Report of the Research Institute Meeting on Reference Points for the Tsushima Warm Current Stock of Japanese Jack Mackerel in 2020

Responsible institute: Saikai National Fisheries Research Institute

Summary

We examined the stock-recruitment (S-R) relationship and the proposed reference points by using the stock assessment data of this stock of 2019. As the S-R relationship of this stock, we apply the hockey stick (HS) S-R relationship that does not consider the autocorrelation of residuals to the data of spawning biomass and recruitment in the period of 1973-2017 as estimated in stock assessment. We use the least absolute value method for parameter estimation of the HS S-R relationship. We propose SBmsy (254 thousand tons), which is the spawning biomass that produces the maximum sustainable yield (MSY), which is calculated based on the S-R relationship as the target reference point, and SB0.6msy (107 thousand tons), which is the spawning biomass that produces a catch of 60% of MSY, as the limit reference point. As the fishing ban level, we propose SB0.1msy (16 thousand tons), which produces 10% of MSY. Fishing mortality that produces MSY (Fmsy) is 1.2 times the current fishing mortality (average fishing mortality during the period from 2016 to 2018).

Spawning biomass (thousand tons)	Ratio to the current spawning biomass (2018)	Ratio to the initial spawning biomass (1.269 million tons)	Average catch expected (thousand tons)	Ratio to the current fishing mortality (2016-2018)*	Explanation
Proposed target reference point					
254	0.88	0.20	158	1.25	Spawning biomass that produces MSY (SBmsy)
Proposed limit reference point					
107	0.37	0.08	95	1.64	Spawning biomass that produces 60% of MSY (SB0.6msy)
Proposed fishing ban level					
16	0.05	0.01	16	1.85	Spawning biomass that produces 10% of MSY

					(SB0.1msy)
2018					
289	1.00	0.23	124**	-	Value of 2018

* Coefficient to multiply the current fishing mortality of each age when calculating the proposed reference points and proposed fishing ban level based on the selectivity by age under the current fishing mortality

**Actual catch in 2018

1. Stock-recruitment relationship

1-1) Data set to be used

In accordance with the "2020 Basic Guidelines for the Harvest Control Rules and the Estimation of the Allowable Biological Catch (ABC) (FRA-SA2020-ABCWG01-01)," we used the following data set for settings of stock-recruitment (S-R) relationships of this stock. We used R package frasyr (v2.01) for analysis. For detail of the equations used in frasyr, see "Technical Note on Estimation of stock-recruitment relationship, reference point calculation and future prediction simulation (2020 Research Institute Meeting Version) (FRA2020-ABCWG01-02)."

Data set	Data source and research
Stock biomass / spawning biomass	Marine fisheries stock assessment and evaluation for Japanese waters (fiscal year 2019/2020) (Fisheries Agency of Japan[; Japan Fisheries Research and Education Agency [FRA])

1-2) Examination of S-R relationship

As the S-R relationship to be used for calculation of the spawning biomass that produces the maximum sustainable yield (MSY) and of the future forecast (Appendix 1), we considered hockey stick (HS), Ricker (RI) and Beverton-Holt (BH) S-R relationships. We chose the least squares method and the least absolute value method as candidates for optimization. We used the data of recruitment and spawning biomass for the period of 1973 to 2018 as estimated in the stock assessment. We excluded the latest 2018 data that is considered to be highly uncertain. Candidates for examination of the S-R relationship are shown in Table 1.

When we compare the corrected version of Akaike's information criterion (AICc), AICc is lower when the HS model is applied compared with when the RI or BH model is applied. AICc is also lower when the least absolute method is used compared with the least squares method. We do not reflect the autocorrelation of residuals in this stock because the autocorrelation coefficient was not significant in optimization with the least squares method nor the least absolute value method by using the HS model (Appendix Figure 1).

1-3) S-R relationship

Based on the examinations above, and following the standards of 3.a. (Predictive Capability) and 3.h (Autocorrelation) of the "Guidelines for Estimation of Stock-recruitment Relationship (FRA-SA2020-ABCWG01-03)," we apply as the S-R relationship of this stock the HS S-R relationship that uses the least absolute method for optimization and does not consider the autocorrelation of residuals for calculation of the spawning biomass that produces MSY (SBmsy) and future prediction.

We show parameter estimates of the S-R relationship in Appendix 1 (Appendix Table 1-1) and their relationship with the observation values of past spawning biomass and recruitment in Figure 1.We assumed a lognormal distribution for error distribution of recruitment. As standard deviation of logarithmic residuals, we used the standard deviation of logarithmic residuals between the predictive values and observation values of the S-R relationship (S.D.; Table 1) ("Technical Note on Estimation of stock-recruitment relationship, reference point calculation and future prediction simulation (2020 Research Institute Meeting Version) (FRA-SA-2020-ABCWG01-02)").

2. Reference points

2-1) Data sets and calculation method

We made calculation of spawning biomass that produces MSY and future prediction according to the rules for one-stock biomass of the "2020 Basic Guidelines for the Harvest Control Rules and the Estimation of the Allowable Biological Catch (ABC) (FRA-SA2020-ABCWG01-01)" and using the S-R relationship presented in 1-3) above and the settings (natural mortality; maturity rate; average body weight at age; etc.) used for the future projection calculation in the Marine fisheries stock assessment and evaluation for Japanese waters (fiscal year 2019/2020) (Fisheries Agency of Japan[and FRA). The stock assessment of this year made future projection by setting Fcurrent to "F value whose average is F of 2018 under the average selectivity at age of the period 2016-2018" (Fcurrent; Table 2). However, according to the default setting of the program that we used for the analysis, we set the current fishing mortality (Fcurrent; Figure 2) to the average of fishing mortality (F) of 2016-2018 (Table 2). For this stock, assuming equilibrium after the simulation period (58 years) that is 20 times the average generation time (2.9 years), we regard the F value that maximizes the average catch under this assumption as Fmsy, and the average spawning biomass at equilibrium when fishing is conducted at Fmsy as SBmsy.

2-2) Proposed reference points and fishing ban level

We propose: SBmsy (254 thousand tons), which is the spawning biomass that produces MSY for the target reference point (SBtarget); SB0.6msy (107 thousand tons), which is the spawning biomass that produces 60% of MSY for the limit reference point (SBlimit); and SB0.1msy (16 thousand tons), which produces 10% of MSY for the fishing ban level (SBban). The ratios of the proposed reference points and fishing ban level to the initial spawning biomass assuming no catch (SB0), the average catch at equilibrium under the corresponding fishing mortality and the ratio of the corresponding fishing mortality to the current fishing mortality are shown in

Table 3. SBmsy, which is proposed as the target reference point is equivalent to 20% of SB0 and the average catch expected with this spawning biomass (MSY) is 158 thousand tons. The ratio of the fishing mortality corresponding to the proposed target reference point (fishing mortality that produces MSY: Fmsy) to the current fishing mortality (Fmsy/Fcurrent) is 1.25 and the exploitation rate (Umsy) in this case is 34%. SB0.6msy, which is proposed as the limit reference point corresponds to 8% of SB0 and SB0.1msy, which is proposed as the fishing ban level corresponds to 1% of SB0. The difference between SBmsy and the average catch at equilibrium when fishing is conducted at Fcurrent (Age 0 = 0.09, Age 1 = 0.83, Age2 = 0.67, Age 3 = 0.20) that is used for the future projection of the stock assessment of this year was as small as about 1%.

