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Follow up work on 2022 skipjack assessment recommendations

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Executive Summary.

This paper presents follow-up work on the diagnostic model of the 2022 skipjack (SKJ) tuna stock assessment in the western and central Pacific Ocean conducted using the MULTIFAN-CL stock assessment software. This paper is part of ongoing work in response to issues and recommendations raised by the SC18 on the 2022 SKJ assessment. A central concern that was raised by the SC18 was that the 2022 assessment diagnostic model may not have converged to a global minimum and did not have a positive definite Hessian solution (PDH). While this is one of several areas requiring follow-up work, it was desirable to explore options to satisfy this important convergence diagnostic before moving on to the other aspects of the follow work. The work described in this paper is primarily focused on the changes made to the modelling procedures for the 2022 diagnostic model that successfully achieved a PDH solution.

The changes to the model resulted in a reduction of estimable model parameters, from 2253 for the 2022 diagnostic model to 2122 for the 2023 follow-up model, which could improve the model's efficiency. Compared to the original 2022 diagnostic model, the 2023 follow-up model with PDH displays very minor differences in stock status estimates or other reference point values. It is therefore expected that applying this model in the 2022 stock assessment would not have resulted in any notable differences in stock status or altered management advice. Statistical uncertainty for management quantities from the diagnostic case model has now been estimated.

Overall, the results of the 2023 follow-up model are positive and have improved the model's stability and reliability. The improved diagnostic model will now be used to continue exploring other concerns and recommendations arising from the 2022 SKJ assessment. As this additional work is conducted it will be important to continue to run the Hessian diagnostic to check that any changes do not compromise achieving a PDH. It is expected the additional follow-up work will be reported at SC20 and provide the major steps towards a new diagnostic model for the 2025 assessment. This will hopefully lead to a more efficient workflow and delivery of the 2025 SKJ assessment.

The next phase of this follow work may include:

- Dirichlet multinomial alternative grouping investigations.
- Lorenzen M–at-age formulation.
- Further exploration of orthogonal polynomial recruitment.
- Exploring data conflicts that affect model outcomes through likelihood profiles.
- Running models with CPUE adjustments for plausible effort creep from project 115.

We invite the SC19 to:

- Note the follow-up work to improve the diagnostic model for the WCPO skipjack assessment with the achievement of a positive definite Hessian solution.
- Note the improved diagnostic model has negligible differences in estimated management quantities to the diagnostic model from the 2022 assessment.

1. Introduction.

This paper represents the latest advancements in the improvement of the stock assessment model for skipjack tuna (*Katsuwonus pelamis*, SKJ) within the western and central Pacific Ocean (WCPO), specifically in the area west of 150 °W. The work described in this paper is part of ongoing follow-work from the 2022 SKJ assessment (Castillo Jordan et al., 2022) in response to the recommendations and concerns raised by SC18.

The basis for the follow-up work is the diagnostic model from the 2022 SKJ assessment which is implemented in the MULTIFAN-CL (MFCL) stock assessment software (http://www.multifan-cl.org) (Fournier et al., 1998; Hampton and Fournier, 2001; Kleiber et al., 2019). This follow-up work does not include new fishery input data or new information on biology and population structure. It includes an updated version of the MFCL software (v2.2.1.0), and changes to other important assumptions such tag reporting rate settings, and initial conditions.

The 2022 SKJ stock assessment report and SC18 comments identified several areas of research that should be explored either prior to or as part of the next assessment in 2025 (Appendix 1). The follow-up work reported here focusses on these areas; 1. incorporating a refined CPUE analysis with thermal constraints, and 2. the pursuit of a positive definite Hessian solution (PDH).

The newly introduced changes and insights obtained from this study will serve as a foundation for continuing the follow-up work towards producing an improved starting model for the development of the diagnostic model for 2025 SKJ assessment. This follow-up work, which has typically not occurred after previous assessments due to limited staff resources/staff turnover, will hopefully improve the efficiency and quality of the next SKJ assessment.

2. Methods.

The following stepwise changes were made from the 2022 diagnostic model presented at the SC18 to the new 2023 follow-up SKJ model:

1. Diagnostic model from the 2022 assessment (Castillo-Jordan et al., 2022, SC18)
2. The 2022 diagnostic model was re-run using an updated MULTIFAN CL version 2.2.1.0.
3. The estimation of reporting rates for fishery/tagging program groups with very small numbers of tag returns (<5) was deactivated. This was done by using new tag file, and by making changes to CPUE for pole-and-line fleets changing the frq file.
4. The maximum bounds for the estimation of tag reporting rates were changed from 0.90 to 0.98.
5. The 'kludge' equilibrium coefficients parameter was deactivated, and the calculation of the equilibrium initial population was changed to no longer use the average total mortality (Z) for the first 20 time periods for the equilibrium initial population. Instead, the previous initial equilibrium condition was used, which applies an initial Z value as a multiple of natural mortality(M); in this case M * 1.1.

Explanation of MFCL Flag Settings

- Par flag 393 controls the kludge_equilib_coffs parameter, which is a method for estimating the equilibrium population size. It was deactivated.
- Age flag 94 controls the type of initial population used in the model. A value of 1 indicates that the equilibrium population is used, while a value of 2 indicates that the average population over a specified period is used. It was changed from 2 to 1.
- Age flag 95 controls the number of time periods used to calculate the average population for age flag 94. It was changed from 20 to zero.
- Par flags 374, 375, and 379 control the 'kludge' initial survival relationship. These flags are deactivated by setting them to zero.
- Age flag 128 controls the initial Z value used in the model. A value of 11 indicates that the initial Z value is M * 1.1.

These modifications to the SKJ 2022 diagnostic model were implemented following SC18 comments, to try to achieve a positive definite Hessian matrix, and improve the numerical stability and robustness of the SKJ diagnostic model. Greater detail is provided below.

CPUE changes for pole-and-line fleet.

One of the key advantages of the geostatistical CPUE standardisation framework is its ability to incorporate the estimated spatial correlation structure of the data and its relationships with environmental covariates. This feature allows the interpolation of abundance values in un-sampled areas. However, when dealing with a tropical species like SKJ tuna, it becomes crucial to ensure that biomass is not interpolated into biologically unsuitable areas, specifically those that are outside of the species' physiological tolerance. In this case, the issue was raised by SC18 that the geospatial model was extrapolating into areas that were too cold for SKJ to occur. To address this concern, modifications were made to the geostatistical model, following on from previous analyses such as the one conducted for 2018 south Pacific albacore assessment (Tremblay-Boyer et al., 2018). In that study, the geostats model was adjusted to utilize only data from grid cells that exceeded a biologically realistic minimum temperature threshold. This ensured the creation of an abundance index that did not involve extrapolation into areas that were not viable thermal habitat. A similar approach was applied in this analysis by employing an 18°C minimum thermal threshold as noted by Kiyofuji et al. (2019) for skipjack tuna.

Changes in the reporting rate and the initial conditions.

Estimating tag-reporting rate

Tag-reporting rates were estimated by groups (termed TRR groups) that were a combination of one or more fisheries and tagging programs. The fisheries that were included in a TRR group were selected on the basis that any tag returns from that tagging program were considered to have been subject to the same or similar tag recovery processes and were therefore likely to have had similar tag reporting rates. Reporting rates for TRR groups were estimated internally in the model if the number of tag returns was >5. This condition was introduced to avoid estimating a reporting rate parameter when very limited numbers of tag returns were involved. For TRR groups that did not meet this condition, we deactivated reporting rate estimation, removed the small number of recoveries for such groups from the tag file and set the tag reporting rate to zero. The listing of tag recoveries by TRR group is given in Table 1. In an attempt reduce estimated reporting rate parameters on the upper bound, the reporting rate upper bound was increased from 0.90 to 0.98.

Initial conditions

Accurately estimating the initial survival rate is crucial for calculating the equilibrium population and understanding population dynamics. However, determining the average initial total mortality, which is used to calculate the survival rate, is often unknown at the start of the assessment period. The 2022 SKJ stock assessment used the average of the total mortality (Z) first 20 quarters to calculate the initial conditions. A spline formulation was used for the age-specific estimated survival rates with the nodes being the independent variables. Since the fishery started in 1972 (M=Z), we assumed that some fishing mortality occurred before the initial year. We accounted for this in the 2023 follow up model by setting the initial total mortality (in 1972) equivalent to 10% greater than natural mortality. We also conducted additional experiments using different percentages of fishing mortality, but the results are not presented here. These experiments only changed the initial part of the series. Using this approach, it is possible to reduce the number of parameters in the calculation of the initial population.

3. Results.

The methods section describes the changes made from the 2022 assessment to the 2023 follow-up model. The results are presented in Figure 1. A summary of the implications of the stepwise progression from the 2022 diagnostic model, with a particular focus on the key management indicators of dynamic spawning potential depletion ($SB/SB_{F=0}$) and spawning potential (SB), is provided. In addition, other estimated parameters such as growth, M, F, selectivity, reporting rate, movement rates and maturity are presented and compared between the two models, as well as some diagnostics to indicated model fits to the data.

Key management quantities.

Stepwise changes

In the stepwise model changes, SB increased, but the trend was the same as the 2022 diagnostic model. The final step of the 2023 follow-up model (i.e. initial condition, Figure 1 top) was similar to the SB from 2022. The model development process led to small changes in the main management quantity of interest are $SB/SB_{F=0}$, with the initial depletion value decreasing when the equilibrium conditions were changed. This value was slightly lower than all the other steps (Figure 1 bottom).

For a comprehensive understanding of the consequences of the model's progression from 2022 to 2023, please refer to the method section and Figure 1.

Comparison of the 2022 diagnostic model to the 2023 follow-up model

Directly comparing the 2022 diagnostic model to the 2023 follow-up model for the different model regions showed that $SB/SB_{F=0}$ (Figure 2 and Figure 3) changed most notably in Region 1 and Region 2. Region 5 however, only showed small differences compared to the 2022 assessment, being slightly more depleted at the end of the series. The rest of the regions showed minor changes. When aggregating across all regions, the main change was in the first years due to the changes in the initial equilibrium conditions, with the 2023 follow-up model starting at a slightly more depleted level. The two models however merged to show very similar recent and historic $SB/SB_{F=0}$.

SB showed notable changes in Region 1 and Region 2. The changes in Region 1 were most pronounced in the first decade and were around four times lower than in Region 2 (Figure 4). However, these regions and also Region 3 are smaller in terms of biomass, so have little effect on the overall biomass differences between the models (below). Region 4 and Region 5 showed smaller changes, specifically from 2005 to the end of the series. The other regions showed small differences, and overall, the changes were minor.

For the aggregated regions the 2023 follow-up model shows SB that is very comparable to the 2022 assessment model, although with a slightly higher scaling (Figure 5).

Comparisons of the typical WCPFC assessment reference points between the two models are provided in Table 2, and show very minor differences across all values.

Other parameter estimations.

Growth (von Bertalanffy curve)

The estimated growth curve from the 2023 follow-up model had a mean length at the first age class of 22.7 cm versus 23 cm for 2022 diagnostic model. Mean length-at-age increased quickly until about age-class 8 quarters, after which growth slowed down until reaching an L_{inf} of 81.1 cm versus 84 cm for the 2022 diagnostic in the oldest fish in the model (age-class 16) (Figure 6). The new growth curve for the 2023 follow-up model showed a small decrease in the average length at age (dotted line, Figure 6) compared to the 2022 diagnostic model (solid line, Figure 6). A clear change in the variance of length at age was observed with the new changes to the MFCL model that incorporated a correction in the estimation of the growth variance (see Davis et al. SC19-SC-IP-02 for more details). This follow-up work used a similar variance approach to the 2022 assessment to maintain consistency in model performance between models.

Natural mortality (M)

Both models use the same natural mortality spline function with five nodes. The estimated M-at-age for the new model exhibits variation comparable to the previous model until age class 8. After 8 quarters the curves differ substantially (Figure 7). The 2022 assessment showed a slightly higher mortality rate for younger ages with a lag of approximately one quarter compared with the 2023 follow-up model. From age five quarters, both models show increase in M reaching a similar peak value but at different ages (2022 model at ten quarters, 2023 model at eight quarters). This change in M can is reflected in the decrease in recruitment (Figure 15). Future follow-up work will explore a simpler Lorenzen functional form of M-at-age.

Selectivity

The same range of selectivity patterns were employed in 2023 follow-up model compared to the 2022 model. Figure 8-14 display the age-specific selectivity coefficients. Notably, pole-and-line fisheries (including the survey fisheries) with the exception of Region 5 and 6, exhibited differences for the 2023 follow-up model when compared to the 2022 diagnostic model, by selecting for older fish to a greater extent (Figure 8 and Figure 9). Additionally, in Regions 1, 2, and 3, the purse seine fisheries in the 2023 follow-up model also show an increased selection for older fish (see Figure 10). The remaining fisheries did not show much difference between the two models (see Figure 11 to Figure 14).

