Research Institute Meeting Report on (Biological) Reference Points for the Tsushima Warm Current 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 Tsushima warm current stock of chub mackerel in FY2018. The stock status is assessed to be “low” based on the spawning stock biomass in the last 45 years, and the trend is assessed to be “increasing” based on the trends in biomass during the last five years (fishing season of 2013-2017). For this stock, we propose the Hockey Stick (HS) model which is optimized by the least squares method as a candidate for the stock-recruitment relationship. SBmsy (310,000 tons) as a candidate for the target reference point, SB0.6msy (143,000 tons) as a candidate for the limit reference point, and SB0.1msy (22,000 tons) as a candidate for the fishing ban level. The fishing pressure for achieving the MSY is 1.00 times the current value (Fcurrent, average fishing pressure from 2015 to 2017).

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 the stock-recruitment relationships

The models listed as candidates for the stock-recruitment (S-R) relationship of this stock, and the results of applying them to the observed data are shown in the table on the next page. All values from 1973 to 2017 were used as the data. There is a weak positive correlation between Spawning Stock Biomass (SSB) and recruitment in this stock (5% significance level). In particular, when the SSB is small, there is a tendency that high recruitment is not observed. In this stock, three functional types of S-R relationship were examined, namely Hockey Stick model (HS), Ricker model (RI), and Beverton-Holt model (BH). RI had the lowest AICc, followed by BH. However, when the SSB was small, RI or BH tended to estimate higher recruitment than that of HS. Moreover, there is no data when the SSB falls below 100,000 tons, so it was concluded that the most conservative scenario of HS was also a valid candidate. The consistency between the change in stock status obtained by applying each S-R relationship, and the stock status and trends shown in the assessments up to last year were also used as a basis to judge the preferable S-R relationship. When RI and BH were used, the results showed that the SSB never fell below Blimit in the past, whereas when HS was used, the results showed that the SSB in recent years has been gradually increasing from below Blimit. In the stock assessment conducted last year, the stock status were assessed to be “low” and the trend as “increasing” in recent years, and were closer to the results when HS was used. Based on the above, we decided to use HS for the S-R relationship for this stock. As for the optimization method, AICc was smaller when using the least absolute value method than when using the least squares method, but the difference in the estimation results was small. In the past 45 years, observations that deviated significantly from the projected S-R curve were rarely obtained, so the least squares method was applied to this stock. Regarding the autocorrelation of the recruitment residuals, the autocorrelation coefficient was not significant when optimized by the least squares method using HS (Supplementary Figure 1-4), so the autocorrelation was not considered in this stock.

S-R relationship equation	Optimization method	AICc	⊿AICc	⊿ AICc ranking	Recruitment S.D.
HS	**Least squares method**	**28.16**	**5.86**	**6**	**0.31**
RI	Least squares method	22.31	0.00	1	0.29
BH	Least squares method	24.75	2.45	3	0.30
HS	Least absolute value method	26.55	4.25	5	0.32
RI	Least absolute value method	24.69	2.38	2	0.32
BH	Least absolute value method	26.30	4.00	4	0.32

* S-R relationship recommended as a candidate is in bold text

1-3) Candidates for the S-R relationships

As mentioned above, we propose HS (Figure 1) which do not consider autocorrelation in recruitments, and was optimized by the least squares method as the S-R relationship of this stock.

2. (Biological) reference points

2-1) Data set and calculation method

To calculate the (biological) reference point of MSY and for the future projection, the S-R relationship that was suggested in 1-3) and the various settings used for the projections in the fishery stock assessment of the waters around Japan in FY2018 (Japan Fisheries Agency, and Japan Fisheries Research and Education Agency) were used (see Table below). In other words, the S-R relationship is the HS model (Figure 1) based on the recruitment and SSB from 1973 to 2017 estimated by the stock assessment, and the selectivity was calculated from the 2013-2017 average of the fishing mortality (F value) for each age. The current fishing pressure (Fcurrent) is the value at which the simple average of the F value for each age is equal to the average for 2015-2017 under this selectivity (Figure 2), and the average weight of the catch was taken as the average for 2015-2017.

Age	Natural mortality	Maturity rate (%)	Average weight (g)	Selectivity	Current fishing pressure (Fcurrent)
0	0.4	0	243	0.31	0.33
1	0.4	60	330	1.00	1.07
2	0.4	85	478	0.65	0.69
3 years or older	0.4	100	619	0.65	0.69

A future projection was made under the above-mentioned conditions and the S-R relationship, and the maximum catch at equilibrium was defined as the Maximum Sustainable Yield (MSY), and the SSB at which MSY is achieved was defined as SBmsy. The simulation, in which the residuals of the recruitment is given as a lognormal distribution and the average recruitment is corrected, was repeated 5,000 times, to estimate the Fmsy. In this stock, the equilibrium state was assumed to be about 68 years after the start of future projection, based on the criteria of 20 times the generation time (about 3.4 years).

2-2) S-R relationship used

HS without recruitment autocorrelation optimized by the least squares method was used as the S-R relationship. The parameters are shown in the table below, and the relationship between the observed values of the past SSB and recruitment is shown in Figure 1.

S-R relationship equation	Optimization method	Autocorrelation	*a*	*b*	S.D.
HS	Least squares method	No	0.00755	237,192	0.31

Here, *a* is the slope of the HS S-R curve from the origin to the break point (million / ton), and *b* is the SSB (ton) at the break point.

2-3) Biological reference points

The SBmsy was used as the target reference point (SBtarget) for this stock, the SSB (SB0.6msy) at which 60% catch of MSY can be obtained is used as the limit reference point (SBlimit), and the SSB (SB0.1msy) at which 10% catch of MSY can be obtained is used as the fishing ban level (SBban). These are all standard values in the ABC calculation rules. The following table shows the SSB at each level.

Biological reference points		SSB	Criteria
Target reference point	SBtarget	310,000 tons	SBmsy
Limit reference point	SBlimit	143,000 tons	SB0.6msy
Fishing ban level	SBban	22,000 tons	SB0.1msy

For each reference point, Table 1 shows the relationship among the ratio to the initial SSB (SB0) assuming no fishery, the average catch at equilibrium, the CV of catch, the catch rate, and the multiplier for the current fishing pressure. Figure 3 shows the average SSB at equilibrium in future projection using the S-R relationship, and the average catch by age with respect to this. When the SSB is below SBlimit, 0-year-old and 1-year-old fish account for the majority, and even when SBmsy is achieved, they account for the majority. However, there is a tendency for the proportion of older fish to increase as the SSB further increases.

2-4) Target reference point and exploitation rate

Figure 4 shows the Kobe plots using the target reference points. Since the catch rate in this stock was at the level that gave MSY from the late 1970s to the 1980s, it is considered that the SSB was maintained at the MSY level during this period. Thereafter, catch rates have increased since the early 1990s and have been maintained above the levels that give MSY. The Spawning Stock Biomass has also been declining since the late 1990s, and has been maintained below or near the SBlimit in the early 2000s. The catch rate in the last five years (2013-2017) has been decreasing, and the SSB has been increasing accordingly. The SSB in 2017 exceeded the limit reference point, but was significantly below the target reference point.

2-5) Harvest control rules

Figure 5 shows the relationship between the SSB and the fishing mortality for the Harvest Control Rules (HCRs) using the target reference point, limit reference point, and fishing prohibition level. Supplementary Figure 3 shows the relationship of SPR (F) when using the F based on the HCRs.

