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

Responsible Fisheries Research Institute: National Research Institute of Fisheries Science

Abstract

The stock-recruitmentrelationships and (biological) reference points of this stock were examined using various data on the Stock assessment of the Pacific stock of blue mackerel in FY2018. The Stock status of this stock is assessed to be medium based on the biomass after the 1995 fishing season, and that the trend has assessed to be decreasing based on the changes in the biomass during the last five years (fishing season of 2013-2017). For this stock, we propose the Ricker model (RI) optimized by the least absolute value method as a candidate for the stock-recruitment function, SBmsy (158,000 tons) as a candidate for the target reference point, SB0.6msy (50,000 tons) as a candidate for the limit reference point, and SB0.1msy (6,000 tons) as a candidate for the fishing ban level. The catch rate (catch / Biomass) for achieving the MSY is 27%, and the fishing pressure for achieving the MSY is 1.15 times the current fishing pressure (Fcurrent, average fishing pressure for the 2013 to 2017 fishing season).

1. Stock-recruitment relationship

1-1) Data set to be used

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

1-2) Examination of stock-recruitment relationship

The parameters for model selection are shown in the table below for each candidate cited as the stock-recruitment relationship of this stock. All values from 1995 to 2017 were used as the data. For this stock, we have considered the Hockey Stick stock-recruitment model (HS), Beverton-Holt model (BH), and the Ricker model (RI). In the selection of a stock-recruitment relationship, it is effective to select a relationship with a low estimated value of recruitment in order to reduce the risk of overfishing when the stock-recruitment relationship is extrapolated to a Spawning Stock Biomass (SSB) lower than the past lowest SSB. In this stock, AICc was lower in BH and HS, but the slope of recruitment could not be estimated properly for BH when the SSB was 38,000 ton or less (Supplementary Figure 1-1). Although RI had a higher AICc than HS, the recruitment slope for a SSB of 38,000 tons or less was gentle (Supplementary Figure 1-1). After examining the risks of overfishing when managed by the HS and RI models, RI produced the recommended results so RI was selected (Supplementary Material 2). As for the optimization method, the AIC was smaller when the least absolute value method was used than that of the least square method. Since the autocorrelation of the residual calculated with the recommended model was not significant (Supplementary Figure 1-4), the autocorrelation was decided not to be included for this stock.

stock-recruitment relationship	Optimization method	AICc	ΔAICc	ΔAICc Ranking	S.D.	Number of data
RI	**Least absolute value method**	**38.0**	**6.5**	**3**	**0.51**	**23**
BH	Least absolute value method	31.5	0.0	1	0.44	23
HS	Least absolute value method	31.6	0.1	2	0.44	23
HS	Least squares method	39.3	7.8	4	0.49	23
BH	Least squares method	39.3	7.8	5	0.49	23
RI	Least squares method	44.2	12.7	6	0.54	23

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

1-3) Candidates for stock-recruitment relationships

As mentioned above, we propose RI (Figure 1) that does not use autocorrelation optimized by the least absolute value method as the stock-recruitment relationship for this stock.

2. (Biological) Reference Point

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 calculation of future projection calculations 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 is RI model based on the recruitment and SSB during the 1995 to 2017 fishing season estimated by the stock assessment, and natural mortality, maturity rate, average weight at age, and catch selectivity rate were used to condition the simulations. The current fishing pressure (Fcurrent, Figure 2) is considered as the average value of the fishing mortality coefficient (F value) for the 2013-2017 fishing season, and the selectivity rate in the future projection is the Fcurrent selectivity rate (table below).

Age	Natural mortality	Maturity rate	Average weight (g)	Selectivity	Current Fisheries Coefficient (Fcurrent)
0	0.4	0.00	129	0.25	0.19
1	0.4	0.00	287	0.36	0.27
2	0.4	1.00	417	0.54	0.41
3	0.4	1.00	476	1.00	0.76
4 years or older	0.4	1.00	580	1.00	0.76

A projection was made for the future under the above conditions in conjunction with the stock-recruitment relationship. The maximum value of the catch at equilibrium was set as the MSY, and the SSB when MSY was achieved was set as SBmsy. In this stock, the equilibrium was established approximately 50 years after the start of future projection, based on 10 times the generation time of blue mackerel.

2-2) Stock-recruitment relationship used

The Ricker model (RI) 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. Here, a and b are the parameters in the Ricker model shown below. R is recruitment (millions) and E is the SSB (thousand tons).

$$R = aEe^{-bE}$$

Stock-recruitment relationship equation	Optimization method	Autocorrelation	a	b	S.D.
RI	Least absolute value method	No	0.0135	5.58e-06	0.507

2-3) (Biological) Reference Points

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

(Biological) Reference Point	Spawning Stock Biomass	Standard
Target Reference Point	158,000 tons	SBmsy
Limit Reference Point	50,000 tons	SB0.6msy
Fishing prohibition level	6,000 tons	SB0.1msy

For each reference point of this stock, Table 1 shows the relationship among the ratio to the initial SSB when there is no fishing (SB0), the average catch at equilibrium, the CV of the catch, the catch rate, and the multiplier for the current fishing pressure. Figure 3 shows the SSB at equilibrium in future projection when F values are changed variously, and the average catch at age with respect to this.

2-4) Target Reference Point and Exploitation Rate

Figure 4 shows the Kobe plots using the target reference points. The exploitation rate in this stock was concluded to be above the level that provides the MSY except for 2009 and 2017. The SSB was above the target reference point for the period 2006-2015, but has been below it since 2016.

2-5) Harvest Control Rules

Figure 5 shows the relationship between the SSB and the fishing mortality coefficient in the Harvest Control Rules (HCR) using the target reference point, limit reference point, and fishing ban level.

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 effort reduction rate (reduction rate from Fcurrent) when values shown in 2-3 were used for the target reference point, limit reference point, and fishing ban level and the standard value of 0.8 was used for β. We have assumed that catch control starts in 2020, and the catches for the 2018 and 2019 fishing seasons were assumed to be based on the current fishing mortality coefficient (Fcurrent).

The fishing pressure is maintained at β Fmsy because the SSB in recent years has exceeded the limit reference point. As can be seen from the stock-recruitment relationship, stable recruitment is expected to continue, therefore, in 2020, the first year of management, the SSB is expected to be close to SBmsy, and thereafter, after a gradual increase, the SSB and the biomass are expected to remain flat.

(2) When tuning parameter β is changed

Tables 2 to 5 show the changes in the probability of exceeding the target reference point, probability of exceeding the limit reference point, average SSB and average catch for the years 2018-2030, 2040, and 2050 when β is changed between 0 and 1 in the future projection. Since the SSB in 2020, which is the first year of management, is close to MSY, the probability of exceeding the target reference point in 2030 with β = 0.9 or less is predicted to be more than 50%. On the other hand, if β is 1, the probability of exceeding the target reference point in 2030 is predicted to be less than 50%. However, the difference in catch between β = 0.9 and 1 was not large.

3. Summary

The stock assessment data of the Pacific stock of blue mackerel was used to examine the stock-recruitment relationships and the (biological) reference points of the stock. In the stock assessment, the stock status of this stock is assessed to be medium based on the biomass after the 1995 fishing season, and that the stock trend is declining based on the changes in the biomass during the last five years (fishing season of 2013-2017). Based on the relationship between the SSB and recruitment since 1995, this stock is expected to have higher biomass levels in the future under the current (2013-2017 average) fishing pressure and it is believed that sustainable use of the stock is possible.

The stock-recruitment relationship of this stock was RI using the least absolute value method as the optimization method and applied without autocorrelation. For each management standard, the target reference point is defined as the stock status that achieves MSY, so SBmsy estimated from this stock-recruitment relationship is used. The limit reference point is set as the SSB at which 60% catch of MSY can be obtained (SB0.6msy) and the SSB at which 10% catch of MSY can be obtained (SB0.1msy) is set as the fishing prohibition level. The catch rate (catch / biomass) for achieving the MSY is 27%, and the fishing pressure for achieving the MSY is 1.15 times the current fishing pressure (Fcurrent, average fishing mortality coefficient for the 2013 to 2017 fishing season).

In the normal future projection conducted under the HCR using these (biological) reference points, the average recruitment expected in this stock is high; therefore, it was estimated that the SSB is maintained at a high level and will exceed the target reference point with a probability of 50% or more if $\beta = 0.9$.

4. Future considerations

In this stock, since the current F is not high, it is predicted that the SSB will recover to around SBmsy in 2020, which is the first year of management. However, the recruitment in 2015-2017 was lower than expected from the stock-recruitment relationship, and this trend is likely to continue in the future. In such cases, it is necessary to examine future projections that consider short-term fluctuations in recruitment.

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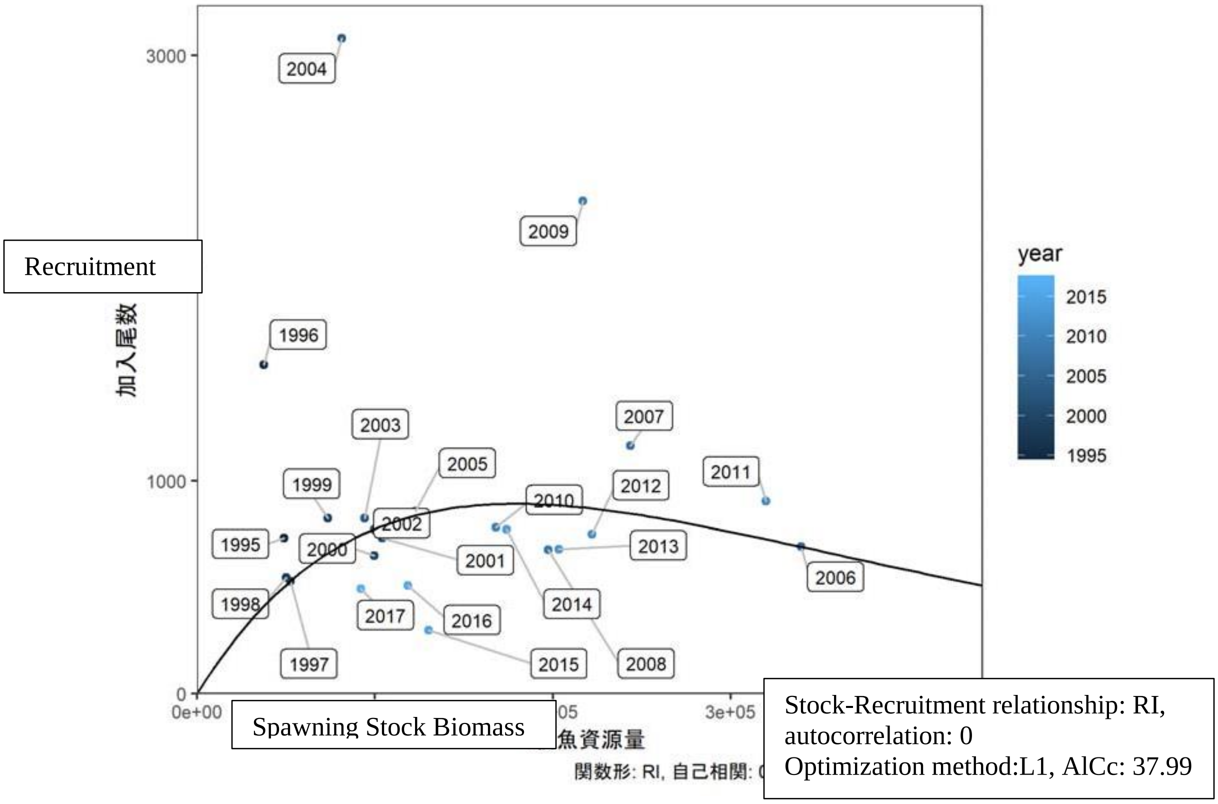


Figure 1. Stock-Recruitment relationship. The numbers in the figure indicate year class. The Ricker model (RI) was used for the stock-recruitment curve and the parameters were estimated by the least absolute value method without considering autocorrelation.

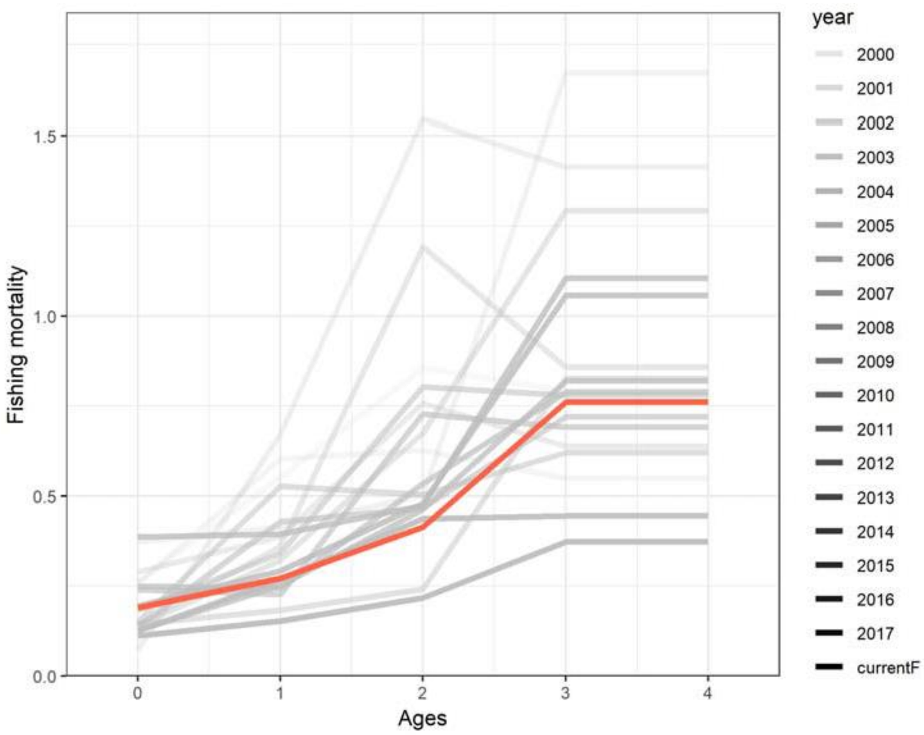


Figure 2. F values at age The current fishing mortality coefficient (Fcurrent) is indicated by a red line, and the values after the 2000 fishing season are indicated by gray lines.

