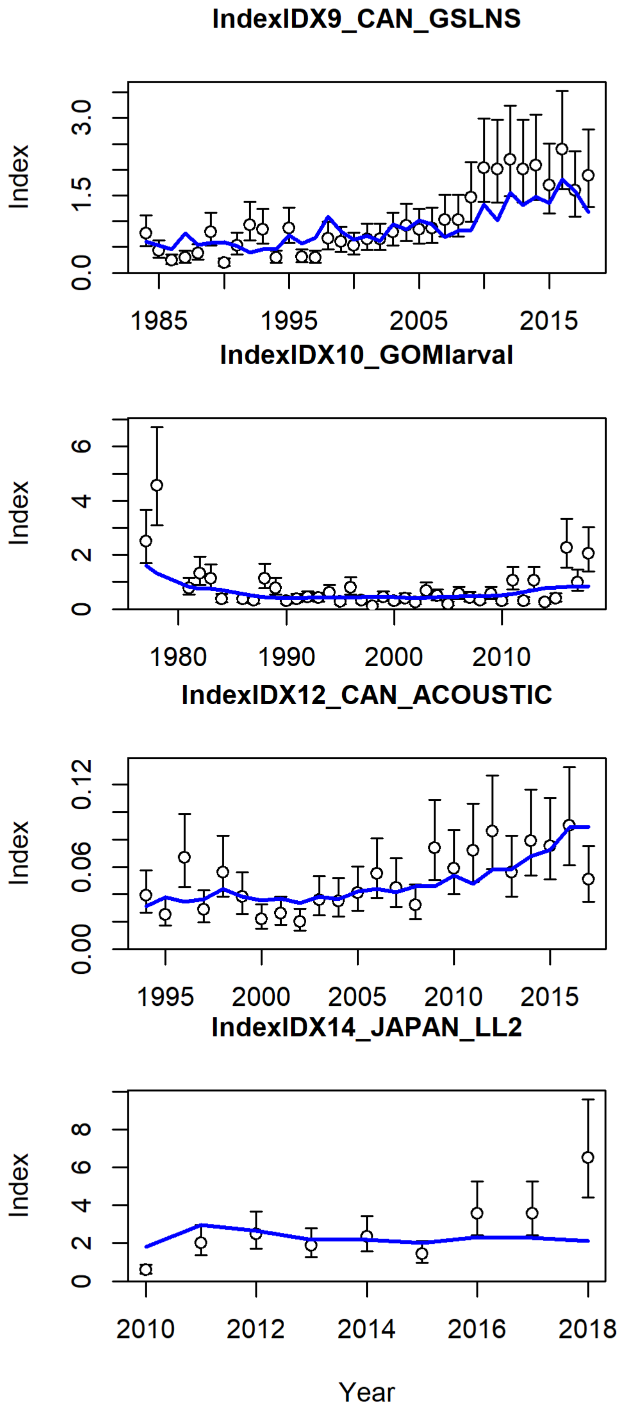



**Figure 5**. Fits to each CPUE index for model 1.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1980
1990
2000
2010
IndexIDX12_CAN_ACOUSTIC
Index
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0.06
0.12
1995
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2014
2016
2018
Year

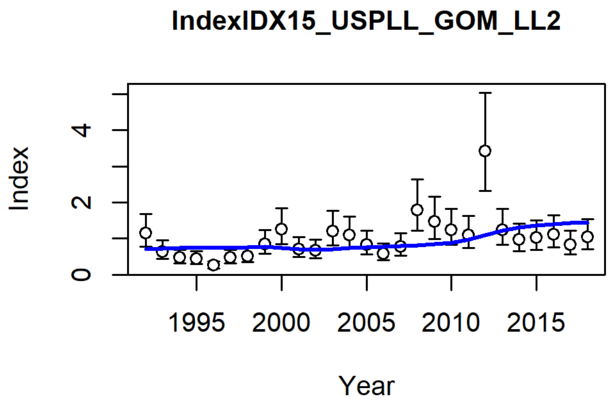
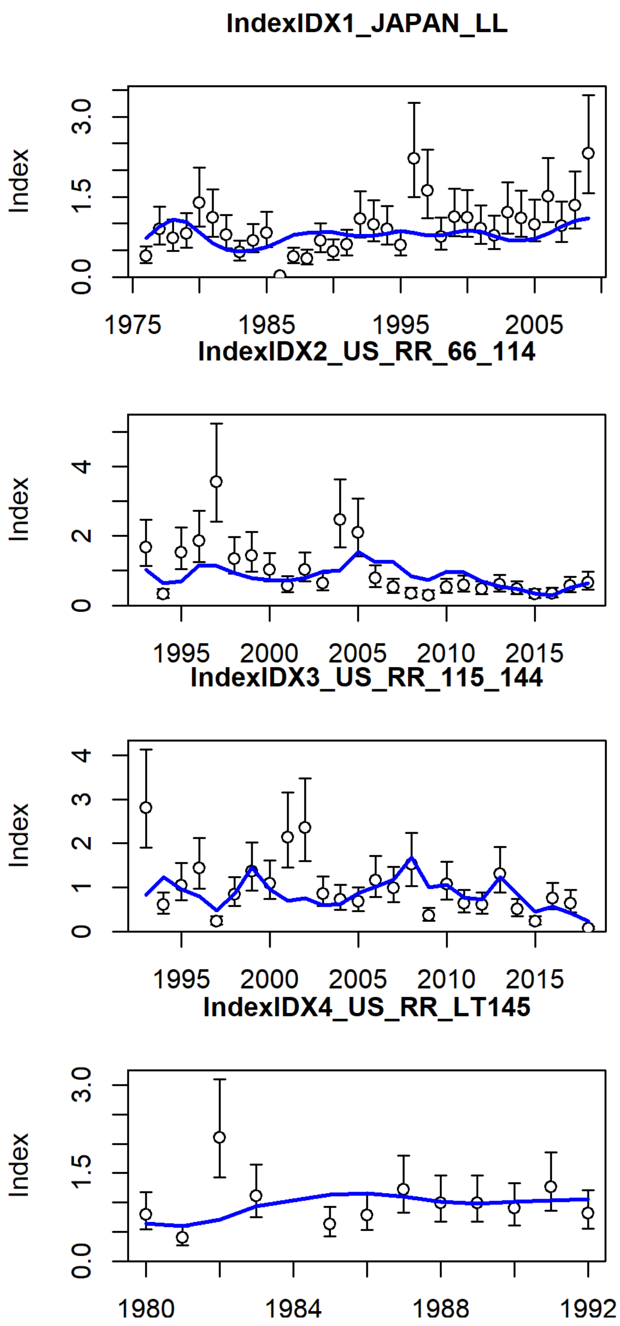



**Figure 5**. Cont.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Index
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1988
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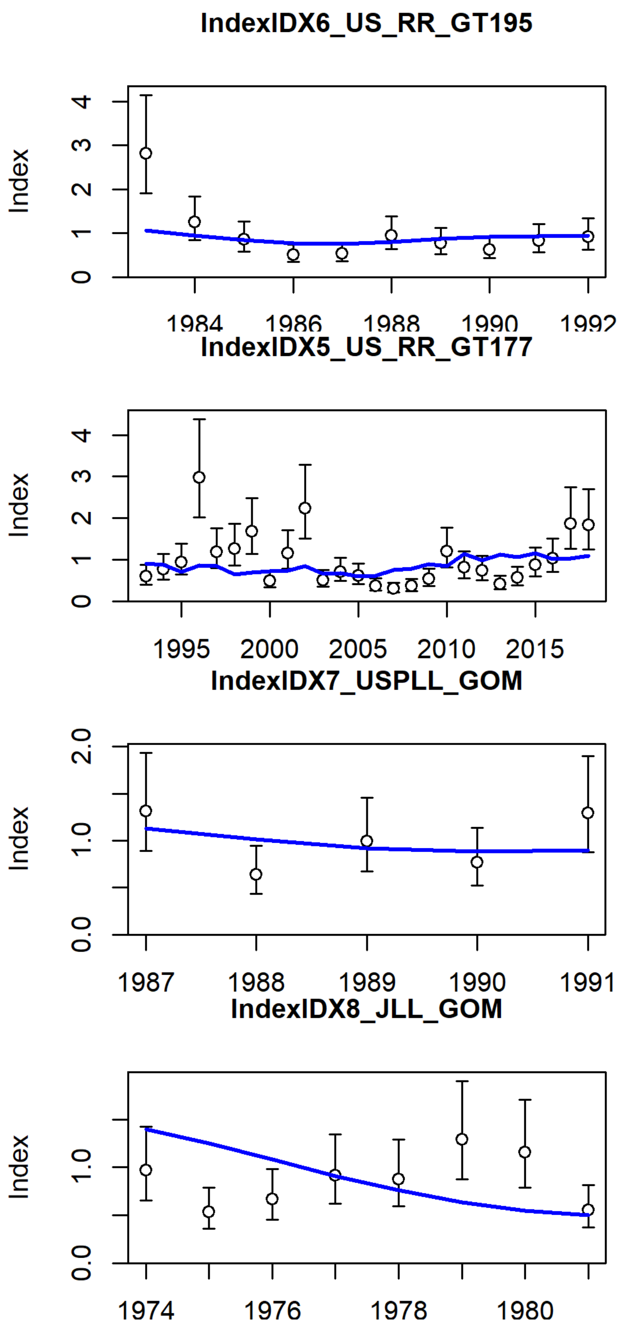



