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Progress report of the development of the state-space age-structured stock assessment model for Pacific saury up to 2023

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SUMMARY

We report the progress of the age-structured model for Pacific saury stock assessment up to 2023. The key assumptions for the next-generation stock assessment of Pacific saury are 1. the steepness of the Beverton-Holt stock recruitment relationship, 2. the natural mortalities for age 0 and age 1 fish, and 3. the treatment of age 0 fish spawning. We narrowed down the candidate hypotheses on these assumptions based on biological point of view, and then observed the sensitivity of the model behaviors against these assumptions.

INTRODUCTION

Following the arguments on the new stock assessment models for Pacific saury in the North Pacific Fisheries Commission (NPFC) Small Scientific Commission (SSC) for Pacific saury (PS), we developed a simple age-structured stock assessment model. Because the behavior of the model largely depends on the biological assumptions, clarifying uncertain parameters and observing the sensitivity of the model behavior against the assumptions of the parameters are essential to identify on which point we should focus. In this document, we introduce the structure of the model, and then observed the sensitivities of the model's behavior against the treatment of some key parameters identified in another document of ours (Nakayama et al., 2023).

The first parameter we focused on was the steepness of the Beverton-Holt stock recruitment relationship (h), which controls the resilience of the stock against population decrease. It takes a value from 0.2 to 1.0. h = 0.2 means that the expected recruitment decreases proportional to the decrease of the spawner's biomass, whereas h = 1.0 indicates the expected recruitment is completely independent from the amount of spawners.

In many stock assessments, M is fixed at plausible levels based on known relationships between M and other easily observable traits (M estimators, reviewed in Nakayama et al., 2019), since M is generally difficult to estimate inside age-structured models. The treatment of M is usually critical for stock assessments, because it determines the scaling of the target population dynamics, and thus affects the level of maximum sustainable yield (MSY) and total allowable catch (TAC). Therefore, even if *M* is successfully estimated inside the stock assessment models, validations of the obtained value of *M* based on biological knowledge is necessary.

The degree of contribution of age 0 fish to the reproduction is another factor that might greatly affect PS stock assessment results. The longevity of PS is two years, thus the stock consists of only two year classes, age 0 and age 1. All age 1 fish and a portion of age 0 fish take part in the spawning activity, and they spawn multiple times in a single spawning season. The relative contribution of the age 0 spawning to the total reproduction is affected by the proportion of matured age 0 fish, fecundity of age 0 per weight relative to age 1, and relative times of spawning of age 0 fish in a spawning season, assuming that the survival rate of the eggs and juvenile before recruitment are equal regardless of the spawner's age. Although the proportion of age 0 fish experienced spawning has been investigated in several years (Fuji et al., 2021a), the degree of age 0 contribution to the total reproduction is still unclear, because the information on fecundity and times of spawning is not available. Some stock assessments put a strong assumption, equal fecundity and times of spawning among ages, on the contribution of partially matured age classes to the total reproduction because of the lack of biological information. However, we should be careful to adopt this assumption to the PS stock assessment, because the degree of the contribution of age 0 spawning might have a large effect on the stock assessment of such a short-living species.

Here we tried to optimize the age-structured model for PS under several treatments on *M* and the age 0 spawning. The treatments of *M* are: 1. *M* for age 0 and 1 are fixed at the values obtained from one of the *M* estimators (Nakayama et al., 2019); 2. The ratio of *M* for age 0 and 1 is fixed at the value obtained by the *M* estimator; 3. *M* for age 0 and 1 are estimated separately inside the stock assessment model. The treatments of the age 0 spawning are: 1. Age 0 spawning was ignored; 2. The annual contributions of age 0 fish to the reproduction are estimated as random effects; and 3. The fecundity and times of spawning for age 0 and 1 are assumed to be equal. We show the behaviors of the model under all combinations of these treatments on *M* and age 0 spawning, and then discuss appropriate treatments for these factors.

METHOD

Input data

The input data of our age-structured model are age-specific abundance indices from the biomass survey, age-aggregated standardized fishery CPUE from five members, age-specific catch in number, and age-specific mean body weight of the fish in the survey, fishery, and winter seasons.

The PS biomass survey by Japan has been conducted every year since 2003, from mid-Jun. to mid-Jul., covering most of the PS habitat. The age-specific abundance indices during 2003–2023 were estimated by the spatiotemporal (VAST) model (Hashimoto et al., 2023a) based on the result of the survey. The average body weight of age 0 and age 1 fish samples, collected in this survey during

2003–2019 was 0.0490 and 0.123 kg, respectively (Fuji et al. 2021b). There were another Japanese survey conducted in Jan.–Mar., in order to investigate the properties of PS spawning (Fuji et al. 2021c). The average body weight of age 0 and age 1 fish samples collected in the spawning season by the winter survey conducted in 2007 and 2011 were 0.0536 and 0.107 kg, respectively (Fuji et al. 2021b).

PS is exploited by the six members (China, Japan, Korea, Russia, Vanuatu, and Chinese Taipei) of NPFC. The fisheries are conducted from May to Dec., mainly using stick-held-dip net. The main target of the fisheries is age 1 fish, although substantial amount of age 0 fish is also exploited. Five age-aggregated standardized fishery CPUE up to 2022 were provided by five members (China, Japan, Korea, Russia, and Chinese Taipei, Hua et al., 2023; Hashimoto et al., 2023b; Song, 2023; Kulik et al., 2023; Huang et al., 2023). The average body weight of 10,195 and 15,423 age 0 and age 1 fish samples, respectively, collected by Japanese fishery during 2003–2019 was 0.0792 and 0.141 kg, respectively (Fuji et al. 2021b).

