Research Institute Meeting Report on (Biological) Reference Points for the Pacific Stock of Chub Mackerel (Scomber Japonicus) in FY2019

Responsible Fisheries Research Institute: National Research Institute of Fisheries Science

Abstract

The stock-recruitment relationships and (biological) reference points of this stock were examined using various data on the Stock assessment of the Pacific stock of Chub Mackerel in FY2018. The Stock status of this stock is assessed to be medium based on the spawning stock biomass after the 1970 rohibition season, and that the stock trend is assessed to be increased based on the changes in the spawning stock biomass during the last five years (fishing season of 2013-2017). For this stock, we propose the Hockey Stick (HS) functional type of the stock-recruitment relationship estimated by the least squares method and considering the autocorrelation of recruitment residuals as a candidate for the stock-recruitment function. SBmsy (1.54 million tons) as a candidate for the target reference point, SB0.6msy (560,000 tons) as a candidate for the limit reference point, and SB0.1msy (70,000 tons) as a candidate for the fishing ban level. The catch rate (catch / Biomass) for achieving the MSY is 10%, and the fishing pressure for achieving the MSY is 0.43 times the current fishing pressure (Fcurrent, average fishing pressure from 2015 to 2017 fishing season).

1. Stock-recruitment relationships

1-1) Data set to be used

Data set	Basic information, related surveys, etc.
Biomass / Spawning Stock Biomass	FY2018 evaluation of fishery stock in waters around Japan (Japan Fisheries Agency and Japan Fisheries Research and Education Agency)

1-2) Examination of stock-recruitment relationships

The parameters for model selection are shown in the table below for each candidate cited as the stock-recruitment (S-R) relationship of this stock. Values from 1970 to 2017 were used as the data. In both the least squares method and least absolute value method, the Hockey Stick (HS) model had a slightly lower AICc than the Ricker (RI) and Beverton Holt (BH) models. Since the density effect of BH and RI is weak, SBmsy greatly exceeds the estimated value of Spawning Stock Biomass so far, so HS was used in the following analysis to set realistic targets. Although the AICc was lower in the least absolute value method than in the least squares method, a diagnosis of the S-R relationship showed that no major problem was found when using the least squares method (Supplementary Figure 1-2), therefore, the results of the least squares method were used in the following analyses. Since the autocorrelation coefficient of the residual was significant, the S-R relationship in which the autocorrelation coefficient was estimated from the residual was examined. The autocorrelation coefficient was 0.38, and the SD of recruitment variation other than autocorrelation was 0.84.

Stock-recruitment relationship	Optimization method	AICc	ΔAIC	SD	Number of data
HS	Least absolute value method	128.48	0.00	0.93	48
RI	Least absolute value method	129.35	0.88	0.93	48
BH	Least absolute value method	129.36	0.88	0.93	48
HS	**Least squares method**	**130.91**	**2.44**	**0.88**	**48**
BH	Least squares method	131.34	2.87	0.89	48
RI	Least squares method	131.35	2.87	0.89	48

* Stock-recruitment relationship recommended as a candidate is in bold text

1-3) Candidates for stock-recruitment relationships

As a candidate for the S-R relationship of this stock, we propose the Hockey Stick model (Figure 1) optimized by the least squares method, with autocorrelation taken into account for the residuals.

2. (Biological) Reference Points

2-1) Data set and calculation method

For the Stock calculation methods, numbers in the stock, fishing mortality, maturity rate, natural mortality, average weight, etc. by age during the 1970-2017 fishing season, and for the selectivity, maturity rate, natural mortality, average weight, etc. by age in the future projection, the values in the FY2018 fishery Stock assessment of the waters around Japan (Japan Fisheries and Fishing Research Agency) were used. The selectivity in future projection is based on the average fishing mortality over the last 10 years (2008-2017 fishing season). The Fcurrent in the stock assessment of this population stock in FY2018 uses the average of the last three years (2015-2017 fishing season), taking into account the increase in the catch by foreign fishing vessels. However, the age composition of catches by foreign fishing vessels is unknown, so the uncertainty of the selectivity in recent years is considered to be large. Since (biological) reference points such as SBmsy are medium-to-long term targets, the selectivity was obtained from the average number of catches by age over the past 10 years. At this time, Fcurrent was adjusted so that %SPR was consistent with the FY2018 Stock assessment. As a result, the fishing mortality by age for Fcurrent increased smoothly from 0 years to 6+ (Figure 2).

The maturity rate and average weight were the values for 2018. In this stock, the average weight decreased and maturity was delayed with the increase in biomass, and similar trends are expected for the levels of biomass and Spawning Stock Biomass (SSB) that achieve MSY; therefore, the most recent values are used.

Age	Average weight (g)	Maturity rate	Fishing mortality	Selectivity
0	94	0	0.03	0.04
1	202	0	0.11	0.14
2	264	0.2	0.23	0.29
3	316	0.8	0.42	0.53
4	349	1	0.44	0.55
5	529	1	0.80	1.00
6	645	1	0.80	1.00

Under the above conditions and the S-R relationship used, future projection were made, and the fishing mortality Fmsy at which the expected catch at equilibrium was maximized, was estimated. The equilibrium was established at approximately 50 years after the start of future projection, the expected catch when fishing is conducted at Fmsy was set as the MSY (Maximum Sustainable Yield), and the expected value of the SSB was set as SBmsy. The simulation, in which the residual value of recruitment is given as a lognormal (distribution) and the average recruitment is corrected, was repeated 5,000 times, and the Fmsy that maximized the expected catch 50 years later was estimated.

2-2) Stock-recruitment relationship used

The Hockey Stick model (HS) considering the autocorrelation optimized by the least squares method is used as the S-R relationship equation, and the relationship between the recruitment (R), spawning stock biomass (SB), and the parameters is expressed by the following equation.

$$\hat{R}_y = \begin{cases} a \times SB_y & \text{if } SB_y < b \\ a \times b & \text{if } SB_y \geq b \end{cases}$$

$$\log(R_y) = \begin{cases} \log(\hat{R}_y) + \varepsilon_y & \text{if } y = 1970 \\ \log(\hat{R}_y) + \rho \times [\log(R_{y-1}) - \log(\hat{R}_{y-1})] + \varepsilon_y & \text{if } y > 1970 \end{cases}$$

The parameters are shown in the table below, and the relationship between the past SSB (tons) and recruitment (millions) is shown in Figure 1.

Stock-recruitment relationship equation	Optimization method	Autocorrelation	*a*	*b*	SD	*ρ*
HS	Least squares method	Yes	0.00758	1,056,000	0.837	0.375

Here, parameter *a* is the steepness (million / ton) of the HS stock-recruitment curve from the origin to the break point, and *b* is the SSB (ton) at the break point.

2-3) (Biological) Reference Points

In this stock, the SSB (SBmsy) at the MSY level is set as the standard value for the target reference point, the SSB (SB0.6msy) at which 60% catch of MSY can be obtained is set as the limit reference point, and the SSB (SB0.1msy) at which 10% catch of MSY can be obtained is set as the fishing ban level. The below table shows the biomass at each level.

(Biological) Reference Points	Spawning Stock Biomass	Standard
Target Reference Point (SBtarget)	1.54 million tons	SBmsy
Limit Reference Point (SBlimit)	560,000 tons	SB0.6msy
Fishing ban level (SBban)	70,000 tons	SB0.1msy

Table 1 shows the reference values for this stock, and Figure 3 shows the SSB and the average catch by age with reference to this at equilibrium (after 50 years) in the future projection using the S-R relationship. The target reference point was slightly higher than the past maximum SSB of 1.4 million tons, but it is predicted that the maximum SSB will be updated due to the recent occurrence of the predominant class. The target reference point was equivalent to 46% of the SSB at equilibrium (SB0) when there is no fishing. The limit reference point was slightly higher than the current 450,000 tons, but there is no significant deviation. The fishing ban level was 70,000 tons, which was higher than the lowest ever SSB of 44,000 tons (2002 fishing season). As a sensitivity analysis, Supplementary Material 2 shows the calculation results of the (biological) reference points when the Fcurrent, the number of years simulated, and the S-R relationship are changed.

2-4) Target Reference Point and Exploitation Rate

Figure 4 shows the Kobe plots when the target reference point is set as the standard value. In this stock, the SSB was lower than the target reference point SBmsy in every year after the 1970 fishing season, and the exploitation rate exceeded Umsy, for achieving MSY, in all years except the 2014 fishing season.

2-5) Harvest Control Rules

Figure 5 shows the relationship between SSB and fishing mortality (*F*) for the Harvest Control Rules (HCRs) when the standard values are used for the target reference point, limit reference point, and fishing ban level, and the standard value of 0.8 is used for β.

2-6) Future projection of Stock based on Harvest Control Rules

（1） When a standard value is used for the (Biological) Reference Point

Figure 6 shows the changes in the biomass, SSB, catch, recruitment, and exploitation rate when the standard values are used for the target reference point, limit reference point, and fishing ban level, and the standard value of 0.8 is used for β. In addition, catch control will start from the 2020 fishing season, and the catches for the 2018 and 2019 fishing seasons are provisional values when the *F* is Fcurrent.

