

Research Institute Meeting Report on (Biological) Reference Points for the East China Sea Stock of Blue Mackerel (*Scomber Australasicus*) 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 East China Sea stock of blue mackerel in FY2018. The stock status of this stock is assessed to be medium based on the Spawning Stock Biomass in the last 26 years (1992-2017), and that the trend has been flat based on the changes in the biomass during the last five years (2013-2017). For this stock, we propose the Hockey Stick model (HS) optimized by the least absolute value method as a candidate for the stock-recruitment relationship equation, SB_{msy} (109,000 tons) as a candidate for the target reference point, SB_{0.6msy} (51,000 tons) as a candidate for the Limit Reference Point, and SB_{0.1msy} (8,000 tons) as a candidate for the fishing prohibition level. The catch pressure to achieve MSY is 0.77 times the current catch pressure (F_{current}: average catch pressure for 2015-2017).

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 Research and Education Agency)

1-2) Examination of stock-recruitment relationships

The models listed as candidates for the stock-recruitment relationship equations of this stock, and the results of applying them to the observed data are shown in the table below. The data used here are all available values for the years 1992 to 2017. In this stock, there is a weak positive correlation between the Spawning Stock Biomass (SSB) and recruitment (5% significance level), and high recruitment tends not to occur when the SSB is low. Here, three stock-recruitment relationships were studied, Hockey Stick model (HS), Ricker model (RI), and Beverton-Holt model (BH). Each stock-recruitment model is optimized by two methods, least absolute value method (L1) and least squares method (L2). Judging from AIC_c, the BH model optimized by the least squares method (BH-L2) was found to be the best, followed by the RI model optimized by the least squares method (RI-L2).

Stock-recruitment relationship	Optimization method	AICc	Δ AIC	Δ AIC ranking	Recruitment S.D.	Autocorrelation coefficient	Number of data items
HS	Least squares method	20.2	2.9	6	0.311	0	26
RI	Least squares method	18.1	0.8	2	0.299	0	26
BH	Least squares method	17.3	0	1	0.295	0	26
HS	Least absolute value method	19.8	2.5	5	0.332	0	26
RI	Least absolute value method	18.5	1.2	4	0.324	0	26
BH	Least absolute value method	18.2	0.9	3	0.322	0	26

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

In the selection of a stock-recruitment relationship, it is effective to select a relationship with a low estimated value of recruitment when the stock-recruitment relationship is extrapolated to a SSB lower than the past lowest SSB, in order to reduce the risk of overfishing. In this stock, the model that estimates the lowest recruitment in the region of less than 32,000 tons of SSB the lowest observed SSB in the past, was HS (HS-L1) optimized by the least absolute value method (Supplementary Figure 1- 1). Even in the case of RI and BH, the models optimized by the least absolute value method (RI-L1 and BH-L1, respectively) tended to underestimate the recruitment in the region of low SSB.

The SBmsy for each stock-recruitment relationship exceeds the maximum SSB (85,000 tons) for the past 26 years (1992-2017), excluding HS (HS-L2) optimized by the least squares method (Supplementary Material 1). The degree was particularly large in RI-L1 and BH-L1. Given these three stock-recruitment relationships, it was determined that past fishing pressures were always above Fmsy.

In the stock assessment in FY2018, the stock status of this stock was considered to be medium. The calculated Btarget value was slightly lower than the SSB in 2017 when assuming HS-L2, but significantly higher than the SSB in 2017 for other stock-recruitment relationships (Supplementary Material 1).

1-3) Candidates for stock-recruitment relationships

In this stock, we propose HS stock-recruitment relationship (HS-L1), which is optimized by the least absolute value method, as a recommended candidate in order to reduce the risk of overfishing and achieve the most realistic Bmsy possible (Figure 1). Under this stock-recruitment relationship, the estimation of recruitment during low stock is restrained, and although SBmsy exceeded the maximum SSB for the past 26 years, the extent was smaller than when RI-L1 and BH-L1 were assumed. For these reasons, it was believed that stock management using HS-L1 for the stock-recruitment relationship had a good balance between the viewpoint of stock protection and the reality of the management objectives. Even judging from AICc, HS-L1 was not significantly inferior to the best model.

In this group, HS-L2 was also examined in detail as a candidate for stock-recruitment relationship (Supplementary Material 2). Although, the HS-L2 overestimates the recruitment at low levels of SSB, which may increase the risk of overfishing if the assumption is incorrect. The fact that the past biomass fluctuated around Btarget is consistent with the results of stock assessment up to now (stock status fluctuated between medium and high levels). According to the current stock assessment, the historically lowest SSB (33,000 tons) is defined as the Blimit, which is defined as the boundary between low and medium levels.

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 stock-recruitment relationship that was suggested in 1-3) and the various settings used for future projections in the fishery Stock assessment of the waters around Japan in FY2018 (Japan Fisheries Research and Education Agency) were used. In other words, the stock-recruitment relationship was assumed as the HS model (Figure 1) based on the recruitment and SSB from 1992 to 2017 estimated by stock assessment, and the selectivity rate was calculated from the 2013-2017 average of the fishing mortality coefficient (F value) for each age. The current fishing pressure (F_{current}) 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 rate (Figure 2), and the average weight of the catch was the average value for 2015-2017 (see table below).

Age	Natural mortality	Maturity rate	Average weight (g)	Selectivity rate	Current fishing mortality Coefficient
0	0.4	0	238	0.18	0.43
1	0.4	60	354	0.36	0.61
2	0.4	85	542	0.60	0.88
3 years or older	0.4	100	709	1.00	0.88

A forecast was made for the future under the above conditions and the stock-recruitment relationship (HS-L1), the maximum value of the catch at equilibrium was set as the MSY, and the SSB when MSY was achieved was set as SB_{msy}. In this stock, the equilibrium was set at about 68 years after the start of future projection, based on 20 times the generation time of blue mackerels (about 3.4 years). The number of simulation trials was 5,000, and the residual of recruitment was set as a Lognormal (Distribution).

2-2) Stock-recruitment relationship used

HS without autocorrelation optimized by the least absolute value method was used as the stock-recruitment relationship. The parameters are shown in the table below, and the relationship between the past SSB and recruitment is shown in Figure 1.

stock-recruitment relationship equation	Optimization method	Autocorrelation	a	b	S.D.
HS	Least absolute value method	No	0.005	84,935	0.33

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

2-3) (Biological) reference points

The target reference point (SB_{target}) for this stock was set to the standard value SB_{msy} and the limit reference point (SB_{limit}) and the fishing ban level (SB_{ban}) were respectively set to the SSB at which 60% (SB_{0.6msy}) and 10% (SB_{0.1msy}) catch of MSY can be obtained. These are all standard values in the ABC calculation rules. The table in the following paragraph shows the biomass at each standard.

(Biological) Reference Points	Spawning Stock Biomass	Standard
Target Reference Point	109,000 tons	SB _{msy}
Limit Reference Point	51,000 tons	SB _{0.6msy}
Fishing prohibition level	8,000 tons	SB _{0.1msy}

For each (biological) 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 the catch, the fishing rate, and the multiplier for the current catch pressure. Figure 3 shows the SSB at equilibrium in future projection using the stock-recruitment relationship, and the average catch at age with respect to this. When the SSB is below the SB_{limit}, most of the catch consists of 0- and 1-year-old fish, but when SB_{msy} is achieved, the proportion of older fish increases.

2-4) Target Reference Point and Exploitation Rate

Figure 4 shows the Kobe plots when the target reference point is set as the recommended value. Assuming HS-L1 as the stock-recruitment relationship, out of the past 26 years, the catch pressure for this stock was estimated to have been below F_{msy} for 24 years, excluding the years 1996 and 2004. The SSB reached a record low in 2010, but since then, the SSB increased as the catch pressure has gradually decreased and it is estimated that the SSB has now recovered to a level slightly below the limit reference point.

2-5) Harvest Control Rules

Figure 5 shows the relationship between the SSB and the fishing mortality coefficient for the Harvest Control Rules using the standard target reference point, limit reference point, and fishing ban level.

2-6) Future prediction of stock based on Harvest Control Rules

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

Figure 6 shows the change in the recruitment, SSB, Biomass, catch, and effort reduction rate when the values shown 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 based on the HCRs (Figure 5) starts from 2020, and the catches for 2018 and 2019 were based on F_{current}. Since the SSB in recent years has fallen below the limit reference point, the fishing pressure has been reduced from β F_{msy} (Figure 5) and reduced to 0.77 times that of F_{current} (Table 1). The catch in 2020 was temporarily reduced by 10,000 tons or more compared to fishing under F_{current}, but was thereafter estimated to increase gradually with the recovery of SSB (Figure 6).

(2) When tuning parameter β is changed

Tables 2 to 5 show the probability of SSB exceeding the target reference point and limit reference point, changes in average SSB, and changes in average catch when β is changed between 0.0 and 1.0 in the future projection. Although the current SSB of this stock is less than 50% of the target reference point, a favorable recovery is expected under the catch restrictions. Even if the standard value of 0.8 is used, it is predicted that the target reference point will be reached with a 83% probability in 2028, 10 years after the latest year of available data (Table 2). On the other hand, when β was 1.0, the probability of recovery to the target reference point was less than 40%. In addition, although the current SSB of this stock is below the limit reference point, even if β is set to 1.0, it is predicted that the SSB will exceed target reference point with a probability of 99% in 2028 (Table 3). If β was reduced to 0.5 or less, it was predicted that the SSB could be maintained at or above the limit reference point from 2022. If the catch restrictions are enforced, the catch in 2020 will be temporarily lower than in 2018 and 2019 when fishing was carried out at F_{current} (Table 5), but an increase in SSB is expected after 2021 (Table 4). The lower the β , the faster the rate of growth in the SSB after 2021 (Table 4), but the lower the catch (Table 5).

(3) Study of tuning parameter β

In order to catches under the catch restrictions after 2022 to exceed catches under F_{current} in 2019, β must be at least 0.7, and the β that maximizes the catch over the nine years from 2020 to 2028 needs to be 0.9 (Table 5). However, considering that the probability of recovery to the target reference point decreases as β increases, the standard value of 0.8 was considered to be appropriate as the value of β .

3. Summary

The stock-recruitment relationships and (biological) reference points of this stock were examined using data on the stock assessment of the East China Sea stock of blue mackerel in FY2018. In this stock assessment, the stock status of this stock is assessed to be medium and that the trend has been flat based on the changes in the biomass during the last five years (2013-2017). Since there is a positive correlation between the SSB and the recruitment, the recovery of the SSB is considered necessary to use the stock effectively and sustainably.

The stock-recruitment relationship of this stock was HS without considering autocorrelation, and the least absolute value method was used as the optimization method. The considerations in selecting this stock-recruitment relationship are that it is effective from a stock protection perspective to underestimate recruitment when SSB is small, and it is possible to set a realistic SB_{target} that does not greatly exceed the maximum SSB in the past 26 years. For each management standard, the target reference point is set as the stock status that achieves MSY, therefore, SB_{msy} (109,000 tons) estimated from the above-mentioned stock-recruitment relationship is used, and the standard values $SB_{0.6\text{msy}}$ (51,000 tons) and $SB_{0.1\text{msy}}$ (8,000 tons) are respectively set as the limit reference point and the fishing prohibition level.

In recent years, the SSB has fallen below the limit reference point and target reference point and the fishing rate for achieving MSY is 32% and the catch pressure is 0.77 times that of F_{current} . Considering the catch in the next 10 years and the probability of recovery to the target reference point, the appropriate adjustment factor β was considered to be 0.8. Under these management measures, it is predicted that the MSY level will be achieved in 2028 with a probability of 83%.

4. Future considerations

One of the factors that brings great uncertainty to the stock assessment results of this stock is that it cannot take into account fishing by Chinese fishing vessels. In addition, uncertainties regarding future

projection include the inability to accurately predict the catches by 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 “mackerels”, combining chub mackerel and blue mackerel. These factors may affect the stock-recruitment relationship, (biological) reference points, and the probability of achieving the management goals, etc.