The catch-at-age data (in number) are available for Japan (1994–2022), Korea (2001–2022), Russia (2000–2021), and Chinese Taipei (2007–2022). Because some members' catch-at-age data was not available, we calculated the total age i catch in year y in number by multiplying the sum of the available age i catch in number and the ratio of total (age 0 and 1) catch from all members in weight and total catch from the members in weight, whose catch-at-age data is available.

The model

We created a state-space model that describes the population dynamics during 1994–2022. The real life history of PS was simplified in the model, as shown in Table 1. The state-space model consists of two parts, the state model and the observation model. The state model expresses the life cycle including recruitment, growth, and spawning taking into account a process error. The recruitment (the number of age 0 fish in year y on Jul. 1, $N_{0,\,y}$) is calculated according to the Beverton-Holt SRR (Beverton and Holt, 1957), in which all age 1 and a portion of age 0 fish are regarded as spawner. The $N_{0,y}$ recruits suffer from natural mortality and exploitation before next Jul. 1, when they are counted as age 1 fish ($N_{1,y}$). The $N_{1,y}$ age 1 fish again suffer from natural mortality and exploitation before being spawners on next Jan. 1. Given the simplified life history, the recruitment calculation is formulated as

$$N_{0,y} = \frac{\alpha\, SSB_y}{1+\beta SSB_y} e^{\varepsilon_{0,y}} \quad (1),$$

where α and β are the Beverton-Holt SRR parameters and $\varepsilon_{0,\,y}$ denotes the error term. $\varepsilon_{0,\,y}$ follows a normal distribution with mean 0 and standard deviation σ_{p0}. The growth process from age 0 to age 1 is expressed as

$$N_{1,y} = N_{0,y-1} e^{-\frac{M_0}{2}} e^{-F_{0,y-1}} e^{-\frac{M_1}{2}} e^{\varepsilon_{1,y}} \quad (2),$$

where M_0 and M_1 are natural mortality coefficient for age 0 and 1 fish, respectively, and $F_{0,y-1}$ denotes the fishing mortality coefficient of age 0 in year $y-1$. $\varepsilon_{1,y}$ denotes the error term. $\varepsilon_{1,y}$ follows a normal distribution with mean 0 and standard deviation σ_{p1}. We fixed σ_{p1} at very small value (= 0.000001). The spawner stock biomass in year y (SSB_y) is calculated as

$$SSB_y = w_1^{sp} N_{1,y-1} e^{-\frac{M_1}{2}} e^{-F_{1,y-1}} + \gamma_y w_0^{sp} N_{0,y-1} e^{-\frac{M_0}{2}} e^{-F_{0,y-1}} \quad (3),$$

where w_1^{sp} and w_0^{sp} (= 0.0536 and 0.107, respectively, see *Input data* section) are the body weight of age 0 and 1 spawner, respectively, and $F_{0,y-1}$ and $F_{1,y-1}$ denotes the fishing mortality coefficients of age 0 and age 1 in year $y-1$, respectively. γ_y is a constant interpreted as the product of the proportion of matured age 0 fish, relative batch fecundity of age 0 fish, and relative times of spawning of age 0 fish in a spawning season in year y. We refer the proportion of the second term or the right hand side to SSB_y as "contribution of age 0 fish" hereafter. Given the population dynamics above, the steepness parameter of the Beverton-Holt stock recruitment relationship (h) is defined as

$$h = \frac{\alpha SPR_0}{4 + \alpha SPR_0},$$

$$SPR_0 = e^{-\frac{M_0}{2}} \left(\bar{\gamma} w_0^{sp} + e^{-M_1} w_1^{sp} \right) \quad (4),$$

where $\bar{\gamma}$ is the mean of γ_y. The fishing mortalities for age 0 and age 1 fish, F0 and F1, respectively, are restricted to correlate and to be smooth year to year by following equation:

$$\left(\log F_{0,y} - \log F_{0,y-1}, \log F_{1,y} - \log F_{1,y-1} \right) \sim MVNormal[(0,0), \mathbf{\Sigma}] \quad (5),$$

where $MVN[(0, 0), \sum]$ denotes a multivariate normal distribution with mean (0, 0) and variance-covariance matrix $\sum$. Given the population dynamics above, the biomass-at-age in the survey [$B_{a,y}$, where a denotes age (0 or 1)] and fishery ($B^*_{a,y}$) are calculated as

$$B_{a,y} = w_a N_{a,y} \quad (6) \text{ and}$$

$$B^*_{a,y} = w^*_a N_{a,y} e^{-\frac{M_a}{4}} \quad (7),$$

respectively, where w_a (= 0.0494 and 0.123 for a = 0 and 1, respectively) and w^*_a (= 0.0792 and 0.141 for a = 0 and 1, respectively) are the mean body weight in the survey and fishery seasons, respectively (see *Input data* section).

The observation model for the survey indices and fishery CPUE ($o_{x,y}$, hereafter x = *survey0* or *survey1* indicates the survey index for age 0 and 1, respectively, or x = *China*, *Chinese Taipei*, *Japan*, *Korea*, or *Russia* is the fishery CPUE from each member, respectively) are given by

$$\log o_{x,y} \sim Normal(\log q_x + \log B_{a,y},\ \sigma_x{}^2), \quad (x,a) = (survey0, 0) or (survey1, 1) \quad (8) \text{ and}$$

$$\log o_{x,y} \sim Normal\left[(\log q_x) + b_x \log\left(\sum_{a=0}^{1} S_{x,a} B^*_{a,y} \right),\ \sigma_x{}^2 \right],$$

$$x = China, Chinese\ Taipei, Japan, Korea, Russia \quad (9),$$

where q_x and σ_x are the catchability and standard deviation for each $\log o_{x,y}$, respectively. b_x and $S_{x,a}$ are the hyperstability/depletion parameter and the selectivity-at-age for x, respectively. We restricted $S_{x,1} = 1 - S_{x,0}$, since PS consists of only two age classes. The observation model for catch is formulated as

$$\log C_{a,y} \sim Normal\left[\log N_{a,y} - \frac{M_a}{4} + \log(1 - e^{-F_{a,y}}),\ \ \sigma_x{}^2\right]$$
$$x = catch0, catch1 \qquad (10),$$

where $C_{a,\,y}$ is the catch at age data of age a fish in year y.

