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Preliminary stock assessment model in Stock Synthesis 3.30 for the Pacific saury in Northwestern Pacific Ocean

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Abstract

In this study, a preliminary stock assessment model in Stock Synthesis 3.30 was developed for the Pacific saury in the Northwestern Pacific Ocean (WNPO) by incorporating historical catch, standardized catch-per-unit-effort (CPUE), and length composition data. This document describes the methodology for the upcoming age-structured stock assessment and contains information on input data, model structure, and parameterization. We also examined the model diagnostics on the preliminary model. Virgin recruitment (R_0) likelihood component profile showed a conflict between relative abundance index and size composition data, and the recruitment deviations component was relatively informative within the total likelihood. This study recognized that there is still uncertainty in life history parameters including maturation, growth, natural mortality, as well as the input length composition data. To improve the stock assessment in the future, we recommend continuing model development work, reducing data conflicts and modelling uncertainties, and re-evaluating and improving input assessment data. These preliminary results cannot and should not be used to determine stock status and conservation of the WNPO saury.

1. Introduction

The Pacific saury (*Cololabis saira*), a migratory small pelagic fish, is widely distributed throughout the middle latitudes of the North Pacific (Fukushima, 1979). Pacific saury is one of the commercially important fish in the Northwestern Pacific (WNPO). The majority of catch has been taken by stick-held dip net vessels from Japan, Chinese Taipei, and China, which accounted for 80% of the total harvest since 2014, with the remaining catch taken by Russia, Korea, and Vanuatu (NPFC, 2021).

The stock condition of Pacific saury has been evaluated using Bayesian State-Space Production Models (BSSPM; NPFC-2021-SSC PS08-WP01, NPFC-2021-SSC PS08-WP02, and NPFC-2021-SSC PS08-WP03). Current stock condition suggested that the estimated biomass in the recent three years (2019 – 2021) was below B_{MSY} and fishing mortality from 2018 – 2020 was above $F_{MSY.}$ The results further indicated that stock biomass fell to the lowest value since 1980 in 2020 and has been still at a historically low level in recent years (2019 – 2021) (NPFC-2021-SSC PS08-Final Report). It was noted that the retrospective analyses showed that BSSPM projections for Pacific saury were less useful than expected and the results were likely to be misinterpreted (NPFC-2020-SSC PS06-Final Report). The SSC PS recommended that age-structured assessment modelling may be required to provide projection results for use by managers, to enhance projection capability and support potential Management Strategy Evaluation (MSE) (NPFC-2021-SSC PS08-Final Report and NPFC-2022-SWG MSE PS01-Final Report).

In this study, we aim to develop an age-structured model for the Pacific saury in WNPO based on the modelling platform of Stock Synthesis 3 (SS3; Methot and Wetzel, 2013). The available data and the preliminary model results and diagnostics were summarized in this paper to inform discussions and recommendations for future work.

2. Material and methods

2.1 Spatiotemporal structure and data used

Based on the general consensus that a single management stock for the Pacific saury is likely in the WNPO (NPFC TWGPSSA, 2017), we presented here an assessment of Pacific saury in the WNPO area. A total of six stick-held dip net fleets of Pacific saury were defined on the basis of NPFC members (Japan, Chinese Taipei, Korea, Russia, China, and Vanuatu). Three types of data were used: fishery-specific catches (in metric ton, mt), relative abundance indices (including fishery-dependent CPUE and fishery-independent biomass survey), and length composition data (in cm). The fishery data were compiled for 1980 – 2020, noting that the catch data and length composition data were compiled and modelled on a quarterly basis. All relative abundance indices were also modelled as a quarterly index. Available data, sources of data, and temporal coverage of the datasets used in the stock assessment were summarized in **Figure 1**.

Time series of the catch of Pacific saury in the WNPO by fisheries (defined as catch fleets) from 1980 – 2020 were shown in **Table 1** and **Figure 2**. In the last decades, annual total catches of the Pacific saury increased from 176,364 mt in 1998 to 617,509 mt in 2008 and then continuously decreased to 262,639 mt in 2017 except for the high catch in 2014 (629,576 mt). The recent average catch is 257,044 mt during 2018 – 2020. Relative abundance indices of the WNPO Pacific saury by fleets were shown in **Table 1** and **Figure 3**. Visual inspection of all indices showed an overall decreasing trend with the last 7 years (2014 – 2020). The early index of Japan generally increased during 1980 – 1993. The coefficient of variation (CV) for each index was assumed to be equal to the standard error (SE) on the log scale. The CVs were set to 0.27 (mean CV value of biomass of Japan across years without 2020).

Quarterly fish length composition data from 1994 – 2020 by fleets were summarized in **Table 1**. Length frequency data were compiled using 1-cm length bins from 14 to 35 cm. **Figure 4** showed the annual variations of quarterly length compositions by fleets. The aggregated length composition distribution generally showed a single mode around 30 cm for F2_TWN, F4_RUS, and F6_VAN but was bimodal with two peaks at around 27 cm and 30 cm for F1_JPN (**Figure 5**).

2.2 Model description

The assessment was conducted with Stock Synthesis (SS) version 3.30.16 (Methot and Wetzel, 2013). The model was set up as a single area and single-gender model with four seasons (quarters). Spawning was assumed to occur in February (month 2). The available biological parameters for the WNPO saury stock were used (**Table 2**). The maximum age of Pacific saury was set to 2, the age at length L1 was set to age 0, and the CV of the growth curve was set to 0.2 for the young and old fish. The growth curve used a von Bertalanffy growth curve refitted from the Gompertz growth curve by Suyama et al. (2015) for ages 0 – 2. The von Bertalanffy growth coefficient parameter (*K*) and the maximum length (*Linf*) were set to 2.02 and 31.45 cm respectively, and the size at age 0 = 0.66 cm. The natural mortality (2.18) of Pacific saury was estimated by using a meta-analytical approach that uses theoretical and empirical models to predict the natural mortality rate as a function of life history parameters (**Table 3**). A Beverton-Holt spawner-recruit relationship was used with steepness (*h*) set at 0.86 (estimated from FishLife, https://github.com/James-Thorson/FishLife, based on the joint distribution of intrinsic growth rate and *h*) and sigmaR (σ_r) set at 0.6.

Initial fishing mortality was estimated for the fleet of Japan (F1_JPN). Main recruitment deviations were estimated from 1978 – 2020. Early recruitment deviations were estimated from 1978 to 1979 as the population was not at equilibrium prior to the start of the model. The population model and the fishery length data had 22 one cm length bins from 14 – 35+ cm. The population had three age groups from age 0 to 2+. Fishery size data were used to estimate selectivity patterns, which controlled the size distribution of the fishery removals. Selectivity of F5_CHN was mirrored to F2_TWN (**Table 4**). The Japanese biomass survey (S7_JPN_bio) selectivity was mirrored to F1_JPN. Model estimated time series of total biomass for age 1+ (B_{age1+} in metric tons), female spawning stock biomass (SSB in metric tons), recruitment (R in 1,000s of fish) and fishing mortality (F in year^{-1}) were tabulated on an annual basis.

2.3 Model convergence and diagnostics

The model was assumed to have converged if the standard error of the estimated parameters could be derived from the inverse of the negative Hessian matrix. Various convergence diagnostics were also evaluated. A gradient of >0.001 would suggest poorly fit parameter estimates. Parameter estimates hitting bounds of the prior was also indicative of poor model fit. Profiling the likelihood on the virgin recruitment (R_0), where the R_0 is fixed at a range of values around the maximum likelihood estimate and then the likelihood is estimated, was used to identify influential data components (Lee et al., 2014). A runs test was used to evaluate randomness in the residuals of the relative abundance index and length composition data (Carvalho et al., 2021). Residual plots of the observed vs expected data were examined to evaluate goodness-of-fit for the relative abundance index and length composition data.

3. Results and discussions

3.1 Model fit and R_0 profile diagnostics

The model development and results shown as the spawning potential depletion $SSB/SSB_{F=0}$ were shown in **Appendix Figure 1**. The WNPO Pacific saury model estimated 66 parameters, and had a total likelihood of 2,612. The inverse Hessian was positive definite, which allowed for the estimation of parameter standard deviations and suggests that the model converged, and the maximum gradient component was 4.84e-05, which is smaller than 0.001. None of the parameter estimates hit a bound, however it was noted that the poor convergence in estimated F_{MSY}. Fits to the relative abundance indices were generally good, with no substantial divergences between the expected and estimated values (**Figures 6 and 7**). However, the S1_JPN_early, S2_JPN_late and

S3_TWN did not pass the run test (**Figure 8**), which suggests that the residuals are not likely random. The estimated selectivity for each fleet was shown in **Figure 9**.