**Figure 6**. Fits to each CPUE index for model 2.

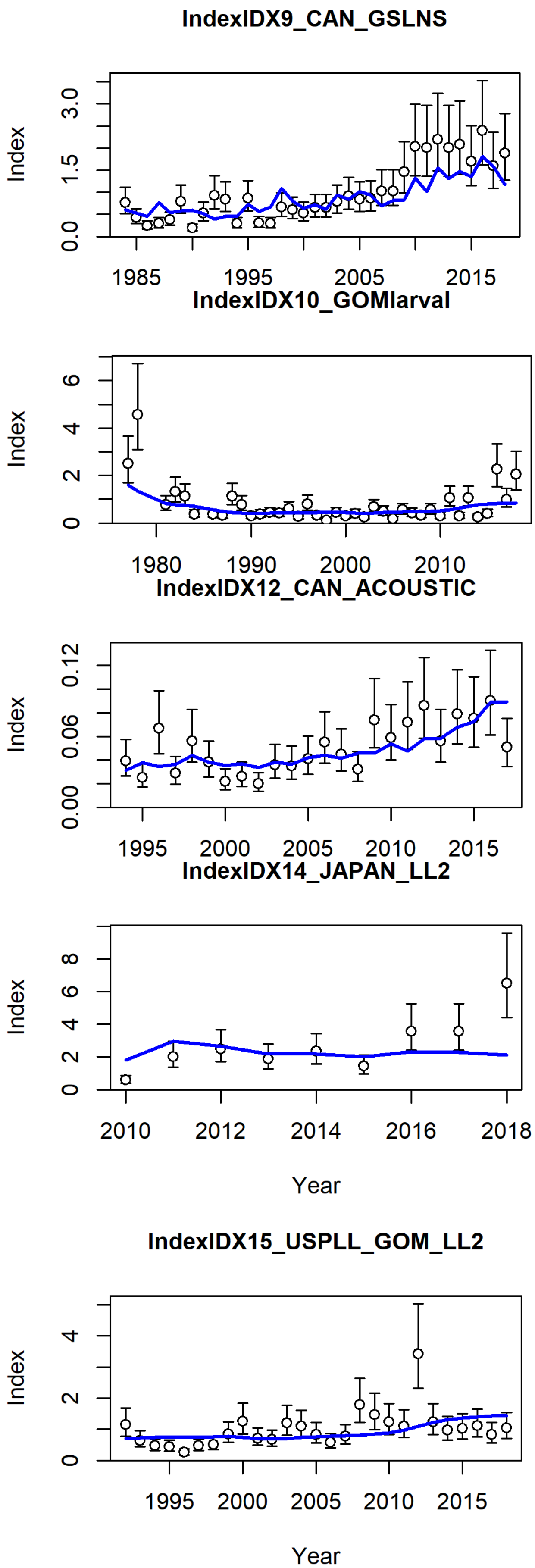



**Figure 6**. Cont.

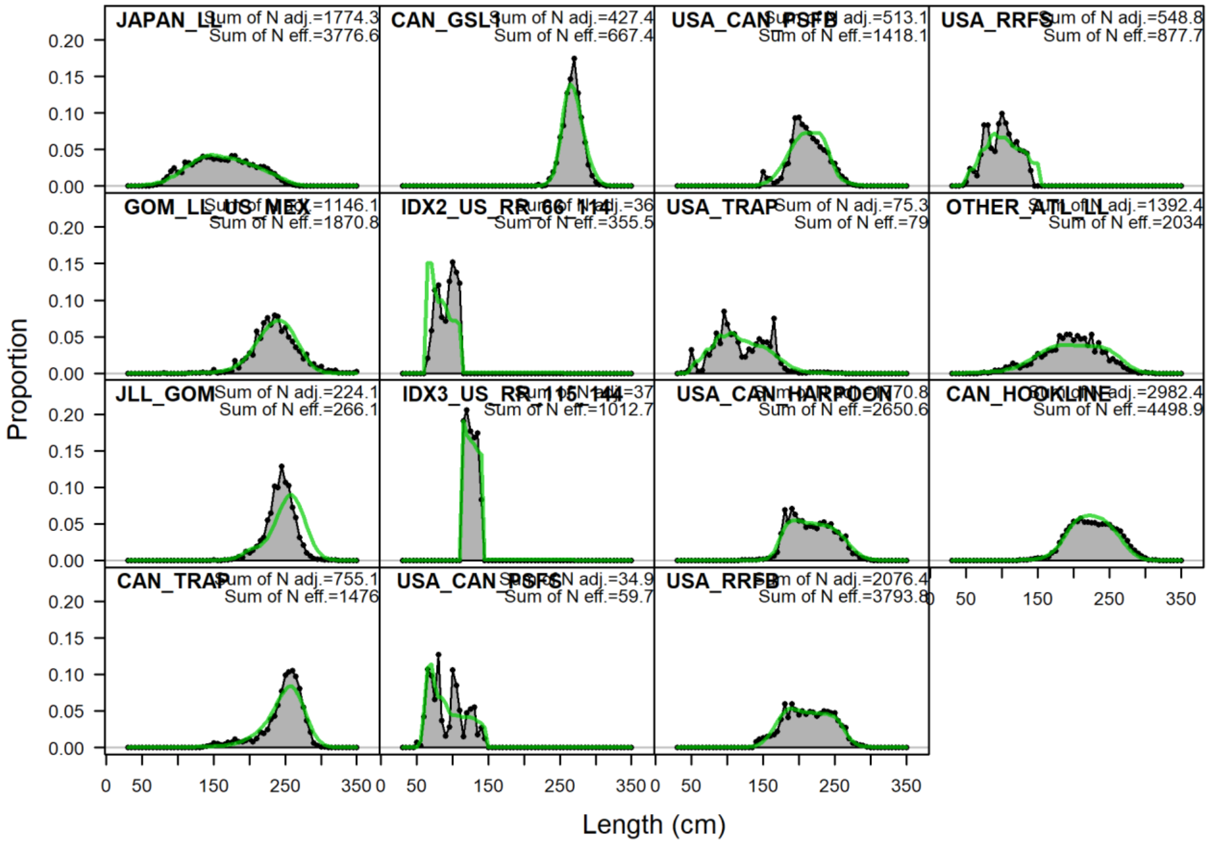



**Figure 7.** Fits to length composition data over all years for model 1.

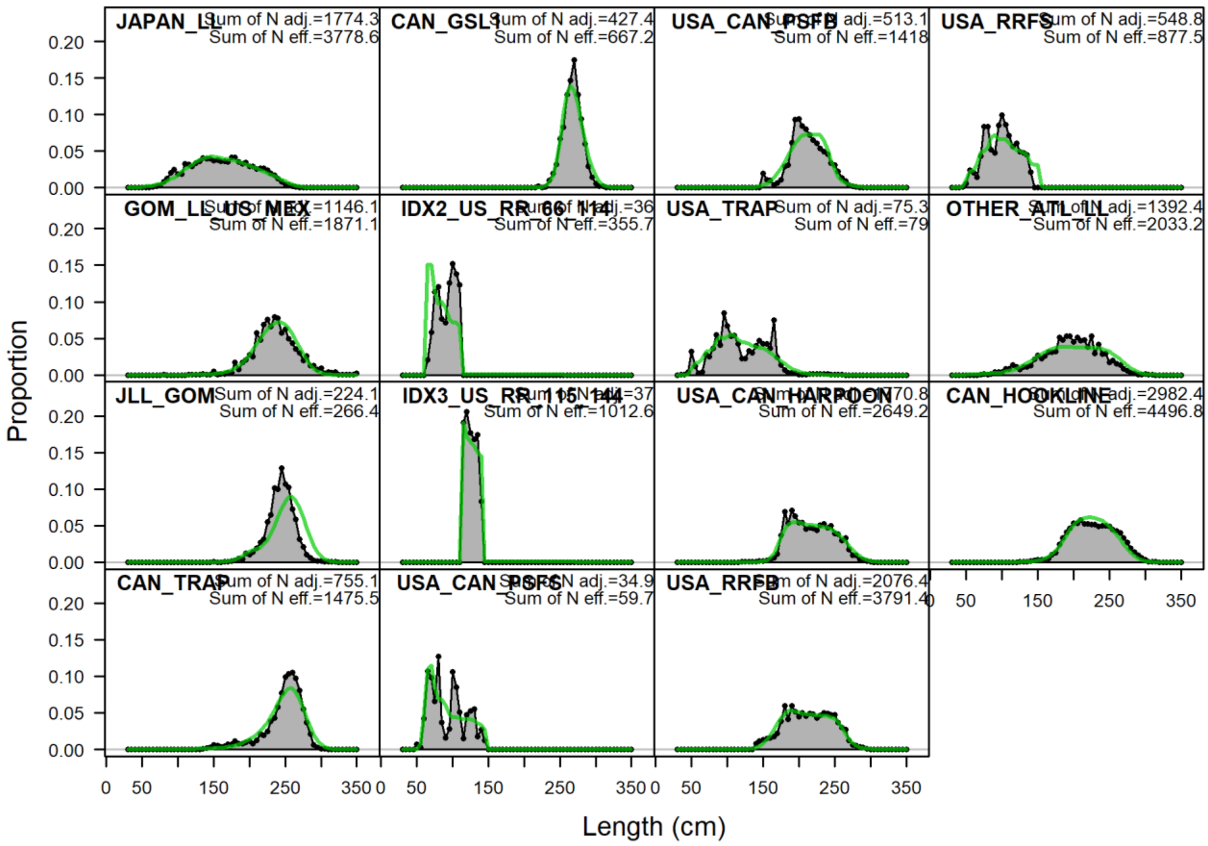