All of the parameters were estimated using the maximum likelihood method. $\log(N_{a,\,y})$, $\log(F_{a,\,y})$, and $\text{logit}(\gamma_y)$ were treated as random effects. Assuming that the catch data is correct, we fixed σ_{catch0} and σ_{catch1} at very small values (= 0.000001). The observation errors for fishery indices were assumed to have five times larger variances than the observation error for the age 1 survey index ($\sigma_{China}{}^2 = \sigma_{Chinese\ Taipei}{}^2 = \sigma_{Japan}{}^2 = \sigma_{Korea}{}^2 = \sigma_{Russia}{}^2 = 5\sigma_{survey1}{}^2$). Only in 2020, the survey indices for age 0 and 1 have larger uncertainties than those in other years due to an accident in the survey (Hashimoto et al., 2020). Considering this large uncertainty, the standard deviations of $\sigma_{survey0}$ and $\sigma_{survey1}$ were fixed at five times or those in other years.

Also, MSY, FMSY (number based), and BMSY (for the biomass in Jul.) were calculated for each trial, assuming that future ratio of exploitation rates for age 0 and age 1 fish are same to the one averaged over recent 5 years (2018–2022).

Treatment of the natural mortalities, age 0 spawning, and steepness

In the discussion on the natural mortalities for PS so far, two sets of (M_0, M_1) are proposed. One is (2.18, 2.18) based on fishlife (Thorson et al., 2017, Hsu et al., 2022) and another is (2.04, 1.57) based on the natural mortality estimator (Charnov et al., 2013, Nakayama et al., 2019). Therefore, we conducted parameter estimations with M_0, M_1 fixed at these values.

The argument of age 0 spawning in another document of ours (Nakayama et al., 2023) concluded that the value of mean γ_y is likely to be less than 0.2. Therefore, here we fixed mean γ_y at three levels, 0.05, 0.1, and 0.2. We also tried to estimate mean γ_y, rather than fixing it at certain values.

We also had a discussion on the value of steepness in Nakayama et al. (2023), concluding that the value of h previously proposed (= 0.86) is plausible, but should not ignore the possibility that h is lower than that. In this document, we tried two treatments for h: fixed at 0.86 and estimated.

We tried all combinations of these treatments of the natural mortalities, age 0 fish spawning, and steepness. We call the four trials with mean γ_y estimation and the twelve trials with fixed mean γ_y as Scenario 1-X and Scenario 2-X, respectively (see table 2 for details).

Model diagnostics

We conducted model diagnostics of the results from the “best model”, which had the highest likelihood out of the 16 trials (Scenario 1-2). We observed the process errors for recruitment and age 1 fish expressed by eqs. (1) and (2). The model fit to the survey indices and fishery CPUEs (observation errors) was also observed. Finally, to evaluate the prediction ability of the model, we conducted five years of hindcasting. The hindcasting was conducted with fixed hyperstability/depletion parameters (b_x) and selectivities ($S_{x,a}$) to guarantee convergence.

RESULTS and DISCUSSION

The parameter estimation were successfully convergent (the maximum gradient component < 10e-5) in the all scenarios other than scenario 11. In general, the estimated biomass was low in 1994 to early 2000s, then experienced a highly productive period until early 2010s, and recently has declined again to the lowest level (Fig. 1 and 2). The fishing pressure of age 0 fish has almost kept stationary, whereas that for age 1 fish suddenly increased from mid-2010s then decreased in most recent years.

The assumption of natural mortalities mainly affected the scale of the population dynamics. Scenarios with high natural mortalities (Scenario 7–12, $M_0 = M_1 = 2.18$) showed approximately twice biomass of age 0 fish, whereas the biomass of age 1 fish were comparable.

The estimated degree of age 0 fish contribution to the spawning (mean of γ) 0.13 and 0.079 (Scenario 1-2 and 1-4, respectively) when h was estimated. These estimated values are inside the plausible range that was derived by biological evidence (Nakayama et al., 2023). On the other hand, the mean of γ were was estimated to be unnaturally small when h was fixed at 0.86 (0.011 and 0.0059 in Scenario 1-1 and 1-3). In most of the cases with fixed mean of γ and h (Scenario 2-1, 2-3, 2-7, 2-9), the estimated fishing mortality coefficients kept smaller than F_{MSY} level throughout the target period, indicating that the observed population dynamics has been driven mainly by external factors such as environment, rather than exploitation. In these cases, the estimated total biomass was above BMSY almost throughout the target period, except for recent years.

The estimated h ranged from 0.38 to 0.56 (in Scenario 2-8 and 2-6, respectively), depending on other settings. These values seemed to be small, because small pelagic fish are generally considered to have high h. Nevertheless, another document of ours (Nakayama et al., 2023) showed that biological evidences indicate a possibility that h of PS can be not as high as generally thought. According to the document, the estimated values of h were within a plausible range that was derived from biological evidence.

