

## Report of the Research Institute Meeting on Reference Points for the Japanese Jack Mackerel Pacific Stock in 2020

Responsible institute: National Research Institute of Fisheries Science

### 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. We apply the weighted average model of Ricker (RI) and Beverton-Holt (BH) S-R relationships to the S-R relationship of this stock. We estimated parameters with the least squares method using the spawning biomass and recruitment from 1982 to 2017 as estimated in the stock assessment, and estimated simultaneously autocorrelation of residuals. Based on the S-R relationship, we propose SBmsy (60 thousand tons), which is the spawning biomass that produces the maximum sustainable yield (MSY), as the target reference point, and SB0.6msy (15 thousand tons), which is the spawning biomass that produces 60% of MSY, as the limit reference point. We propose SB0.1msy (1.7 thousand tons), which is the spawning biomass that produces 10% of MSY as the fishing ban level. Fishing mortality that produces MSY (Fmsy) is 0.73 times of 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 (204 thousand tons)	Expected average catch (thousand tons)	*Ratio to the current fishing mortality (2016-2018)*	Explanation
<b>Proposed target reference point</b>					
60	2.61	0.29	38	0.73	Spawning biomass that produces MSY (SBmsy)
<b>Proposed limit reference point</b>					
15	0.65	0.08	23	1.50	Spawning biomass that produces 60% of MSY (SB0.6msy)
<b>Proposed fishing ban level</b>					
1.7	0.07	0.01	3.8	2.00	Spawning biomass that produces 10% of MSY (SB0.1msy)
<b>2018</b>					
23	1.00	0.11	19**	1.03	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) (FRA-SA2020-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 Japaqn, Japan Fisheries Research and Education Agency [FRA])

### 1-2) Examination of S-R relationship

We examined the scenarios that assume the hockey stick (HS) model, Ricker (RI) model and Beverton-Holt (BH) model as the S-R relationship to be used for calculation of the spawning biomass that produces the maximum sustainable yield (MSY) and future forecast (Appendix 1). We examined the least squares method and the least absolute value method as a candidate for optimization. As data, we used the recruitment and spawning biomass during the period from 1982 to 2017 as estimated by the stock assessment. We did not use the data of 2018 because the stock assessment of this year is highly uncertain. Examination results of the S-R relationship are shown in Table 1. Because it is confirmed that the residuals of the recruitment projected based on the S-R relationship from the observed values (values of the stock assessment) were normally distributed, we used the least squares method for optimization (Appendix 1).

Because high autocorrelation was found in the residuals in application of either of the S-R relationships (Appendix 1), consideration of autocorrelation was deemed necessary. A significant difference is found in the estimated autocorrelation coefficient between simultaneous estimation of the parameters of the S-R relationship and autocorrelation coefficient, and two-stage estimation where the autocorrelation coefficient is estimated after the estimation of S-R relationship parameters (Appendix 1). When the difference in autocorrelation coefficient is especially big between the two-stage estimation and the

simultaneous estimation, it is recommended to use the result of the simultaneous estimation after confirming the stability of the estimated parameters (Evaluation of estimation bias of simultaneous estimation of the autocorrelation coefficient using simulation (FRA-SA2020-BRP01-6)). Accordingly, we used the simultaneous estimation method to obtain the autocorrelation coefficient of this stock. However, as instability (existence of localized solutions) was found in parameter estimation of the HS model (Appendix 2), we chose RI and BH models as candidates of the S-R relationship (Appendix 1). The accuracy of parameter estimation tends to be lower in the BH model compared with the RI model.

When we compared the corrected version of Akaike's information criterion (AICc) of the S-R relationships of simultaneous estimation, AICc of the BH model was lower than that of the RI model, but the difference was 1.80, which does not justify dismissal of the BH model (Table 1). However, in the RI model, a strong density effect was assumed in the range of the spawning biomass that is larger than the past largest spawning biomass (Figure 1). The spawning biomass that produces MSY greatly varied between the RI model and BH model (Appendix 3). For this reason, in order to reflect the uncertainty of model selection of the S-R relationship as uncertainty of reference points, we considered the S-R relationship averaging the RI and BH models also as a candidate (Estimation of reference points using the model average of multiple S-R relationships (FRA-SA2020-BRP01-8)). The model average was weighted with Akaike weight (Burnham and Anderson 2002) calculated based on the AICc difference. The ratio of the Akaike weight is: RI:BH = 0.71:0.29. For details of the calculation method and results of model averaging, see "Estimation of reference points using model average of multiple S-R relationships (FRA-SA2020-BRP01-8)."

### **1-3) S-R relationship**

We evaluated the robustness of the three S-R relationships that are considered as candidate models (the BH and RI models that estimate autocorrelation simultaneously, and the weighted average model of them) against uncertainty and the influence of selection of a wrong S-R relationship in each scenario (risk of decrease in catch and spawning biomass) by using simplified Management Strategy Evaluation (MSE: Punt 2001) (Appendix 4). For the calculation method of the simplified MSE, see "Comparison of robustness of multiple reference points and examination of HCRs using simplified MSE (FRA-SA2020-BRP01-7)." We implemented MSE of different combinations of the three S-R relationships as the S-R relationship for calculation of the spawning biomass that produces MSY and the true S-R relationship. The results are: in comparison with adopting either the RI or BH model, which have widely varying S-R relationships, the weighted average model had an intermediate value of the risk of decrease in the spawning biomass, and the catch of this model did not fall greatly when control started. For these reasons, we adopt the weighted average model of the BH and RI models where autocorrelation is estimated simultaneously as the S-R relationship of this stock and use the model for calculation of the spawning biomass that produces MSY (SBmsy) and future projection (Figure 1). However, because estimation of parameters of the BH S-R

relationship is not accurate enough, we also assessed the uncertainty of reference points when the weighted average model is used.

For calculation of reference points, the F value is changed variously and simulation is made up to equilibrium with each F value to explore the Fmsy with which the average catch is the maximum. This simulation is to be conducted 10,000 times, of which 7,100 times are for the RI model and 2,900 times are for the BH model for the weighted average model according to the ratio of Akaike weight (RI:BH = 0.71:0.29) (FRA-SA2020-BRP01-8). Estimates of the parameters of the S-R relationship are shown in Appendix 1 (Appendix Table 1-1) and the relationship between the spawning biomass and the observed value of recruitment is shown in Figure 1. We assumed a lognormal distribution for error distribution of recruitment and used the standard deviation of log residuals (S.D.; Table 1) between the predictive value and observed value of the S-R relationship ("Technical Note on Estimation of the stock-recruitment relationship, reference point calculation and future prediction simulation (FRA2020-ABCWG01-02)").

## **2. Reference points**

### **2-1) Data sets and calculation method**

We conducted the calculation of spawning biomass that produces MSY and future prediction according to the rules set for the one-stock biomass of the 2020 Basic Guidelines for the Harvest Control Rules and the Estimation of the Allowable Biological Catch (ABC) 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 Japaqn and FRA). For the S-R relationship, we used the weighted average model of the RI and BH S-R relationships, which is proposed in 1-3). Here, the current fishing mortality (Fcurrent; Figure 2) is the average of fishing mortality (F) during the period from 2016 to 2018 (Table 2). For this stock, assuming equilibrium after the simulation years (45.8 years) that are 20 times as long as the average generation time (2.92 years), we set the F value that maximizes the average catch to Fmsy and the average spawning biomass at the equilibrium when fishing is conducted at Fmsy to SBmsy. We used R Package frasyr (v1.20) for analysis.

### **2-2) Proposed reference points and fishing ban level**

We propose the spawning biomass that produces MSY (SBmsy: 60 thousand tons) as the target reference point (SBtarget) of this stock; the spawning biomass that promises 60% of MSY (SB0.6msy: 15 thousand tons) as the limit reference point (SBlimit); and the spawning biomass that produces 10% of MSY (SB0.1msy: 1.7 thousand tons) as the fishing ban level.