Overall, the model fit the length modes in composition data aggregated by fleets generally well (**Figure 5**). However, the model predicted size compositions did not match the observations in some years (**Figures 10 and 11**). For example, the pattern of Pearson residuals for F3_KOR showed large negative residuals in recent years and the annual mean length predictions were estimated to be larger than the observed values. Furthermore, the results of the run test indicated that F2_TWN and F3_KOR did not pass the run test (**Figure 12**), which suggests that their residuals are likely not random.

Profiling on R_0 showed that the recruitment estimates were influential in the model results (**Figure 13**), and there were some conflicts between the relative abundance index and the length composition data (**Figures 14 and 15**).

3.2 Preliminary stock assessment model outputs

Preliminary estimates of population biomass (age 1 and older; quarter 1) showed an increasing trend from 1980 – 1992. After then, the total biomass showed a decreased pattern from 1993 to 1999. The total biomass increased and fluctuated during 2000 – 2010. After 2014, the apparently decreased total biomass trend was observed, and the total biomass in 2020 reached the lowest biomass level in the recent decade (2010 – 2020) (**Figure 16a**). Spawning biomass also exhibited a declining trend from 2014 to 2020 (**Figure 16b**). Recruitment (age-0 fish) estimates showed a fluctuated pattern over years, but recruits were at a relatively low level during 2018 – 2020 (reached a historically low value in 2019) (**Figure 16c**). Estimates of fishing mortality were stable and fluctuated around 0.5 $year^{-1}$ over the assessment period. However, a slightly increased pattern of fishing mortality was observed from 2016 to 2020 (**Figure 16d**).

This study recognized that there is still uncertainty in life history parameters including maturation, growth, natural mortality, as well as the input length composition data. To improve the stock assessment in the future, we recommend continuing model development work, reducing data conflicts and modelling uncertainties and re-evaluating and improving input assessment data. This document describes the methodology for the upcoming WNPO saury assessment and contains information on input data, model structure, and parameterization. These preliminary results cannot and should not be used to determine stock status and conservation of the WNPO saury.

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Table 1. Descriptions of fisheries catch, relative abundance indices, and length composition data included in the model for the WNPO Pacific saury stock assessment including reference code, members, description, unit, time-period, and data sources.

Fleet No	**Reference code**	**Members**	**Catch unit**	**Source**
F1	F1_JPN	Japan	B	NPFC (2021)
F2	F2_TWN	Chinese Taipei	B	NPFC (2021)
F3	F3_KOR	Korea	B	NPFC (2021)
F4	F4_RUS	Russia	B	NPFC (2021)
F5	F5_CHN	China	B	NPFC (2021)
F6	F6_VAN	Vanuatu	B	NPFC (2021)
Relative abundance No	**Reference code**	**Description**	**Time-series**	**Source**
S1	S1_JPN_early	Japanese early index	1980 – 1993	Oshima et al. (2018)
S2	S2_JPN_late	Japan late index	1994 – 2020	Hashimoto et al. (2021a)
S3	S3_TWN	Chinese Taipei	2001 – 2020	Huang et al. (2021)
S4	S4_KOR	Korea	2001 – 2020	Park and Lee (2021)
S5	S5_RUS	Russia	1994 – 2020	Kulik et al. (2021)
S6	S6_CHN	China	2013 – 2020	Hua et al. (2021)
S7	S7_JPN_bio	Japanese biomass survey	2003 – 2020	Hashimoto et al. (2021b)
Length composition data No	**Reference code**	**Members**	**Time-series**	**Source**
F1	F1_JPN	Japan	1994 – 2020	NPFC (2021)
F2	F2_TWN	Chinese Taipei	2007 – 2020	NPFC (2021)
F3	F3_KOR	Korea	2001 – 2020	NPFC (2021)
F4	F4_RUS	Russia	2000 – 2018	NPFC (2021)
F6	F6_VAN	Vanuatu	2013 – 2020	NPFC (2021)

Table 2. Key life-history and recruitment parameters used for the WNPO Pacific saury assessment model.

Parameter	Value	Comments	Reference
Reference age (a1)	0	Fixed parameter	Suyama et al. (2015)
Maximum age (a2)	2	Fixed parameter	Suyama et al. (2015)
Length at a1 (L1)	0.66	Fixed parameter	Refit Suyama et al. (2015)
Length at a2 (L2)	31.45	Fixed parameter	Refit Suyama et al. (2015)
Growth rate (*K*)	2.02	Fixed parameter	Refit Suyama et al. (2015)
CV of L1	0.20	Fixed parameter	Assumed
CV of L2	0.20	Fixed parameter	Assumed
Wtlen_1_Fem	2.44e-06	Fixed parameter	Fuji et al. (2019)
Wtlen_2_Fem	3.34694	Fixed parameter	Fuji et al. (2019)
Size-at-50% Maturity	28.7	Fixed parameter	Refit Kosaka (2000) and Suyama (2002)
Slope of maturity ogive	-0.80	Fixed parameter	Refit Kosaka (2000) and Suyama (2002)
Natural mortality (*M*)	2.18	Fixed parameter	Estimated by meta-analysis
Fecundity	Proportional to spawning biomass	Fixed parameter	Fuji et al. (2019)
Spawning season	February	Model structure	Fuji et al. (2020)
Spawner-recruit relationship	Beverton-Holt	Model structure	Assumed
R_0	-	Estimated	
Steepness (*h*)	0.86	Fixed parameter	FishLife; Thorson et al. (2017)
Recruitment variability (σ_R)	0.6	Fixed parameter	Assumed

Table 3. The eleven potential models to estimate natural mortality rates (*M*) of Pacific saury based on life history parameters of maximum expected age (t_{max}), age at maturity (t_m), Brody growth coefficient (*K*), length at maturity (L_m), asymptotic length (L_∞), and temperature (*T*).

No.	**Estimator**	**Reference**
1	$M = 0.985 L_\infty^{-0.279} K^{0.654} T^{0.463}$	Pauly (1980)
2	$M = 4.30 / t_{\max}$	Hoenig (1983)
3	$M = 1.8K$	Hoenig (1983)
4	$M = 1.65 / t_m$	Jensen (1996)
5	$M = 1.5K$	Jensen (1996)
6	$M = 2 / t_m$	Charnov and Berrigan (1991)
7	$M = 1.6K$	Jensen (1996)
8	$M = \dfrac{3K}{(\exp(Kt_m) - 1)}$	Roff (1984)
9	$M = \dfrac{3KL_\infty (1 - L_m / L_\infty)}{L_m}$	Roff (1984)
10	$M = 4.118 K^{0.73} L_\infty^{-0.33}$	Then et al. (2015)
11	$M = 4.899 t_{\max}^{-0.916}$	Then et al. (2015)

Table 4. Fishery-specific selectivity assumptions for the WNPO Pacific saury stock assessment. The selectivity curves for fleets lacking length composition data were assumed to be the same as (i.e., mirror) closely related fisheries or fisheries operating in the same area.

Fleet	**Selectivity function**
F1_JPN	Double normal
F2_TWN	Double normal
F3_KOR	Double normal
F4_RUS	Double normal
F5_CHN	Mirror F2
F6_VAN	Double normal
S1_JPN_early	Mirror F1
S2_JPN_late	Mirror F1
S3_TWN	Mirror F2
S4_KOR	Mirror F3
S5_RUS	Mirror F4
S6_CHN	Mirror F2
S7_JPN_bio	Mirror F1

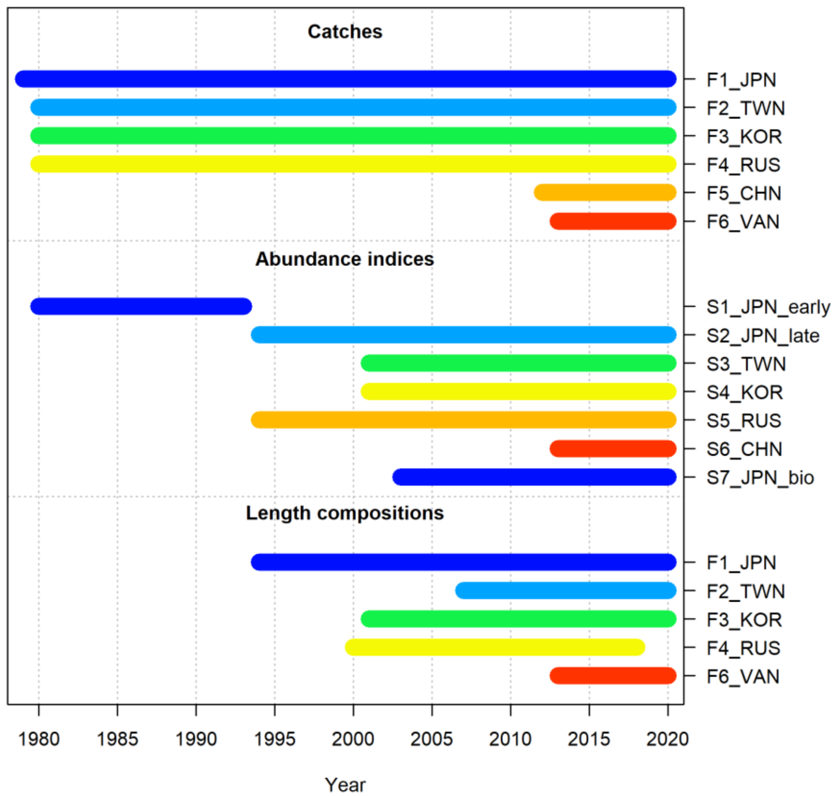


Figure 1. Catch, relative abundance index, and length composition data included in the preliminary age-structured model for the Pacific saury in the Northwestern Pacific Ocean.