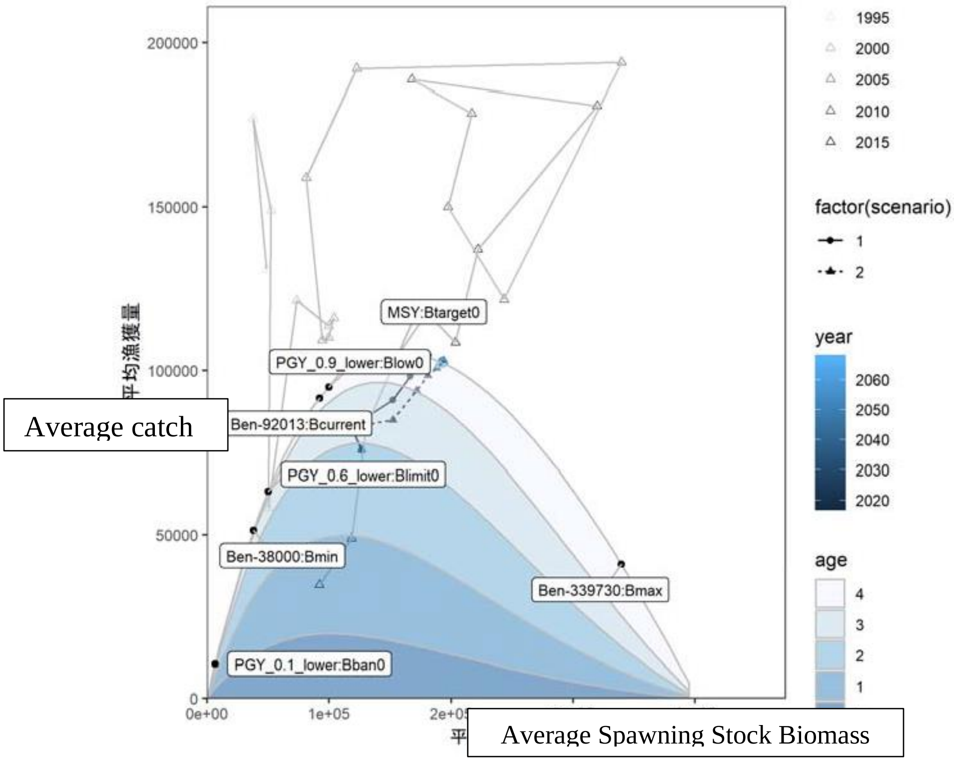
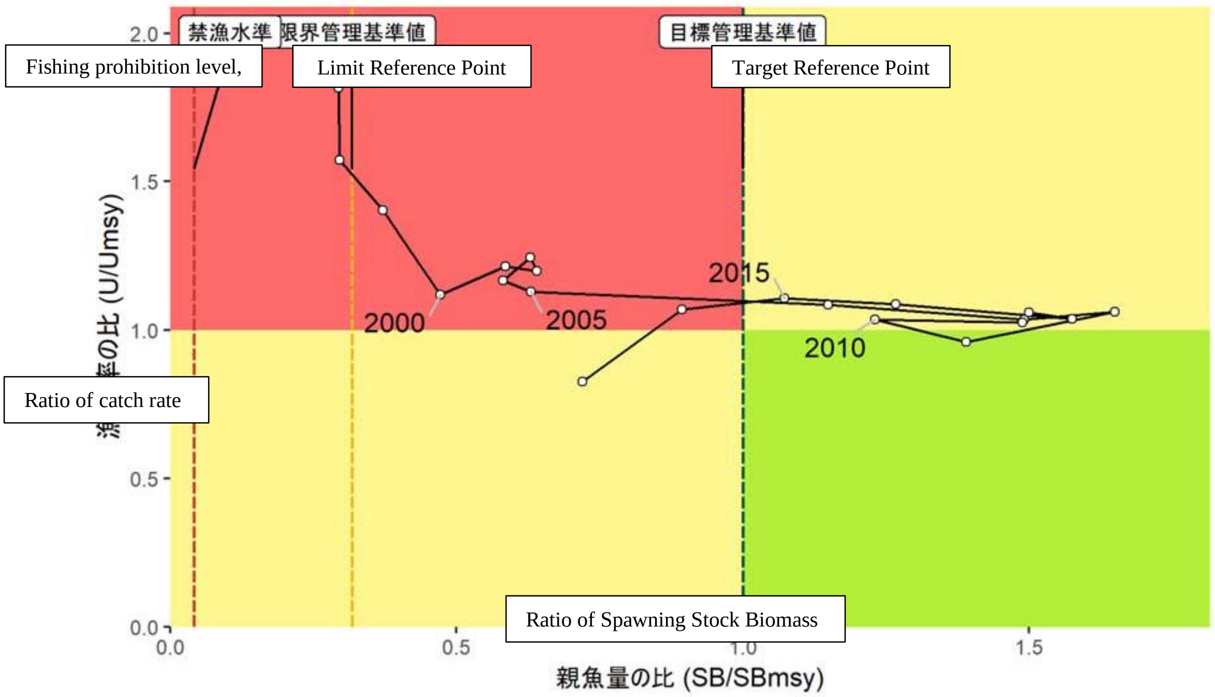


Figure 3. Relationship between the (biological) reference points and the curves for the catch at age. The average value of the catch at age with respect to the SSB at equilibrium in the future projection using the assumed stock-recruitment relationship is indicated by the area, the changes in the observed value (△) 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)

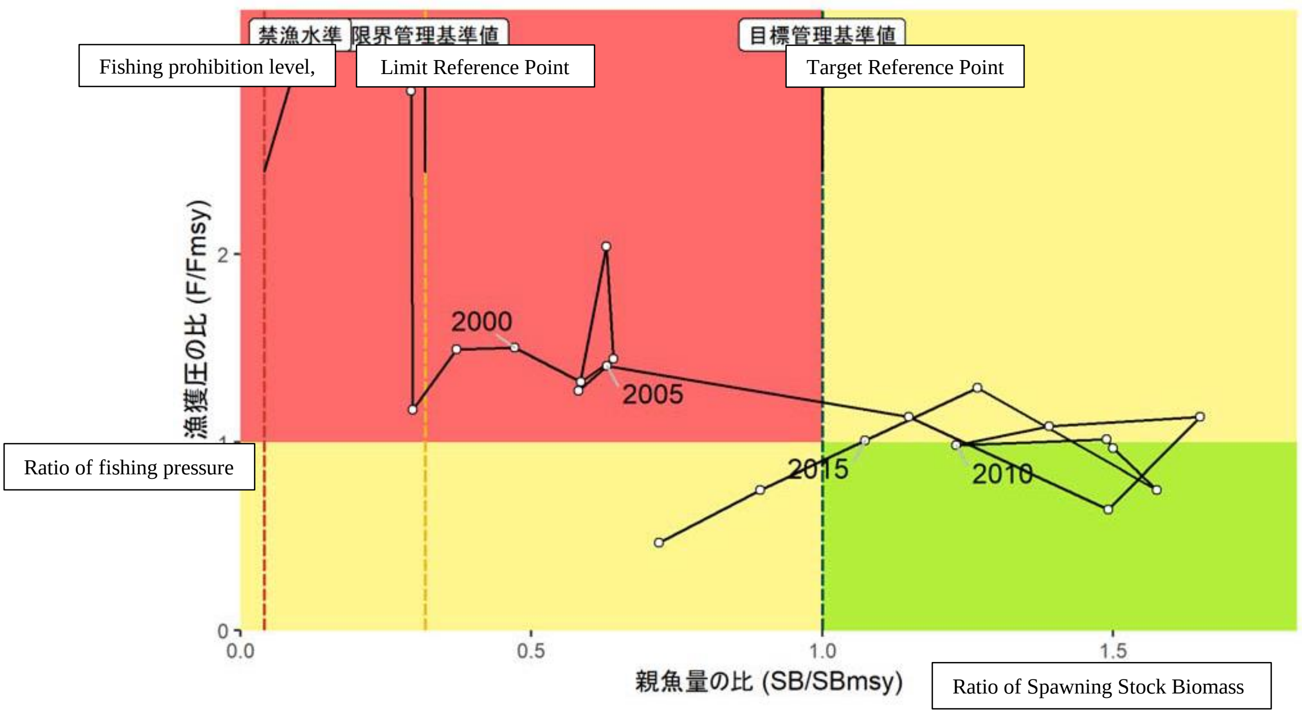


Figure 4. Kobe plot (Four sections) The (biological) reference points, SBtarget, SBlimit, and SBban, were respectively set to SBmsy, SB0.6msy, and SB0.1msy. The figure illustrates the value smoothed with a three-year moving average.

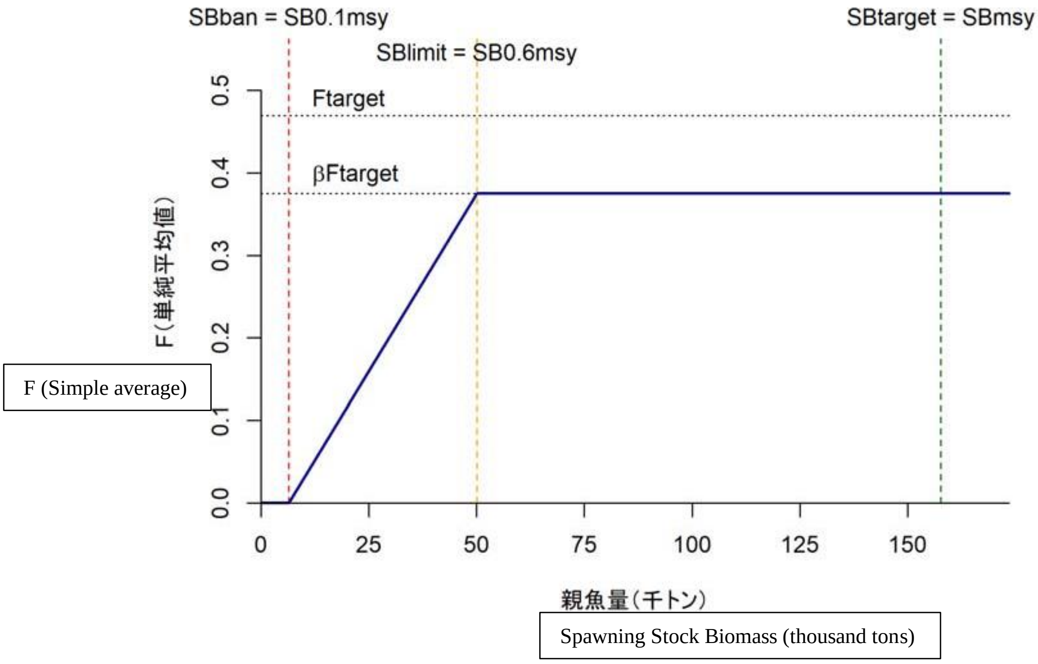


Figure 5. Harvest Control Rules The (biological) reference points, SBtarget, SBlimit, and SBban, were set to SBmsy, SB0.6msy, and SB0.1msy, respectively. The standard value of 0.8 was used for β.