The ratio of the reference points and the fishing ban level to the initial spawning biomass assuming zero catch (SB0), average catch at equilibrium under the corresponding fishing mortality, %SPR-converted fishing mortality, exploitation rate and the ratio to the current fishing mortality are shown in Table 3. SBmsy, which is proposed as the target reference point

(60 thousand tons) is equivalent to 29% of SB0 and the average catch expected with this spawning biomass (MSY) is 38 thousand tons. The ratio of the fishing mortality corresponding to the proposed target reference point (fishing mortality that produces MSY:  $F_{msy}$ ) to the current (2016 to 2018) fishing mortality ( $F_{msy}/F_{current}$ ) is 0.73 and the exploitation rate ( $U_{msy}$ ) in this case is 35%. SB0.6msy, which is proposed as the limit reference point corresponds to 8% of SB0. The ratio of the fishing mortality corresponding to SB0.6msy to the current fishing mortality is 1.50 and the corresponding exploitation rate is 50%. The average catch expected at SB0.6msy is 23 thousand tons. SB0.1msy, which is proposed as the fishing ban level, corresponds to 1% of SB0, and the average expected catch is 3.8 thousand tons. Average spawning biomass at equilibrium when  $F$  is changed variously and the corresponding average catch at age are shown in Figure 3. There is a tendency that the higher the stock status of the spawning biomass, the higher the ratio of older fish in catch is on average.

However, as shown in the document (FRA-SA2020-BRP01-8), we need to pay attention to the fact that SBmsy can vary in the range of 4.9 thousand to 7.6 thousand tons and the fishing mortality that produces MSY can vary in the range of 0.64 to 0.80 of the current fishing mortality ( $F_{current}$ ), depending on the handling of data.

### **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 ( $F_{msy}$ ) or exploitation rate ( $U_{msy}$ ) corresponding to the proposal are shown in Figure 4. It is judged that the fishing mortality of this stock has been over the MSY level, excluding in 2012. The exploitation rate is also judged to have been over the MSY level, excluding in 2012 and 2016. Current spawning biomass (23 thousand tons in 2018) is below 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 are 2.61, 0.65 and 0.07, 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  $F_{msy}$  by  $\beta$  that is proposed by the HCRs. Figure 5a shows the relationship between spawning biomass and fishing mortality in the proposed HCRs, while Figure 5b shows the relationship between spawning biomass and average prospective catch under the same condition. All proposed HCRs illustrated in the figure use the standard value 0.8 for  $\beta$ .

### **2-5) Future projection based on the proposed HCRs**

#### **(1) When safety coefficient $\beta$ is set to the standard value**

Percentage changes of stock 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  $\beta$  to 0.8 (Figure 5) are shown in Figure 6. For the future projection based on the weighted average model, simulation is conducted 10,000 times, of which 7,100 times are for the RI model and 2,900 times are for the BH model according to the ratio of Akaike weight (FI:BH = 0.71:0.29) (FRA-SA2020-BRP01-8). 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  $F_{current}$ .

Because the spawning biomass in 2021 is below the proposed target reference point and above the proposed limit reference point, fishing will be conducted at  $\beta F_{msy}$  based on the proposed HCRs. When  $\beta$  is set to 0.8, the fishing mortality  $0.8F_{msy}$  corresponds to the fishing mortality that decreases the current fishing effort by 42%. As a result, the catch in the first year after introducing the proposed HCRs would be lower than the catch of fishing at  $F_{current}$ . The probability that the spawning biomass will exceed the proposed target reference point will become 51% in 2027 and the spawning biomass is expected to continue to increase also after that.

## **(2) When safety coefficient $\beta$ 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 for spawning biomass to 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  $\beta$  is changed between 0.0 and 1.0 are shown in Tables 4 to 8. The spawning biomass of this stock is projected to increase in 2021 and after with every value of  $\beta$ . When  $\beta$  is set to 0.8 and under, the probability of recovery to the proposed target reference point will exceed 50% in 2027. When  $\beta$  is set to 0.9, the probability of recovery to the proposed target reference point is 48% in 2031, 10 years after starting fishing based on the proposed HCRs, and 52% in 2041. The probability of maintaining the proposed limit reference point will exceed 95% in 2023 and after for every value of  $\beta$ .

As the S-R relationship of this stock, we applied the weighted average model of the BH and RI models with simultaneous estimation of autocorrelation in 1-3). This assumes that the true S-R relationship is either the BH or RI model. Therefore, we implemented simplified MSE with varying  $\beta$  values in order to assess the influence when the true S-R relationship is not the weighted average model (Appendix 4). The result suggests that, when the catch is calculated with the reference points based on the S-R relationship of the weighted average model and the proposed HCRs that are based on the calculation, and when fishing is continued according to the calculated catch but the true S-R relationship is the BH model, it is necessary to lower  $\beta$  to 0.6 in order to achieve the true proposed target reference point after 10 years with a probability

of 50% or higher. On the other hand, if the true S-R relationship is the RI model, the true target control point can be achieved with  $\beta$  set to 0.9. However, the result of MSE with weighted averaging with 0.7 for the RI model and 0.3 for the BH model shows that the proposed target reference point will be reached after 10 years with a probability of 50% or higher when  $\beta$  is set to 0.8 and lower.

### 3. Summary

As the S-R relationship of this stock, we apply the S-R relationship where the RI and BH models with simultaneous autocorrelation estimation using the least squares method for optimization are weight-averaged according to Akaike weight.

Parameters of the S-R relationship are estimated based on the recruitment and spawning biomass of the 1982-2017 period as estimated by the stock assessment.

We propose SB<sub>msy</sub> estimated based on the S-R relationship above as the target reference point, SB<sub>0.6msy</sub> as the limit reference point and SB<sub>0.1msy</sub> as the fishing ban level. The fishing mortality that produces MSY is 0.73 times  $F_{current}$ . However, the uncertainty of the reference points is high.

The current spawning biomass of this stock is considered to be lower than the proposed target reference point. In the future projection based on this proposed target reference point, it is projected that the probability of exceeding the proposed target reference point 10 years after the application of the proposed HCRs is 50% or higher with  $\beta$  set to 0.8 and lower.

As described below, it is assumed that this stock includes the stock migrating from the East China Sea, but, because spawning biomass and recruitment have been estimated by separating this stock from Tsushima Warm Current stock, examination in this material is made accordingly.

### 4. Future considerations

It is thought that stocks born in the East China Sea migrate and join this stock with yearly fluctuation. However, because quantitative assessment of the stock migrating from the East China Sea is difficult at the present stage, we assume S-R within the Pacific stock for the S-R relationship of this stock in this material. We handled this introduction as part of yearly fluctuation of recruitment by considering autocorrelation (effect of recruitment that is better or worse than the expectation from the S-R relationship for a certain period) in estimation of the S-R relationship. However, because autocorrelation does not explicitly consider the influence of introduction, it is necessary to continue to work on quantitative assessment of migrating stock. It is important to pay close attention to the stock trend while implementing management of this stock based on the S-R relationship applied in this material.

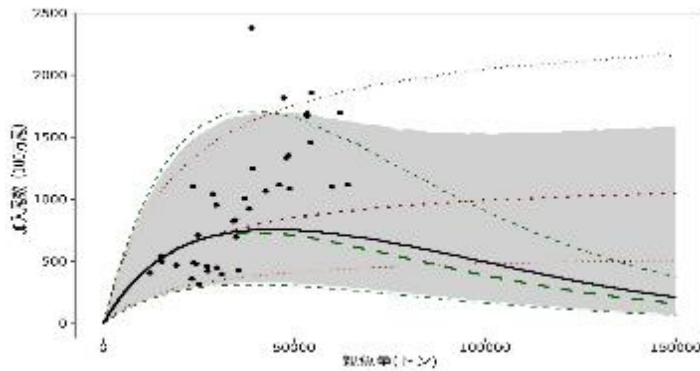
In recent years, recruitment of this stock has been extremely low. In the future projection of the weighted average model, the median of the residuals of recruitment is negative up to around 2023 due to a high autocorrelation coefficient but will come close to 0 year by year (Appendix 5). For this reason, we can say that the low recruitment in recent years is considered in calculation of the catch in 2021. It is difficult to predict the possibility that recruitment will

continue to be low after that year. However, if the low recruitment level continues further, it will take many years for the spawning biomass to reach the spawning biomass that produces MSY and the low catch period will also be long (Appendix 6). For this reason, it is necessary to continuously assess the level of recruitment.