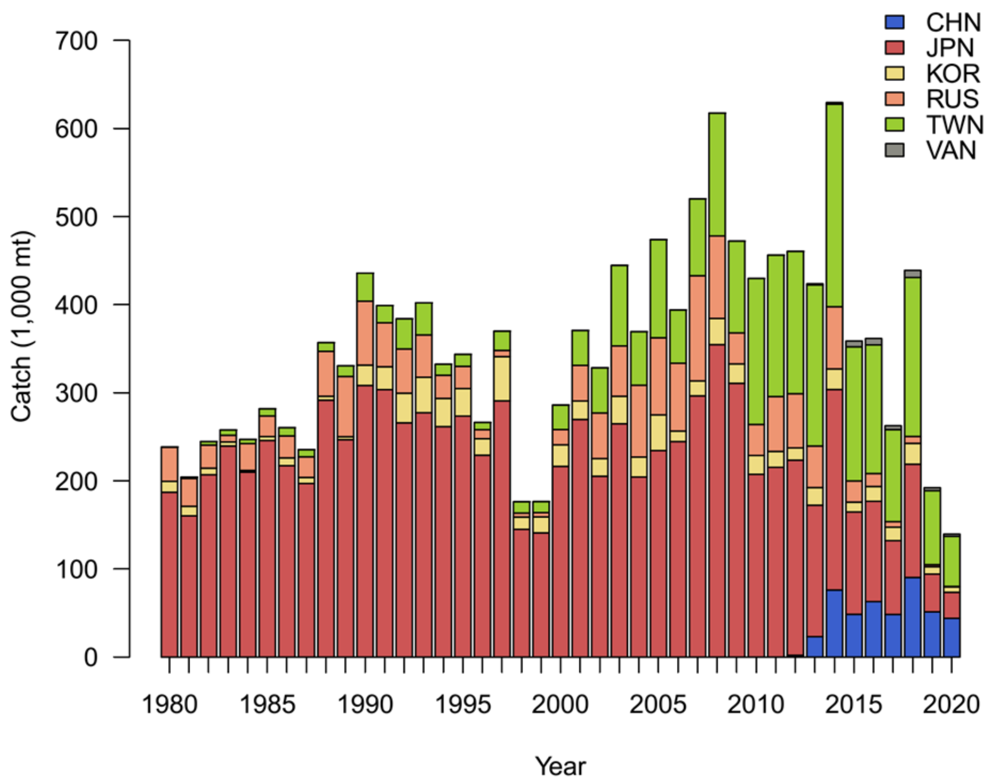


Figure 2. Time-series of catches (in metric tons) of the Pacific saury in Northwestern Pacific Ocean from 1980 to 2020 by members (“CHN” = China, “JPN” = Japan, “KOR” = Korea, “RUS” = Russia, “TWN” = Chinese Taipei, and “VAN” = Vanuatu).

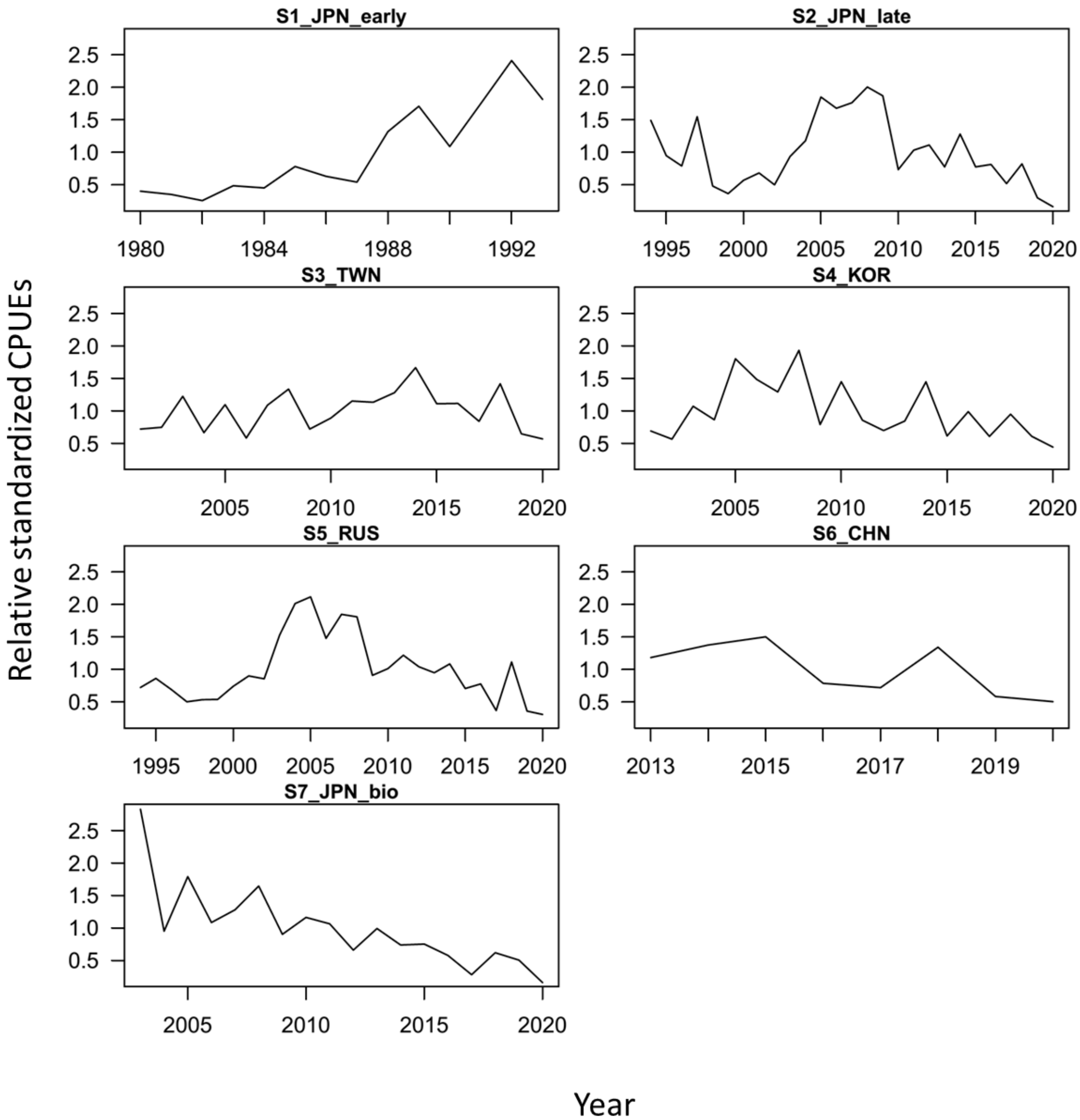


Figure 3. Time-series of Pacific saury relative abundance indices (relative to mean) from early Japan (S1_JPN_early), late Japan (S2_JPN_late), Chinese Taipei (S3_TWN), Korea (S4_KOR), Russia (S5_RUS), China (S6_CHN) stick-held dip net fisheries and biomass survey index of Japan (S7_JPN_bio) during 1980 – 2020 in the Northwestern Pacific Ocean.