**Figure 8.** Fits to length composition data over all years for model 2.

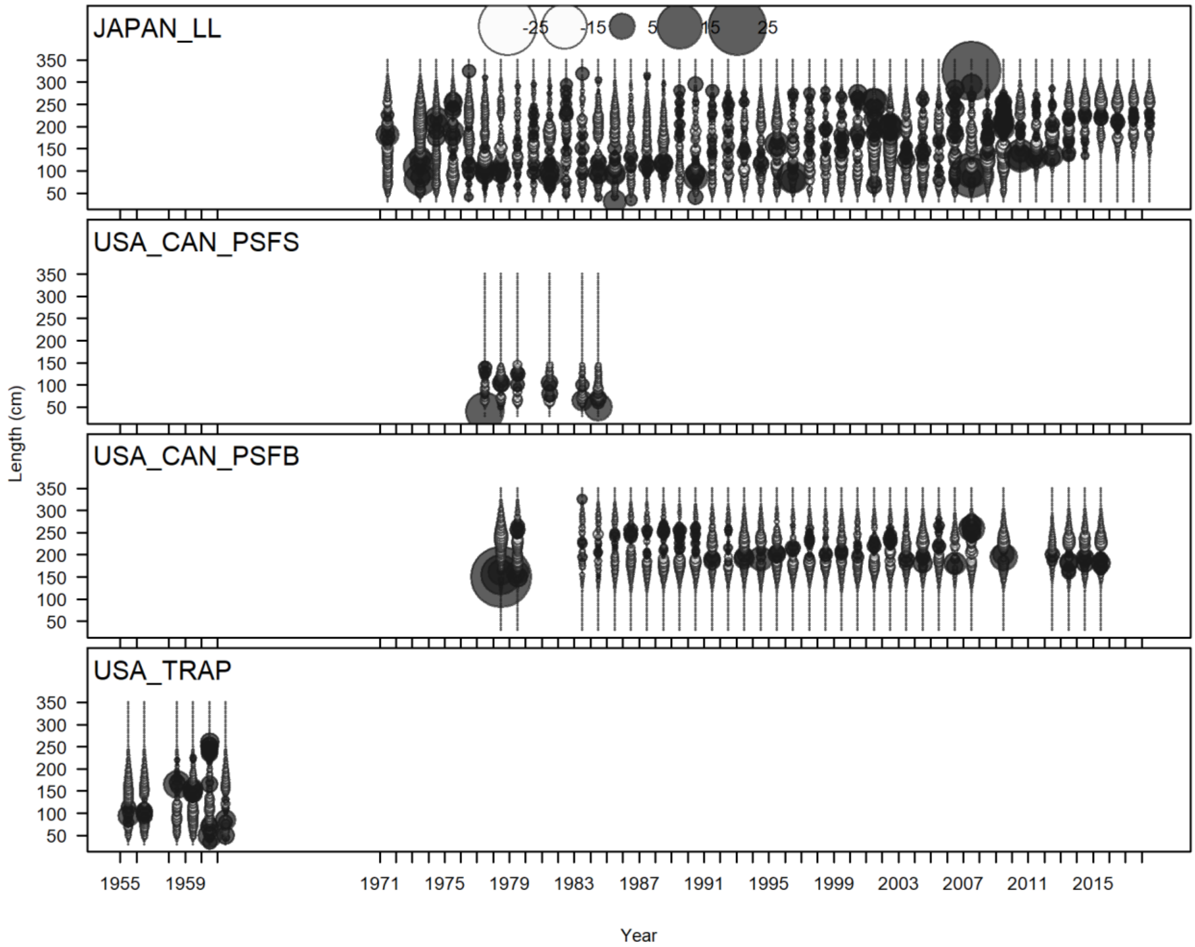



**Figure 9**. Time series of Pearson residuals on the length composition data by fleets for model 1.

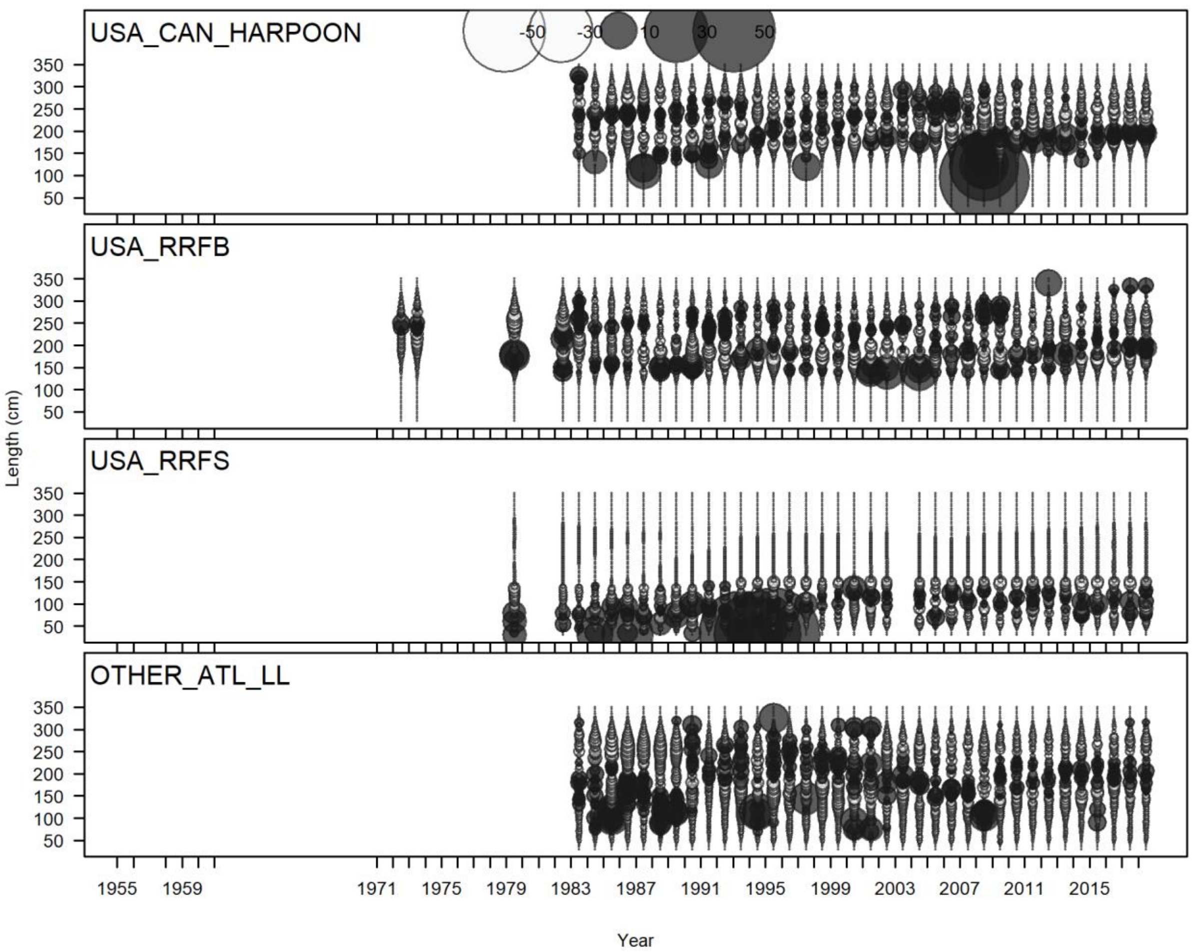