Recruitment

The estimated stock recruitment relationships for the 2022 diagnostic and 2023 follow-up models are shown in Figure 15. There are generally decreased levels of recruitment predicted in the 2023 follow-up model. The estimated recruitment, aggregated across all regions (see Figure 16), shows the same interannual variation for the two models. The trend in recruitment over the initial decade of the assessment period appears relatively stable for both models. When aggregated across regions, the 2023 follow-up model scales recruitment lower, but there are some differences in regional proportions between the two models such as in region 2 and 4 (Figure 17).

Tag reporting rates

The tagging reporting rate estimates are shown in Figure 18. The zero reporting rates have been not included as per the 2022 assessment. The new reporting rate groupings (Table 1) and increase to the upper bound resulting in 11 (22%) reporting rates being on the upper bound for the 2023 follow-up model compared to 9 (24%) for the 2022 diagnostic model (Figure 18).

Fishing mortality

Average fishing mortality rates for juvenile and adult age-classes have increased continually and with similar rates and dynamics throughout the time series for both models. The main difference is that the recent juvenile mortality is estimated to be higher in the 2023 follow-up model (Figure 19).

Movement

The movement coefficients between regions are shown in Figure 20. The main differences between models were that; movement from region 1 to 2 in quarter 1 was higher for the 2022 diagnostic model, movement from region 1 to 3 in quarter 1 was higher for the 2023 follow-up model, and movement from region 2 to 4 was also higher for the 2023 follow-up model.

Maturity-at-age

Maturity-at-age calculated in this study is similar to the 2022 assessment due to similar mean growth and the use of the same length at maturity relationship. The changes are imperceptible since the 2023 follow-up model is on top of the 2022 diagnostic model maturity relationship (Figure 21).

Standardized CPUE index fisheries

Applying the CPUE SST threshold filter to restrict the SKJ distribution to thermally suitable areas, as expected reduced the magnitude of the VAST abundance indices for the northern regions 1 and 2, and maintaining the seasonal variability (Figure 22).

Diagnostics.

Fit of the models to data sources.

The seasonal variability in pole-and-line CPUE indices in Regions 1, 2, 3, 4, 7 and 8 were generally consistent for the 2022 diagnostic model and the 2023 follow-up model. The 2023 follow-up model show slightly different fits for Region 1, with lower values at the beginning of the series (Figure 23). These changes are likely influenced by the new initial conditions. For Region 2 the new fit scales down this index, being lower than the 2022 diagnostic model. For Region 3 the trend is similar but is scaled up compared to that in 2022. Similar situations occur for Regions 4, 7 and 8. The purse seines indices do not show big differences between models.

Size composition data

The model estimates of the composite length composition for all fisheries does not change substantially between the models. We have included all the aggregate fleet compositions in all regions, to show the small differences between fits between the models (Figure 24 to Figure 29).

Tagging data

When considering the overall tag attrition fits, there is negligible difference between the models (Figure 30).

4. Conclusions.

The 2023 follow-up model of the skipjack tuna stock in the western and central Pacific Ocean did not change considerably compared to the 2022 diagnostic model in terms of estimated management quantities. However, the model was able to achieve a positive definite Hessian matrix (PDH), which is a significant improvement. This means that the model is more stable and reliable, and we were able to estimate the statistical uncertainty for the management quantities. The statistical uncertainty is low for the management quantities estimated by this follow-up SKJ assessment model with the PDH.

The 2023 follow-up model also confirmed the results of the 2022 diagnostic model, with estimates of the spawning potential and depletion being consistent between models. This provides further confidence in the findings of the 2022 stock assessment. The changes to the modelling resulted in a reduction of estimable model parameters from 2253 for the 2022 diagnostic model to 2122 for the 2023 follow-up model. This is a significant reduction, and it is likely to improve the efficiency of the model.

The change in the $SB_{recent}/SB_{F=0}$ is 1.18% (2022 diagnostic model = 0.503; 2023 follow-up model = 0.509 (CI95% 0.490 – 0.528). In addition, the change in the estimated $SB_{latest}/SB_{F=0}$ is less than 1%.

We have recently begun investigations to test different options for M-at-age formulation. One option that we are trying is the Lorenzen M-at-age, as suggested at the recent CAPAM workshop and in recent reviews (Punt 2023), which suggests that M is higher for younger fish and then asymptotic from age 8. However, the Lorenzen M configuration did not reach a PDH, which is one of the goals for the follow-up model. Therefore, more work is needed to investigate this model. The fishing effort-F relationship for projection purposes will also be investigated further, however, we believe we have a viable solution to this issue, by simply reducing the length of time over which this regression is calculated at the end of the model period. Preliminary research indicates that using the average of the last 3 years of effort does not affect the SB estimations.

We invite the SC19 to:

- Note the follow-up work to improve the diagnostic model for the WCPO skipjack assessment with achievement of a positive definite Hessian solution.
- Note the improved diagnostic model has negligible differences in estimated management quantities to the diagnostic model from the 2022 assessment.

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5. References.

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6. Tables.

Table 1. Tagging group (Grp) summary for 2022 diagnostic model and 2023 follow-up model including the number of tags by group (grps in bold were removed).

Grp2022	Name	Grp2023	Name	tags by Grp
1	SSAP_L-,P-JP,S-JP	1	SSAP_L-,P-JP,S-JP	495
2	SSAP_Z(PH)-5	2	SSAP_Z(PH)-5	**0**
3	SSAP_Z(ID)-5	3	SSAP_Z(ID)-5	**0**
4	SSAP_S(PH,ID)-5	4	SSAP_S(PH,ID)-5	**0**
		5	SSAP_P-5	118
5	SSAP_S-5	6	SSAP_S-5	33
6	SSAP_Z(VN)-5	7	SSAP_Z(VN)-5	**0**
		8	SSAP_P-6	1324
7	SSAP_S-6	9	SSAP_S-6	39
8	SSAP_S-7	10	SSAP_S-7	131
		11	SSAP_P-8	2108
9	SSAP_S-8	12	SSAP_S-8	**1**
10	IDX ALL	13	IDX ALL	
11	RTTP_L-,P-JP,S-JP	14	RTTP_L-,P-JP,S-JP	122
12	RTTP_Z(PH)-5	15	RTTP_Z(PH)-5	424
13	RTTP_Z(ID)-5	16	RTTP_Z(ID)-5	**1**
14	RTTP_S(PH,ID)-5	17	RTTP_S(PH,ID)-5	1677
		18	RTTP_P-5	955
15	RTTP_S-5	19	RTTP_S-5	175
16	RTTP_Z(VN)-5	20	RTTP_Z(VN)-5	**0**
		21	RTTP_P-6	739
17	RTTP_S-6	22	RTTP_S-6	2795
18	RTTP_S-7	23	RTTP_S-7	2581
		24	RTTP_P-8	587
19	RTTP_S-8	25	RTTP_S-8	843
20	PTTP_L-,P-JP,S-JP	26	PTTP_L-,P-JP,S-JP	83
		27	PPTP_S-8	38
21	PTTP_S-5	28	PTTP_S-5	12
22	PTTP_Z(ID)-5	29	PTTP_Z(ID)-5	697
23	PTTP_S(PH,ID)-5	30	PTTP_S(PH,ID)-5	4047
24	PTTP_Z(PH)-5	31	PTTP_Z(PH)-5	1130
25	PTTP_Z(VN)-5	32	PTTP_Z(VN)-5	**0**
		33	PTTP_P-6	257
26	PTTP_S-6	34	PTTP_S-6	27366
27	PTTP_S-7	35	PTTP_S-7	7014
		36	PTTP_P-8	32
28	PTTP_S-8	37	PTTP_S-8	1744
29	JPTP_L-,P-JP,S-JP	38	JPTP_L-,P-JP,S-JP	4836
30	JPTP_Z(PH)-5	39	JPTP_Z(PH)-5	**3**
31	JPTP_Z(ID)-5	40	JPTP_Z(ID)-5	**0**
32	JPTP_S(PH,ID)-5	41	JPTP_S(PH,ID)-5	**3**
		42	JPTP_P-5	**5**
33	JPTP_S-5	43	JPTP_S-5	51
34	JPTP_Z(VN)-5	44	JPTP_Z(VN)-5	**0**
		45	JPTP_P-6	**2**
35	JPTP_S-6	46	JPTP_S-6	**4**
36	JPTP_S-7	47	JPTP_S-7	715
		48	JPTP_P-8	39
37	JPTP_S-8	49	JPTP_S-8	79

Table 2. Comparison of reference points for the 2022 diagnostic model and the 2023 follow-up model

Reference point	**2022 diagnostic**	**2023 follow-up**	**Ratio 2023/2022**
Clatest	1,530,207	1,530,207	1
MSY	2,416,000	2,382,400	0.986
$Y_{fcurrent}$	440,600	440,300	0.999
F_{mult}	2.861	2.761	0.965
F_{MSY}	0.244	0.243	0.995
F_{recent}/F_{MSY}	0.350	0.362	1.034
SB_{MSY}	1,073,000	1,116,000	1.040
SB_0	5,686,000	5,742,000	1.009
SB_{MSY}/SB_0	0.189	0.194	1.026
$SB_{F=0}$	6,147,340	6,294,480	1.023
$SB_{MSY}/SB_{F=0}$	0.175	0.177	1.011
SB_{latest}/SB_0	0.479	0.482	1.006
$SB_{latest}/SB_{F=0}$	0.443	0.440	0.993
SB_{latest}/SB_{MSY}	2.539	2.480	0.976
*$SB_{recent}/SB_{F=0}$	0.503	0.509	1.011
SB_{recent}/SB_{MSY}	2.880	2.869	0.996

*2023 follow-up with positive definite Hessian: 95% confidence interval $SB_{recent}/SB_{F=0}$ = 0.490 – 0.528

7. Figures.

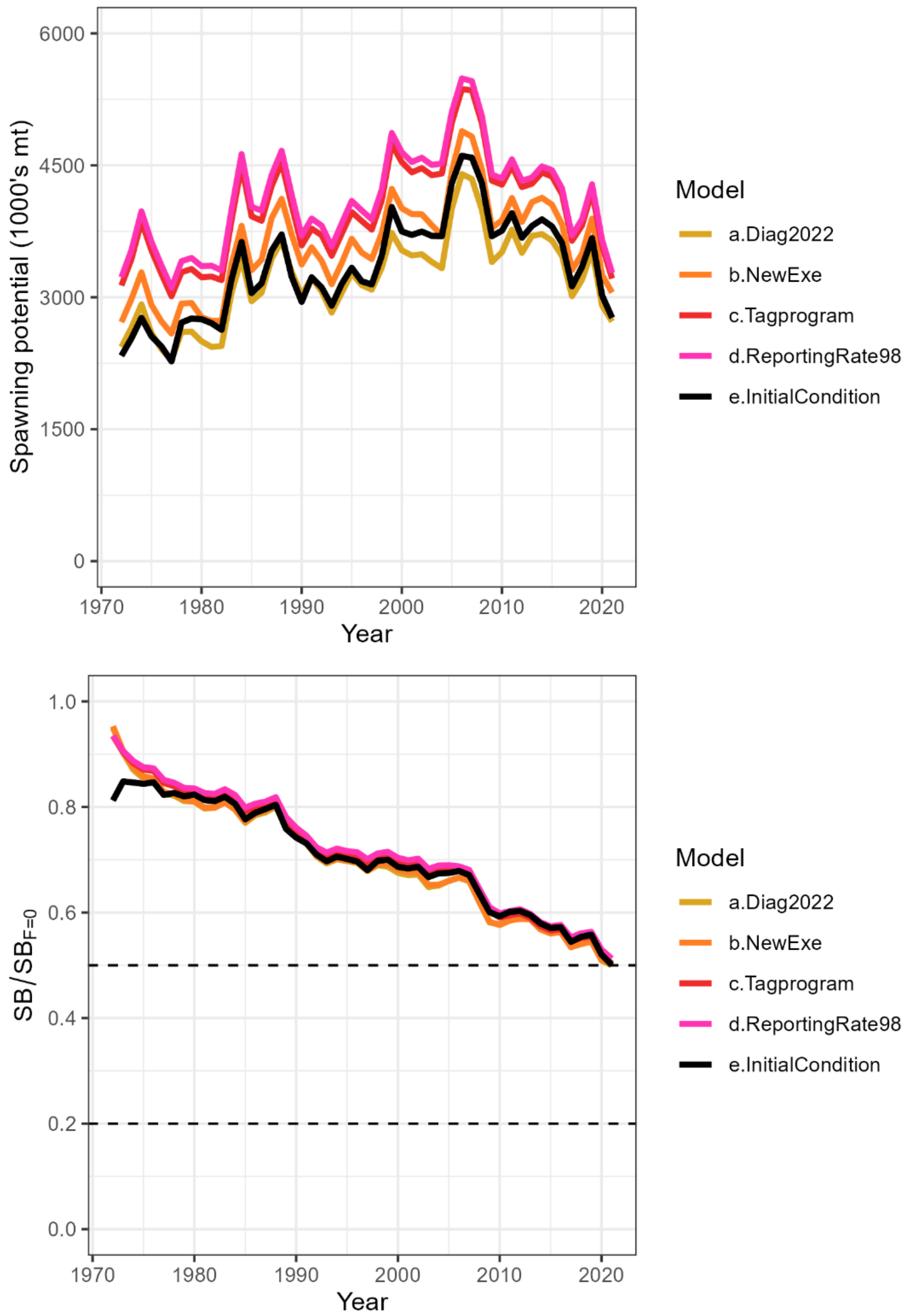

Figure 1. Stepwise development for spawning potential (top plot) and spawning potential depletion (bottom plot).

