North Pacific Fisheries Commission

NPFC-2022-SSC PS10-WP03

Updates of stock assessment for Pacific saury in the North Pacific Ocean up to 2022

Libin Dai, Siquan Tian
Shanghai Ocean University

Summary

This working paper presents the results of update of stock assessment for the North Pacific Ocean Pacific Saury stock using the Bayesian state-space production model. The assessment was conducted based on the model specification (2 base cases and 2 sensitivity cases) updated in the 9th Meeting of the Small Scientific Committee on Pacific saury. The model parameters were estimated based on Bayesian framework with a Markov chain Monte Carlo method. The assessment results were diagnosed with the Gelman and Rubin's statistic, standardized residual plots, the shapes of posterior distributions for key parameters, and retrospective analysis. The main assessment results were concluded as follows:

The estimated median B2021 from the two base case scenarios was 266,250 (80%CI 124,400-426,500) and 622,750 (80%CI 165,500-1,173,000) metric tons, respectively. The median B2021/BMSY and F2021/FMSY over the two base case scenarios were 0.31 (80%CI 0.20-0.46) and 0.73 (80%CI 0.47-1.25), respectively. Over the two base case scenarios, large interannual variability was shown in biomass trajectory during the recent years. A decreasing biomass trend was found in 2019 and 2020, followed by an increase in 2021 and 2022. The probability of the population being in the yellow Kobe quadrant in 2021 was estimated to be greater than 79%.

1. Introduction

The Pacific saury (*Cololabis sarira*) is one of the most commercially important fish species in the North Pacific Ocean. The regular update of stock assessment for Pacific saury in each year is conducted by the Small Scientific Committee on Pacific saury (SSC PS) established under the Scientific Committee of the North Pacific Fisheries Commission (NPFC). Currently, the benchmark assessment model for Pacific saury stock assessment is Bayesian state-space production model (BSSPM). In the 9th SSC PS meeting, the model specification of BSSPM was revised, and the group agreed to conduct a stock assessment update with two base cases and two sensitivity cases based on updated input data.

In this report, we conducted an update of stock assessment for Pacific saury by using BSSPM, and summarized the estimates of key parameters and biological reference points as well as other assessment results for all case scenarios.

2. Materials and methods

2.1. Input data

The input data used in this assessment included (Figure 1):

1) The total catch from 1980 to 2021 were included.
2) The Japanese fishery-independent survey biomass estimates up to 2022 were included.
3) The fishery-dependent abundance indices, including Japanese late CPUE (1994-2021), Russian CPUE (1994-2021), Chinese Taipei CPUE (2001-2021), Korean CPUE (2001-2021) and Chinese CPUE (2013-2021) were updated.

2.2. Assessment methods

The assessment used a Bayesian state-space production model. The population dynamics were modeled by the following equations:

$$B_t = B_{t-1} + r \times B_{t-1}(1 - (\frac{B_{t-1}}{K})^M) - C_{t-1}$$

$$P_t = B_t/K$$

$$P_{t+1} = (P_t + r \times P_t \times (1 - P_t^M) - \frac{C_t}{K})exp(\mu_t)$$

$$\mu_t \sim N(0, \tau^2)$$

Where B_t and C_t denote biomass and catch, respectively, in year *t*. Parameters *r*, *K*, *M* represent intrinsic population growth rate, carrying capacity, and production shape parameter respectively. P_t and μ_t denote the ratio between biomass and carrying capacity and the process error, respectively, in year t. μ_t has a mean of zero and variance τ^2.

The multiple indices were modeled by the following equations:

$$I_{i,t} = q_{i,t}(KP_t)^{b_i}exp(\varepsilon_{i,t})$$

$$\varepsilon_{i,t} \sim N(0, \sigma_i^2)$$

Where $I_{i,t}$ is the relative abundance of index *i* at year *t*. $q_{i,t}$ is the catchability coefficient for index *i* at year *t*. b_i is the hyperdepletion parameter. $\varepsilon_{i,t}$ is the observation error with a mean of zero and variance σ_i^2.

All base case and sensitivity case scenarios were built based on SSC PS09 recommendation and used uniform prior distribution for catchability (*q*), carrying capacity (K), intrinsic population growth rate (r), initial biomass as a proportion of carrying capacity (P1), and shape (s) (Table 1-2). Inverse gamma prior distribution was used for the process (τ^2) and observation (σ^2) error variance (Table 2).

Random walk approach was selected to estimate the time-varying catchability of Japanese early CPUE due to its relatively well performance and its ability to obtain a realistic increase of catchability over time (Wilberg et al. 2009; NPFC-2019-TWG PSSA04-WP08).

The convergence of the posterior distributions of model parameters was examined with Gelman and Rubin's statistics (Gelman and Rubin 1992). MSY-based biological reference points were estimated from the models. Mean error between predicted and observed indices was calculated to determine the model goodness of fit. Mean errors of each scenario were used to compare the performance of models. A lower mean error indicates a better fit. A retrospective analysis was conducted to verify whether any possible systematic inconsistencies exist among the model estimates of biomass and harvest rate based on increasing periods of data (Mohn 1999). The data were removed from the year 2022 to 2017. Sensitivity analysis was established based on the incorporation of Japanese early CPUE (NS1 and NS2).

3. Assessment results

The posterior densities of model parameters from all case scenarios showed that the densities were smooth and unimodal (Appendix Figure 1-4). The estimated mean, median, and 80% CI of posterior estimates of reference points were summarized in Table 3 and Appendix Table 1-4. Mean, median, and 80% CI of the posterior estimates of model parameters from each scenario were summarized in Appendix Table 5-8. The time series of biomass and harvest rate, Bratio (B/BMSY), Fratio (F/FMSY), and B/K from two base case scenarios were summarized (Figure 2-11).

4. Diagnostics and caveats

1) All parameters from the base case and sensitivity case scenarios showed well convergence of posterior distributions with Gelman and Rubin's statistic for all parameters were close to 1.
2) The standardized residuals between predicted and observed indices from base case scenarios and sensitivity case scenarios showed similar patterns (Appendix Figure 5-8). Temporal patterns were observed in the standardized residuals of some members' indices (Appendix Figure 5 and 7).
3) The sensitivity analysis results showed that the incorporation of Japanese early CPUE (NS1 and NS2) would lead to lower scales of biomass time trajectory, but the difference of scales between base cases and sensitivity cases decreased over time (Figure 15-19).
4) Mohn's rho values of biomass and harvest rate from all case scenarios were shown in Table 4. The plots of biomass and harvest rate from the retrospective analysis indicated larger model instability (but not typical retrospective patterns) in the base cases (Appendix Figure 9-16).

5. Time series of stock size and harvest rate

The time series of biomass and harvest rate between base case 1 and base case 2 showed different scales, indicating the use of joint CPUE would highly impact the scale of assessment results. The scale difference between base case 1 and sensitivity case 1 was smaller than that of base case 2 and sensitivity case 2. The scale issue is more apparent in early period. The Bratio and B/K of case scenarios with member-specific CPUE (NB1 and NS1) showed higher interannual variability compared to those with joint CPUE. The Fratio of all case scenarios were similar except for beginning years. The Kobe plots showed that the Bratio and Fratio in 2021 over two base cases were in yellow quadrant (Figure 12). The averaged Bratio (2020-2022) and Fratio (2019-2021) over two base cases fell in the red quadrant of the Kobe plot (Figure 13). Kobe plot with median Fratio and Bratio time series from 1980 to 2021 over two base cases was shown in Figure 14.

References

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Table 1. Definition of base cases and sensitivity cases (NPFC-2022-SSC PS09-Final Report Annex F).

	Base case (NB1)	**Base case (NB2)**	**Sensitivity case (NS1)**	**Sensitivity case (NS2)**
Initial year	1980	1980	1980	1980
Biomass survey	$I_{t,bio} = q_{bio} B_t e^{v_{t,bio}}$ $v_{t,bio} \sim N(0, cv_{t,bio}^2 + \sigma^2)$ $q_{bio} \sim U(0,1)$ (2003-2022)	Same as left	Same as left	Same as left
CPUE	CHN(2013-2021) JPN_late(1994-2021) KOR(2001-2021) RUS(1994-2021) CT(2001-2021) $I_{t,f} = q_f B_t^b e^{v_{t,f}}$ $v_{t,f} \sim N(0, \sigma_f^2)$ $\sigma_f^2 = c \cdot (ave(cv_{t,bio}^2) + \sigma^2)$, where $ave(cv_{t,bio}^2)$ is computed except for 2020 survey (*c*=5)	Joint CPUE (1994-2021) $I_{t,joint} = q_{joint} B_t^b e^{v_{t,joint}}$ $v_{t,joint} \sim N(0, cv_{t,joint}^2 + \sigma^2)$	CHN(2013-2021) JPN_early(1980-1993, time-varying *q*) JPN_late(1994-2021) KOR(2001-2021) RUS(1994-2021) CT(2001-2021) $I_{t,f} = q_f B_t^b e^{v_{t,f}}$ $v_{t,f} \sim N(0, \sigma_f^2)$ $\sigma_f^2 = c \cdot (ave(cv_{t,bio}^2) + \sigma^2)$ where $ave(cv_{t,bio}^2)$ is computed except for 2020 survey (*c*=6)	JPN_early(1980-1993, time-varying *q*) $I_{t,JE} = q_{t,JE} B_t^b e^{v_{t,JE}}$ $v_{t,JE} \sim N(0, \sigma_{JE}^2)$ $\sigma_{JE}^2 = c \cdot (ave(cv_{t,joint}^2) + \sigma^2)$ Joint CPUE (1994-2021) $I_{t,joint} = q_{joint} B_t^b e^{v_{t,joint}}$ $v_{t,joint} \sim N(0, cv_{t,joint}^2 + \sigma^2)$
Hyper-depletion/ stability	A common parameter for all fisheries with a prior distribution, b~U(0, 1)	b~U(0, 1)	A common parameter for all fisheries but JPN_early, with a prior distribution, b~U(0, 1) [b for JPN_early is fixed at 1]	b~U(0, 1) for joint CPUE. [b for JPN_early is fixed at 1]
Prior for other than q_bio	Own preferred options	Own preferred options	Own preferred options	Own preferred options

Table 2. Prior assumptions of parameters that are not listed in SSC PS05 Report Annex G.

	q_CPUE	K	r	P1	s	σ^2	τ^2
NB1	U(0,1) for qJPN_late and qCT; U(0,5) for qRUS, qKOR and qCHN	U(63,1890)	U(0,3)	U(0,1)	U(0,3)	$1/\sigma^2$~Gamma(0.001, 0.001)	$1/\tau^2$~Gamma(0.001, 0.001)
NB2	U(0,1) for qJoint						
NS1	U(0,1) for qJPN_early, qJPN_late, and qCT; U(0,5) for qRUS, qKOR and qCHN						
NS2	U(0,1) for qJPN_early and qJoint						

Table 3. Summary of reference points over 2 base case scenarios.

	Mean	Median	Lower	Upper
C2021	9.22	9.22	9.22	9.22
AveC2019-2021	14.14	14.14	14.14	14.14
AveF2019-2021	0.43	0.40	0.12	0.77
F2021	0.26	0.24	0.08	0.48
FMSY	0.37	0.36	0.09	0.65
MSY	42.42	41.32	30.05	52.94
F2021/FMSY	0.90	0.73	0.47	1.25
AveF2019-2021/FMSY	1.42	1.20	0.79	1.88
K	402.33	249.20	138.60	927.52
B2021	60.23	38.26	19.13	122.70
B2022	88.06	62.19	36.07	154.31
AveB2020-2022	67.66	44.85	24.56	130.60
BMSY	185.31	118.80	69.35	409.83
BMSY/K	0.48	0.46	0.39	0.58
B2021/K	0.16	0.15	0.09	0.23
B2022/K	0.25	0.24	0.13	0.39
B2020-2022/K	0.18	0.18	0.11	0.26
B2021/BMSY	0.33	0.31	0.20	0.46
B2022/BMSY	0.54	0.50	0.29	0.81
B2020-2022/BMSY	0.38	0.36	0.24	0.54

Table 4. Summary of Mohn's rho values of biomass and harvest rate from all case scenarios.

	Rho_B	Rho_F
B1	1.41	-0.52
B2	0.03	0.04
S1	0.22	-0.05
S2	0.09	0.04

Appendix table 1. Summary of reference points from base case scenario 1.