With the emergence of the predominant class group in recent years, the SSB has increased significantly and is expected to exceed SBtarget. The catch increased significantly during the 2018 and 2019 fishing seasons when fishing was conducted at Fcurrent, but will decrease significantly after the 2020 fishing season when the HCRs are applied. However, the catch in the 2020 fishing season depends on the catch in the 2018 and 2019 fishing season (see Supplementary Material 3). With the predominant class group reaching maturity in recent years, the SSB greatly increases, and thereafter, the expected SSB gradually decreases.

（2） When tuning parameter β is changed

Tables 2 to 5 show the probability of achieving the target reference point, the probability of achieving the limit reference point, the average SSB, and the average catch when β is changed between 0.1 and 1.0 in the future projection. The higher the β of the SSB, the higher the expected catch, but the lower the probability of achieving the target. The probability of achieving the target reference point in 2030 was 49% when β was 1, but exceeded 50% if β was 0.9 or less (β = 0.9: 53%, β = 0.8: 58%). The reason why the value is below 50% when β = 1.0 is that the average value (SBmsy) is higher than the median value because the bottom part of the probability distribution of the SSB, when fishing is conducted at Fmsy, extends to the right.

3. Summary

Regarding the S-R relationship of this stock, since only a weak density effect was observed within the observation range of the data and the effect of autocorrelation was large, the least squares method was used as the optimization method, and HS with autocorrelation taken into account for residuals was used. For each management standard, the target reference point SBtarget is defined as the stock status that achieves MSY, so SBmsy estimated from this S-R relationship was used, and the limit reference point and the fishing ban level were set to the standard values SB0.6msy and SB0.1msy, respectively. SBmsy is higher than the largest SSB ever, and the SSB has never reached SBmsy since the 1970 fishing season when stock assessment started. The exploitation rate Umsy for achieving the MSY was 10%, and the exploitation rate was higher than Umsy in all years except the 2014 fishing season. In order to achieve MSY, it is necessary to reduce the current fishing pressure (effort) to about 43%. When a future projection was made based on these (biological) reference points, if the multiplier β for Fmsy is 0.8, which is the standard value, the probability of exceeding the Target Reference Point, 10 years after applying the HCRs, was predicted to be 50% or more.

4. Future considerations

This stock is a fish species subject to stock assessment by the North Pacific Fisheries Commission (NPFC), and in the future, data such as the number of catches by age in recent years is likely to change by the clarification of the details of catches by foreign vessels. Also, given the high uncertainty of the number of catches by age and the estimated recruitment in recent years, it is possible that the current stock assessment method will shift to a State-Space Stock assessment model. The impact of these changes on S-R relationships and (biological) reference points is a matter for future study.

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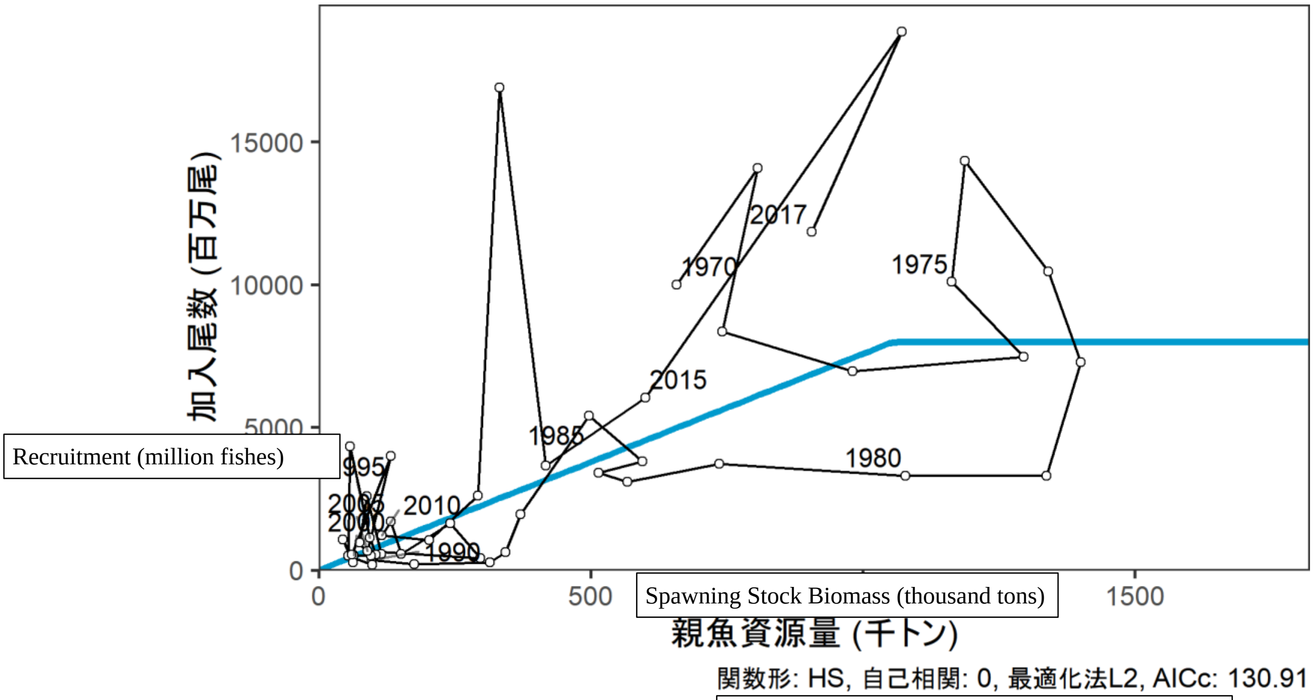

S-R relationship: HS, autocorrelation: 0
Optimization methodL2, AICc: 130.91

Figure 1. Stock-Recruitment relationship

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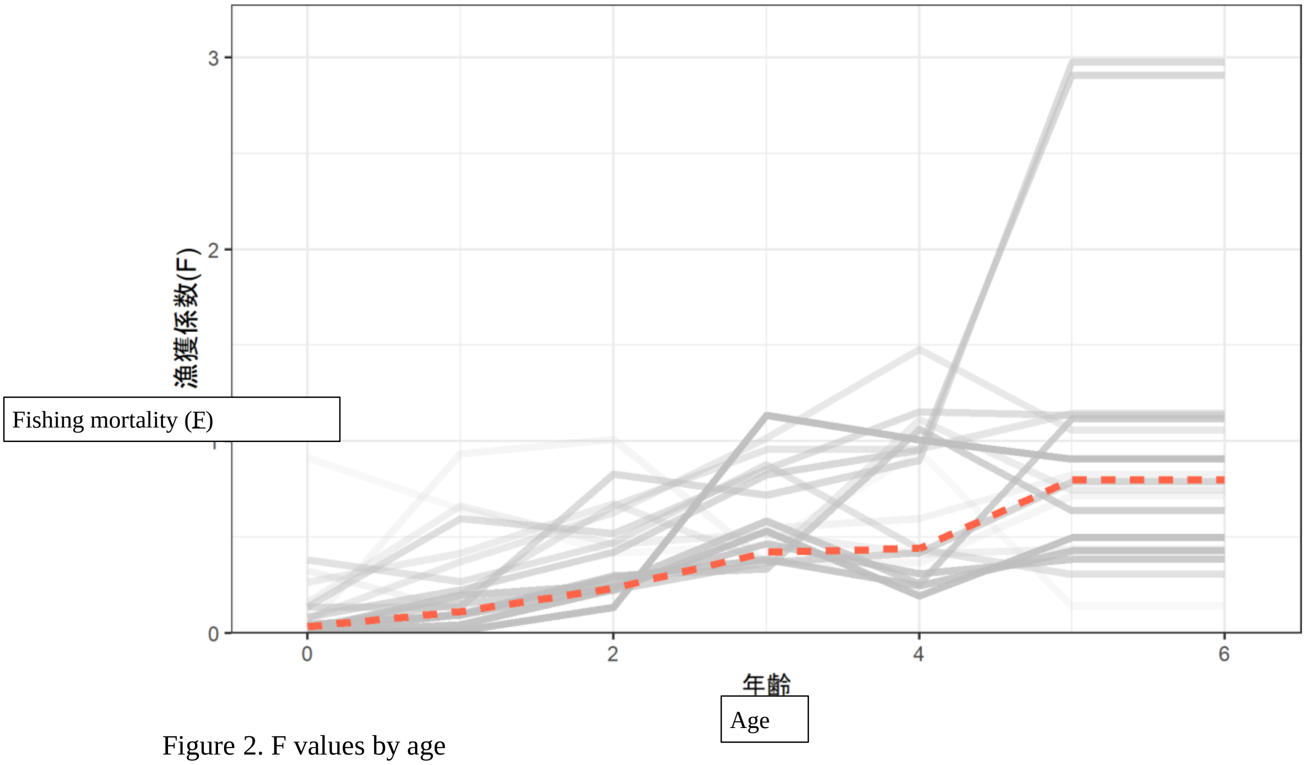


Figure 2. F values by age

The red dotted line shows the values used for future projection, and the solid gray line shows the values for each year in the 2002-2017 fishing season.