### **References**

Burnham K P., and Anderson D R (2002). Model Selection and Multimodel Inference. Springer,75p.

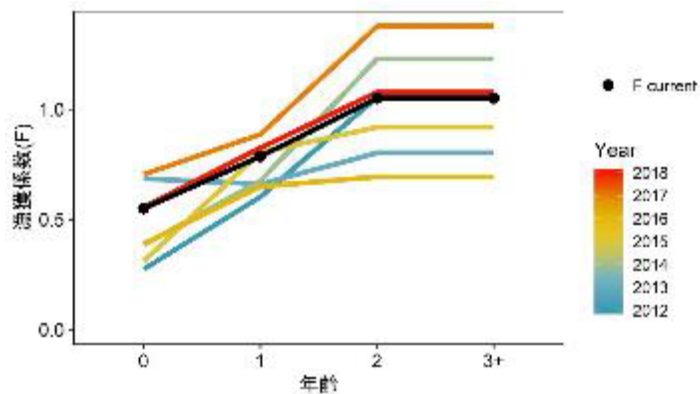
(Authors: Sayoko Isu, Ryuji Yukami, Masayasu Nakagami, Chikako Watanabe, Norio Takahashi, Yasuhiro Kamimrura, Sho Furuichi, Ryosuke Watanabe )



加入尾数 (100 万尾)	Recruitment (million individuals)
親魚量 (トン)	Spawning biomass (tons)

Figure 1. Median of the averaged S-R relationship (black solid line) and the 90% confidence interval (grey area)

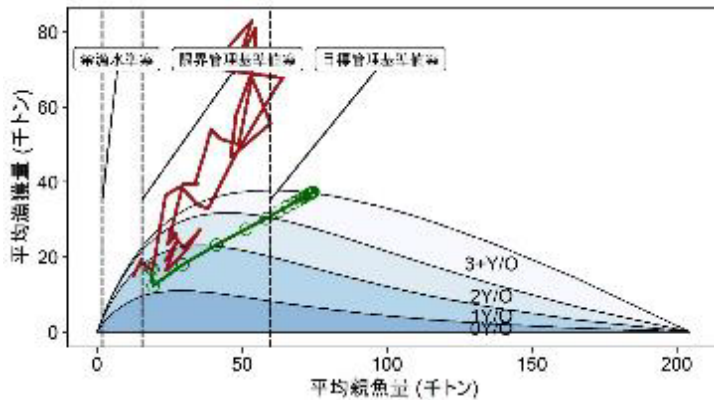
The confidence interval of the averaged S-R relationship is the area of the 5th to 95th percentile when recruitment is generated with random error based on the expected values of the RI model (the thick green line represents the median; the thin green line represents the 90% confidence interval) and the BH model (the thick red line represents the median; the thin red line represents the 90% confidence interval) and samples of recruitment are taken based on Akaike weight (FRA-SA2020-BRP01-8).



漁獲係数	Fishing mortality (F)
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 the Fcurrent that is the average F of the period from 2016 to 2018.

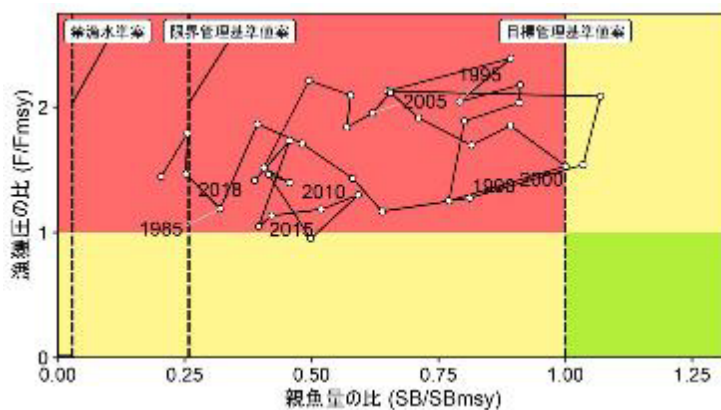


平均漁獲量 (千トン)	Average catch (thousand tons)
平均親魚量 (千トン)	Average spawning biomass (thousand tons)
禁漁水準案	Proposed fishing ban level
限界管理基準値案	Proposed limit reference point
目標管理基準値案	Proposed target reference point

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

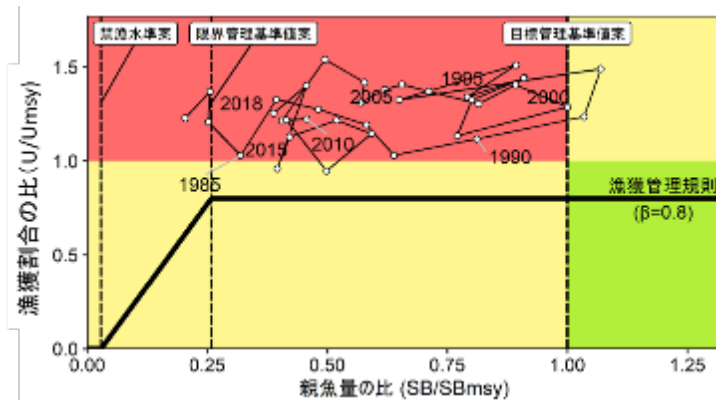
The figure shows the average catch at age corresponding to the average spawning biomass, and the relationship between the proposed reference points and fishing ban level at equilibrium in the future projection simulation. The red line represents changes in the spawning biomass and catch, which are estimated by the stock assessment, while the green line represents changes in the average spawning biomass and average catch in the future projection when fishing is conducted based on the proposed HCRs. Safety coefficient  $\beta$  used in the proposed HCRs is 0.8. The initial spawning biomass assuming no catch (SB0) is 204 thousand tons. Part of the past spawning biomass and catch are outside the scope (maximum values: spawning biomass: 64 thousand tons; catch: 83 thousand tons).

a) When the vertical axis is the ratio of the fishing mortality ( $F/F_{msy}$ )



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)

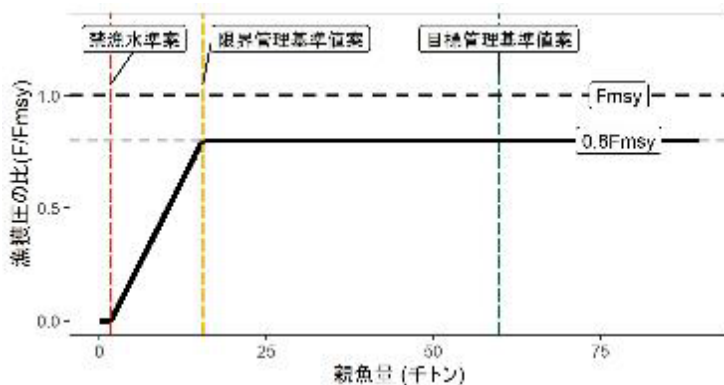


漁獲割合の比	U/Umsy
親魚量の比	SB/SBmsy
禁漁水準案	Proposed SBban
限界管理基準値案	Proposed SBlimit
目標管理基準値案	Proposed SBtarget
漁獲管理規則	HCRs

Figure 4. Kobe plot (four sections)

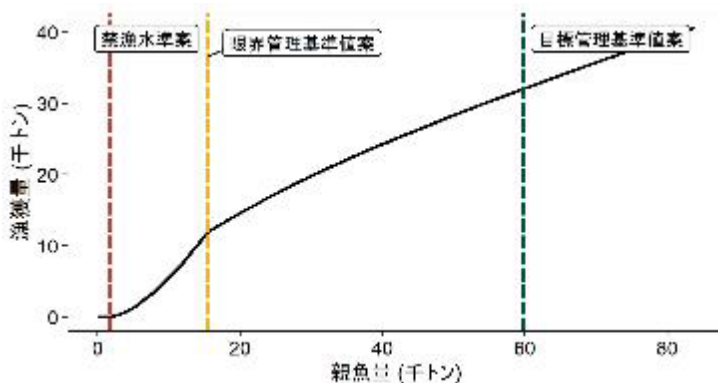
When the ratio of fishing mortality is put on the vertical axis (upper figure) and when the ratio of exploitation rate is put on the vertical axis (lower figure). For the proposed target reference point (SBtarget), limit reference point (SBlimit) and fishing ban level (SBban) in the figures, we used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