2-6) Future projection of stock based on HCRs

(1) When a standard value is used for the tuning parameter β

Figure 6 shows the change in the recruitment, SSB, biomass, catch, effort reduction rate, and multiplier for Fcurrent when the values indicated in 2-3) are used for target reference point, limit reference point, and fishing ban level, and the standard value of 0.8 is used for β. We have assumed that catch control starts in 2020, and the catches for 2018 and 2019 were based on Fcurrent. The fishing pressure is maintained at β Fmsy because the SSBs in recent years has exceeded the limit reference point. The catch in 2020 will be similar to the catch when fishing is carried out at Fcurrent. Thereafter, the biomass and catch were projected to increase slowly.

(2) When tuning parameter β is changed

Tables 2 to 5 show the probability of recovery to the target reference point, the probability of recovery to the limit reference point, changes in the average SSB, and changes in the average catch when β is changed between 0.5 and 1 in the future projection. The probability of recovery to the target reference point in this stock is high, and even if the standard value of 0.8 is used, it is predicted that the target reference point will be reached with an 89% probability in 2030, which is 10 years from the latest data (Table 2). If β was 0.9 or less, it was predicted that the target reference point would be reached with a probability of 50% or more in 2030, 10 years after the start of catch control. On the other hand, when β was 1, the probability of reaching the target reference point was less than 50%. In addition, it was shown that if β is 1 or less, it is possible to maintain the SSB above the limit reference point (Table 3). If catch is controlled from 2020, the future SSB after 2021 will increase as β decreases (Table 4), and if β is less than 0.9, the catch in 2020 was lower than in 2019. (Table 5).

3. Summary

The S-R relationships and (biological) reference points of this stock were examined using data on the stock assessment of the Tsushima warm current stock of chub mackerel in FY2018. In this stock assessment, the stock status of this stock is assessed to be low and that the stock trend has increased based on the changes in the biomass during the last five years (2013-2017). Since there is a positive correlation between the SSB and recruitment, the recovery of the SSB is considered necessary in order to use the stock safely and effectively.

The S-R relationship of this stock was HS without considering autocorrelation in recruitment, and the least squares method was used as the optimization method. In examining the S-R relationships, consideration was given to the fact that the S-R relationship equations other than HS tended to be optimistic when the SSB was small, and to consistency with the stock status shown in stock assessments up to the previous year. For each management standard, the target reference point is defined as the stock status that achieves MSY, so SBmsy (310,000 tons) estimated from this S-R relationship, and the limit reference point and the fishing ban level were set to the standard values SB0.6msy (143,000 tons) and SB0.1msy (22,000 tons), respectively. Here, catch rate to achieve MSY is 37% and fishing pressure is 1.0 times of Fcurrent. If β is less than 0.9, it is predicted that the MSY level will be achieved in 2030 with a probability of more than 50%.

4. Future considerations

One of the factors that brings great uncertainty to the stock assessment results of this stock is that the impact of fishing by Chinese fishing vessels has not been taken into account in the stock assessment. In addition, uncertainties regarding future projections include the inability to accurately predict the catches of foreign fishing vessels such as from China and South Korea, and also, regarding the Japanese catch, it is difficult to predict the catch for each species because the TAC is collectively set as “mackerel” for chub mackerel and blue mackerel. These factors may affect the S-R relationship, (biological) reference points, and the probability of achieving the management goals, etc.

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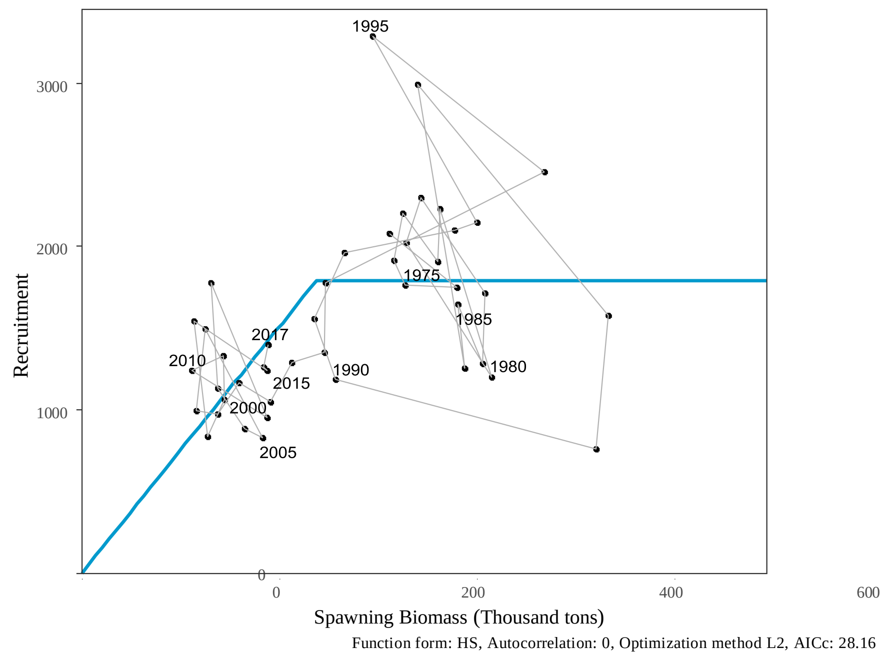


Figure 1. S-R relationship

The numbers in the figure indicate year-class groups. The Hockey Stick model (HS) was used for the S-R relationship equation, and the parameters were estimated by the least squares method without considering autocorrelation in recruitment.

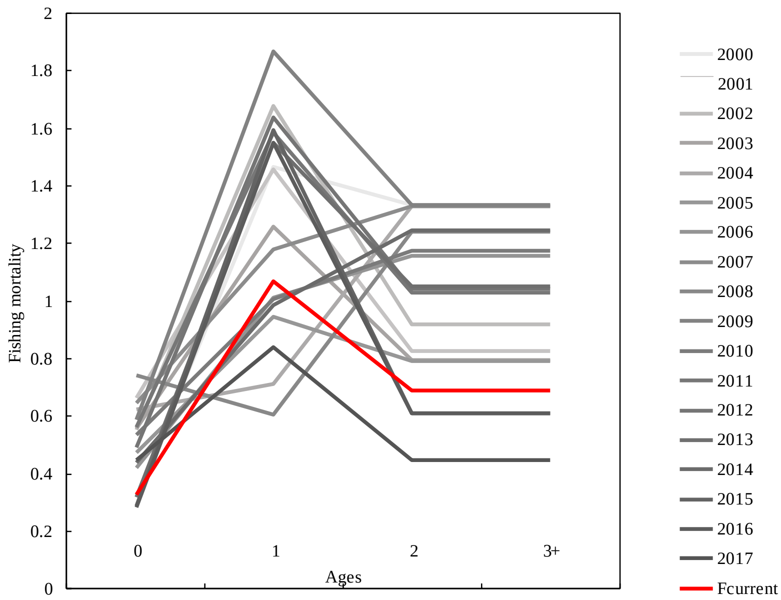


Figure 2. F values by age

The F value by age, which indicates the current fishing pressure (Fcurrent, average catch pressure for 2015-2017), is shown by a red line, and the F value for each year after the 2000 fishing season is shown by a gray line.