	Mean	Median	Lower 10th	Upper 10th
C2021	9.22	9.22	9.22	9.22
AveC2019-2021	14.14	14.14	14.14	14.14
AveF2019-2021	0.56	0.57	0.27	0.85
F2021	0.35	0.35	0.15	0.52
FMSY	0.48	0.49	0.28	0.72
MSY	46.47	43.89	34.48	52.48
F2021/FMSY	0.76	0.71	0.45	1.02
AveF2019-2021/FMSY	1.20	1.16	0.76	1.57
K	250.31	187.70	104.40	292.90
B2021	36.08	26.63	12.44	42.65
B2022	71.00	51.78	27.45	81.28
AveB2020-2022	45.86	33.74	18.82	52.91
BMSY	116.68	89.28	54.20	136.90
BMSY/K	0.48	0.47	0.39	0.55
B2021/K	0.15	0.14	0.09	0.21
B2022/K	0.29	0.28	0.16	0.40
B2020-2022/K	0.19	0.18	0.12	0.25
B2021/BMSY	0.31	0.30	0.18	0.41
B2022/BMSY	0.61	0.57	0.34	0.81
B2020-2022/BMSY	0.39	0.38	0.25	0.51

Appendix table 2. Summary of reference points from base case scenario 2.

	Mean	Median	Lower 10th	Upper 10th
C2021	9.22	9.22	9.22	9.22
AveC2019-2021	14.14	14.14	14.14	14.14
AveF2019-2021	0.30	0.24	0.05	0.48
F2021	0.18	0.15	0.03	0.28
FMSY	0.25	0.21	0.02	0.41
MSY	38.38	38.11	25.78	48.05
F2021/FMSY	1.03	0.76	0.36	1.26
AveF2019-2021/FMSY	1.63	1.26	0.68	1.96
K	554.35	398.20	109.10	867.10
B2021	84.38	62.28	16.55	117.30
B2022	105.13	79.17	27.72	138.60
AveB2020-2022	89.45	66.36	19.31	122.14
BMSY	253.94	184.10	63.62	390.70
BMSY/K	0.48	0.46	0.37	0.56
B2021/K	0.16	0.15	0.08	0.22
B2022/K	0.22	0.20	0.09	0.31
B2020-2022/K	0.18	0.17	0.08	0.24
B2021/BMSY	0.35	0.32	0.18	0.46
B2022/BMSY	0.46	0.42	0.19	0.63
B2020-2022/BMSY	0.37	0.35	0.19	0.49

Appendix table 3. Summary of reference points from sensitivity case scenario 1.

	Mean	Median	Lower 10th	Upper 10th
C2021	9.22	9.22	9.22	9.22
AveC2019-2021	14.14	14.14	14.14	14.14
AveF2019-2021	0.58	0.58	0.36	0.82
F2021	0.36	0.35	0.21	0.50
FMSY	0.52	0.52	0.33	0.72
MSY	43.44	42.29	35.60	48.36
F2021/FMSY	0.72	0.69	0.44	0.91
AveF2019-2021/FMSY	1.16	1.12	0.78	1.51
K	208.55	167.15	100.50	245.70
B2021	29.45	26.09	15.16	37.83
B2022	51.90	46.47	28.48	63.97
AveB2020-2022	35.70	31.66	20.05	44.05
BMSY	96.69	81.25	53.18	113.10
BMSY/K	0.48	0.47	0.39	0.56
B2021/K	0.16	0.16	0.10	0.22
B2022/K	0.29	0.29	0.16	0.40
B2020-2022/K	0.20	0.20	0.12	0.26
B2021/BMSY	0.33	0.32	0.21	0.44
B2022/BMSY	0.59	0.57	0.34	0.80
B2020-2022/BMSY	0.40	0.39	0.25	0.52

Appendix table 4. Summary of reference points from sensitivity case scenario 2.

	Mean	Median	Lower 10th	Upper 10th
C2021	9.22	9.22	9.22	9.22
AveC2019-2021	14.14	14.14	14.14	14.14
AveF2019-2021	0.43	0.40	0.15	0.66
F2021	0.25	0.23	0.09	0.37
FMSY	0.37	0.36	0.17	0.60
MSY	42.03	41.92	35.02	47.67
F2021/FMSY	0.70	0.66	0.40	0.89
AveF2019-2021/FMSY	1.19	1.16	0.77	1.51
K	302.75	240.80	115.30	385.20
B2021	49.52	39.99	16.85	66.46
B2022	68.85	57.39	28.22	90.82
AveB2020-2022	53.94	44.07	20.41	72.10
BMSY	143.30	116.20	62.15	179.60
BMSY/K	0.49	0.48	0.38	0.57
B2021/K	0.17	0.16	0.10	0.23
B2022/K	0.25	0.24	0.14	0.34
B2020-2022/K	0.19	0.18	0.11	0.25
B2021/BMSY	0.35	0.34	0.22	0.45
B2022/BMSY	0.51	0.48	0.30	0.68
B2020-2022/BMSY	0.39	0.37	0.25	0.50

Appendix table 5. Summary of parameter estimates from base case scenario 1.

	Mean	Median	Lower 10th	Upper 10th
r	1.36	1.20	0.44	2.12
K	250.31	187.70	104.40	292.90
qCHN	1.46	1.37	0.54	2.10
qJPN2	0.25	0.23	0.10	0.37
qKOR	1.06	0.98	0.38	1.55
qRUS	2.53	2.38	1.02	3.76
qCT	0.27	0.25	0.10	0.40
qBio	0.64	0.66	0.44	1.00
Shape	0.91	0.70	0.09	1.51
sigma_com	0.08	0.07	0.02	0.11
sigma_Bio	0.04	0.03	0.01	0.05
tau	0.30	0.30	0.12	0.50
FMSY	0.48	0.49	0.28	0.72
BMSY	116.68	89.28	54.20	136.90
MSY	46.47	43.89	34.48	52.48
b	0.49	0.48	0.33	0.61

Appendix table 6. Summary of parameter estimates from base case scenario 2.

	Mean	Median	Lower 10th	Upper 10th
r	0.885	0.678	0.016	1.418
K	554.349	398.200	109.100	867.100
qBio	0.403	0.361	0.095	0.640
qJoint	0.192	0.145	0.012	0.296
Shape	0.917	0.629	0.002	1.692
sigma_com	0.261	0.262	0.174	0.353
sigma_Bio	0.261	0.262	0.174	0.353
tau	0.117	0.087	0.019	0.174
FMSY	0.247	0.209	0.018	0.413
BMSY	253.944	184.100	63.620	390.700
MSY	38.377	38.110	25.780	48.050
b	0.375	0.367	0.151	0.580

Appendix table 7. Summary of parameter estimates from sensitivity case scenario 1.

	Mean	Median	Lower 10th	Upper 10th
r	1.42	1.26	0.52	2.11
K	208.55	167.15	100.50	245.70
qCHN	0.56	0.50	0.18	0.81
qJPN1_1980	0.02	0.02	0.00	0.03
qJPN1_1981	0.02	0.02	0.00	0.03
qJPN1_1982	0.02	0.01	0.00	0.02
qJPN1_1983	0.02	0.01	0.00	0.03
qJPN1_1984	0.02	0.02	0.00	0.03
qJPN1_1985	0.02	0.02	0.00	0.03
qJPN1_1986	0.02	0.02	0.01	0.03
qJPN1_1987	0.02	0.02	0.01	0.03
qJPN1_1988	0.03	0.02	0.01	0.04
qJPN1_1989	0.03	0.03	0.01	0.05
qJPN1_1990	0.04	0.03	0.01	0.05
qJPN1_1991	0.05	0.04	0.02	0.06
qJPN1_1992	0.06	0.05	0.02	0.09
qJPN1_1993	0.08	0.07	0.03	0.11
qJPN2	0.08	0.07	0.03	0.11
qKOR	0.36	0.32	0.11	0.52
qRUS	0.88	0.78	0.28	1.27
qCT	0.09	0.08	0.03	0.13
qBio	0.72	0.74	0.56	1.00
Shape	0.98	0.72	0.06	1.65
sigma_com	0.07	0.06	0.02	0.10
sigma_Bio	0.03	0.03	0.01	0.04
Tau	0.23	0.23	0.09	0.37
FMSY	0.52	0.52	0.33	0.72
BMSY	96.69	81.25	53.18	113.10
MSY	43.44	42.29	35.60	48.36
b	0.77	0.77	0.63	0.90

Appendix table 8. Summary of parameter estimates from sensitivity case scenario 2.

	Mean	Median	Lower 10th	Upper 10th
r	1.05	0.88	0.20	1.63
K	302.75	240.80	115.30	385.20
qBio	0.56	0.55	0.27	0.85
qJPN1_1980	0.01	0.01	0.00	0.02
qJPN1_1981	0.01	0.01	0.00	0.02
qJPN1_1982	0.01	0.01	0.00	0.02
qJPN1_1983	0.01	0.01	0.00	0.02
qJPN1_1984	0.01	0.01	0.00	0.02
qJPN1_1985	0.01	0.01	0.00	0.02
qJPN1_1986	0.01	0.01	0.00	0.02
qJPN1_1987	0.01	0.01	0.00	0.02
qJPN1_1988	0.02	0.01	0.00	0.02
qJPN1_1989	0.02	0.02	0.01	0.03
qJPN1_1990	0.02	0.02	0.01	0.03
qJPN1_1991	0.02	0.02	0.01	0.03
qJPN1_1992	0.02	0.02	0.01	0.03
qJPN1_1993	0.02	0.02	0.01	0.03
qJoint	0.19	0.16	0.02	0.29
Shape	1.04	0.84	0.05	1.83
sigma_com	0.22	0.23	0.14	0.31
sigma_Bio	0.22	0.23	0.14	0.31
tau	0.12	0.10	0.02	0.19
FMSY	0.37	0.36	0.17	0.60
BMSY	143.30	116.20	62.15	179.60
MSY	42.03	41.92	35.02	47.67
b	0.39	0.38	0.19	0.59

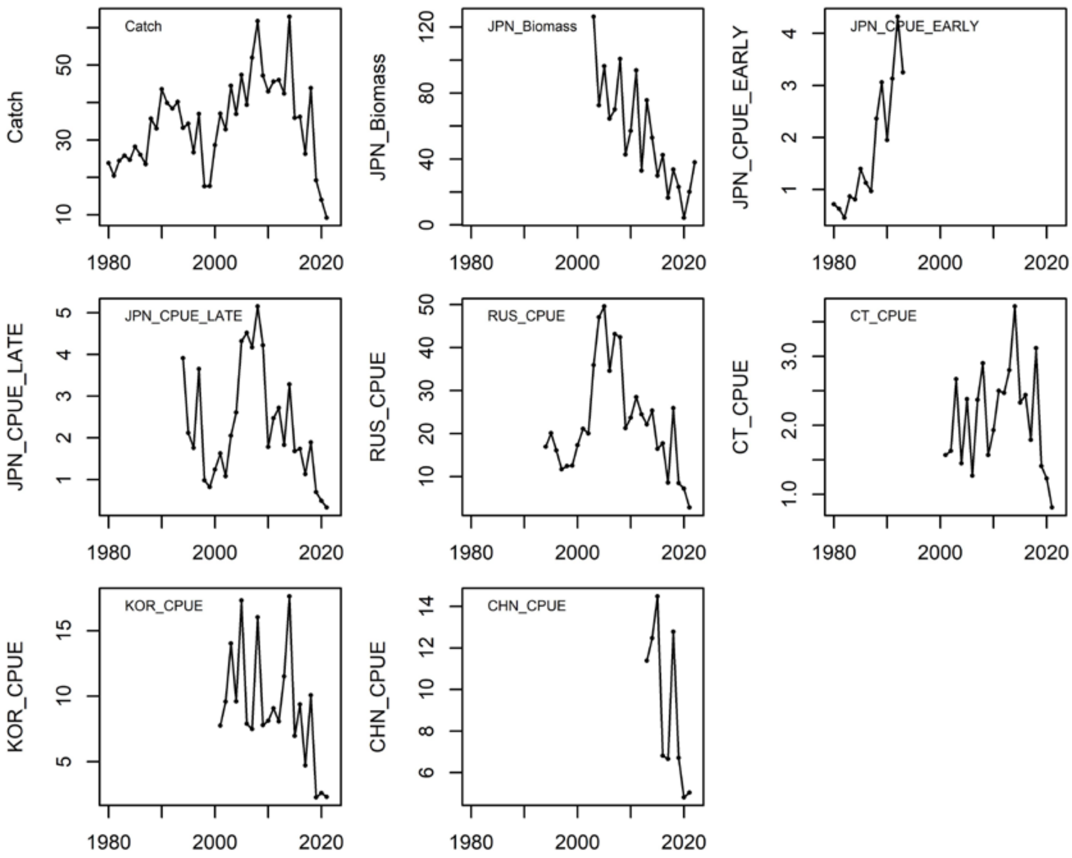


Figure 1. Input data for 2022 Pacific saury stock assessment.