**Figure 9**. Cont.

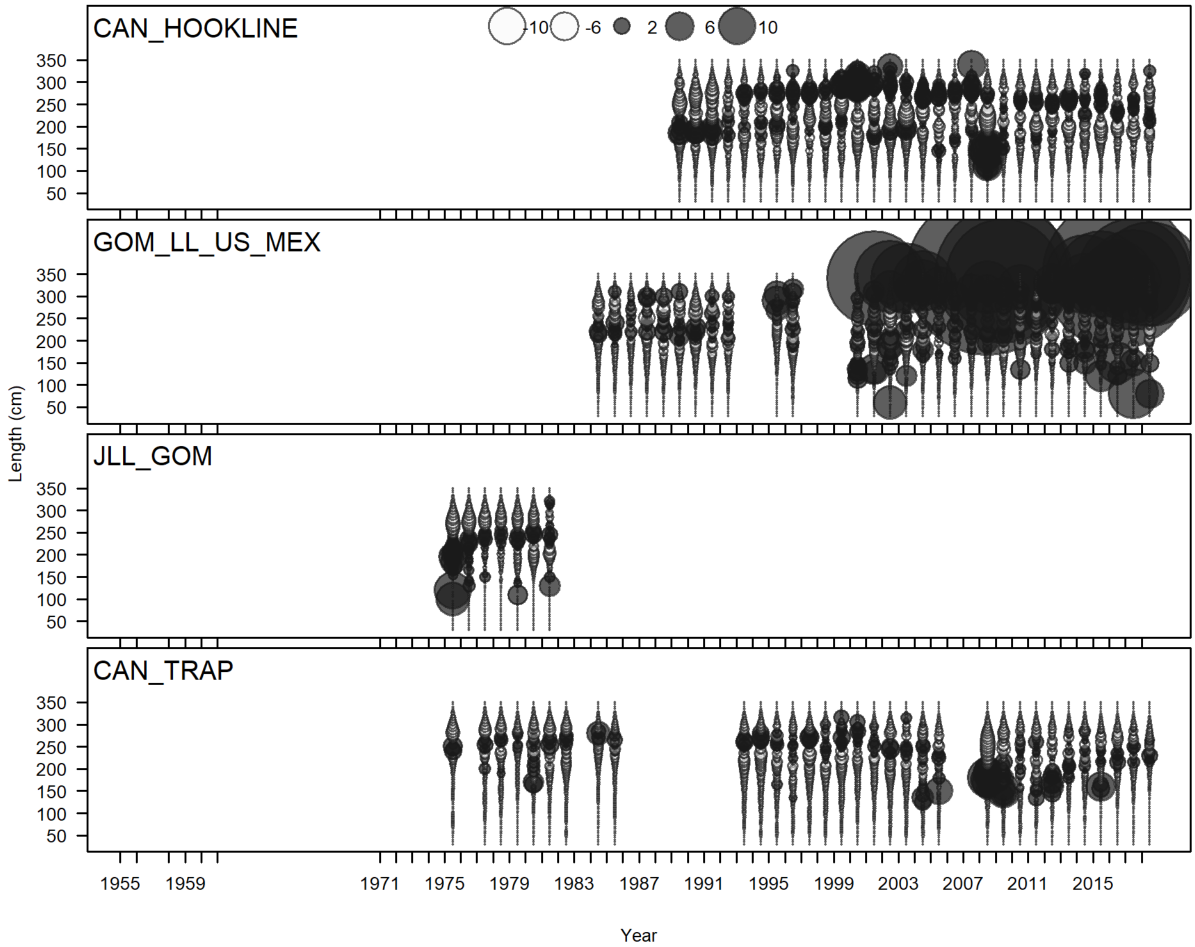



**Figure 9**. Cont.

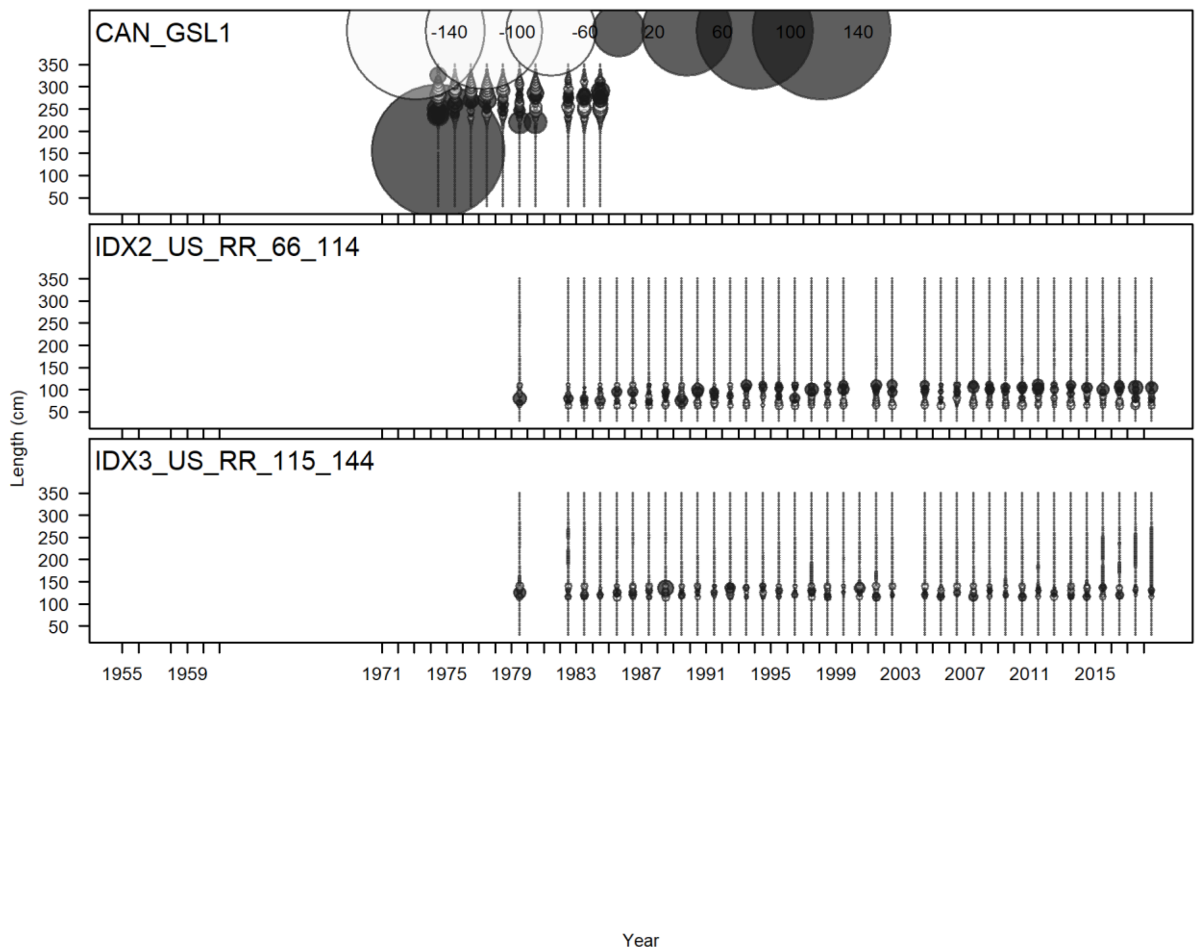



**Figure 9**. Cont.

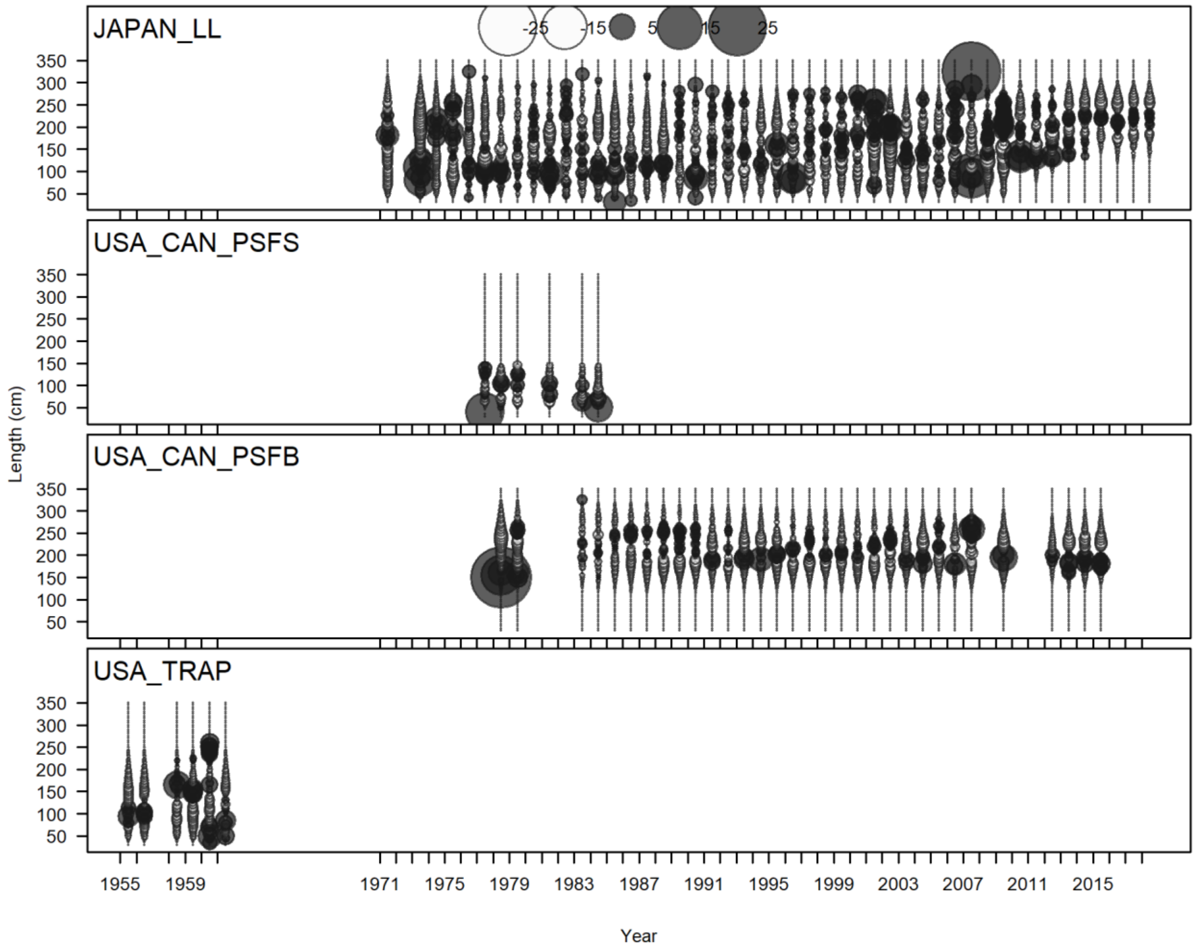



**Figure 10**. Time series of Pearson residuals on the length composition data by fleets for model 2.