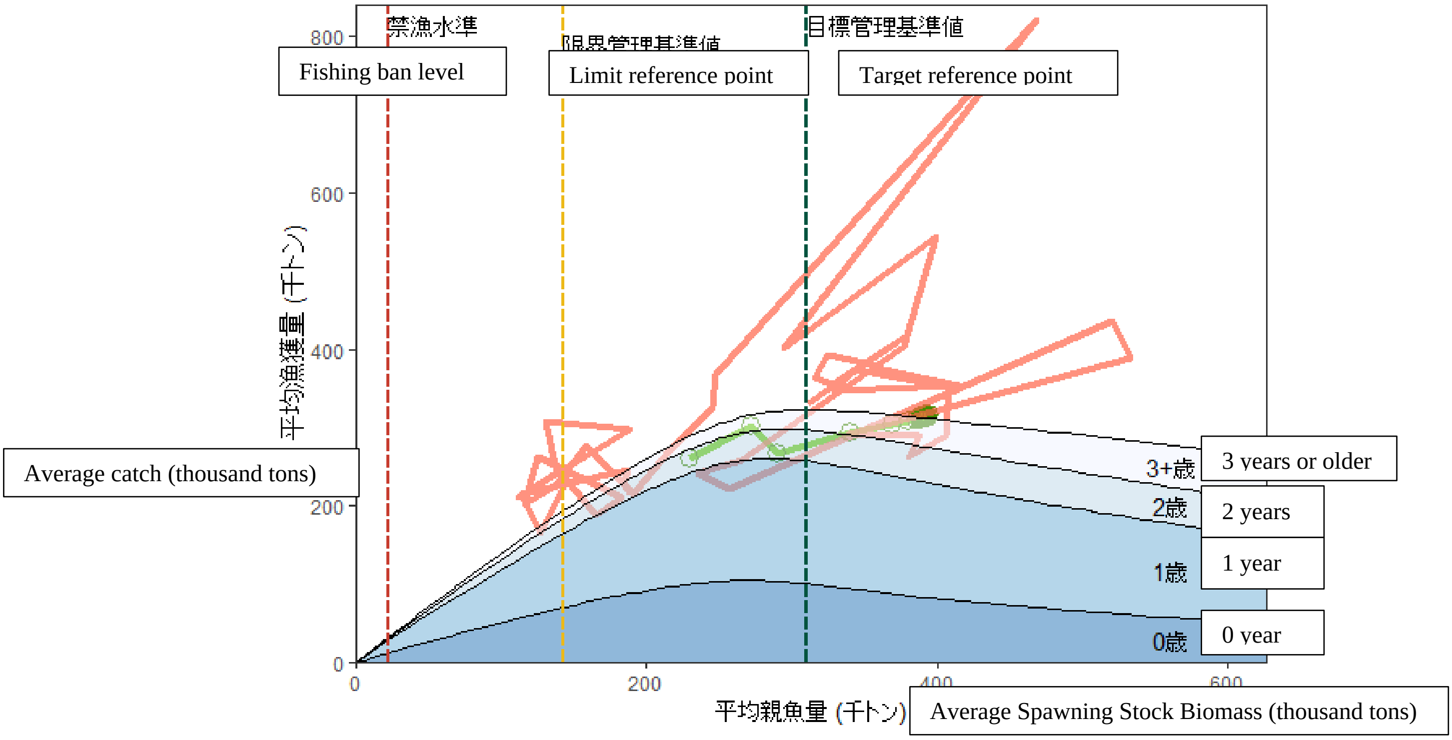
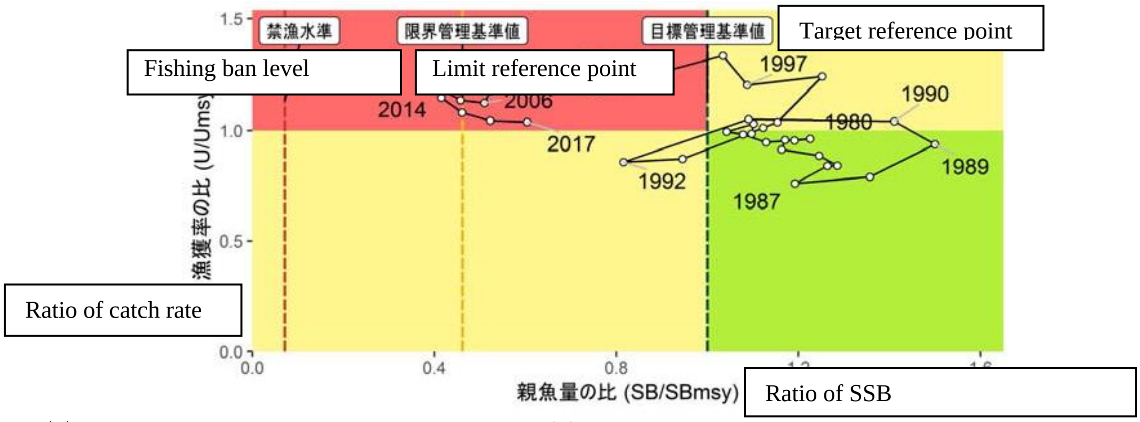


Figure 3. Relationship between the (biological) reference points and the catch by age curves

Average catch by age with respect to the SSB at equilibrium in future projection using the assumed S-R relationship. The red line shows the locus of the relationship between the SSB and the catch from 1973 to 2017, and the green line shows the locus of the relationship between the SSB and the catch when the fishing is based on the HCR with β set to the standard value of 0.8. The initial SSB (SB0) is 1,577,000 tons. The target reference point, limit reference point, and fishing ban level in the figure indicate the (biological) reference points (SBmsy, SB0.6msy, and SB0.1msy) with respect to the SSB respectively.

（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)

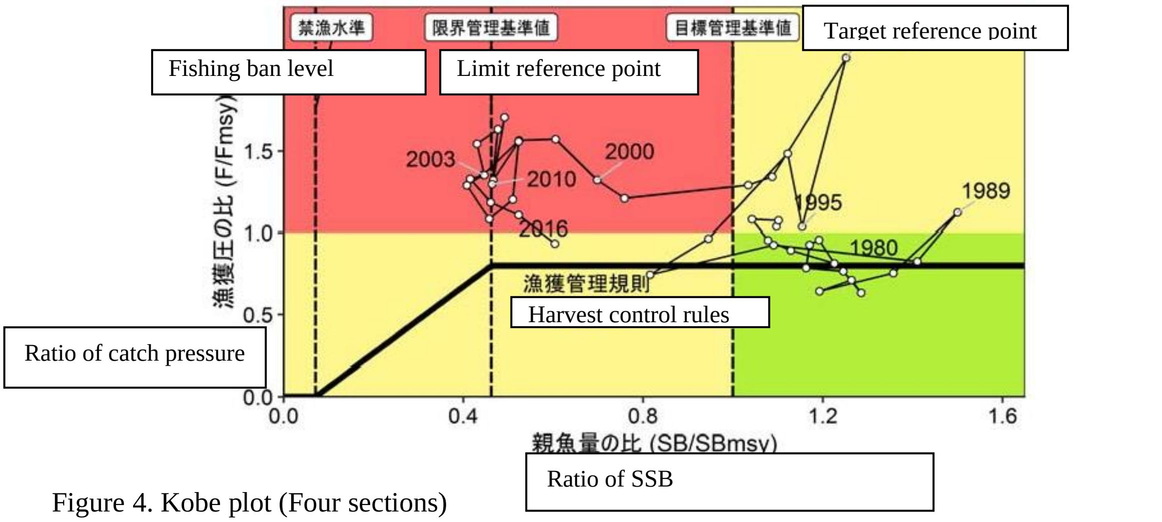


Figure 4. Kobe plot (Four sections)

The value smoothed with a three-year moving average. The target reference point, limit reference point, and fishing ban level in the figure indicate the (biological) reference points (SBmsy, SB0.6msy, and SB0.1msy) with respect to the SSB respectively.