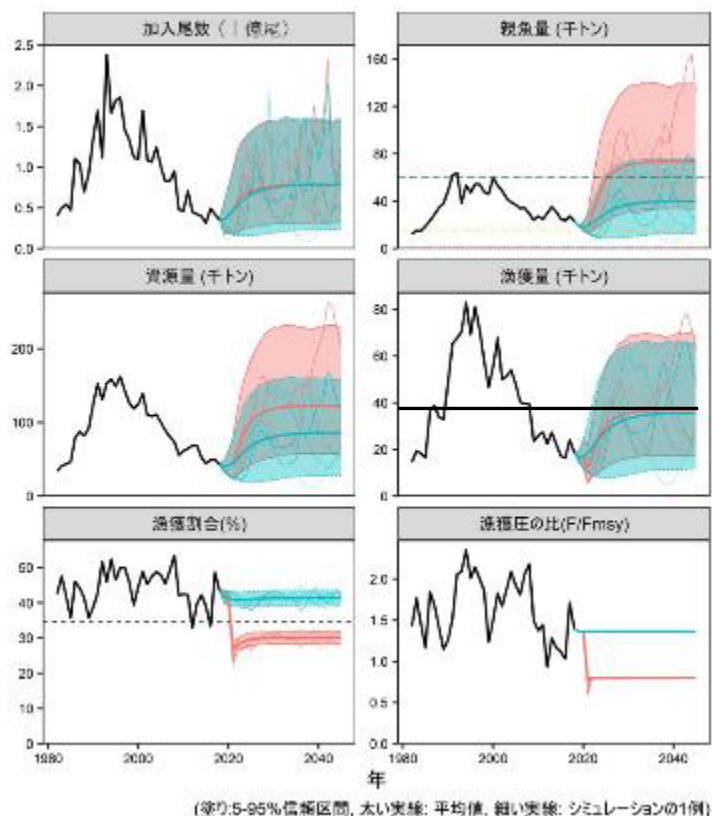


漁獲量 (千トン)	Catch (thousand tons)
親魚量 (千トン)	Spawning biomass (thousand tons)
禁漁水準案	Proposed SBban
限界管理基準値案	Proposed SBlimit
目標管理基準値案	Proposed SBtarget

Figure 5. Proposed HCRs

The proposed target reference point (SBtarget) is SBmsy, which is calculated based on the S-R relationship applied to this stock. Standard values are used for the proposed limit control point (SBlimit) and the proposed fishing ban level (SBban). For safety coefficient  $\beta$ , we used 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. a) is when the ratio of fishing mortality is put on the vertical axis, while b) is when 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 (十億尾)	Recruitment (billion 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	F/Fmsy
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% prediction interval; thick solid line: average value; thin solid 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 figure 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 figure of catch shows MSY, while the dashed line in the figure of exploitation rate shows  $U_{msy}$ . The catch in 2019 and 2020 are assumed based on the projected stock biomass and  $F_{current}$ , while the catch in 2021 and after is based on the proposed HCRs (Figure 5). Safety coefficient  $\beta$  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	$\Delta AICc$	$\Delta AICc$ の 順位	S.D.	データ数
リッカー型	最小二乗法	同時	<b>27.2</b>	NA	<b>1</b>	<b>0.306</b>	<b>36</b>
ホッケー・スティック 型	最小二乗法	同時	27.4	NA	2	0.309	36
ベバートン・ホルト型	最小二乗法	同時	<b>29.0</b>	NA	<b>3</b>	<b>0.315</b>	<b>36</b>

再生産関係式	S-R relationship
最適化法	Optimization method
自己相関	Autocorrelation
$\Delta AICc$ の順位	Order of $\Delta AICc$
データ数	Data quantity
リッカー型	Ricker
ホッケー・スティック型	Hockey stick
ベバートン・ホルト型	Beverton and Holt
最小二乗法	Least squares method
同時	Simultaneous

The S-R relationships to be applied are 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 ( $F_{current}$ )
0	0.5	0.0	40	0.524	0.549
1	0.5	0.5	106	0.749	0.785
2	0.5	1	224	1.000	1.049
3歳以上	0.5	1	404	1.000	1.049

年齢	Age
自然死亡係数	Natural mortality
成熟率	Maturity rate

平均重量	Average body 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	60	0.29	38	0.22	0.34	0.73
限界管理基準値案	SB0.6msy	15	0.08	23	0.08	0.50	1.50
禁漁水準案	SB0.1msy	1.7	0.01	3.8	0.05	0.57	2.00
MSYを実現する漁獲圧	Fmsy	(0歳, 1歳, 2歳, 3歳以上) = (0.40, 0.57, 0.76, 0.76)					

管理基準値案又は禁漁水準案	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	F/Fcurrent
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) = (0.40, 0.57, 0.76, 0.76)	(Ages 0, 1, 2, 3 and above) = (0.40, 0.57, 0.76, 0.76)

\* 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 the results of the future projection based on the proposed HCRs (Figure 5) when safety coefficient  $\beta$  is changed from 0.0 to 1.0 in 0.1 intervals. The projection assumes  $F_{current}$  catch for 2019 and 2020 and a catch corresponding to the proposed HCRs for 2021 and after.

(%)

$\beta$	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2041	2051
1.0	0	0	0	1	8	17	24	28	32	34	36	38	39	42	43
0.9	0	0	0	1	11	23	32	37	41	43	46	47	48	52	52
0.8	0	0	0	2	15	30	41	47	51	53	56	57	57	62	62
0.7	0	0	0	3	21	39	51	57	61	63	65	66	67	71	71
0.6	0	0	0	4	27	49	62	68	70	72	74	75	76	79	79
0.5	0	0	0	6	34	59	72	78	79	80	82	83	84	86	86
0.4	0	0	0	8	42	68	82	86	86	87	88	89	90	91	92
0.3	0	0	0	10	50	77	88	92	92	92	93	94	94	96	95
0.2	0	0	0	12	58	85	94	96	96	96	96	97	97	98	98
0.1	0	0	0	15	66	91	97	99	99	98	98	99	99	99	99
0.0	0	0	0	19	74	95	99	100	100	100	99	100	100	100	100

Table 5. Probability for future spawning biomass to exceed the proposed limit reference point  
 The table shows the results of the future projection based on the proposed HCRs (Figure 5) when safety coefficient  $\beta$  is changed from 0.0 to 1.0 in 0.1 intervals. The projection assumes  $F_{current}$  catch for 2019 and 2020 and a catch corresponding to the proposed HCRs for 2021 and after.

(%)

$\beta$	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2041	2051
1.0	100	95	74	91	95	96	97	98	98	98	99	99	99	99	99
0.9	100	95	74	94	97	98	99	99	99	99	99	99	99	100	100
0.8	100	95	74	96	98	99	99	100	100	100	100	100	100	100	100
0.7	100	95	74	97	99	100	100	100	100	100	100	100	100	100	100
0.6	100	95	74	98	100	100	100	100	100	100	100	100	100	100	100
0.5	100	95	74	99	100	100	100	100	100	100	100	100	100	100	100
0.4	100	95	74	99	100	100	100	100	100	100	100	100	100	100	100
0.3	100	95	74	99	100	100	100	100	100	100	100	100	100	100	100
0.2	100	95	74	100	100	100	100	100	100	100	100	100	100	100	100
0.1	100	95	74	100	100	100	100	100	100	100	100	100	100	100	100
0.0	100	95	74	100	100	100	100	100	100	100	100	100	100	100	100

Table 6. Probability for future spawning biomass to exceed the proposed fishing ban level  
 The table shows the results of the future projection based on the proposed HCRs (Figure 5) when safety coefficient  $\beta$  is changed from 0.0 to 1.0 in 0.1 intervals. The projection assumes  $F_{current}$  catch for 2019 and 2020 and a catch corresponding to the proposed HCRs for 2021 and after.