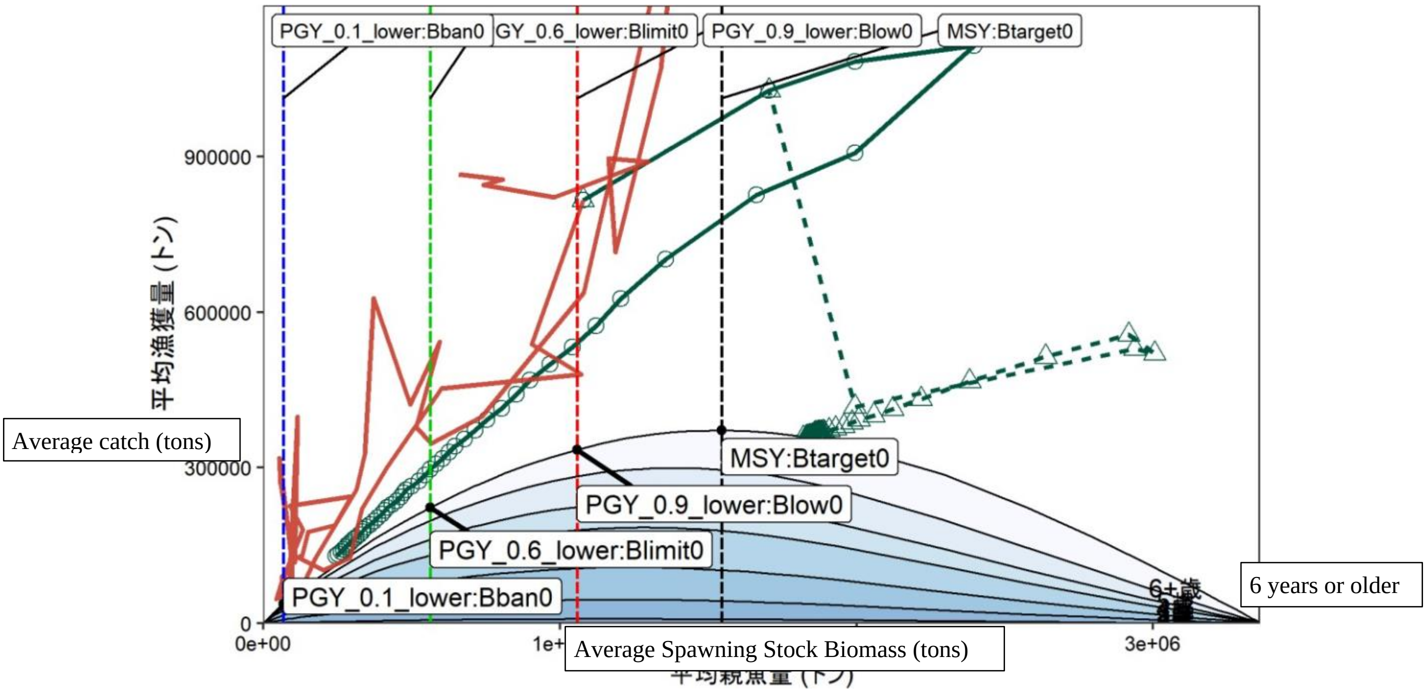
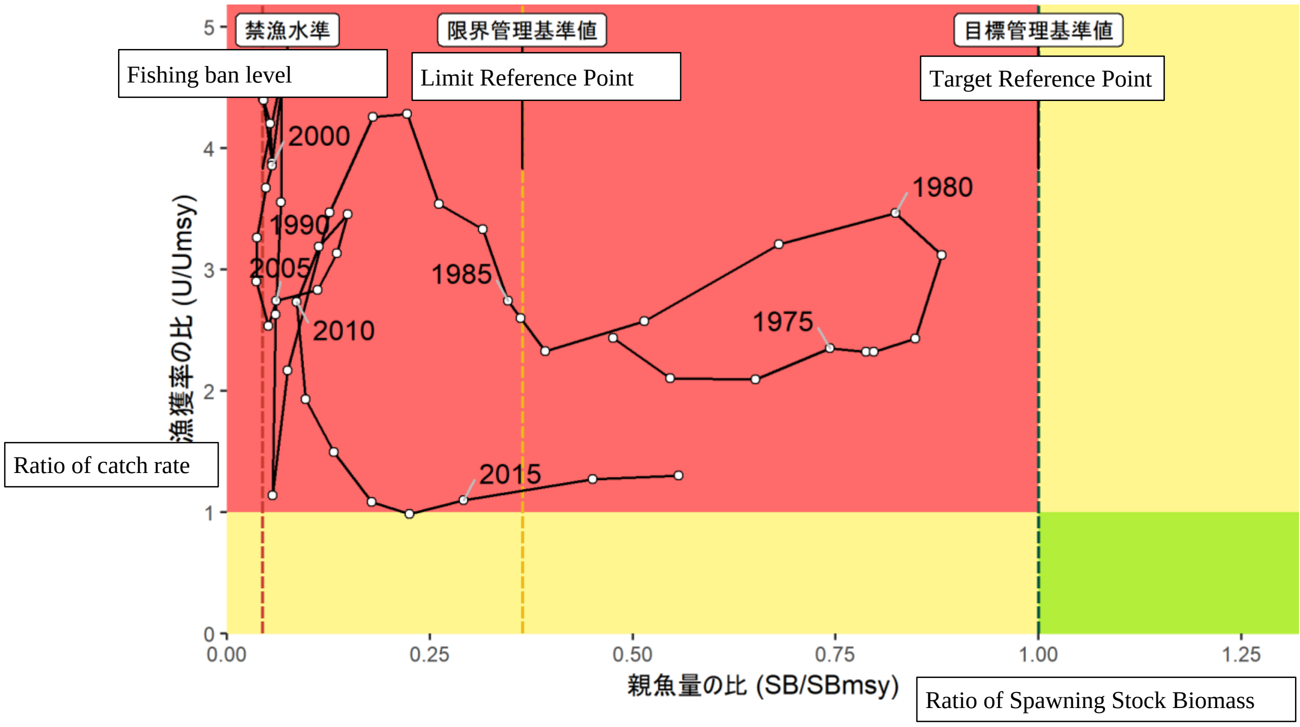


Figure 3. Relationship between the (biological) reference points and the catch by age curves

The average value of the catch by age with respect to the SSB at equilibrium in the future projection using the assumed S-R relationship is indicated by the area, the changes in the observed value (red solid line) and future projection (○: fishing based on Fcurrent, △: fishing based on HCR using the standard values) of the catch and the SSB are indicated by the broken line.

（a） When the vertical axis shows the ratio of catch rate (U / Umsy)



（b） When the vertical axis shows the ratio of fishing pressure (F / Fmsy)