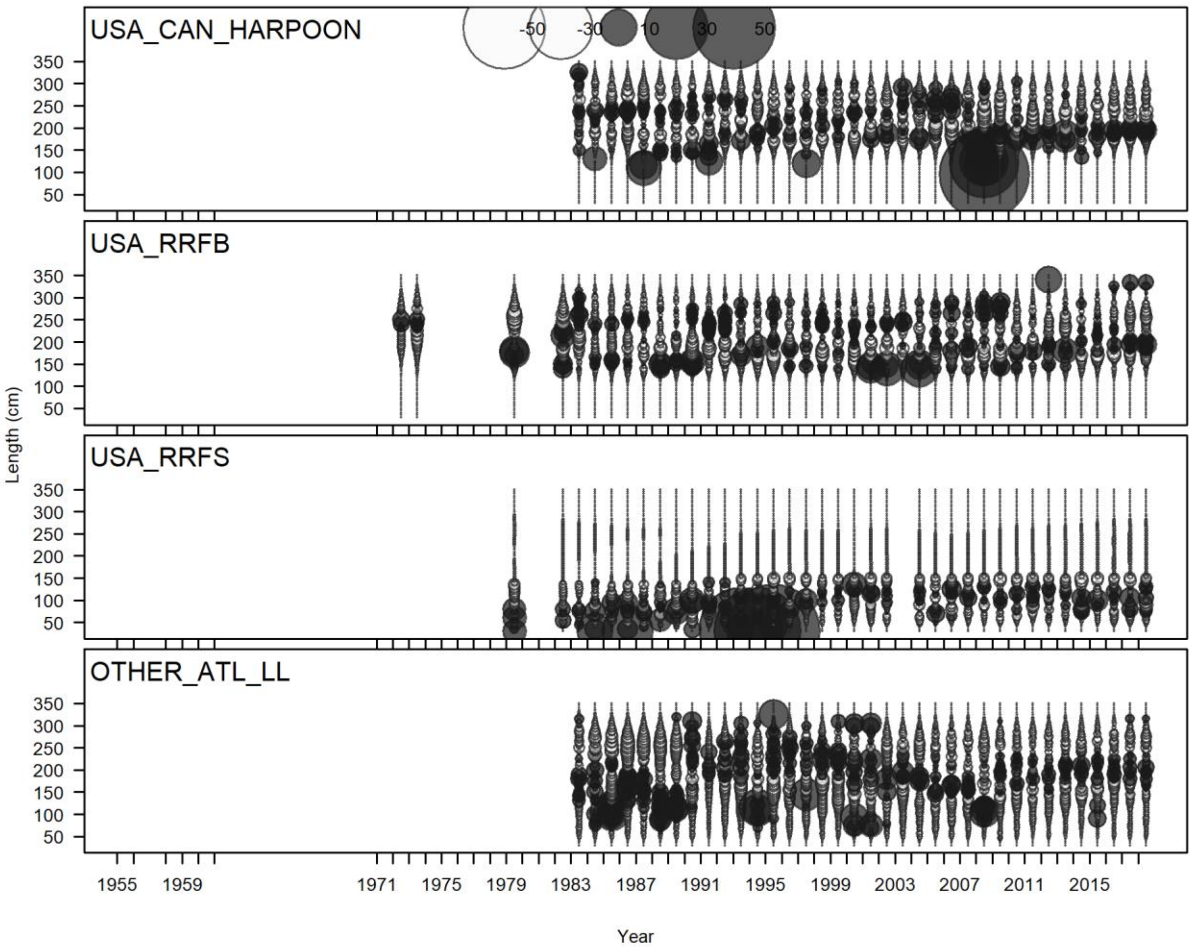



**Figure 10**. Cont.

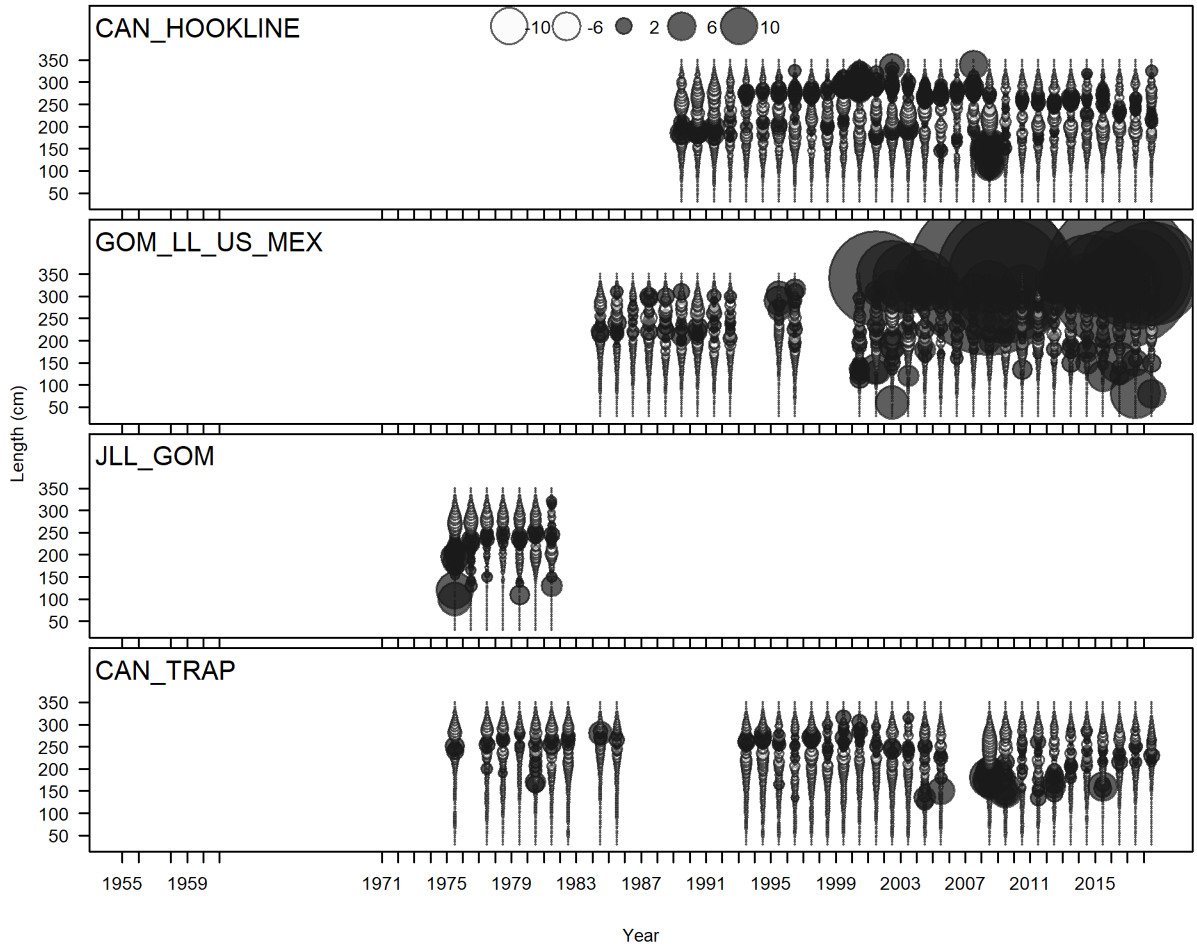



**Figure 10**. Cont.

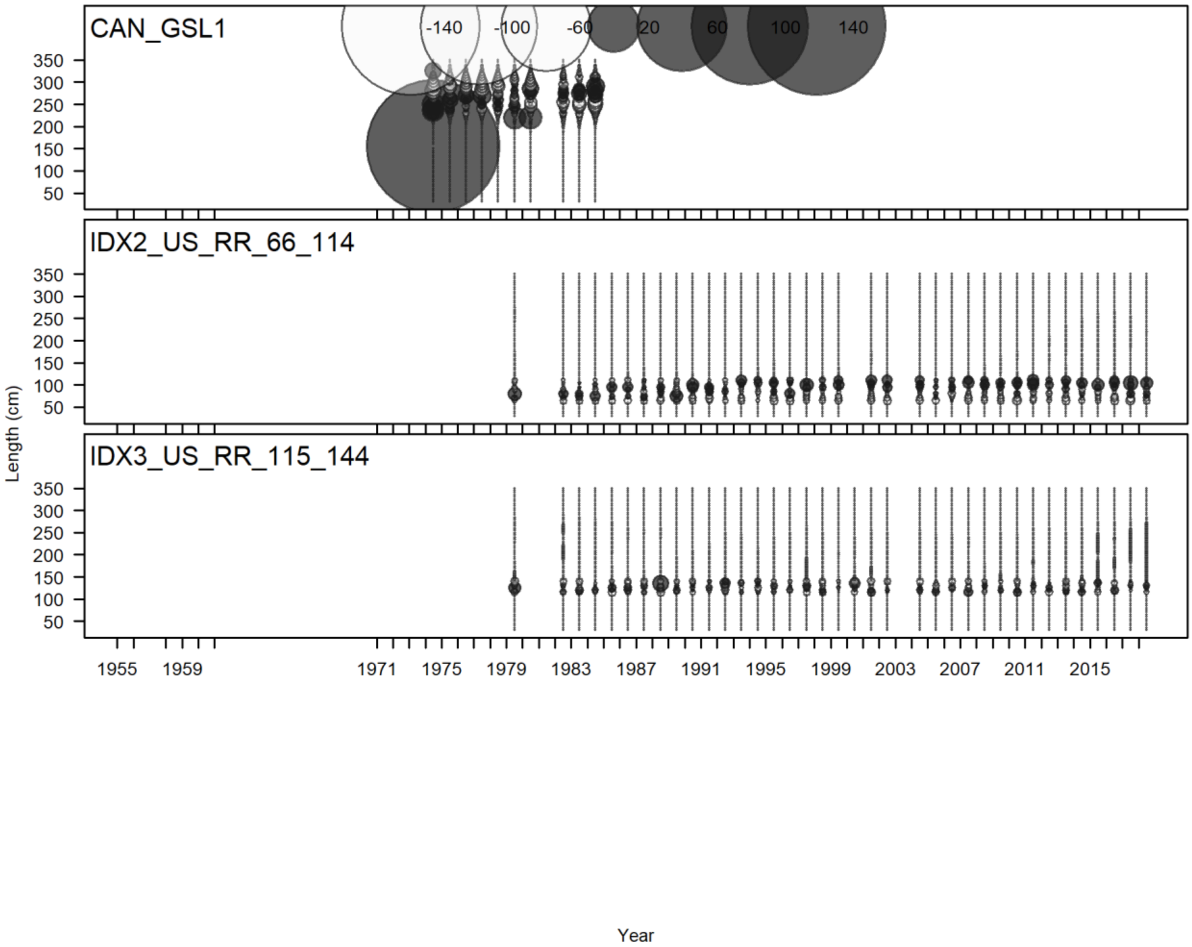
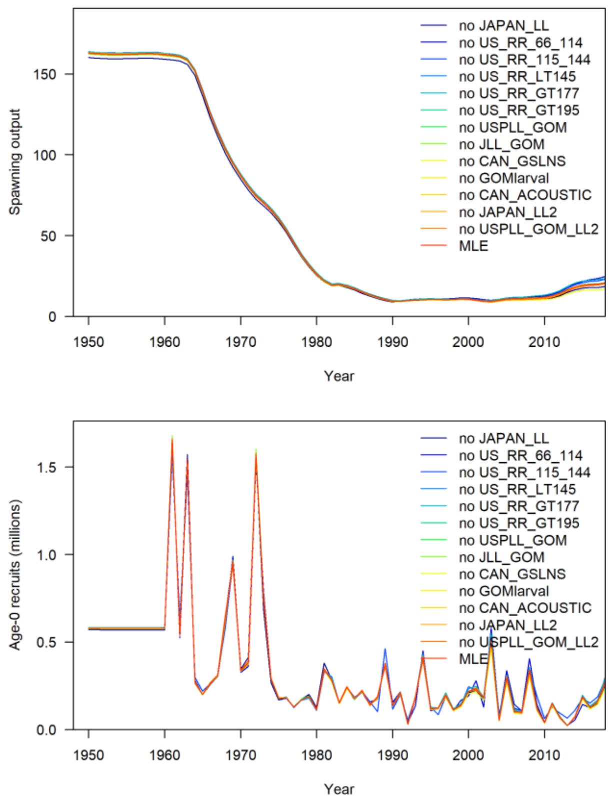
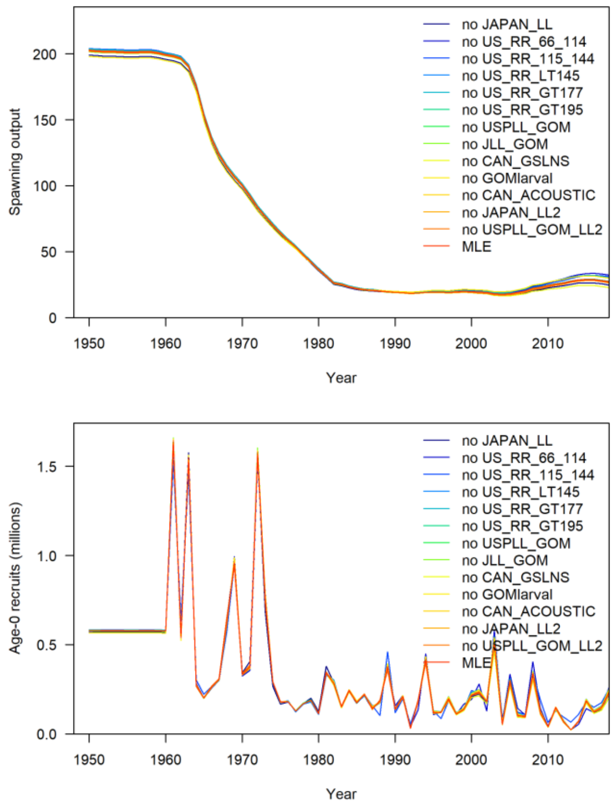