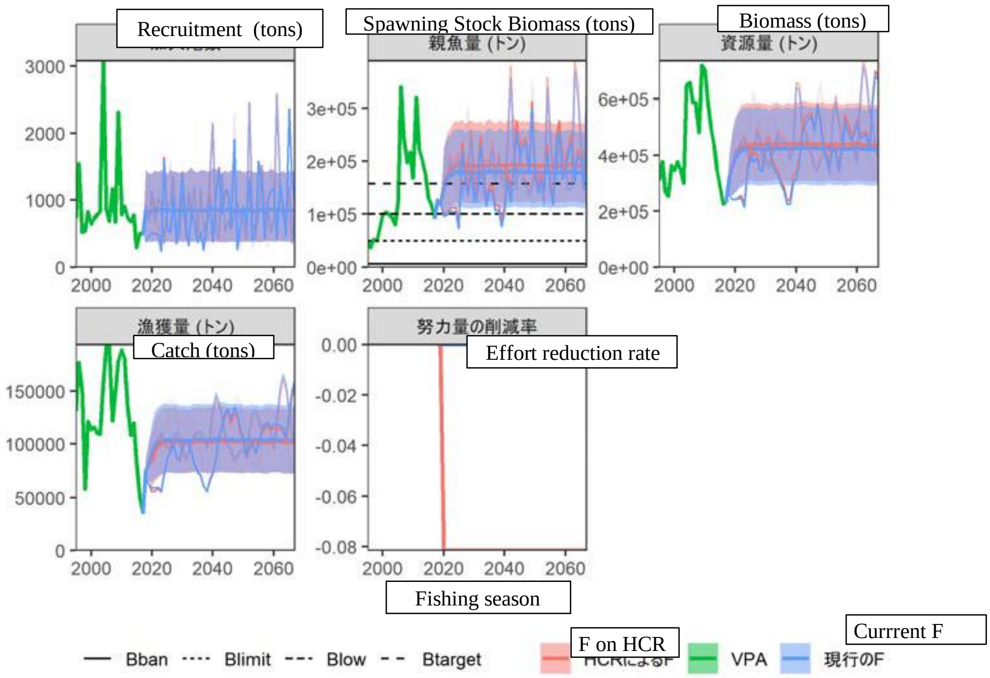


Figure 6. Average value of future projection based on the Harvest Control Rules (solid line) and 80% confidence intervals. The (biological) reference points, SBtarget, SBlimit, and SBban, were set to SBmsy, SB0.6msy, and SB0.1msy, respectively. The catches for the 2018 and 2019 fishing seasons were given by Fcurrent and the standard value of 0.8 was used for β. The unit of recruitment is one million.

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

(Biological) Reference Point	Spawning Biomass	Ratio to B0	Catch	CV of catch	Catch rate	Effort multiplier
Bmax	339730	0.85	41026	0.17	0.07	0.20
Btarget0 (SBmsy)	157694	0.39	105482	0.26	0.27	1.15
Blow0 (SB0.9msy)	100005	0.25	94933	0.33	0.3	1.58
Bcurrent	92013	0.23	91511	0.34	0.3	1.65
Blimit0 (SB0.6msy)	50100	0.13	63288	0.46	0.36	2.0
Bmin	37621	0.10	362	0.52	0.37	2.1
Bban (SB0.1msy)	6436	0.02	10547	1.12	0.40	2.47

Bmax indicates the highest observed SSB, Blow indicates the lower SSB at which 90% of MSY can be obtained, Bcurrent indicates the 2017 SSB, and Bmin indicates the lowest observed SSB.

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	2050
1.0	0	0	36	42	41	41	43	42	42	41	42	42	42	41	42
0.9	0	0	36	47	50	53	55	54	54	54	55	54	54	53	54
0.8	0	0	36	52	59	64	66	66	67	67	66	67	67	67	66
0.7	0	0	36	57	69	75	77	78	79	78	78	77	78	79	78
0.6	0	0	36	62	77	84	87	88	88	88	88	87	87	88	87
0.5	0	0	36	68	84	92	94	95	95	94	95	94	94	95	94
0.4	0	0	36	73	90	96	98	98	98	98	98	98	98	98	98
0.3	0	0	36	78	94	98	100	100	100	100	100	100	100	100	100
0.2	0	0	36	82	97	100	100	100	100	100	100	100	100	100	100
0.1	0	0	36	86	98	100	100	100	100	100	100	100	100	100	100
0.0	0	0	36	89	99	100	100	100	100	100	100	100	100	100	100

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 (%) that future SSB will exceed the Limit Reference Point

β	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040	2050
1.0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.9	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.8	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.7	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.6	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.5	100	100	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	100	100
0.3	100	100	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	100	100
0.1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

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 4. Changes in future average SSB (tons)

β	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040	2050
1.0	126,426	118,278	152,204	157,753	156,334	157,767	158,785	157,875	158,207	156,180	157,683	157,435	156,565	156,510	156,901
0.9	126,426	118,278	152,204	164,537	168,141	172,159	174,455	174,148	174,786	172,813	174,431	174,258	173,413	173,361	173,683
0.8	126,426	118,278	152,204	171,665	181,022	188,106	191,699	191,832	192,596	190,562	192,206	192,051	191,221	191,127	191,384
0.7	126,426	118,278	152,204	179,158	195,096	205,837	210,749	211,073	211,714	209,486	211,087	210,916	210,107	209,958	210,160
0.6	126,426	118,278	152,204	187,037	210,498	225,625	231,902	232,078	232,253	229,679	231,197	231,017	230,256	230,053	230,215
0.5	126,426	118,278	152,204	195,327	227,384	247,799	255,553	255,155	254,399	251,280	252,711	252,584	251,930	251,664	251,814
0.4	126,426	118,278	152,204	204,054	245,928	272,757	282,222	280,772	278,471	274,512	275,858	275,916	275,479	275,125	275,296
0.3	126,426	118,278	152,204	213,246	266,329	300,982	312,612	309,652	305,029	299,753	300,943	301,381	301,358	300,889	301,122
0.2	126,426	118,278	152,204	222,932	288,816	333,061	347,664	342,911	335,063	327,698	328,418	329,416	330,120	329,599	329,930
0.1	126,426	118,278	152,204	233,144	313,648	369,714	388,657	382,271	370,326	359,718	359,127	360,608	362,410	362,224	362,662
0.0	126,426	118,278	152,204	243,917	341,123	411,824	437,316	430,350	413,877	398,578	394,977	396,091	399,075	400,314	400,822

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	2040	2050
1.0	75,652	82,844	101,484	104,956	105,532	105,608	105,814	105,438	105,229	105,197	105,040	104,926	104,773	105,474	104,957
0.9	75,652	82,844	93,357	99,825	102,469	103,687	104,457	104,401	104,327	104,360	104,252	104,189	104,057	104,701	104,204
0.8	75,652	82,844	84,849	93,866	98,428	100,712	101,939	102,086	102,056	102,086	101,984	101,947	101,828	102,388	101,924
0.7	75,652	82,844	75,938	86,973	93,240	96,496	98,079	98,314	98,242	98,219	98,099	98,076	97,971	98,440	98,023
0.6	75,652	82,844	66,599	79,029	86,703	90,808	92,652	92,873	92,684	92,571	92,426	92,417	92,333	92,712	92,354
0.5	75,652	82,844	56,807	69,897	78,566	83,348	85,368	85,500	85,134	84,904	84,738	84,754	84,704	84,995	84,705
0.4	75,652	82,844	46,534	59,420	68,522	73,727	75,842	75,845	75,271	74,907	74,728	74,781	74,779	74,986	74,771
0.3	75,652	82,844	35,750	47,417	56,188	61,425	63,533	63,424	62,664	62,164	61,971	62,064	62,123	62,256	62,115
0.2	75,652	82,844	24,423	33,681	41,084	45,740	47,659	47,513	46,685	46,098	45,884	45,991	46,105	46,190	46,115
0.1	75,652	82,844	12,518	17,968	22,608	25,709	27,063	26,984	26,353	25,851	25,647	25,711	25,825	25,892	25,864
0.0	75,652	82,844	0	0	0	0	0	0	0	0	0	0	0	0	0

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. Model Diagnosis Results of Stock-Recruitment Relationship

The RI model was applied using the data after the 1995 fishing season for the stock-recruitment relationship of the Pacific stock of blue mackerel. Various diagnostic results for the application of data to this model are shown below.

Supplementary Figure 1-1 shows the respective stock-recruitment curves for the HS, BH, and RI models optimized by the least absolute value method. The results showed that the BH model stock-recruitment relationship had the lowest AICc value, but could not properly estimate the recruitment slope for a SSB of 38,000 tons or less. Although RI had a higher AICc than HS, the recruitment slope for a SSB of 38,000 tons or less was gentle.

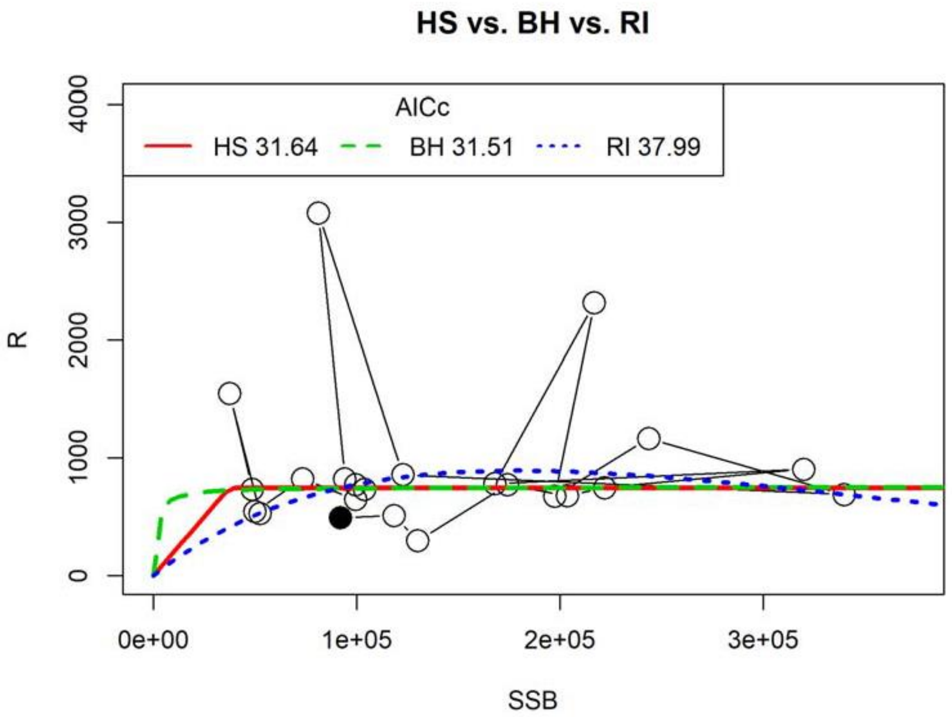
Supplementary Figure 1-2 shows profile likelihood with respect to the estimation parameters of the RI curve, 80% confidence interval for residual bootstrap, and the estimated values for Jackknife analysis. It was confirmed that the profile likelihood when the parameters a and b were changed was the maximum at the point estimation value.

In the normality of the residuals for the models (Supplementary Figure 1-3), deviations were observed in both Shapiro-Wilk test and the Kolmogorov-Smirnov test. From this, it is concluded that optimization by the least absolute value method is appropriate.

In the chronological trend of residuals (Supplementary Figure 1-4), residuals have shown a clear downward trend since 2011, and in particular, 2015 was negatively inclined to a large extent. The autocorrelation coefficient was low in each year, and no clear trend was observed.

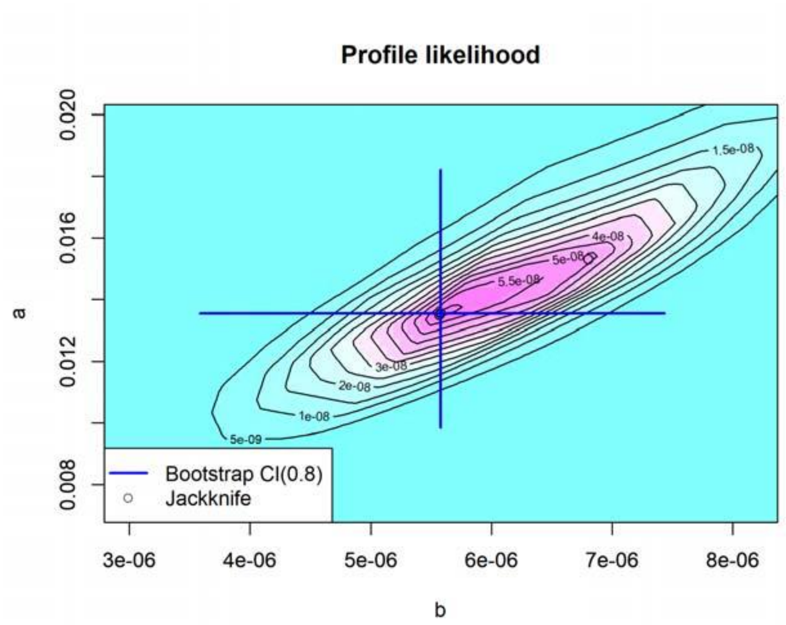
The reliability of parameter estimation was verified by performing residual bootstrap (Supplementary Figures 1-5 and 1-6). For a and b, the median and the point estimate were almost the same, but for sd, the median and the point estimate were slightly different.

In order to confirm the robustness of parameter estimation, Jackknife analysis was performed excluding data one by one (Supplementary Figures 1-7 and 1-8). For both a and b, it was shown that the estimated values were larger except for the years 2006, 2007, 2009, and 2011. For sd, the changes in the estimated values were small and relatively robust to the removal of each data.