The annual process error of the stock recruitment relationship seemed to have some degree of autocorrelation (Fig. 7, top left panel). This implies the existence of some factors that affect recruitment efficiency and is not explicitly considered in the model. Environmental factors can be candidates of the unexplained factors, therefore clarifying and including them into the model structure is a meaningful future work.

Too many and too less estimates were outside the 90 percent prediction intervals of the survey index of age 1 and the fishery CPUE, respectively (8 out of 21 estimates and 5 out of 111 estimates, respectively. Fig. 7, top right and bottom left panels). This is presumably because of the restriction that the fishery CPUE have five times larger variance (shared among members) compared to the one in survey age 1 index.

The hindcasting showed different tendencies depending on whether the 2020 data was included or not (Fig. 7, bottom right). This implies that the model has some extent of predictability, but could not predict the situation in 2020.

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Table 1. Life history of PS and related human activities in the model.

Month	Biological event	Survey	Fishery
Jan.	Hatching	Winter survey	
Feb.			
Mar.			
Apr.			
May			
Jun.			
Jul.	Recruitment	Summer survey	
Aug.			
Sep.			
Oct.			Exploitation
Nov.			
Dec.			
Jan.	Age 0 spawning Become age 1	Winter survey	
Feb.			
Mar.			
Apr.			
May			
Jun.			
Jul.		Summer survey	
Aug.			
Sep.			
Oct.			Exploitation
Nov.			
Dec.			
Jan.	Spawning	Winter survey	

Each event is conducted on the 1st day of the month.

Table 2. Summary of the treatments of the parameters.

Scenario	M	mean(γ)	h	nll	Note
1-1	$M_0 = 2.04, M_1 = 1.57$	estimated (0.011)	0.86	−849	small γ
1-2		estimated (0.13)	estimated (0.47)	−854.8	maximum likelihood
1-3	$M_0 = 2.18, M_1 = 2.18$	estimated (0.0059)	0.86	−847.9	small γ
1-4		estimated (0.079)	estimated (0.45)	−850.9	
2-1	$M_0 = 2.04, M_1 = 1.57$	0.2	0.86	−844.2	small F
2-2			estimated (0.44)	−852.1	
2-3		0.1	0.86	−843.4	small F
2-4			estimated (0.49)	−853	
2-5		0.05	0.86	−845.5	
2-6			estimated (0.56)	−852.3	
2-7	$M_0 = 2.18, M_1 = 2.18$	0.2	0.86	−845.5	small F
2-8			estimated (0.38)	−851.8	
2-9		0.1	0.86	−841.3	small F
2-10			estimated (0.43)	−852	
2-11		0.05	0.86	–	Did not converge
2-12			estimated (0.49)	−851.5	

The numbers inside the parenthes are the estimated h.