Average spawning biomass at equilibrium when F is changed variously and the corresponding average catch at age are shown in Figure 3. Fish of age 0 to 1 account for most of the catch when the spawning biomass is not over SBlimit, and a large part of the catch when SBmsy is reached. However, with a further increase of spawning biomass, the ratio of older fish tends to increase.

2-3) Proposed target reference point and exploitation rate

The proposed target reference point (SBtarget) and Kobe plot that is based on the fishing mortality (Fmsy) or exploitation rate (Umsy) corresponding to the proposal are shown in Figure 4. Fishing mortality (F) of this stock had been mostly over the MSY level since 1973, but it is judged to be under the MSY level in recent years. A similar tendency is found also in the exploitation rate (U). Current spawning biomass (289 thousand tons in 2018) is over the proposed target reference point. The ratios of the proposed target reference point, the proposed limit reference point and the proposed fishing ban level to the current spawning biomass is 0.88, 0.37 and 0.05, respectively.

2-4) Proposed harvest control rules

The proposed harvest control rules (HCRs) are rules to change fishing mortality (F), which is the basis of harvest control at the threshold of spawning biomass, for which the proposed limit reference point and the proposed fishing ban level are to be used. In this rule, when spawning biomass falls below the proposed limit reference point, fishing mortality is lowered directly to the proposed fishing ban level. The upper limit of F is obtained by multiplying Fmsy by β. Figure 5a shows the relationship between spawning biomass and fishing mortality in the proposed HCRs when standard values are used for the proposed limit reference point (SBlimit) and proposed fishing ban level (SBban) (proposed SBlimit set to SB0.6msy; proposed SBban set to SB0.1msy), while Figure 5b shows the relationship between spawning biomass and the average prospective catch under the same condition. β is set to the standard value 0.8 in the proposed HCRs illustrated in the figures.

2-5) Future projection based on the proposed HCRs

(1) When safety coefficient β is set to the standard value

Percentage changes of biomass, spawning biomass, catch, recruitment and fishing effort when future projection is made based on the proposed HCRs that use standard values for the proposed limit reference point and proposed fishing ban level, and set β to 0.8 (Figure 5a) are shown in Figure 6. This future projection assumes that fishing based on the proposed HCRs starts in 2021 and catch of 2019 and 2020 are assumed based on the predicted biomass and Fcurrent.

Because the spawning biomass projected for 2021 is over the proposed target reference point, fishing will start at βFmsy following the proposed HCRs. When β is set to 0.8, fishing mortality at 0.8Fmsy roughly corresponds to the fishing mortality of the current fishing effort. In the medium- to long-term, it is projected that continued fishing at 0.8Fmsy will maintain the catch and spawning biomass at the MSY level.

(2) When safety coefficient β is changed

In the future projection based on the proposed HCRs that use standard values for the proposed limit reference point and proposed fishing ban level, the probability that spawning biomass will exceed the proposed target reference point, probability of its exceeding the proposed limit reference point, probability of its exceeding the proposed fishing ban level, and changes in the average spawning biomass and average catch when β is changed between 0.0 and 1.0 are shown in Tables 4 to 8. Because this stock exceeded the proposed target reference point in 2018, it is projected that it will exceed the proposed target reference point in 2031, 10 years after starting fishing based on the proposed HCRs, with the probability of 85%, even when the standard value 0.8 is used (Table 4). With β set to 0.9 and under, it is projected that spawning biomass can be maintained over the proposed target reference point in 2031 with a probability of 50% or higher. When β is set to 1, the probability that spawning biomass will exceed the proposed target reference point in 2031 is below 50%, but the probability of its exceeding the limit reference point is 100% (Table 5). If fishing based on the proposed HCRs starts in 2021, the lower the β value, the higher the future spawning biomass in 2022 and after (Table 7). With β set to 0.8 or higher, the catch in 2021 is more than the catch in 2019 (Table 8).

3. Summary

Based on AICc we applied the S-R relationship model of this stock to the recruitment and spawning biomass of 1973-2017 as estimated by stock assessment. We adopted the HS S-R relationship that does not consider autocorrelation and estimated its parameters with the least absolute value method.

As the target reference point, we propose SBmsy (254 thousand tons), which is estimated based on the S-R relationship described above. As the limit reference point and fishing ban level, we propose standard values SB0.6msy (107 thousand tons) and SB0.1msy (16 thousand tons), respectively.

The current spawning biomass of this stock is considered to be above the proposed target reference point. The exploitation rate that produces MSY is 34% and fishing mortality that produces MSY is 1.25 times Fcurrent (Table 3). It is projected that, if β is set to 0.9 and under, the spawning mass will be maintained above the proposed target reference point with a probability higher than 50%.

4. Future considerations

One of the factors that may cause significant uncertainty of stock assessment of this stock is that the assessment could not consider the impact of fishing by Chinese fishing vessels. The catch of Japanese jack mackerel by Chinese fishing vessels is considered to be smaller than the catch by Japan, but fishing of this stock by Chinese fishing vessels can influence the spawning biomass that produces MSY and the probability of achieving the management objectives, for example.

5. References

None

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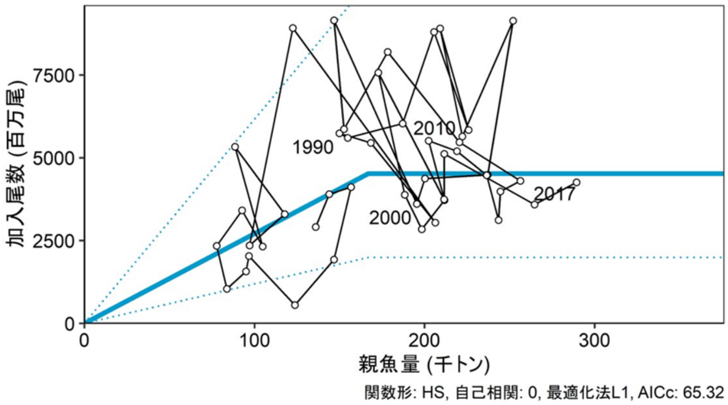
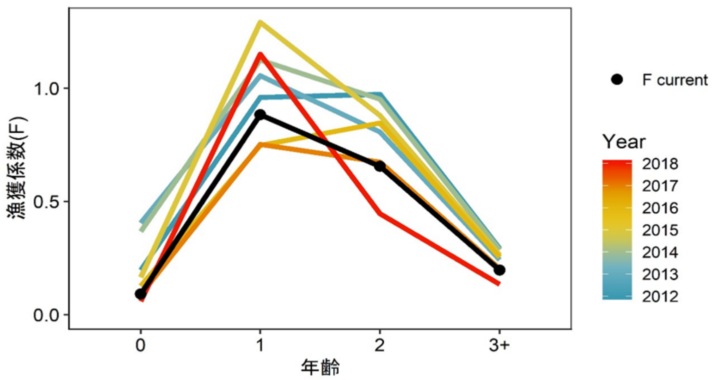


加入尾数（百万尾）	Recruitment (million individuals)
親魚量（千トン）	Spawning biomass (thousand tons)
関数形：HS，自己相関：0，最適化法 L1，AlCc: 65.32	Model: HS; autocorrelation: 0; optimization method: L1; AlCc: 65.32