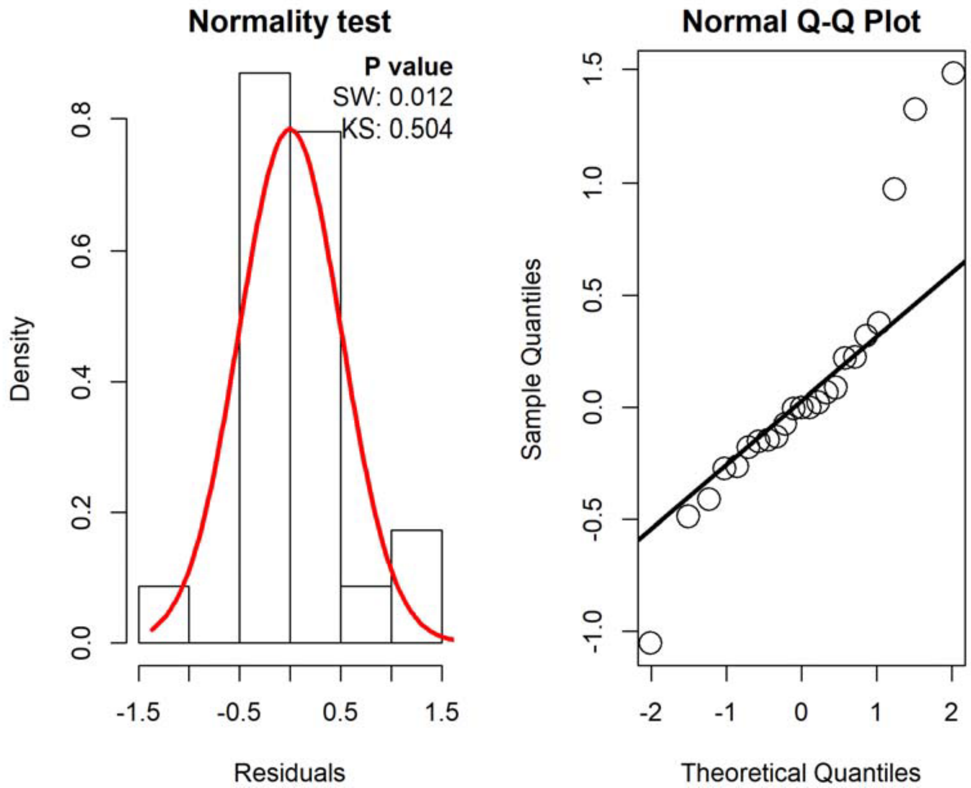
Supplementary Figure 1-1. Stock-Recruitment curves for each model estimated by the least absolute value method

The red line shows the estimated values on the Hockey Stick model (HS), the green dash line shows the estimated values on the Beverton-Holt model (BH), and the blue dotted line shows the estimated values on the Ricker model (RI), respectively.

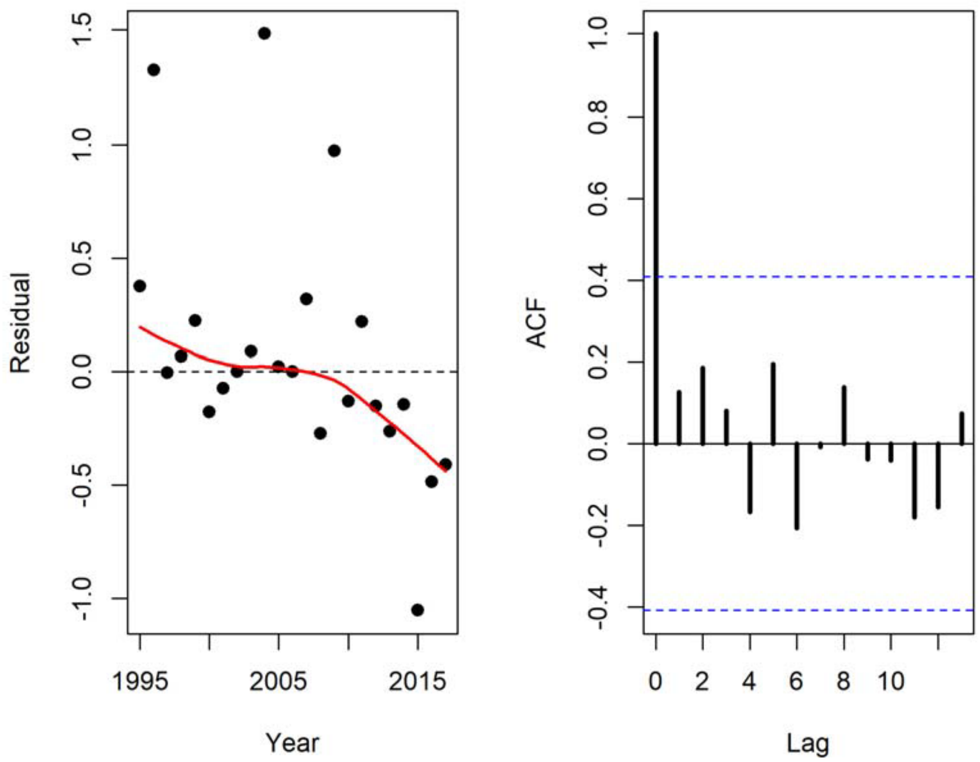


Supplementary Figure 1-2. Profile likelihood with respect to the estimation parameters of the RI curve

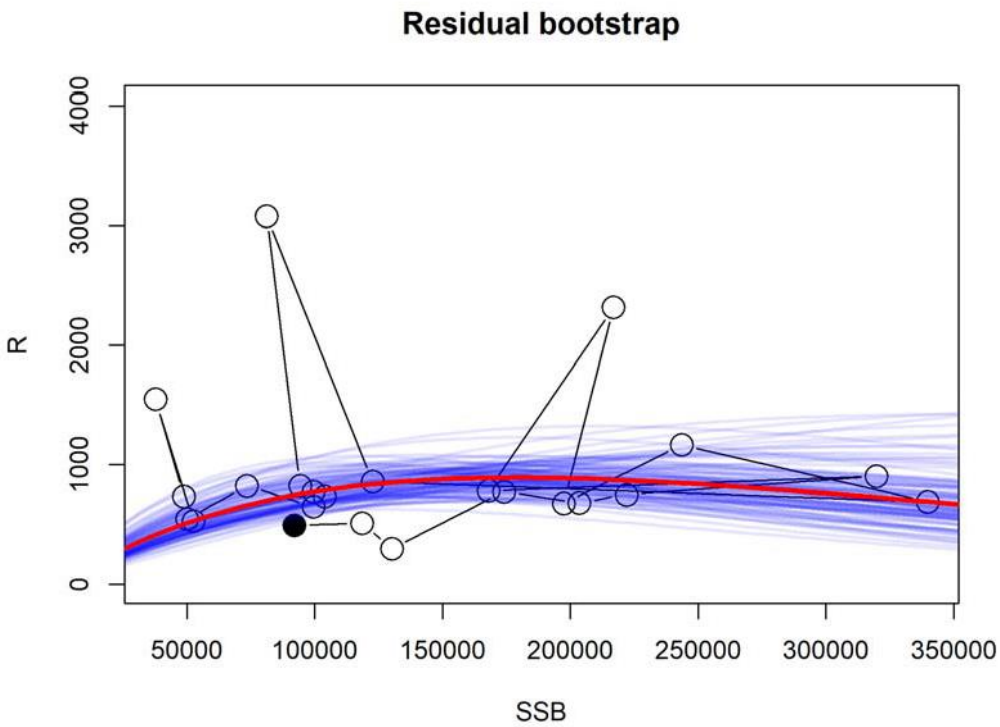
The figure also shows 80% confidence interval (blue line) for residual bootstrap and the estimated values (◯) for Jackknife analysis.



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

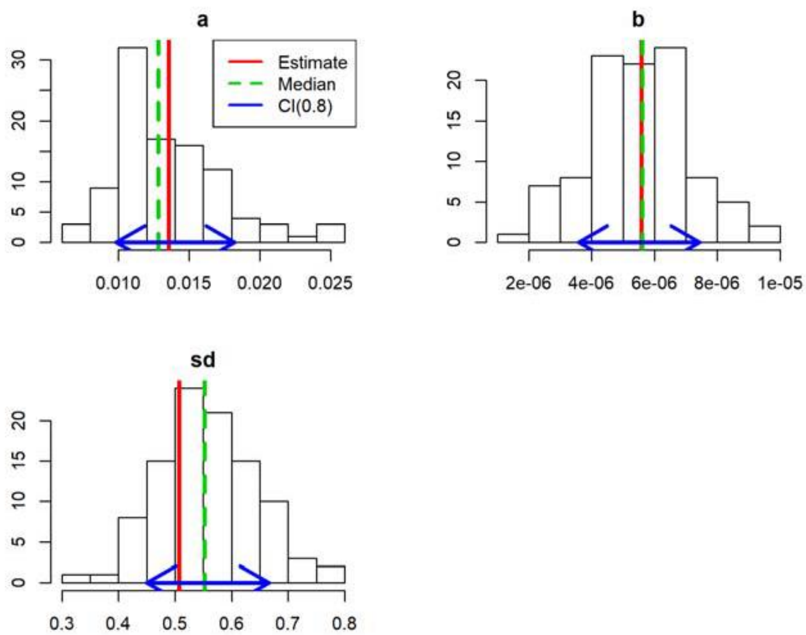


Supplementary Figure 1-4. Trends in residuals (left) and autocorrelation coefficient (right)



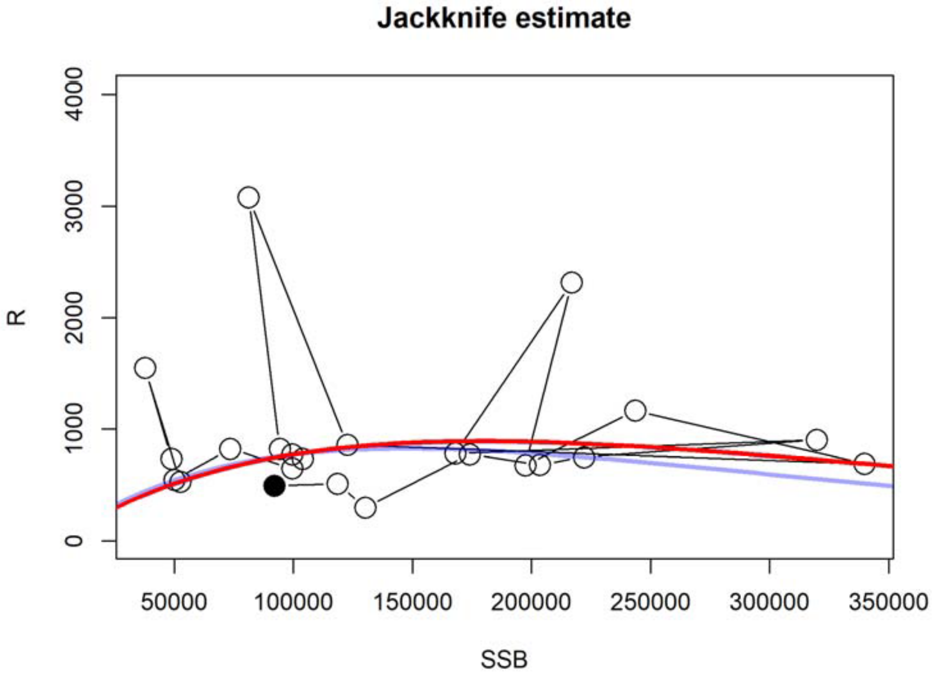
Supplementary Figure 1-5. RI model estimation results for residual bootstrap

The red line is the estimated value for the original data, and the blue line is the estimated value for each bootstrap.



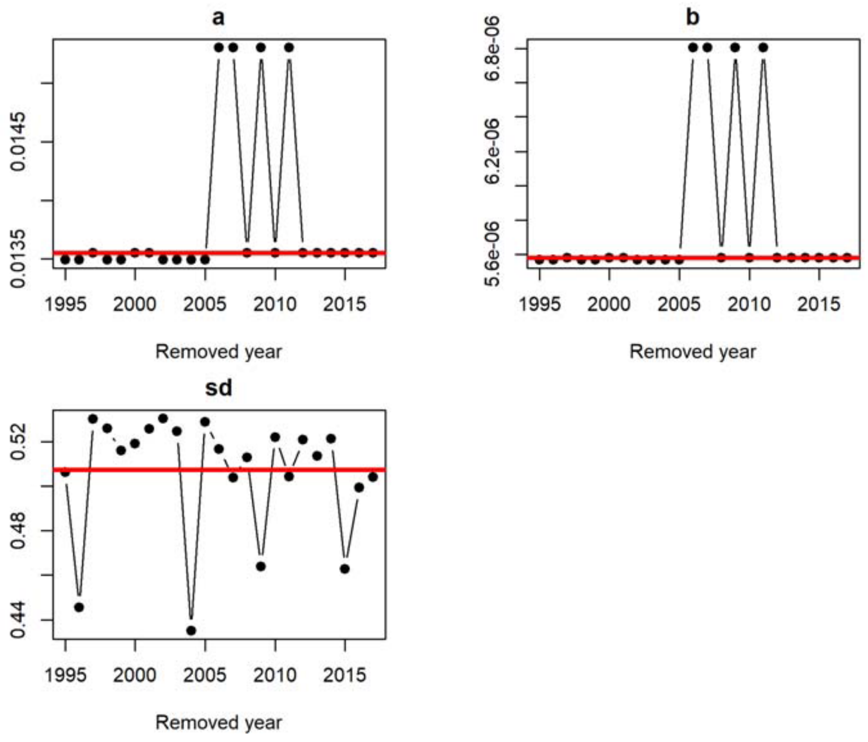
Supplementary Figure 1-6. Parameter estimates of RI curve for residual bootstrap.