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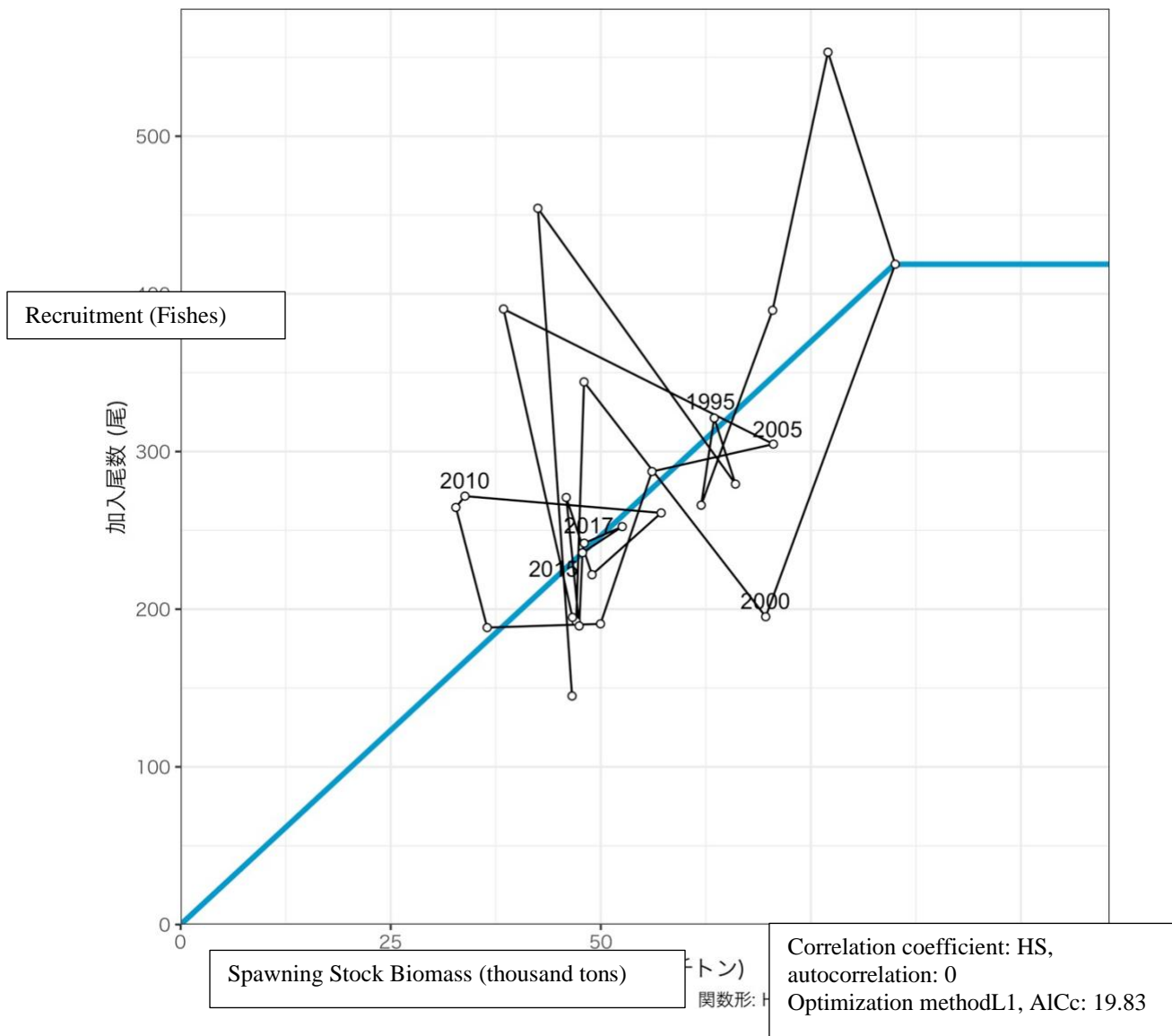


Figure 1. stock-recruitment relationships

The numbers in the figure indicate class groups. The Hockey Stick model (HS) was used for the stock-recruitment curve, and the parameters were estimated by the least absolute value method without considering autocorrelation.

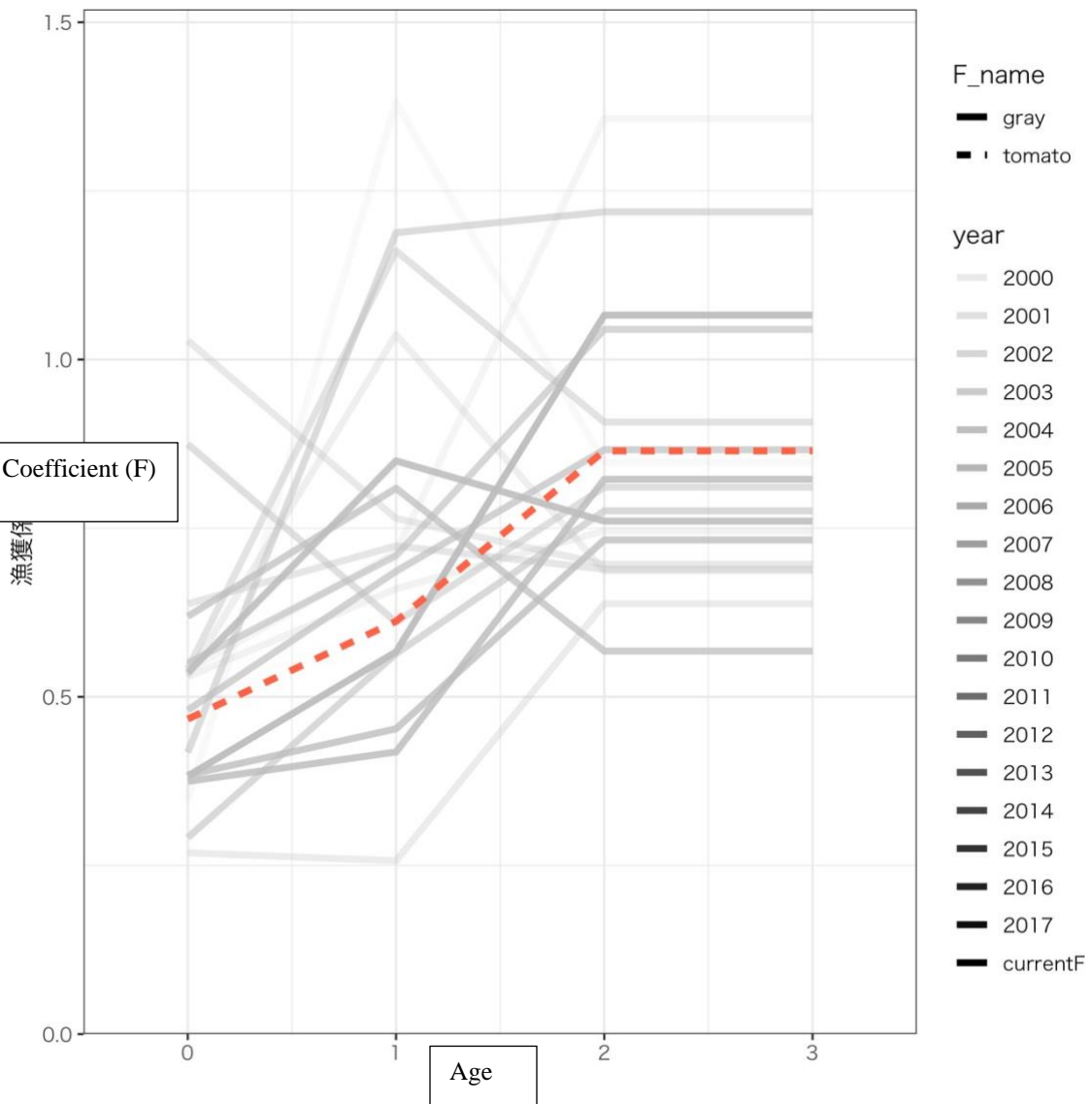


Figure 2. F values by age

The F value by age, which indicates the current catch pressure ($F_{current}$), is shown by a red line, and the values after the 2000 fishing season are indicated by a gray line.

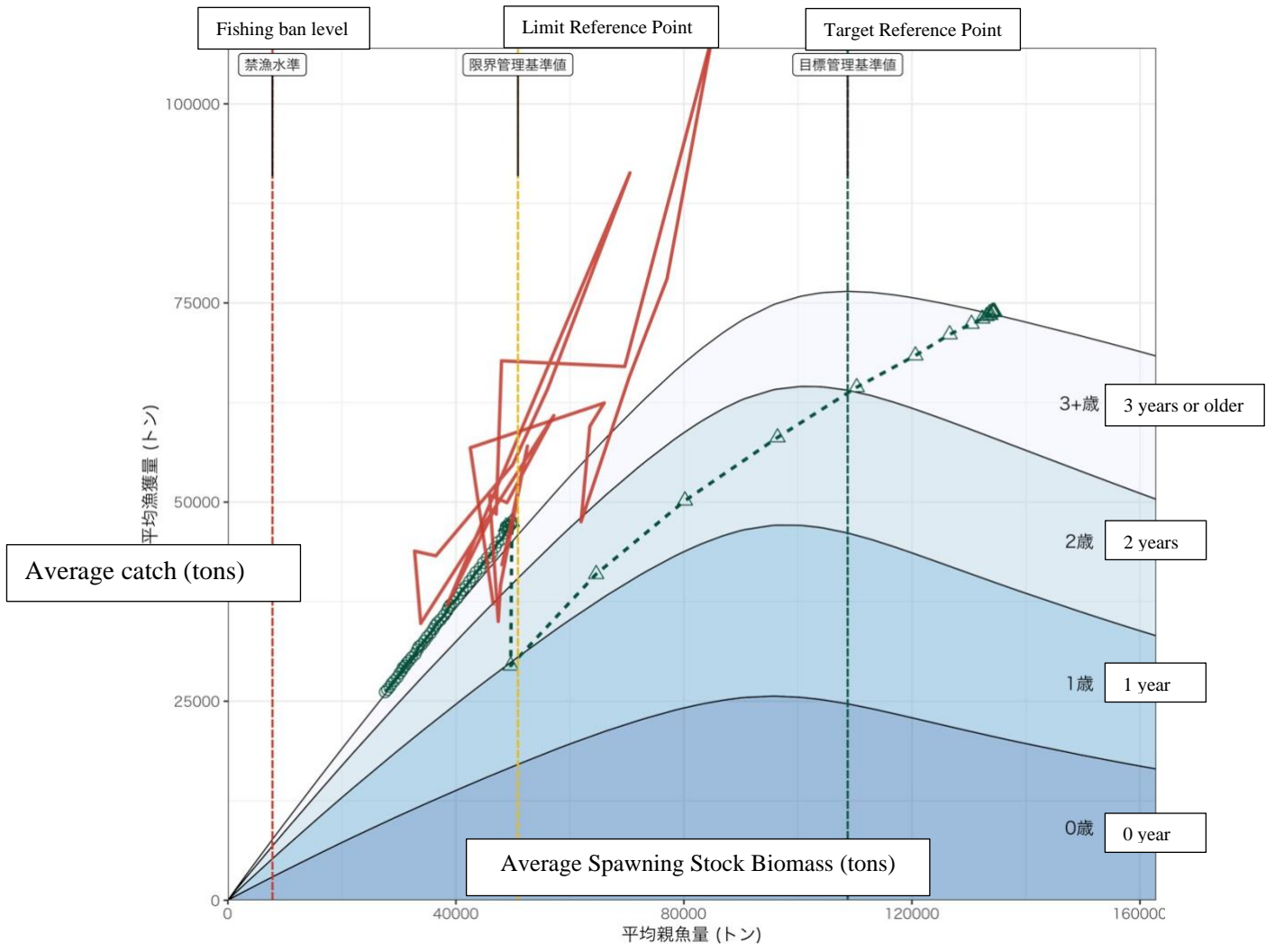


Figure 3. Relationship between the (biological) reference points and the catch at age curves

The average value of the catch at age with respect to the SSB at equilibrium in the future projection using the assumed stock-recruitment relationship is indicated by the area, the observed values of the catch and the SSB (red line), and the locus of the relationship between the SSB and the catch in the future projection (solid green line and \circ : catch by $F_{current}$, green broken line and Δ : catch by the Harvest Control Rules (HCR) when β is the standard value of 0.8) are respectively shown below. The initial SSB (SB_0) is 417,000 tons.

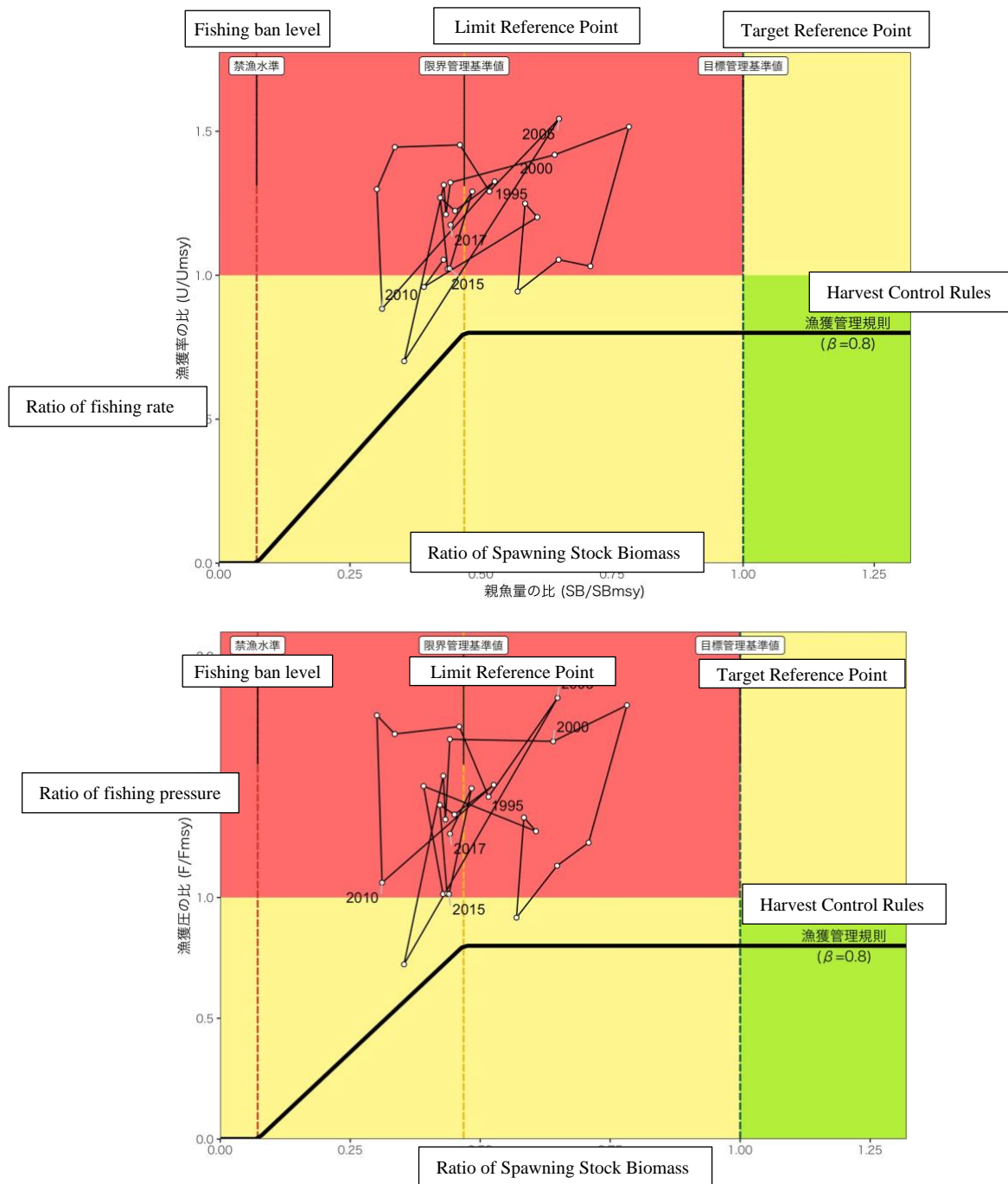


Figure 4. Kobe plot based on fishing rate (top) and fishing pressure (bottom) (Four sections)

The target reference point, limit reference point, and fishing ban level in the figure indicate the three (biological) reference points, SB_{target} , SB_{limit} , and SB_{ban} , for the SSB, respectively. SB_{msy} , $SB_{0.6msy}$, and $SB_{0.1msy}$ were used as these reference points, respectively.