**Figure 10**. Cont.

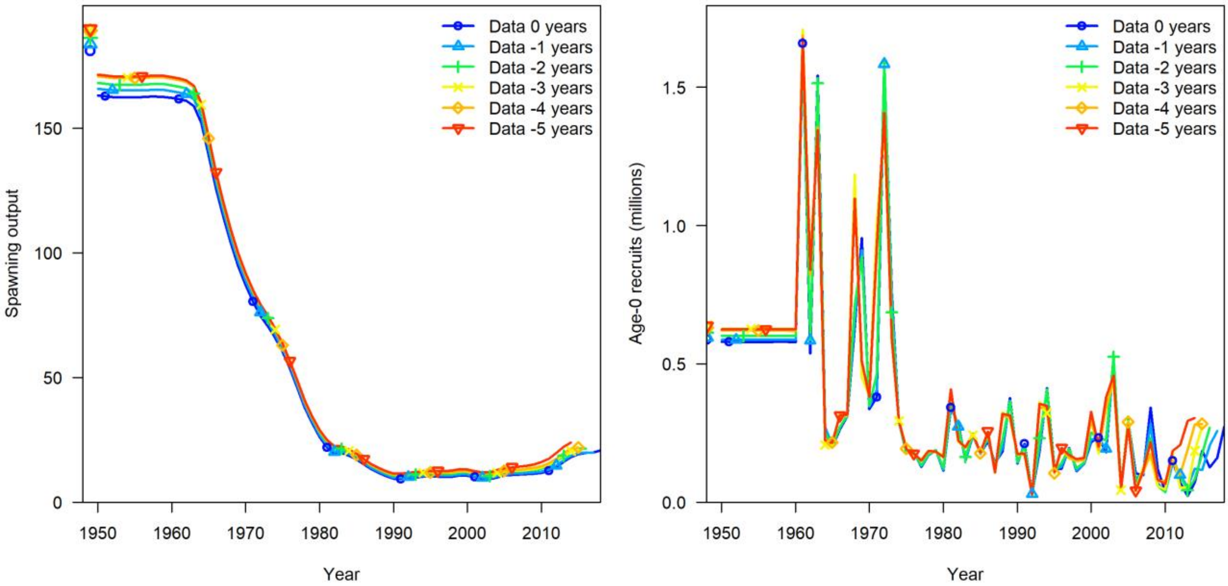



(a) model 1

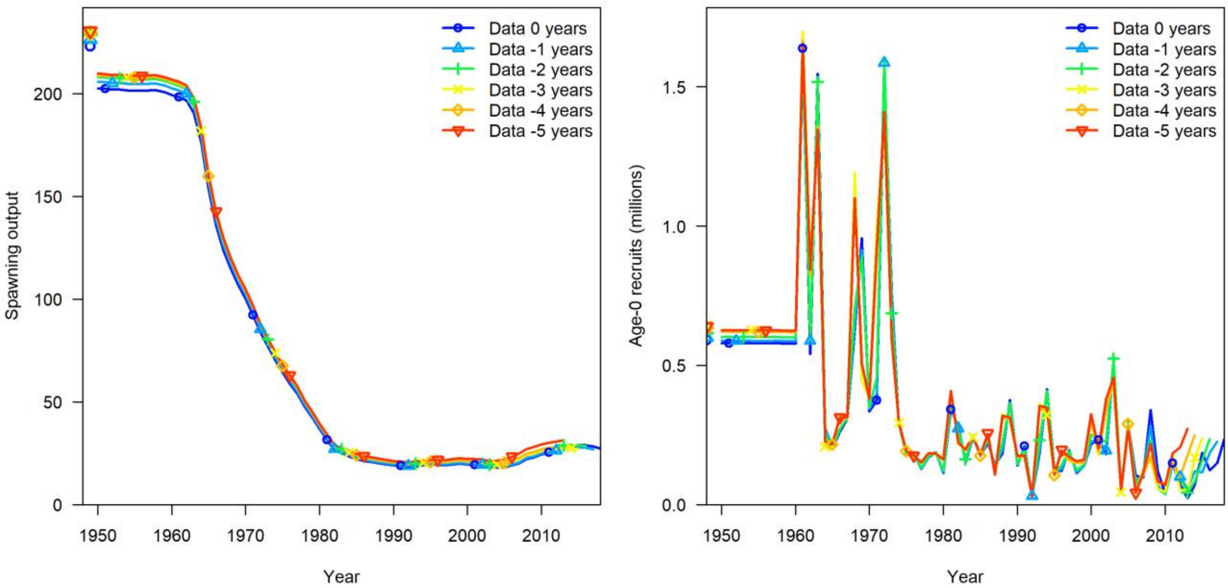



(b) model 2

**Figure 11.** The result of jackknife analysis regarding abundance indices for (a) model 1 and (b) model 2.

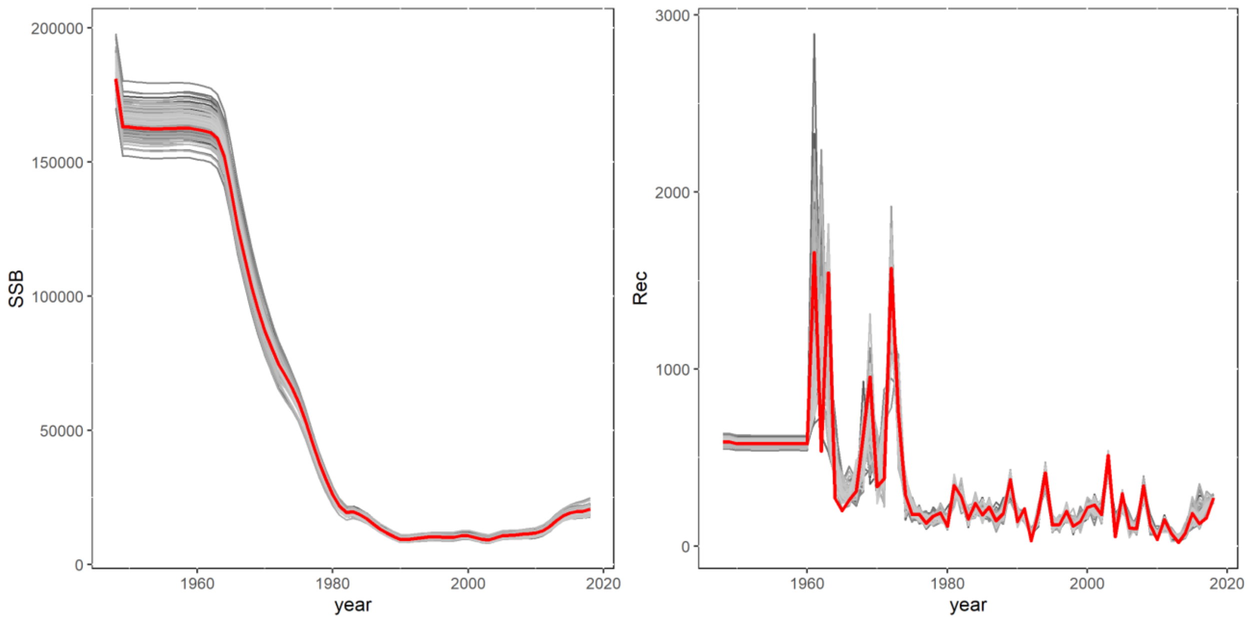



(a) Model 1

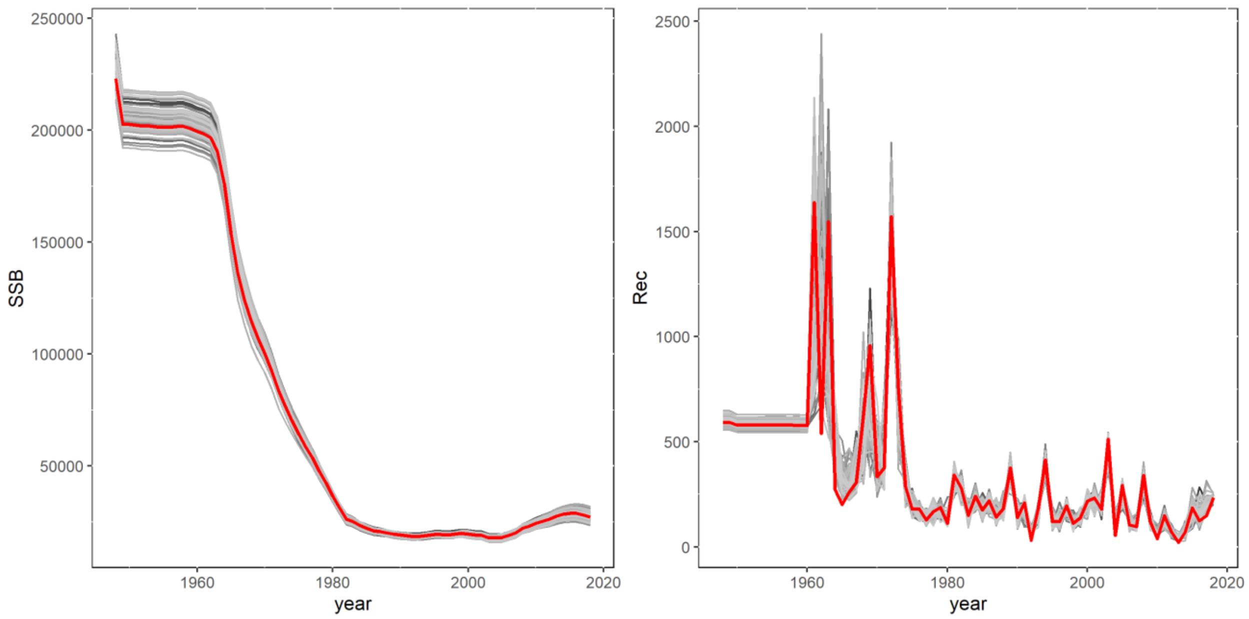



(b) Model 2

**Figure 12.** Retrospective plots of SSB and recruitment trends for (a) model 1 and (b) model 2.

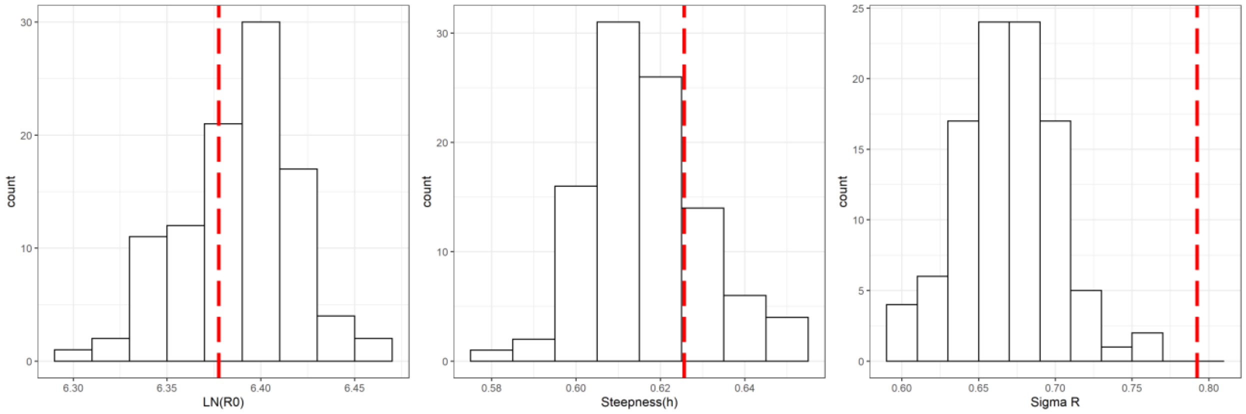



(a) Model 1