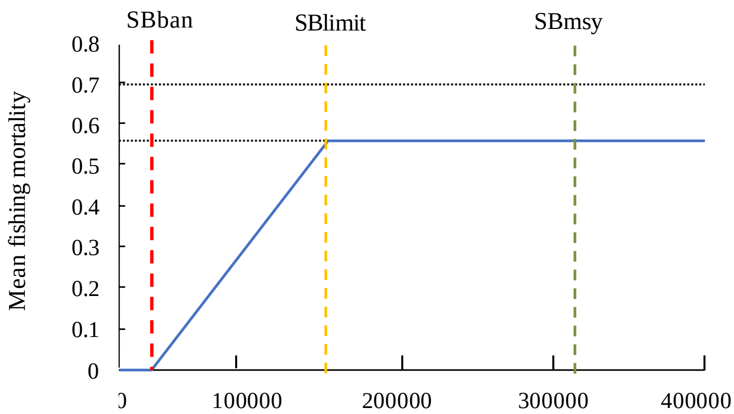


Figure 5. Harvest Control Rules (HCR)

The (biological) reference points in the figure, SBtarget,SBlimit,andSBban were respectively set to SBmsy,SB0.6msy, and SB0.1msy. The tuning parameter β is the standard value of 0.8.

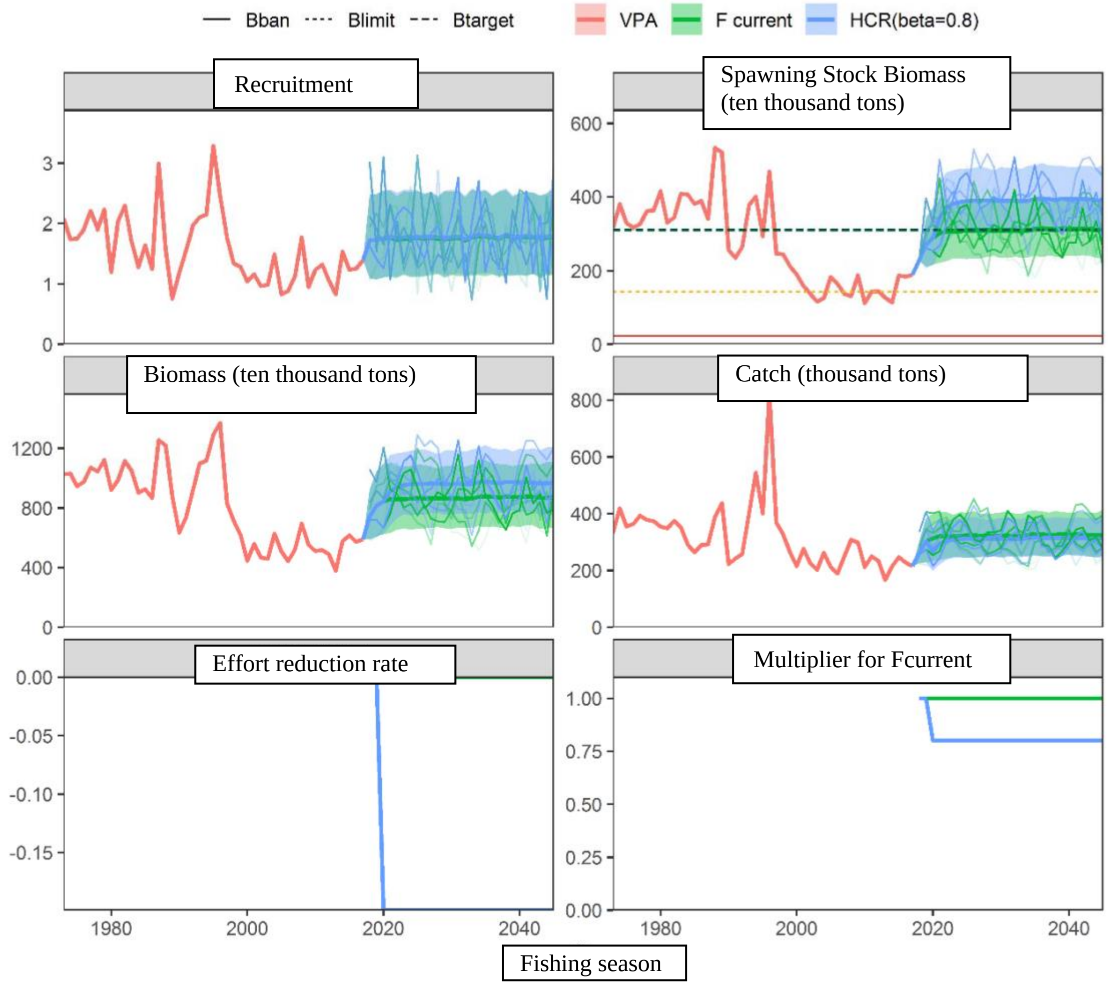


Figure 6. Average value of future projection based on the HCRs (solid line) and 80% confidence intervals

Shows the future projection results when fishing is conducted based on the HCRs 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. These are the results of using the standard value of 0.8 for the tuning parameter β in the HCRs. The thin line of each color shows the results of five trials randomly selected from 5000 future projections.

Table 1 Relationship among the various (biological) reference points, the average SSB at equilibrium, the ratio to the initial SSB (SB0) assuming no fishery, the average catch, the catch rate, and the effort multiplier for the current fishing pressure (Fcurrent, average catch pressure for 2015-2017)

(Biological) Reference Points	Optimization method	Spawning Biomass (Thousand tons)	Ratio to SB0	Catch (thousand tons)	CV of catch	Catch rate	Effort multiplier
SBmsy(SBtarget)	Least squares method	310	0.20	323	0.2	0.37	1
SB0.6msy(SBlimit)	Least squares method	143	0.09	194	0.59	0.42	1.26
SB0.1msy(SBban)	Least squares method	22	0.01	3	1.66	0.44	1.35

Table 2. Probability (%) of future SSB exceeding the target reference point

β	2018	2019	2020	2021	2022	2023	2024	2025	**2030**	**2040**
1	0	21	33	41	46	46	44	45	45	49
0.9	0	21	33	53	64	67	68	68	70	73
0.8	0	21	33	65	78	86	88	88	89	92
0.7	0	21	33	75	89	95	99	98	98	99
0.6	0	21	33	83	96	99	100	100	100	100
0.5	0	21	33	89	99	100	100	100	100	100

Future projection results when fishing is conducted based on the HCRs 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 SSB exceeding the limit reference point

β	2018	2019	2020	2021	2022	2023	2024	2025	**2030**	**2040**
1	100	100	100	100	100	100	100	100	100	100
0.9	100	100	100	100	100	100	100	100	100	100
0.8	100	100	100	100	100	100	100	100	100	100
0.7	100	100	100	100	100	100	100	100	100	100
0.6	100	100	100	100	100	100	100	100	100	100
0.5	100	100	100	100	100	100	100	100	100	100

Future projectino results when fishing is conducted based on the HCRs 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 SSB (tons)

β	2018	2019	2020	2021	2022	2023	2024	2025	**2030**	**2040**
1	230000	272000	290000	302000	307000	307000	307000	308000	308000	312000
0.9	230000	272000	290000	321000	337000	341000	344000	346000	346000	350000
0.8	230000	272000	290000	341000	369000	381000	386000	388000	389000	393000
0.7	230000	272000	290000	362000	407000	426000	435000	439000	440000	445000
0.6	230000	272000	290000	385000	449000	480000	493000	500000	504000	510000
0.5	230000	272000	290000	411000	497000	543000	565000	575000	584000	590000

Future projection results when fishing is conducted based on the HCRs 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	**2030**	**2040**
1	262000	302000	314000	320000	321000	320000	322000	323000	322000	326000
0.9	262000	302000	291000	309000	315000	316000	318000	320000	319000	322000
0.8	262000	302000	267000	294000	305000	308000	311000	312000	311000	315000
0.7	262000	302000	241000	276000	291000	297000	300000	302000	301000	305000
0.6	262000	302000	213000	254000	273000	281000	286000	288000	288000	291000
0.5	262000	302000	184000	228000	251000	261000	267000	270000	271000	274000

Future projection results when fishing is conducted based on the HCRs 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 Model Diagnosis Results of S-R Relationship Equation

The HS model was applied using the data from 1973 onward to the S-R relationship of Tsushima warm current population stock of chub mackerel. Various diagnostic results for the application of data to this model are shown below.