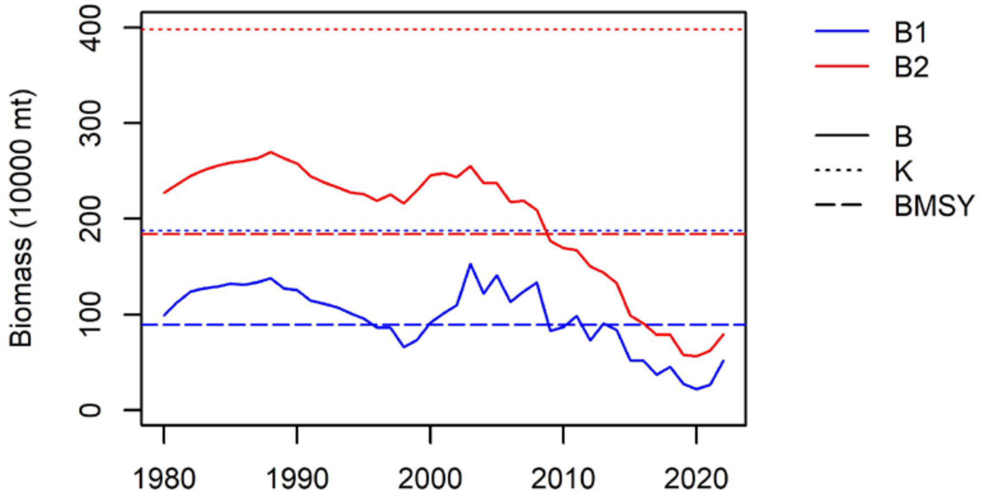


Figure 2. Median biomass over time from each base case scenario (B1-B2).

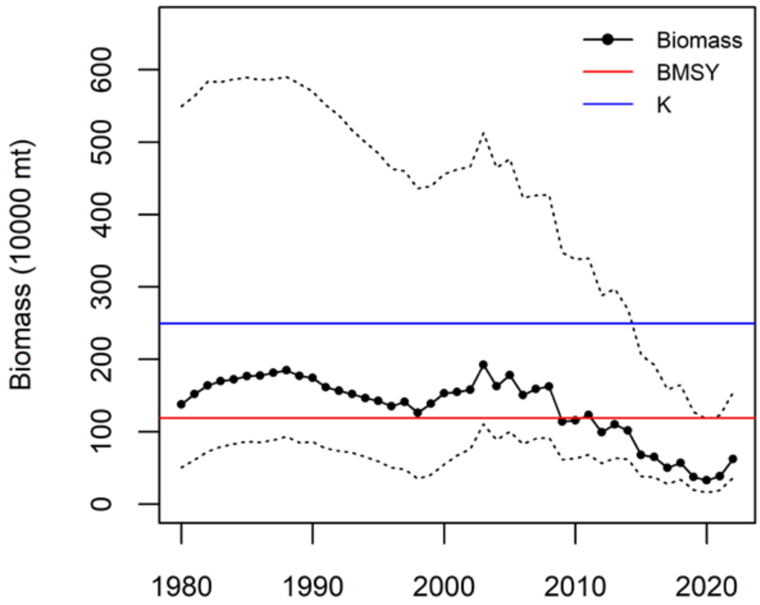


Figure 3. Median biomass and 80% CI over base case scenarios 1-2.

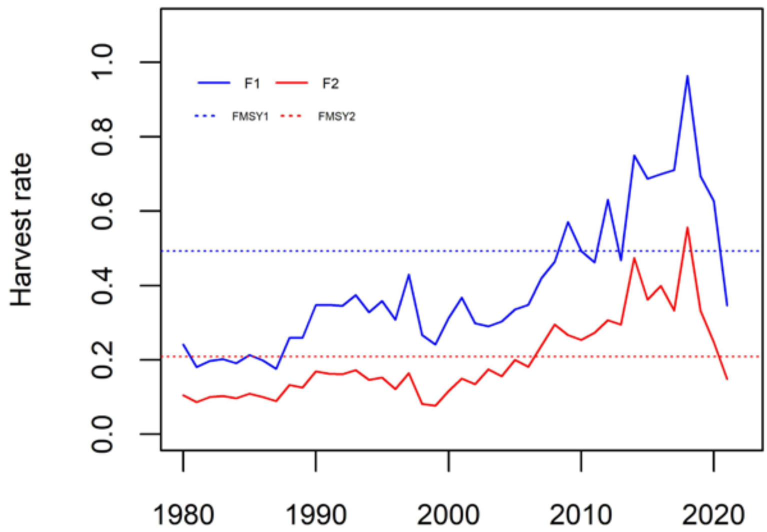


Figure 4. Median harvest rate over time from two base case scenarios (B1-B2).

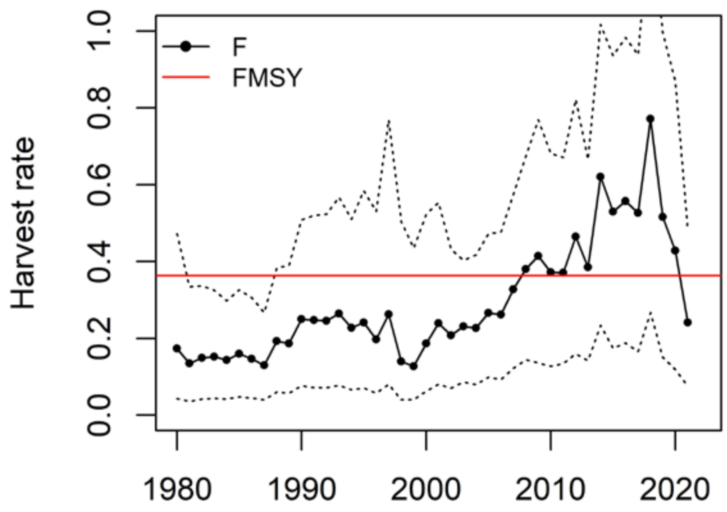


Figure 5. Median harvest rate and 80% CI over base case scenarios 1-2.

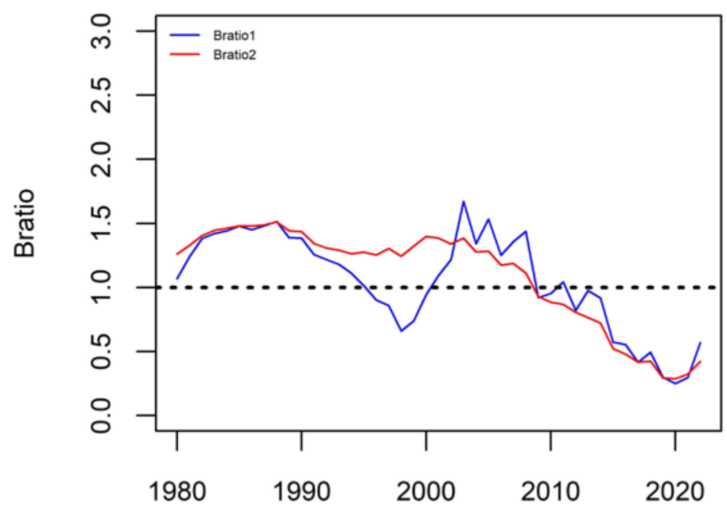


Figure 6. Median Bratio over time from each base case scenario (1-2).

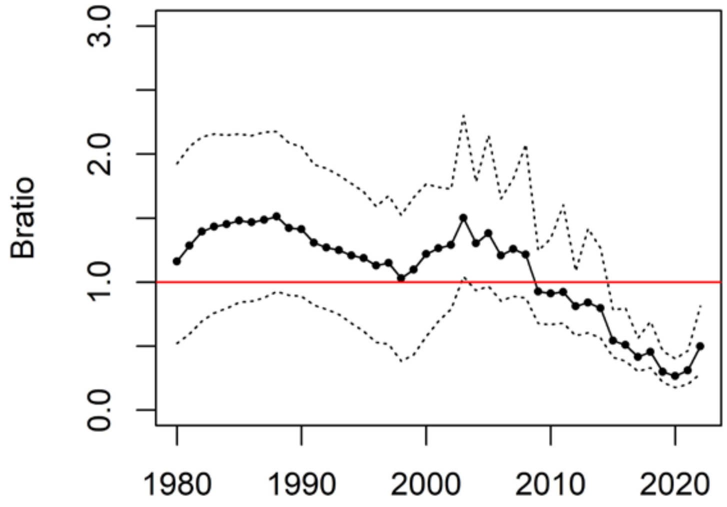


Figure 7. Median Bratio and 80% CI over base case scenarios 1-2.

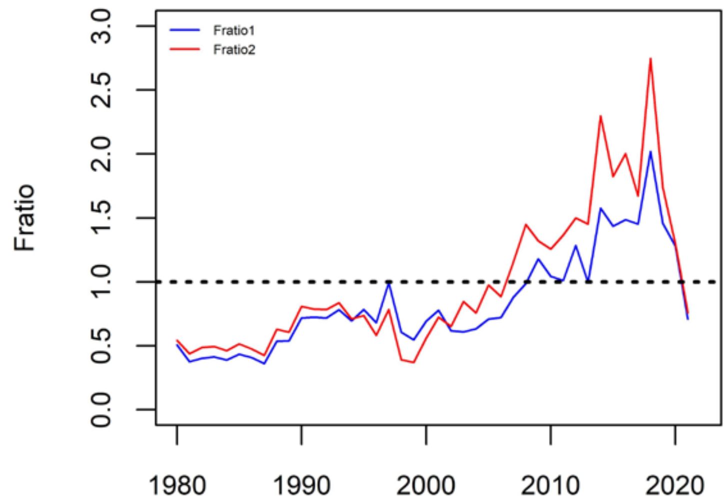


Figure 8. Median Fratio over time from each base case scenario (1-2).

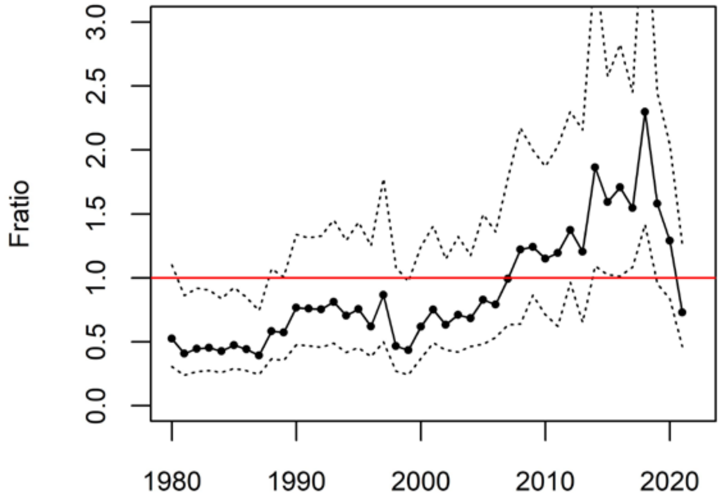


Figure 9. Median Fratio and 80% CI over base case scenarios 1-2.

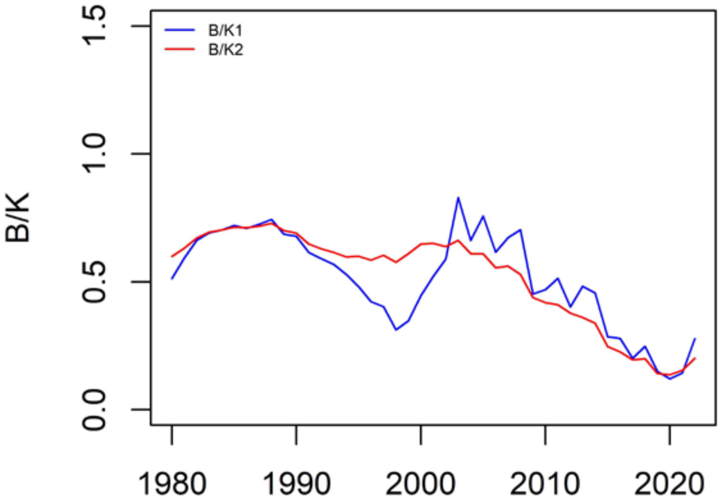


Figure 10. Median B/K over time from each base case scenario (1-2).