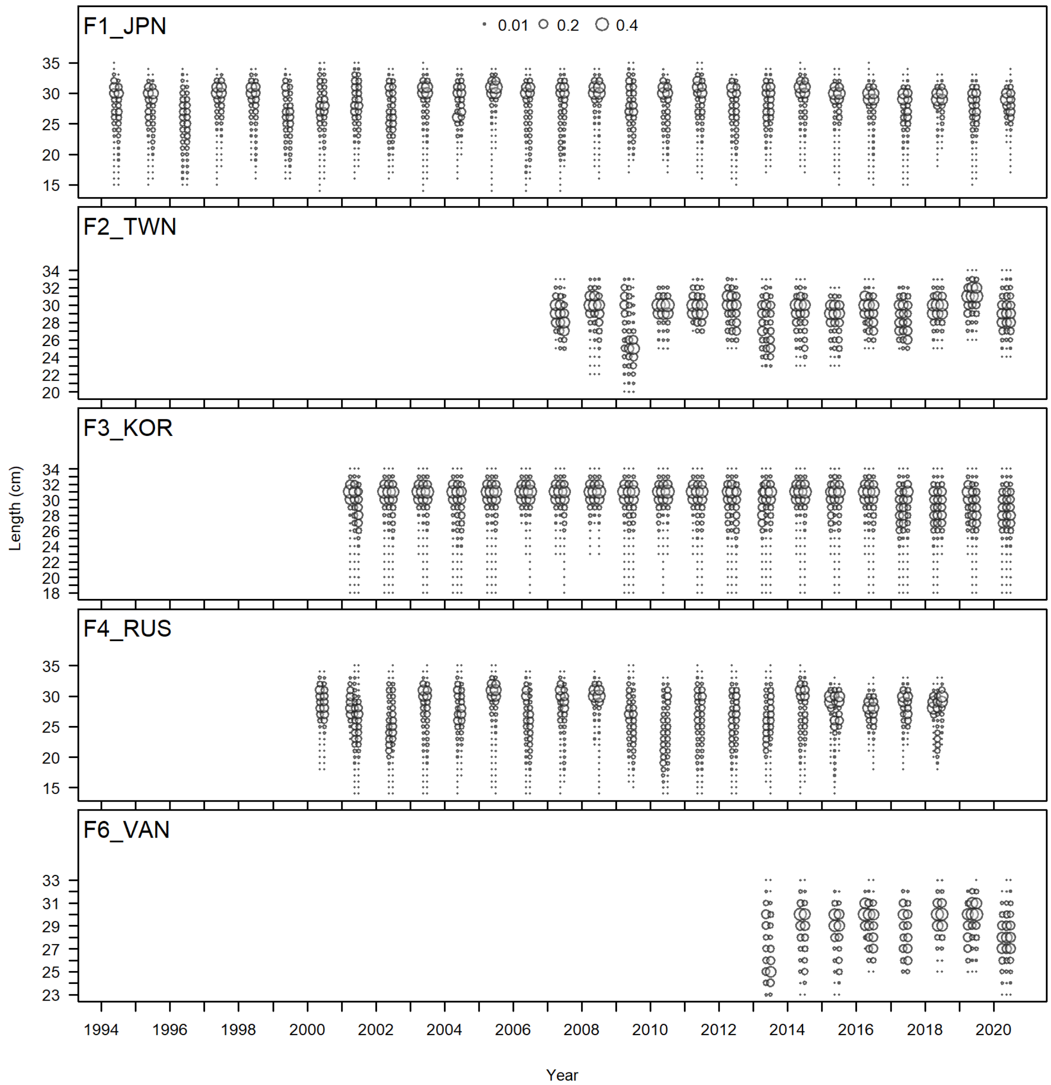


Figure 4. Quarterly length composition data (in 1-cm size bins) by fleets for the WNPO Pacific saury stock assessment.

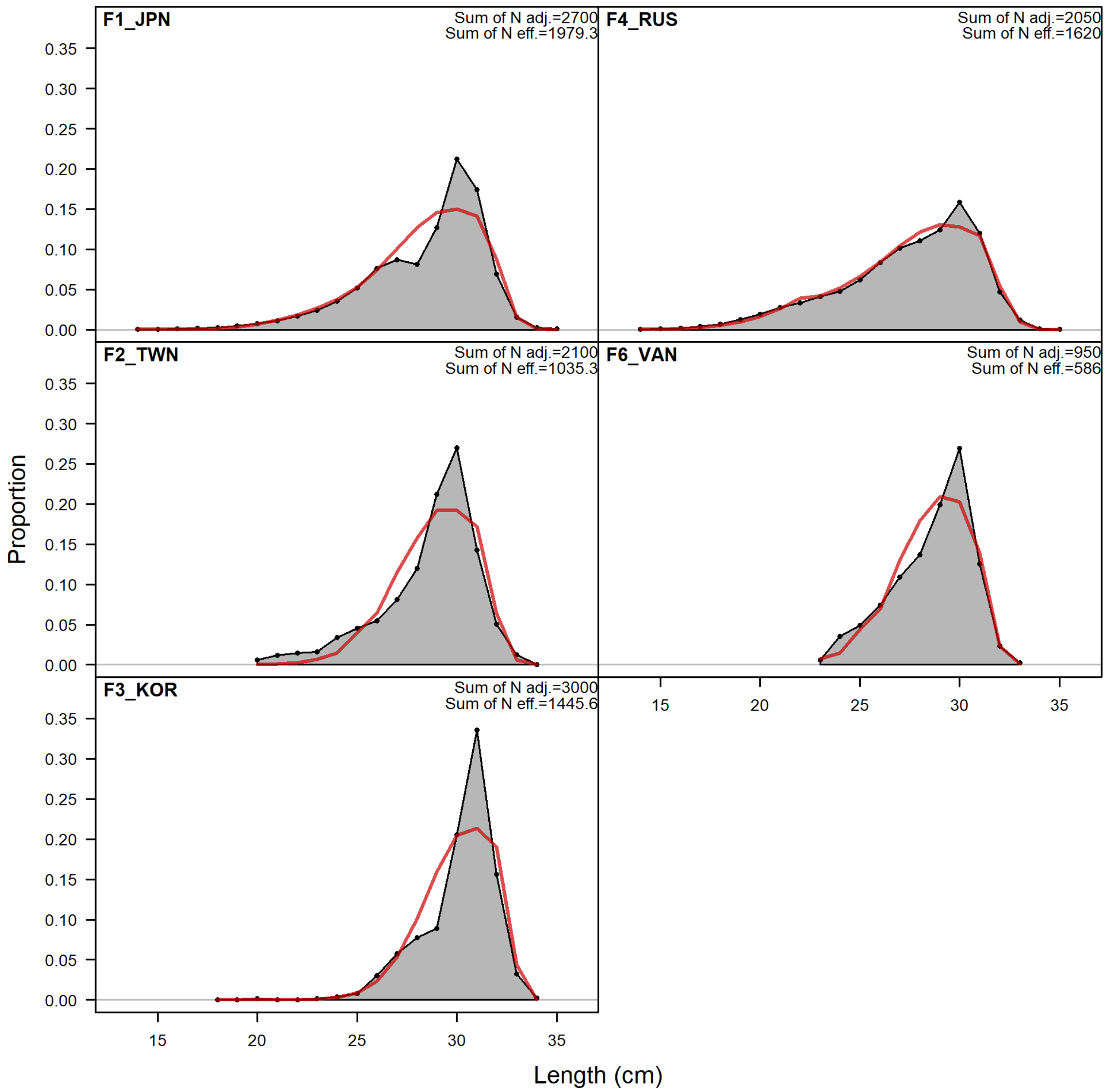


Figure 5. Aggregated length composition data by fleets for the WNPO Pacific saury stock assessment, grey shading indicates observed data, and red line indicates expected distribution based upon the estimated selectivity.