Supplementary Figure 1-1 shows the S-R curves for the HS, BH, and RI models, respectively. These models were optimized by the least squares method. RI had the lowest AICc, followed by BH. However, outside the observation range, when the SSB was small, the recruitment when using RI or BH tended to be more optimistic than when using HS. BH was the most optimistic when the SSB was high, and HS was located between BH and RI.

Supplementary Figure 1-2 shows Kobe plots indicating changes in stock status obtained when the HS, BH, and RI S-R relationship equations were used. In this comparison, we used the result of estimating the MSY by repeating the simulation 1000 times. In the case of using RI or BH, the SSB has never fallen below the limit reference point (SBlimit) in the past, and there is no observation data at SBlimit, whereas in the case of using HS, it was shown that the SSB in recent years has been gradually increasing from below SBlimit. In the stock assessment conducted in the last fiscal year, the levels and trends of this stock were low and increasing, and were closer to the results for when HS was used. In addition, a difference observed was that BH has never reached the MSY level in the past. The difference in SSB corresponding to SBban and SBlimit was the largest in HS and the smallest in BH. Compared to RI and BH, when HS is applied, urgent situations are less likely to occur when the SSB falls below the SBlimit. The decrease in the catch rate in the last five years (2013-2017) and the increase in the SSB along with this produced the same results with all the S-R relationship equations. Another common point was that the SSB in 2017 exceeded the limit reference point, but was significantly below the target reference point.

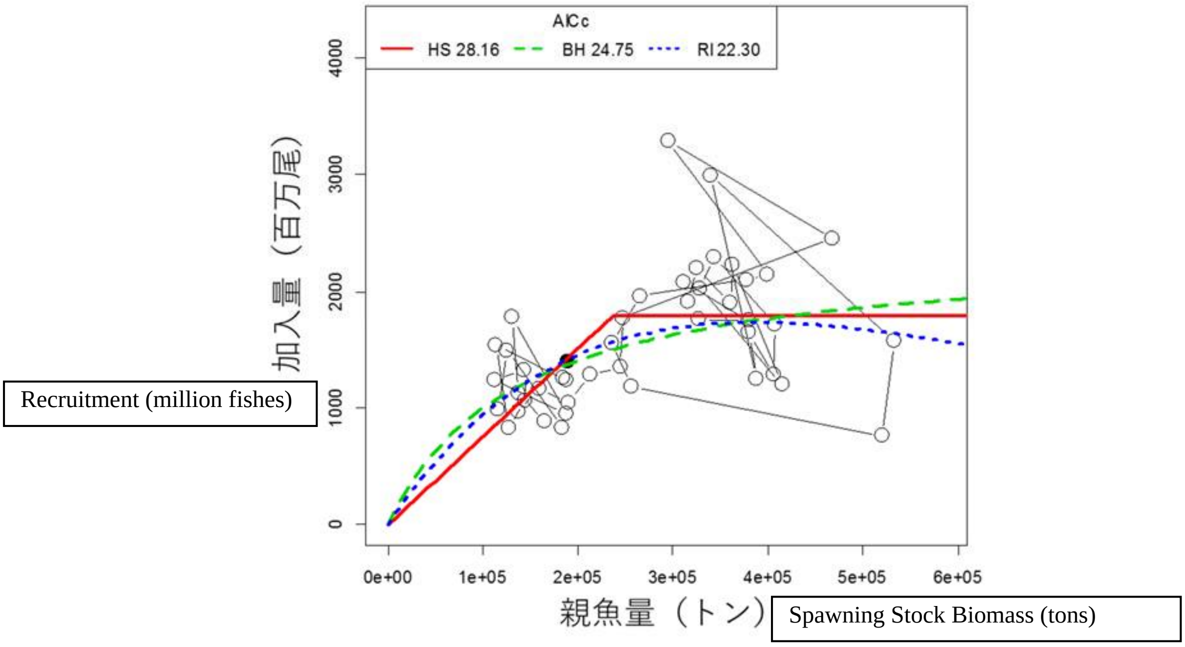
Supplementary Figure 1-3 shows the frequency distribution of residuals when HS is used. About the normality of the residuals, no significant deviation from the normal distribution was detected in both the Shapiro-Wilk test and the Kolmogorov-Smirnov test. The residuals did not show any significant changes over time, and the autocorrelation coefficients were low and not significant (Supplementary Figure 1-4).

Supplementary Figure 1-5 shows the comparison between the S-R curves and the parameter estimates due to the difference in the optimization method. The SSB at the break point was 268,000 tons when the least absolute value method was used for optimization, which was slightly higher than that when optimization was carried out by the least squares method (237,000 tons).

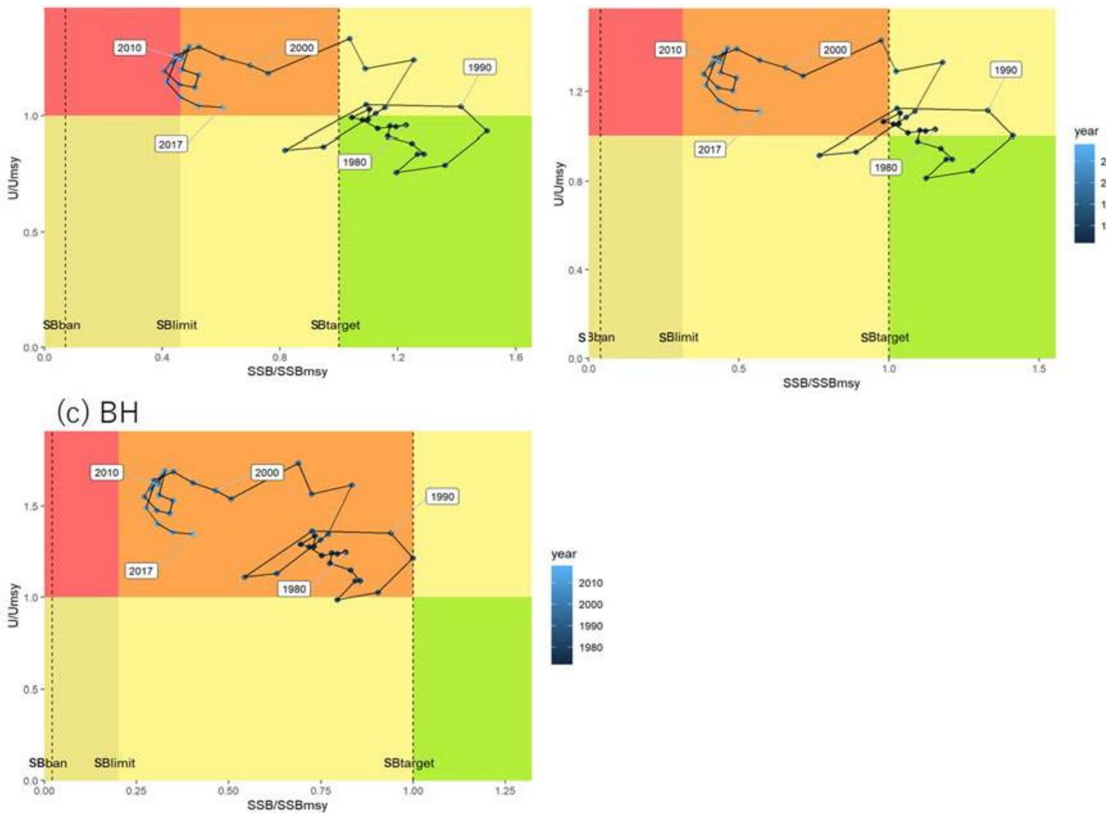
Supplementary Figure 1-6 shows the results of verifying the reliability of HS parameter estimation by residual bootstrap. When the least squares method was used for optimization, no discrepancy was found between the median and the point estimates in all parameter estimates. When the least absolute value method was used for optimization, discrepancy was observed between the median and the point estimate in standard deviation.