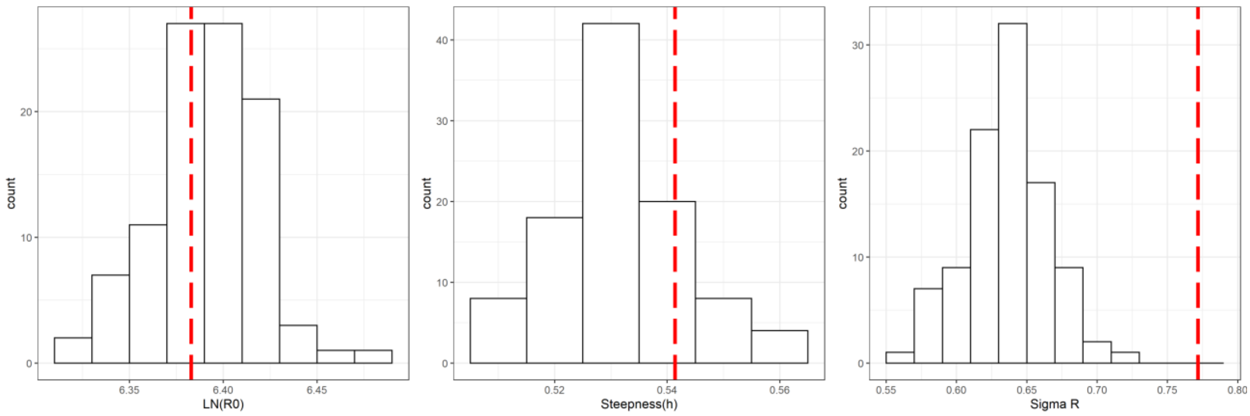



(b) Model 2

**Figure 13**. Results of SSB and recruitment trends came from original runs (red line) and 100 bootstrap replicates (gray line) for (a) model 1 and (b) model 2.




(a) Model 1




(b) Model 2

**Figure 14**. Results of the distribution of 3 parameter estimates related to SR relationship came from 100 bootstraps replicates for (a) model 1 and (b) model 2, ln(R0) (left), steepness (middle) and sigmaR (Right). Red line shows the estimates in original run without data pertuerbation.