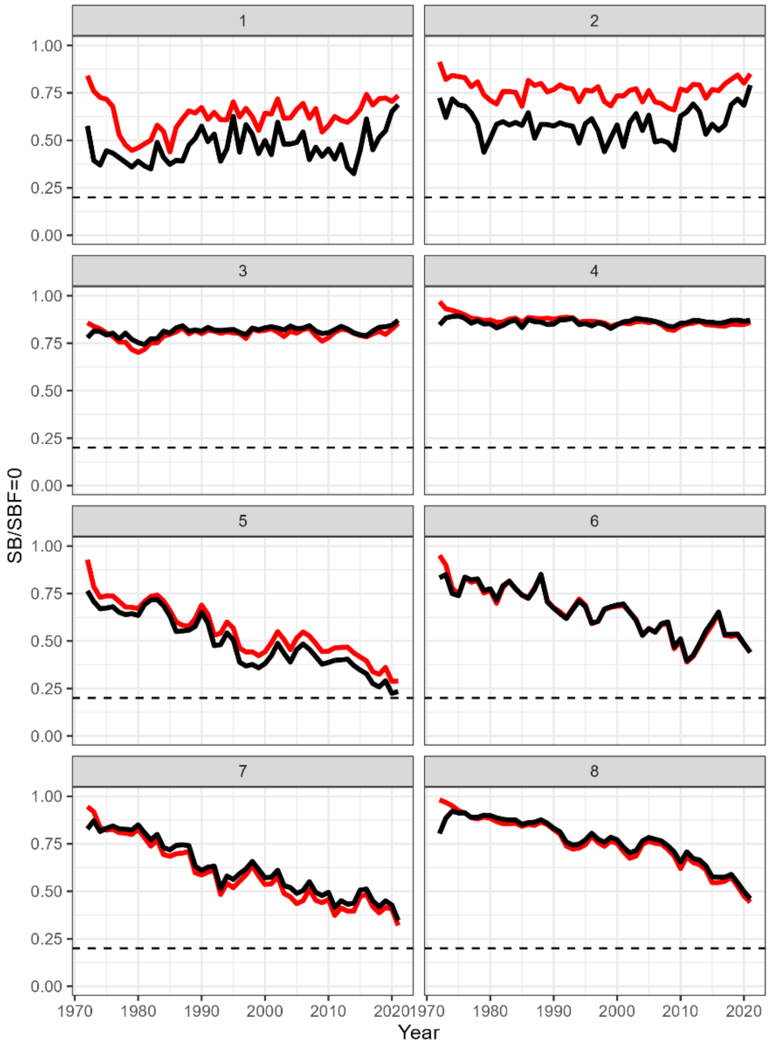

Figure 2. Depletion by region for the 2022 diagnostic model (red line) and 2023 follow-up model (black line).

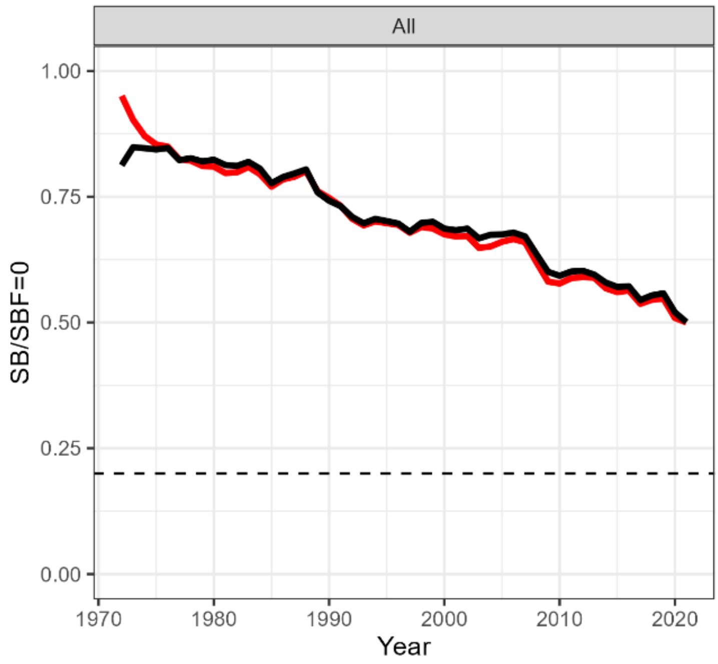

Figure 3. Depletion for 2022 diagnostic model (red line) and 2023 follow-up model (black line).

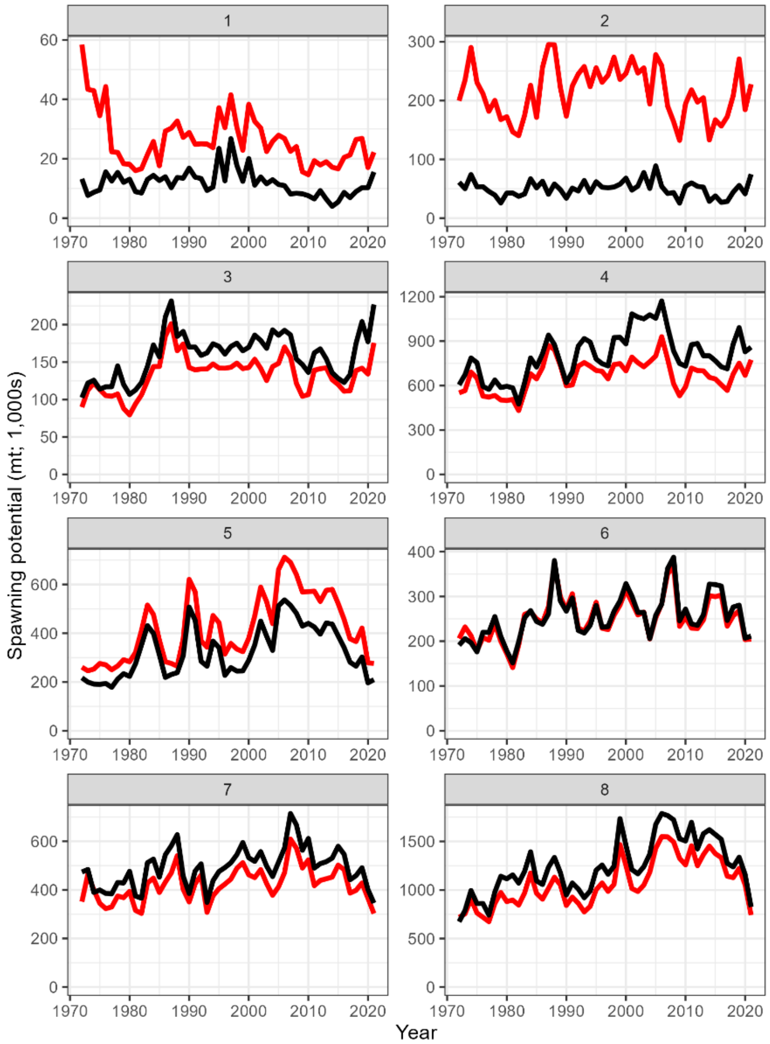

Figure 4. Spawning potential by region for 2022 diagnostic model (red line) and 2023 follow-up model (black line).

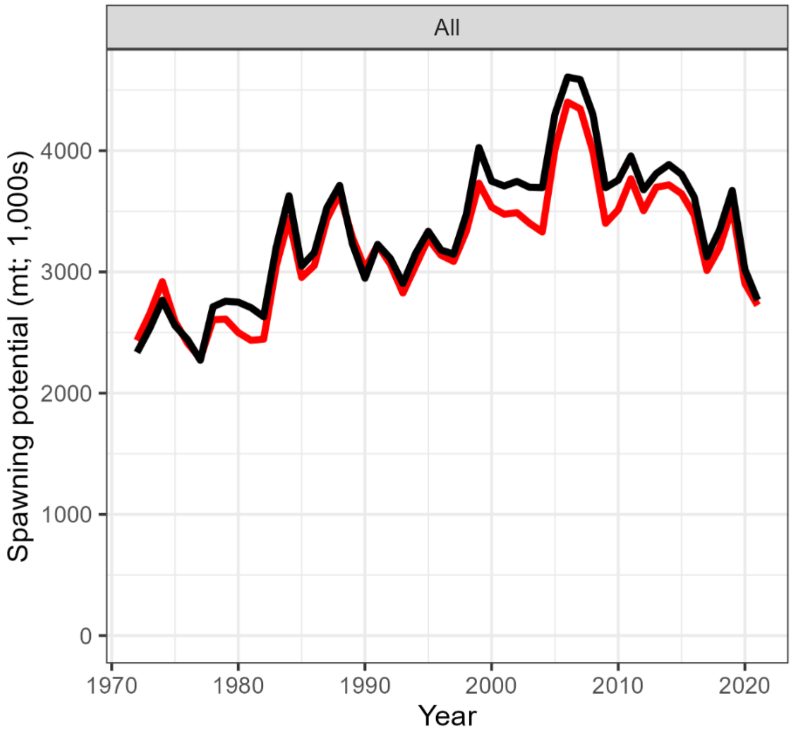

Figure 5. Spawning potential for 2022 diagnostic model (red line) and 2023 follow-up model (black line).

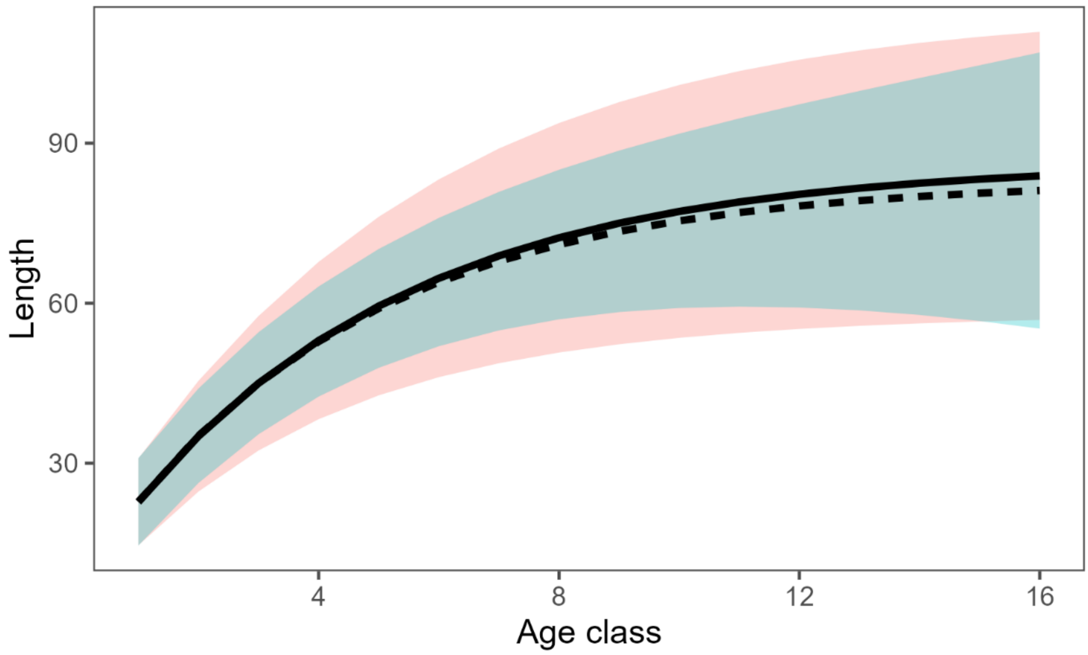

Figure 6. Growth curve comparison between 2022 diagnostic model (solid line, red uncertainty) and the 2023 follow-up model (dash line, green uncertainty).