Supplementary Figure 1-7 shows the results of Jackknife analysis to confirm the robustness of parameter estimation. Here, b was strongly affected by the data of 1989, and excluding this data increased the estimated value of b by about 10%. The year 1989 was the second largest SSB ever, but recruitment was at a record low.

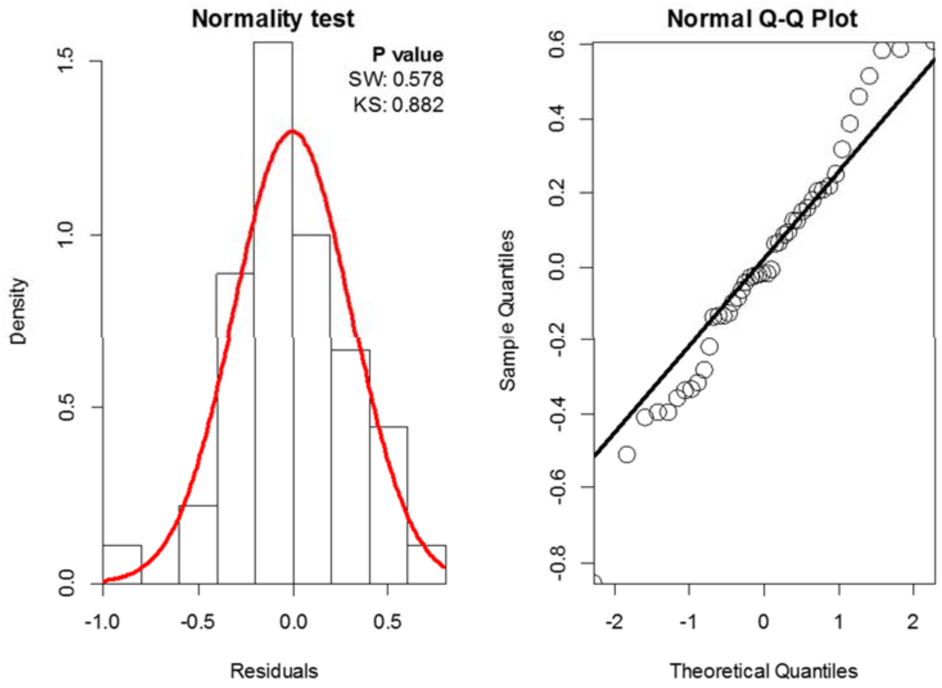
Supplementary Figure 1-8 shows the profile likelihood for the estimated parameters. The likelihood did not change significantly within the confidence interval of the residual bootstrap.



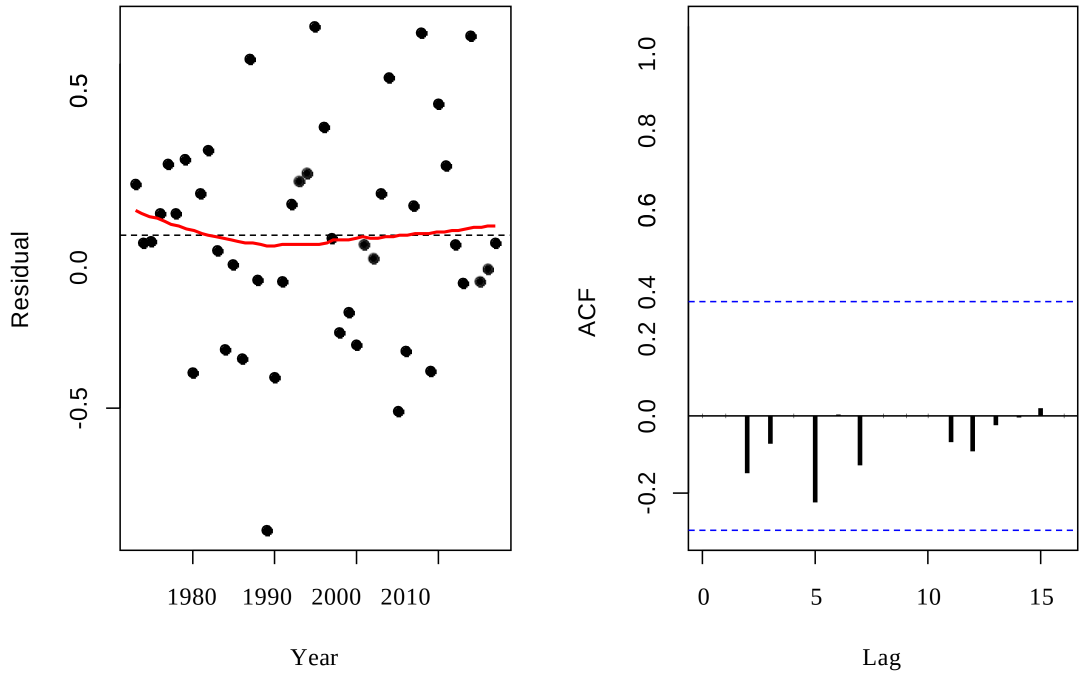
Supplementary Figure 1-1. S-R curves and AICc in each S-R relationship equation. Red line indicates HS, green line indicates BH, and blue line indicates RI respectively.



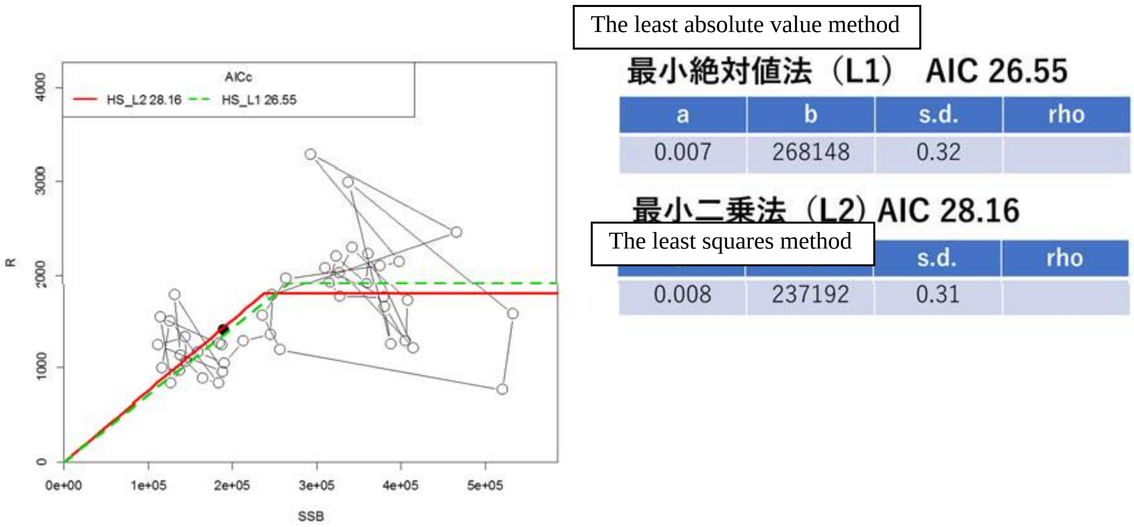
Supplementary Figure 1-2. Kobe plots showing changes in stock status obtained when the (a) HS, (b) RI, and (c) BH S-R relationship equations are used.