(%)

$\beta$	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	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Table 7. Changes in future average spawning biomass

The table shows the results of the future projection based on the proposed HCRs (Figure 5) when safety coefficient  $\beta$  is changed from 0.0 to 1.0 in 0.1 intervals. The projection assumes  $F_{\text{current}}$  catch for 2019 and 2020 and a catch corresponding to the proposed HCRs for 2021 and after.

(千トン)

$\beta$	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2041	2051
1.0	19	18	19	27	34	41	46	50	52	54	56	57	57	60	60
0.9	19	18	19	28	38	46	52	56	59	61	62	63	64	66	67
0.8	19	18	19	30	41	51	58	63	65	68	69	71	71	74	74
0.7	19	18	19	31	45	57	65	70	73	75	77	79	80	82	82
0.6	19	18	19	33	49	64	73	78	82	84	87	88	89	92	92
0.5	19	18	19	35	54	71	82	88	91	94	97	99	100	103	103
0.4	19	18	19	37	59	80	93	98	102	106	109	112	113	116	116
0.3	19	18	19	39	65	90	105	111	114	119	123	127	128	131	132
0.2	19	18	19	41	72	101	119	125	129	134	140	145	147	150	151
0.1	19	18	19	43	79	114	135	143	146	152	160	167	170	173	174
0	19	18	19	46	87	129	155	164	168	174	184	194	199	204	205

(Thousand tons)

Table 8. Changes in future average catch

The table shows the results of the future projection based on the proposed HCRs (Figure 5) when safety coefficient  $\beta$  is changed from 0.0 to 1.0 in 0.1 intervals. The projection assumes  $F_{\text{current}}$  catch for 2019 and 2020 and a catch corresponding to the proposed HCRs for 2021 and after.

(千トン)

$\beta$	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2041	2051
1.0	17	17	15	20	24	28	31	32	34	35	36	36	36	38	38
0.9	17	17	14	19	24	28	31	32	34	35	36	36	36	38	38
0.8	17	17	12	18	23	27	30	32	33	34	35	36	36	37	37
0.7	17	17	11	17	22	27	30	31	33	34	34	35	35	36	36
0.6	17	17	10	15	21	26	28	30	31	32	33	33	34	34	35
0.5	17	17	8	14	19	24	27	28	29	30	31	31	32	32	32
0.4	17	17	7	12	17	21	24	25	26	27	28	28	29	29	29
0.3	17	17	5	10	14	18	20	22	22	23	24	24	25	25	25
0.2	17	17	4	7	10	14	16	16	17	18	18	19	19	19	19
0.1	17	17	2	4	6	8	9	9	10	10	11	11	11	11	11
0	17	17	0	0	0	0	0	0	0	0	0	0	0	0	0

(Thousand tons)

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

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

$\beta$	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	57	39%	15	32	36	99%
0.9	64	48%	14	32	36	99%
0.8	71	57%	12	32	36	100%
0.7	80	67%	11	31	35	100%
0.6	89	76%	10	30	34	100%
0.5	100	84%	8	28	32	100%
0.4	113	90%	7	25	29	100%
0.3	128	94%	5	22	25	100%
0.2	147	97%	4	16	19	100%
0.1	170	99%	2	9	11	100%
0	199	100%	0	0	0	100%

10年後(2031年)の平均親魚量	Average spawning biomass 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 an S-R relationship candidate of Japanese jack mackerel Pacific stock to be used for calculation of the spawning biomass that produces MSY and future projection, we chose HS (Clark et al., 1985), BH (Beverton and Holt 1957) and RI (Ricker 1954) S-R relationships. Mathematical equations of the respective S-R relationships are as follows:

$$R_y = \begin{cases} ab & \text{if } B_y > b \\ aB_y & \text{if } B_y \leq b \end{cases} \quad (\text{Hockey stick, HS})$$

$$R_y = \frac{aB_y}{(1 + bB_y)} \quad (\text{Beverton Holt, BH})$$

$$R_y = aB_y \exp(-bB_y) \quad (\text{Ricker, RI})$$

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

We chose the least squares method and the least absolute value method as a candidate for optimization and examined the normality of residuals against the S-R relation models with a Shapiro-Wilk test. Because significant deviation was not found in any S-R relationship, we used the least squares method for optimization (Appendix Figures 1-1a, b and c). Residual trend and autocorrelation plot when the S-R relationship is applied using the least squares method is shown in Appendix Figure 1-2. Because a trend is found in time series of residuals with assumption of any of the S-R relationships, and the autocorrelation coefficient is significant as it does not fall within the 95% confidence interval up to a 3 to 5-year lag, it is deemed that we need to consider autocorrelation for this stock. There was a big difference in estimated autocorrelation coefficient between the simultaneous estimation and the two-stage estimation (for example,  $\rho$  of inside of the RI model is 0.81 with the simultaneous estimation while it was 0.43 with the two-stage estimation. Appendix Table 1-1). When the difference of  $\rho$  is especially big between the two-stage estimation and the simultaneous estimation, it is recommended to adopt the result of simultaneous estimation after confirming the stability of estimated parameters (FRA-SA2020-BRP01-6). Accordingly, we used the simultaneous estimation method to obtain autocorrelation coefficient of this stock. However, estimated parameter values greatly varied in the HS model but multiple local solutions with similar likelihood were found (Appendix 2). For this reason, we adopted RI and BH models as candidate models of the S-R relationship.

When we compared the corrected version of AICc of the S-R relationships that use simultaneous estimation method, the difference between the RI and BH models was not significant (Table 1). The RI model shows an assumption of a strong density effect when the spawning biomass is large. The tendency greatly varies from that of the BH model (Appendix Figure 1-3a,b). The difference is also big in the spawning biomass that produces MSY, which is calculated based on the respective S-R relationship (Appendix 3).

Based on the result of Jack Knife examination of individual data's influence on the RI and BH S-R relationships where autocorrelation is estimated simultaneously, it was judged that the mode of the S-R relationship was susceptible to change in both the models when data of 1993 (the year of the highest recruitment) is removed (Appendices Figures 1-4 and 1-5). We also conducted residual bootstrapping. In the RI model, the point estimates of a and b were consistent with the bootstrap median, but the confidence intervals of sd and autocorrelation coefficient rho are somewhat wide and the bootstrap median is slightly lower than the point estimates (Appendix Figure 1-6). Curves with extremely different shapes were not found (Appendix Figure 1-7). In the BH model, sometimes a and b that are greatly different from the point estimates are estimated (Appendix Figure 1-6). There were extreme results, including constant recruitments and recruitments proportionate to the spawning biomass (Appendix Figure 1-7). When we calculated profile likelihood, the confidence interval of the RI model was narrow, whereas the confidence interval of parameters was wide in the BH model (Appendix Figure 1-8).

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	推定法	a	b	S.D.	Rho	AICc
リッカー (RI)	<b>最小二乗法</b>	有	同時	<b>0.0588</b>	<b><math>2.58 \times 10^{-5}</math></b>	<b>0.306</b>	<b>0.805</b>	27.2
ベバートン・ホルト (BH)	<b>最小二乗法</b>	有	同時	<b>0.0667</b>	<b><math>5.11 \times 10^{-5}</math></b>	<b>0.315</b>	<b>0.698</b>	29.0
ホッケー・スティック (HS)	最小二乗法	有	同時	0.0273	39200	0.309	0.635	27.4
リッカー (RI)	<b>最小二乗法</b>	有	二段階	0.0251	$3.67 \times 10^{-5}$	0.329	0.429	30.2
ベバートン・ホルト (BH)	<b>最小二乗法</b>	有	二段階	0.0251	$5.16 \times 10^{-11}$	0.329	0.429	30.2
ホッケー・スティック (HS)	最小二乗法	有	二段階	0.0253	54500	0.318	0.474	27.6

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
リッカー (RI)	Ricker (RI)
ベバートン・ホルト (BH)	Beverton-Holt (BH)
ホッケー・スティック (HS)	Hockey stick (HS)
最小二乗法	Least squares method
有	Yes
同時	Simultaneous
二段階	Two-stage

The S-R relationships to be applied are 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

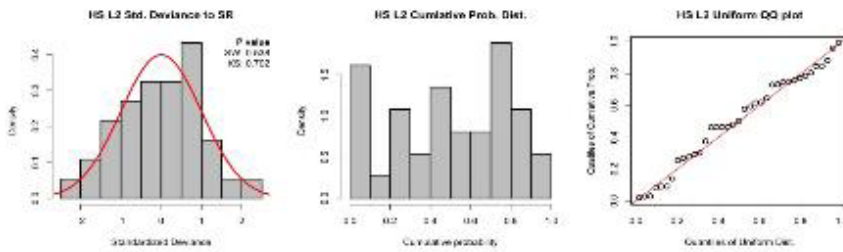
square error).