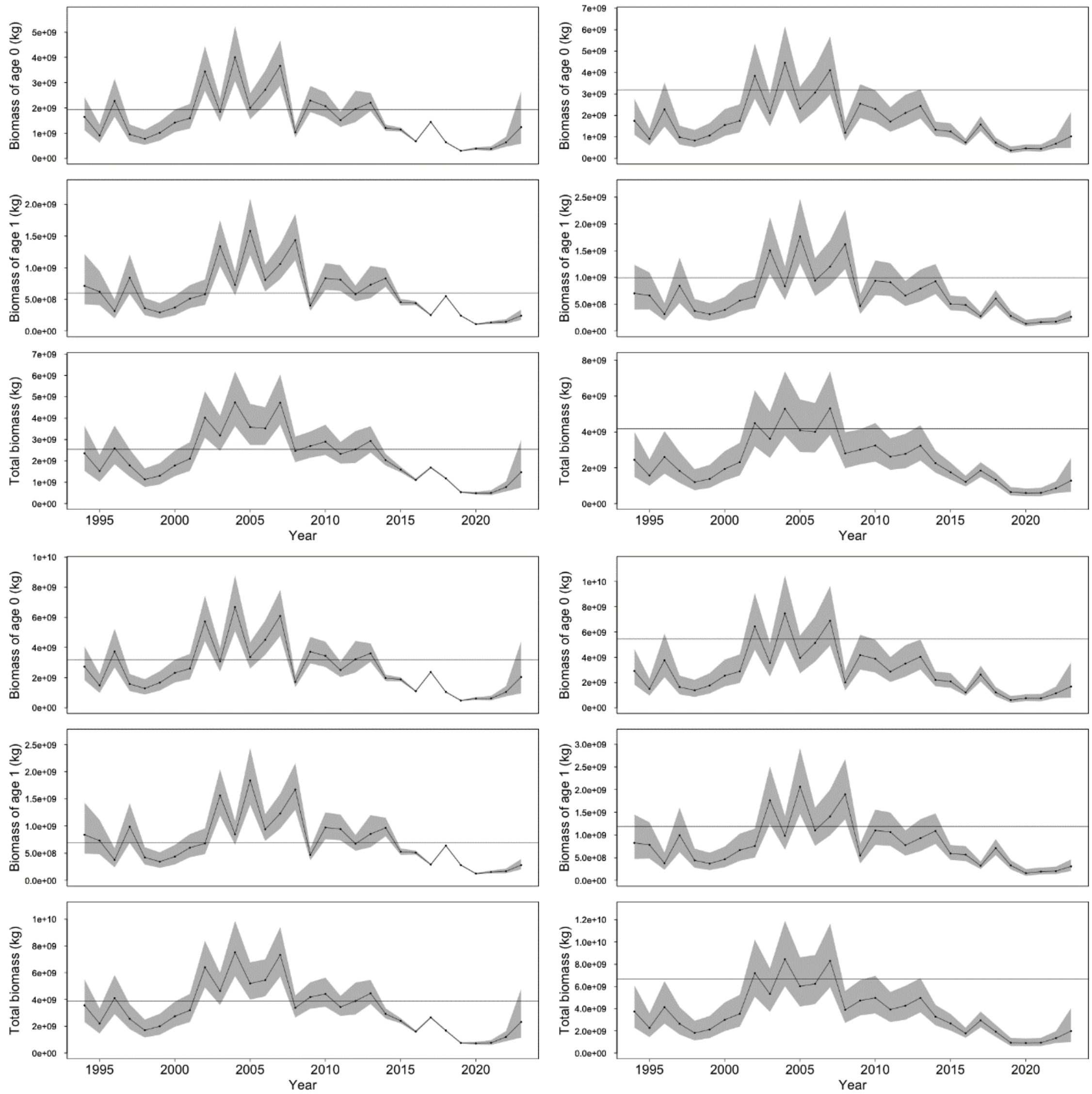

Figure 1. Estimated age 0, 1, and total biomass in the trials with γ estimation. The solid lines and gray shadows are median and 90 percentile confidence intervals. The horizontal lines are estimated BMSY. Top left, top right, and bottom left bottom right panels correspond to Scenario 1-1, 1-2, 1-3, and 1-4, respectively.

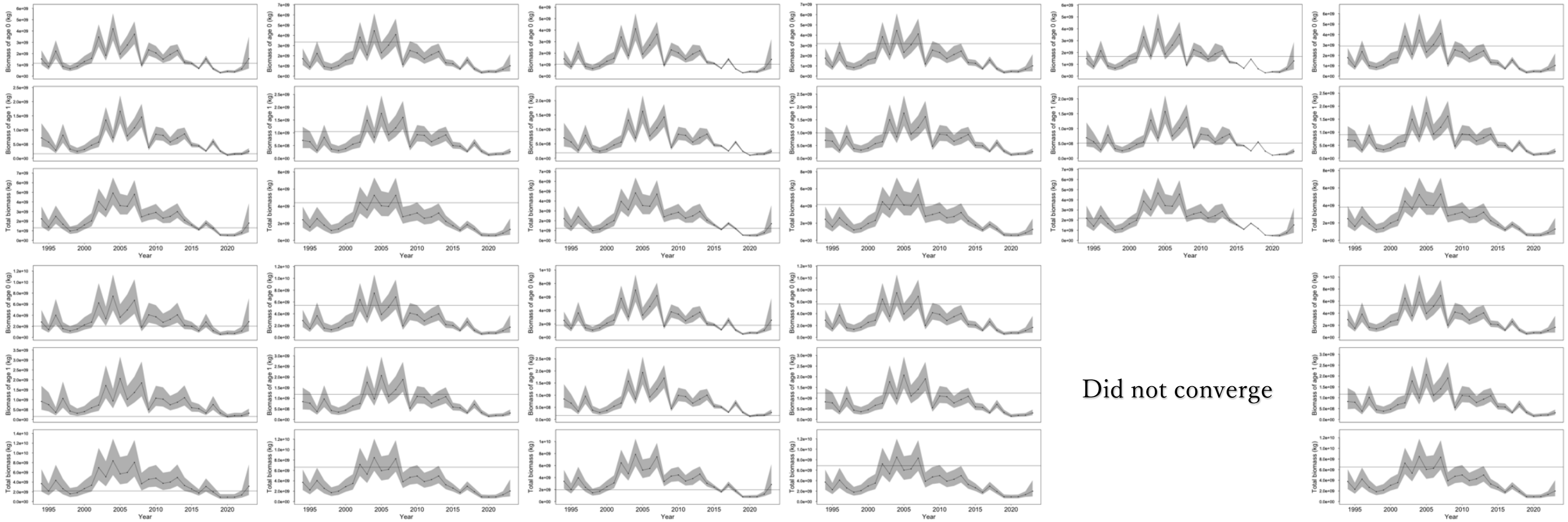

Figure 2. Estimated age 0, 1, and total biomass in the trials with fixed γ. The solid lines and gray shadows are median and 90 percentile confidence intervals. The horizontal lines are estimated BMSY. The upper and bottom row corresponds to Scenario 2-1 to 2-6 and 2-7 to 2-12, respectively.