Figure 1. S-R relationship

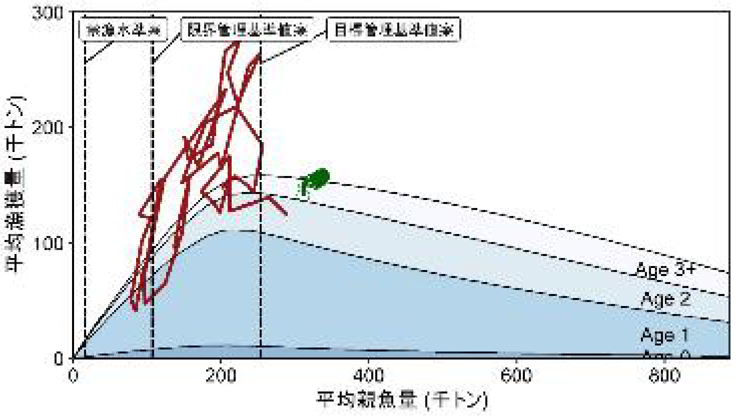
Spawning biomass and recruitment for the period of 1973-2018. Numbers in the figure indicate the class of recruited group (birth year). For the S-R relationship, we used the HS S-R relationship where autocorrelation is not considered and estimated parameters using the least absolute value method. Data of 2018 where the uncertainty of recruitment estimates is high are excluded from parameter estimation. Dotted lines over and below the S-R relationship (solid line) show the range supposed to include 90% of the observed data of the respective S-R relationship.



漁獲係数	Fishing mortality
年齢	Age

Figure 2. Fishing mortality (F) at age

F at age of each year from 2012 is shown in different colors. The black line represents Fcurrent that is the average F of the period from 2016 to 2018.

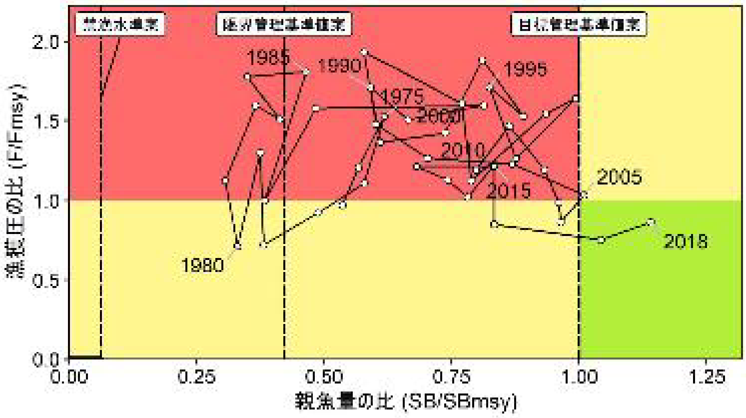


平均漁獲量（千トン）	Average catch (thousand tons)
平均親魚量（千トン）	Average spawning biomass (thousand tons)
禁漁水準案	Proposed fishing ban level
限界管理基準値案	Proposed limit reference point
目標管理基準値案	Proposed target reference point

Figure 3. Relationship between the proposed reference points / fishing ban level and curves of catch at age

The figure shows the relationship of average catch at age corresponding to the average spawning biomass, with the proposed reference points and fishing ban level at equilibrium in the future projection simulation. The red line represents changes in the spawning biomass and catch, which are estimated by the stock assessment, while the green line represents the average spawning biomass and average catch in the future projection assuming fishing conducted based on the proposed HCRs. Safety coefficient β used in the proposed HCRs is 0.8. The initial spawning biomass assuming no catch (SB0) is 1.269 million tons.

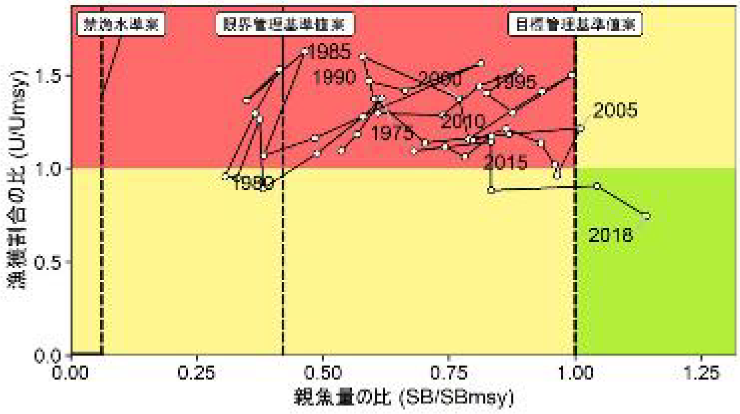
a) When the vertical axis is the ratio of the fishing mortality (F/Fmsy)



漁獲圧の比	F/Fmsy
親魚量の比	SB/SBmsy

禁漁水準案	Proposed SBban
限界管理基準値案	Proposed SBlimit
目標管理基準値案	Proposed SBtarget

b) When the vertical axis is the ratio of the exploitation rate (U/Umsy)

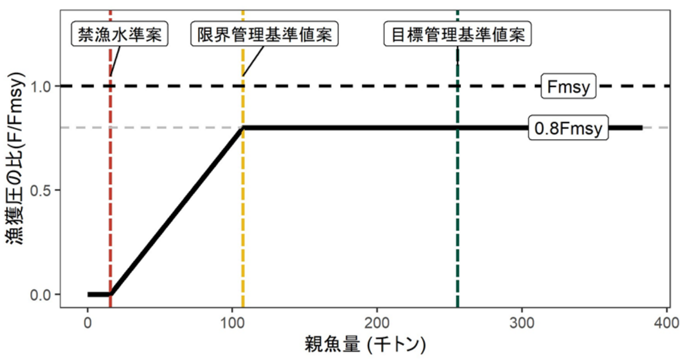


漁獲割合の比	U/Umsy
親魚量の比	SB/SBmsy
禁漁水準案	Proposed SBban
限界管理基準値案	Proposed SBlimit
目標管理基準値案	Proposed SBtarget

Figure 4. Kobe plot (four sections)

When the ratio of fishing mortality is put on the vertical axis (upper figure) and when the ratio of exploitation rate is put on the vertical axis (lower figure). As the proposed target reference point (SBtarget), limit reference point (SBlimit) and fishing ban level (SBban) in the figures, we used SBmsy, SB0.6msy and SB0.1msy, respectively.

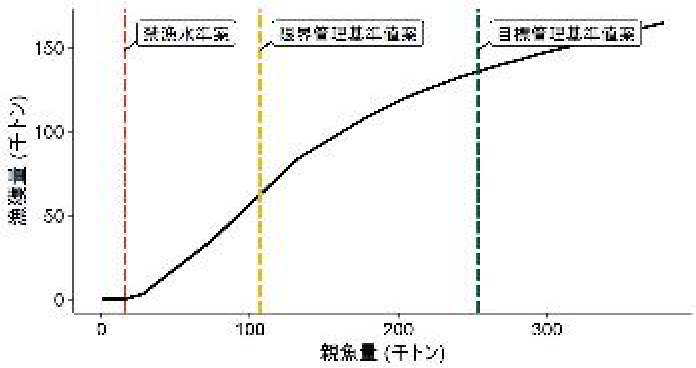
a) When the vertical axis is fishing mortality



漁獲圧の比	F/Fmsy
親魚量（千トン）	Spawning biomass (thousand tons)