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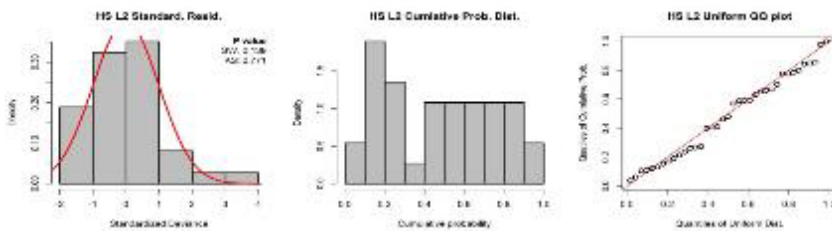
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When autocorrelation is estimated in two stages in the HS model (least squares method)

- Residuals of the S-R relationship

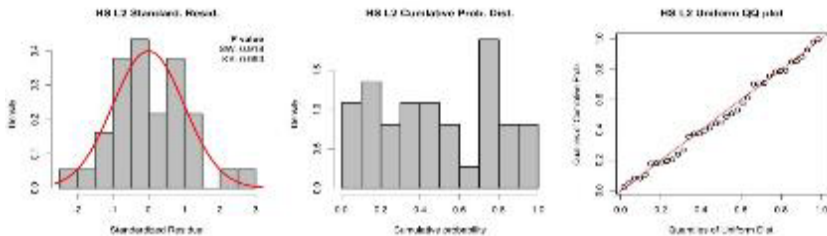


- Residuals in estimation of autocorrelation



When autocorrelation is estimated simultaneously in the HS model (least squares method)

- Residuals of the S-R relationship when autocorrelation is removed

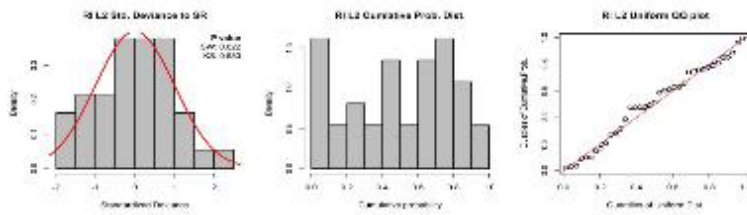


Appendix Figure 1-1a. HS S-R relationship: Histogram of standardized residuals and result of normality test (left); Histogram of cumulative probability density of errors (center); and QQ plot assuming uniform distribution (right)

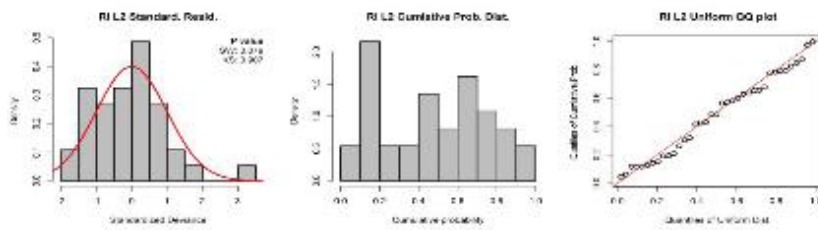
When autocorrelation is estimated in two stages, the residual distribution of the S-R relationship and residuals in estimation of autocorrelation are shown. When autocorrelation is estimated simultaneously, the residual distribution of the S-R relationship where autocorrelation is removed is shown. The 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.

When autocorrelation is estimated in two stages in the RI model (least squares method)

- Residuals of the S-R relationship

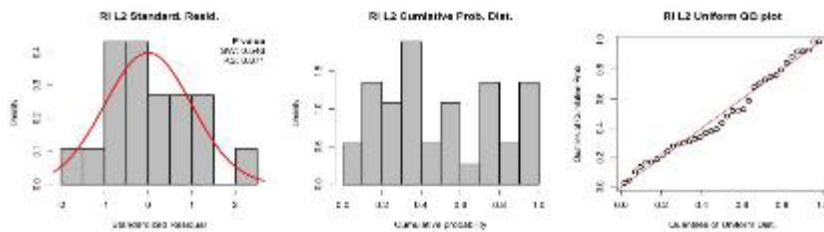


- Residuals in estimation of autocorrelation



When autocorrelation is estimated simultaneously in the RI model (least squares method)

- Residuals of the S-R relationship when autocorrelation is removed

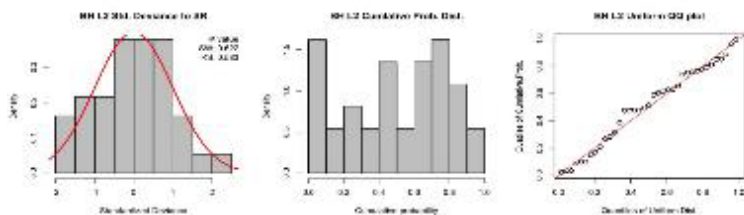


Appendix Figure 1-1b. RI S-R relationship: histogram of standardized residuals and the result of normality test (left); Histogram of cumulative probability density of residuals (center) and; QQ plot assuming uniform distribution (right)

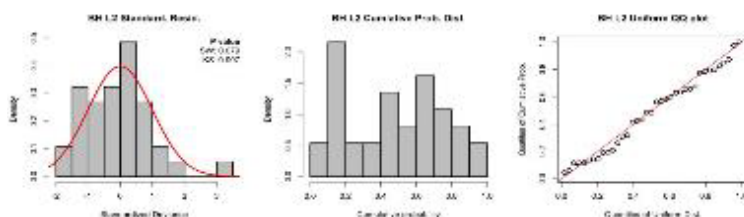
When autocorrelation is estimated in two stages, the residual distribution of the S-R relationship and residuals in estimation of autocorrelation are shown. When autocorrelation is estimated simultaneously, the residual distribution of the S-R relationship where autocorrelation is removed is shown. The 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.

When autocorrelation is estimated in two stages in the BH model (least squares method)

- Residuals of the S-R relationship

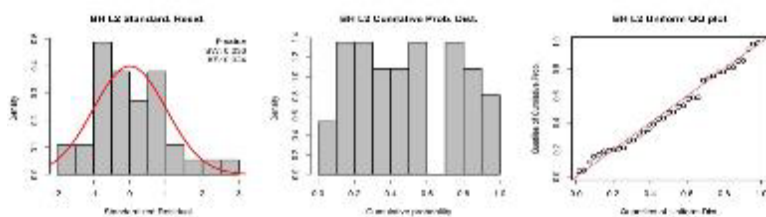


• Residuals in estimation of autocorrelation



When autocorrelation is estimated simultaneously in the BH model (least squares method)

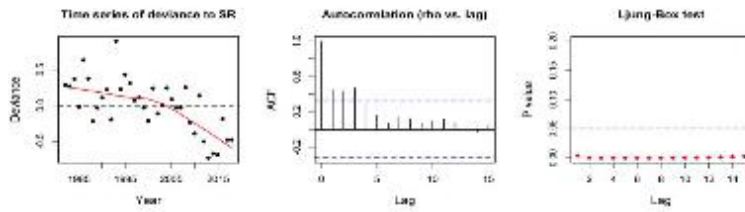
• Residuals of the S-R relationship when autocorrelation is removed



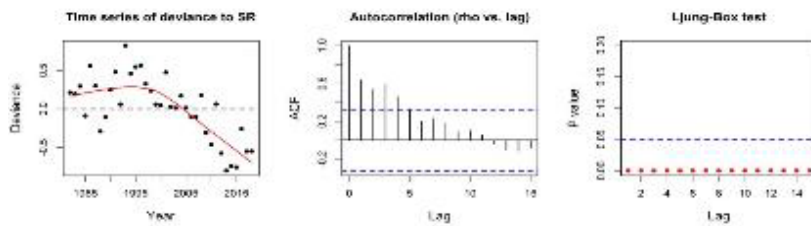
Appendix Figure 1-1c. BH S-R relationship: Histogram of standardized residuals and result of normality test (left); Histogram of cumulative probability density of residuals (center) and; QQ plot assuming uniform distribution (right)

When autocorrelation is estimated in two stages, the residual distribution of the S-R relationship and residuals in estimation of autocorrelation are shown. When autocorrelation is estimated simultaneously, the residual distribution of the S-R relationship where autocorrelation is removed is shown. The upper-left 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.