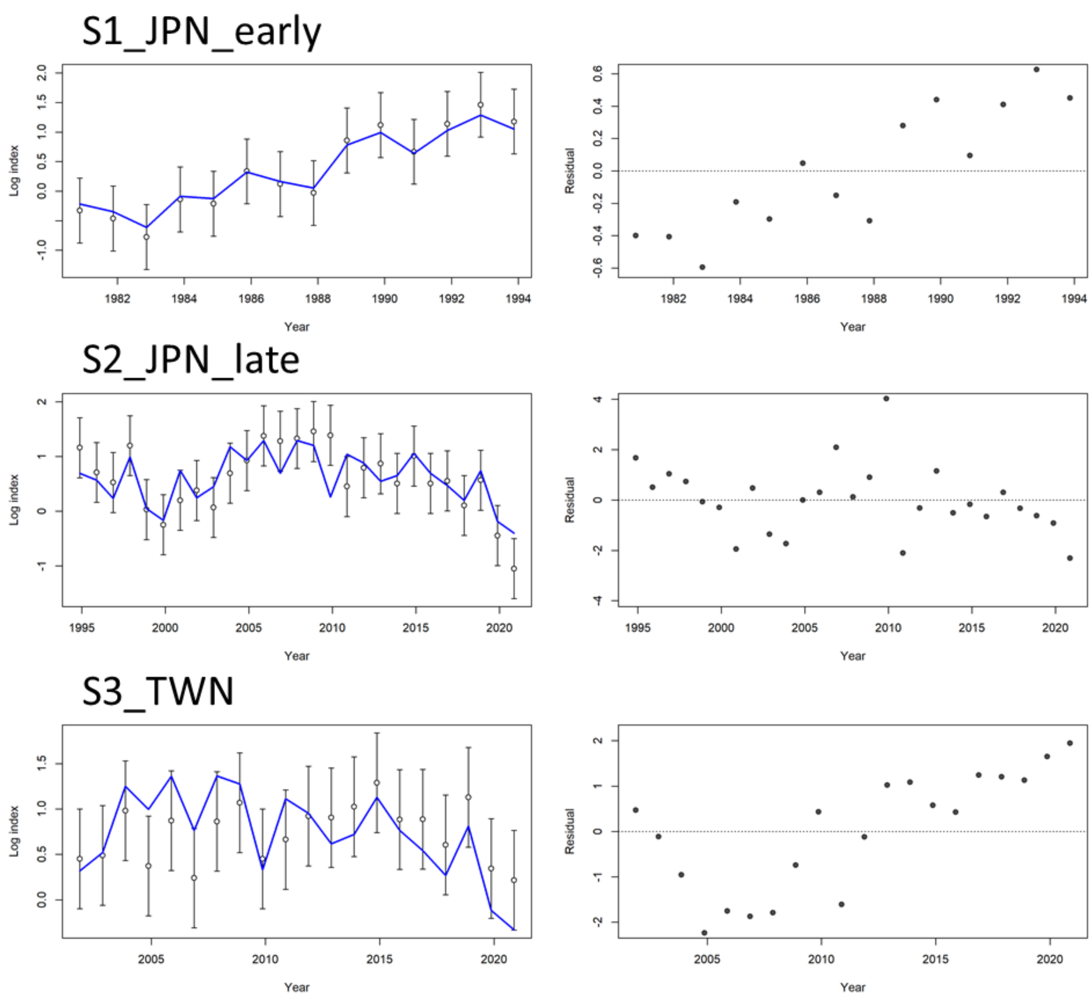


Figure 6. Fits to the early and late Japan indices (S1_JPN_early and S2_JPN_late) and Chinese Taipei index (S3_TWN) for the WNPO Pacific saury stock assessment. Left is the input values (opened circles) with CVs (vertical bars) and the model predictions (blue line). Right is the annual residuals of that fit.

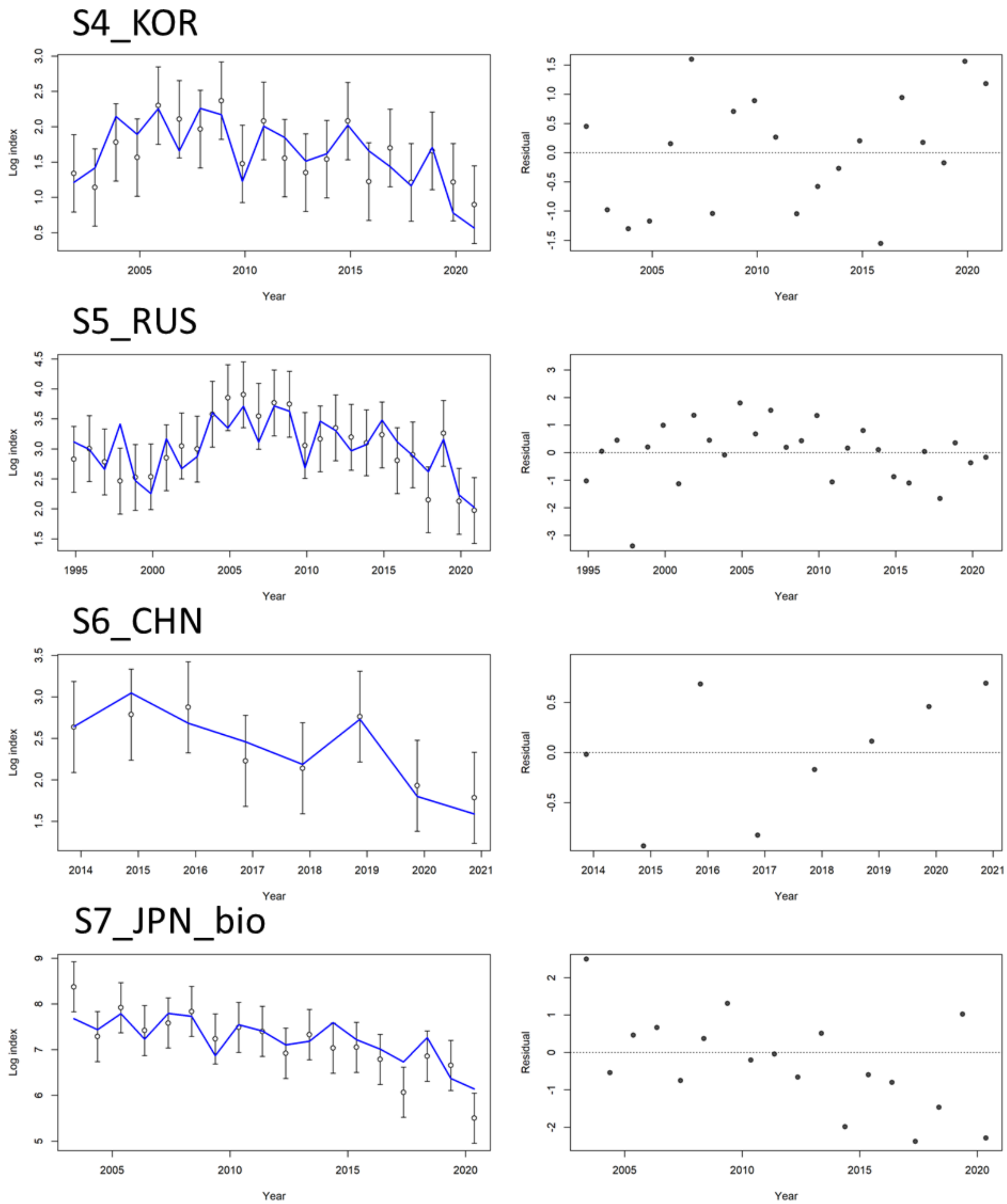


Figure 7. Fits to Korea (S4_KOR), Russia (S5_RUS), China (S6_CHN) and Japanese biomass survey (S7_JPN_bio) indices for the WNPO Pacific saury stock assessment. Left is the input values (opened circles) with CVs (vertical bars) and the model predictions (blue line). Right is the annual residuals of that fit.

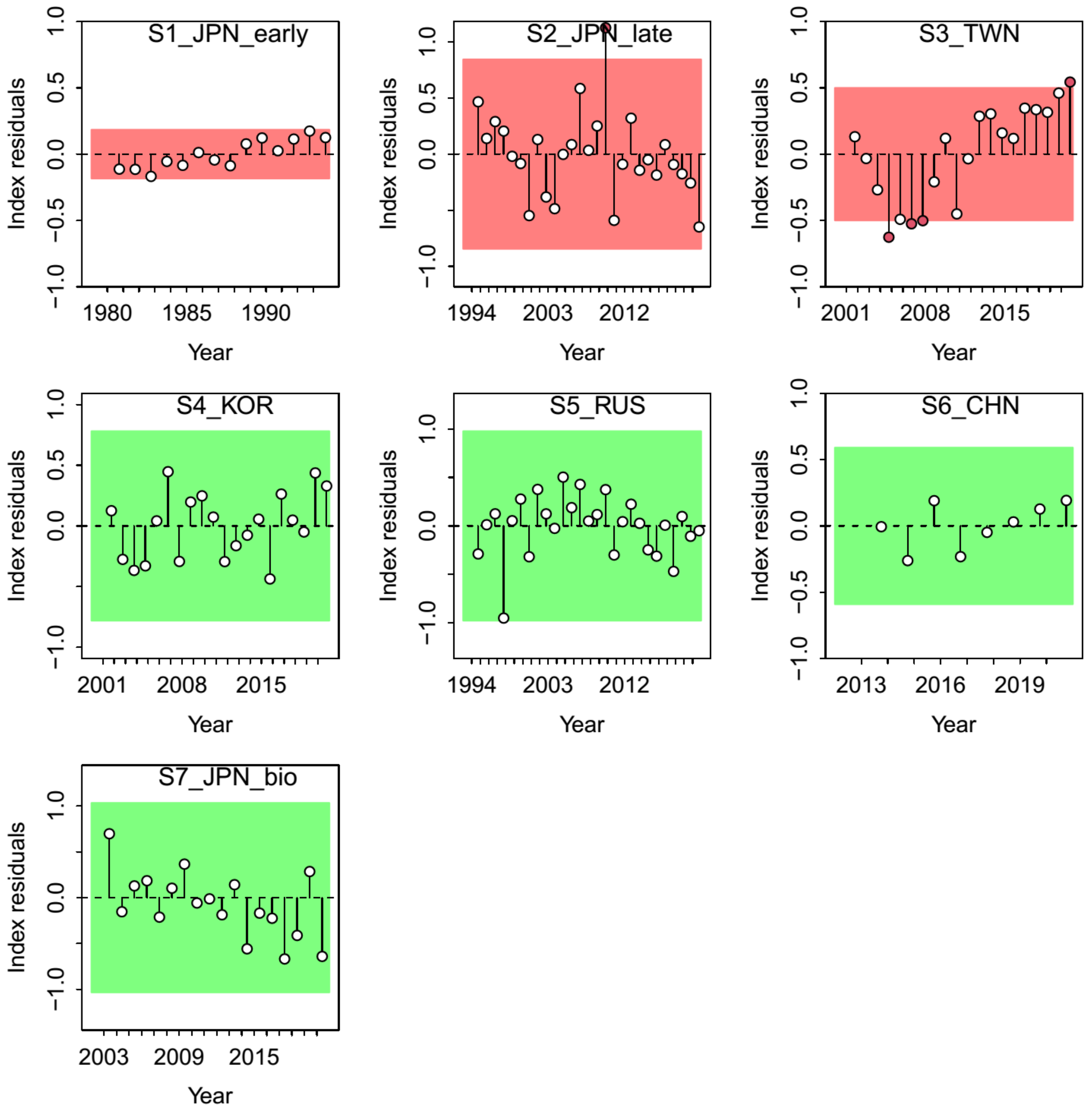


Figure 8. Result from a runs test for each relative abundance index. Red shade indicates the index failed the test (residuals are not random), green shade indicates the index passed the test. Red circles indicate the residuals hit a boundary of 3 times of sigma (residual standard deviations).