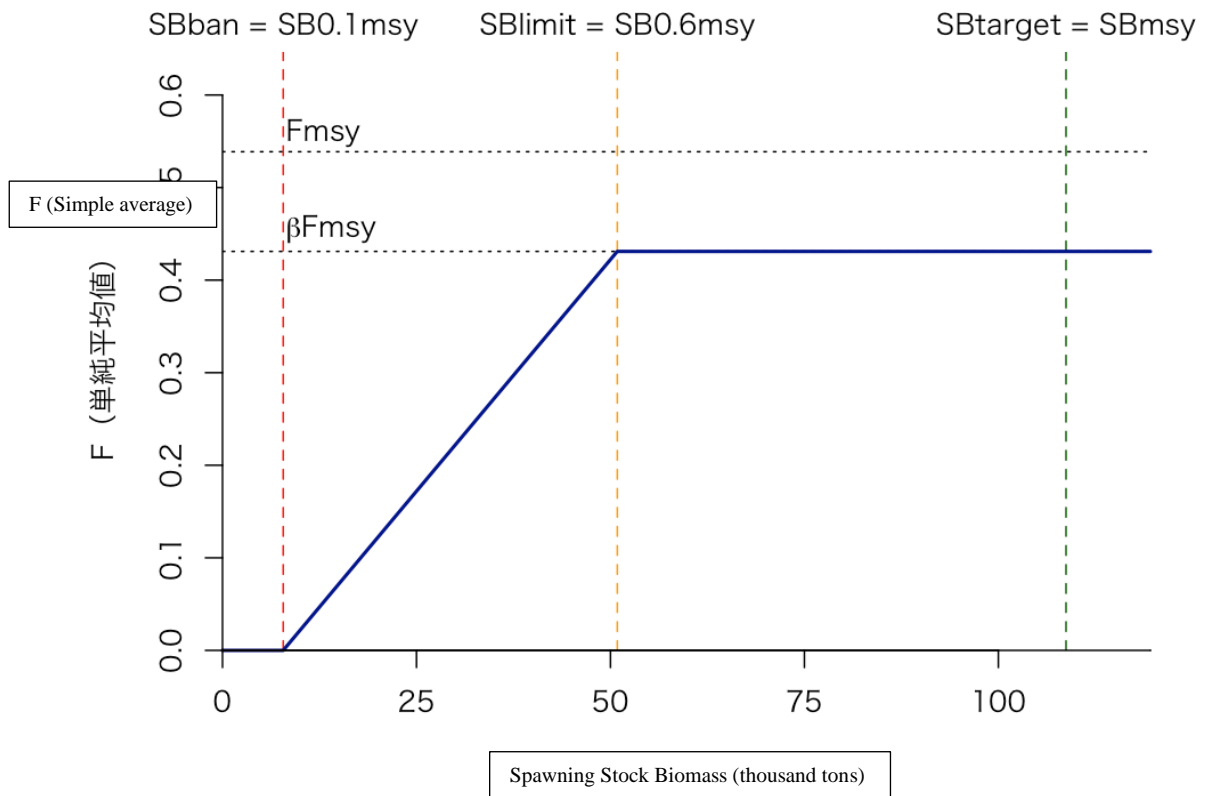


Figure 5. Harvest Control Rules

Btarget, Blimit, and Bban in the figure indicate the three (biological) reference points, SBtarget, SBlimit, and SBban, respectively, for the SSB. SBmsy, SB0.6msy, and SB0.1msy are used for these reference points, respectively, and the HCR based on the standard values is shown by a blue line. The standard value of 0.8 was used for the tuning parameter β .

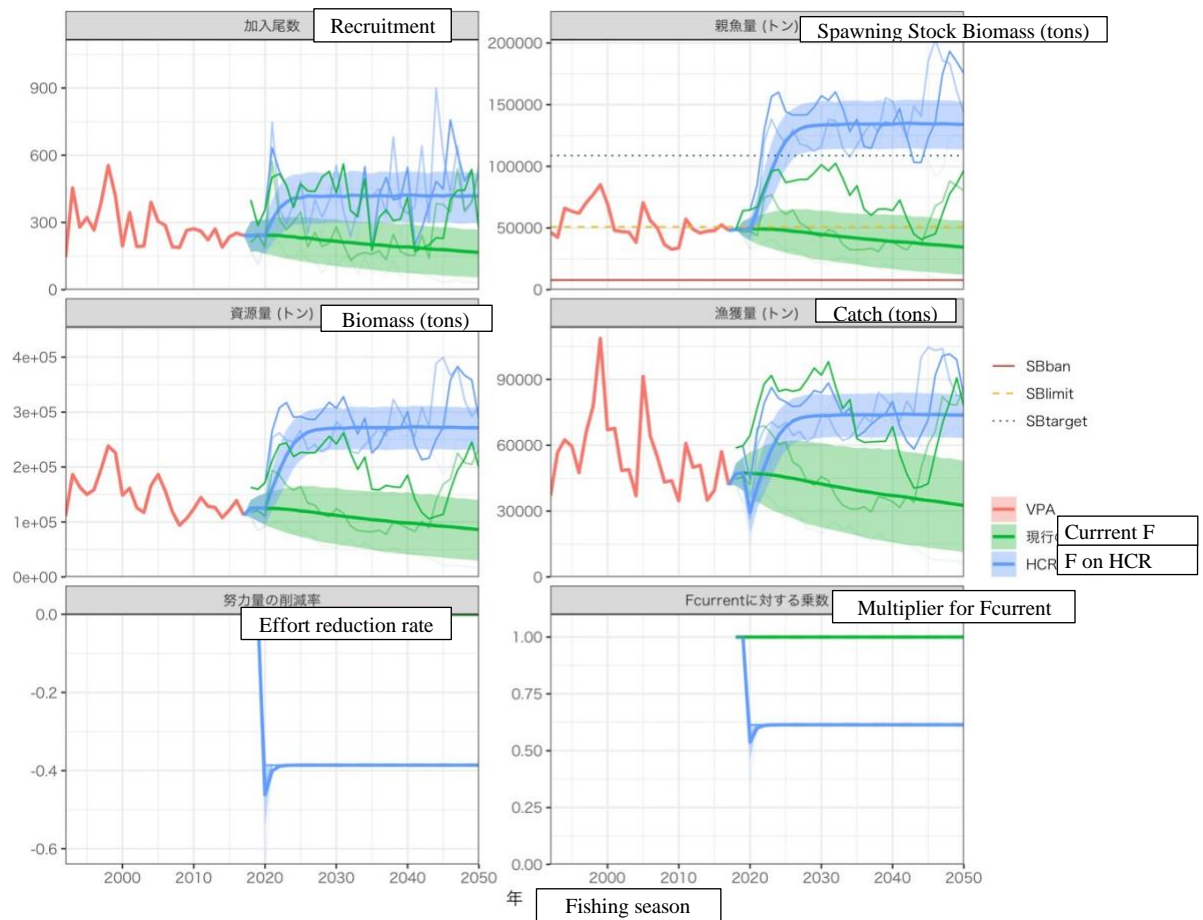


Figure 6. Average value of future projection based on the Harvest Control Rules (solid line) and 80% confidence intervals

The following shows the changes when the three (biological) reference points, SBtarget, SBlimit, and SBban of the HCRs are set to SBmsy, SB0.6msy, and SB0.1msy, respectively. It was assumed that fishing based on the HCRs would be carried out from the 2020 fishing season, and the catch in the 2018 and 2019 fishing seasons was based on Fcurrent. The standard value of 0.8 was used for β .

Table 1 Relationship among the various (biological) reference points, the average SSB at equilibrium, the ratio to the initial SSB (B0) assuming no fishery, the average catch, the fishing rate, and the effort multiplier for the current fishing pressure

(Biological) Reference Point	Spawning Stock Biomass	Ratio to B0	Catch	CV of catch	Fishing rate	Effort multiplier
Btarget0	109000	0.26	76000	0.18	0.32	0.77
Blimit0	51000	0.12	46000	0.59	0.37	0.95
Bban0	8000	0.02	8000	1.59	0.39	1.04

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

β	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040
1.0	0	0	0	1	4	10	18	24	29	35	38	42	43	47
0.9	0	0	0	2	7	18	32	44	53	59	63	65	67	70
0.8	0	0	0	2	11	31	50	66	76	82	83	85	85	86
0.7	0	0	0	3	18	45	69	85	91	95	95	96	96	97
0.6	0	0	0	4	27	62	85	95	98	99	99	99	99	100
0.5	0	0	0	6	37	76	95	99	100	100	100	100	100	100
0.4	0	0	0	8	48	87	99	100	100	100	100	100	100	100
0.3	0	0	0	10	61	93	100	100	100	100	100	100	100	100
0.2	0	0	0	13	71	97	100	100	100	100	100	100	100	100
0.1	0	0	0	17	80	99	100	100	100	100	100	100	100	100
0.0	0	0	0	22	87	100	100	100	100	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	2026	2027	2028	2029	2030	2040
1.0	0	38	39	69	83	91	95	97	98	99	99	99	99	100
0.9	0	38	39	75	90	96	99	99	100	100	100	100	100	100
0.8	0	38	39	81	95	99	100	100	100	100	100	100	100	100
0.7	0	38	39	85	98	100	100	100	100	100	100	100	100	100
0.6	0	38	39	89	99	100	100	100	100	100	100	100	100	100
0.5	0	38	39	91	100	100	100	100	100	100	100	100	100	100
0.4	0	38	39	93	100	100	100	100	100	100	100	100	100	100
0.3	0	38	39	95	100	100	100	100	100	100	100	100	100	100
0.2	0	38	39	96	100	100	100	100	100	100	100	100	100	100
0.1	0	38	39	97	100	100	100	100	100	100	100	100	100	100
0.0	0	38	39	98	100	100	100	100	100	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 4. Changes in future average SSB (tons)

β	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040
1.0	48776	49813	49612	59384	68266	77088	84825	91345	96038	100008	102751	104470	105712	108900
0.9	48776	49813	49612	61933	73928	86205	96943	105487	111087	115230	117670	118897	119636	121074
0.8	48776	49813	49612	64600	80181	96425	110315	120607	126618	130443	132337	133074	133437	134193
0.7	48776	49813	49612	67392	87036	107711	124848	136669	142887	146427	147981	148492	148707	149343
0.6	48776	49813	49612	70316	94515	120060	140632	154063	160725	164320	165860	166378	166589	167289
0.5	48776	49813	49612	73377	102644	133510	157941	173419	181029	185132	186978	187692	187996	188870
0.4	48776	49813	49612	76583	111468	148218	177230	195528	204778	209900	212380	213492	214005	215220
0.3	48776	49813	49612	79942	121020	164422	199027	221176	232962	239782	243355	245169	246085	247975
0.2	48776	49813	49612	83461	131341	182369	223950	251322	266842	276299	281652	284666	286329	289592
0.1	48776	49813	49612	87148	142489	202366	252702	287099	307999	321467	329685	334739	337772	343917
0.0	48776	49813	49612	91013	154519	224747	286078	329894	358478	378011	390836	399364	404910	417301

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	2026	2027	2028	2029	2030	2040
1.0	47000	48000	35000	45000	52000	58000	63000	66000	70000	72000	73000	74000	75000	77000
0.9	47000	48000	32000	43000	51000	58000	64000	68000	71000	73000	74000	75000	75000	76000
0.8	47000	48000	29000	41000	50000	58000	64000	68000	71000	72000	73000	73000	74000	74000
0.7	47000	48000	26000	38000	48000	57000	63000	67000	69000	70000	71000	71000	71000	71000
0.6	47000	48000	23000	35000	45000	54000	60000	64000	66000	67000	67000	67000	67000	68000
0.5	47000	48000	20000	31000	41000	49000	56000	59000	61000	62000	63000	63000	63000	63000
0.4	47000	48000	16000	26000	36000	44000	50000	53000	55000	56000	56000	57000	57000	57000
0.3	47000	48000	12000	21000	29000	36000	42000	45000	47000	48000	48000	49000	49000	49000
0.2	47000	48000	8000	15000	21000	27000	31000	34000	36000	37000	37000	37000	38000	38000
0.1	47000	48000	4000	8000	11000	15000	18000	19000	21000	21000	22000	22000	22000	22000
0.0	47000	48000	0	0	0	0	0	0	0	0	0	0	0	0

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.