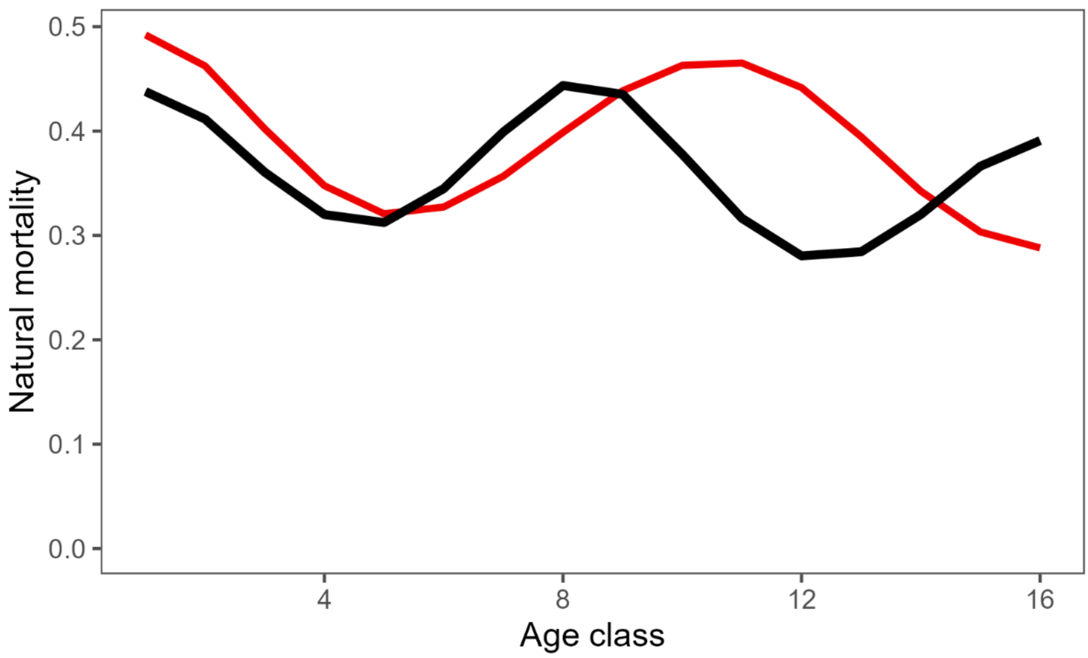

Figure 7. Natural mortality curve comparison between 2022 diagnostic model (red line) and the 2023 follow-up model (black line).

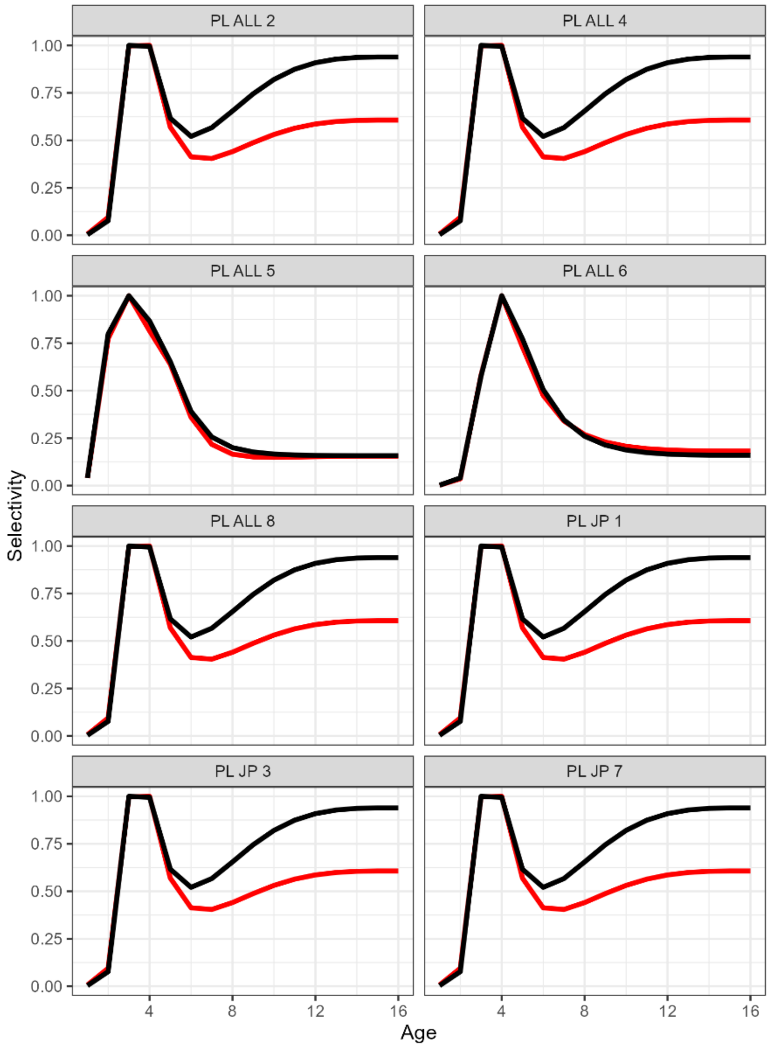

Figure 8. Selectivity for the pole-and-line (PL) fishery by region. (red line for 2022 diagnostic model and black line for 2023 follow-up model).

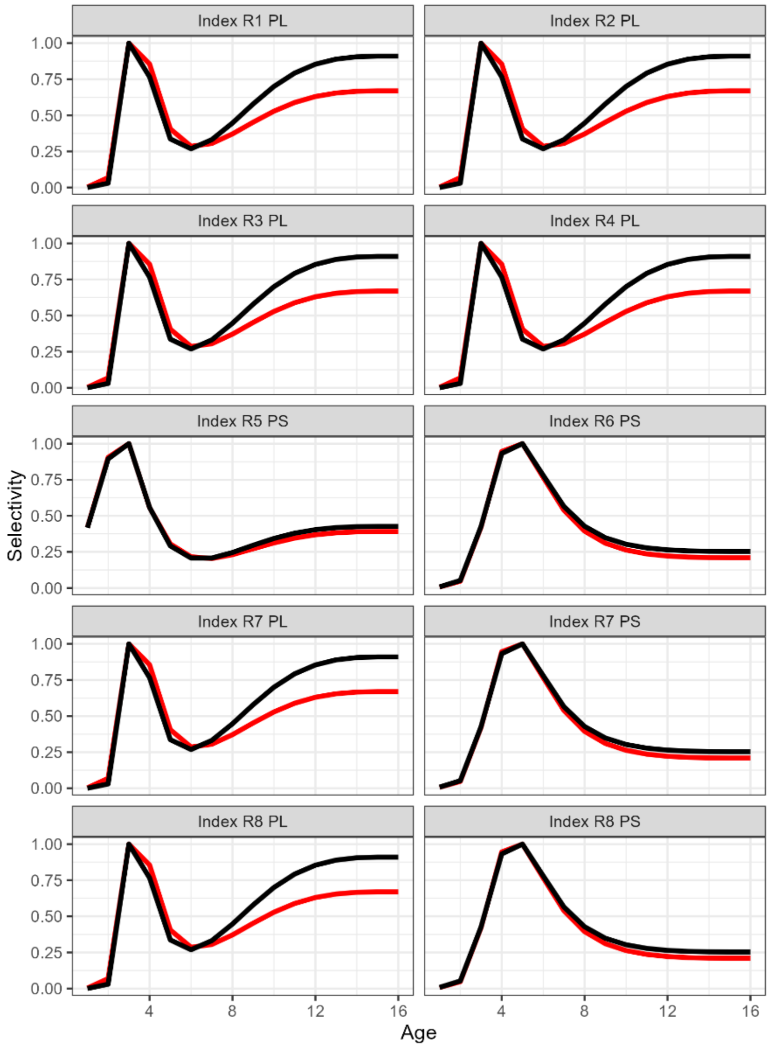

Figure 9. Selectivity for the index fishery by region (red line for 2022 diagnostic model and black line for 2023 follow-up model).

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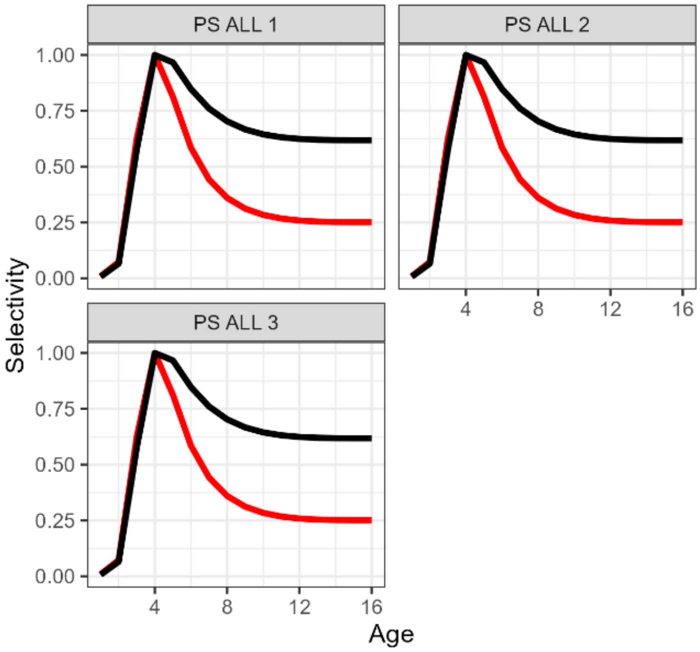

Figure 10. Selectivity for the purse seine (PS) fishery by region (red line for 2022 diagnostic model and black line for 2023 follow-up model).

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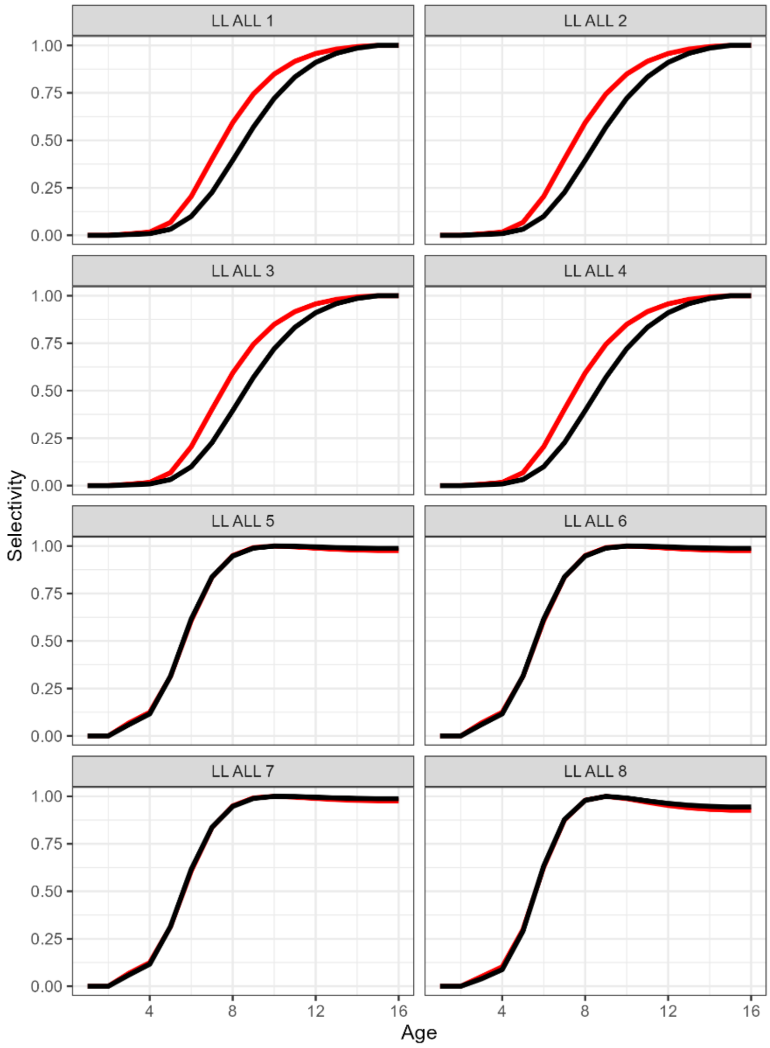

Figure 11. Selectivity for longline fishery (LL) by region (red line for 2022 diagnostic model and black line for 2023 follow-up model).

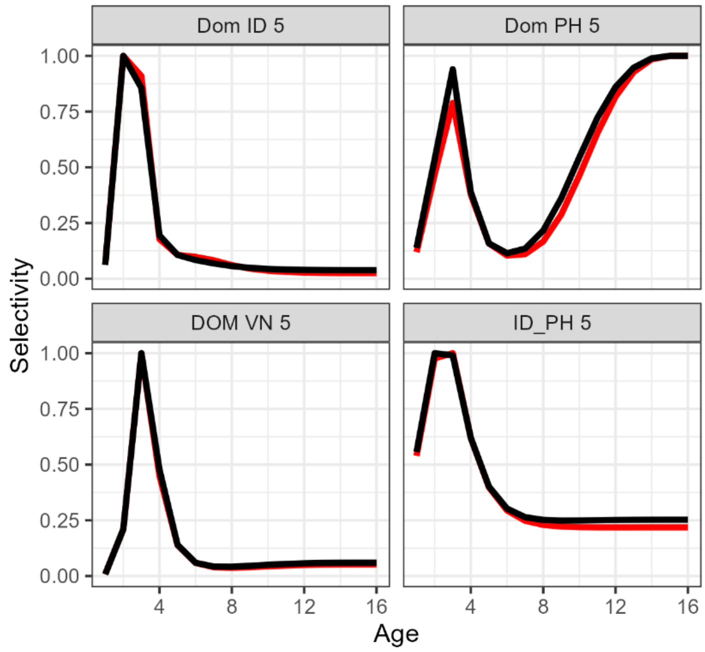

Figure 12. Selectivity for domestic fishery (ID: Indonesia, PH: Philippines, VN: Vietnam, region 5) (red line for 2022 diagnostic model and black line for 2023 follow-up model).