The figure shows the histograms of the slope (a), break point (b), residual (c), and the estimated values (red line), median values (green broken line), and 80% confidence interval (blue line range) in original data.



Supplementary Figure 1-7. RI curve estimation results for Jackknife analysis

The red line is the estimated value for all data, and the blue line is the estimated value excluding each year.



Supplementary Figure 1-8. Parameter estimates of RI curve for Jackknife analysis

The figure shows the estimated value (broken line) when each year is excluded, and the estimated value (red line) in all data for the slope (a), break point (b), and residual (c).

Supplementary Material 2 Examination of stock-recruitment relationship

As a candidate for the stock-recruitment relationship of this stock, BH could not properly estimate the recruitment slope when SSB of 38,000 ton or less, so we considered applying RI or HS. Although AICc was lower in HS than in RI, there is little data for low SSB, and it is difficult to determine the appropriateness of stock-recruitment relationship using AICc alone. Therefore, we performed sensitivity analysis for the incorrect assumption of stock-recruitment relationship, and examined which of the stock-recruitment relationships was more robust, RI or HS.

Method

Future projections were made for the event where the true stock-recruitment relationship was RI and the fishery was managed by the HCR which incorrectly assumed HS, and event where true stock-recruitment relationship was HS and the fishery was managed by the HCR which incorrectly assumed RI as the stock-recruitment relationship. The (biological) reference points when adopting RI are described in this document, and the (biological) reference points when HS is adopted are shown in Supplementary Material 3.

Result

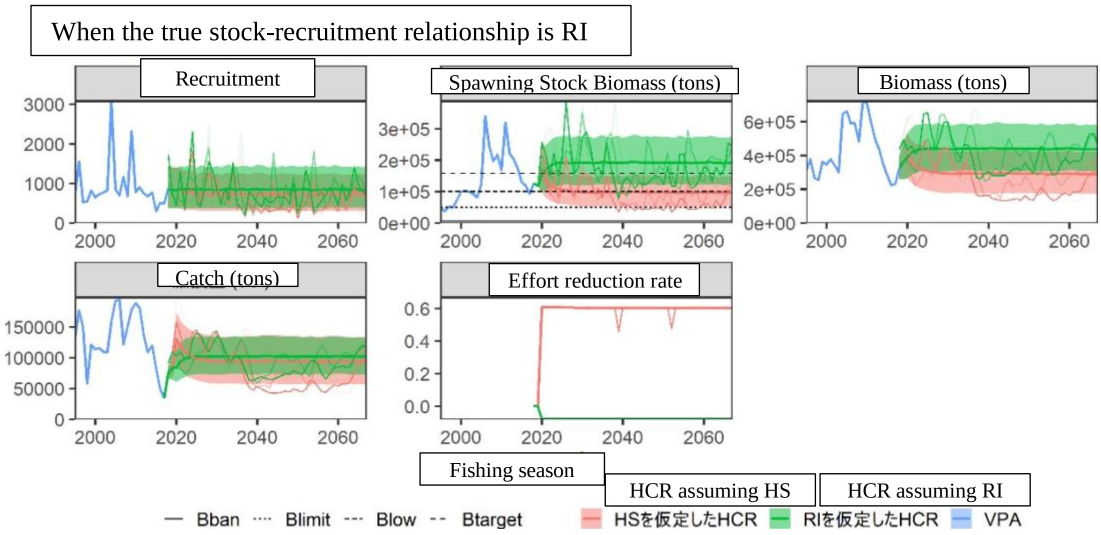
When the true stock-recruitment relationship is RI and fishing is managed with HCR assuming HS, F becomes higher and the average catch ($\beta = 0.8$) is slightly lower than HCR assuming RI (Supplementary Figure 2-1). The SSB was at a lower level than when assuming RI (Supplementary Figure 2-1), and in some cases was lower than the lowest ever SSB (Supplementary Table 2-2).

When the true stock-recruitment relationship is HS and fishing is managed with HCR assuming RI, F was lower and SSB was maintained at a high level compared to those with HCR assuming HS (Supplementary Figure 2-2). The value did not fall below the historically lowest level of SSB (Supplementary Table 2-4). On the other hand, the average catch ($\beta = 0.8$) was at a slightly lower level than when assuming HS (Supplementary Figure 2-2).

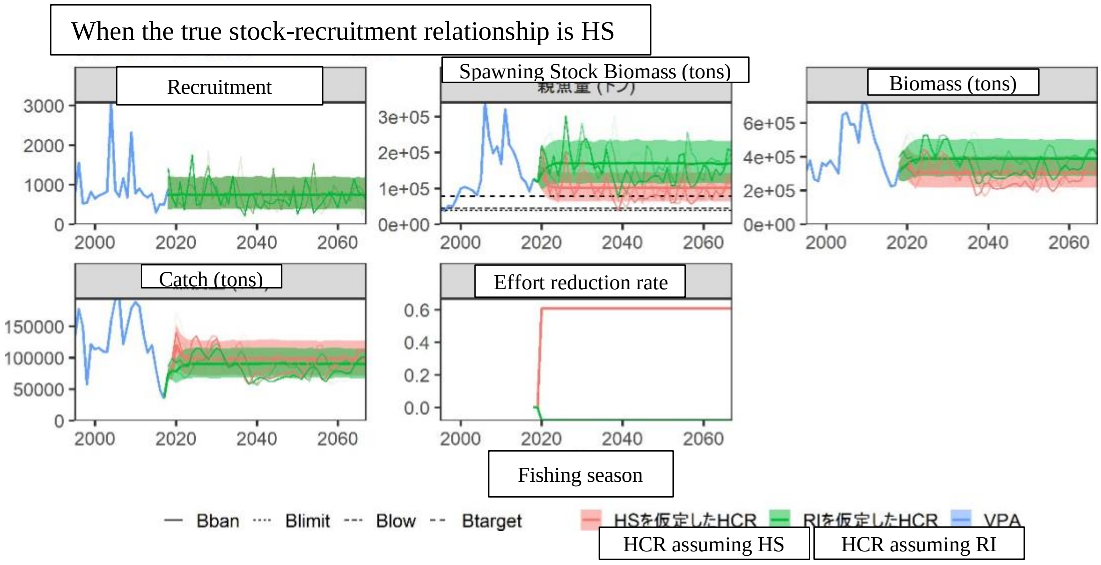
Considerations

Incorrect assumption of HS when the true stock-recruitment relationship is RI would result in maintaining a low level of SSB, sometimes lower than the historically lowest SSB. On the other hand, if RI was incorrectly assumed when the true stock-recruitment relationship was HS, the SSB would be maintained at a high level and catches would be slightly lower, but not significantly different from the HS assumption. When RI is assumed, F is lower than when HS is assumed, but it is probable that the catch itself would not change greatly due to the increased biomass.

Summarizing the above, there is a high risk that the SSB will decrease if HS is adopted incorrectly. On the other hand, even if RI is adopted incorrectly, the risk of a decrease in the SSB is little and catches decrease mildly. Therefore, we propose the adoption of a more robust RI as the stock-recruitment relationship. In this stock, which recruitment in 2015-2017 has remained low, it is desirable to adopt RI that has a low risk of decrease in SSB.



Supplementary Figure 2-1. Average values (solid line) and 80% confidence interval (shaded area) of the future projection based on the HCR assuming HS when the true stock-recruitment relationship is R. The unit of recruitment is one million.



Supplementary Figure 2-2. Average values (solid line) and 80% confidence interval (shaded area) of the future projection based on the HCR assuming RI when the true stock-recruitment relationship is HS. The unit of recruitment is one million.

Supplementary Table 2-1. Catch managed by HCR assuming HS when the true stock-recruitment relationship is RI

(Tons)

β	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040	2050
1.0	75,652	82,844	152,237	124,619	108,259	98,433	91,801	86,380	82,656	79,884	77,660	75,883	74,723	72,378	72,021
0.9	75,652	82,844	141,823	122,341	109,925	102,528	97,760	93,722	91,006	89,047	87,413	86,060	85,089	83,350	82,882
0.8	75,652	82,844	130,604	118,863	110,451	105,437	102,428	99,735	98,055	96,923	95,903	95,095	94,499	94,080	93,606
0.7	75,652	82,844	118,502	113,935	109,525	106,820	105,385	103,882	103,019	102,542	102,040	101,643	101,331	101,797	101,300
0.6	75,652	82,844	105,428	107,251	106,743	106,223	106,106	105,526	105,213	105,121	104,919	104,765	104,588	105,289	104,773
0.5	75,652	82,844	91,281	98,428	101,563	103,053	103,947	103,952	103,897	103,935	103,832	103,778	103,649	104,273	103,784
0.4	75,652	82,844	75,951	86,983	93,249	96,503	98,086	98,320	98,249	98,226	98,106	98,083	97,977	98,446	98,029
0.3	75,652	82,844	59,309	72,309	80,775	85,407	87,391	87,550	87,233	87,034	86,873	86,881	86,821	87,134	86,827
0.2	75,652	82,844	41,215	53,630	62,677	67,959	70,086	70,027	69,353	68,919	68,734	68,808	68,835	69,003	68,826
0.1	75,652	82,844	21,506	29,953	36,814	41,191	43,015	42,877	42,066	41,477	41,260	41,362	41,483	41,562	41,501
0.0	75,652	82,844	0	0	0	0	0	0	0	0	0	0	0	0	0

Supplementary Table 2-2. Probability (%) of SSB>SBmin when fishing is managed by HCR assuming HS when the true stock-recruitment relationship is RI

β	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040	2050
1.0	100	100	100	100	99	98	95	92	90	87	85	83	83	80	80
0.9	100	100	100	100	100	99	98	98	96	95	95	94	93	92	92
0.8	100	100	100	100	100	100	100	99	99	99	99	99	99	98	98
0.7	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.6	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.5	100	100	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	100	100
0.3	100	100	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	100	100
0.1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Supplementary Table 2-3. Catch managed by HCR assuming RI when the true stock-recruitment relationship is HS

(Tons)

β	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040	2050
1.0	73,890	78,437	93,536	94,971	94,890	94,653	94,725	94,455	94,293	94,219	94,068	94,005	93,942	94,398	94,106
0.9	73,890	78,437	86,080	90,307	91,947	92,514	92,857	92,701	92,562	92,491	92,341	92,288	92,218	92,643	92,382
0.8	73,890	78,437	78,268	84,922	88,254	89,716	90,408	90,408	90,314	90,255	90,108	90,065	89,992	90,384	90,154
0.7	73,890	78,437	70,079	78,717	83,642	86,063	87,187	87,395	87,377	87,343	87,206	87,174	87,101	87,459	87,262
0.6	73,890	78,437	61,488	71,575	77,902	81,300	82,928	83,406	83,504	83,517	83,402	83,383	83,315	83,638	83,474
0.5	73,890	78,437	52,472	63,364	70,778	75,086	77,264	78,071	78,334	78,424	78,350	78,352	78,295	78,583	78,452
0.4	73,890	78,437	43,003	53,931	61,947	66,968	69,676	70,852	71,329	71,534	71,528	71,562	71,526	71,785	71,689
0.3	73,890	78,437	33,054	43,099	51,013	56,348	59,434	60,953	61,670	62,023	62,116	62,201	62,202	62,446	62,383
0.2	73,890	78,437	22,593	30,664	37,481	42,423	45,500	47,190	48,090	48,585	48,795	48,945	48,998	49,249	49,217
0.1	73,890	78,437	11,586	16,389	20,734	24,120	26,396	27,776	28,595	29,092	29,358	29,541	29,636	29,892	29,886
0.0	73,890	78,437	0	0	0	0	0	0	0	0	0	0	0	0	0

Supplementary Table 2-4. Probability (%) of SSB>SBmin when fishing is managed by HCR assuming RI when the true stock-recruitment relationship is RI

β	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040	2050
1.0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.9	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.8	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.7	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.6	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.5	100	100	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	100	100
0.3	100	100	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	100	100
0.1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Supplementary Material 3 When using the Hockey Stick model (HS) as stock-recruitment relationship

1) Future projection and (biological) reference points

As a reference, the (biological) reference points calculated using the HS stock-recruitment relationship without considering the autocorrelation optimized by the least absolute value method, considered as a candidate, is also shown in this document. The parameters are shown in the table below, and the relationship between the past SSB and recruitment is shown in Supplementary Figure 3-1. Here, a is the slope of the stock-recruitment relationship up to the break point of HS (fish / kg), and b is the SSB (tons) that becomes the break point of HS.