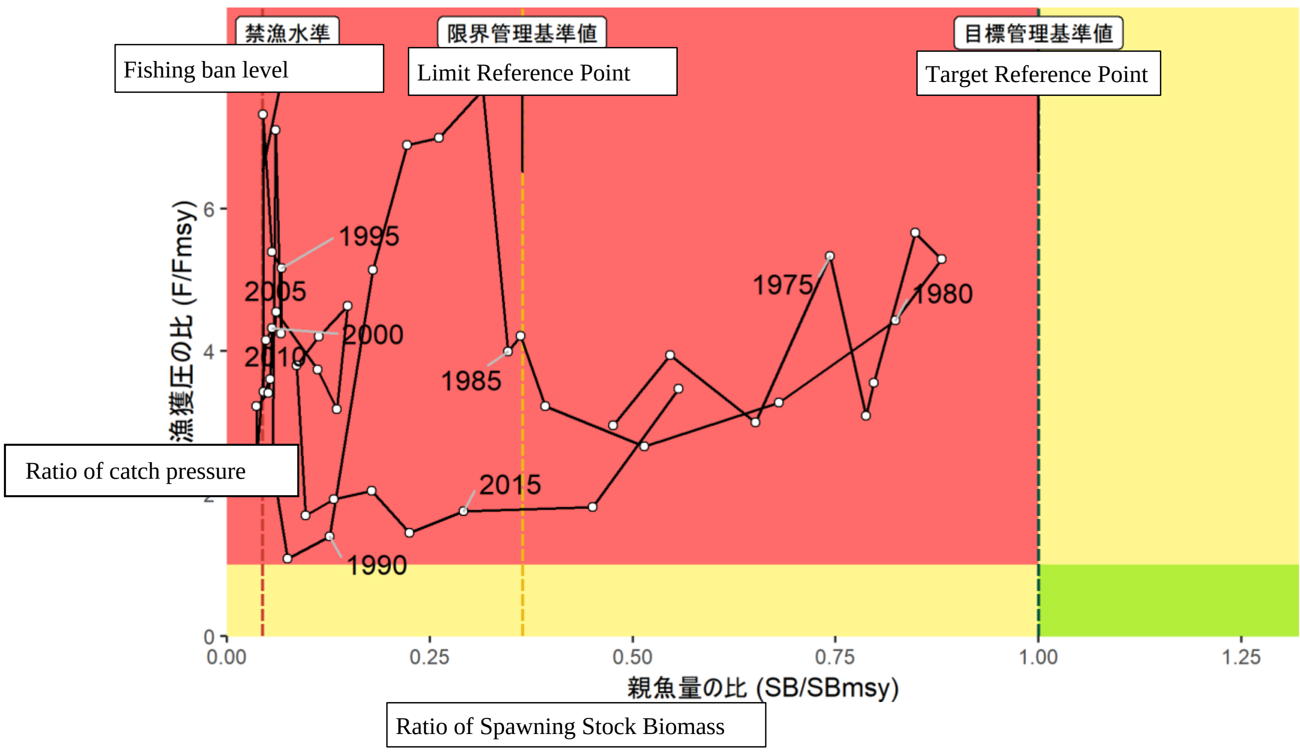
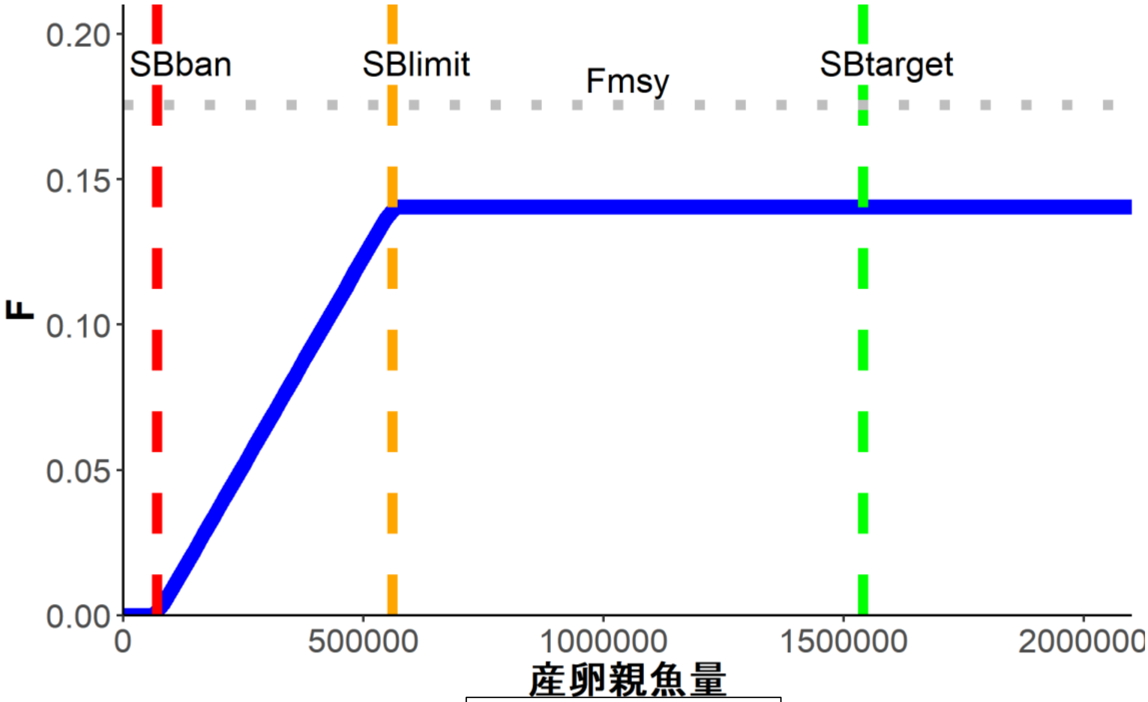


Figure 4. Kobe plot (Four sections)

The Target Reference Point, Limit Reference Point, and fishing ban level in the figure were set to SBmsy, SB0.6msy, and SB0.1msy respectively.



Spawning Stock Biomass

Figure 5. Relationship between Spawning Stock Biomass (tons) and F (simple average) for the Harvest Control Rules. The (biological) reference points SBtarget, SBlimit, and SBban were set to SBmsy, SB0.6msy, and SB0.1msy respectively. The standard value of 0.8 was used for β.

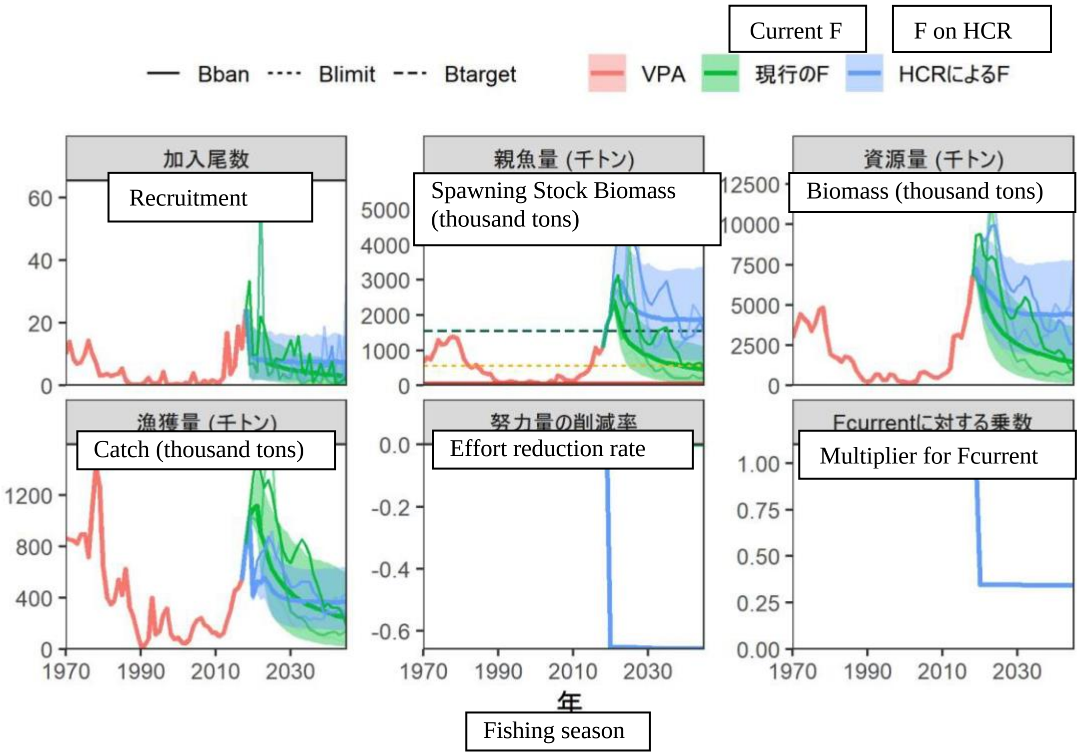


Figure 6. Average value of future projection based on the Harvest Control Rules (solid line) and 90% confidence intervals. The (biological) reference points SBtarget, SBlimit, and SBban were set to SBmsy, SB0.6msy, and SB0.1msy respectively, and the standard value of 0.8 was used for β. The fishing mortality for the 2018 and 2019 fishing seasons is assumed to be Fcurrent, and (red) is shown when following the Harvest Control Rules and (blue) is shown when being Fcurrent from the 2020 fishing season.

Table 1 Relationship of the various (Biological) Reference Points with the average Spawning Stock Biomass at equilibrium, the ratio to the initial Spawning Stock Biomass (SB0) assuming no fishery, the catch rate, the average catch, the CV of catch, and the effort multiplier for the current catch pressure

(Biological) Reference Points	Spawning Biomass (Tons)	Ratio to SB0	Biomass (Tons)	Catch rate	Catch (Tons)	CV of catch	Effort Multiplier
SBtarget	1,540,000	0.46	3,810,000	0.10	370,000	0.67	0.43
SBlimit	560,000	0.17	1,630,000	0.14	220,000	1.27	0.74
SBban	70,000	0.02	220,000	0.17	40,000	3.45	1.04

Table 2. Probability (%) of future Spawning Stock Biomass exceeding the Target Reference Point

β	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
1	0	100	100	100	100	99	80	65	57	53	51	49	48
0.9	0	100	100	100	100	100	85	70	62	57	55	53	53
0.8	0	100	100	100	100	100	89	75	67	62	59	58	57
0.7	0	100	100	100	100	100	94	81	72	67	64	63	62
0.6	0	100	100	100	100	100	97	85	77	73	69	68	67
0.5	0	100	100	100	100	100	99	90	82	78	74	73	71
0.4	0	100	100	100	100	100	100	93	87	83	80	78	76
0.3	0	100	100	100	100	100	100	96	92	87	85	83	82
0.2	0	100	100	100	100	100	100	99	95	92	90	88	87
0.1	0	100	100	100	100	100	100	100	97	96	94	92	91

Future projection results when fishing is conducted based on the Harvest Control Rules from 2020 using SBmsy, SB0.6msy, and SB0.1msy for the (Biological) Reference Points SBtarget, SBlimit, and SBban, respectively. For 2018 and 2019, fishing is assumed based on Fcurrent.