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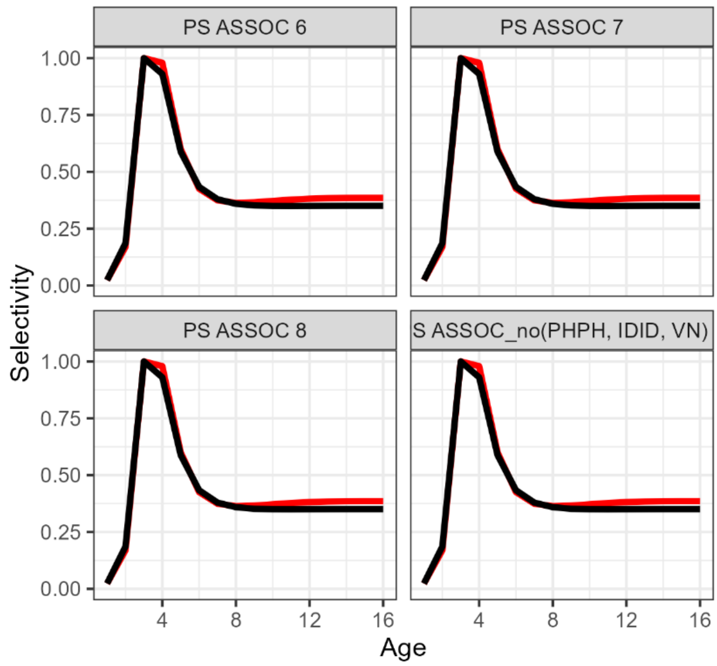

Figure 13. Selectivity for the purse seine associated fishery (PS ASSOC) by region (number on top) (red line for 2022 diagnostic model and black line for 2023 follow-up model).

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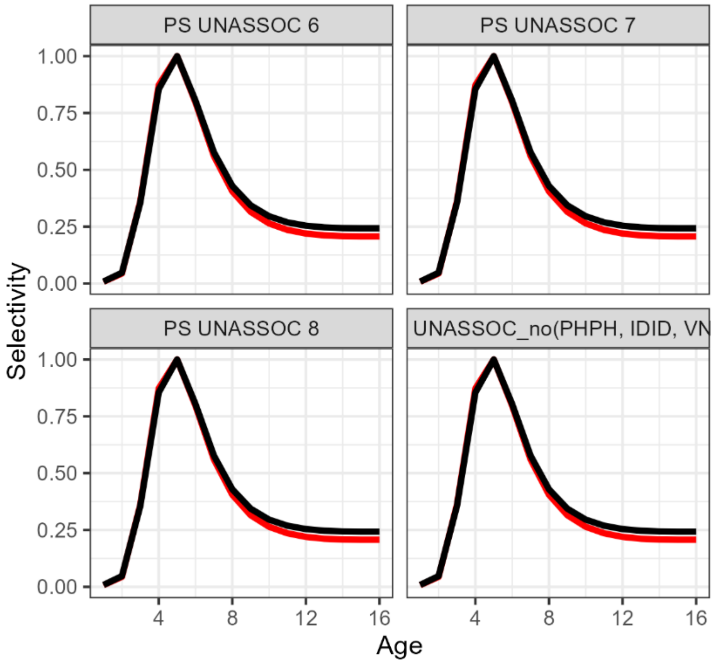

Figure 14. Selectivity for the purse seine unassociated fishery (PS UNASSOC) by region (number on top) (red line for 2022 diagnostic model and black line for 2023 follow-up model).

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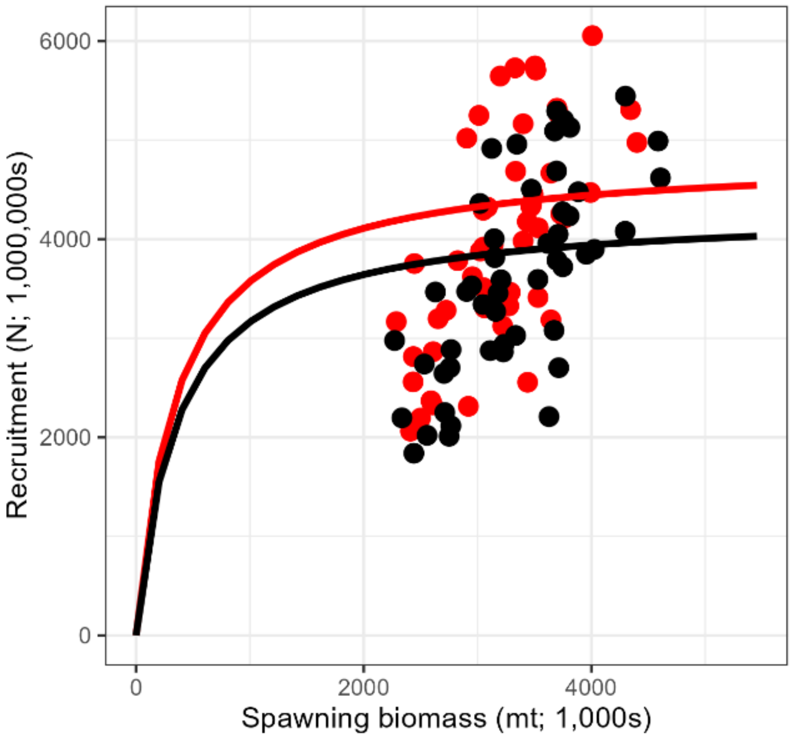

Figure 15. Stock recruitment relationship for 2022 diagnostic model (red dots and line) and 2023 follow-up model (black dots and line).

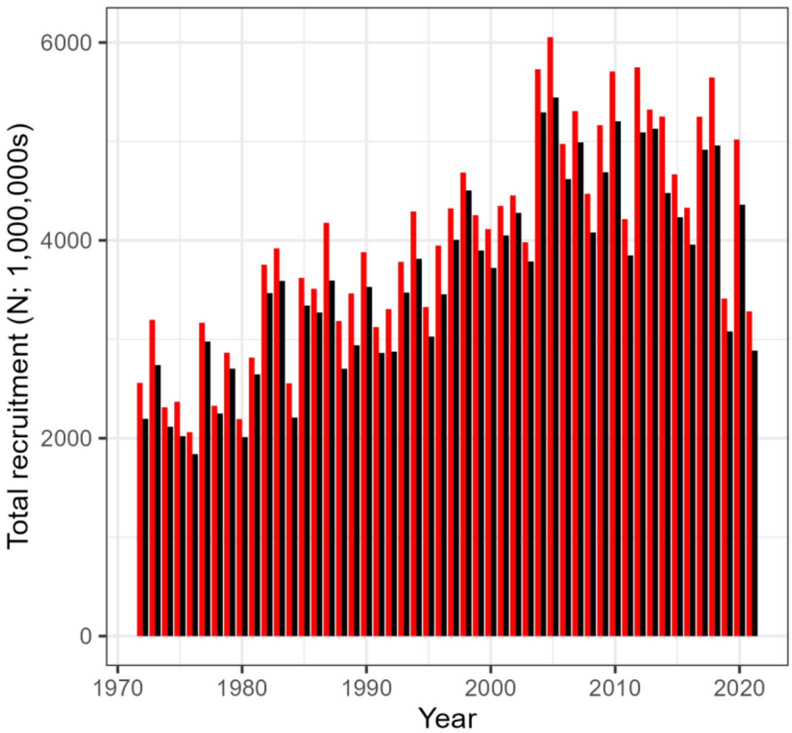

Figure 16. Annual recruitment for all regions for the 2022 diagnostic model (red bars) and 2023 follow-up model (black bars).

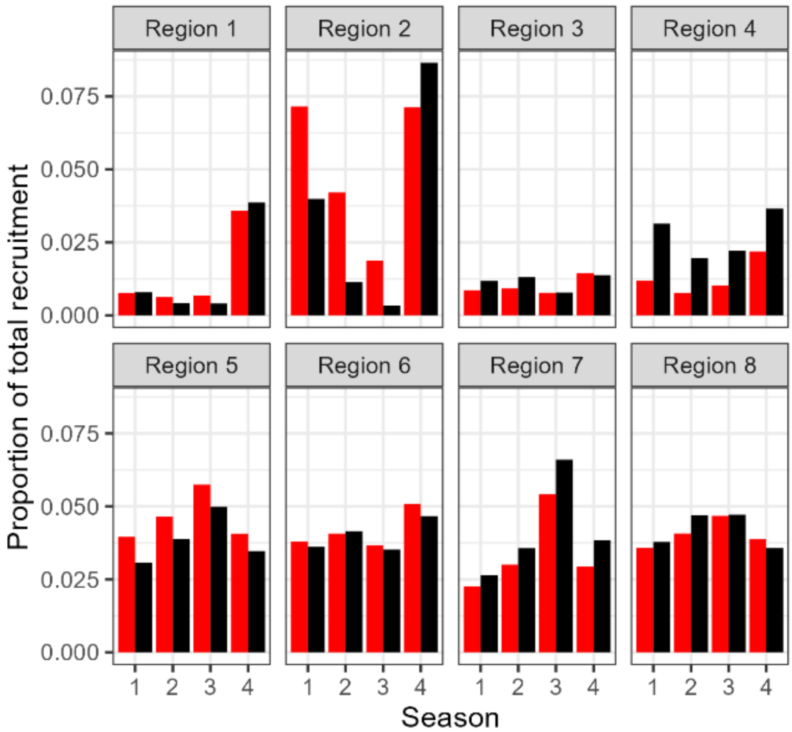

Figure 17. Recruitment proportion by region and season for 2022 diagnostic model (red bars) and 2023 follow-up model (black bars).

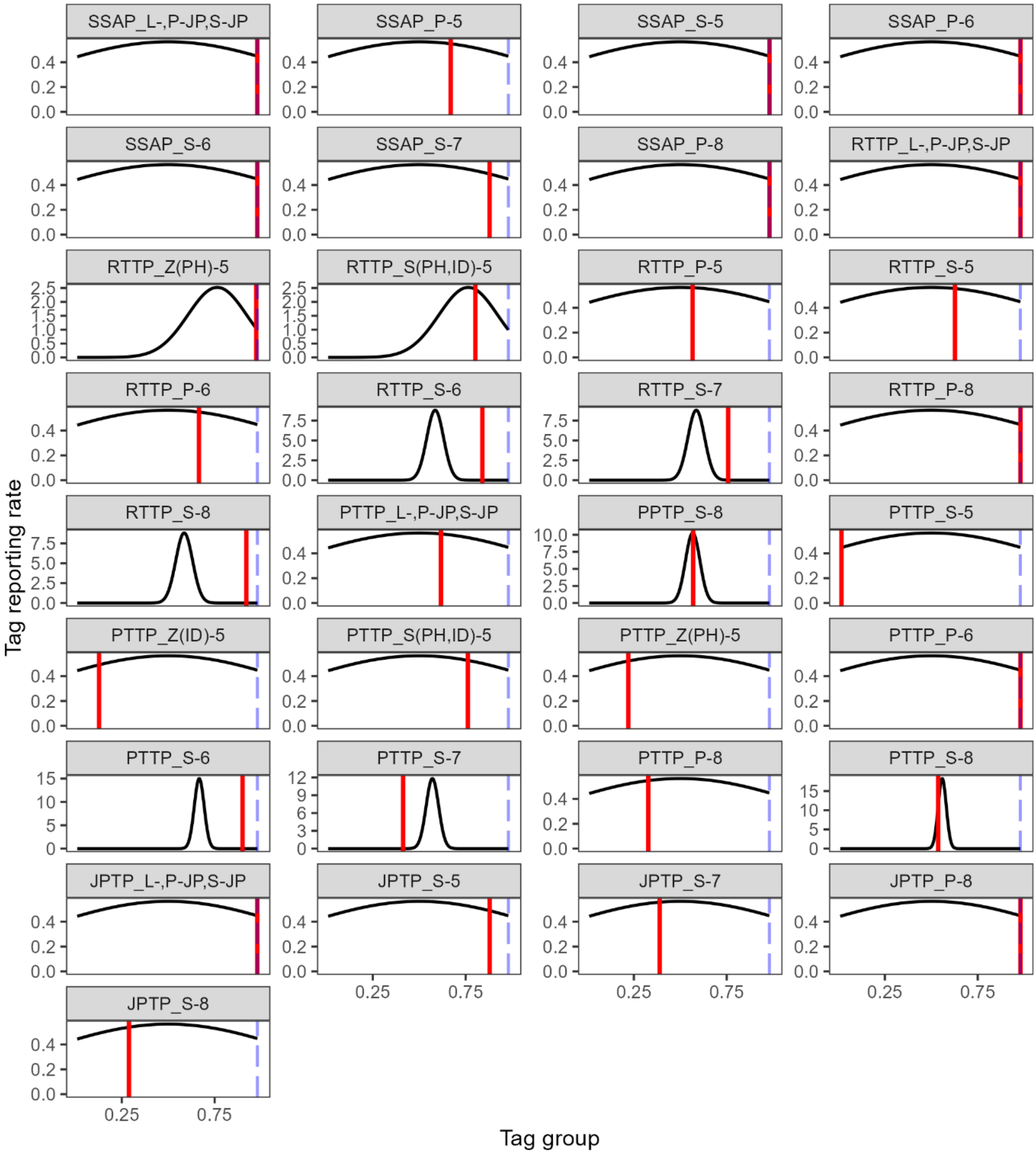

Figure 18. Tag reporting rate (red line) and priors (black line) for every tagging group by program. Upper bound is 0.98 (blue line) for the 2023 follow-up model.