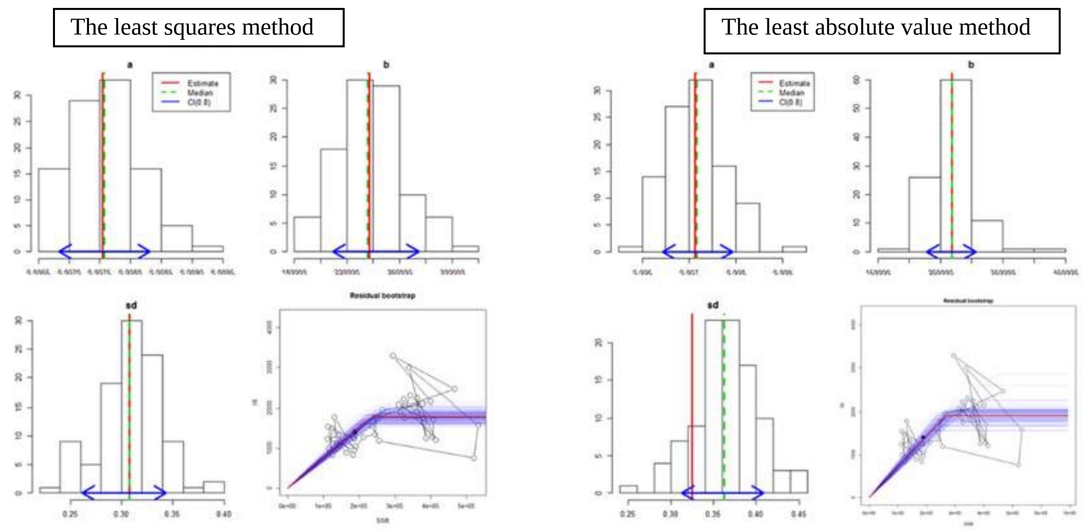
Supplementary Figure 1-3. Normality test result of residual distribution (left) and QQ plot (right)



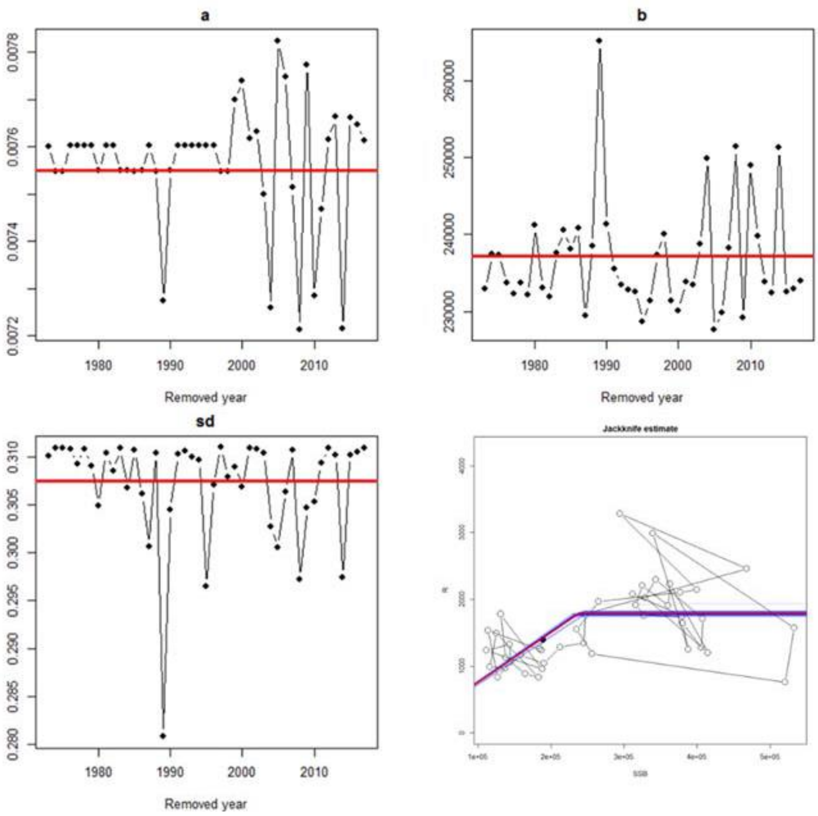
Supplementary Figure 1-4. Yearly change in recruitment residuals and autocorrelation coefficient



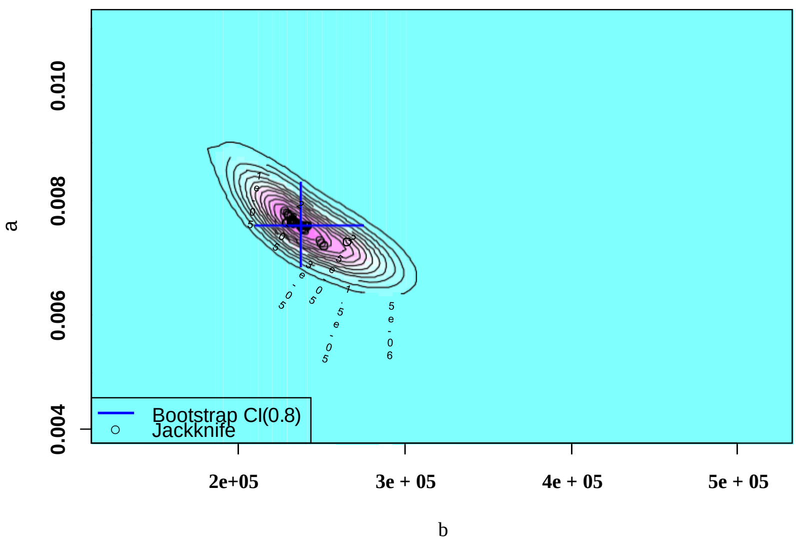
Supplementary Figure 1-5. Comparison between S-R curves and parameter estimates due to the difference in the optimization methods. The red line shows the curve when the least absolute value method is used for optimization and the green line shows the curve when the least squares method is used for optimization. Neither S-R equation considers autocorrelation.



Supplementary Figure 1-6. Result of reliability test of parameter estimation by residual bootstrap method.



Supplementary Figure 1-7. Result of robustness test of slope (a), breakpoint (b), and residual (c) in HS parameter estimates using Jackknife analysis. The figure shows the estimated values when each year is excluded (broken line) and estimated values for all data (red line). The least squares method was used as the optimization method.



Supplementary Figure 1-8. Profile likelihood for the estimated parameters. The figure shows 80% confidence interval (blue line) by bootstrap as well as the estimated values in Jackknife analysis. The least squares method was used as the optimization method.