Table 3. Probability (%) of future Spawning Stock Biomass exceeding the Limit Reference Point

β	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
1	100	100	100	100	100	100	100	100	99	99	98	97	96
0.9	100	100	100	100	100	100	100	100	100	99	99	98	97
0.8	100	100	100	100	100	100	100	100	100	99	99	99	98
0.7	100	100	100	100	100	100	100	100	100	100	100	99	99
0.6	100	100	100	100	100	100	100	100	100	100	100	100	99
0.5	100	100	100	100	100	100	100	100	100	100	100	100	100
0.4	100	100	100	100	100	100	100	100	100	100	100	100	100
0.3	100	100	100	100	100	100	100	100	100	100	100	100	100
0.2	100	100	100	100	100	100	100	100	100	100	100	100	100
0.1	100	100	100	100	100	100	100	100	100	100	100	100	100

Future forecast results when fishing is conducted based on the Harvest Control Rules from 2020 using SBmsy, SB0.6msy, and SB0.1msy for the (Biological) Reference Points SBtarget, SBlimit, and SBban, respectively. For 2018 and 2019, fishing is assumed based on Fcurrent.

Table 4. Changes in future average Spawning Stock Biomass (tons)

β	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
1	1078000	1705000	1994000	2858000	2840000	2692000	2386000	2136000	1987000	1904000	1844000	1794000	1769000
0.9	1078000	1705000	1994000	2898000	2921000	2802000	2508000	2254000	2097000	2008000	1946000	1897000	1872000
0.8	1078000	1705000	1994000	2938000	3006000	2918000	2638000	2382000	2218000	2122000	2058000	2008000	1984000
0.7	1078000	1705000	1994000	2979000	3093000	3041000	2779000	2521000	2350000	2249000	2181000	2129000	2105000
0.6	1078000	1705000	1994000	3021000	3184000	3170000	2930000	2674000	2497000	2389000	2317000	2263000	2238000
0.5	1078000	1705000	1994000	3063000	3278000	3306000	3093000	2841000	2660000	2545000	2468000	2410000	2384000
0.4	1078000	1705000	1994000	3106000	3376000	3450000	3268000	3024000	2840000	2720000	2638000	2576000	2548000
0.3	1078000	1705000	1994000	3149000	3477000	3603000	3457000	3225000	3041000	2917000	2830000	2763000	2732000
0.2	1078000	1705000	1994000	3194000	3582000	3763000	3662000	3446000	3266000	3139000	3048000	2977000	2942000
0.1	1078000	1705000	1994000	3239000	3691000	3934000	3883000	3689000	3517000	3391000	3297000	3222000	3183000

Future projection results when fishing is conducted based on the Harvest Control Rules from 2020 using SBmsy, SB0.6msy, and SB0.1msy for the (Biological) Reference Points SBtarget, SBlimit, and SBban, respectively. For 2018 and 2019, fishing is assumed based on Fcurrent.

Table 5. Changes in future average catch (tons)

β	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
1	816000	1027000	514000	633000	604000	629000	570000	514000	477000	455000	441000	431000	424000
0.9	816000	1027000	466000	582000	564000	595000	544000	492000	456000	436000	423000	414000	407000
0.8	816000	1027000	417000	529000	520000	556000	514000	466000	433000	413000	401000	393000	387000
0.7	816000	1027000	368000	474000	473000	512000	478000	436000	405000	386000	375000	368000	363000
0.6	816000	1027000	318000	415000	421000	463000	437000	400000	372000	355000	345000	338000	334000
0.5	816000	1027000	267000	354000	364000	407000	388000	358000	334000	319000	310000	303000	299000
0.4	816000	1027000	215000	290000	303000	343000	332000	308000	289000	276000	268000	262000	259000
0.3	816000	1027000	162000	222000	236000	272000	267000	250000	235000	225000	218000	213000	210000
0.2	816000	1027000	109000	152000	164000	192000	191000	180000	170000	163000	159000	155000	153000
0.1	816000	1027000	55000	78000	85000	102000	102000	98000	93000	89000	87000	85000	84000

Future projection results when fishing is conducted based on the Harvest Control Rules from 2020 using SBmsy, SB0.6msy, and SB0.1msy for the (Biological) Reference Points SBtarget, SBlimit, and SBban, respectively. For 2018 and 2019, fishing is assumed based on Fcurrent.

Supplementary Material 1 Diagnosis Results of Stock-Recruitment Relationship Models

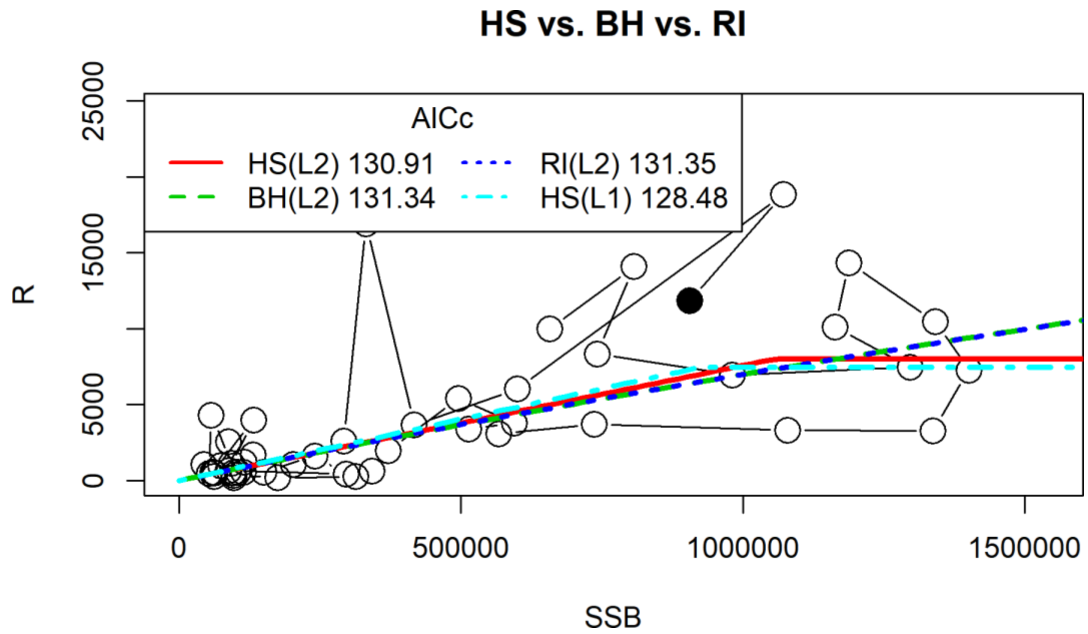
The results of various diagnoses for S-R relationships in this stock are shown below. Although the HS estimated by the least squares method was used, the change in the S-R relationship was small even when estimated by the least absolute value method (Supplementary Figure 1-1). In addition, the density effect was not clear for BH and RI models, and the recruitment tended to increase linearly with the SSB (Supplementary Figure 1-1).

QQ plots tended to deviate from the predicted line at the ends, but no significant difference was detected when the normality of the residuals was tested using the Shapiro-Wilk test and the Kolmogorov-Smirnov test (Supplementary Figure 1-2). Significant differences were detected in the autoregressive coefficients of the residuals of recruitment and S-R relationships with a one-year lag. The observed pattern was that the residuals were positive in the 1970s, negative in the 1980s and early 2000s, and positive again thereafter. (See Supplementary Figure 1-3).

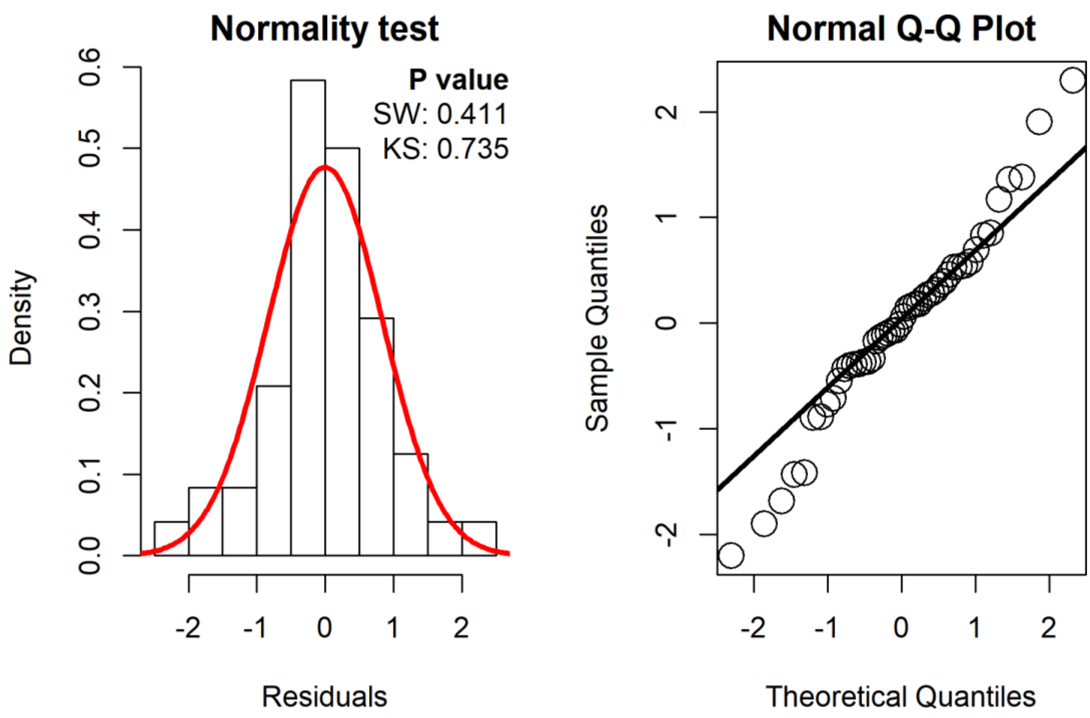
When the parametric bootstrap of the residual was performed 1000 times, the parameters *a*, *b*, and SD showed almost no bias, but the autocorrelation coefficient ρ tended to be slightly underestimated (bias = 3% (a), 2% (b), -1% (SD), -19% (ρ)) (Supplementary Figure 1-4). The CV for each parameter was 21% (a), 31% (b), 11% (SD), and 45% (ρ), respectively (Supplementary Figure 1-4). Since no bias was observed for parameters *a* and *b*, the S-R relationship estimated from the actual data was roughly at the center of the S-R relationship using the bootstrap data (Supplementary Figure 1-5).