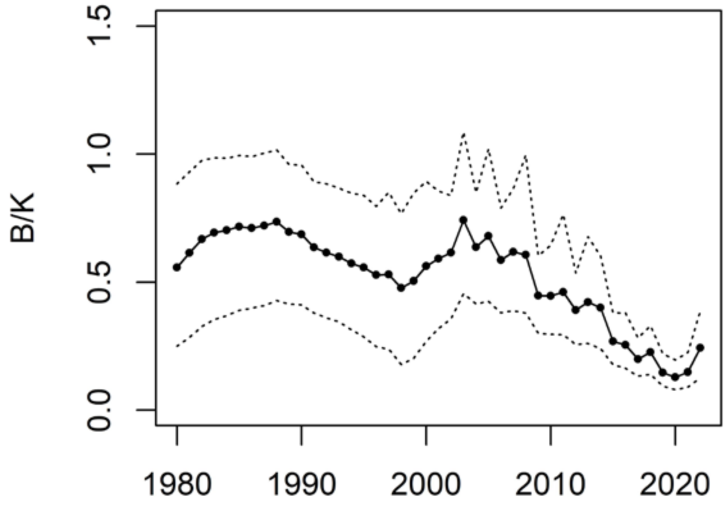


Figure 11. Median B/K and 80% CI over base case scenarios 1-2.

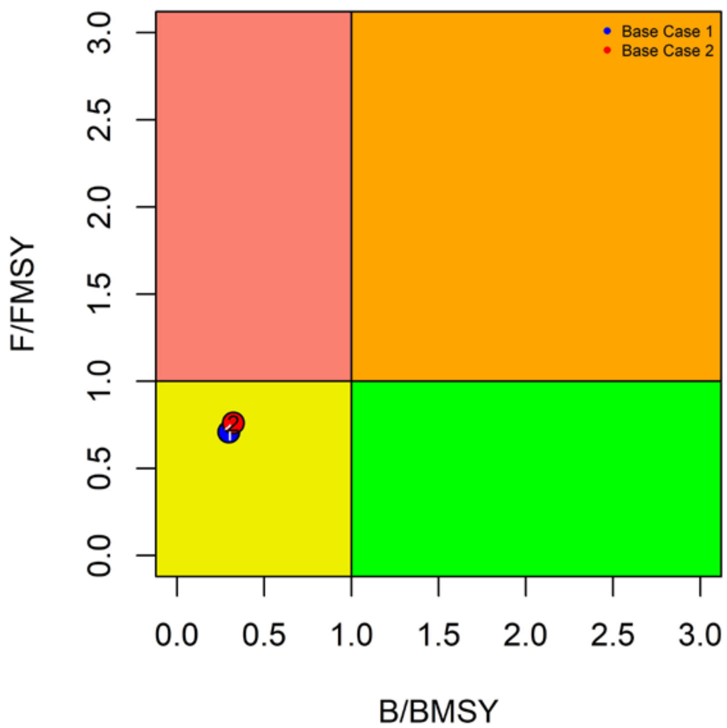


Figure 12. Median Fratio2021 and Bratio2021 calculated from each base case scenario (1-2).

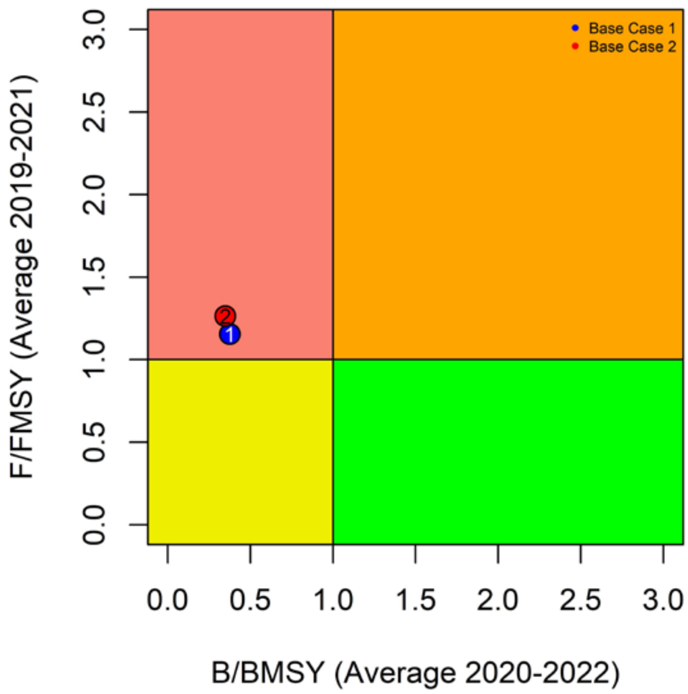


Figure 13. Median Fratio (average from 2019-2021) and Bratio (average from 2020-2022) calculated from each base case scenario (1-2).

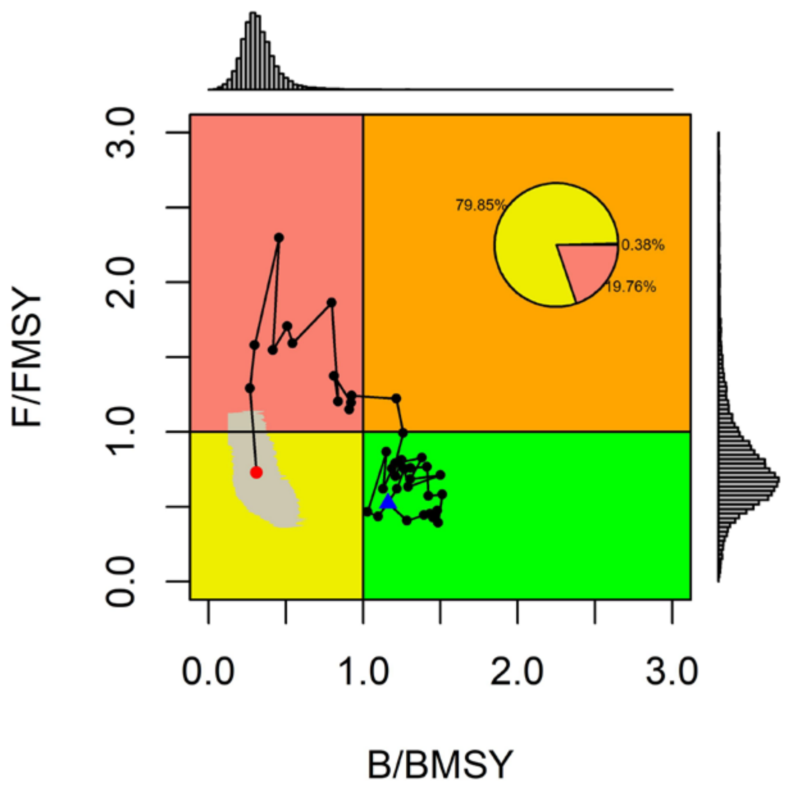


Figure 14. Kobe plot with median Fratio and Bratio time series from 1980 to 2021 over base case scenarios 1-2. The blue dot represents initial year 1980 and the red dot represents the terminal year 2021.

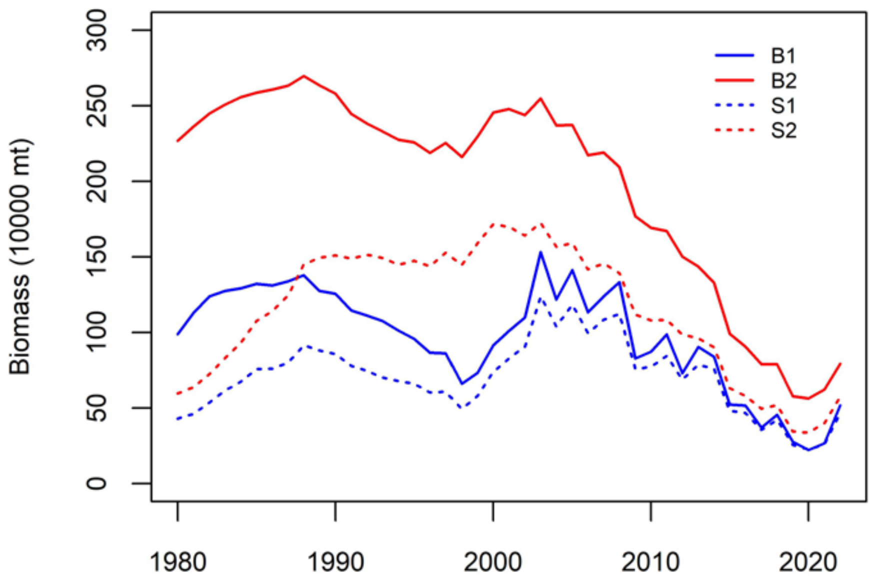


Figure 15. Median biomass over time from each case scenario.

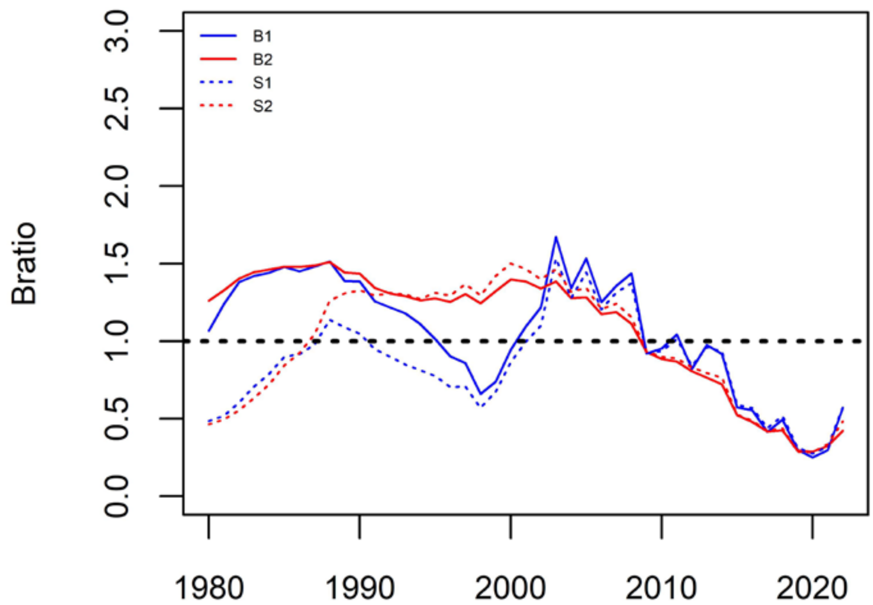


Figure 16. Median Bratio over time from each case scenario.

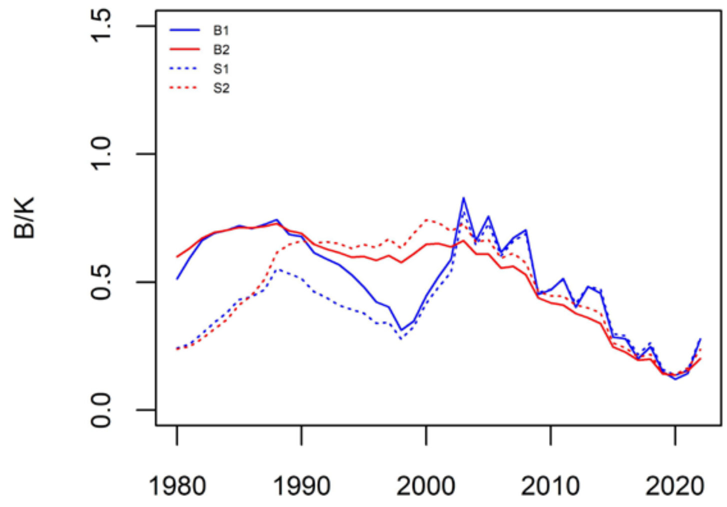


Figure 17. Median B/K over time from each case scenario.

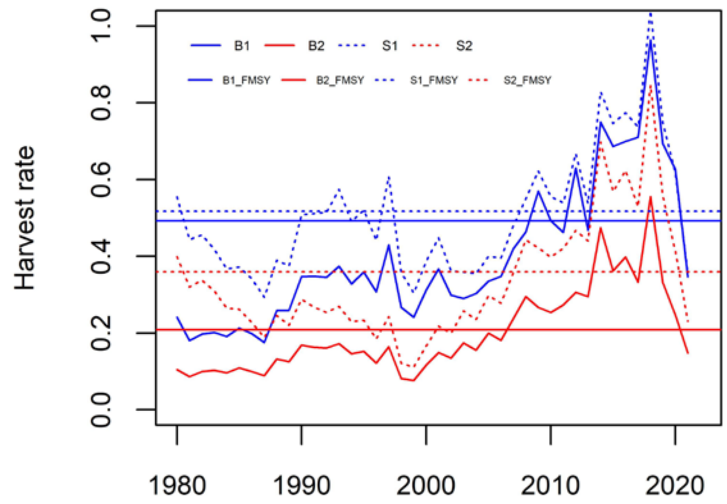


Figure 18. Median F over time from each case scenario.