The HS model was applied using the data from 1992 onwards for the stock-recruitment relationship of East China Sea stock of blue mackerel. Various diagnostic results for the application of data to this model are shown below.

The Hockey Stick model (HS), Ricker model (RI), and Beverton-Holt model (BH) without considering autocorrelation, and optimized by the least absolute value method (L1) and the least squares method (L2) were studied as the candidate stock-recruitment curves. Supplementary Figure 1-1 shows the results of application of each model to the data for this stock. In this stock, the model that estimates the lowest recruitment in the region less than the historical lowest SSB (32,000 tons), was HS-L1. The management policy based on HS-L1 as the stock-recruitment relationship was considered to be effective in terms of reducing the risk of overfishing during low levels of SSB. From the similar perspective, RI-L1 and BH-L1 were also considered to be relatively good models. On the other hand, HS-L2 tended to overestimate the recruitment in regions of low SSB, while it tended to underestimate the recruitment in regions of high SSB.

The changes in stock status under the assumption of HS-L1, HS-L2, RI-L1, and BH-L1 are shown in Kobe plots (Supplementary Figure 1-2). According to the ABC calculation rules, when SB_{target} is SB_{msy} , the SB_{target} when assuming RI-L1 and BH-L1 is 209,000 tons (Supplementary Table 1-1c) and 124,000 tons (Supplementary Table 1-1d), respectively, and this will greatly exceed the maximum SSB of the past 26 years (85,000 tons). The SB_{target} when assuming HS-L1 was 109,000 tons (Supplementary Table 1-1a), which was still higher than the SSB in 2017, but to a lesser extent than that of RI-L1 and BH-L1. Therefore, it was concluded that a management policy assuming HS-L1 as a stock-recruitment relationship could set a more realistic SB_{limit} than RI-L1 and BH-L1.

If HS-L2 is assumed, the current SSB is assessed to be slightly higher than MSY. Although this result was more optimistic than when the above three stock-recruitment relationships were assumed, it was in good agreement with the stock assessment results of this stock. The stock status in FY2018 is assessed to be medium based on the SSB in the last 26 years, and that the trend has been flat based on the changes in the biomass during the last five years (2013-2017).

Supplementary Figure 1-3 shows the results of the normality test for the residual of the estimated recruitment value for HS-L1, which was a candidate for the stock-recruitment relationship in this stock. No significant deviation from the normal distribution was detected in both the Shapiro-Wilk test and the Kolmogorov-Smirnov test. No clear trend was observed in the aging of residuals, and the autocorrelation coefficient was low (Supplementary Figure 1-4).

In this stock, HS-L1 is recommended as a candidate stock-recruitment relationship; however, when the optimization method is changed to the least squares method (HS-L2), the position of the break point changes greatly (Supplementary Figure 1-5), so HS-L2 was also examined in detail (Supplementary Table 1-2, Supplementary Material 2). The SSB at the break point of HS (parameter b) was the maximum SSB for the past 26 years (85,000 tons) in HS-L1, but the minimum SSB (33,000 tons) in HS-L2 (Supplementary Table 1-2). The slope of HS (parameter a) was larger for HS-L2.

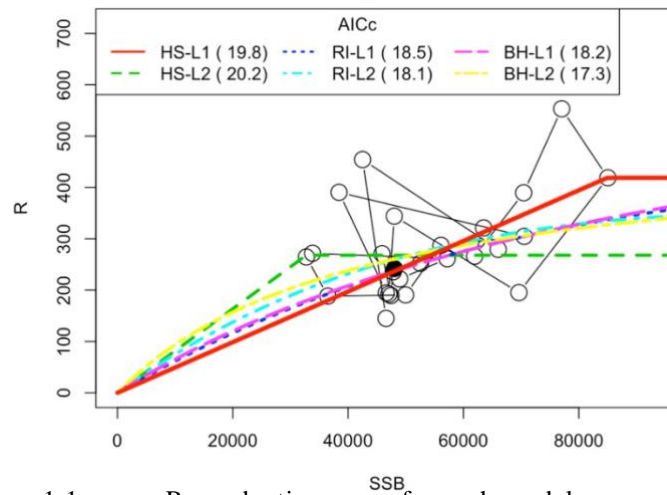
Supplementary Figures 1-6 and 1-7 show the results of verifying the reliability of HS parameter estimation by residual bootstrap. In the results for HS-L1, no difference was found between the point estimate and the median of the bootstrap sample for both parameters a and b (Supplementary Figure 1-6).

Since parameter b was estimated at the position of the largest SSB in the past, the bootstrap sample showed a long-tailed distribution on the low SSB side. The results for HS-L2 also showed little difference between the point estimate and the median of the bootstrap sample for parameters a and b (Supplementary Figure 1-7). Since parameter b was estimated at the position of the minimum SSB in the past, the bootstrap sample showed a long-tailed distribution on the high SSB side.

Jackknife analysis was performed to confirm the robustness of the HS curve parameter estimation. The parameters of HS-L1 were strongly affected by the low recruitment and low SSB of 1992-2008, and the high recruitment and high SSB of 1997-1999 (Supplementary Figure 1-8). When the data for each of these years was removed, the values of each parameter fluctuated significantly and were close to the values of the HS-L2 parameters (Supplementary Table 1-2). The parameters of HS-L2 were strongly affected by the low SSB of 2009-2010, the low SSB but high recruitment of 1993-2004, and the high SSB but low recruitment of 2000 (Supplementary Figure 1-9). The HS-L2 parameters also fluctuated significantly when the data for these years was removed, and were close to the HS-L1 parameters (Supplementary Table 1-2).

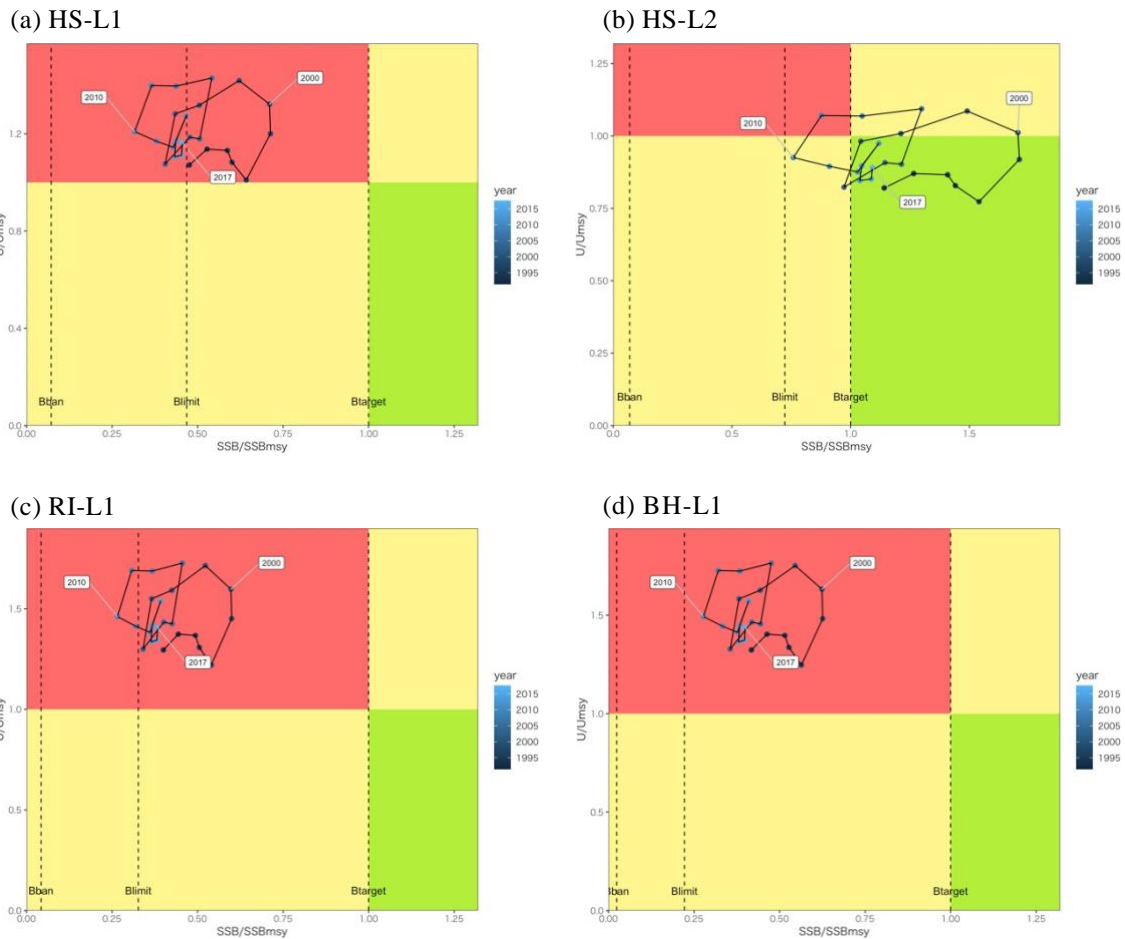
Profile likelihoods for HS-L1 and HS-L2 parameter estimates are shown in Supplementary Figures 1-10 and 1-11, respectively. Although the likelihood did not change significantly within the range of 80% confidence interval of the residual bootstrap, in both models, a region with a slightly high likelihood was found outside the range of the confidence interval, which corresponded to the region of the parameter estimates when the optimization method was changed.

Based on the above, it is assumed that there is a degree of uncertainty in the parameter estimates that cannot be ignored when applying HS to the data of this stock. As described above, the management policy assuming HS-L1 is judged to have an excellent balance between overfishing risk and realistic management objectives, but assuming that the true MSY was close to the MSY value when HS-L2 was assumed, the management policy under the assumption of HS-L2 was also examined in detail (Supplementary Material 2).



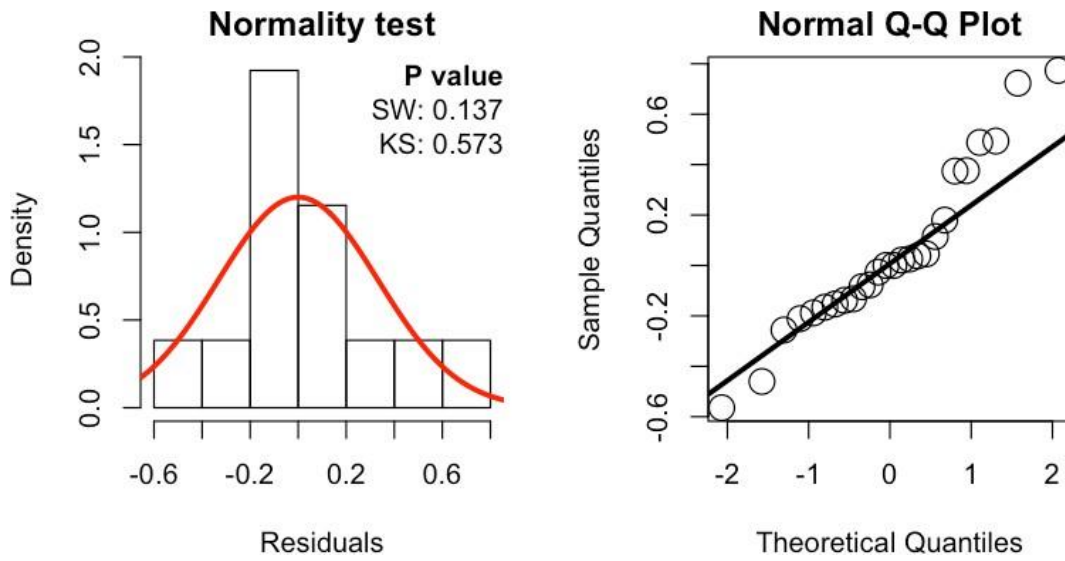
Supplementary Figure 1-1. Reproduction curve for each model

The figure shows the Hockey Stick model (HS), Ricker model (RI), and Beverton-Holt model (BH) stock-recruitment relationship equations optimized by the least absolute value method (L1) and the least squares method (L2). The number in parentheses is the AICc of each model.