When Jackknife analysis was performed, excluding data one year at a time, no significant change was observed in the estimated values of each parameter, and the estimated S-R relationship was robust (Supplementary Figures 1-6 and 1-7). In addition, it was confirmed that the profile likelihood when the parameters *a* and *b* were changed was the largest in the estimated value (Supplementary Figure 1-8).

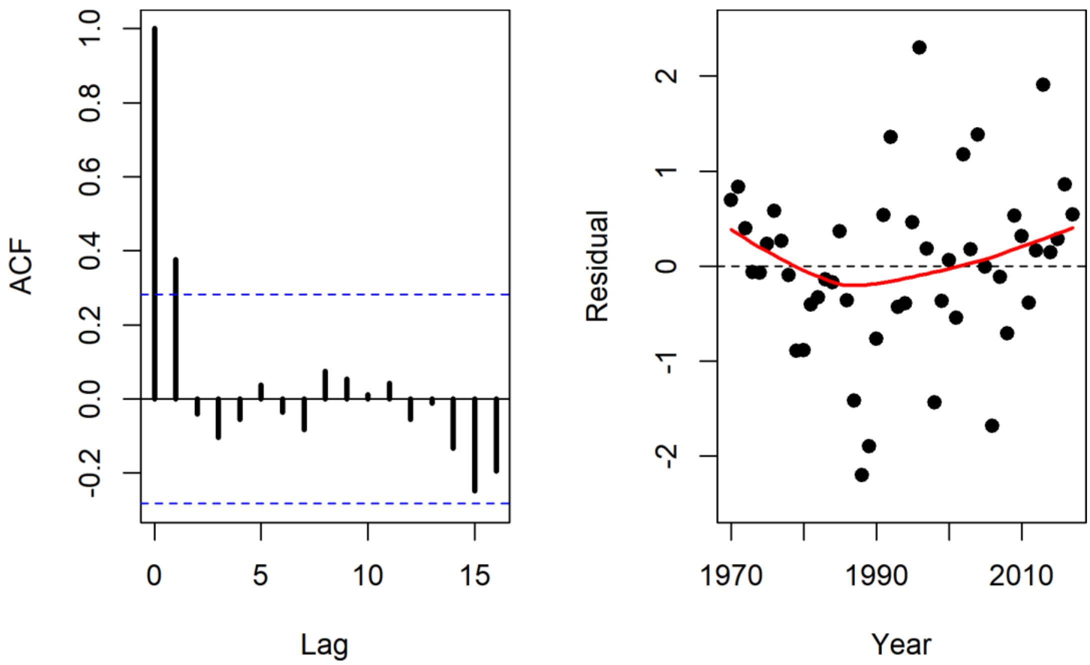
As a result of these diagnoses, it was concluded that there were no major problems in using this S-R relationship. However, it became clear that the autocorrelation coefficients tended to be underestimated and that the time series pattern of the residuals was observed even when autocorrelation was taken into account; therefore, a future challenge is to more accurately estimate patterns of temporal fluctuations that cannot be explained with S-R relationships.



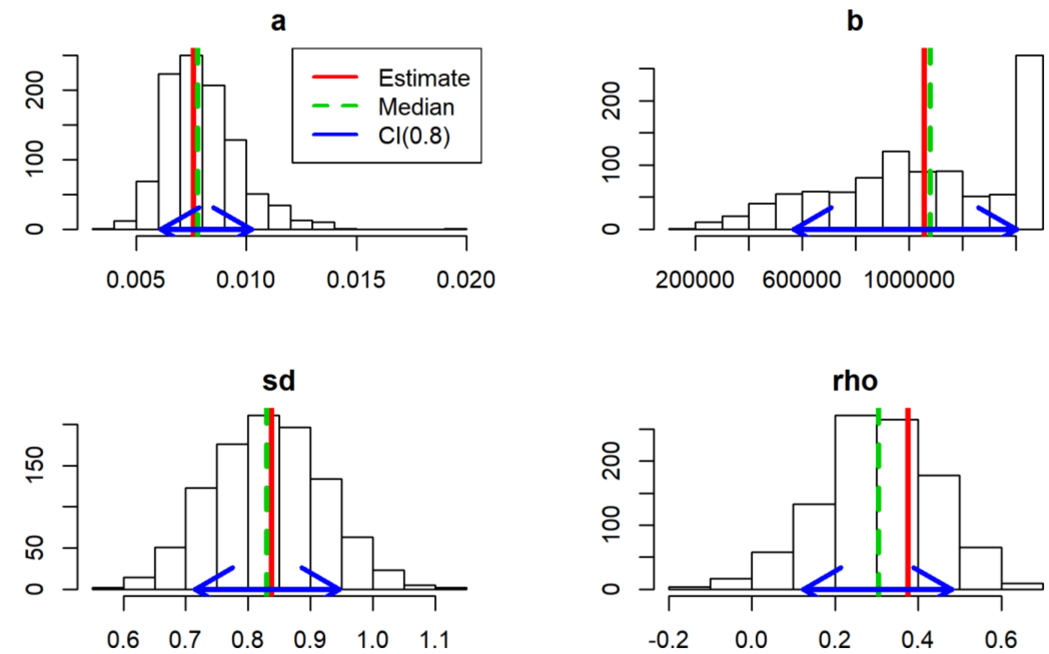
Supplementary Figure 1-1. Stock-recruitment relationships when HS is estimated by the least squares method (solid red line), when BH is estimated by the least squares method (broken green line), when RI is estimated by the least squares method (blue dotted line), and when HS is estimated by the least absolute value method (light blue dotted line).



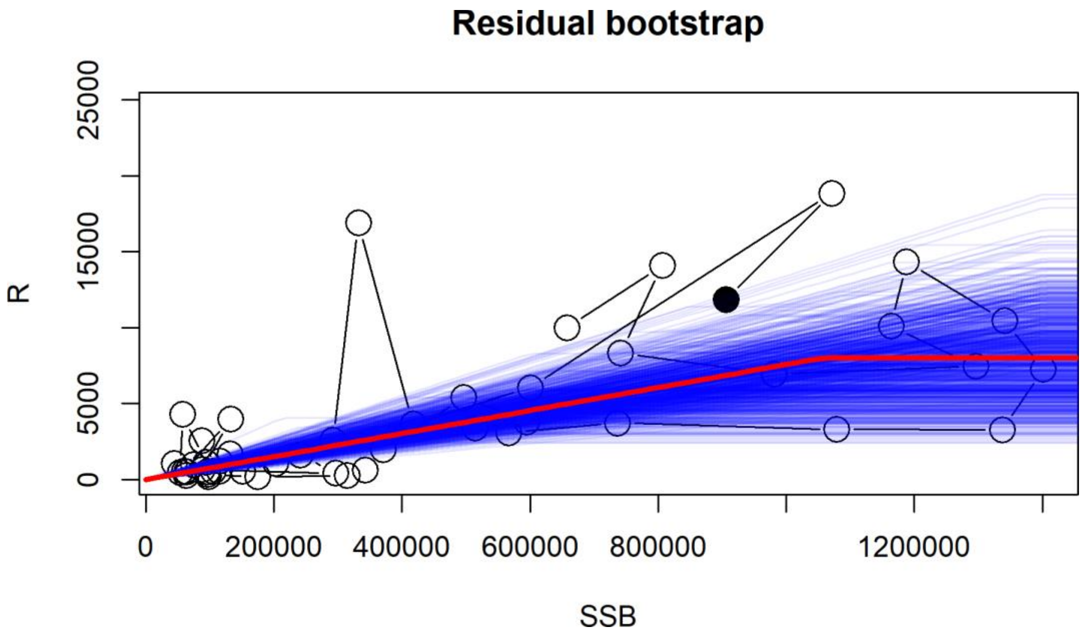
Supplementary Figure 1-2. Histogram of residuals for stock-recruitment relationships (left) and QQ plot (right).