Supplementary Material 2 Results When the Least Absolute Value Method is Used as the Optimization Method

For each reference point when the least absolute value method is used as the optimization method, Supplementary Table 2-1 shows the relationship among the ratio to the initial SSB (SB0) assuming no fishery, the average catch at equilibrium, the CV of catch, the catch rate, and the multiplier for the current fishing pressure. Supplementary Tables 2.2 to 2.5 show the probability of recovery to the target reference point, the probability of recovery to the limit reference point, changes in the average SSB, and changes in the average catch respectively. Here, the (biological) reference points SBtarget, SBlimit, and SBban were set to SBmsy, SB0.6msy, and SB0.1msy respectively. For 2018 and 2019, fishing is assumed based on Fcurrent.

Although the difference was smaller than when the least squares method was used, the SSB at the target reference point and the limit reference point increased. On the other hand, the CV of catch increased. When β was set to the standard value of 0.8, the probability of exceeding the target reference point was slightly lower than that using the least squares method. Future SSB was larger than that using the least squares method after 2021. This is probably because there is a difference between the break points and the expected maximum recruitment in each optimization method. The catch was higher from 2022, the following year of 2021 than that using the least squares method.

Supplementary Table 2-1 Relationship among the various (biological) reference points, the average SSB at equilibrium, the ratio to the initial SSB (SB0) assuming no fishery, the average catch, the catch rate, and the effort multiplier for the current fishing pressure (Fcurrent, average catch pressure for 2015-2017)

(Biological) Reference Points	Optimization method	Spawning Biomass (Thousand tons)	Ratio to SB0	Catch (thousand tons)	CV of catch	Catch rate	Effort multiplier
SBmsy(SBtarget)	Least squares method	310	0.20	323	0.2	0.37	1
	Least absolute value method	351	0.21	341	0.21	0.36	0.94
SB0.6msy(SBlimit)	Least squares method	143	0.09	194	0.59	0.42	1.26
	Least absolute value method	162	0.10	204	0.62	0.41	1.18
SB0.1msy(SBban)	Least squares method	22	0.01	32	1.66	0.44	1.35
	Least absolute value method	25	0.01	34	1.72	0.43	1.28

Supplementary Table 2-2. Probability (%) of future SSB exceeding the target reference point

β	2018	2019	2020	2021	2022	2023	2024	2025	2030	2040
1	0	7	15	29	37	40	40	42	43	48
0.9	0	7	15	37	52	59	63	64	67	71
0.8	0	7	15	45	67	79	84	85	87	90
0.7	0	7	15	56	80	91	96	97	97	99
0.6	0	7	15	64	88	97	100	100	100	100
0.5	0	7	15	72	94	99	100	100	100	100

Table 2-3. Probability (%) that future SSB will exceed the limit reference point

β	2018	2019	2020	2021	2022	2023	2024	2025	2030	2040
1	100	100	99	99	99	99	100	100	100	100
0.9	100	100	99	99	100	100	100	100	100	100
0.8	100	100	99	99	100	100	100	100	100	100
0.7	100	100	99	100	100	100	100	100	100	100
0.6	100	100	99	100	100	100	100	100	100	100
0.5	100	100	99	100	100	100	100	100	100	100

Table 2-4. Changes in future average SSB (tons)

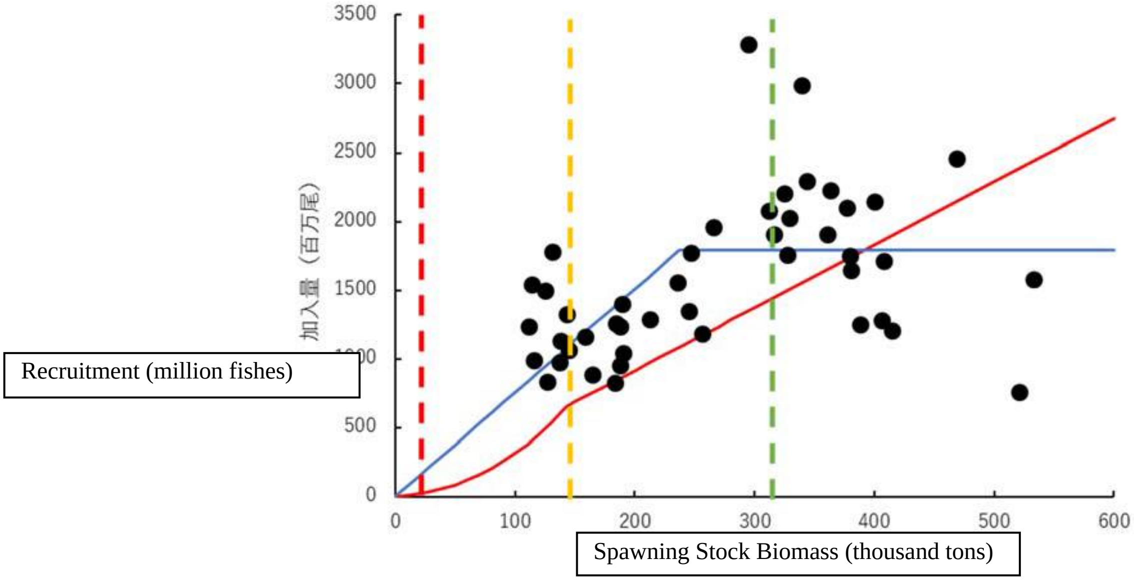
β	2018	2019	2020	2021	2022	2023	2024	2025	2030	2040
1	230000	262000	285000	313000	330000	336000	341000	345000	349000	354000
0.9	230000	262000	285000	331000	361000	375000	382000	388000	392000	397000
0.8	230000	262000	285000	351000	396000	418000	429000	436000	439000	445000
0.7	230000	262000	285000	371000	434000	467000	483000	491000	496000	502000
0.6	230000	262000	285000	394000	477000	523000	546000	558000	566000	572000
0.5	230000	262000	285000	418000	526000	588000	621000	638000	652000	660000

Table 2-5. Changes in future average catch (tons)

β	2018	2019	2020	2021	2022	2023	2024	2025	2030	2040
1	256000	293000	299000	318000	326000	329000	334000	337000	339000	344000
0.9	256000	293000	277000	305000	320000	326000	331000	335000	336000	340000
0.8	256000	293000	254000	290000	310000	319000	324000	327000	327000	331000
0.7	256000	293000	229000	272000	296000	307000	312000	300000	316000	320000
0.6	256000	293000	202000	250000	277000	290000	297000	315000	302000	305000
0.5	256000	293000	174000	223000	253000	268000	276000	280000	282000	285000

Supplementary Material 3 Relationship of SPR (F) When Using Fishing mortality Coefficient *F* Based on Harvest Control Rules

In order to show the control behavior based on the HCRs, the SPR (*F*) when the fishing mortality coefficient *F* was used based on the HCRs, was calculated and illustrated with the S-R relationship (Supplementary Figure 3). In this figure, if the curve showing the S-R relationship (blue solid line) is above the SPR (red solid line), the SSB increases, and if the curve is below the SPR, the SSB decreases. The intersection of the blue solid line and the red solid line is the SSB that becomes the equilibrium when β is 0.8. From this figure, it can be seen that if fishing is carried out at 0.8 Fmsy, the SSB increases until equilibrium is reached. In addition, the rule is such that when the SSB falls below the limit reference point (yellow broken line), the SSB is further increased.



Supplementary Figure 3. SPR (*F*) relationship when using the fishing mortality coefficient *F* based on the HCRs (red solid line) and S-R relationship estimated using HS (blue solid line). β was set to the standard value of 0.8. Black dots are scatter plots of the observed SSB and recruitment. The target reference point, limit reference point, and fishing ban level are indicated by the green broken line, yellow broken line, and red broken line, respectively.