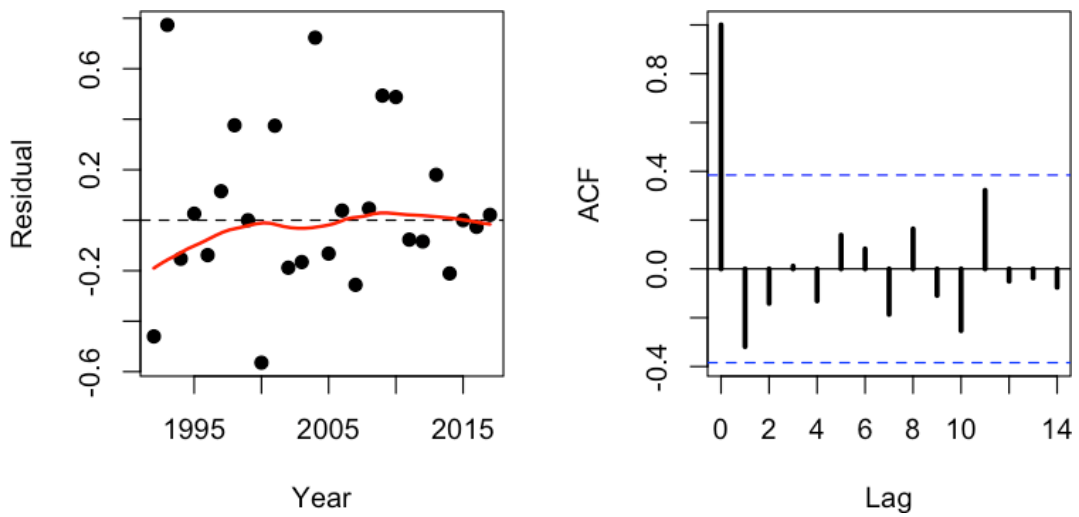


Supplementary Figure 1-2. Kobe plots obtained assuming each stock-recruitment relationship

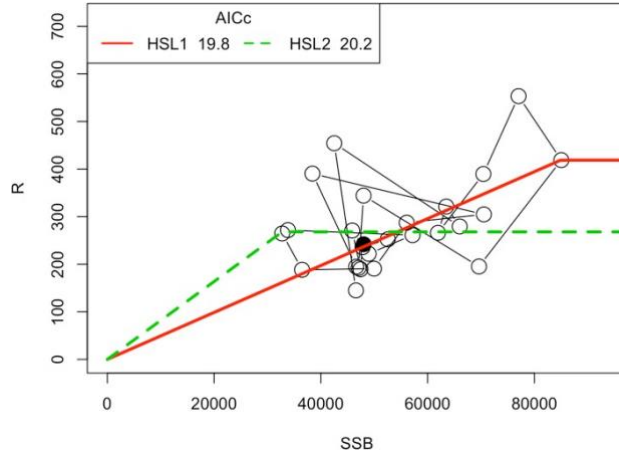
The figures show the cases where HS optimized by the least absolute value method (a) and the least squares method (b), and the RI (b) and BH (c) optimized by the least absolute value method are respectively assumed.



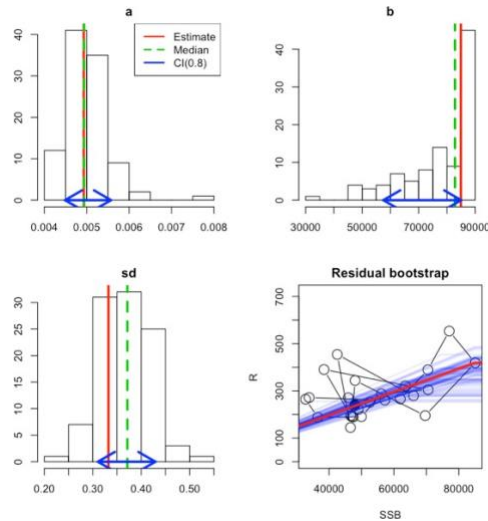
Supplementary Figure 1-3. Residual distribution (left) and QQ plot (right) of estimated recruitment values when HS-L1 is assumed as the stock-recruitment relationship



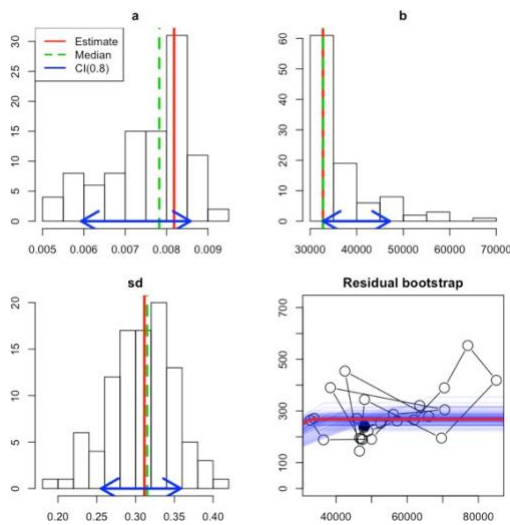
Supplementary Figure 1-4. Aging of residuals and autocorrelation coefficient of estimated recruitment values when HS-L1 is assumed as the stock-recruitment relationship



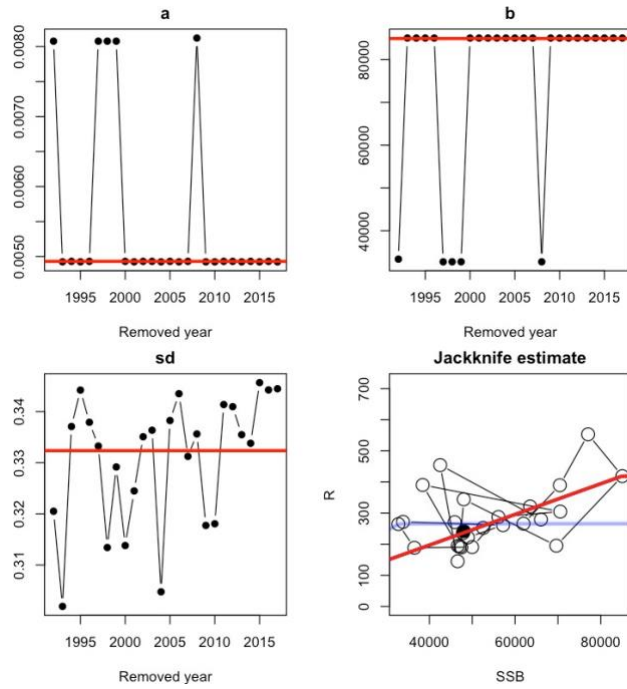
Supplementary Figure 1-5. Differences in the application of HS to this stock data when the optimization method is changed



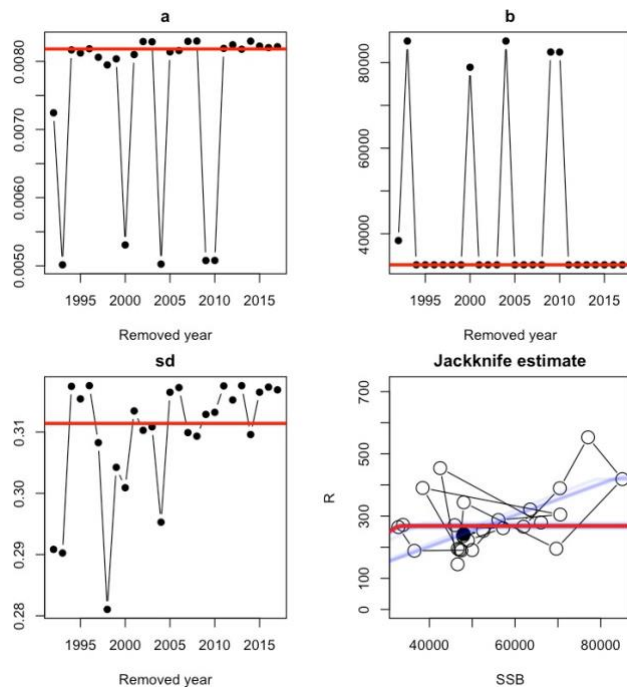
Supplementary Figure 1-6. Bootstrap test results for HS-L1 parameter estimates



Supplementary Figure 1-7. Bootstrap test results for HS-L2 parameter estimates



Supplementary Figure 1-8. Jackknife analysis results for HS-L1 parameter estimates



Supplementary Figure 1-9. Jackknife analysis results for HS-L2 parameter estimates

Supplementary Table 1-1. Relationship of the various (biological) reference points assuming each model with the average SSB at equilibrium, the ratio to the initial SSB (B0) assuming no fishery, the average catch, the fishing rate, and the effort multiplier for the current catch pressure

(a) HS-L1

(Biological) Reference Point	Spawning Stock Biomass	Ratio to B0	Catch	CV of catch	Fishing rate	Effort multiplier
Btarget0	109000	0.26	76000	0.18	0.32	0.77
Blimit0	51000	0.12	46000	0.59	0.37	0.95
Bban0	8000	0.02	8000	1.59	0.39	1.04

(b) HS-L2

(Biological) Reference Point	Spawning Stock Biomass	Ratio to B0	Catch	CV of catch	Fishing rate	Effort multiplier
Btarget0	45000	0.17	52000	0.18	0.41	1.17
Blimit0	33000	0.12	47000	0.29	0.46	1.39
Bban0	3000	0.01	5000	1.63	0.49	1.58

(c) RI-L1

(Biological) Reference Point	Spawning Stock Biomass	Ratio to B0	Catch	CV of catch	Fishing rate	Effort multiplier
Btarget0	209000	0.32	80000	0.18	0.21	0.44
Blimit0	54000	0.08	48000	0.29	0.36	0.95
Bban0	6000	0.01	8000	0.74	0.44	1.30

(d) BH-L1

(Biological) Reference Point	Spawning Stock Biomass	Ratio to B0	Catch	CV of catch	Fishing rate	Effort multiplier
Btarget0	124000	0.28	63000	0.16	0.26	0.57
Blimit0	27000	0.06	38000	0.27	0.45	1.34
Bban0	3000	0.01	6000	0.67	0.54	1.85

Supplementary Table 1-2. Parameter estimation results of Hockey Stick model optimized by the least absolute value method and the least squares method. Parameters a and b are the slope of the HS model and the SSB at the break point (ton) respectively

Stock-recruitment relationship equation	Optimization method	Autocorrelation	a	b	Recruitment S.D.
HS	Least absolute value method	No	0.005	84,935	0.332
HS	Least squares method	No	0.008	32,751	0.311

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

Supplementary Material 2 Results when the least squares method is used as the optimization method

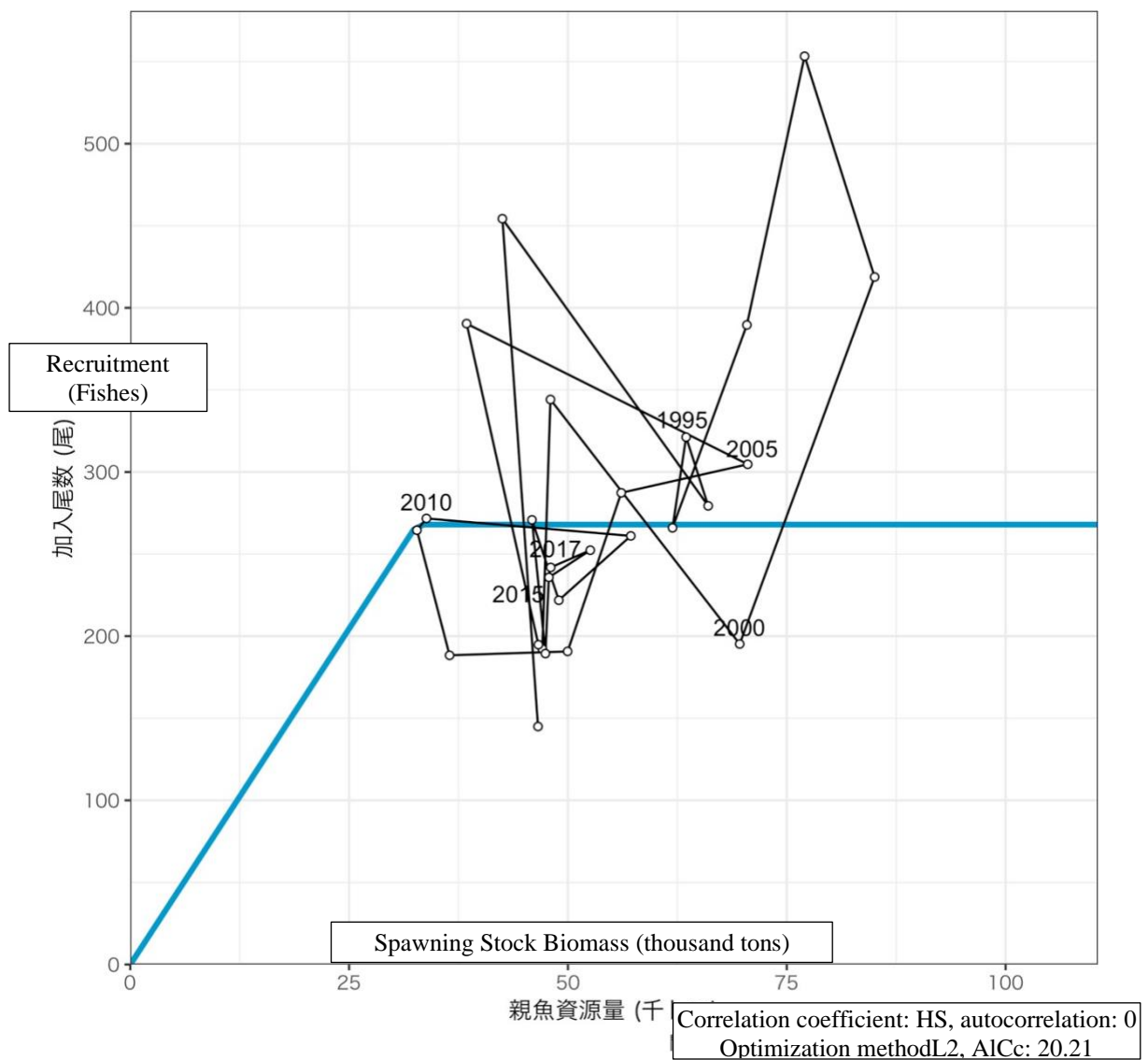
When HS is assumed for the stock-recruitment relationship of this stock, the calculated MSY varies greatly depending on the optimization method. In this stock, HS-L1 was proposed to reduce the risk of overfishing when the SSB was low, but here it is assumed that the true MSY is close to the MSY when HS-L2 was assumed, and the management policy when HS-L2 was assumed for the stock-recruitment relationship (Supplementary Figure 2-1) was examined.