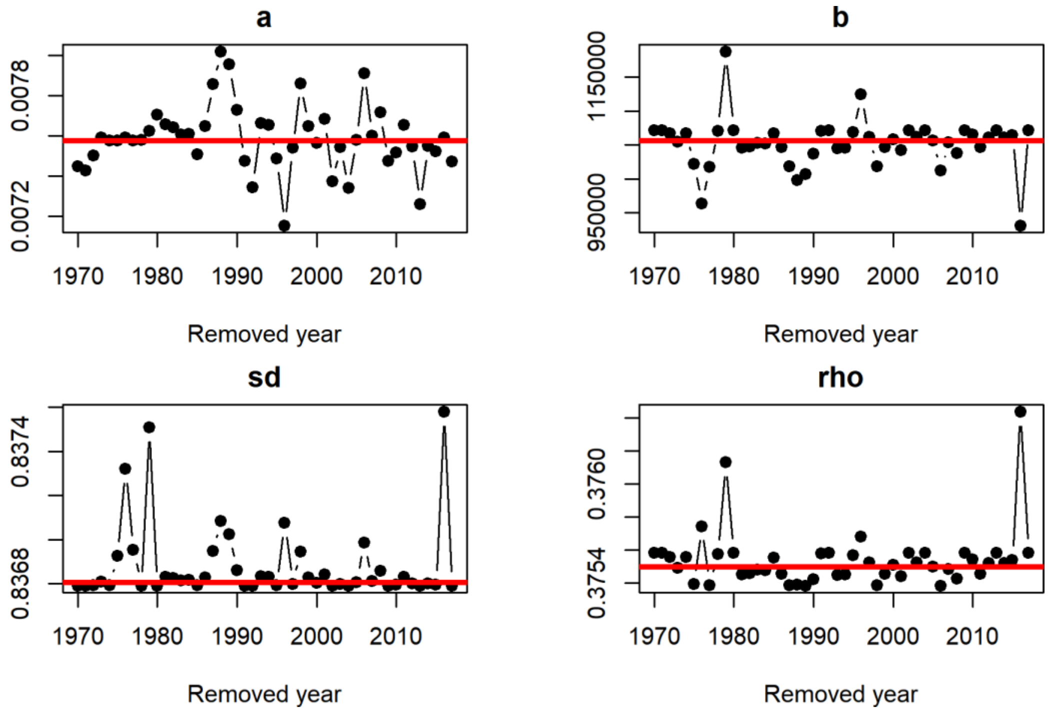
Supplementary Figure 1-3. Autoregressive coefficient of residuals for stock-recruitment relationships (left) and time series plot of residuals (right).



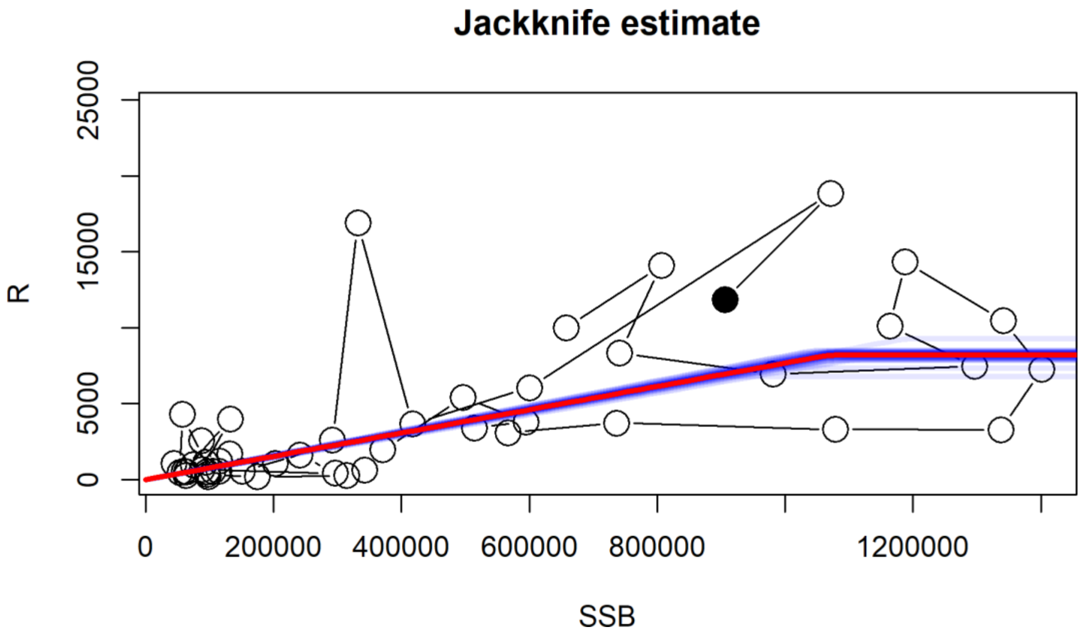
Supplementary Figure 1-4. Histogram of each parameter when residual parametric bootstrap is performed 1000 times. The solid red line indicates the point estimates, the green dotted line indicates the bootstrap median, and the blue arrow indicates the 80% confidence interval.



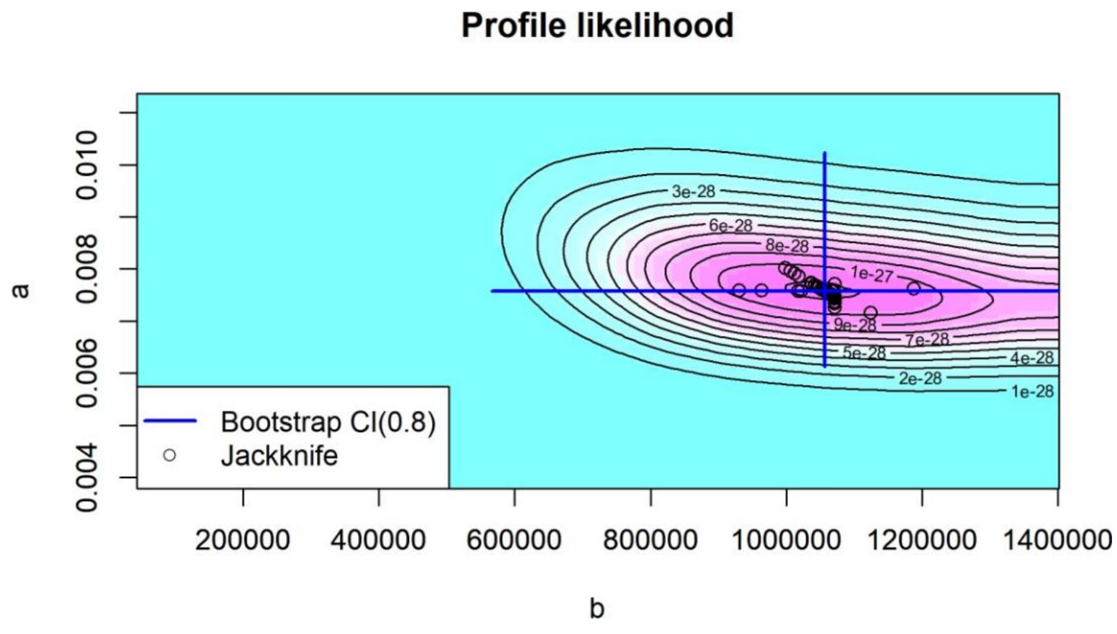
Supplementary Figure 1-5. Stock-recruitment relationships when residual bootstrap is performed 1000 times.



Supplementary Figure 1-6. Change of each parameter in Jackknife analysis.



Supplementary Figure 1-7. Stock-recruitment relationships in Jackknife analysis.



Supplementary Figure 1-8. Profile likelihood when parameters *a* and *b* are changed.

Supplementary Material 2 Sensitivity Analysis of (Biological) Reference Points

Sensitivity analysis of (biological) reference points was performed in the following six scenarios: (1) Fcurrent is set to an average for three years, similar to the 2018 Stock assessment (three-year selectivity scenario), (2) Set the year for calculating the (biological) reference point by simulation to be 100 years from now (100-year later scenario), (3) Use BH as the S-R relationship (BH scenario, consider autocorrelation by least squares method), (4) Use RI as the S-R relationship (RI scenario, consider autocorrelation by least squares method), (5) Estimate HS S-R relationship by least squares method without considering autocorrelation (AR0 scenario), (6) Estimate HS S-R relationship using the least absolute value method and consider autocorrelation (L1 scenario).