Stock-recruitment relationship equation	Optimization method	Autocorrelation	a	b	S.D.
HS	Least absolute value method	No	0.0199	37,621	0.442

The SSB (SBmsy) at the MSY level, which is a standard value, was used as the target reference point (SBtarget), the historical lowest SSB (SBmin) was used as the limit Reference point (SBlimit), and the SSB at which 10% catch of MSY can be obtained (SB0.1 msy) was used as the fishing prohibition level (SBban). The standard value of the limit reference point is the SSB at which 60% catch of MSY can be obtained (SB 0.6 msy), but that value is 25,000 tons, which is lower than the lowest ever SSB (SBmin: 38,000 tons); therefore, SBmin was set. This is consistent with the Blimit used in the FY2018 Stock assessment. The below table shows the Biomass at each level.

(Biological) Reference Point	Spawning Stock Biomass	Standard
Target Reference Point	78,000 tons	SBmsy
Limit Reference Point	38,000 tons	SBmin
Fishing prohibition level	4,000 tons	SB0.1msy

For each reference point, Supplementary Table 3-1 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 catch rate, and the multiplier for the current fishing pressure in the future projection using the stock-recruitment relationship. Supplementary Figure 3-2 shows the SSB at equilibrium in future projection when the F values are variously changed, and the average catch by age with respect to this.

Supplementary Figure 3-3 shows Kobe plots using the target reference points. The exploitation rate in this stock has been concluded to be below the level that gives MSY since 1998, the SSB has exceeded the MSY since 2000, and the current SSB exceeds the target reference point.

Supplementary Figure 3-4 shows the relationship between the SSB and the fishing mortality coefficient in the Harvest Control Rules (HCR) using the target reference point, limit reference point, and fishing prohibition level.

Supplementary Figure 3-5 shows the changes in the biomass, SSB, catch, recruitment, and effort reduction rate (reduction rate from Fcurrent) when values shown in the above table were used for the target reference point, limit reference point, and fishing prohibition level and the standard value of 0.8 was used for β. We have assumed that catch control starts from the 2020 fishing season, and the catches for the 2018 and 2019 fishing seasons were assumed to be based on the current fishing mortality coefficient (Fcurrent).

It is estimated that the SSB and Biomass tend to level off as recruitment continues to be stable after 2018 based on the stock-recruitment relationship. Since the SSB is higher than MSY, the catch will be higher than Fcurrent because there will be an upward revision in fishing pressure from Fcurrent.

Supplementary Tables 3-2 to 5 show the changes in the probability of exceeding the target reference point, probability of exceeding the limit reference point, average SSB and average catch for the years 2018-2030, 2040, and 2050 when β is changed between 0 and 1 in the future projection. Since the SSB in 2020, which is the first year of management, exceeds MSY, the probability of exceeding the target reference point is relatively high when β = 0.8 or less, and reaches equilibrium at about 75%, but at β = 1, the probability after 2023 was less than 50%. The catch tends to increase as the value of β increases.

2) Model diagnosis

The HS model was applied using the data after the 1995 fishing season for the stock-recruitment relationship of the Pacific stock of blue mackerel. Various diagnostic results for the application of data to this model are shown below.

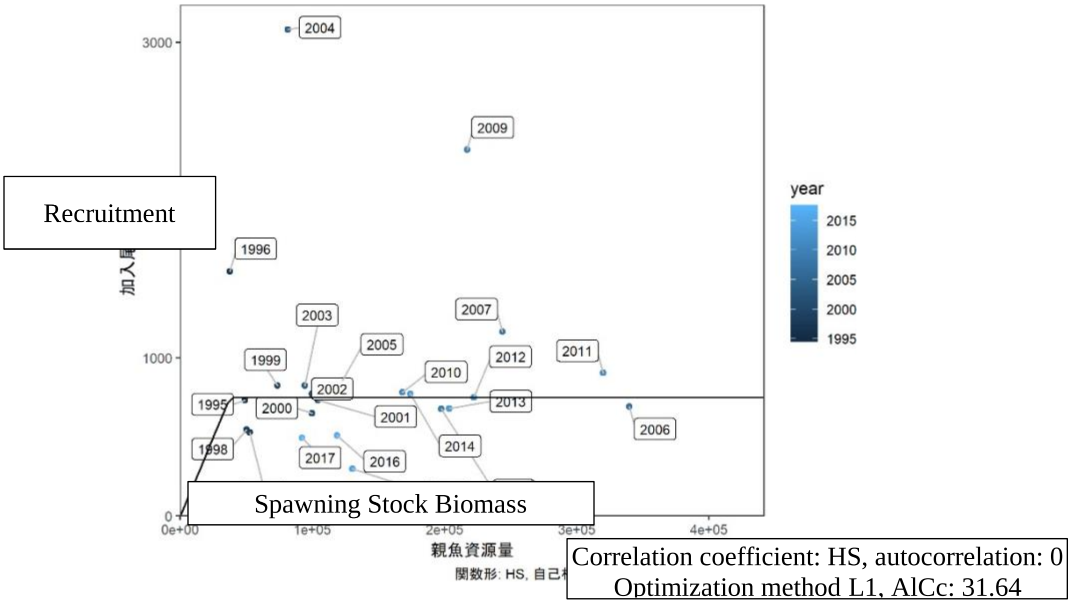
Supplementary Figure 3-6 shows profile likelihood with respect to the estimation parameters of the HS curve, 80% confidence interval for residual bootstrap, and the estimated values for Jackknife analysis. The likelihood of the value of parameter b was small, but the likelihood of the value of a was large.

In the normality of the residuals for the models (Supplementary Figure 3-7), deviations were observed in both Shapiro-Wilk test and the Kolmogorov-Smirnov test. For this reason, the HS stock-recruitment relationship using the least absolute value method was examined in this supplementary material.

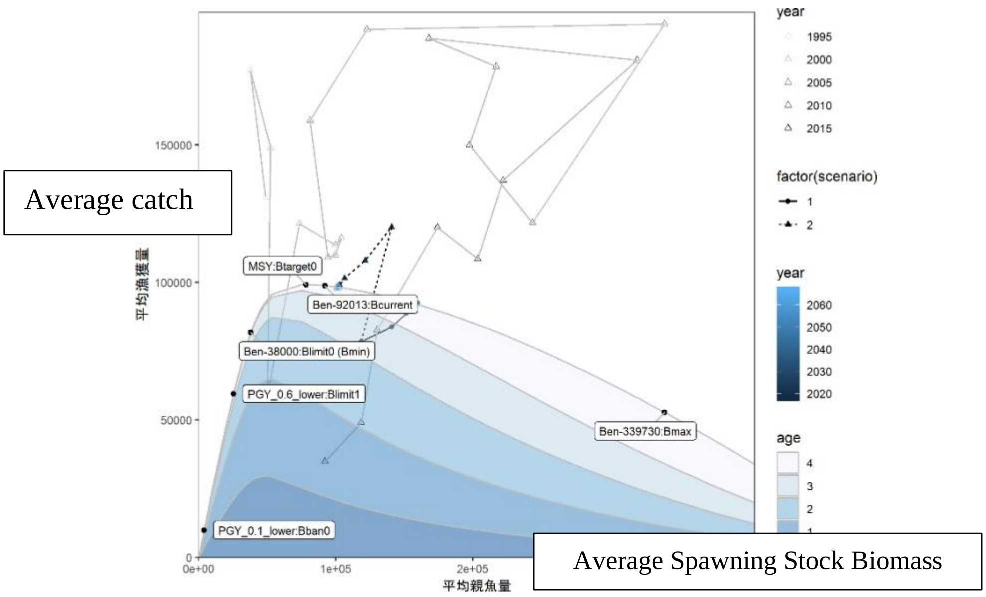
In the chronological trend of residuals (Supplementary Figure 3-8), residuals have shown a clear downward trend since 2010, in particular, 2015 was negatively inclined to a large extent. The autocorrelation coefficient was low in each year, and no clear trend was observed.

The reliability of parameter estimation was verified by performing residual bootstrap (Supplementary Figures 3-9 and 3-10). For b, it was estimated to be almost the lowest ever SSB, and the confidence interval was narrow, but for a and sigma, the confidence interval was somewhat wide, and the median and the point estimates were slightly different.

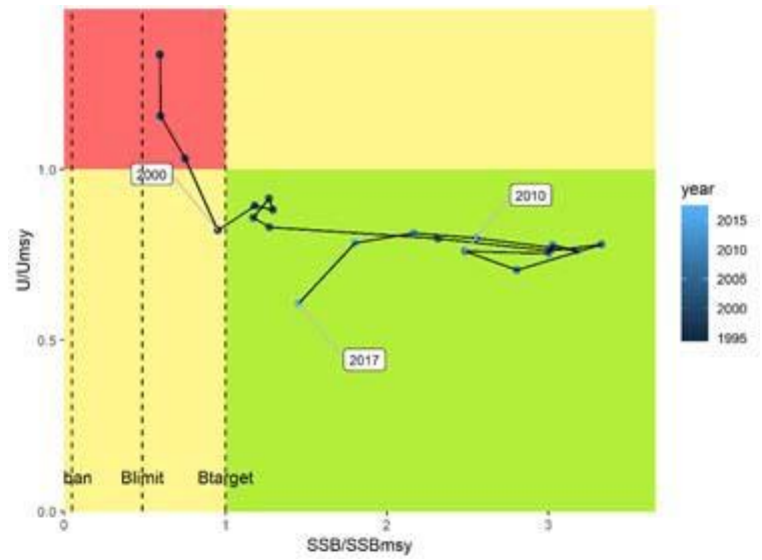
In order to confirm the robustness of parameter estimation, Jackknife analysis was performed excluding data one by one (Supplementary Figures 3-11 and 3-12). The effect of the lowest ever SSB in 1996, which is estimated to be the break point, is very strong, so if the data for this year is excluded, the estimated value of a was small and the estimated value of b was large. For sigma, the changes in the estimated values were small and relatively robust to the removal of each data.



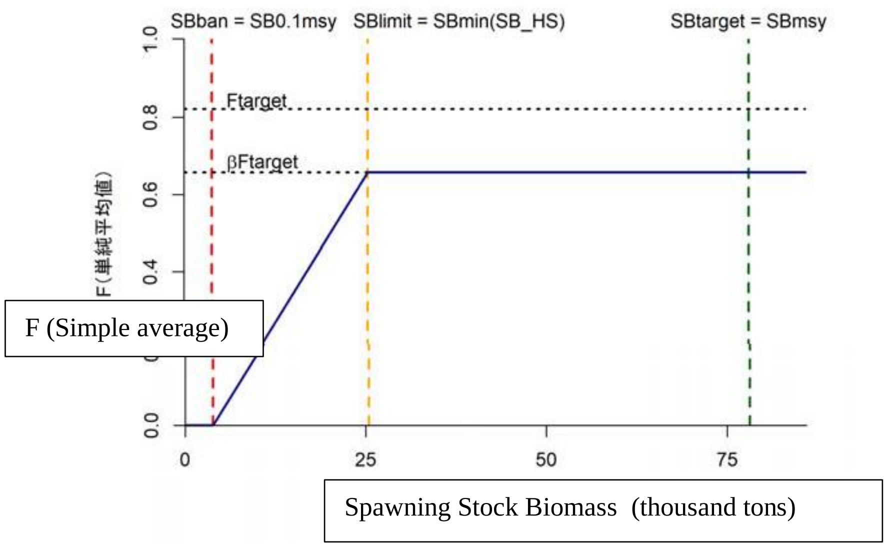
Supplementary Figure 3-1. Stock-recruitment relationships. The numbers in the figure indicate year class. The Hockey Stick model (HS) was used for the stock-recruitment curve, and the parameters were estimated by the least absolute value method without considering autocorrelation.



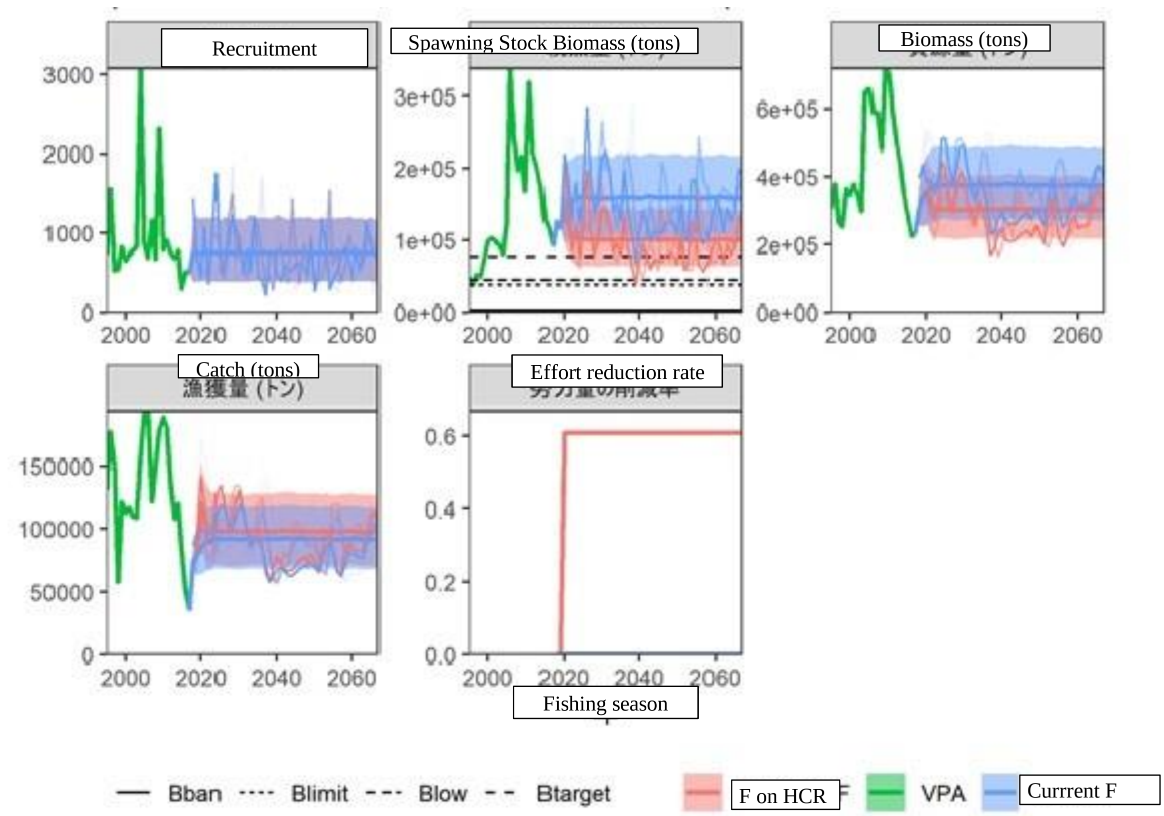
Supplementary Figure 3-2. Relationship between the (biological) reference points and the curves for the catch by age The average value of the catch by age with respect to the SSB at equilibrium in the future projections using the assumed stock-recruitment relationship is indicated by the area, the changes in the observed value (△) 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.