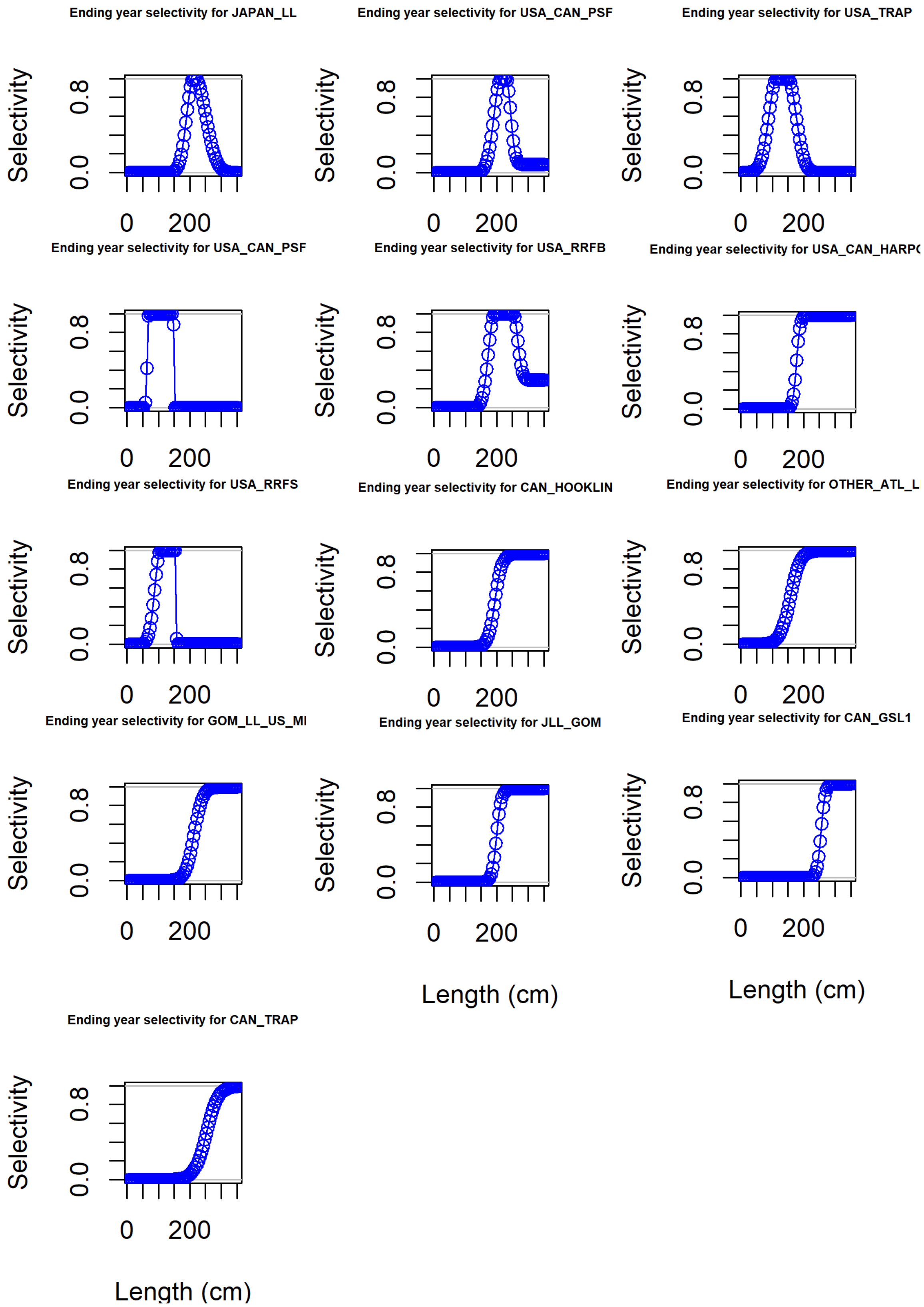



**Figure 15**. Estimated selectivity at end year for model 1.

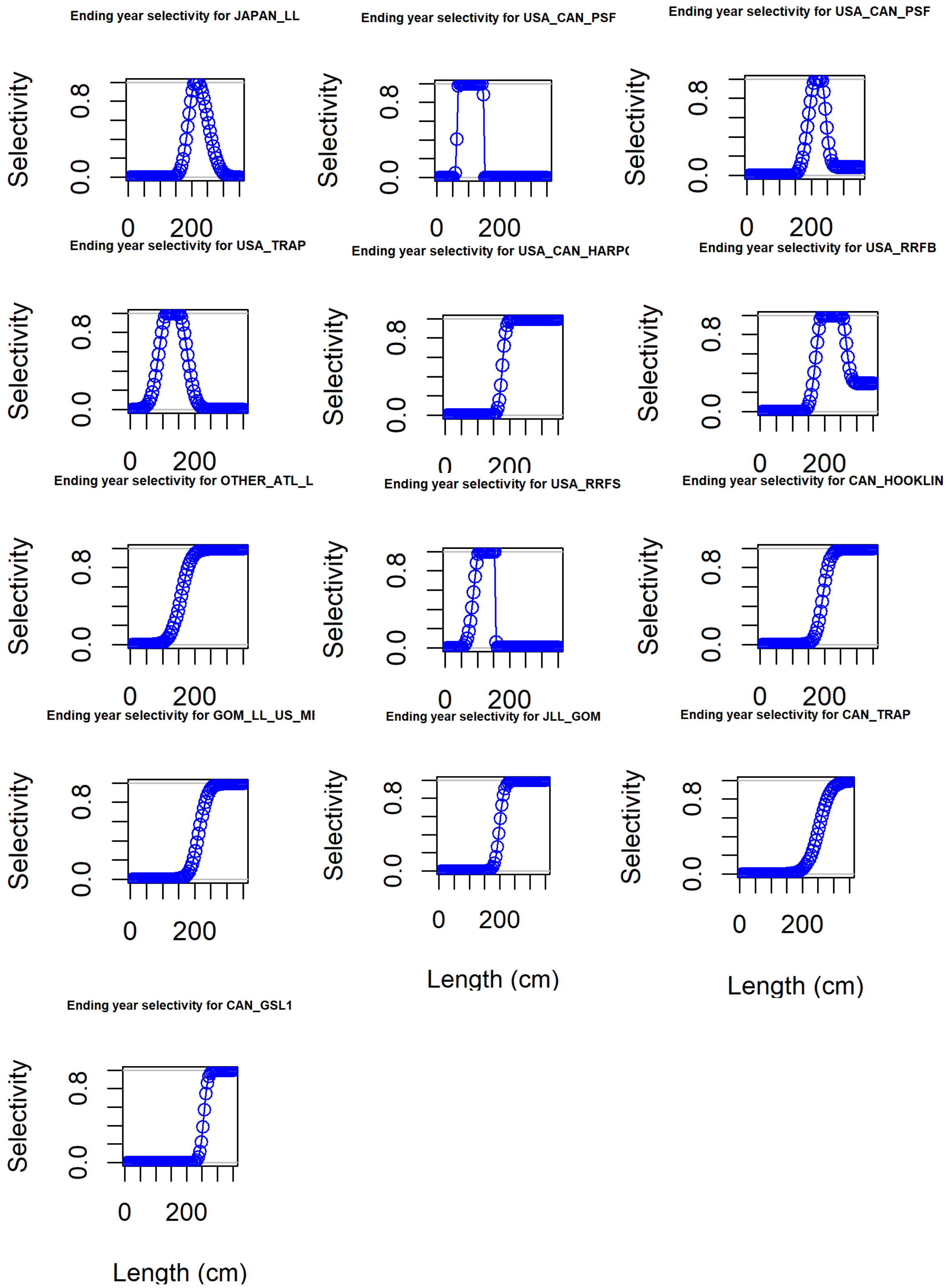



**Figure 16**. Estimated selectivity at end year for model 2.

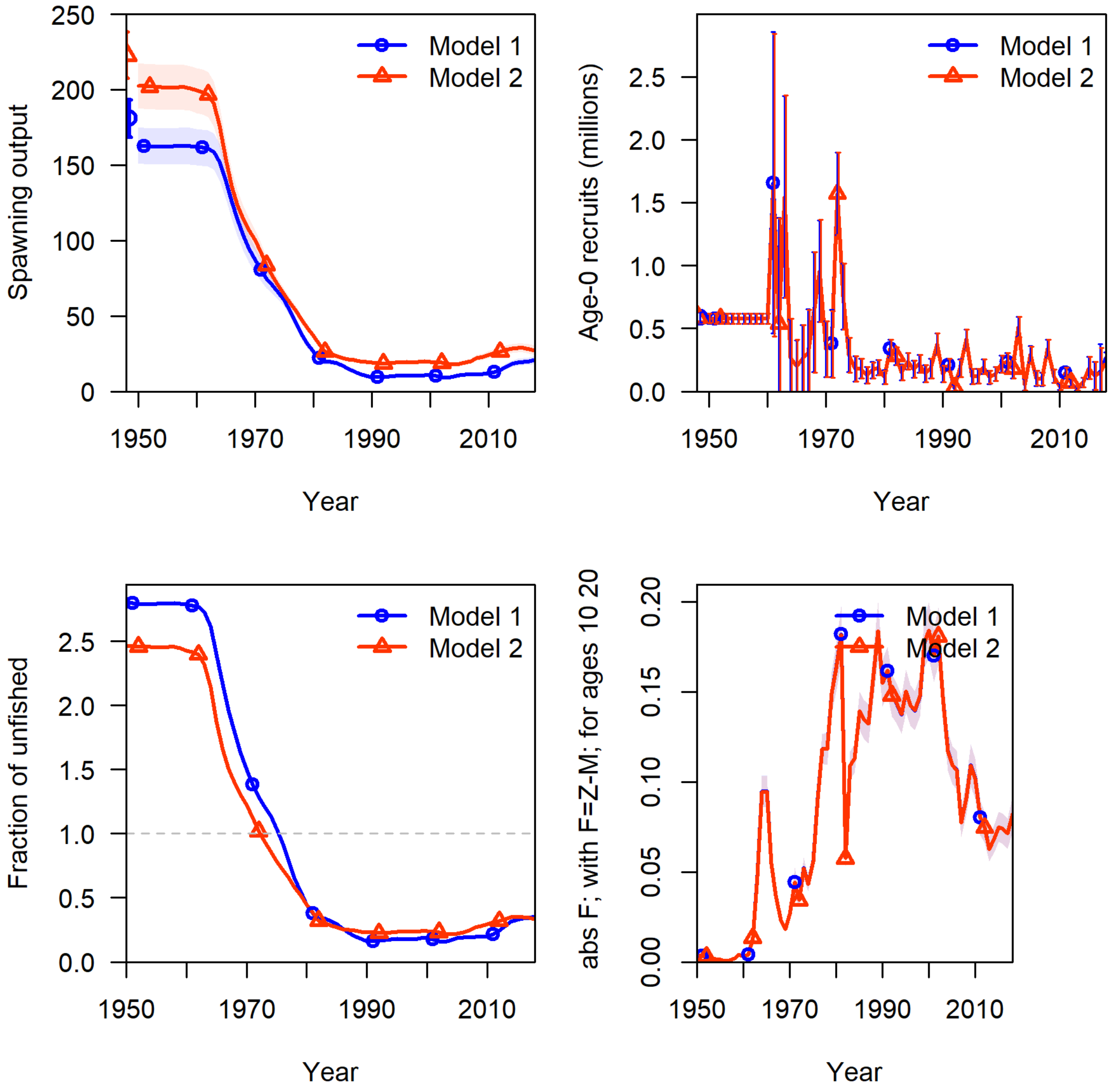



**Figure 17.** The comparison plot of time series of SSB (top left), recruitment (top right), biomass ratio to unfished levels (bottom left) and fishing mortality (bottom right) between model 1 and model 2, i.e. maturity schedule.