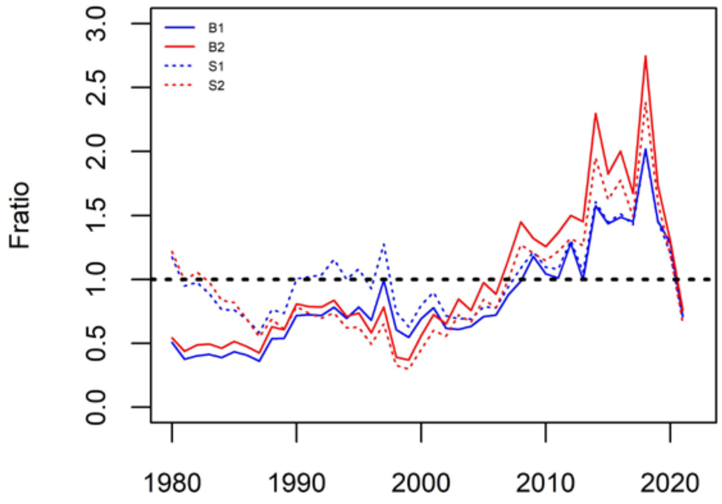
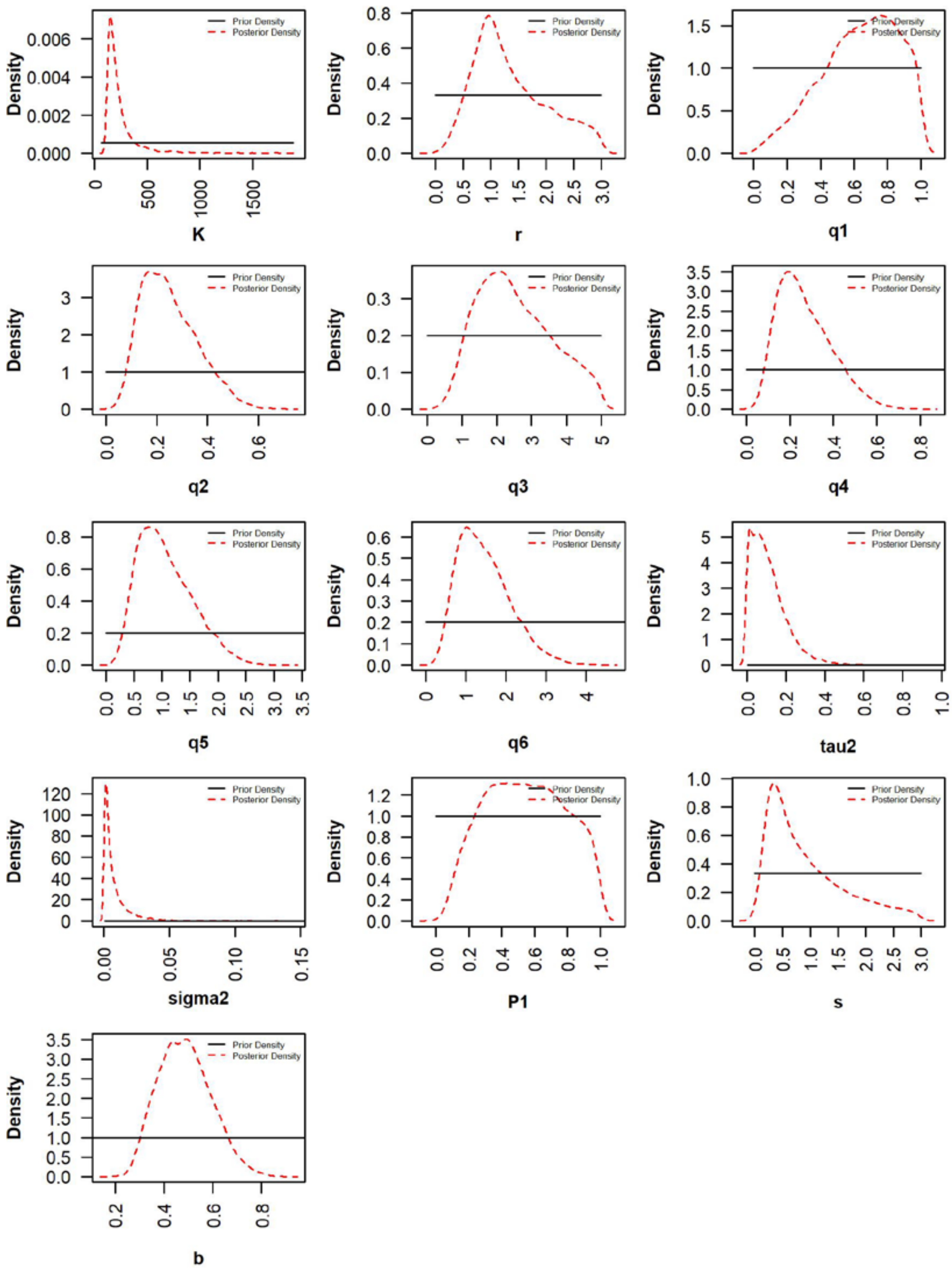
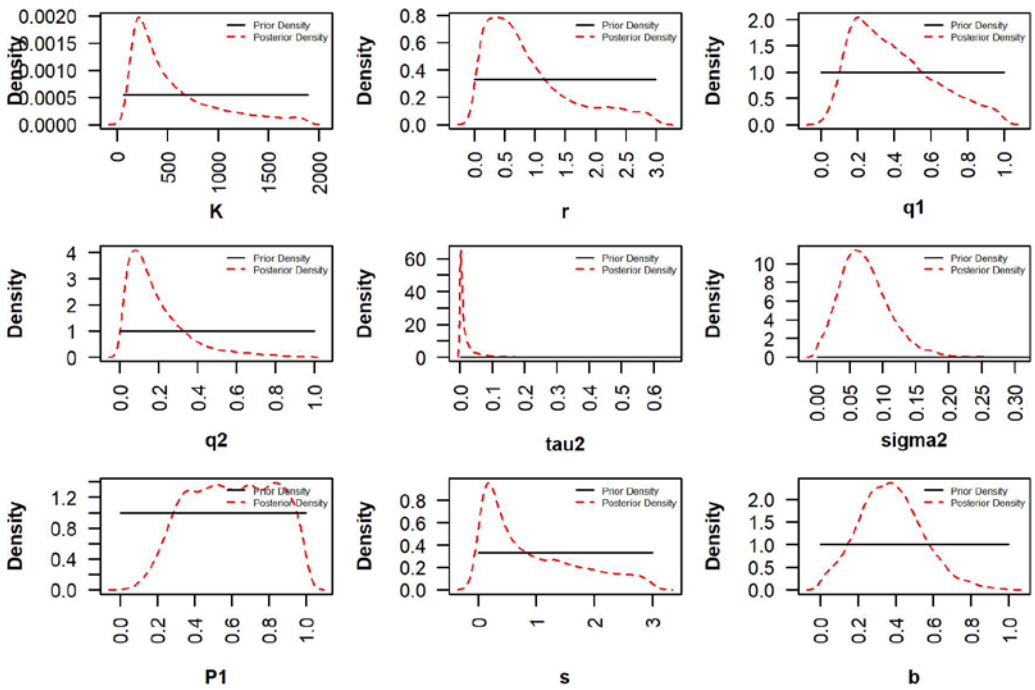


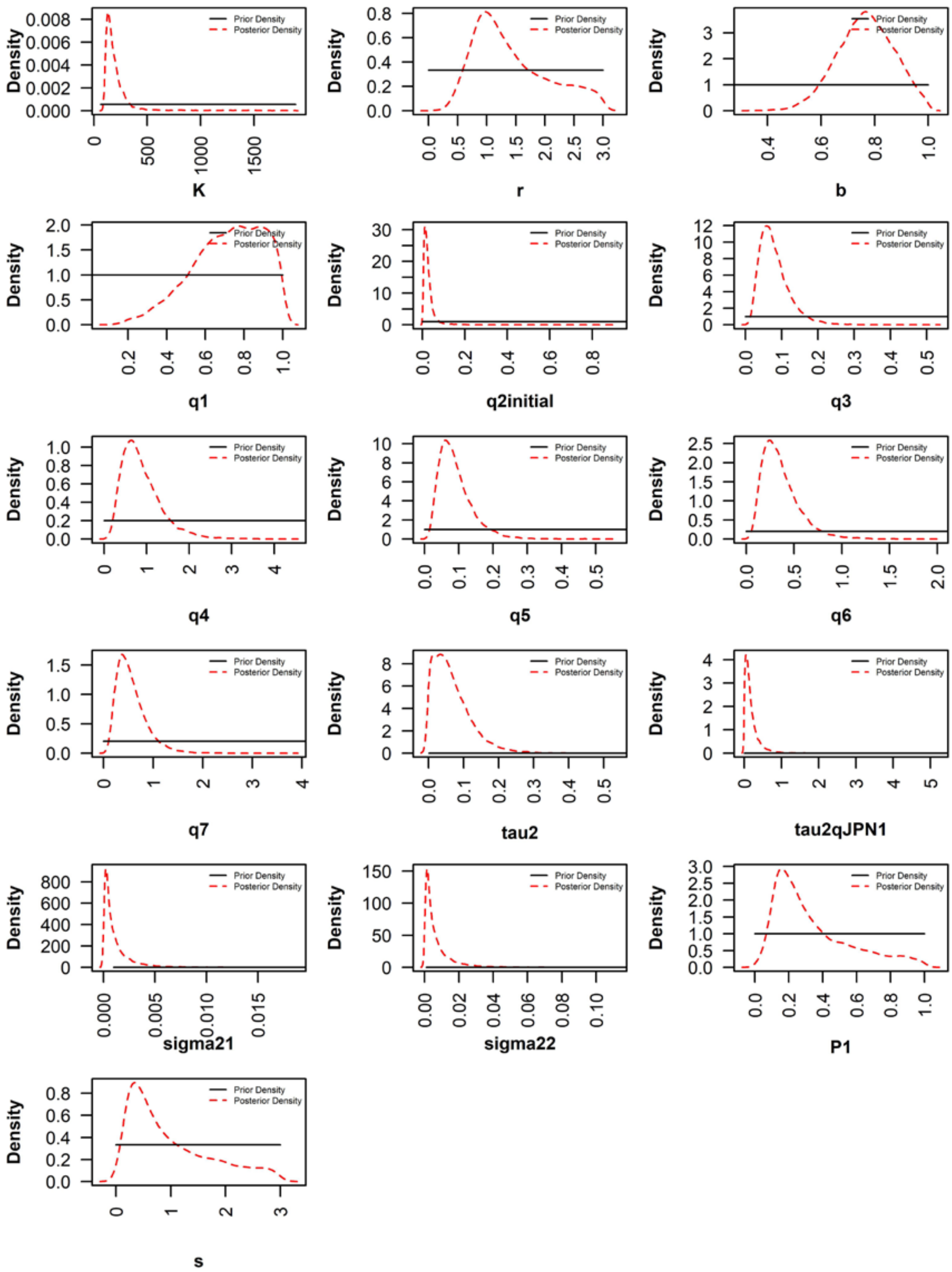
Figure 19. Median Fratio over time from each case scenario.