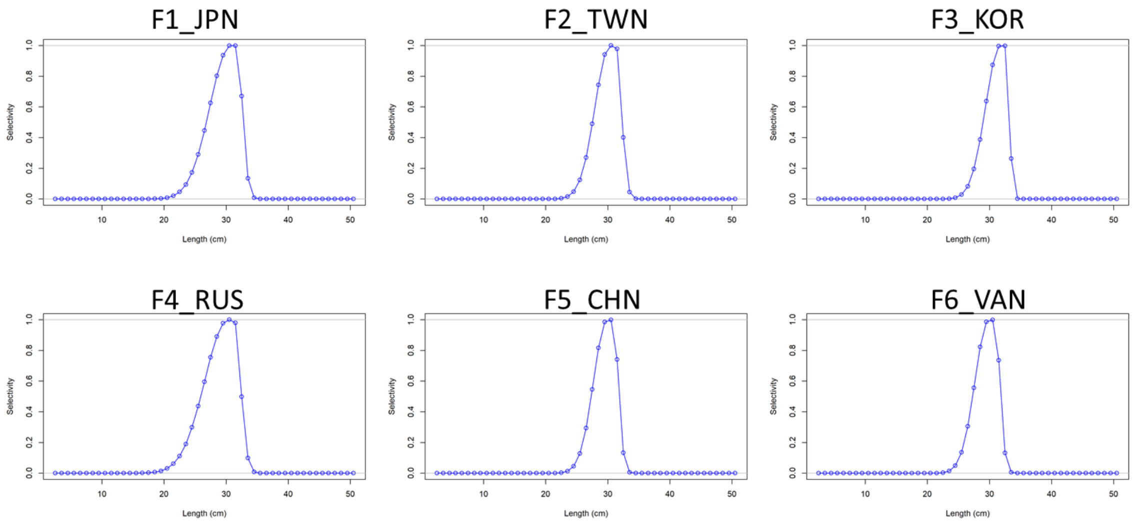


Figure 9. Selectivity estimates for the six fleets.

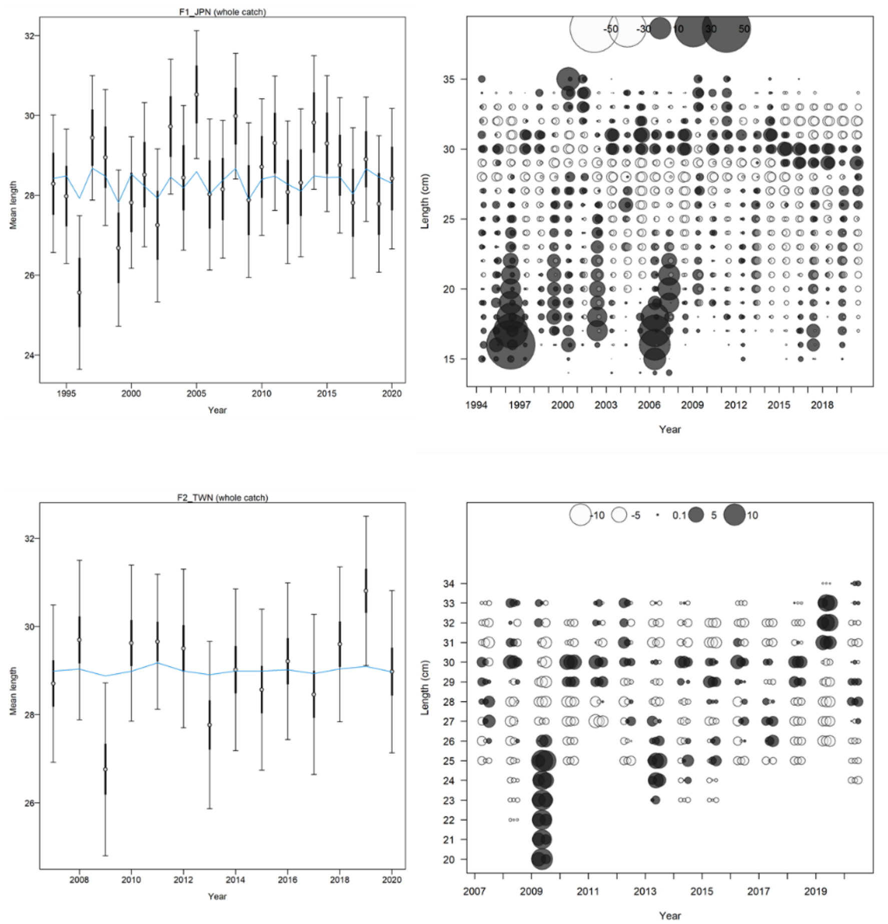


Figure 10. Fits to the annual mean length (left panels) and quarterly residuals (right panels) for Japan (F1_JPN, top) and Chinese Taipei (F2_TWN, bottom) length composition data. The blue line indicates the estimated mean length, open dots indicate input mean length with black bars showing the distribution of the length data with the added variance. Open circles indicate negative residuals and closed circles indicate positive residuals.

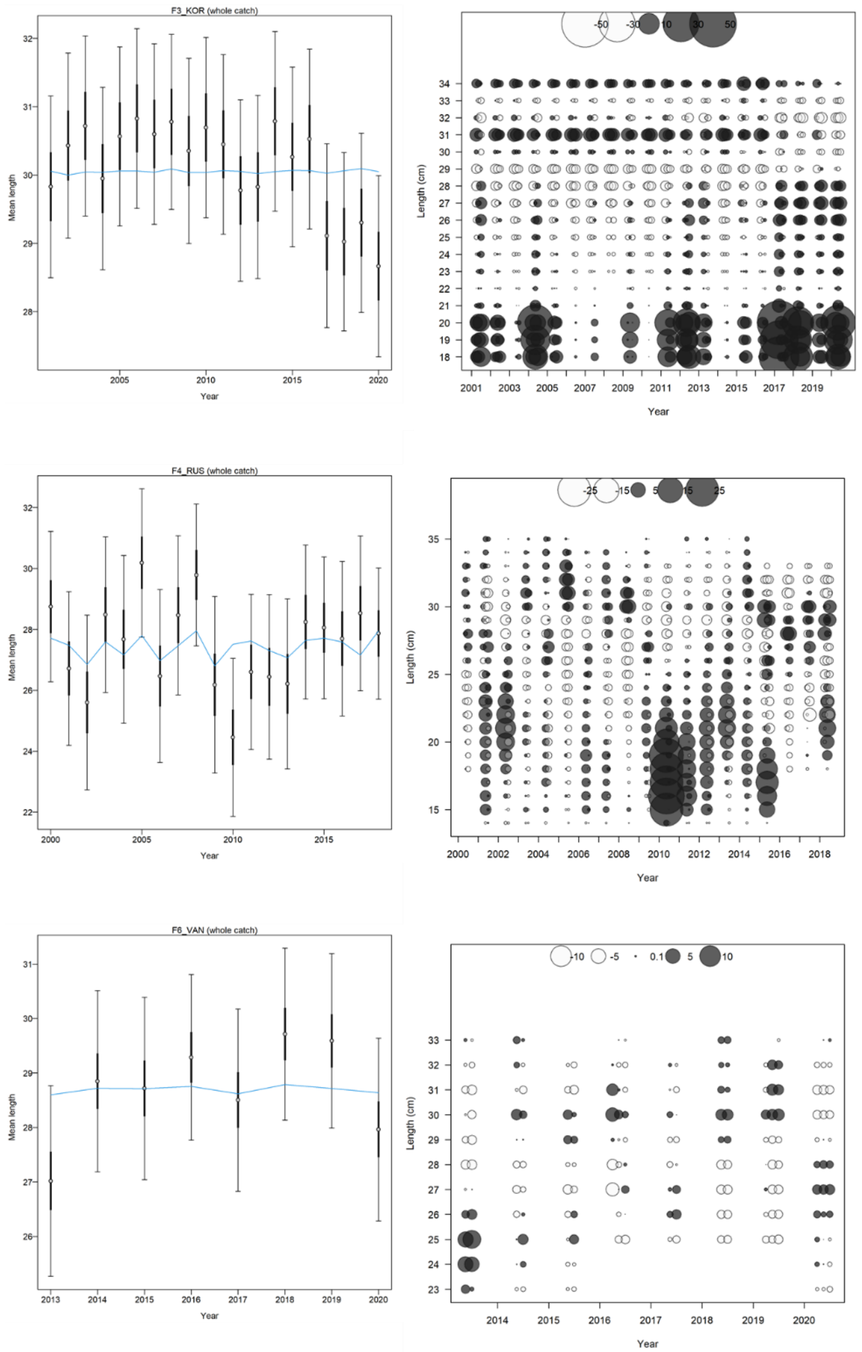


Figure 11. Fits to the annual mean length (left panels) and quarterly residuals (right panels) for Korea (F3_KOR, top), Russia (F4_RUS, middle) and Vanuatu (F6_VAN, bottom) length composition data. The blue line indicates the estimated mean length, open dots indicate input mean length with black bars showing the distribution of the length data with the added variance. Open circles indicate negative residuals and closed circles indicate positive residuals.