First, in the three-year selectivity scenario and the 100-year later scenario, the (biological) reference points were almost the same as the scenarios in this document (considered as standard scenarios) (Supplementary Table 2-1). Thus, the equilibrium was satisfactorily reached after 50 years, suggesting that the standard scenario is robust to selectivity. When the BH and RI models of S-R relationships were used, SBmsy was 7.45 million tons and 4.74 million tons, respectively, which was significantly higher than the largest SSB ever recorded (1.4 million tons) (Supplementary Table 2-1). Therefore, setting a target reference point based on these S-R relationships was considered to be unrealistic. In the AR0 scenario, which excludes the autocorrelation, the (biological) reference point of the SSB was not much different from the standard scenario, but the MSY and the exploitation rate at that time were higher than those in the standard scenario. This suggests that if it is true that there is autocorrelation in the S-R relationship, there is a possibility of overfishing if the (biological) reference points and fishing control rules are defined without assuming the autocorrelation. In the L1 scenario in which the S-R relationship was estimated by the greatest absolute value method, the (biological) reference points (SBtarget, SBlimit, and SBban) for the SSB decreased. The MSY was slightly reduced from the standard scenario, but the exploitation rate was higher at that time.

Supplementary Table 2-1. (Biological) Reference Points for each scenario in sensitivity analysis and values for each item associated with them

(Biological) Reference Points	Item	Scenario Standard	Three-year Selectivity	100-year later	BH	RI	AR0	L1
SBtarget = SBmsy	Spawning Stock Biomass (tons)	1540000	1530000	1540000	7450000	4740000	1460000	1400000
	SBref / SB0	0.459	0.456	0.459	0.403	0.453	0.434	0.445
	Biomass (tons)	3810000	3840000	3810000	16830000	11070000	3860000	3530000
	Exploitation Rate	0.098	0.095	0.098	0.074	0.083	0.112	0.103
	Catch (tons)	370000	370000	370000	1250000	920000	430000	360000
	CV of catch	0.669	0.725	0.669	0.788	0.726	0.483	0.667
	Fref / Fcurrent	0.433	0.441	0.433	0.294	0.345	0.539	0.471
SBlimit = SB0.6msy	Spawning Stock Biomass (tons)	560000	560000	560000	2290000	1580000	580000	510000
	SBref / SB0	0.167	0.166	0.167	0.124	0.151	0.171	0.162
	Biomass (tons)	1630000	1650000	1630000	6200000	4380000	1780000	1520000
	Exploitation Rate	0.137	0.133	0.137	0.121	0.127	0.146	0.144
	Catch (tons)	220000	220000	220000	750000	550000	260000	220000
	CV of catch	1.265	1.334	1.265	1.238	1.247	0.950	1.255
	Fref / Fcurrent	0.738	0.737	0.738	0.599	0.646	0.836	0.799
SBban = SB0.1msy	Spawning Stock Biomass (tons)	70000	70000	70000	250000	180000	80000	60000
	SBref / SB0	0.020	0.020	0.020	0.013	0.017	0.022	0.020
	Biomass (tons)	220000	230000	220000	790000	570000	250000	210000
	Exploitation Rate	0.167	0.160	0.167	0.158	0.161	0.173	0.173
	Catch (tons)	40000	40000	40000	120000	90000	40000	40000
	CV of catch	3.453	3.592	3.453	2.900	3.105	2.574	3.431
	Fref / Fcurrent	1.042	1.038	1.041	0.940	0.973	1.086	1.118

Supplementary Material 3 Future Projection When the Catch Setting for the 2018 and 2019 Fishing Season is Changed

In the calculation of future projection in this document, it is assumed that the fishing mortality for the 2018 and 2019 fishing seasons is Fcurrent (considered as standard scenario). As a result, the catches during the 2018 and 2019 fishing seasons were 816,000 tons and 1,027,000 tons, indicating that the catches became larger. In order to examine the robustness of the future projection results with respect to that assumption, a scenario where the catch in the 2018 and 2019 fishing seasons was assumed to be equal to the catch in the 2017 fishing season (538,000 tons) was studied.

As a result of the analysis, the probability that the SSB would reach the target reference point was 100% until the 2023 fishing season, as in the standard scenario, and for the next 2 to 3 years, the probability of reaching the target reference point was a few percentage points higher than in the standard scenario

(Supplementary Table 3-1). The probability of achievement after 2027 is equivalent to that of the standard scenario, with β less than 0.9 and the probability of achievement as of 2030 being 50% or more (Supplementary Table 3-1). The change in probability of achievement in the two scenarios was small because although the average SSB was higher than in the standard scenario, it is expected to greatly exceed SBmsy in either case due to the emergence of the predominant class group in recent years.

(Supplementary Table 3-3). The average catch up to around the 2024 fishing season tended to be higher than the standard scenario. For example, when β = 0.8, the average catch during the 2020 fishing season was 417,000 tons in the standard scenario, but was 498,000 tons in the scenarios studied here. Therefore, the catch for several years after applying the new fishing control rules will depend on the catch in the 2018 and 2019 fishing season.

Supplementary Table 3-1. Probability (%) of future Spawning Stock Biomass exceeding the Target Reference Point

β	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
1	0	100	100	100	100	100	86	68	58	54	51	49	48
0.9	0	100	100	100	100	100	90	74	63	58	56	54	53
0.8	0	100	100	100	100	100	94	79	69	63	60	58	57
0.7	0	100	100	100	100	100	97	84	74	69	65	63	62
0.6	0	100	100	100	100	100	99	89	79	74	70	68	67
0.5	0	100	100	100	100	100	100	93	84	79	75	73	72
0.4	0	100	100	100	100	100	100	96	90	84	81	78	77
0.3	0	100	100	100	100	100	100	98	93	89	86	84	82
0.2	0	100	100	100	100	100	100	100	97	94	91	89	87
0.1	0	100	100	100	100	100	100	100	99	97	95	93	92

Supplementary Table 3-2. Probability (%) of future Spawning Stock Biomass exceeding the Target Reference Point

β	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
1	100	100	100	100	100	100	100	100	100	99	98	97	96
0.9	100	100	100	100	100	100	100	100	100	99	99	98	97
0.8	100	100	100	100	100	100	100	100	100	100	99	99	98
0.7	100	100	100	100	100	100	100	100	100	100	100	99	99
0.6	100	100	100	100	100	100	100	100	100	100	100	100	99
0.5	100	100	100	100	100	100	100	100	100	100	100	100	100
0.4	100	100	100	100	100	100	100	100	100	100	100	100	100
0.3	100	100	100	100	100	100	100	100	100	100	100	100	100
0.2	100	100	100	100	100	100	100	100	100	100	100	100	100
0.1	100	100	100	100	100	100	100	100	100	100	100	100	100

Supplementary Table 3-3. Changes in future average Spawning Stock Biomass (tons)

β	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
1	1078000	1889000	2515000	3341000	3169000	2893000	2492000	2188000	2012000	1916000	1852000	1801000	1774000
0.9	1078000	1889000	2515000	3389000	3265000	3017000	2625000	2313000	2126000	2023000	1956000	1903000	1878000
0.8	1078000	1889000	2515000	3439000	3365000	3148000	2768000	2449000	2252000	2140000	2069000	2015000	1990000
0.7	1078000	1889000	2515000	3489000	3469000	3287000	2922000	2598000	2391000	2270000	2194000	2137000	2111000
0.6	1078000	1889000	2515000	3540000	3576000	3434000	3089000	2762000	2545000	2415000	2332000	2272000	2244000
0.5	1078000	1889000	2515000	3592000	3688000	3589000	3268000	2941000	2716000	2577000	2486000	2421000	2391000
0.4	1078000	1889000	2515000	3645000	3804000	3754000	3462000	3139000	2907000	2759000	2661000	2590000	2556000
0.3	1078000	1889000	2515000	3699000	3925000	3928000	3672000	3356000	3121000	2965000	2859000	2781000	2743000
0.2	1078000	1889000	2515000	3754000	4050000	4113000	3900000	3597000	3360000	3198000	3085000	3000000	2956000
0.1	1078000	1889000	2515000	3810000	4180000	4309000	4147000	3862000	3629000	3463000	3344000	3253000	3203000

Supplementary Table 3-4. Changes in future average catch (tons).

β	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
1	538000	538000	613000	733000	674000	676000	596000	526000	483000	458000	443000	433000	425000
0.9	538000	538000	556000	675000	630000	641000	570000	505000	463000	439000	425000	415000	408000
0.8	538000	538000	498000	614000	583000	601000	539000	479000	440000	417000	403000	394000	388000
0.7	538000	538000	439000	551000	531000	555000	503000	449000	412000	390000	377000	369000	364000
0.6	538000	538000	379000	483000	474000	502000	461000	414000	380000	360000	347000	339000	334000
0.5	538000	538000	319000	413000	411000	443000	411000	371000	341000	323000	312000	305000	300000
0.4	538000	538000	257000	338000	343000	375000	353000	321000	296000	280000	270000	264000	259000
0.3	538000	538000	194000	260000	268000	298000	284000	260000	241000	228000	220000	215000	211000
0.2	538000	538000	131000	178000	187000	211000	204000	188000	175000	166000	161000	156000	154000
0.1	538000	538000	66000	91000	97000	112000	110000	103000	96000	91000	88000	86000	84000