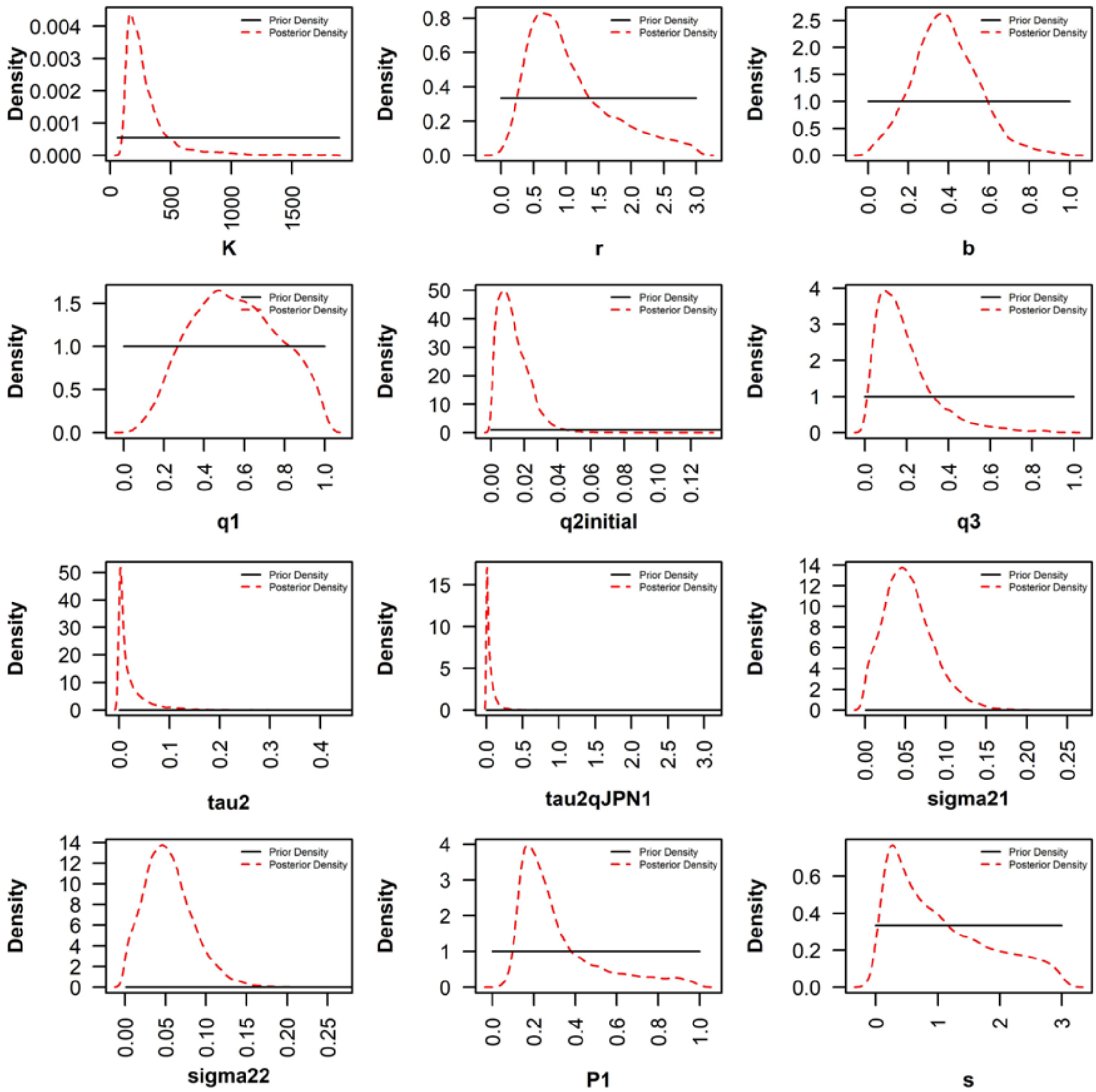
Appendix Figure 1. Prior and posterior distributions of parameters from base case scenario 1. q1 to q6 represent catchability of fishery-independent survey biomass index, Japanese late CPUE, Russian CPUE, Chinese Taipei CPUE, Korean CPUE, and Chinese CPUE respectively. tau2 represents process error variance, sigma2 represents common observation variance of CPUE. P1 represents B1980/K, s represents shape, and b represents hyperdepletion parameter.



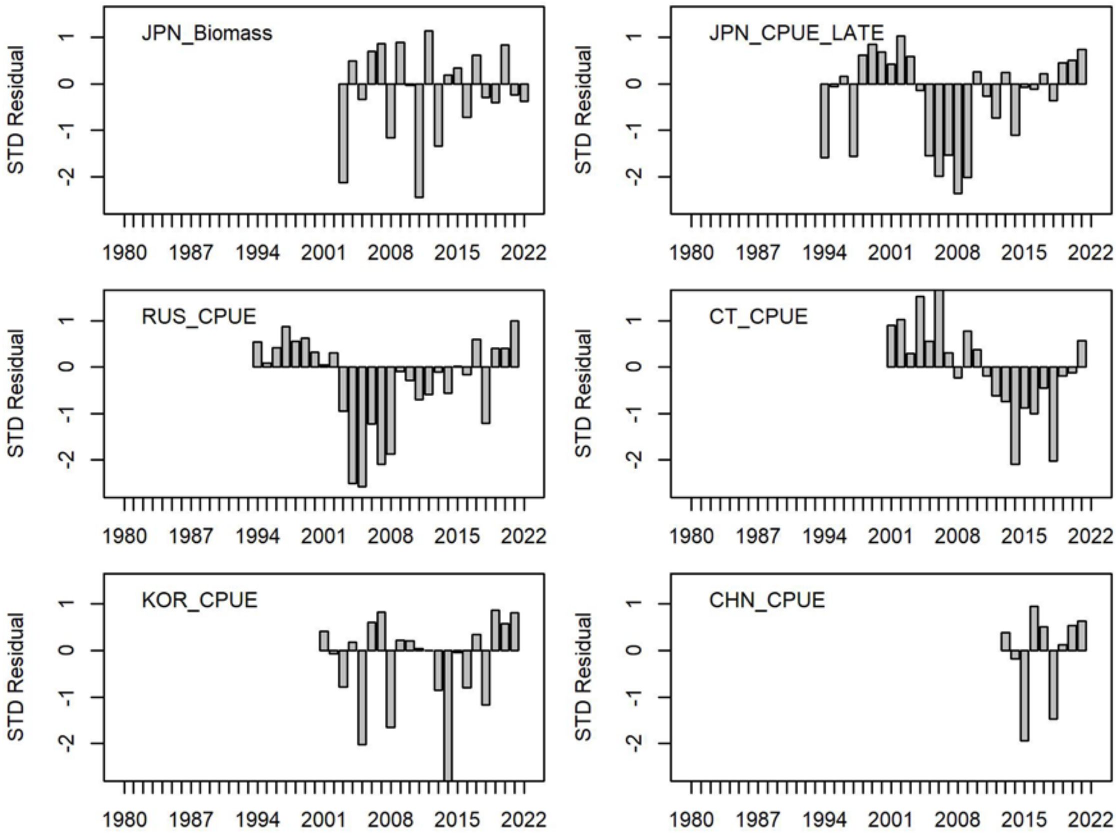
Appendix Figure 2. Prior and posterior distributions of parameters from base case scenario 2. q1 and q2 represent catchability of fishery-independent survey biomass index and joint CPUE respectively. tau2 represents process error variance, sigma2 represents common observation variance of CPUE. P1 represents B1980/K, s represents shape, and b represents hyperdepletion parameter.



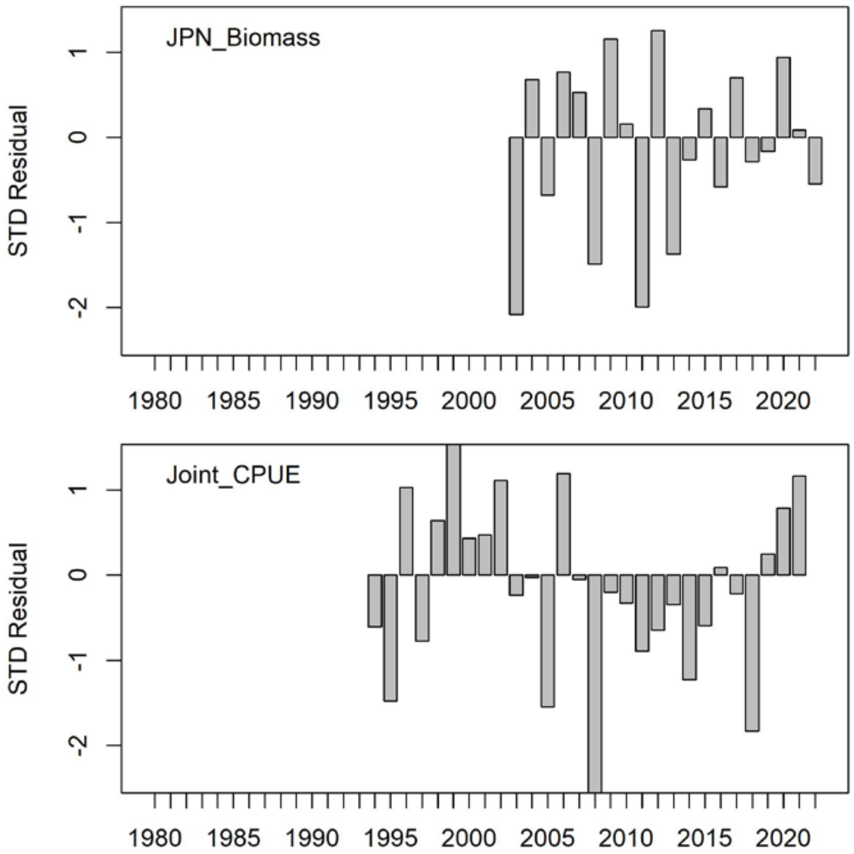
Appendix Figure 3. Prior and posterior distributions of parameters from sensitivity case scenario 1. q1 to q7 represent catchability of fishery-independent survey biomass index, Japanese early CPUE, Japanese late CPUE, Russian CPUE, Chinese Taipei CPUE, Korean CPUE, and Chinese CPUE respectively. q2initial represents q1980. tau2 represents process error variance, tau2qJPN1 represents error variance of Japanese early CPUE, sigma21 represents observation variance of biomass index, and sigma22 represents common observation variance of CPUE. P1 represents B1/K and s represents shape.



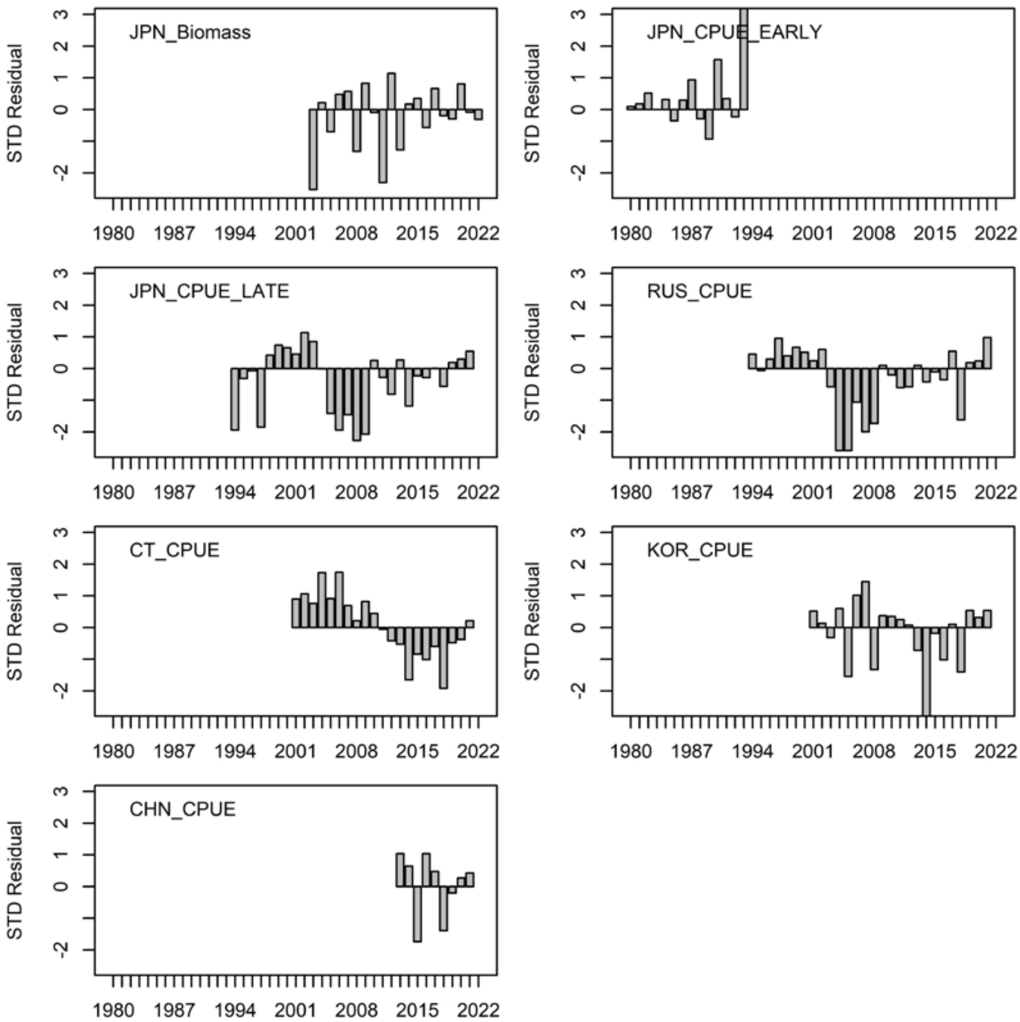
Appendix Figure 4. Prior and posterior distributions of parameters from sensitivity case scenario 2. q1 to q3 represent catchability of fishery-independent survey biomass index, Japanese early CPUE, and joint CPUE respectively. q2initial represents q1980. tau2 represents process error variance, tau2qJPN1 represents error variance of Japanese early CPUE, sigma21 represents observation variance of biomass index, and sigma22 represents observation variance of joint CPUE. P1 represents B1/K and s represents shape.