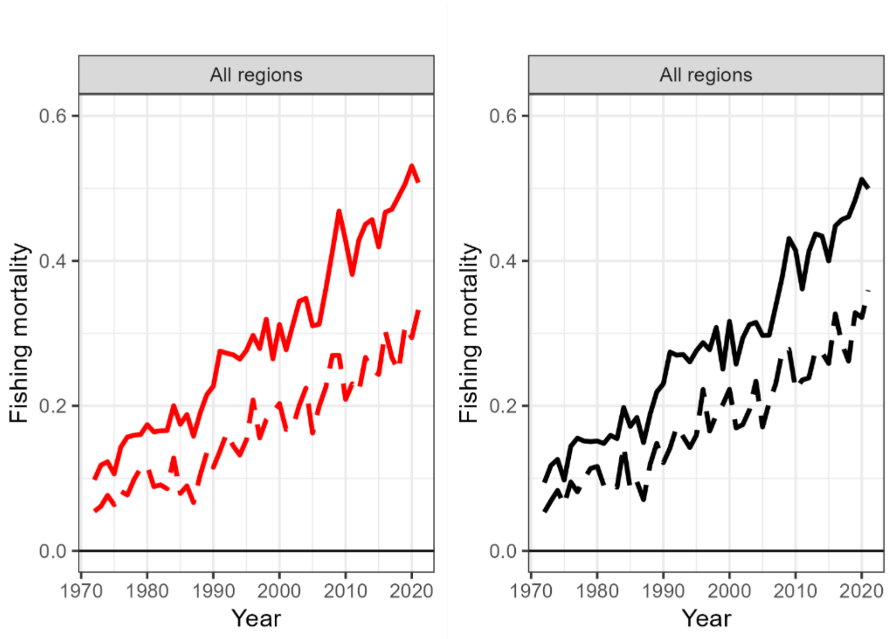

Figure 19. Fishing mortality adult (solid line) and juveniles (dot line) for 2022 diagnostic model (red line) and 2023 follow-up model (black line).

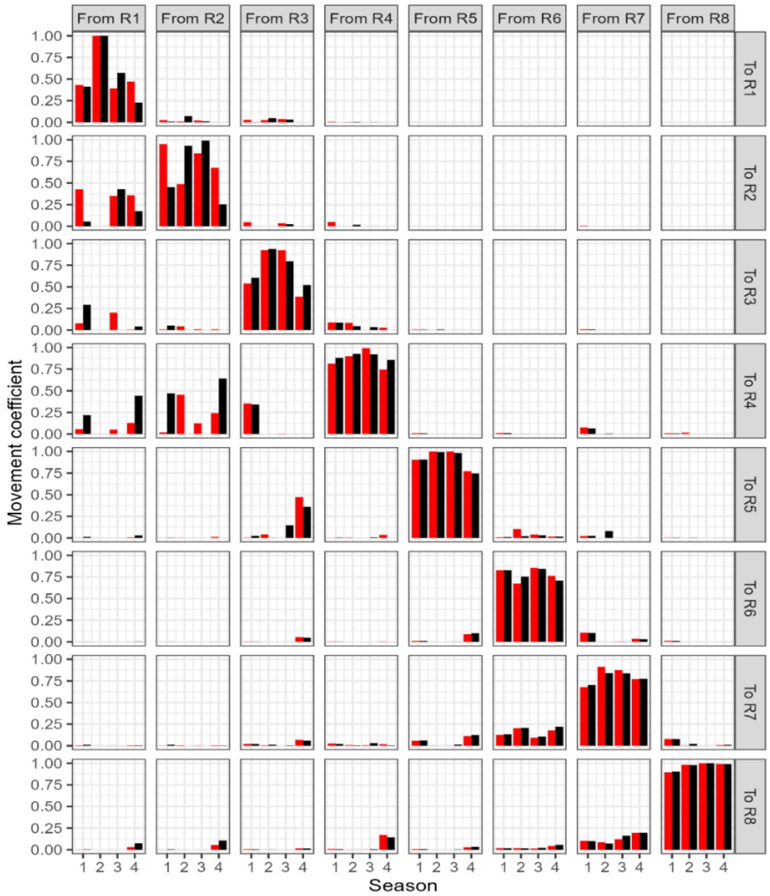

Figure 20. Movement coefficient per season from region Ri to region Ri (i=1 to 8) for 2022 diagnostic model (red bars) and 2023 follow-up model (black bars).

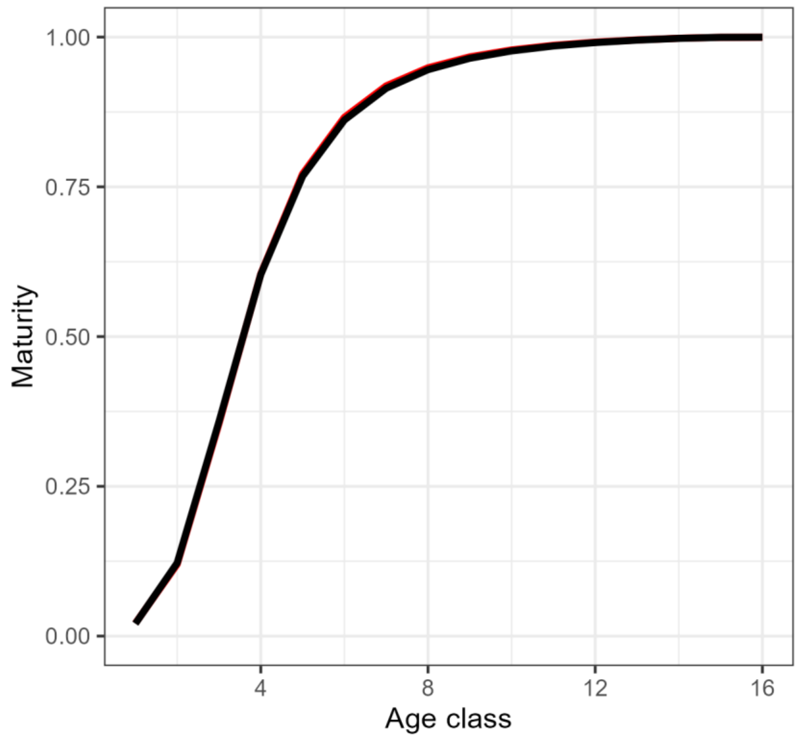

Figure 21. Maturity at age for 2022 diagnostic model (red line) and 2023 follow-up model (black line).

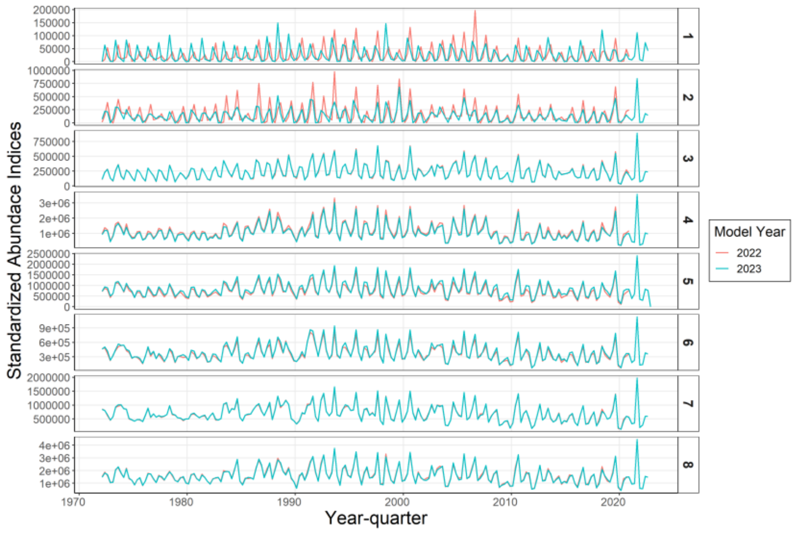

Figure 22. Standardized abundance indices used for 2022 diagnostic model (red) and the 2023 follow-up model (green) with the 18 C temperature threshold for SKJ in the WCPO.

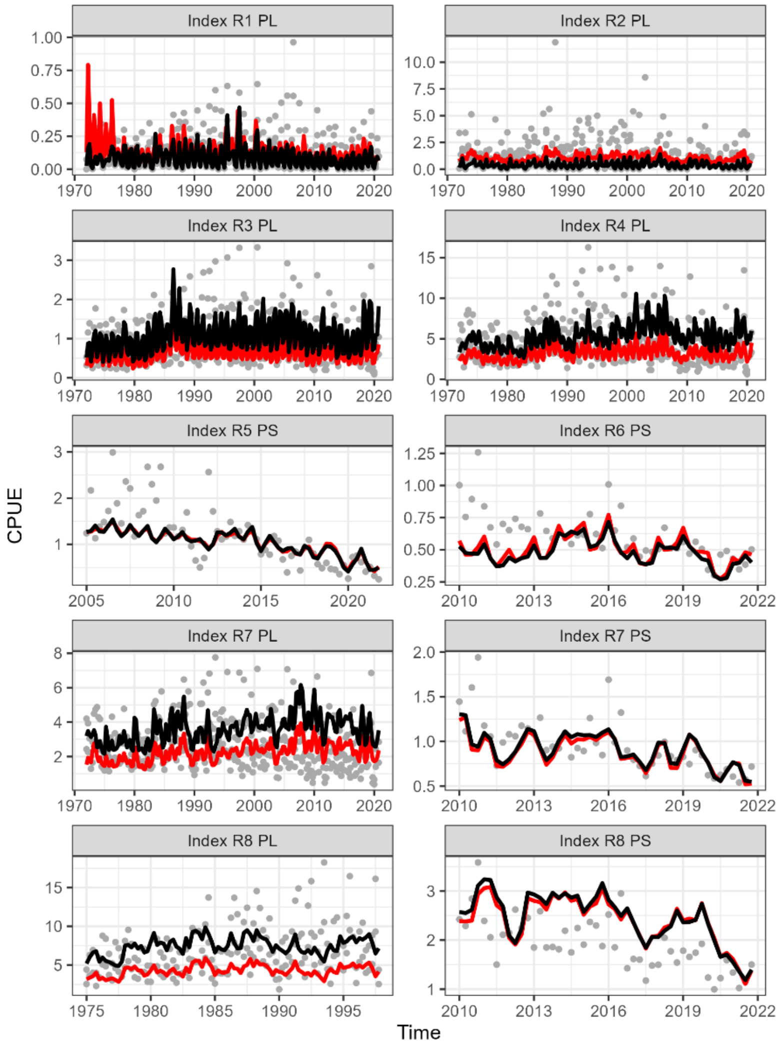

Figure 23. CPUE fits for 2022 diagnostic model (red line) and 2023 follow-up model (black line). Dots represent the 2023 follow-up CPUE.

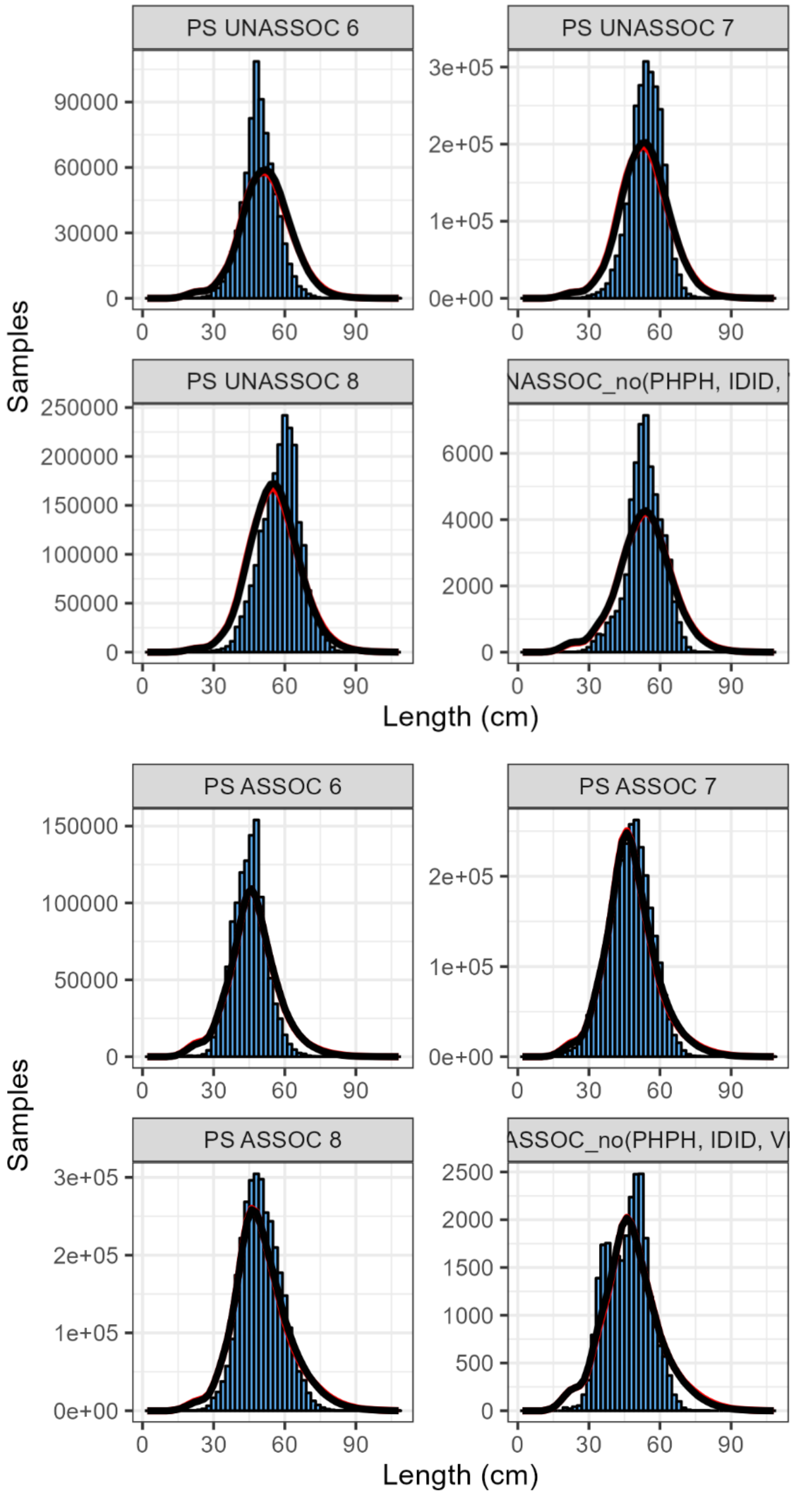

Figure 24. Composite (all time periods combined) observed (blue histograms) and predicted (red line for 2022 diagnostic model and black line for 2023 follow-up model) catch-at-length for purse seine fisheries, unassociated (top) and associated (bottom) in Regions5, 6, 7, and 8 for the diagnostic model.