禁漁水準案	Proposed SBban
限界管理基準値案	Proposed SBlimit
目標管理基準値案	Proposed SBtarget

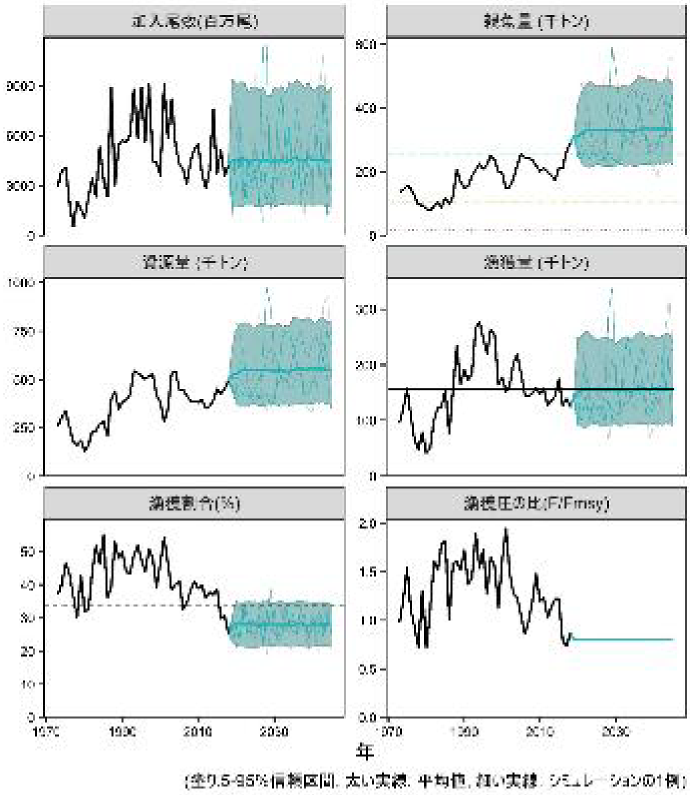
b) When the vertical axis is catch



漁獲量（千トン）	Catch (thousand tons)
親魚量（千トン）	Spawning biomass (thousand tons)
禁漁水準案	Proposed SBban
限界管理基準値案	Proposed SBlimit
目標管理基準値案	Proposed SBtarget

Figure 5. Proposed HCRs

The proposed target reference point (SBtarget) is SBmsy calculated based on the HS S-R relationship. Standard values are used for the proposed limit reference point (SBlimit) and the proposed fishing ban level (SBban). Safety coefficient β is set to 0.8, which is the standard value. The black dashed line represents Fmsy; the grey dashed line represents 0.8Fmsy; the black thick line represents the proposed HCRs; the red dashed line represents the proposed fishing ban level; the yellow dashed line represents the proposed limit reference point; and the green dashed line represents the proposed target reference point. In a) the ratio of fishing mortality is put on the vertical axis, while in b) the catch is put on the vertical axis. Regarding b), the catch varies a little depending on the age composition of the fishing year but here we show the catch of average age composition at equilibrium.



加入尾数（百万尾）	Recruitment (million individuals)
資源量（千トン）	Stock biomass (thousand tons)
漁獲割合	Exploitation rate (%)
親魚量（千トン）	Spawning biomass (thousand tons)
漁獲量（千トン）	Catch (thousand tons)
漁獲圧の比	Ratio of the fishing mortality to MSY
年	Year
（塗り：5-95%信頼区間，太い実線：平均値，細い実線：シミュレーションの 1 例）	(Shaded: 5-95% confidence interval; thick solid line: average value; thin slid line: simulation example)

Figure 6. Comparison of the future projection based on the proposed HCRs (in red) with the future projection that assumes continued fishing at the current fishing mortality level (in green) The thick solid line, shaded area and thin lines represent average value, the 90% prediction interval that includes 90% of the simulation results and three future projection examples, respectively. In the chart of spawning biomass, the green dashed line represents the proposed target reference point, the yellow dotted line represents the proposed limit reference point and the red line shows the proposed fishing ban level. The dashed line in the chart of catch expresses MSY. The dashed line in the chart of exploitation rate expresses Umsy. The catch in 2019 and 2020 are assumed based on the projected biomass and Fcurrent, while the catch

in 2021 and after is based on the proposed HCRs (Figure 2-5). Safety coefficient β is set to 0.8.

Table 1. Candidates for S-R relationship

再生産関係式	最適化法	自己相関	AICc	ΔAICc	ΔAICc の順位	S.D.	データ数
ホッケー・スティック型	**最小絶対値法**	**無**	**65.32**	**0**	**1**	**0.486**	**45**
リッカー型	最小絶対値法	無	69.58	4.26	3	0.496	45
ベバートン・ホルト型	最小絶対値法	無	69.88	4.55	4	0.498	45
ホッケー・スティック型	最小二乗法	無	68.72	3.40	2	0.483	45
リッカー型	最小二乗法	無	71.03	5.71	5	0.496	45
ベバートン・ホルト型	最小二乗法	無	71.17	5.84	6	0.495	45

再生産関係式	S-R relationship
最適化法	Optimization method
自己相関	Autocorrelation
ΔAICc の順位	Order of ΔAICc
データ数	Data quantity
ホッケー・スティック型	Hockey stick
リッカー型	Ricker
ベバートン・ホルト型	Beverton-Holt
最小二乗法	Least squares method
最小絶対値法	Least absolute value method
無	No

The S-R relationship to be applied is indicated in bold face. S.D. is an index expressing magnitude of dispersion of recruitment, which is the standard deviation of log residuals (square root of mean square error).

Table 2. Settings used for calculation of the spawning biomass that produces MSY and future projection

年齢	自然死亡係数	成熟率	平均重量 (g)	選択率	現状の漁獲圧 (Fcurrent)
0	0.50	0.0	28	0.104	0.091
1	0.50	0.5	75	1.000	0.883
2	0.50	1.0	154	0.742	0.655
3 歳以上	0.50	1.0	359	0.223	0.197

年齢	Age
自然死亡係数	Natural mortality
成熟率	Maturity rate
平均重量	Average weight
選択率	Selectivity
現状の漁獲圧	Current fishing mortality

3 歳以上	Age 3 and above

Table 3. Catch, fishing mortality, etc. corresponding to the proposed reference points and fishing ban level

管理基準値案又は禁漁水準案	説明	親魚量 (千トン)	SB0 に対する比※	漁獲量※※ (千トン)	漁獲圧※※※	漁獲割合※※※※	現状の漁獲圧に対する比※※※※※
目標管理基準値案	SBmsy	254	0.20	158	20.2	0.34	1.25
限界管理基準値案	SB0.6msy	107	0.08	95	14.4	0.42	1.64
禁漁水準案	SB0.1msy	16	0.01	16	12.5	0.45	1.85
MSY を実現する漁獲圧	Fmsy	（0 歳, 1 歳, 2 歳, 3 歳以上） ＝（0.11, 1.10, 0.82, 0.24）					

管理基準値案または禁漁水準案	Proposed reference points or fishing ban level
説明	Explanation
親魚量（千トン）	Spawning biomass (thousand tons)
SB0 に対する比	Ratio to SB0
漁獲量（千トン）	Catch (thousand tons)
漁獲圧	Fishing mortality
漁獲割合	Exploitation rate
現状の漁獲圧に対する比	Ratio to the current fishing mortality
目標管理基準値案	Proposed target reference point
限界管理基準値案	Proposed limit reference point
禁漁水準案	Proposed fishing ban level
MSY を実現する漁獲圧	Fishing mortality that produces MSY
（0 歳, 1 歳, 2 歳, 3 歳以上） ＝（(0.11, 1.10, 0.82, 0.24）	(Ages 0, 1, 2, 3 and above) = (0.11, 1.10, 0.82, 0.24)

* Ratios of the proposed reference points and fishing ban level to the initial spawning biomass assuming zero catch (SB0)

** Average catch at equilibrium under the fishing mortality corresponding to the proposed reference points and fishing ban level

*** %SPR-converted value of fishing mortality corresponding to the proposed reference points and fishing ban level

**** Exploitation rate corresponding to the proposed reference points and fishing ban level

***** Ratios of the fishing mortality corresponding to the proposed reference points and fishing ban level to the current fishing mortality

Table 4. Probability for future spawning biomass to exceed the proposed target reference point (%)

The table shows results of the future projection based on the proposed HCRs (Figure 5) when safety coefficient β is changed from 0.0 to 1.0 in 0.1 intervals. The projection assumes Fcurrent catch for 2019 and 2020 and a catch corresponding to the proposed HCRs for 2021 and after.