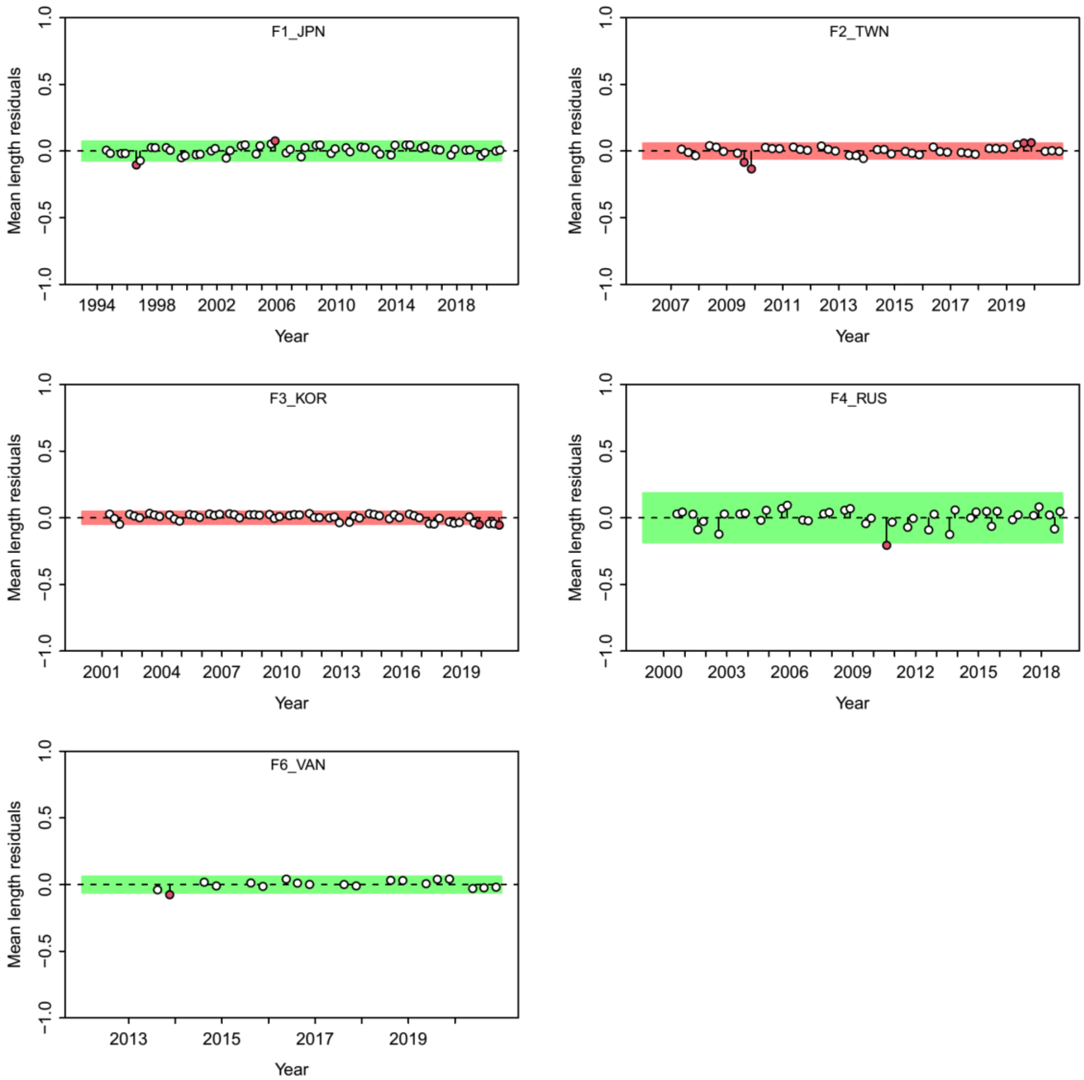


Figure 12. Result from a runs test for each length composition time series. Red indicates the data failed the test (residuals are not random), green indicates the data passed the test. Red circles indicate the residuals hit a boundary of 3 times of sigma (residual standard deviations).

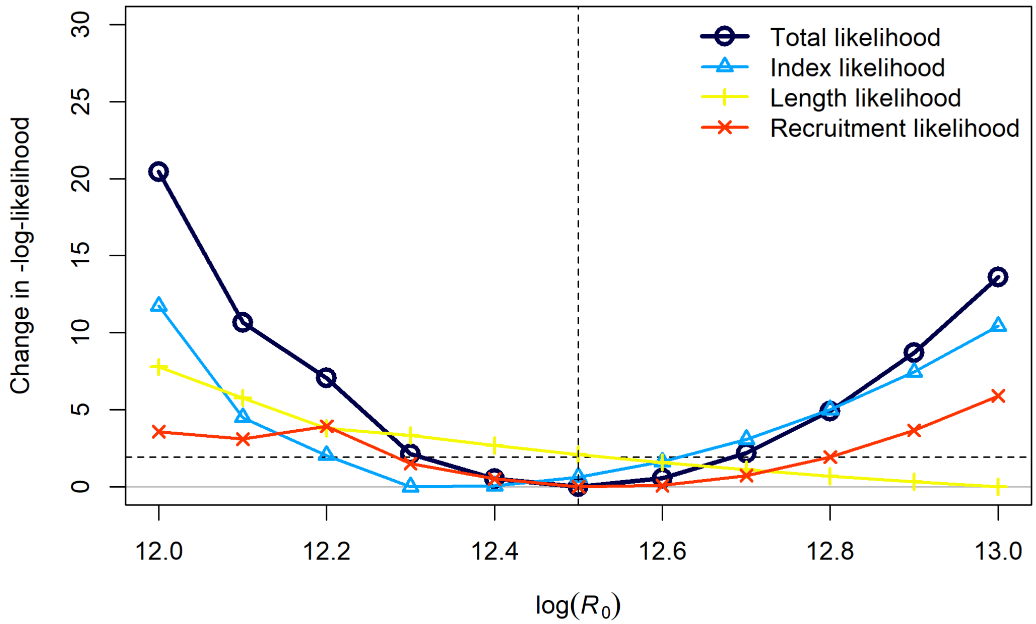


Figure 13. Profiles of the relative-negative log likelihoods by different likelihood components for the virgin recruitment in log-scale (log(R0)) of the WNPO Pacific saury assessment model.

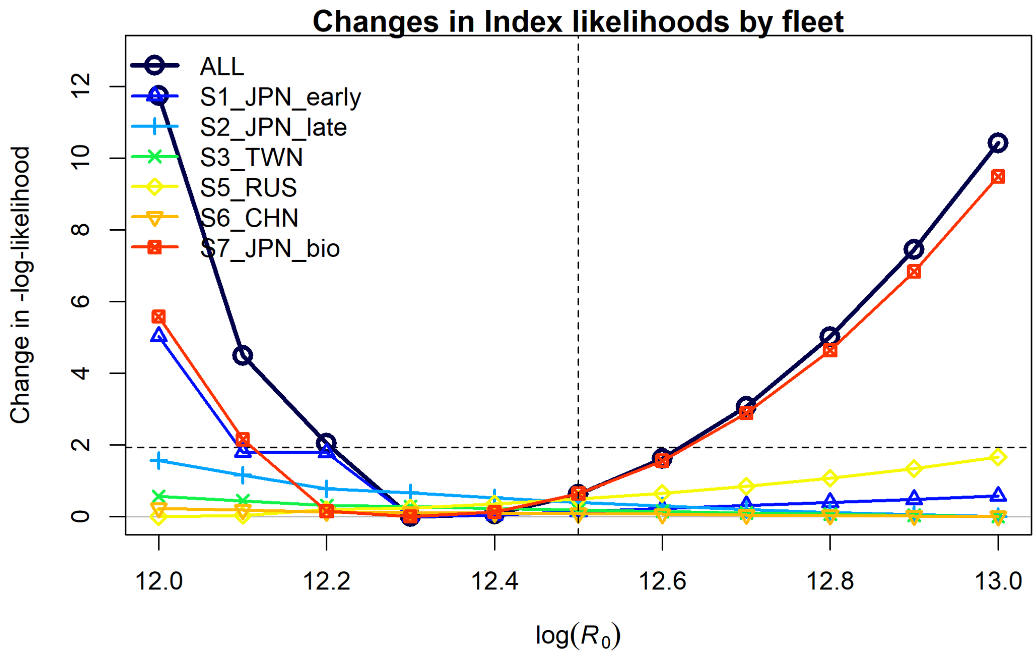


Figure 14. Profiles of the relative-negative log likelihoods by various relative abundance indices for the virgin recruitment in log-scale (log(R0)) of the WNPO Pacific saury assessment model.