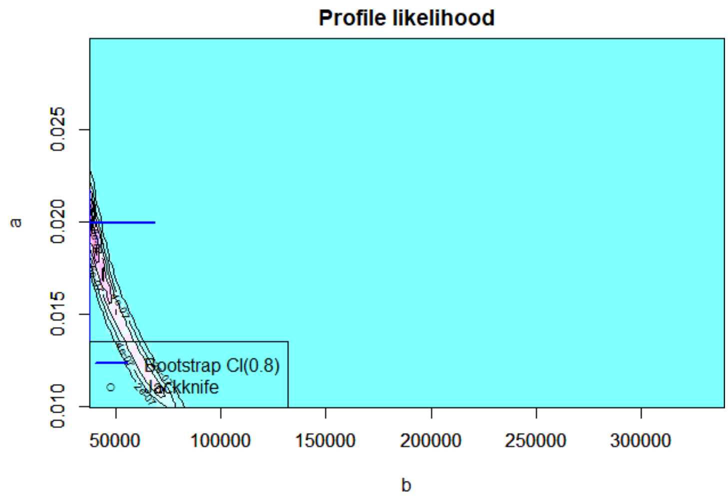
Supplementary Figure 3-3. Kobe Plot (Four sections)The (biological) reference points, SBtarget, SBlimit, and SBban, were respectively set to SBmsy, SBmin, and SB0.1msy.



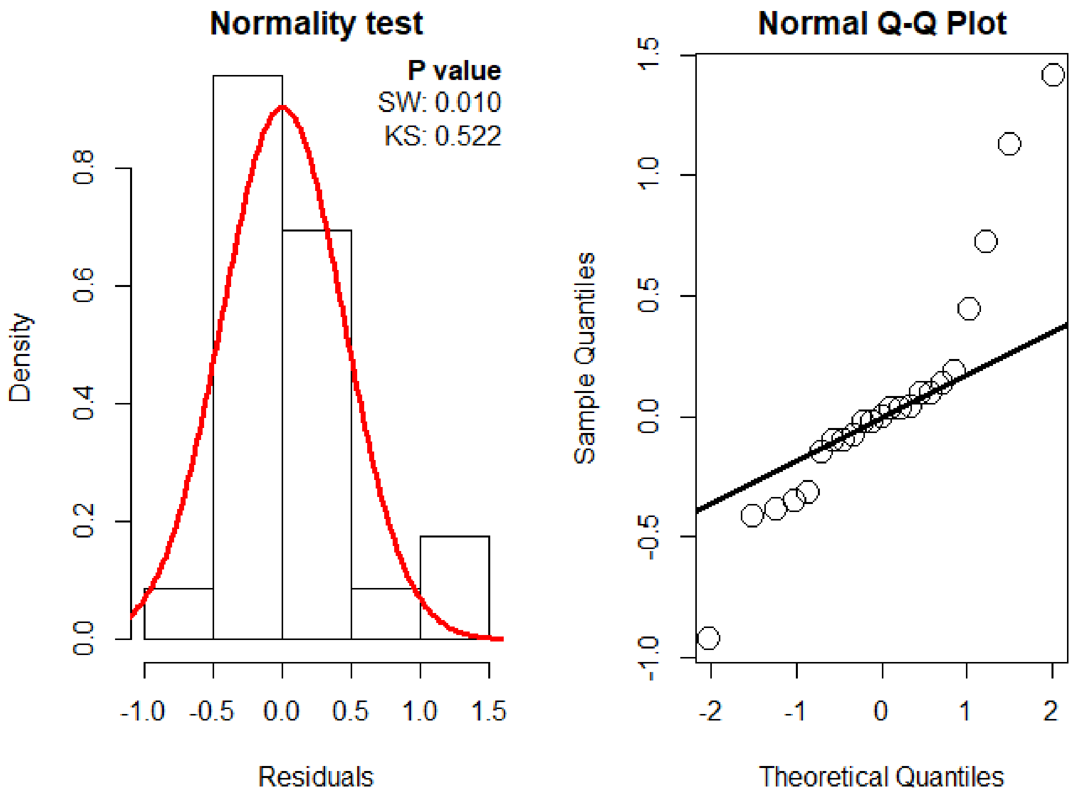
Supplementary Figure 3-4 Harvest Control Rules The (biological) reference points, SBtarget, SBlimit, and SBban were respectively set to SBmsy, SBmin, and SB0.1msy, and the standard value of 0.8 was used for β.



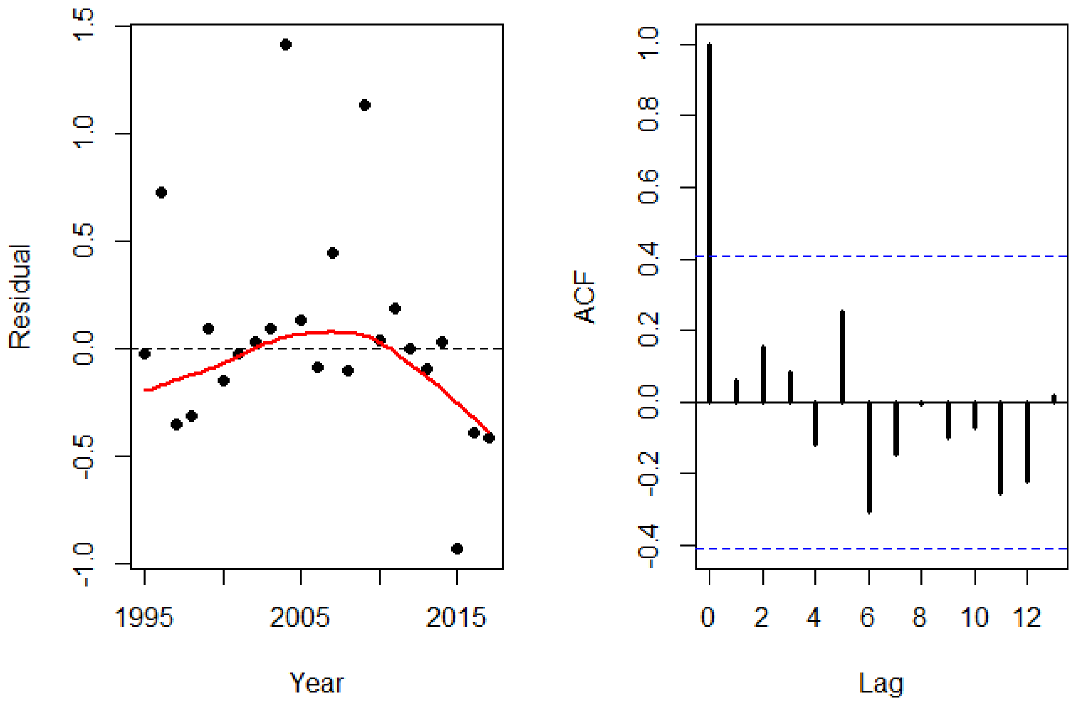
Supplementary Figure 3-5. Average value of future projection based on the Harvest Control Rules (solid line) and 80% confidence interval (shaded area). The (biological) reference points, SBtarget, SBlimit, and SBban, were respectively set to SBmsy, SBmin, and SB0.1msy, respectively. The catches for the 2018 and 2019 fishing seasons were given by Fcurrent. The standard value of 0.8 was used for β. The unit of recruitment is one million.



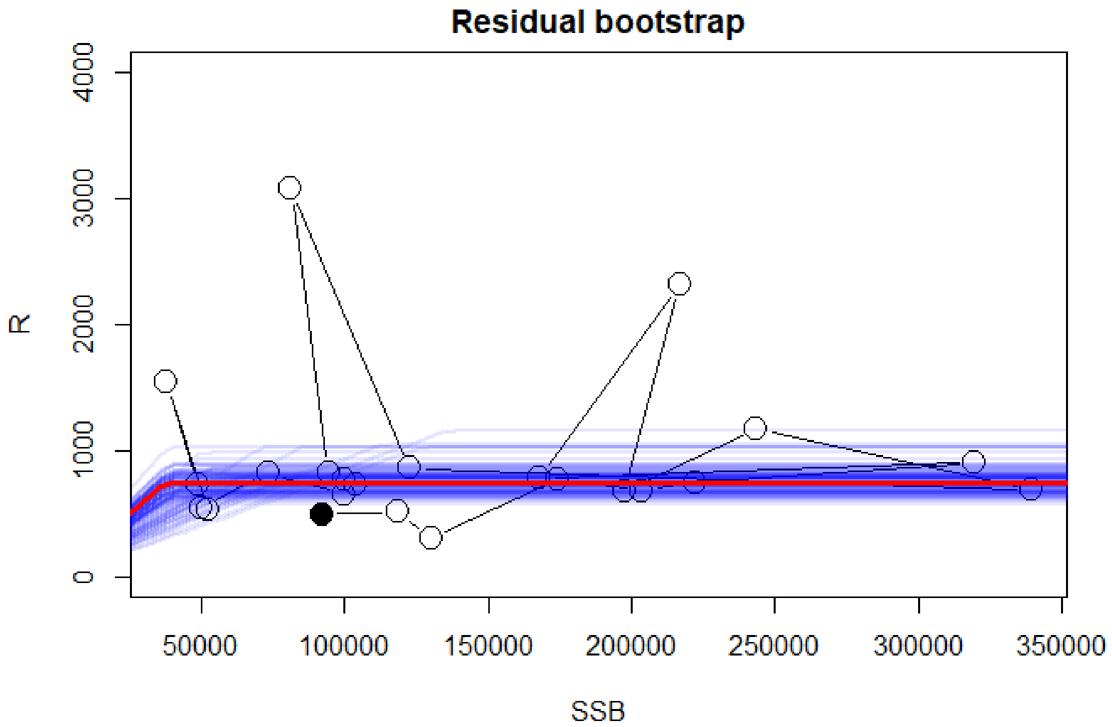
Supplementary Figure 3-6 Profile likelihood with respect to the estimation parameters of the HS curve. The figure also shows 80% confidence interval (blue line) for residual bootstrap and the estimated values for Jackknife analysis (〇).