β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2041	2051
1.0	100	95	85	68	59	53	50	46	48	47	48	47	45	48	48
0.9	100	95	85	76	72	70	68	68	67	67	67	69	68	68	70
0.8	100	95	85	83	82	85	85	84	85	85	86	85	85	88	86
0.7	100	95	85	87	90	94	96	95	95	95	95	95	96	97	97
0.6	100	95	85	92	96	98	99	100	99	99	99	99	99	100	99
0.5	100	95	85	95	98	99	100	100	100	100	100	100	100	100	100
0.4	100	95	85	97	100	100	100	100	100	100	100	100	100	100	100
0.3	100	95	85	99	100	100	100	100	100	100	100	100	100	100	100
0.2	100	95	85	99	100	100	100	100	100	100	100	100	100	100	100
0.1	100	95	85	100	100	100	100	100	100	100	100	100	100	100	100
0.0	100	95	85	100	100	100	100	100	100	100	100	100	100	100	100

Table 5. Probability for the future spawning biomass to exceed the proposed limit reference point (%)

The table shows results of the future projection based on the proposed HCRs (Figure 5) when safety coefficient β is changed from 0.0 to 1.0 in 0.1 intervals. The projection assumes Fcurrent catch for 2019 and 2020 and a catch corresponding to the proposed HCRs for 2021 and after.

β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2041	2051
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

Table 6. Probability that future spawning biomass will exceed the proposed fishing ban level (%)

The table shows results of the future projection based on the proposed HCRs (Figure 5) when safety coefficient β is changed from 0.0 to 1.0 in 0.1 intervals. The projection assumes Fcurrent catch for 2019 and 2020 and a catch corresponding to the proposed HCRs for 2021 and after.

β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2041	2051
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

Table 7. Changes in average spawning biomass in the future (thousand tons)

The table shows results of the future projection based on the proposed HCRs (Figure 5) when safety coefficient β is changed from 0.0 to 1.0 in 0.1 intervals. The projection assumes Fcurrent catch for 2019 and 2020 and a catch corresponding to the proposed HCRs for 2021 and after.

β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2041	2051
1.0	311	311	321	293	277	266	260	258	257	256	255	254	254	259	261
0.9	311	311	321	310	303	297	293	292	291	290	290	289	289	294	296
0.8	311	311	321	328	333	333	332	332	332	331	331	330	330	336	337
0.7	311	311	321	348	367	375	378	379	381	381	381	380	380	386	388
0.6	311	311	321	370	407	425	433	437	440	441	441	441	440	448	449
0.5	311	311	321	394	453	485	500	507	512	514	516	515	515	524	525
0.4	311	311	321	421	507	556	580	593	601	605	607	607	607	618	618
0.3	311	311	321	449	569	641	678	697	710	716	720	721	721	734	734
0.2	311	311	321	481	642	742	796	825	843	854	860	862	863	878	878
0.1	311	311	321	516	726	863	940	982	1,009	1,025	1,034	1,038	1,040	1,059	1,059
0	311	311	321	554	826	1,008	1,114	1,174	1,213	1,237	1,251	1,257	1,261	1,287	1,286

Table 8. Changes in average catch in the future (thousand tons)

The table shows results of the future projection based on the proposed HCRs (Figure 5) when safety coefficient β is changed from 0.0 to 1.0 in 0.1 intervals. The projection assumes Fcurrent catch for 2019 and 2020 and a catch corresponding to the proposed HCRs for 2021 and after.

β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2041	2051
1.0	141	152	180	169	166	161	160	161	160	159	159	158	158	161	164
0.9	141	152	168	163	162	159	158	159	158	158	158	157	157	160	162
0.8	141	152	154	156	157	155	154	155	155	154	155	154	154	157	159
0.7	141	152	140	147	150	149	149	150	150	150	150	149	149	152	154
0.6	141	152	124	136	141	141	142	143	143	143	143	143	142	145	147
0.5	141	152	107	123	130	131	132	133	134	133	134	133	133	136	137
0.4	141	152	89	107	115	117	118	120	120	120	121	120	120	123	124
0.3	141	152	69	87	96	98	100	102	102	102	103	103	102	105	106
0.2	141	152	48	64	71	74	76	77	78	78	78	78	78	80	80
0.1	141	152	25	35	40	42	43	44	45	45	45	45	45	46	46
0	141	152	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 9. Summary of the projected spawning biomass, catch and the probability for spawning biomass to exceed the proposed reference points

The table shows results of future projection when safety coefficient β is changed from 0.0 to 1.0 in 0.1 intervals.

β	10 年後（2031 年）の平均親魚量	10 年後（2031 年）に親魚量が目標管理基準値案を上回る確率	0 年後（2021 年）の予測漁獲量（千トン）	5 年後（2026 年）の予測漁獲量（千トン）	10 年後（2031 年）の予測漁獲量（千トン）	10 年後（2031 年）に親魚量が限界管理基準値案を上回る確率
1	254	45%	180	161	158	100%
0.9	289	68%	168	159	157	100%
0.8	330	85%	154	155	154	100%
0.7	380	96%	140	150	149	100%
0.6	440	99%	124	143	142	100%
0.5	515	100%	107	133	133	100%
0.4	607	100%	89	120	120	100%
0.3	721	100%	69	102	102	100%
0.2	863	100%	48	77	78	100%
0.1	1,040	100%	25	44	45	100%
0	1,261	100%	0	0	0	100%

10 年後（2031 年）の平均親魚量	Average spawning biomass (thousand tons) after 10 years (2031)
10 年後（2031 年）に親魚量が目標管理基準値案を上回る確率	Probability for spawning biomass to exceed the proposed target reference point after 10 years (2031)
0 年後（2021 年）の予測漁獲量（千トン）	Projected catch (thousand tons) after 0 years (2021)
5 年後（2026 年）の予測漁獲量（千トン）	Projected catch (thousand tons) after 5 years (2026)
10 年後（2031 年）の予測漁獲量（千トン）	Projected catch (thousand tons) after 10 years (2031)
10 年後（2031 年）に親魚量が限界管理基準値案を上回る確率	Probability for spawning biomass to exceed the proposed limit reference point after 10 years (2031)

Appendix 1. Diagnosis result of S-R relationship models

As a candidate for calculation of the spawning biomass that produces MSY and future projection, we considered HS (Clark et al 1985), BH (Beverton-Holt 1957) and RI (Ricker 1954) S-R relationships. Mathematical equations of the respective S-R relationships are as follows:

$$R_y = \begin{cases} \begin{cases} ab & \text{if } B_y > b \\ aB_y & \text{if } B_y \leq b \end{cases} & \text{(Hockey stick, HS)} \\ \dfrac{aB_y}{(1 + bB_y)} & \text{(Beverton Holt, BH)} \\ aB_y \exp(-bB_y) & \text{(Ricker, RI)} \end{cases}$$

Here, R_y represents recruitment in year y and B_y represents the spawning biomass of year y. In the case of the HS model, parameter a represents the steepness (individual/g) of the S-R curve from the origin to the break point, while b represents the spawning biomass (tons) at the break point. In all S-R relationships, two parameters - a and b - are estimated. When examining the S-R relationship, we also calculated the residual standard deviation (s.d.) of the recruitment from the estimated S-R curve.