If HS-L2 is assumed for the stock-recruitment relationship, MSY (45,000 tons) is estimated to be slightly below the current SSB (48,000 tons), so the Stock status of this stock is assessed to be good. As a result, under the management policy assuming HS-L2, the effort multiplier is 1.17, and the catch pressure is kept relatively high even after 2020, when the management starts (Supplementary Table 2-1).

According to the ABC calculation rules, the standard Blimit is SB0.6msy, but when HS-L2 is assumed as the stock-recruitment relationship, SB0.6msy is 20,000 tons, which is lower than the lowest SSB in the past 26 years, which is (33,000 tons) (Supplementary Figure 2-2). Therefore, in order to reduce the risk of the SSB falling below the past minimum value, Blimit is set here as the SSB at the break point of HS, which is the lowest past SSB (B_HS, 33,000 tons) (Supplementary Figure 2-3). As a result of adjusting Blimit, the difference between Blimit and Btarget narrowed from 25,000 tons to 12,000 tons.

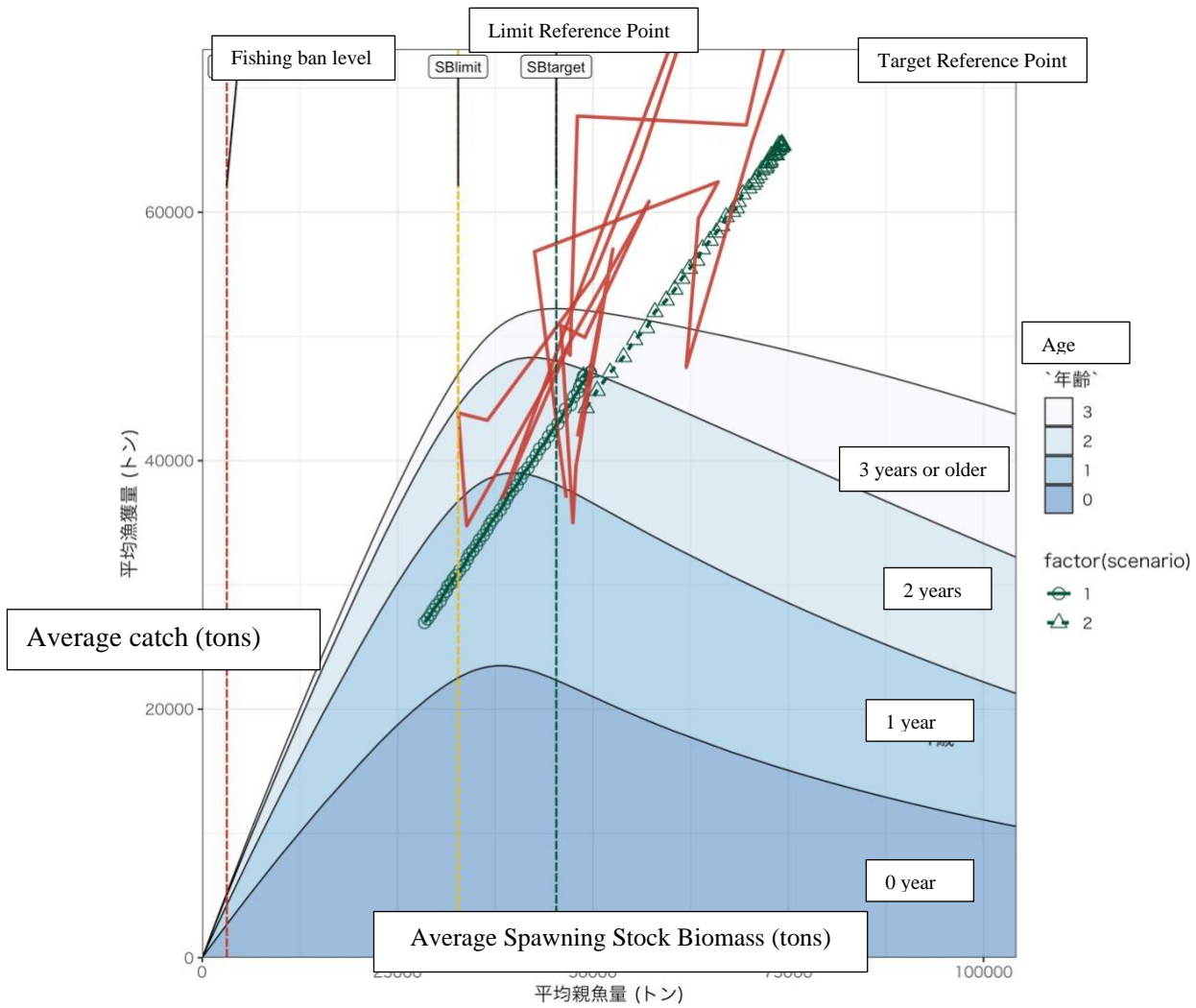
Assuming HS-L2 as the stock-recruitment relationship, the catch pressure for this stock was assessed to have been used under appropriate catch pressure except for the years 2000-2002 and 2007-2009 (Supplementary Figure 2-3). This result is consistent with the stock assessment of this stock considering that the stock status has been fluctuating between medium and high. Since the current SSB is higher than the Blimit, the catch will be maintained at β Ftarget even after 2020, the year when management starts (Supplementary Figure 2-4). Even if the standard value of 0.8 is used for β , the drop in catch pressure after the start of management in 2020 is negligible (Supplementary Figure 2-5), and under this management policy, it was predicted that the SSB could be maintained above Btarget with a probability of 80% or more during the period up to 2028

(Supplementary Table 2-2). Under this management policy, it was predicted that the SSB could almost certainly be maintained at a level above the Blimit (Supplementary Table 2-3). Even if the catch was maintained at the same level as in 2018 and 2019 with β set to the standard value of 0.8 (Supplementary Table 2-5), it was predicted that the SSB would generally increase until 2028 (Supplementary Table 2-4). The CV of the catch under this management policy was 0.18, which was the same as when the HS-L1 was assumed for the stock-recruitment relationship (Supplementary Table 1-1).



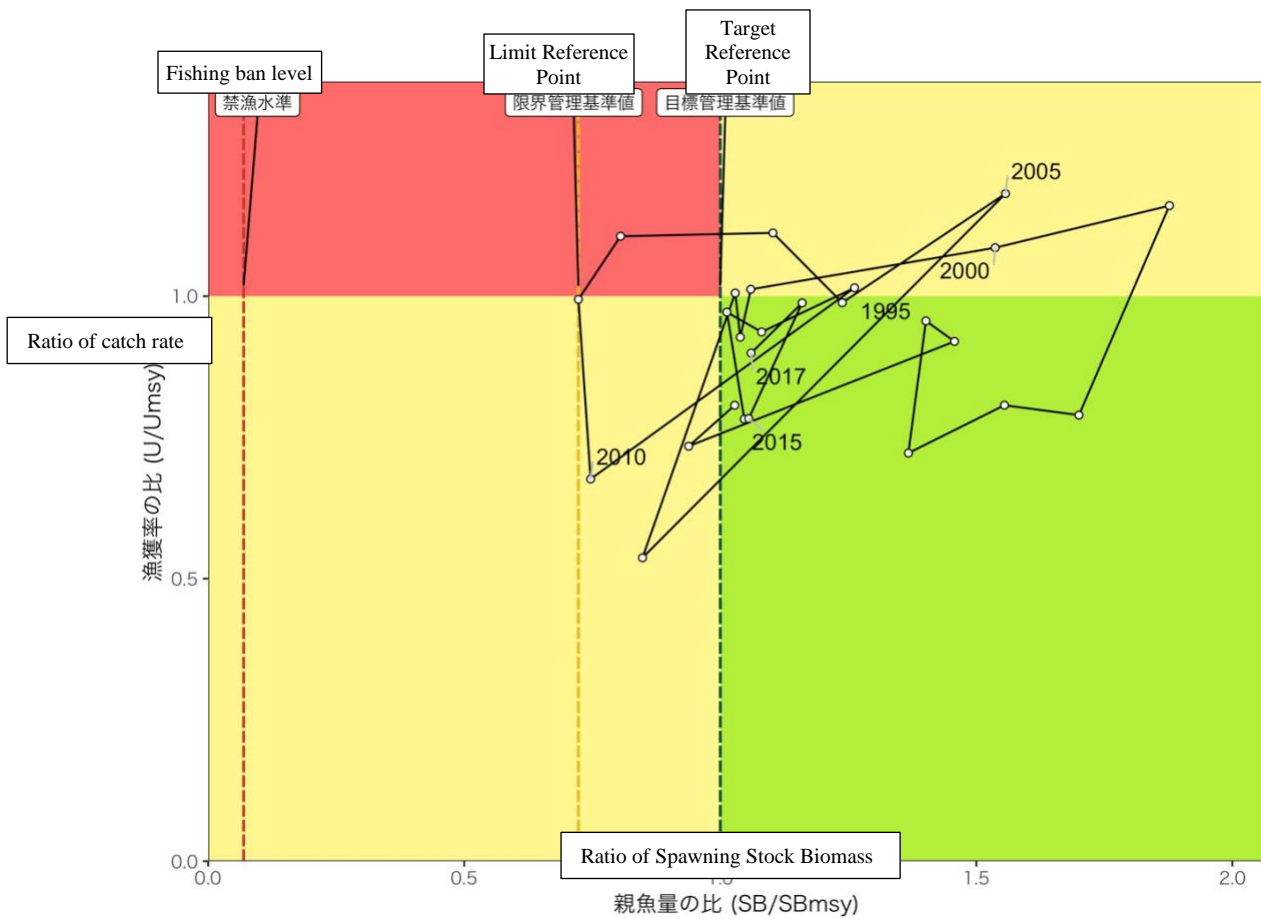
Supplementary Figure 2-1. stock-recruitment relationships

The numbers in the figure indicate class groups. The Hockey Stick model (HS) was used for the reproduction curve, and the parameters were estimated by the least squares method without considering autocorrelation.



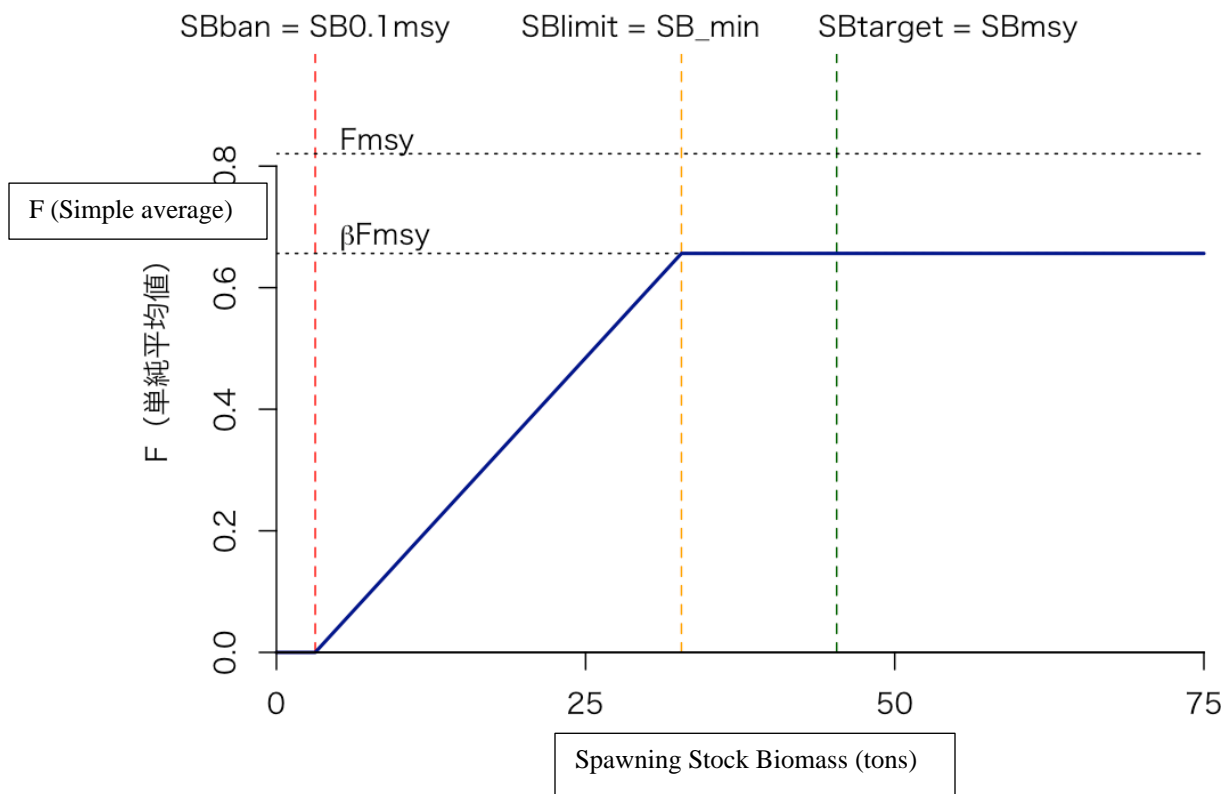
Supplementary Figure 2-2. Relationship between the (biological) reference points and the catch at age curves

The average value of the catch at age with respect to the SSB at equilibrium in the future projection using the assumed stock-recruitment relationship is indicated by the area, the observed values of the catch and the SSB (red line), and the locus of the relationship between the SSB and the catch in the future projection (solid green line and \circ : catch by $F_{current}$, green broken line and Δ : catch by the HCRs when β is the standard value of 0.8) are respectively shown below. The initial SSB (SB_0) is 85,000 tons.