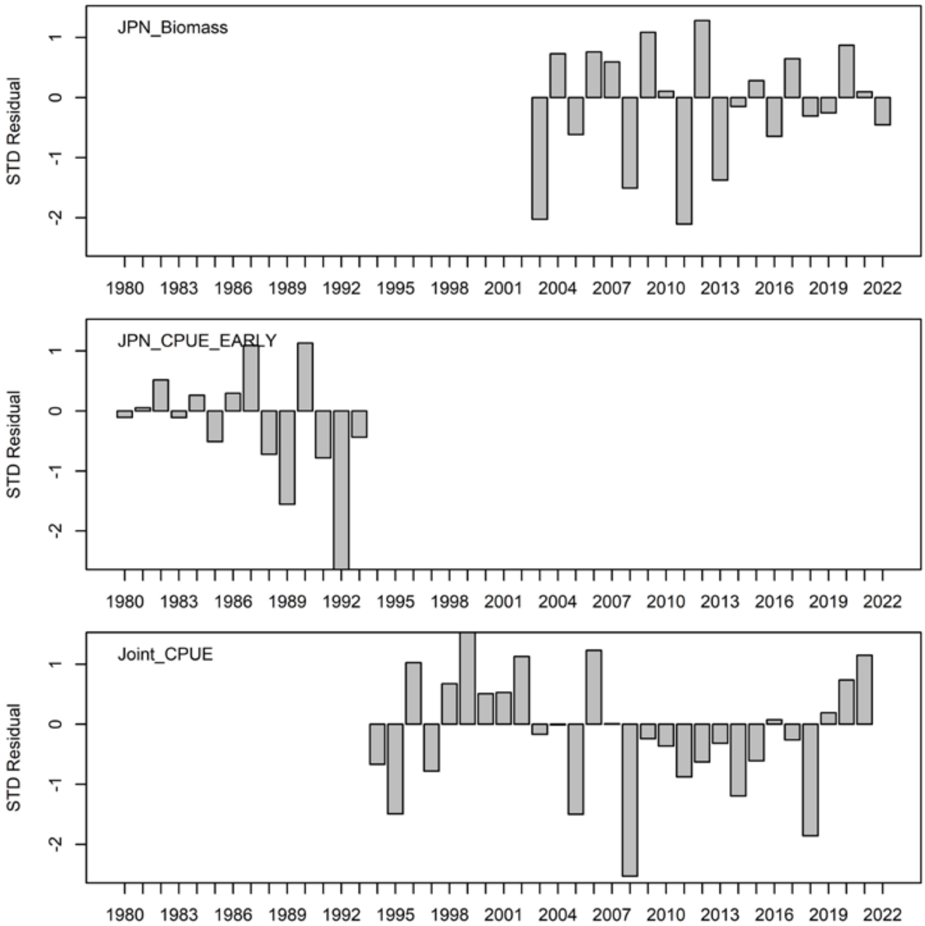
Appendix Figure 5. Standardized residuals between predicted and observed indices from base case scenario 1.



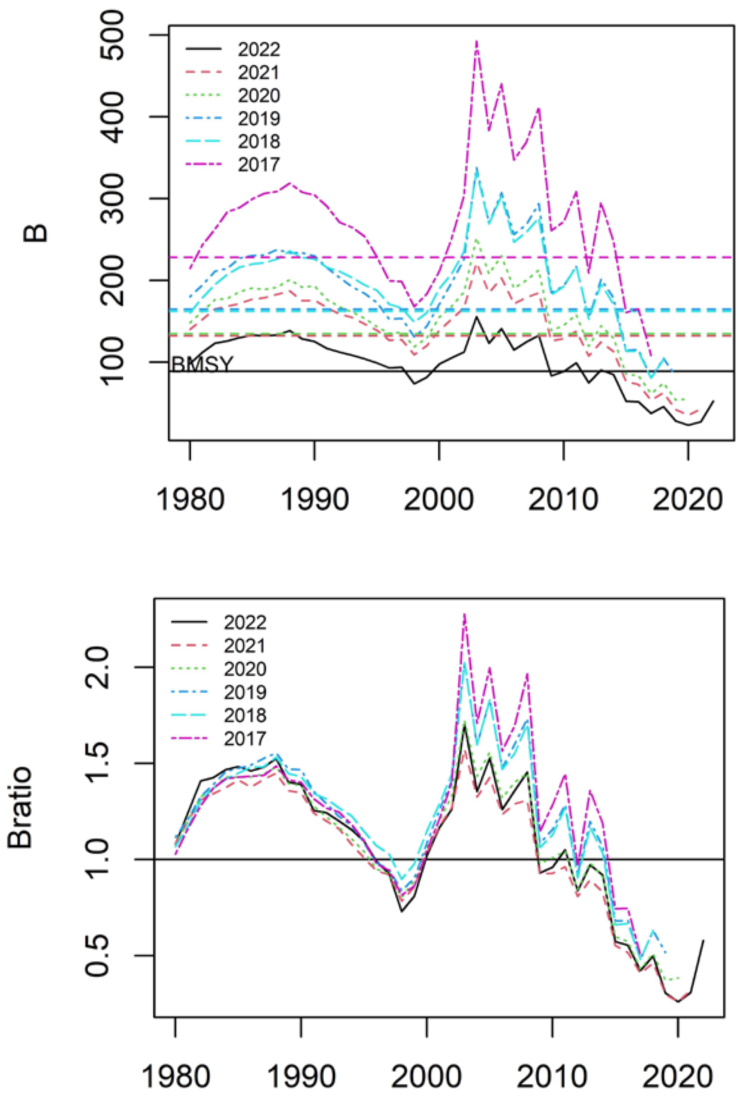
Appendix Figure 6. Standardized residuals between predicted and observed indices from base case scenario 2.



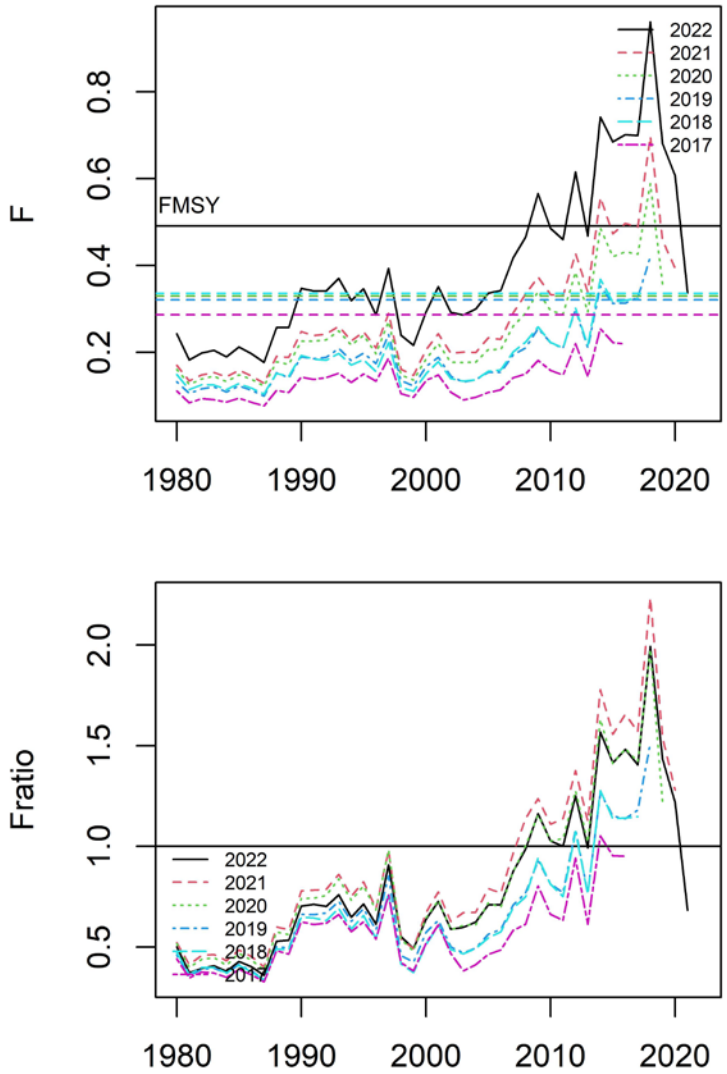
Appendix Figure 7. Standardized residuals between predicted and observed indices from sensitivity case scenario 1.



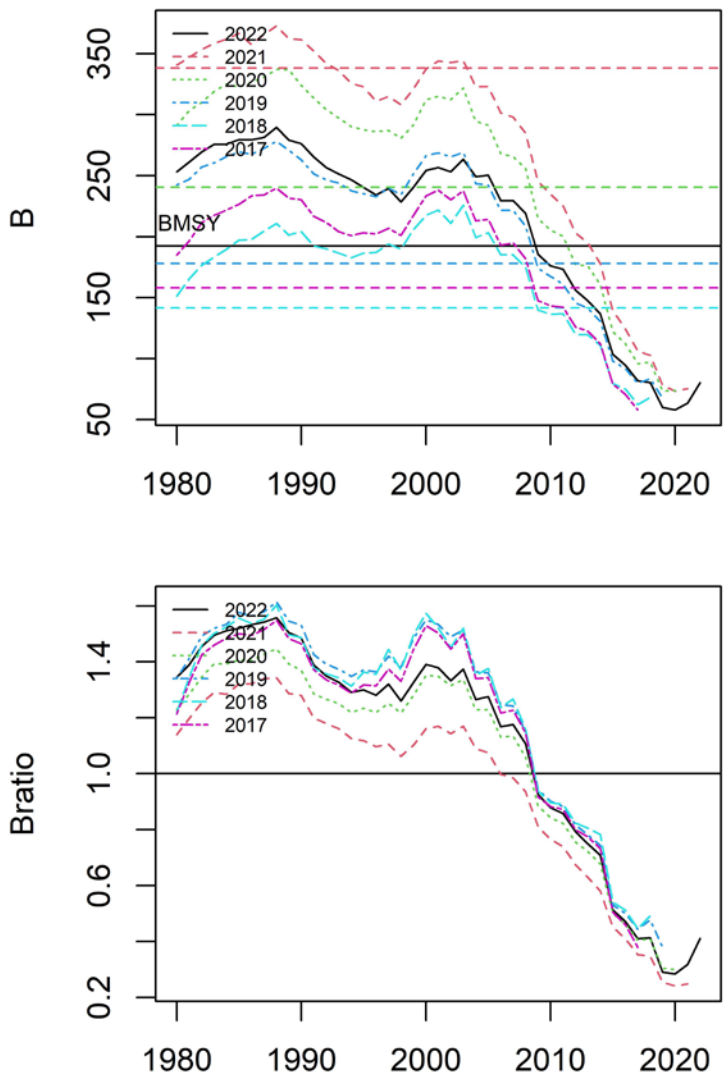
Appendix Figure 8. Standardized residuals between predicted and observed indices from sensitivity case scenario 2.



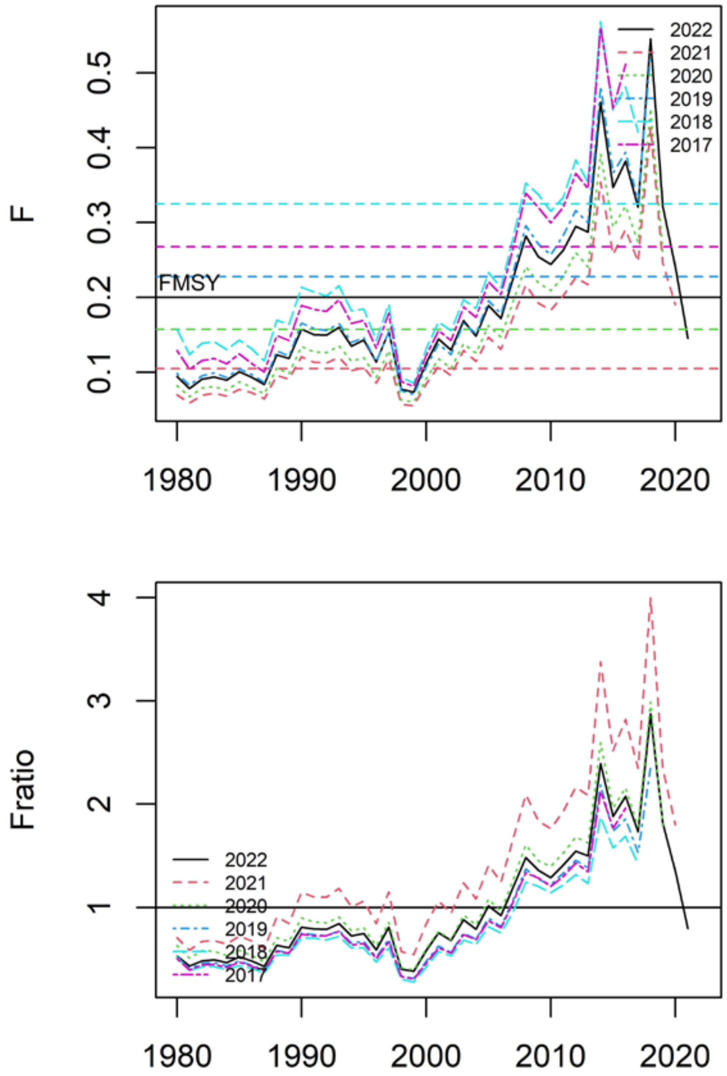
Appendix Figure 9. Time trajectories of biomass and Bratio from a retrospective analysis of base case scenario 1.