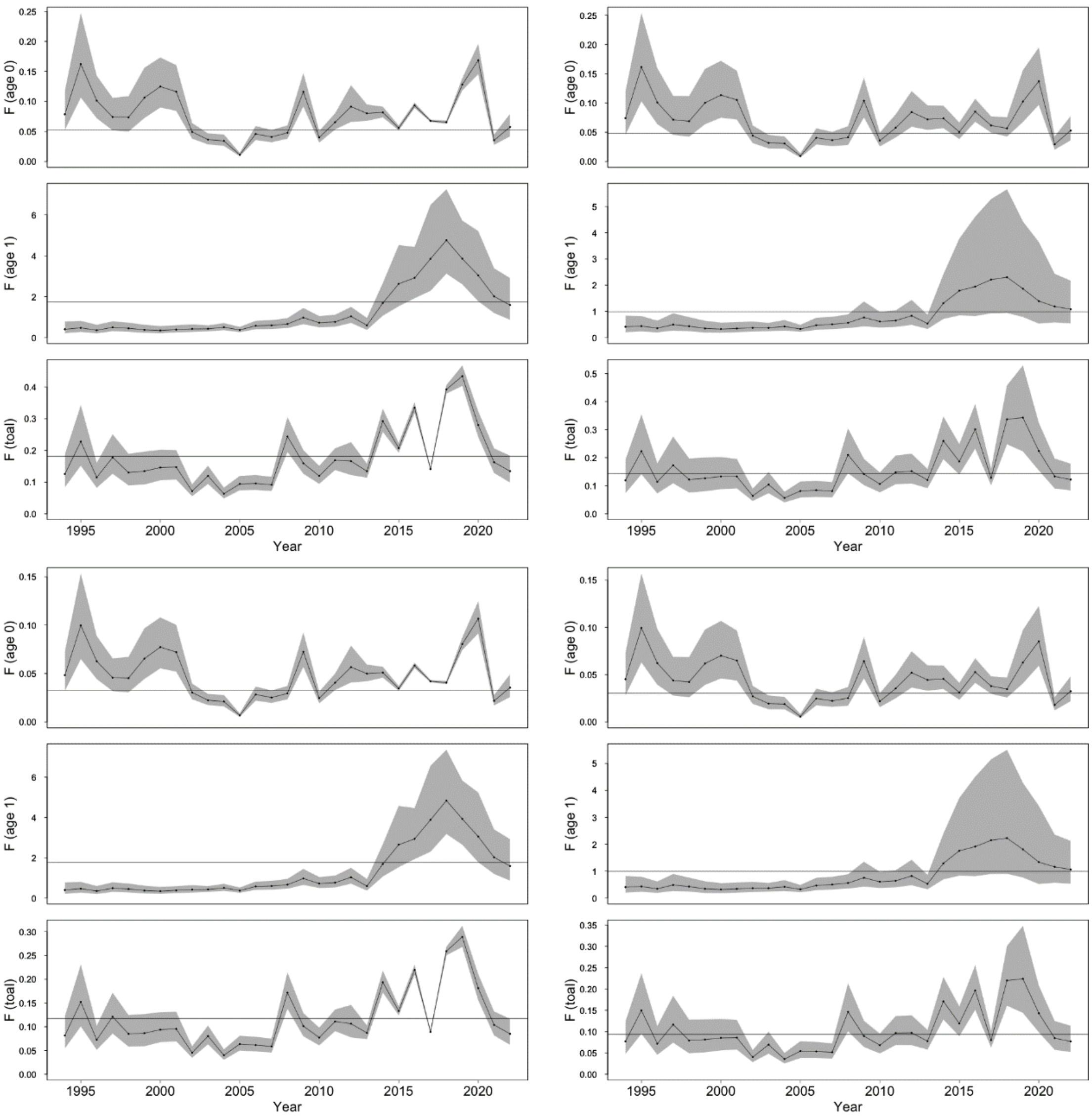

Figure 3. Estimated age 0, 1, and total fishing mortality coefficients in the trials with γ estimation. The solid lines and gray shadows are median and 90 percentile confidence intervals. The horizontal lines are estimated FMSY. Top left, top right, and bottom left bottom right panels correspond to Scenario 1-1, 1-2, 1-3, and 1-4, respectively.

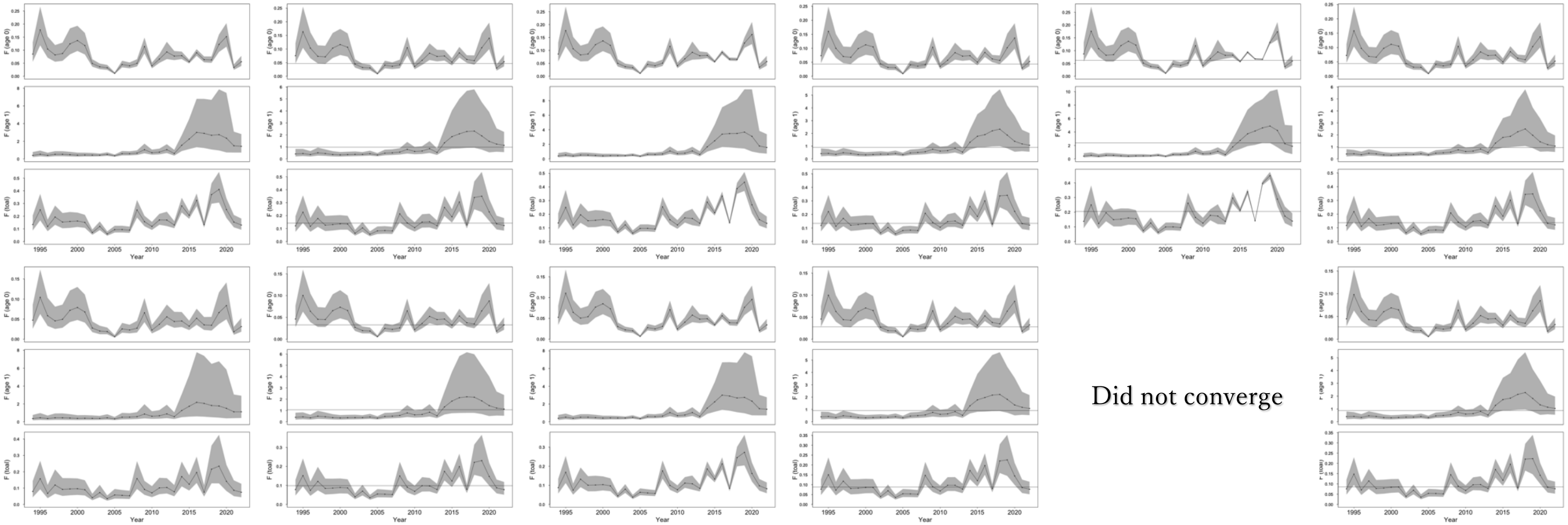

Figure 4. Estimated age 0, 1, and total fishing mortality coefficients in the trials with fixed γ. The solid lines and gray shadows are median and 90 percentile confidence intervals. The horizontal lines are estimated FMSY. The upper and bottom row corresponds to Scenario 2-1 to 2-6 and 2-7 to 2-12, respectively.