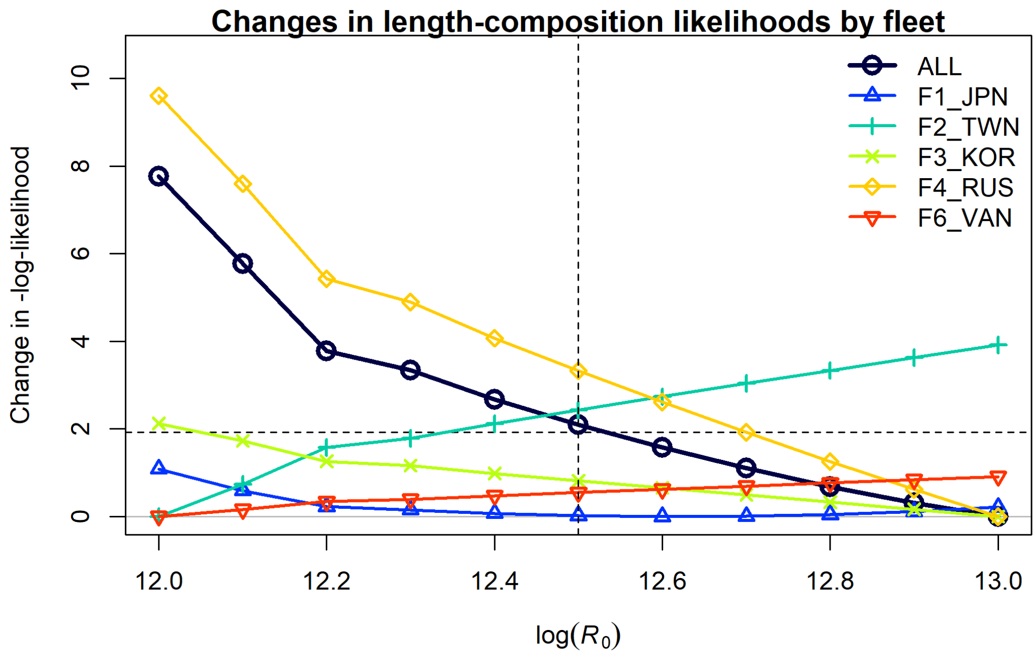


Figure 15. Profiles of the relative-negative log likelihoods by different length composition data for the virgin recruitment in log-scale (log(R0)) of the WNPO Pacific saury assessment model.

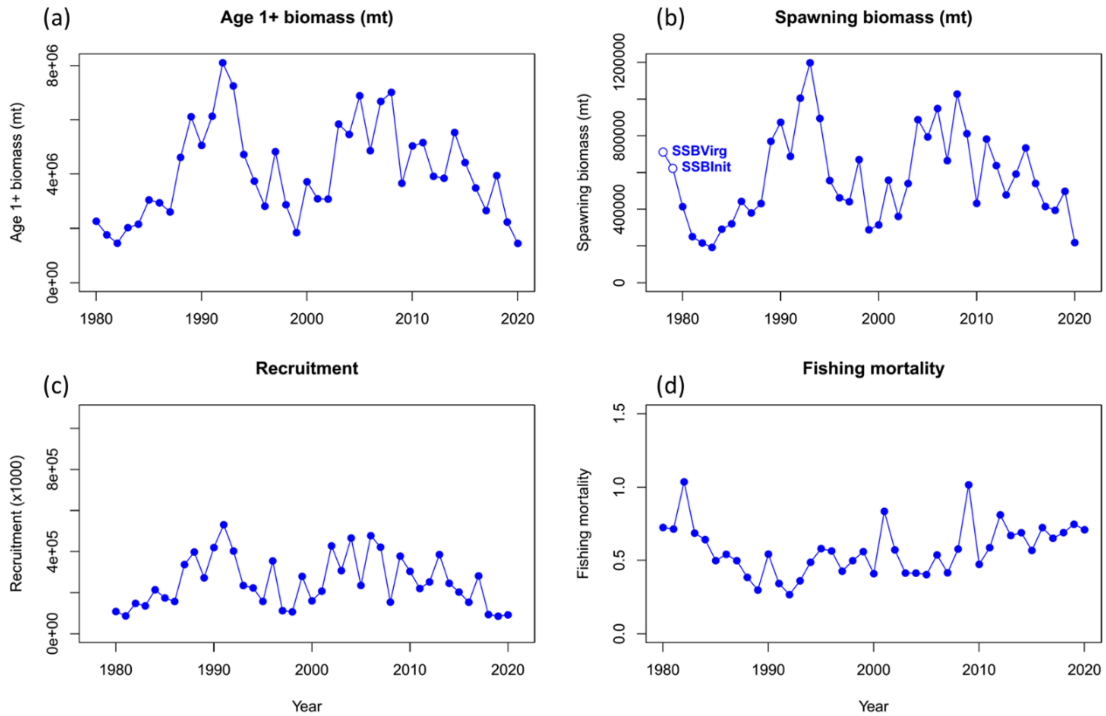
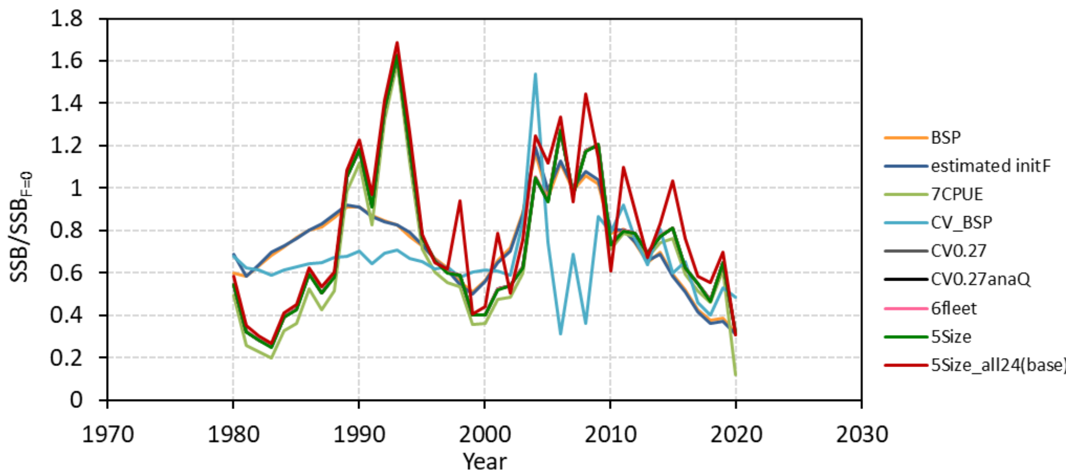


Figure 16. Estimated time-series of (a) total biomass (age 1 and older), (b) spawning biomass, (c) age-0 recruitment, and (d) instantaneous fishing mortality (year^{-1}) for the WNPO Pacific saury during –1980 – 2020. The blue horizontal solid line indicated the SSB_{MSY}. The open blue circle indicated the virgin (SSB_{virg}) and initial spawning biomass (SSB_{init}), respectively.



Appendix Figure 1. Estimated spawning stock biomass depletion ($SSB/SSB_{F=0}$) trajectory for each of the stepwise model run. “BSP” = using the estimated biomass from joint BSP results as an absolute abundance index (*q* = 1); “estimated initF” = estimating the initial fishing mortality; “7CPUE” = including the 7 relative abundance indices (CV = 0.2); “CV_BSP” = CVs for the CPUE indices were 6 times of min(CV) of the survey index; “CV0.27” = setting the CV of all relative abundance indices as 0.27; “CV0.27anaQ” = closed-formed estimation of catchability; “6 fleet” = separating the total catch into the six fleets; “5Size” = including the five length composition data with logistic selectivity curves; “5Size_all24” = using the double normal selectivity curves for all fleets. The base model (in red line) is the WNPO Pacific saury assessment model presented in this preliminary analysis.