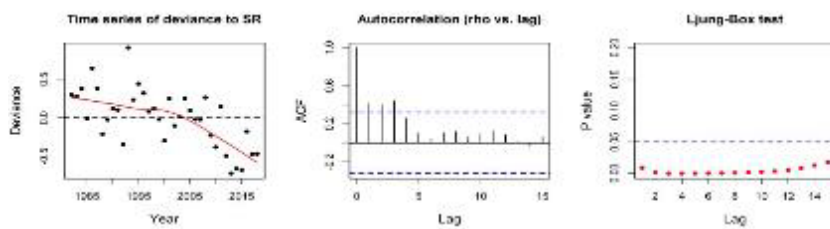
When autocorrelation is estimated in two stages in the HS model (least squares method)



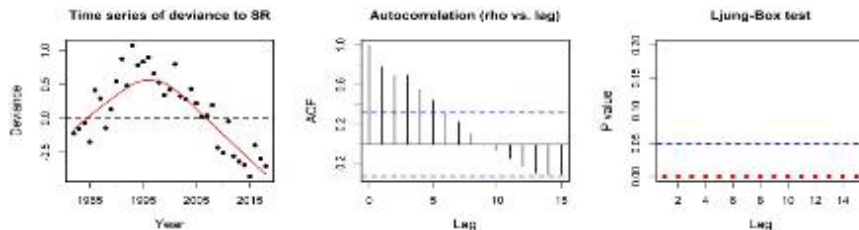
When autocorrelation is estimated simultaneously in the HS model (least squares method)



When autocorrelation is estimated in two stages in the RI model (least squares method)



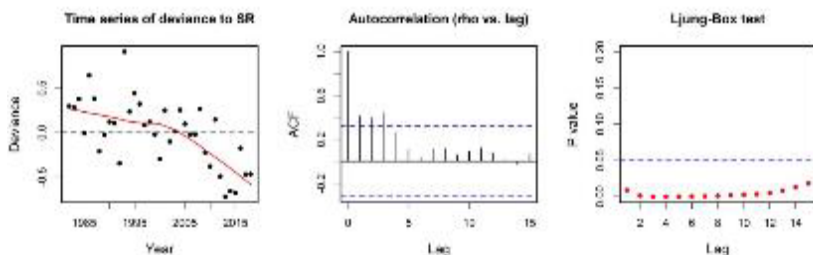
When autocorrelation is estimated simultaneously in the RI model (least squares method)



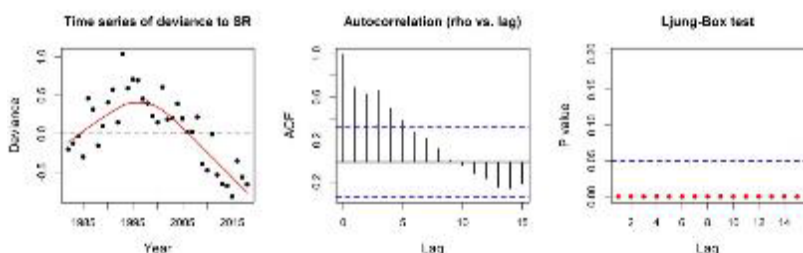
Appendix Figure 1-2. HS and RI S-R relationships: Time-series trend of standardized residuals (left); Correlogram (center); and P value of Ljung-Box test (right)

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.

When autocorrelation is estimated in two stages in the BH model (least squares method)

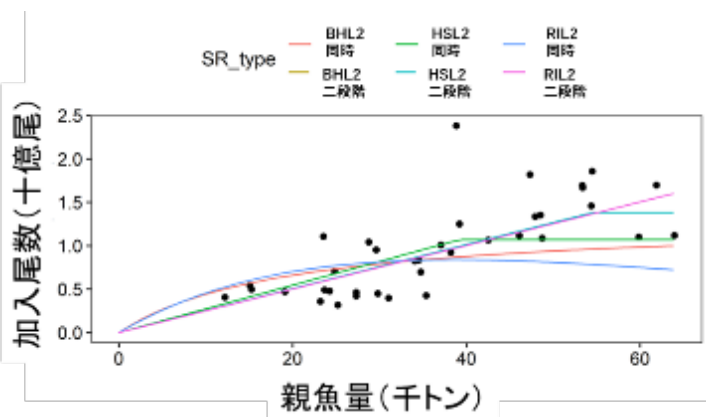


When autocorrelation is estimated simultaneously in the BH model (least squares method)



Appendix Figure 1-2 (continued). BH S-R relationship: 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.

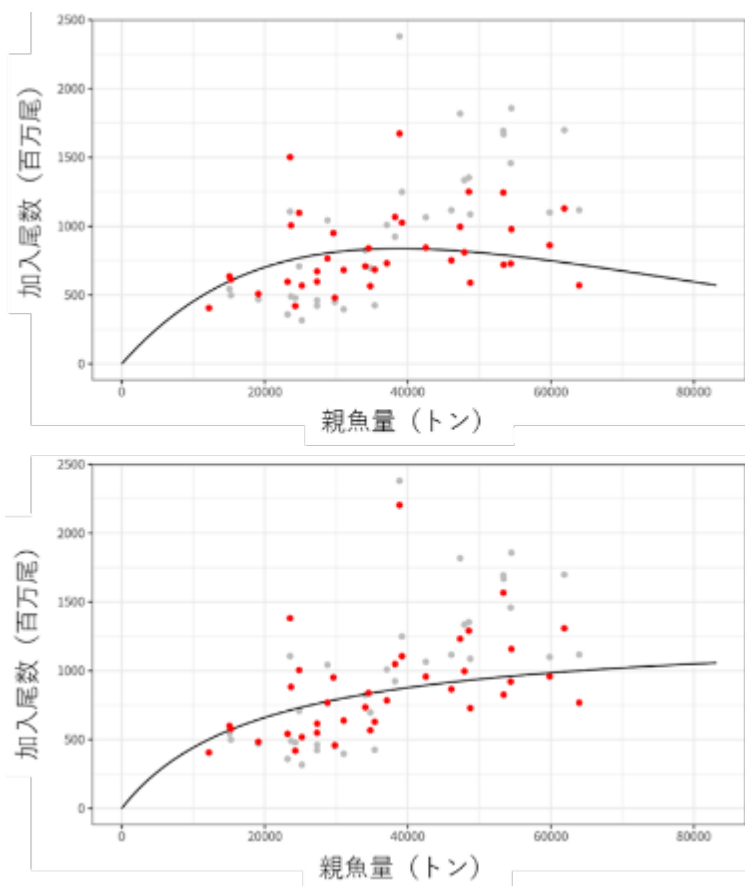


加入尾数 (十億尾)	Recruitment (billion individuals)
親魚量 (千トン)	Spawning biomass (thousand tons)
BHL2 同時	Simultaneous BHL2
HSL2 同時	Simultaneous HSL2
RIL2 同時	Simultaneous RIL2
BHL2 二段階	Two-stage BHL2

HSL2 二段階	Two-stage HSL2
RIL2 二段階	Two-stage RIL2

Appendix Figure 1-3a. S-R relationship of each model

We applied the HS, RI and BH S-R relationships to the model that estimates autocorrelation in residuals in two stages (same as the model that does not consider autocorrelation) and the model with simultaneous estimation, by using the least squares method (L2) in both cases. The BH and RI S-R relationships that estimate autocorrelation in two stages showed a linear relationship and overlap. The black circles represent the spawning biomass and recruitment (1982-2017) used for the analysis.