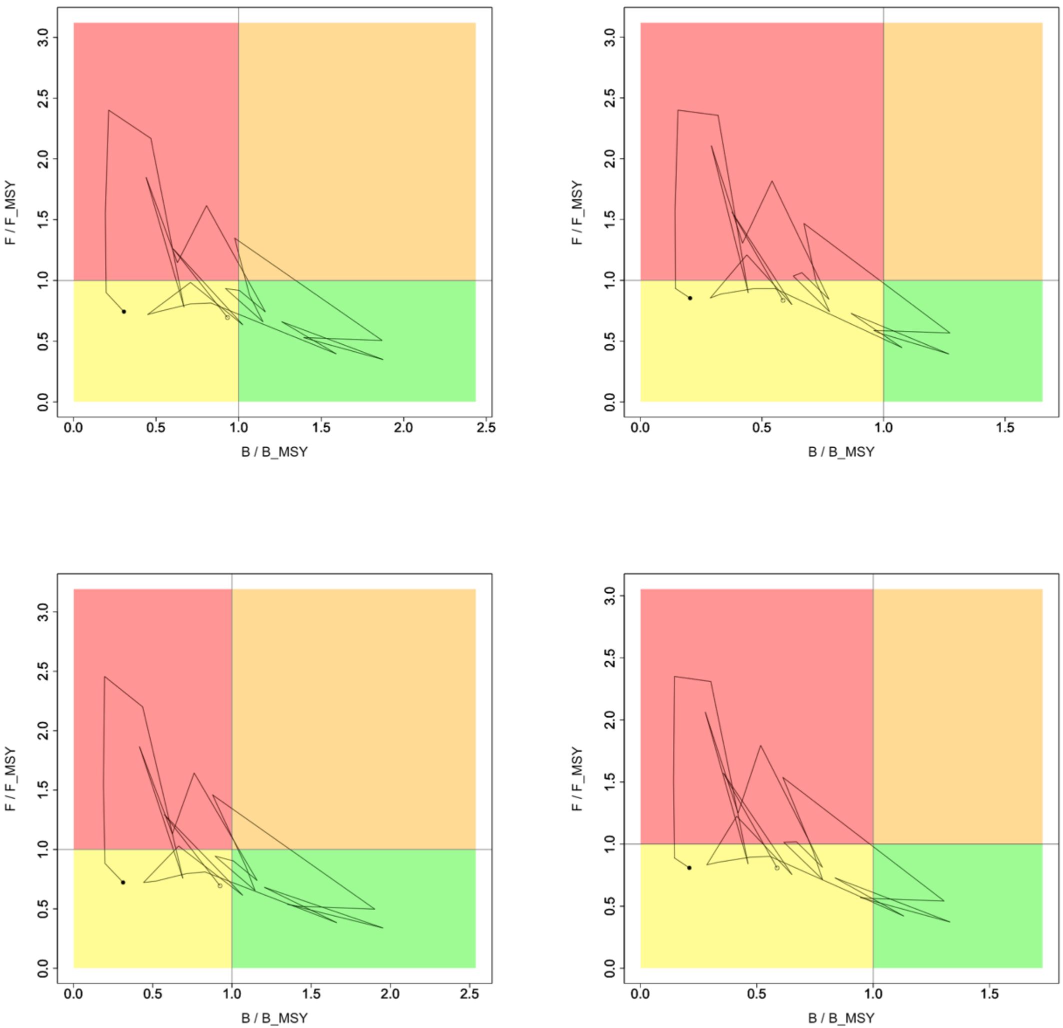

Figure 5. Estimated Kobe plots in the trials with γ estimation. The open and solid circles indicate the initial and terminal year, respectively. Top left, top right, and bottom left bottom right panels correspond to Scenario 1-1, 1-2, 1-3, and 1-4, respectively.