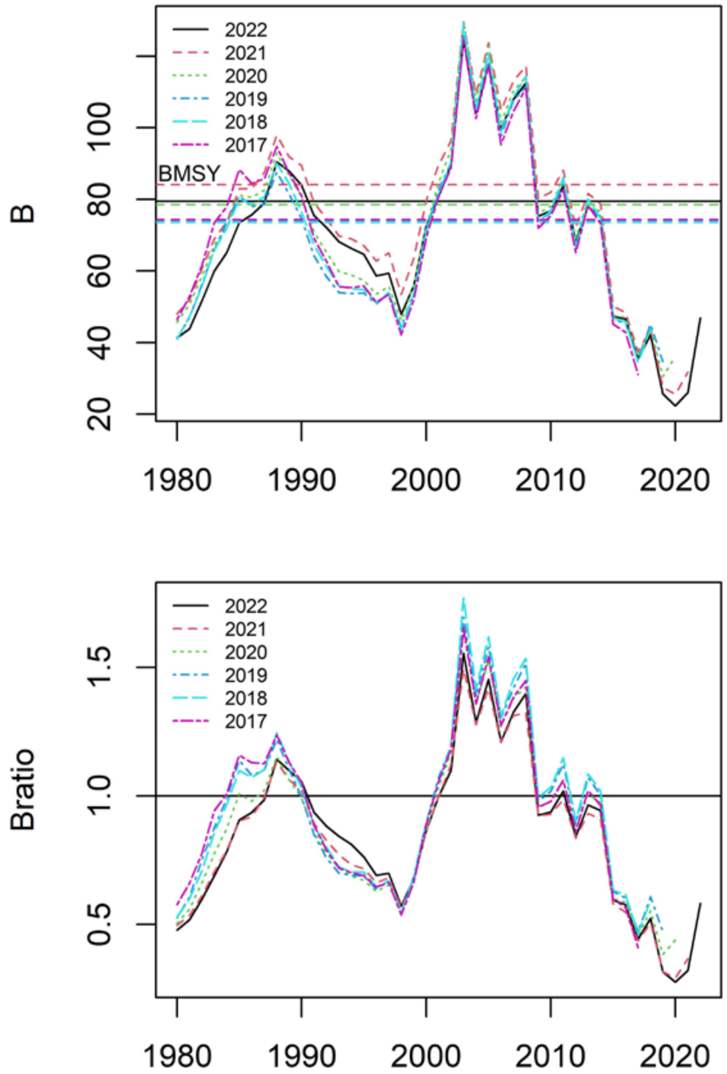
Appendix Figure 10. Time trajectories of harvest rate and Fratio from retrospective analysis of base case scenario 1.



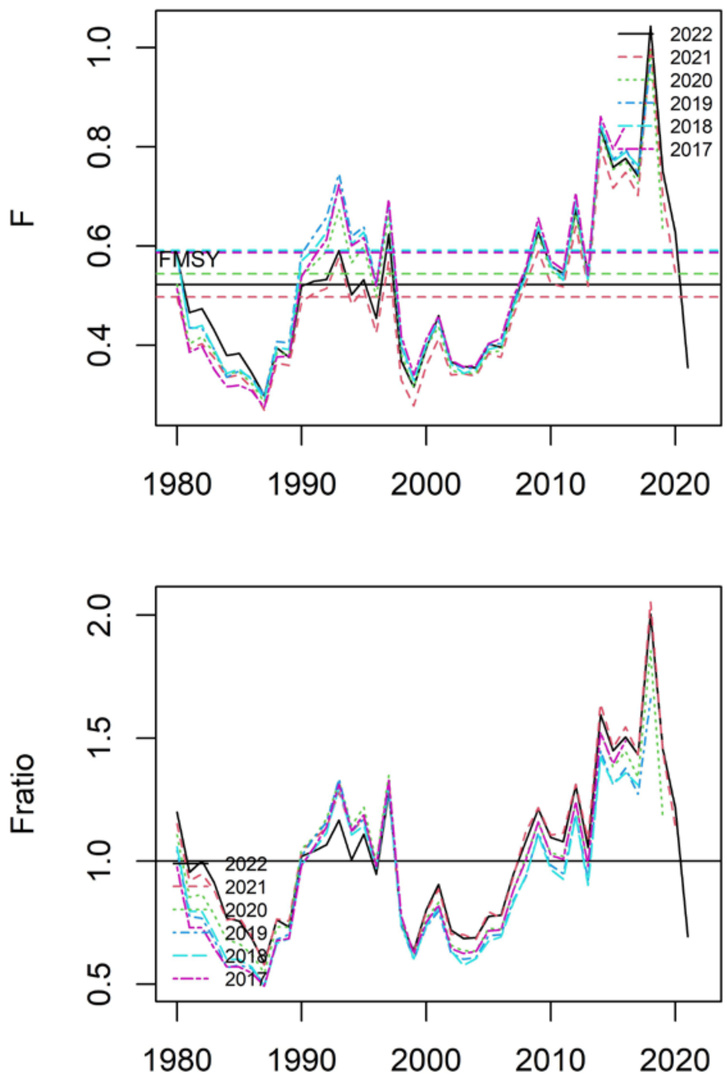
Appendix Figure 11. Time trajectories of biomass and Bratio from a retrospective analysis of base case scenario 2.



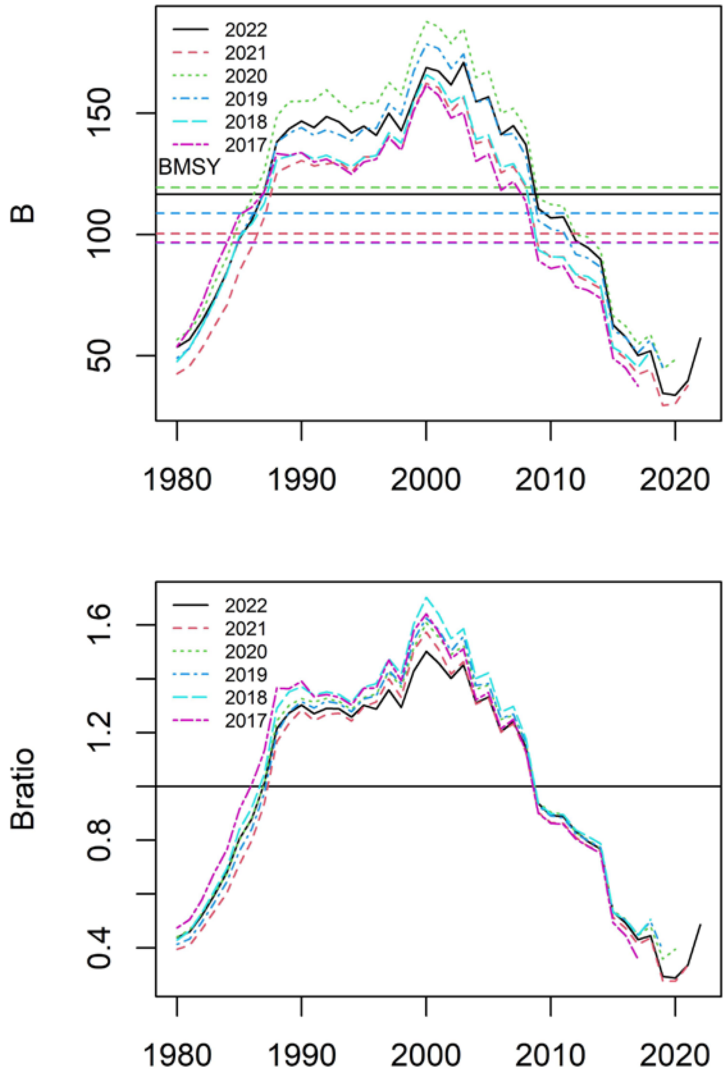
Appendix Figure 12. Time trajectories of harvest rate and Fratio from retrospective analysis of base case scenario 2.



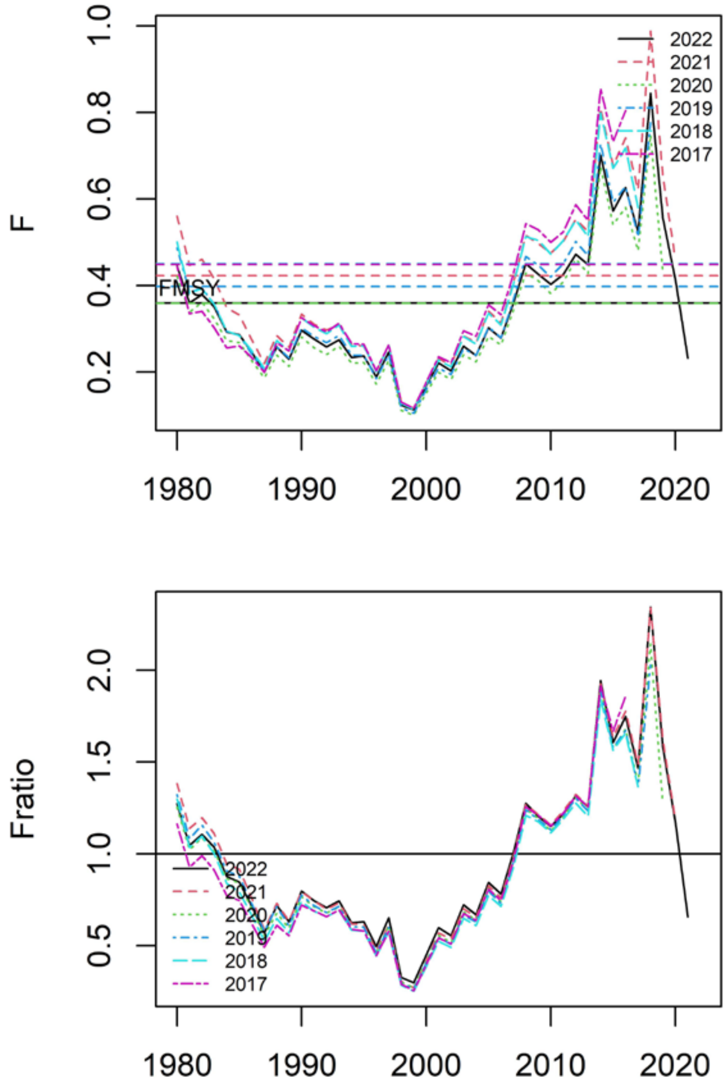
Appendix Figure 13. Time trajectories of biomass and Bratio from a retrospective analysis of sensitivity case scenario 1.



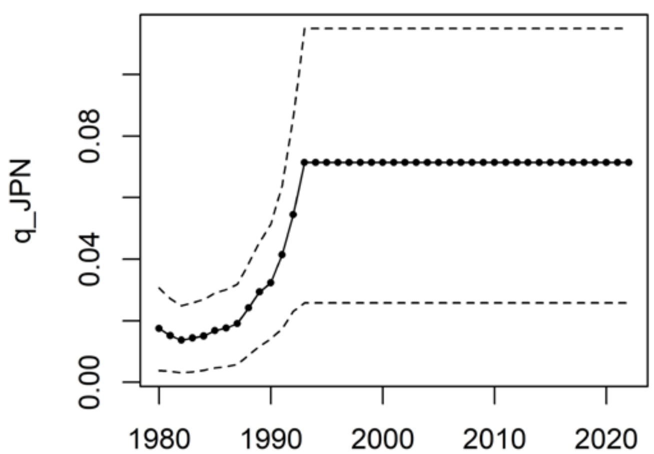
Appendix Figure 14. Time trajectories of harvest rate and Fratio from retrospective analysis of sensitivity case scenario 1.



Appendix Figure 15. Time trajectories of biomass and Bratio from a retrospective analysis of sensitivity case scenario 2.



Appendix Figure 16. Time trajectories of harvest rate and Fratio from retrospective analysis of sensitivity case scenario 2.



Appendix Figure 17. Time-varying catchability of Japanese early CPUE (1980-1994) estimated by a random walk approach (sensitivity case 1).