As the S-R relationship of the Tsushima Warm Current Stock of Japanese Jack Mackerel, we applied the HS, RI and BH S-R relationships to the 1973-2017 data of recruitment and spawning biomass with the least squares method and the least absolute value method. None of the models considers autocorrelation (AR) in residuals (Appendix Figure 1-1). As a result, we found an almost lineal relationship for a certain period of the observation data in the RI and BH S-R relationships.

The residuals trend and autocorrelation plot when the HS S-R relationship is applied using the least squares method and the least absolute value method are shown in Appendix Figure 1-2. Autocorrelation is not significant when the HS S-R relationship is assumed. We examined the normality of residuals against the S-R relationship model with a Shapiro-Wilk test. Because we found a significant deviation at the 5% level when the least squares method is applied, we adopted the S-R relationship that is applied with the least absolute value method. AICc of the S-R relationship obtained with the least absolute value method was also lower than that obtained with the least squares method (Table 1, Appendix Figure 1-3).

We used the Jack Knife method to examine the influence of individual data when the HS S-R relationship that does not consider autocorrelation is applied with the least squares method and the least absolute value method. As a result, we did not find any significant difference in the robustness of estimation between the least squares method and the least absolute value method (Appendix Figures 1-4 and 1-5). We examined the confidence interval of parameter estimation with residual bootstrapping (Appendix Figures 1-6 and 1-7). The profile likelihood is shown in Appendix Figure 1-8. Because it was found that parameter b had the same maximum likelihood within the range of about 2% (166 thousand to 168 thousand tons) when it was estimated with the least absolute value method, we conducted exhaustive examination with varying initial value and chose the S-R relationship with the b value that is closest to the median. In this way, we could limit bias up to 1%.

Appendix Table 1-1. Parameter estimates in the S-R relationships used for calculation of the spawning biomass that produces MSY

再生産関係式	最適化法	自己相関	a	b	S.D.	Rho	AICc
ホッケー・スティック（HS）	最小二乗法	無	0.0272	1.78e+05	0.483	0	68.7
ベバートン・ホルト（BH）	最小二乗法	無	0.0329	2.00e-06	0.496	0	71.2
リッカー（RI）	最小二乗法	無	0.0327	1.66e-06	0.495	0	71.0
ホッケー・スティック（HS）	**最小絶対値法**	**無**	**0.0271**	**1.67e+05**	**0.486**	**0**	**65.3**
ベバートン・ホルト（BH）	最小絶対値法	無	0.0354	2.25e-06	0.498	0	69.9
リッカー（RI）	最小絶対値法	無	0.0345	1.77e-06	0.496	0	69.6

再生産関係式	S-R relationship
最適化法	Optimization method
自己相関	Autocorrelation
推定法	Estimation method
ホッケー・スティック	Hockey stick
リッカー	Ricker
ベバートン・ホルト	Beverton-Holt
最小二乗法	Least squares method
最小絶対値法	Least absolute value method
無	No

The S-R relationship to be applied is indicated in bold face. S.D. is an index expressing magnitude of dispersion of recruitment, which is the standard deviation of log residuals (square root of mean square error).

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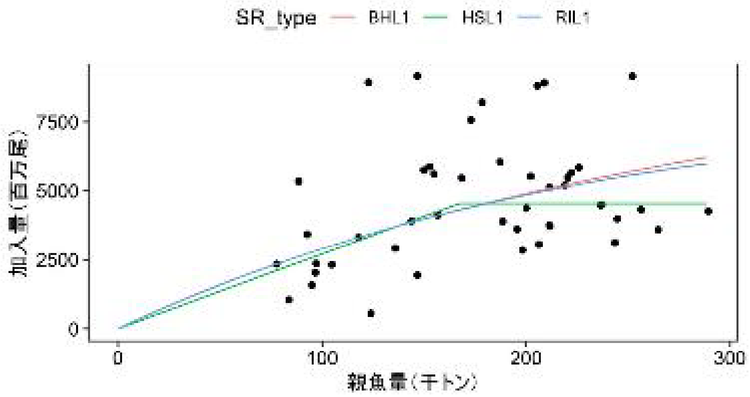
Clark C. W., Charles A. T., Beddington J. R. and M. Mangel (1985). Optimal capacity decisions in a developing fishery. Marine Resource Economics, 2: 25-53.

Beverton R. J. H., and S. J. Holt (1957). On the dynamics of exploited fish populations. Her Majesty's Stationary Office, London.

Ricker W. E. (1954). Stock and recruitment. Journal of the Fisheries Research Board of Canada, 11: 559-623.

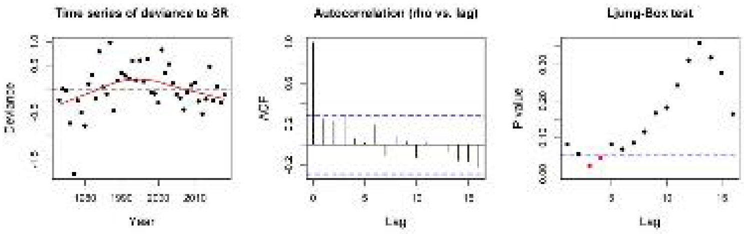


加入尾数（百万尾）	Recruitment (million individuals)
親魚量（千トン）	Spawning biomass (thousand tons)

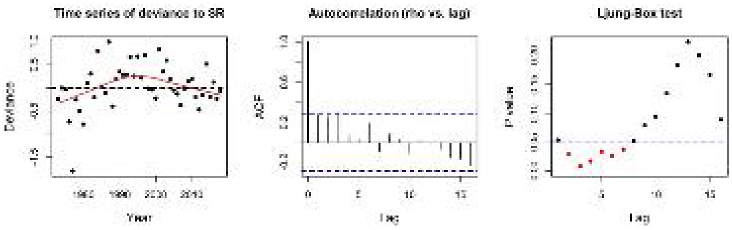
Appendix Figure 1-1. S-R relationship of each model

We applied the HS, RI and BH S-R relationships using the least absolute value method. The black circles represent the spawning biomass and recruitment (1973-2017) used for the analysis.

HS model: least squares method



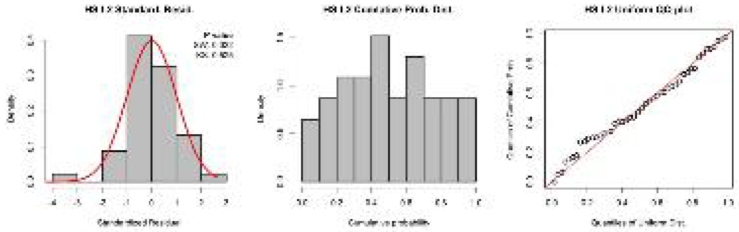
HS model: least absolute value method



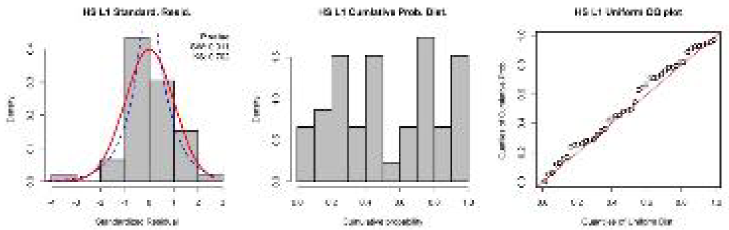
Appendix Figure 1-2. HS S-R relationships: Time-series trend of standardized residuals (left); correlogram (center); and P value of Ljung-Box test (right)

In the figure of time series of standardized residuals, the red line expresses a smoothed curve and the vertical blue dotted line represents the switching points of the S-R relationship. The blue dotted lines in the correlogram express the 95% confidence interval. The blue dotted line in the figure of P value of Ljung-Box test expresses the 5% level.