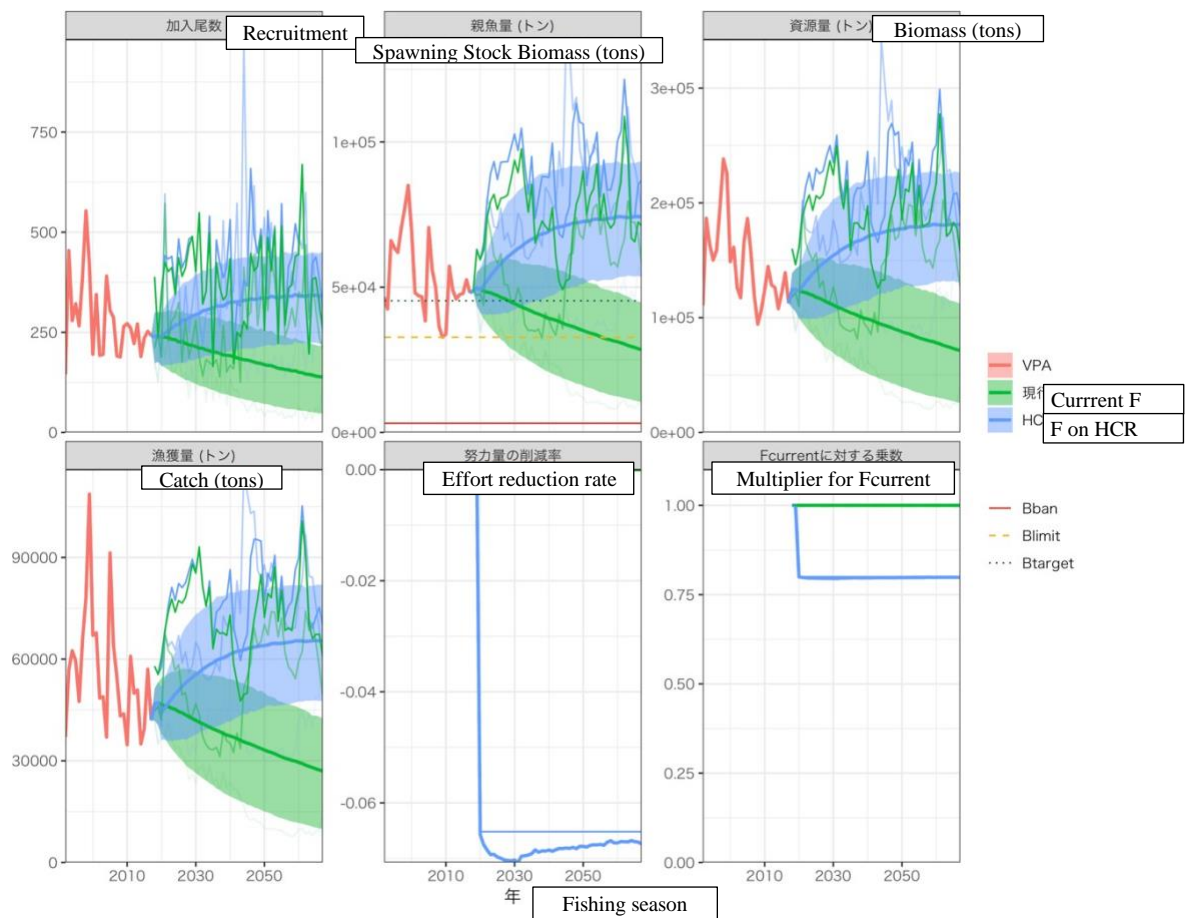
Supplementary Figure 2-3. Kobe plot (Four sections)

The target reference point, limit reference point, and fishing prohibition level in the figure indicate the (biological) reference points SB_{target} , SB_{limit} , and SB_{ban} for the SSB, respectively. SB_{msy} , B_{HS} , and $SB_{0.1msy}$ were used as these reference points, respectively.



Supplementary Figure 2-4 Harvest Control Rules

B_{target}, B_{limit}, and B_{ban} in the figure indicate the (biological) reference points SB_{target}, SB_{limit}, and SB_{ban}, respectively, for the SSB. SB_{msy}, B_{HS}, and SB_{0.1msy} are used for these reference points, respectively, and the HCR based on the standard values is shown by a blue line. The standard value of 0.8 was used for the tuning parameter β .



Supplementary Figure 2-5. Average value of future projection based on the Harvest Control Rules (solid line) and 80% confidence intervals

The following shows the changes when the (biological) reference points SBtarget, SBlimit, and SBban of the HCRs are set to SBmsy, B_{HS}, and SB0.1msy, respectively. It was assumed that fishing would be carried out based on the HCRs from the 2020 fishing season, and the catch in the 2018 and 2019 fishing seasons was based on F_{current}. The standard value of 0.8 was used for β .

Supplementary Table 2-1. Relationship among various (biological) reference points and SSB at equilibrium, catch, fishing rate and effort multiplier for current catch pressure

(Biological) Reference Point	Spawning Stock Biomass	Ratio to B0	Catch	CV of catch	Fishing rate	Effort multiplier
Btarget0	45000	0.17	52000	0.18	0.41	1.17
Blimit0	33000	0.12	47000	0.29	0.46	1.39
Bban0	3000	0.01	5000	1.63	0.49	1.58

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

β	2018	2019	2020	2021	2022	2023	2024	2025	2030
1.0	100	71	62	38	26	17	12	8	1
0.9	100	71	62	51	44	39	35	32	20
0.8	100	71	62	64	66	67	68	70	75
0.7	100	71	62	75	83	88	92	94	99
0.6	100	71	62	84	94	98	99	100	100
0.5	100	71	62	91	98	100	100	100	100
0.4	100	71	62	95	100	100	100	100	100
0.3	100	71	62	98	100	100	100	100	100
0.2	100	71	62	99	100	100	100	100	100
0.1	100	71	62	100	100	100	100	100	100
0.0	100	71	62	100	100	100	100	100	100

Supplementary Table 2-3. Probability (%) of future SSB exceeding the limit reference point

β	2018	2019	2020	2021	2022	2023	2024	2025	2030
1.0	100	100	99	88	73	58	45	37	17
0.9	100	100	99	93	88	82	76	72	59
0.8	100	100	99	97	96	95	95	95	94
0.7	100	100	99	99	99	99	99	100	100
0.6	100	100	99	100	100	100	100	100	100
0.5	100	100	99	100	100	100	100	100	100
0.4	100	100	99	100	100	100	100	100	100
0.3	100	100	99	100	100	100	100	100	100
0.2	100	100	99	100	100	100	100	100	100
0.1	100	100	99	100	100	100	100	100	100
0.0	100	100	99	100	100	100	100	100	100

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

β	2018	2019	2020	2021	2022	2023	2024	2025	2030
1.0	48,776	49,675	49,135	43,910	39,910	36,734	34,186	32,467	28,836
0.9	48,776	49,675	49,135	47,097	45,583	44,282	42,936	41,906	38,026
0.8	48,776	49,675	49,135	50,532	52,190	53,915	55,337	56,860	62,366
0.7	48,776	49,675	49,135	54,234	59,833	65,803	71,471	77,056	94,610
0.6	48,776	49,675	49,135	58,225	68,639	80,117	91,034	100,681	118,460
0.5	48,776	49,675	49,135	62,531	78,753	96,890	113,173	125,544	139,382
0.4	48,776	49,675	49,135	67,176	90,325	116,071	137,514	151,869	165,087
0.3	48,776	49,675	49,135	72,191	103,477	137,665	164,937	182,264	198,872
0.2	48,776	49,675	49,135	77,606	118,367	162,285	197,290	219,713	244,791
0.1	48,776	49,675	49,135	83,455	135,176	190,975	236,967	267,629	309,635
0.0	48,776	49,675	49,135	89,776	154,043	224,931	286,646	330,340	405,419

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

β	2018	2019	2020	2021	2022	2023	2024	2025	2030
1.0	47,000	47,000	52,000	47,000	42,000	38,000	34,000	32,000	27,000
0.9	47,000	47,000	48,000	46,000	45,000	43,000	42,000	40,000	36,000
0.8	47,000	47,000	44,000	46,000	47,000	48,000	50,000	51,000	55,000
0.7	47,000	47,000	40,000	44,000	49,000	53,000	57,000	61,000	73,000
0.6	47,000	47,000	35,000	42,000	49,000	56,000	62,000	67,000	76,000
0.5	47,000	47,000	30,000	39,000	48,000	56,000	63,000	68,000	73,000
0.4	47,000	47,000	25,000	34,000	44,000	53,000	60,000	64,000	68,000
0.3	47,000	47,000	20,000	28,000	38,000	47,000	53,000	57,000	61,000
0.2	47,000	47,000	13,000	21,000	29,000	36,000	42,000	45,000	49,000
0.1	47,000	47,000	7,000	11,000	17,000	21,000	25,000	28,000	31,000
0.0	47,000	47,000	0	0	0	0	0	0	0

Supplementary Material 3 Sensitivity Analysis Results When Reproduction Assumptions are Incorrect

Assuming a Hockey Stick model (HS) without considering autocorrelation as the stock-recruitment relationship of this stock, uncertainty in the parameter estimates was existent when optimized by the least absolute value method (L1) and the least squares method (L2) (Supplementary Material 1). In both optimization methods, two parameter regions showing the same high likelihood were found (Supplementary Figures 1-10 and 1-11). The management objectives calculated when the stock-recruitment relationship is assumed to be HS differ greatly between the two optimization methods (Supplementary Materials 1 and 2); therefore, it is necessary to investigate the assumed risks of overfishing and catch loss that could occur if the stock-recruitment relationship assumptions were incorrect.

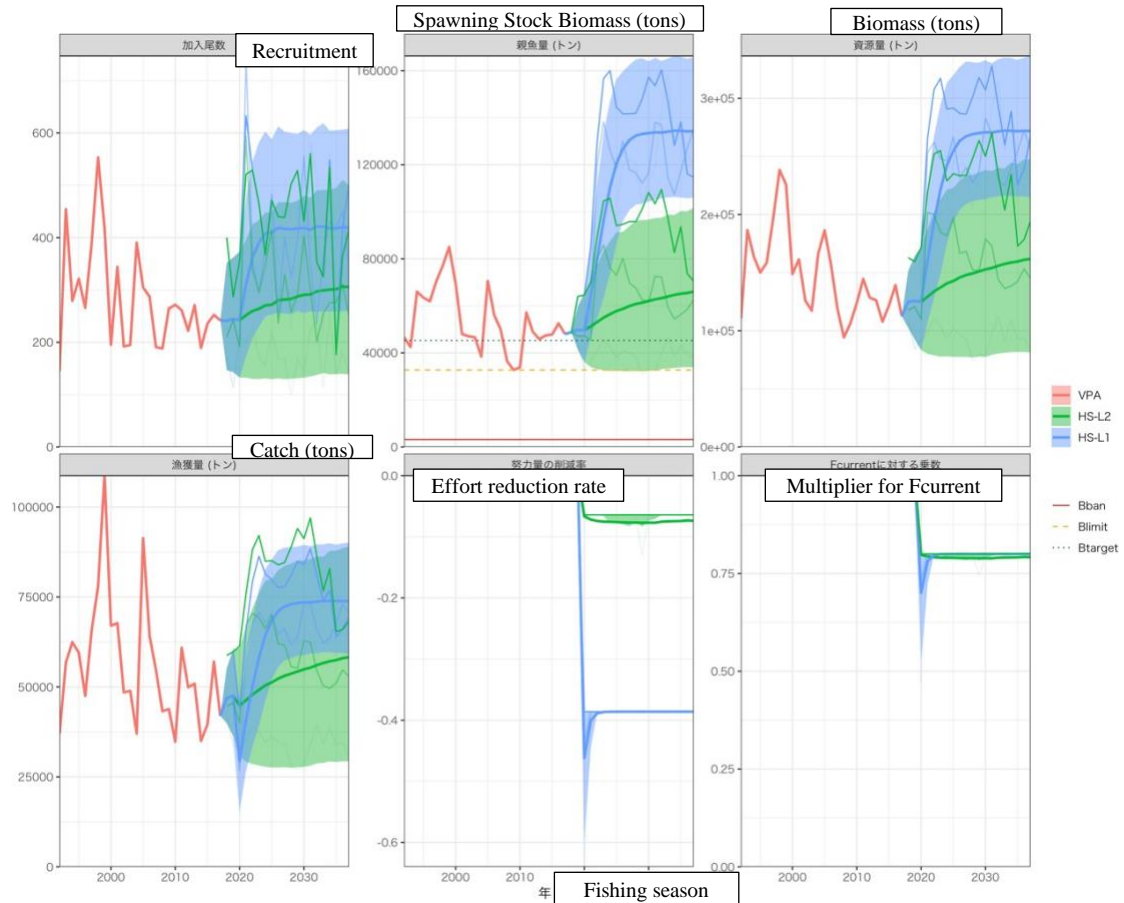
When the stock-recruitment relationship of this stock is HS with the parameters optimized by L1 (HS-L1), the recruitment of this stock is assumed to be positively correlated with the SSB. (Supplementary Material 2). On the other hand, when HS with parameters optimized by L2 (HS-L2) is used, it is assumed that the recruitment of this stock is constant regardless of the SSB.