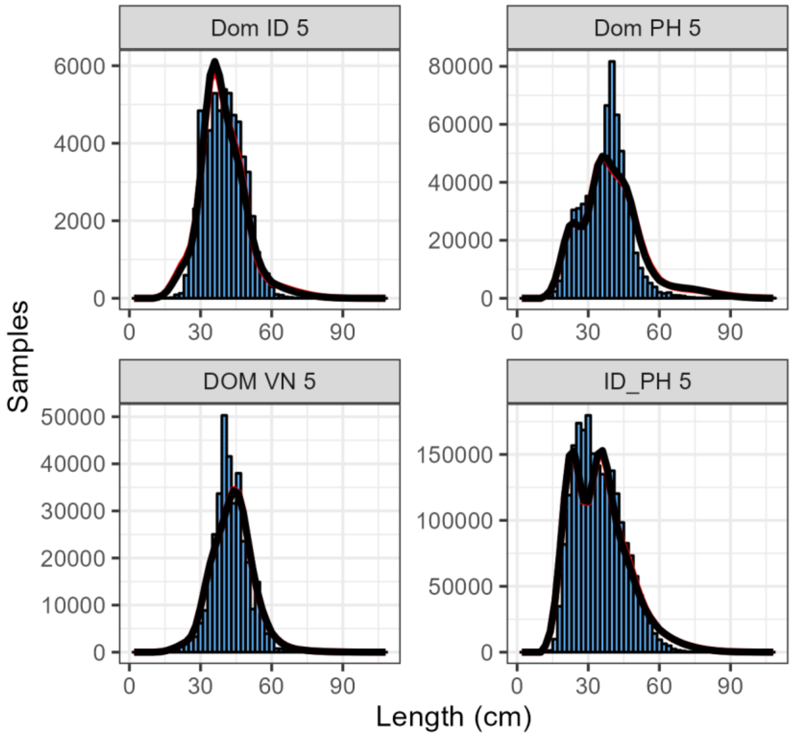

Figure 25. Composite (all time periods combined) observed (blue histograms) and predicted (red line for 2022 diagnostic model and black line for 2023 follow-up model) catch-at-length for ID, VN and PH domestic fisheries for the diagnostic model.

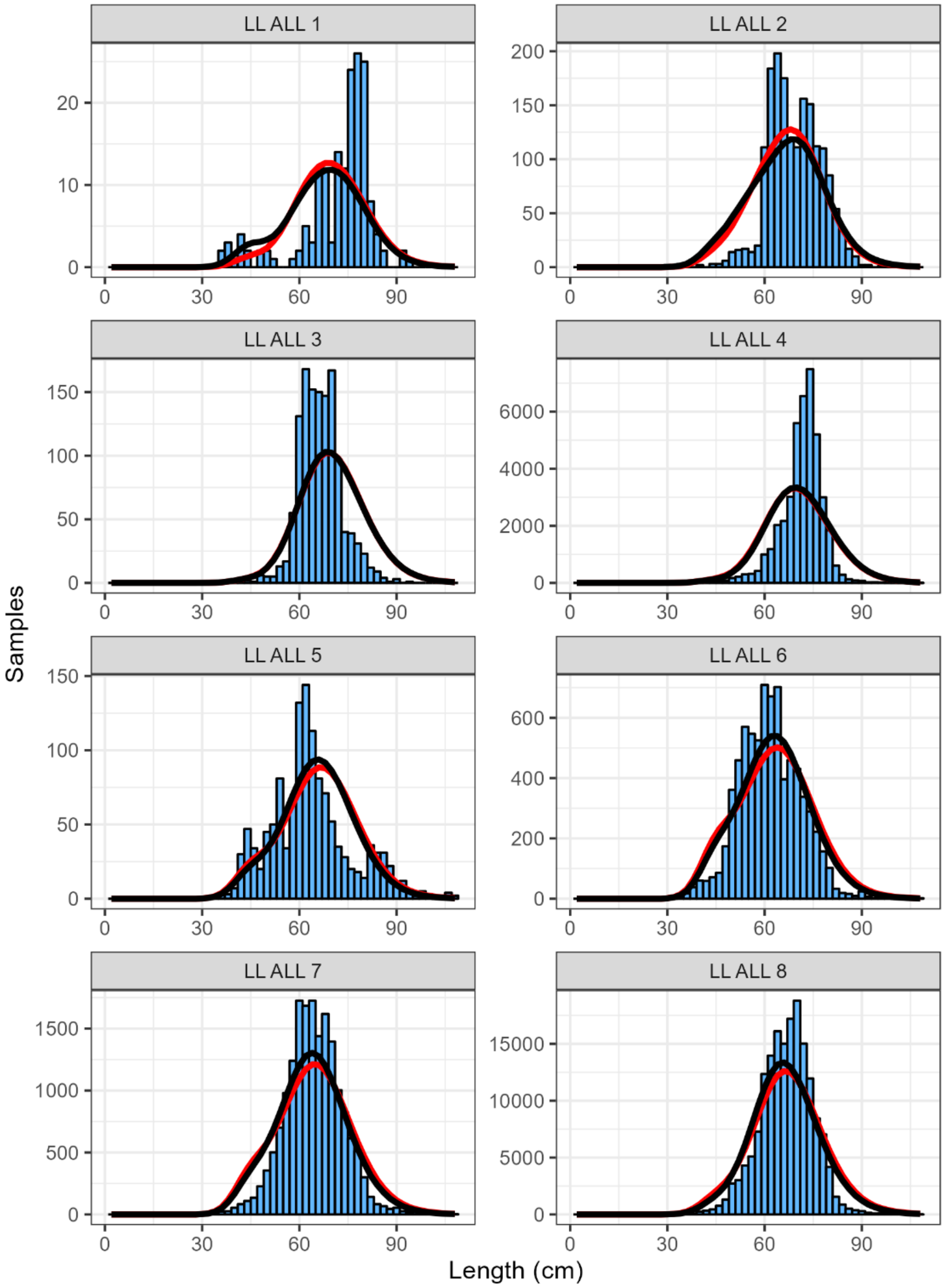

Figure 26. Composite (all time periods combined) observed (blue histograms) and predicted (red line for 2022 diagnostic model and black line for 2023 follow-up model) catch-at-length for longline fisheries for the diagnostic model.

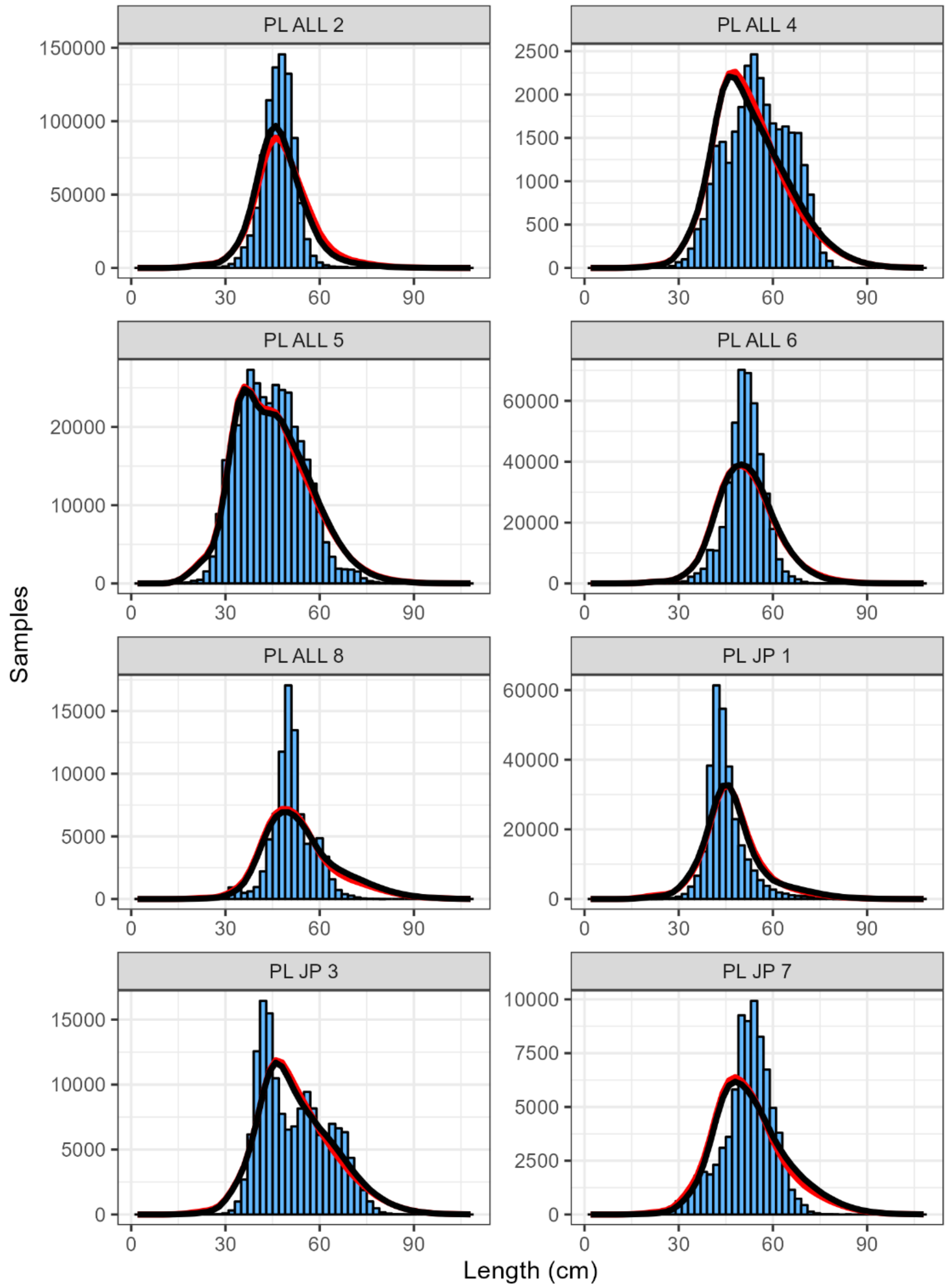

Figure 27. Composite (all time periods combined) observed (blue histograms) and predicted (red line for 2022 diagnostic model and black line for 2023 follow-up model) catch-at-length for pole-and-line fisheries for the diagnostic model.