HS model: least squares method



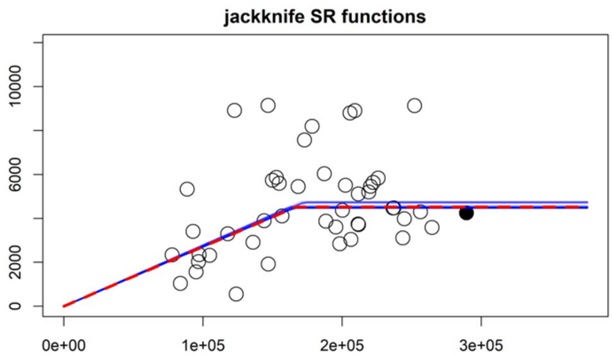
HS model: least absolute value method



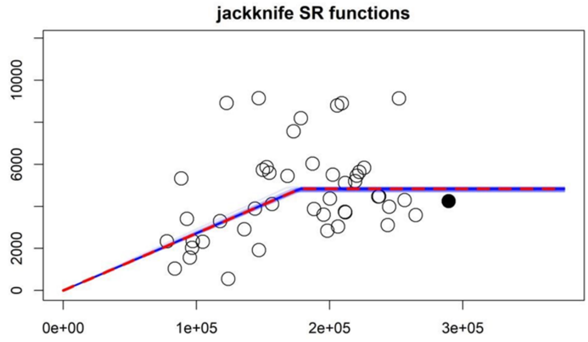
Appendix figure 1-3. HS S-R relationship: Histogram of standardized residuals and result of normality test (left); Histogram of cumulative probability density of errors (center) and; QQ plot assuming uniform distribution (right)

The upper-right numbers of the residual distribution chart represent the results of a Shapiro-Wilk test (SW) and Kolmogorov-Smirnov test (KS) (both are based on a null hypothesis of "normally distributed"). The red line of the QQ plot represents theoretical value.

HS model: least squares method

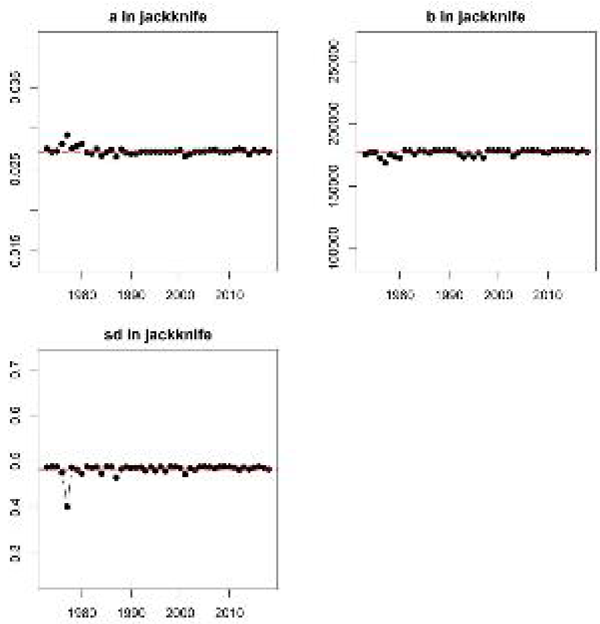


HS model: least absolute value method

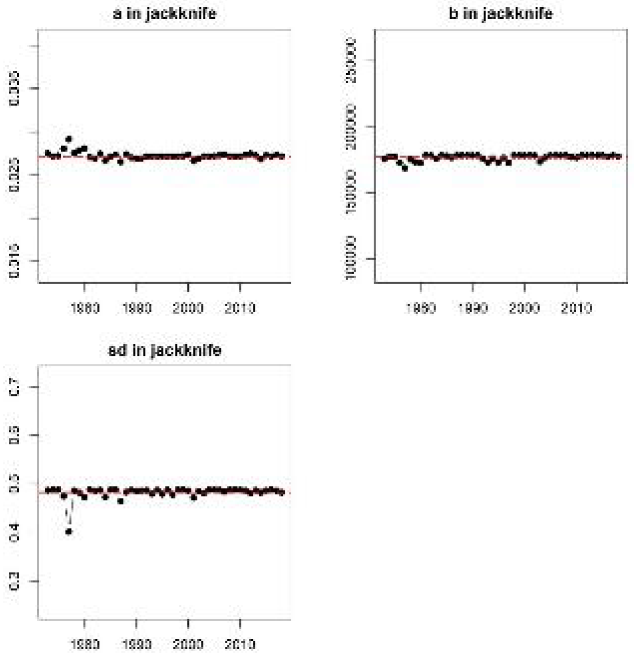


Appendix Figure 1-4. Estimation results of Jack Knife analysis with HS S-R relationship
The red line expresses the estimates of all data, while the blue line expresses the estimates when data of the respective year is removed. The horizontal axis shows spawning biomass (tons) while the vertical axis shows recruitment (million individuals). Circles express the plots of the spawning biomass and recruitment used for the analysis. The black circle indicates the last year of the data period used (2017).

HS model: least squares method

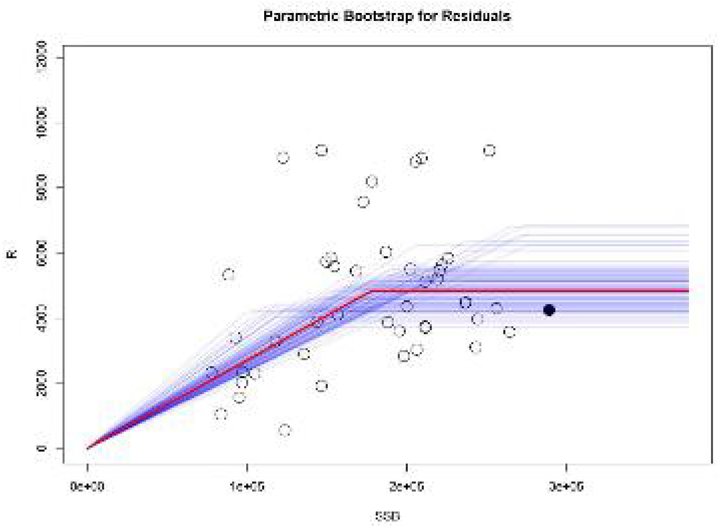


HS model: least absolute value method

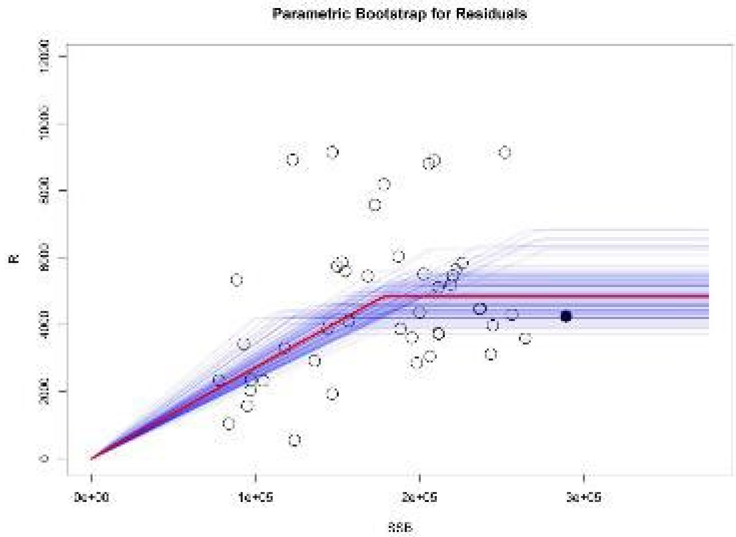


Appendix Figure 1-5. Influence by parameter in HS S-R relationship with Jackknife analysis
No major difference is found in the robustness of estimation of the parameters between the least squares method and the least absolute value method.