First, for the case where the true stock-recruitment relationship of this stock was such that the recruitment increased in proportion to the SSB, we compared the stock management effects based on the differences in the assumed stock-recruitment relationship. In order to obtain MSY under the true stock-recruitment relationship, a simulation was performed using HS-L1 as the assumed stock-recruitment relationship. To obtain the management objectives for managing this true stock-recruitment relationship by assuming an incorrect stock-recruitment relationship and a correct stock-recruitment relationship, MSY was calculated assuming HS-L2 and HS-L1 as the stock-recruitment relationships, respectively. Under the management assuming HS-L2 as the stock-recruitment relationship, the MSY is incorrectly underestimated; therefore, it is concluded that the SSB in 2017 (48,000 tons) has already exceeded the estimated SBtarget (45,000 tons). In addition, although the catch pressure actually needs to be reduced, it will be maintained as at present even after 2020, when management begins (Supplementary Figure 3-1). Although the expected average value of the SSB will increase until 2030, ten years after the start of management, the lower confidence limit of 80% is low enough to reach the lowest ever SSB (33,000 tons in 2009). Even if β was set to 0.8, it was assumed that the SSB could fall below the past minimum with a 10% probability within five years from the start of management (Supplementary Table 3-1). For recruitment, biomass, and catch, the lower confidence limits of 80% were each predicted to be below the past lows. As a result, it was estimated that the predicted average catch when the HS-L2 was incorrectly assumed and managed as the stock-recruitment relationship decreased by about 17% as compared to when the HS-L1 was correctly assumed and managed.

In contrast to the above, for the case where the true stock-recruitment relationship of this stock is such that the recruitment is constant regardless of the SSB, the stock management effects were compared based on the differences in the assumed stock-recruitment relationships. MSY under the true stock-recruitment relationship was obtained through simulation using HS-L2 as the stock-recruitment relationship. Under a management that incorrectly assumes HS-L1 as the stock-recruitment relationship, in order to set SBtarget to a value that is significantly higher (109,000 tons) than the SSB (48,000 tons) in 2017, the catch pressure will be significantly reduced from 2020 when management starts (Supplementary Figure 3-2). The expected average value of the SSB will increase until 2025, but since recruitment is constant, it is expected to remain flat thereafter. As a result, the expected average catch when HS-L1 is assumed and managed as the stock-recruitment relationship is lower than that under the correct assumption of HS-L2, but the extent of decrease was estimated to be less than 10% (reduced by 4,000 tons) (Supplementary Table 3-2, $\beta = 0.8$).

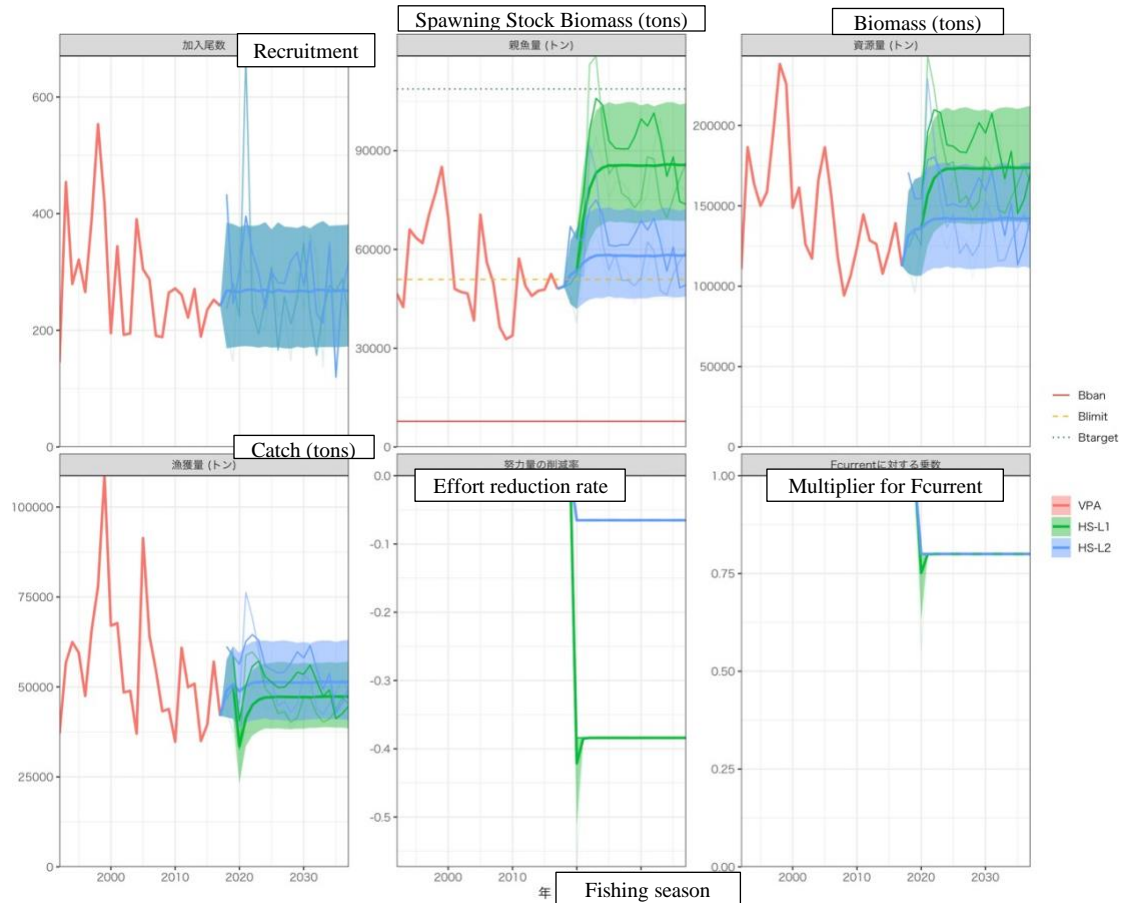
From the above verification, it was found that the catch loss in an incorrectly assumed stock-recruitment relationship was smaller under management assuming HS-L1. On the other hand, in

management assuming HS-L2 as the stock-recruitment relationship, it was found that if the assumption was incorrect, there was a risk that the SSB would fall below the past minimum. Considering the uncertainty of the parameter estimates, it was judged that management assuming HS-L1 as the stock-recruitment relationship was reasonable for this stock from the viewpoint of stock protection and effective utilization of the stock.



Supplementary Figure 3-1. Average value of future projection based on the Harvest Control Rules (solid line) and 80% confidence intervals

For stock in which recruitment is positively correlated with the SSB, the figure shows the management effects when an incorrect stock-recruitment relationship with constant recruitment is assumed (HS-L2, green) and when a correct stock-recruitment relationship is assumed (HS-L1, blue). The following shows the changes when the (biological) reference points SB_{target} , SB_{limit} , and SB_{ban} of the HCRs are set to SB_{msy} , SB_{min} , and $SB_{0.1msy}$, respectively. It was assumed that fishing based on the HCRs would be carried out from the 2020 fishing season, and the catch in the 2018 and 2019 fishing seasons was based on $F_{current}$. The standard value of 0.8 was used for β .



Supplementary Figure 3-2. Average value of future projection based on the Harvest Control Rules (solid line) and 80% confidence intervals

For stock in which recruitment is constant regardless of the SSB, the figure shows the management effects when an incorrect stock-recruitment relationship with the recruitment positively correlated to the SSB is assumed (HS-L1, green) and when a correct stock-recruitment relationship is assumed (HS-L2, blue). The following shows the changes when the (biological) reference points SBtarget, SBlimit, and SBban of the HCRs are set to SBmsy, SB0.6msy, and SB0.1msy, respectively. It was assumed that fishing based on the HCRs would be carried out from the 2020 fishing season, and the catch in the 2018 and 2019 fishing seasons was based on Fcurrent. The standard value of 0.8 was used for β .

Supplementary Table 3-1. Probability (%) of future average SSB exceeding the limit reference point

This table shows the management effect of a stock whose recruitment is positively correlated with the SSB, assuming an incorrect stock-recruitment relationship with a constant recruitment.

β	2018	2019	2020	2021	2022	2023	2024	2025	2030
1.0	100	100	96	82	67	53	42	34	10
0.9	100	100	96	88	80	74	67	62	44
0.8	100	100	96	92	90	88	87	86	83
0.7	100	100	96	95	96	96	97	97	99
0.6	100	100	96	98	99	99	100	100	100
0.5	100	100	96	99	100	100	100	100	100
0.4	100	100	96	99	100	100	100	100	100
0.3	100	100	96	100	100	100	100	100	100
0.2	100	100	96	100	100	100	100	100	100
0.1	100	100	96	100	100	100	100	100	100
0.0	100	100	96	100	100	100	100	100	100

Supplementary Table 3-2. Changes in future average catch (tons)

This table shows the management effect of a stock whose recruitment is positively correlated with the SSB, assuming an incorrect stock-recruitment relationship with a constant recruitment.

β	2018	2019	2020	2021	2022	2023	2024	2025	2030
1.0	47,000	48,000	53,000	48,000	43,000	39,000	35,000	32,000	22,000
0.9	47,000	48,000	49,000	47,000	46,000	44,000	43,000	41,000	35,000
0.8	47,000	48,000	45,000	46,000	48,000	49,000	50,000	51,000	54,000
0.7	47,000	48,000	40,000	45,000	49,000	53,000	57,000	60,000	69,000
0.6	47,000	48,000	36,000	42,000	49,000	56,000	61,000	65,000	75,000
0.5	47,000	48,000	31,000	39,000	48,000	56,000	62,000	67,000	73,000
0.4	47,000	48,000	25,000	34,000	44,000	53,000	59,000	63,000	68,000
0.3	47,000	48,000	20,000	29,000	38,000	46,000	53,000	57,000	60,000
0.2	47,000	48,000	14,000	21,000	29,000	36,000	42,000	45,000	49,000
0.1	47,000	48,000	7,000	12,000	17,000	21,000	25,000	28,000	31,000
0.0	47,000	48,000	0	0	0	0	0	0	0

Supplementary Table 3-3. Probability (%) of future average SSB exceeding the limit reference point

This table shows the management effect of a stock whose recruitment is constant regardless of the SSB, assuming an incorrect stock-recruitment relationship with recruitment positively correlated with the SSB.

β	2018	2019	2020	2021	2022	2023	2024	2025	2030
1.0	100	100	100	100	100	100	100	100	100
0.9	100	100	100	100	100	100	100	100	100
0.8	100	100	100	100	100	100	100	100	100
0.7	100	100	100	100	100	100	100	100	100
0.6	100	100	100	100	100	100	100	100	100
0.5	100	100	100	100	100	100	100	100	100
0.4	100	100	100	100	100	100	100	100	100
0.3	100	100	100	100	100	100	100	100	100
0.2	100	100	100	100	100	100	100	100	100
0.1	100	100	100	100	100	100	100	100	100
0.0	100	100	100	100	100	100	100	100	100

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

This table shows the management effect of a stock whose recruitment is constant regardless of the SSB, assuming an incorrect stock-recruitment relationship with recruitment positively correlated with the SSB.

β	2018	2019	2020	2021	2022	2023	2024	2025	2030
1.0	49,000	51,000	40,000	47,000	49,000	49,000	50,000	50,000	50,000
0.9	49,000	51,000	37,000	44,000	47,000	48,000	49,000	48,000	49,000
0.8	49,000	51,000	33,000	41,000	45,000	46,000	47,000	47,000	47,000
0.7	49,000	51,000	30,000	38,000	42,000	44,000	45,000	45,000	45,000
0.6	49,000	51,000	26,000	34,000	39,000	41,000	43,000	43,000	43,000
0.5	49,000	51,000	22,000	30,000	35,000	38,000	39,000	40,000	40,000
0.4	49,000	51,000	18,000	26,000	31,000	34,000	35,000	36,000	36,000
0.3	49,000	51,000	14,000	20,000	25,000	28,000	30,000	30,000	31,000
0.2	49,000	51,000	9,000	14,000	18,000	21,000	22,000	23,000	24,000
0.1	49,000	51,000	5,000	8,000	10,000	12,000	13,000	13,000	14,000
0.0	49,000	51,000	0	0	0	0	0	0	0