Supplementary Figure 3-7. Normality test result of residual distribution (left) and QQ plot (right)

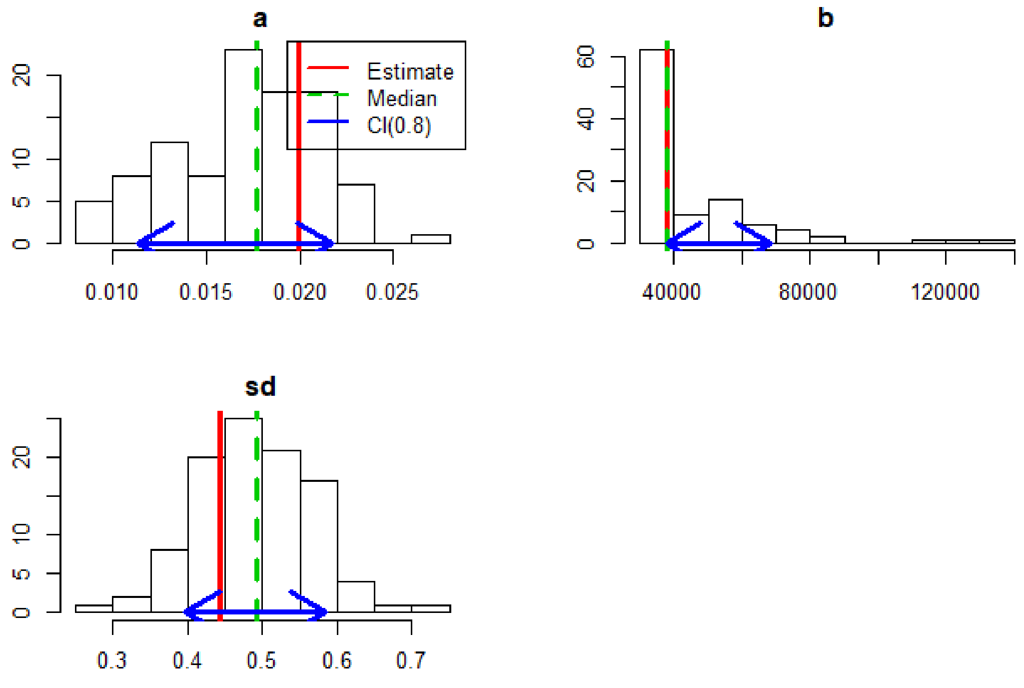


Supplementary Figure 3-8. Trends in residuals (left) and autocorrelation coefficient (right)



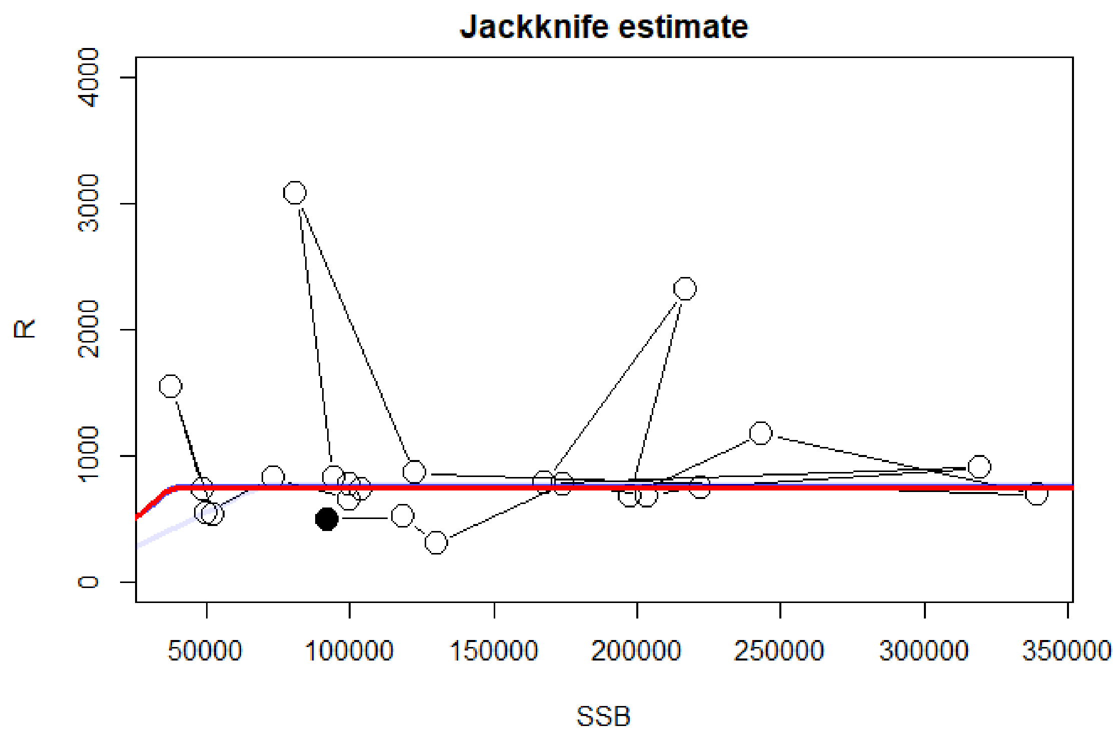
Supplementary Figure 3-9. Estimation result of HS curve for residual bootstrap.

The red line is the estimated value in the original data, and the blue line is the estimated value in each bootstrap.



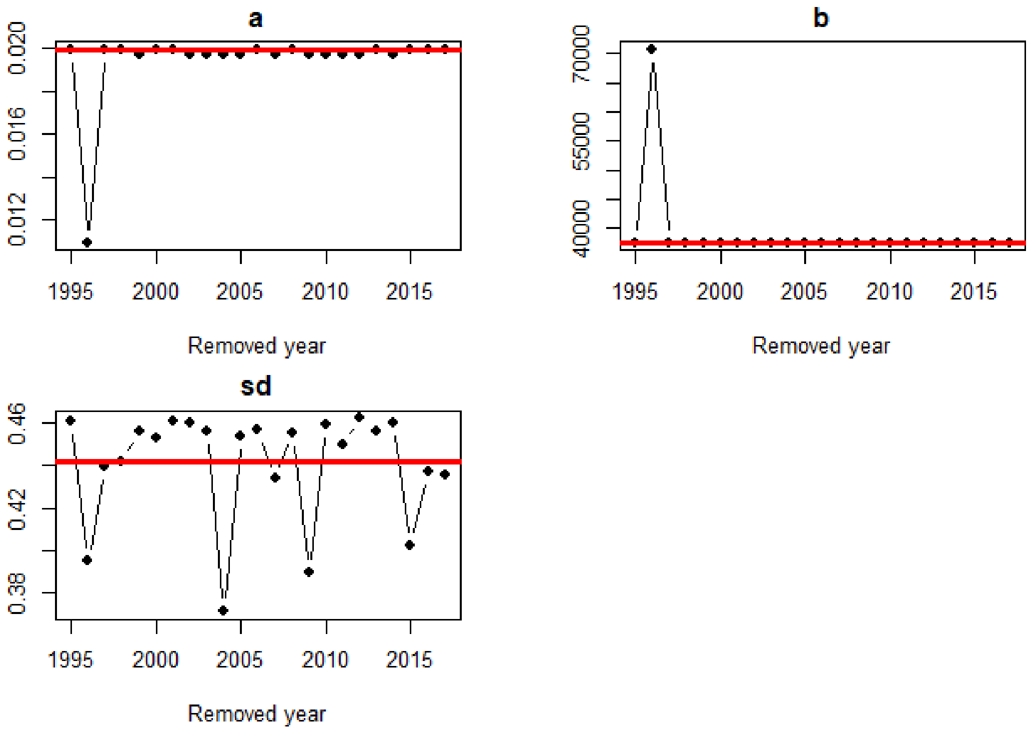
Supplementary Figure 3-10. Parameter estimates of HS curve for residual bootstrap.

The figure shows the histogram for the slope (a), break point (b), residual (c) and the estimated value (red line), median value (green broken line), and 80% confidence interval (blue line range) in original data.



Supplementary Figure 1-11. HS curve estimation results for Jackknife analysis

The red line is the estimated value for all data, and the blue line is the estimated value excluding each year.



Supplementary Figure 1-12. Parameter estimates of HS curve for Jackknife analysis.

The figure shows the estimated value (broken line) with each year excluded for the slope (a), break point (b), residual (c) and the estimated value for all data (red line).

Supplementary Table 3-1. Relationship among various (biological) reference points and SSB at equilibrium, catch, catch rate and effort multiplier for current fishing pressure

(Biological) Reference Point	**Spawning Biomass**	**Ratio to SB0**	**Catch**	**CV of catch**	**Catch rate**	**Effort multiplier**
Bmax	339730	0.66	52797	0.18	0.09	0.26
Bcurrent	92013	0.18	98831	0.23	0.	1.76
Btarget0 (SBmsy)	100005	0.15	99208	0.24	0.	2.01
Blow0 (SB0.9msy)	100005	0.09	89286	0.31	0.43	2.80
Blimit0 (SBmin)	50100	0.07	81848	0.36	0.44	2.93
Blimit1 (SB0.6msy)	50100	0.05	59523	0.55	0.45	3.09
Bban (SB0.1msy)	6436	0.01	9919	1.61	0.47	3.33

Bmax indicates the highest observed SSB, Bcurrent indicates the 2017 SSB, Blow indicates the lower SSB at which 90% of MSY can be obtained, and Bmin indicates the lowest observed SSB.

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

β	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040	2050
1.0	100	100	99	79	51	44	44	42	43	43	43	42	42	41	42
0.9	100	100	99	85	67	61	60	58	59	58	58	58	58	57	58
0.8	100	100	99	90	81	76	75	74	75	74	74	73	74	74	73
0.7	100	100	99	94	91	89	88	88	88	87	87	87	87	88	87
0.6	100	100	99	97	97	97	96	96	96	96	96	95	96	96	96
0.5	100	100	99	99	99	99	99	99	99	99	99	99	99	99	99
0.4	100	100	99	100	100	100	100	100	100	100	100	100	100	100	100
0.3	100	100	99	100	100	100	100	100	100	100	100	100	100	100	100
0.2	100	100	99	100	100	100	100	100	100	100	100	100	100	100	100
0.1	100	100	99	100	100	100	100	100	100	100	100	100	100	100	100
0.0	100	100	99	100	100	100	100	100	100	100	100	100	100	100	100

The (biological) reference points SBtarget, SBlimit, and SBban were respectively set to SBmsy, SBmin, and SB0.1msy.

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

β	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040	2050
1.0	100	100	100	100	99	99	99	98	98	98	98	98	98	98	98
0.9	100	100	100	100	100	100	100	100	100	99	99	99	99	99	99
0.8	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.7	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.6	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.5	100	100	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	100	100
0.3	100	100	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	100	100
0.1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

The (biological) reference points SBtarget, SBlimit, and SBban were respectively set to SBmsy, SBmin, and SB0.1msy.

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

β	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040	2050
1.0	126,426	118,278	140,730	105,287	83,856	79,385	78,992	78,356	78,604	77,574	78,376	78,106	77,747	77,644	77,899
0.9	126,426	118,278	140,730	113,028	94,328	90,131	89,685	88,991	89,248	88,122	88,958	88,678	88,290	88,176	88,475
0.8	126,426	118,278	140,730	121,435	106,335	102,779	102,373	101,621	101,885	100,656	101,532	101,238	100,813	100,697	101,028
0.7	126,426	118,278	140,730	130,578	120,155	117,765	117,565	116,789	117,063	115,720	116,637	116,329	115,862	115,748	116,111
0.6	126,426	118,278	140,730	140,536	136,128	135,680	135,990	135,282	135,590	134,125	135,082	134,758	134,246	134,136	134,532
0.5	126,426	118,278	140,730	151,395	154,671	157,307	158,682	158,256	158,674	157,097	158,098	157,753	157,197	157,089	157,530
0.4	126,426	118,278	140,730	163,257	176,302	183,699	187,131	187,456	188,191	186,569	187,640	187,275	186,676	186,578	187,074
0.3	126,426	118,278	140,730	176,232	201,664	216,288	223,518	225,591	227,164	225,734	226,988	226,638	226,018	225,956	226,526
0.2	126,426	118,278	140,730	190,449	231,565	257,038	271,098	276,984	280,680	280,169	282,014	281,880	281,355	281,466	282,143
0.1	126,426	118,278	140,730	206,052	267,017	308,678	334,818	348,738	357,653	360,168	364,002	364,946	365,069	366,229	367,085
0.0	126,426	118,278	140,730	223,204	309,302	375,031	422,314	452,834	474,347	485,824	496,261	501,706	505,014	513,242	514,595

Shows the average values when the (biological) reference points SBtarget, SBlimit, and SBban were respectively set to SBmsy, SBmin, and SB0.1msy.

Supplementary Table 3-5. Changes in future average catch (tons)

β	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040	2050
1.0	73,890	78,437	139,946	114,247	103,392	100,069	99,592	99,047	98,940	98,898	98,726	98,584	98,625	99,263	98,756
0.9	73,890	78,437	130,445	111,608	102,783	99,818	99,341	98,833	98,703	98,659	98,496	98,376	98,381	98,982	98,533
0.8	73,890	78,437	120,197	108,028	101,541	99,099	98,668	98,192	98,039	97,989	97,836	97,732	97,709	98,268	97,871
0.7	73,890	78,437	109,127	103,278	99,439	97,767	97,464	97,046	96,876	96,813	96,665	96,580	96,532	97,051	96,697
0.6	73,890	78,437	97,152	97,071	96,128	95,526	95,489	95,175	95,006	94,934	94,784	94,717	94,654	95,125	94,820
0.5	73,890	78,437	84,175	89,041	91,106	91,887	92,310	92,188	92,058	91,989	91,839	91,789	91,718	92,134	91,881
0.4	73,890	78,437	70,091	78,726	83,649	86,069	87,192	87,400	87,382	87,348	87,211	87,179	87,106	87,464	87,266
0.3	73,890	78,437	54,777	65,534	72,713	76,805	78,843	79,563	79,780	79,847	79,761	79,756	79,696	79,992	79,853
0.2	73,890	78,437	38,098	48,710	56,779	62,023	64,950	66,307	66,904	67,180	67,220	67,277	67,257	67,506	67,427
0.1	73,890	78,437	19,897	27,282	33,629	38,313	41,285	42,959	43,876	44,393	44,630	44,794	44,861	45,116	45,092
0.0	73,890	78,437	0	0	0	0	0	0	0	0	0	0	0	0	0

Shows the average values when the (biological) reference points SBtarget, SBlimit, and SBban were respectively set to SBmsy, SBmin, and SB0.1msy.