HS model: least squares method



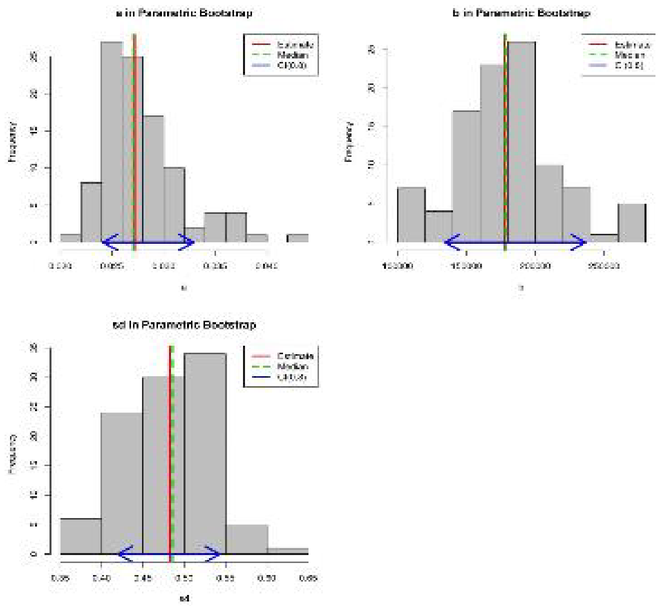
HS model: least absolute value method



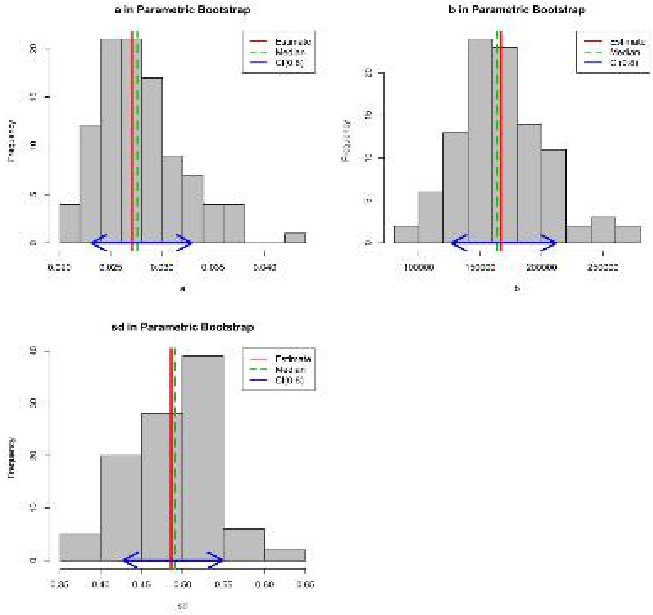
Appendix Figure 1-6. Results of residual bootstrap analysis with the HS S-R relationship

The red line represents the estimated value of the original data. The blue lines represent estimated values of nonparametric bootstrapping. The horizontal axis shows spawning biomass (tons) while the vertical axis shows recruitment (million individuals). Circles express the plots of the spawning biomass and recruitment used for the analysis. The black circle indicates the last year of the data period used (2017).

HS model: least squares method

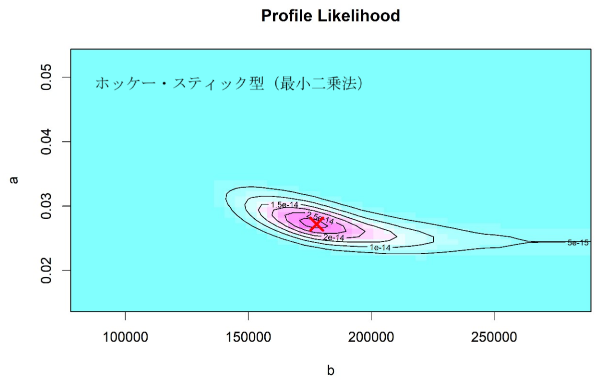


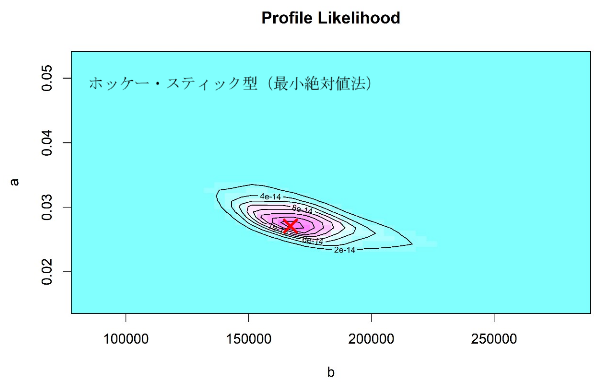
HS model: least absolute value method



Appendix Figure 1-7. Median (green dotted line) and 80% confidence interval (blue line) of residual bootstrap analysis of the HS S-R relationships

Red line represents point estimation of parameters.





ホッケー・スティック型（最小二乗法）	HS (least absolute value method)

ホッケー・スティック型（最小絶対値法）	RI (least absolute value method)

Appendix Figure 1-8. Profile likelihood of estimated parameters of HS S-R relationship
The × mark corresponds to the likelihood at the estimated parameter values.

Appendix 2. Sensitivity test of estimation of the spawning biomass that produces MSY by using S-R relationship

1) Difference in MSY reference points depending on the S-R relationship

In order to assess the difference in the spawning biomass that produces MSY (SBmsy) depending on the assumed S-R relationship, we estimated SBmsy of three combinations of S-R relationships and an optimization method, which are determined to be well applicable based on AICc. We compared HS, RI and BH S-R relationships when they are applied with the least absolute value method for optimization. SBmsy, SB0.6msy and SB0.1msy, which are estimated based on the respective S-R relationship and the optimization method, are shown in the table below.

	HS 型（最小絶対値法）	RI 型（最小絶対値法）	BH 型（最小絶対値法）
SBmsy	253,764 t	493,384 t	1,154,906 t
SB0.6msy	106,938 t	159,839 t	276,903 t
SB0.1msy	15,795 t	20,405 t	30,599 t
MSY	158,448 t	234,888 t	346,189 t
Umsy	0.339	0.285	0.204
Fmsy/Fcurrent	1.25	1.01	0.702

HS 型（最小絶対値法）	HS (least absolute value method)
RI 型（最小絶対値法）	RI (least absolute value method)
BH 型（最小絶対値法）	BH (least absolute value method)

When the RI or HS S-R relationship is used, SBmsy, SB0.6msy and SB0.1msy have higher value compared with the HS model. The ratio of Fmsy to Fcurrent is smaller and the expected MSY is higher.