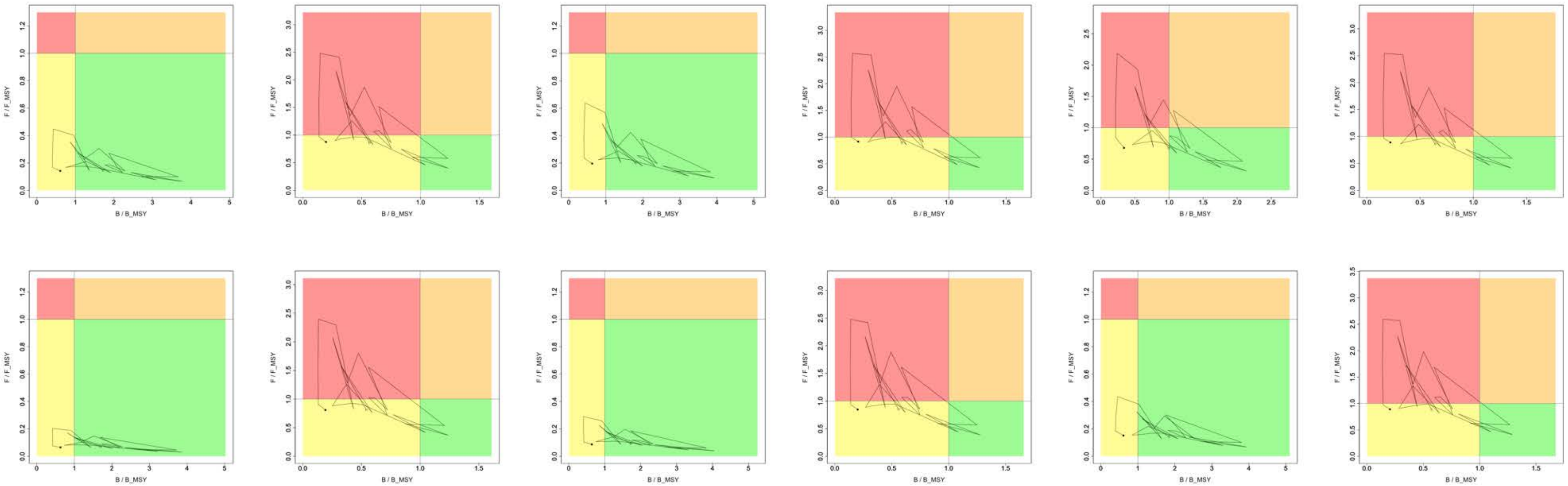

Figure 6. Estimated Kobe plots in the trials with fixed γ. The open and solid circles indicate the initial and terminal year, respectively. The upper and bottom row corresponds to Scenario 2-1 to 2-6 and 2-7 to 2-12, respectively.

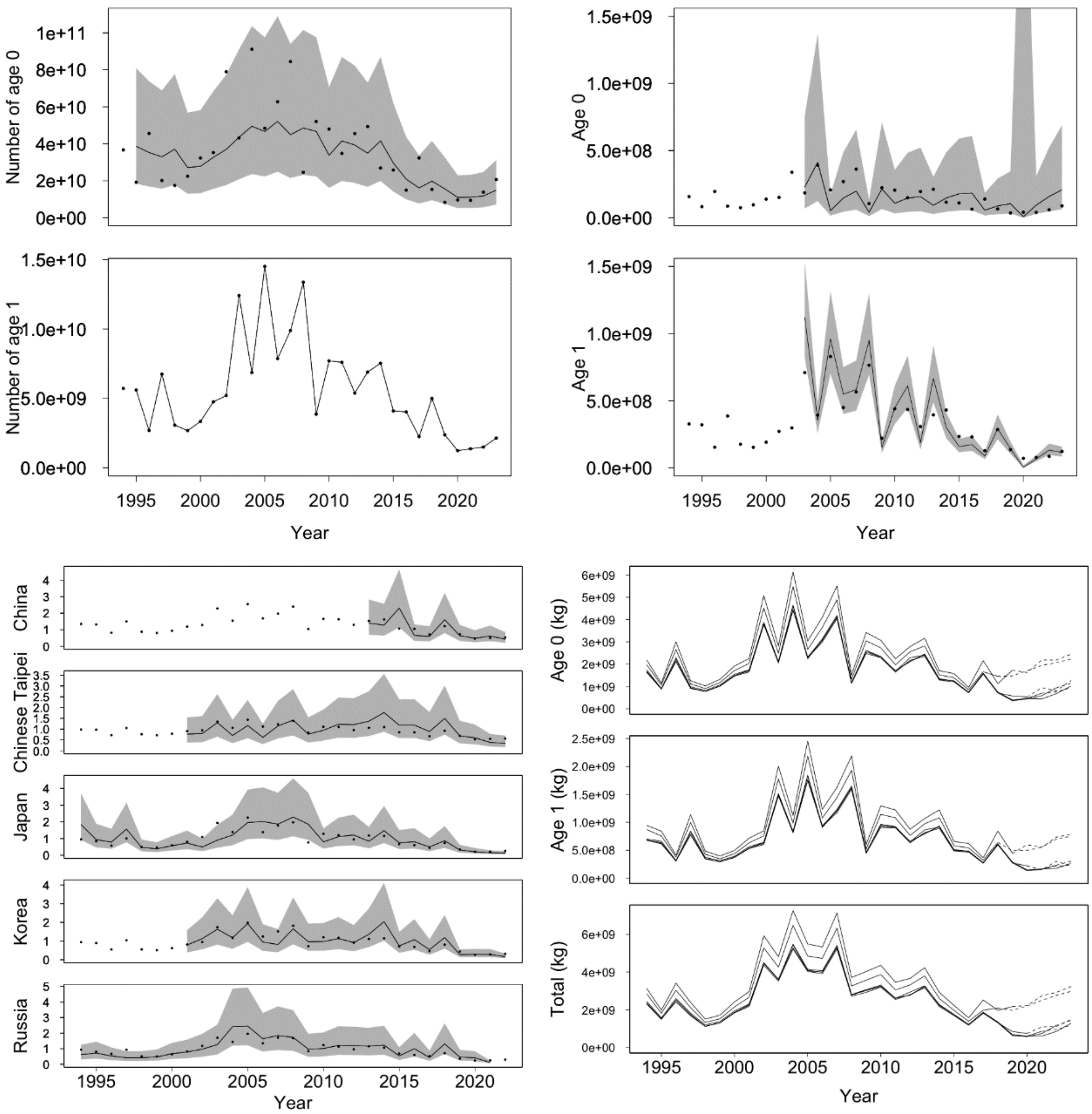

Figure 7. Results of the model diagnostics. Top left: Observation of the process errors. The closed circles are estimated N_0 and N_1. The solid lines indicates the results of deterministic calculations from eqs. (1) and (2). The gray shadows are the 90 percent prediction intervals. Top right: Observation of the observation errors for the survey indices. The closed circles are the results of deterministic calculations from eq. (8). The solid lines are the survey indices. The gray shadows are the 90 percentiles of the observation errors. Bottom left: Observation of the observation errors for the fishery CPUE. The closed circles are the results of deterministic calculations from eq. (9). The solid lines are the fishery CPUEs. The gray shadows are the 90 percentiles of the observation errors. Bottom right: The result of the hindcasting. The solid lines are estimated age-0, age-1, and total biomass with the data up to 2023, 2022,…, and 2018. The dashed lines indicate the projections from the terminal years.