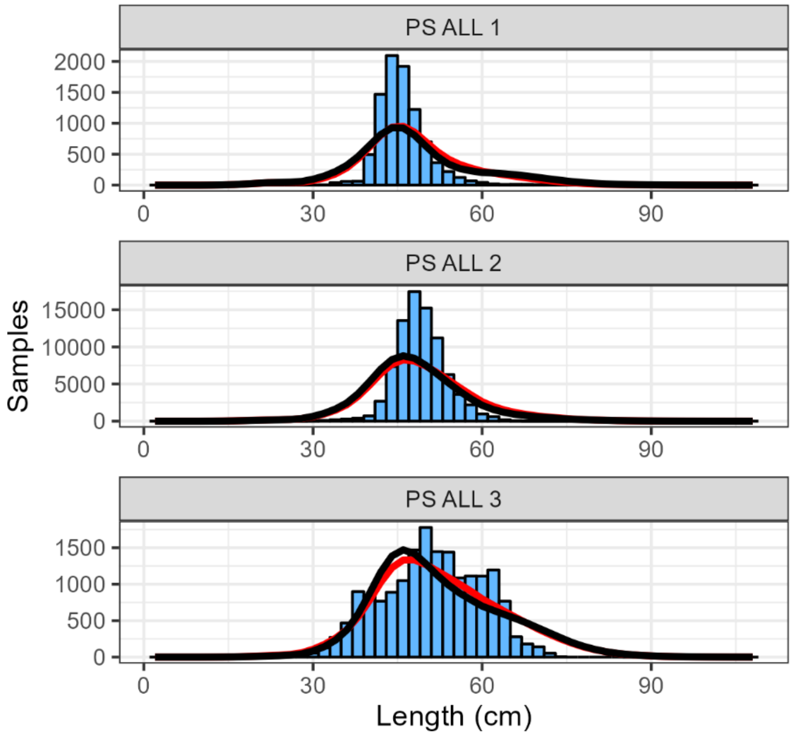

Figure 28. Composite (all time periods combined) observed (blue histograms) and predicted (red line for 2022 diagnostic model and black line for 2023 follow-up model) catch-at-length for purse seine fisheries in Regions 1, 2, and 3 for the diagnostic model.

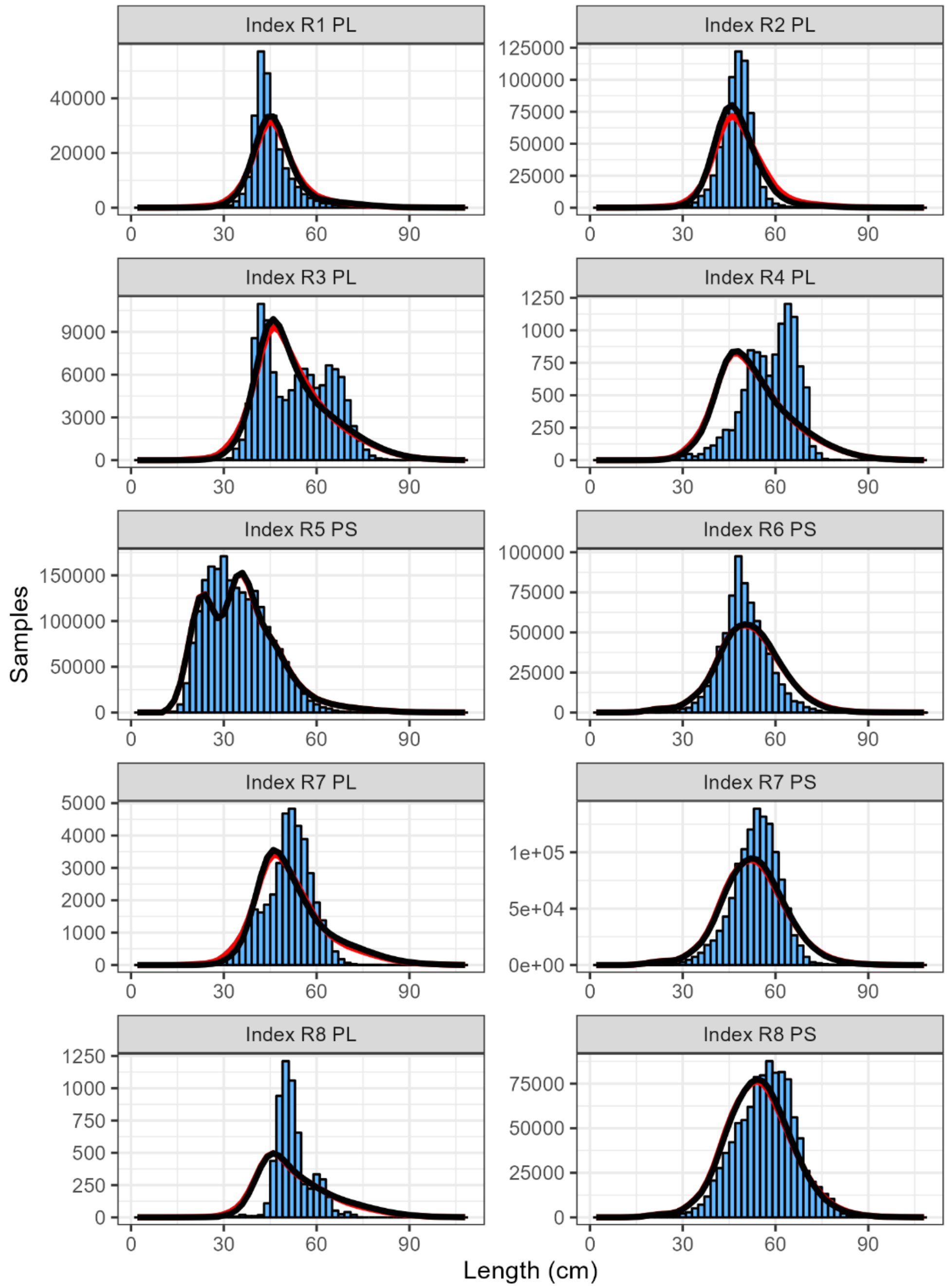

Figure 29. Composite (all time periods combined) observed (blue histograms) and predicted (red line for 2022 diagnostic model and black line for 2023 follow-up model) catch-at-length for index fisheries for the diagnostic model.

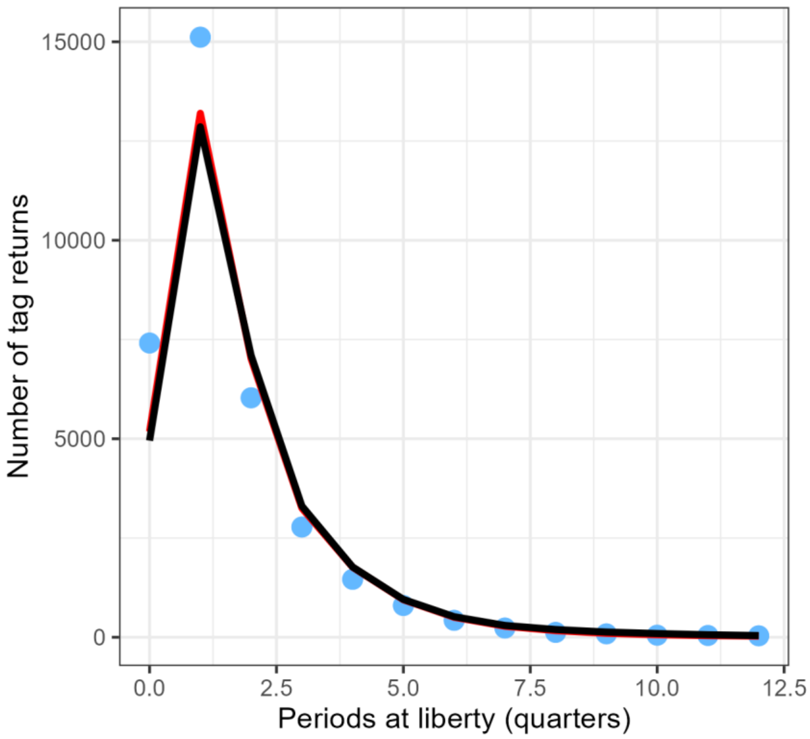

Figure 30. Tag attrition for 2022 diagnostic model (red line) and 2023 follow-up model (black line). Dots are the observations. Lines are the model predictions.

Appendix 1. Items for consideration as high-priority research areas for skipjack identified by SC18.

	Research area	State
	Hyperstability and effort creep in the CPUE indices, and incorporation of CPUE uncertainty in assessment results (i.e. inclusion as an axis in the structural uncertainty grid), including alternative model assumptions related to regional scaling	WCPFC project 115 to provide effort creep scenarios to adjust CPUE and run sensitivity models. Alternative CPUE models will be explored for the next assessment. Depending on effort creep related analysis and any new CPUE models, we will consider the need for a grid axis in the next assessment.
	Data conflicts that affect assessment outcomes, and approaches to resolving them.	Aim to run likelihood profiles to see if we can better pinpoint sources of data conflict.
	Review the model specification with the goal of conforming to the set of diagnostic criteria to determine whether an assessment model is suitable to provide management advice.	In progress, PDH diagnostic obtained.
	Assumptions dealing with the parametrization of key model settings, such as the fishing effort regression used in the catch-conditioned approach to minimize their impact on estimates of stock status	We believe we have a viable solution for fishing effort-F relationship for projection purposes by reducing the length of time over which this regression is calculated at the end of the model period
	Tag mixing, including estimation using observed data, simulation, and simulation validation.	To be considered further with SPC tagging scientists.
	SC18 noted the terms of reference (TOR) for Project 18X2a and 18X2b (Further development of ensemble model approaches for presenting stock assessment uncertainty) and Project 18X4 (Exploring evidence and mechanisms for a long-term increasing trend in recruitment of skipjack tuna in the equatorial Pacific and the development and modelling of defensible effort creep scenarios) in SC18-GN-IP-07, which would address further issues of importance.	As above re – project 115
	Investigate a range of hypotheses which encompass the uncertainties in the spatial-temporal dynamics of the stock and the fishing effort	Unclear on the specifics or this?
	Refine effort creep scenarios for the Japanese pole-and-line fishery and equatorial purse seine fisheries.	As above re – project 115
	Develop alternative approaches for the interpolation of abundance into unfished areas when spatially averaging predictions to compute regional scalers.	Will consider as part of CPUE modelling for next assessment.

	The use of preferential sampling models for standardizing CPUE data should be considered.	
	Consider the biological limits to the spatiotemporal distribution of skipjack when making predictions of biomass in unfished areas with spatiotemporal models.	CPUE is considering a exclusion of area with temperature over 18 C degrees, applies in the follow up model
	Conduct analyses to incorporate additional process error in CPUE indices	Will consider approaches applied in yellowfin and bigeye assessments.
	Evaluation of alternative sources of CPUE time series, such as FAD echo sounder buoys or additional indices for the purse seine fishery.	Our understanding of this is that FAD acoustics are currently quite unreliable, for much more than presence/absence. We will be focusing on purse seine free school based CPUE indices, and alternative effort metrics.
	Likelihood profiles show conflict between data sources included in the model. The cause of these conflicts should be identified and methods to address them should be explored.	As above – conduct a more detailed likelihood profile analysis.
	Estimated WCPO skipjack recruitment steadily increased between 1975 and 2010. Possible explanations for this trend should be researched, including model misspecification. If the trend is related to model misspecification options to resolve it within the model should be presented, The SC noted the TOR for Project 18X4 (Exploring evidence and mechanisms for a long-term increasing trend in recruitment of skipjack tuna in the equatorial Pacific and the development and modelling of defensible effort creep scenarios) in SC18-GN-IP-07.	Covered in WCPFC project 115
	Consider the thermal limits to the spatiotemporal distribution of skipjack recruitment within the model settings.	CPUE thermal limits have be applied to constrain the model area.
	Model diagnostics for each growth curve indicate poor fit to some components of the size data. Given the potential for spatial and temporal growth variation which any assessment cannot represent, recommend approaches to modeling growth and fitting size data that are robust to the potential for bias due to systematic lack of fit.	Not sure about options for improving this for skipjack without better growth information, noting we still cannot age skipjack.
	Support epigenetic aging for skipjack in the long-term while work progressing age validation and age estimation using otolith and spines should still be pursued.	Agree – but need some way to validate epigenetic ages.
	Examine the utility of alternative approaches for including tagging data in	To be considered by the SPC tagging scientist.

	the assessment, such as estimating movement and harvest rate parameters outside the assessment model and including them as priors.	
	Review evidence for rates of tag mixing based on the tagging data included in the stock assessment.	To be considered by the SPC tagging scientist.
	Consider the role of the Ikamoana simulation model in exploring scenarios of tag mixing, and the need for validation by comparing simulated and observed tag recovery patterns.	Tag data is already used to fit the models.
	Identify approaches to prevent tag reporting rates being estimated on the boundary, as these indicate some form of model misspecification such as incomplete tag mixing or data conflicts.	The follow up work has marginally reduced the reporting rates on the upper bounds but more work is needed to explore this problem.
	Review the model structure as it relates to achieving a converged solution. This includes consideration of the spatial structure as well as confirming that estimated parameters are identifiable and well-determined. Consider the utility of such models for the provision of management advice, including evaluation of relevant CMMs.	The follow up model achieved a well converged solution, with a positive definite hessian matrix. This is a first for the WCPO SKJ assessment.
	Estimation of the required fishing mortality spline regression parameters attracted a large penalty in the likelihood and modified population scale. The impact of parameterization on estimated quantities should be examined.	We now understand this issue and have developed a solution.
	Review grouping assumptions when setting up the Dirichlet-Multinomial likelihood for size composition data, and identify if the model is sensitive to grouping assumptions.	Currently looking into this, testing with no groupings.
	SC18 recommended that SC19 consider the need for a review of the skipjack tuna stock assessment taking into account the outcomes of the 2023 yellowfin review	NA

Appendix 2. SKJ structure for 2022 diagnostic model and 2023 follow up model.