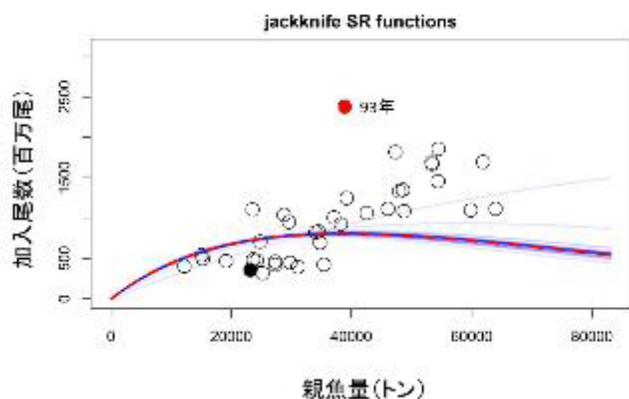
加入尾数 (百万尾)	Recruitment (million individuals)
親魚量 (トン)	Spawning biomass (tons)

Appendix Figure 1-3b. The S-R curve of the RI model (upper figure) and BH model (lower figure) and the recruitment when the autocorrelation part projected in the S-R relationship is removed from the observed recruitment (grey)

When autocorrelation is estimated simultaneously, it seems to correspond to the observation data very badly, but this is because the observation data of high spawning biomass and high

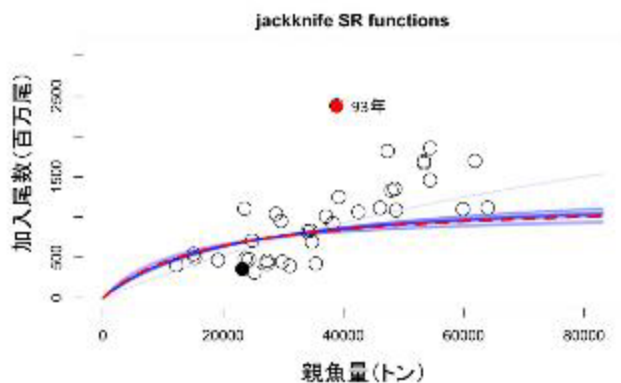
recruitment are explained with high autocorrelation. For example, when the autocorrelation part projected in the model is removed from the observed recruitment, the result is as shown in the figure. The observation data minus the autocorrelation part well fit the S-R relationship.

When autocorrelation is estimated simultaneously in the RI model (least squares method)



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

When autocorrelation is estimated simultaneously in the BH model (least squares method)



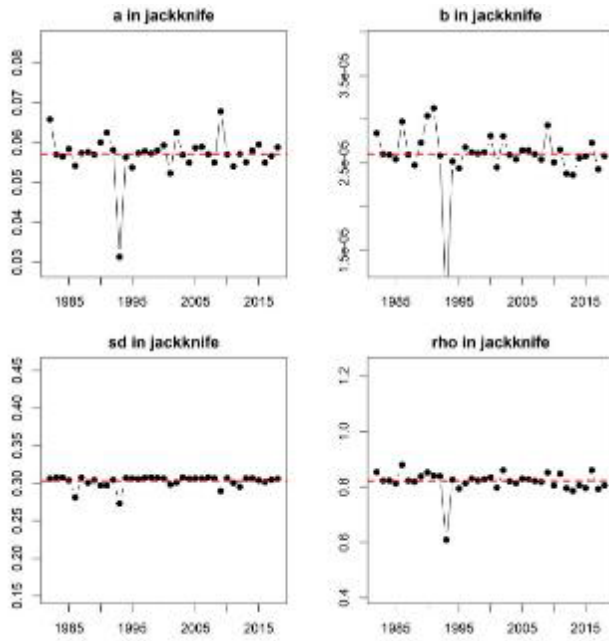
加入尾数 (百万尾)	Recruitment (million individuals)
親魚量 (トン)	Spawning biomass (tons)

Appendix Figure 1-4. Result of estimation with Jack Knife analysis when autocorrelation is estimated simultaneously in the RI and BH S-R relationships

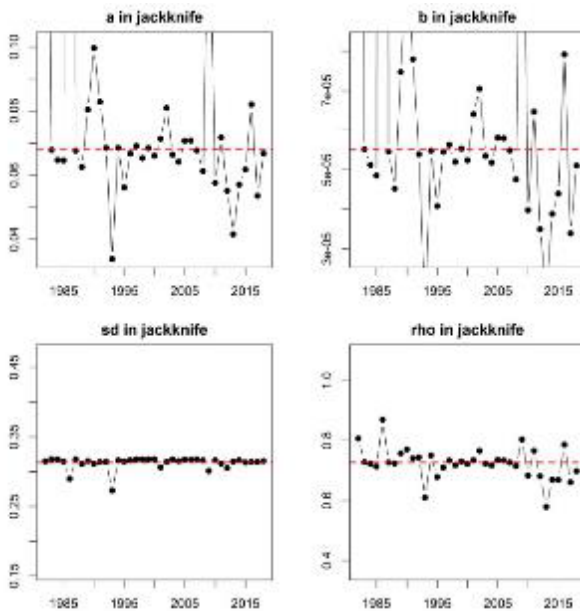
Red lines represent the estimates using all data, while blue lines represent the estimates when data of one year is removed. Circles express the spawning biomass and recruitment used for the analysis. The black circle shows the last year of the data period (2017) and the

red circle shows 1993, where the effect of removal is big.

When autocorrelation is estimated simultaneously in the RI model (least squares method)

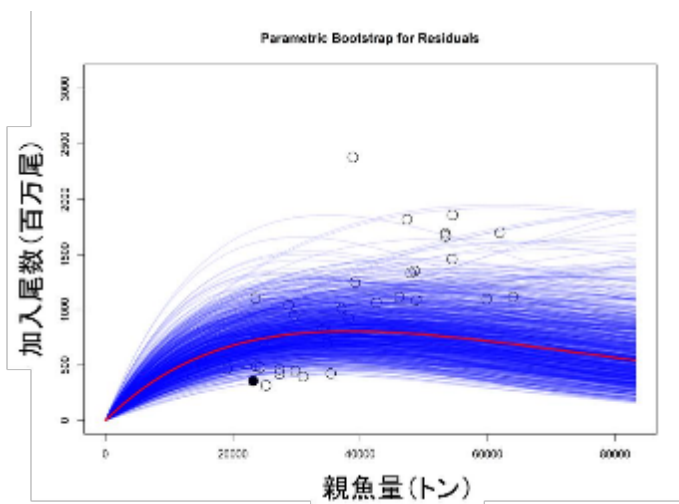


When autocorrelation is estimated simultaneously in the BH model (least squares method)



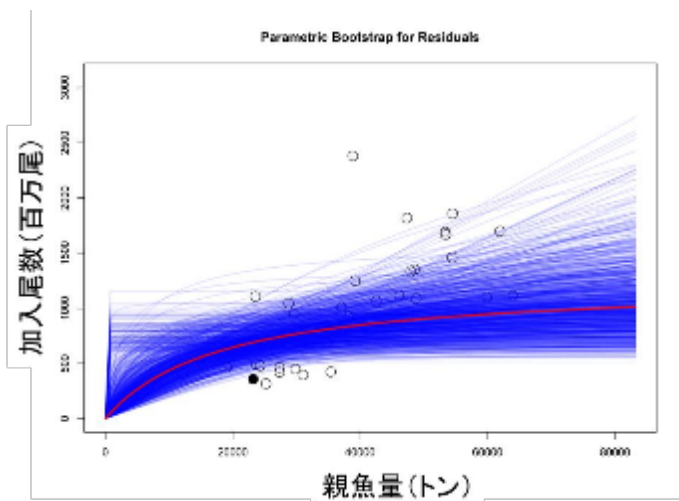
Appendix Figure 1-5. Influence by parameter in Jack Knife analysis when autocorrelation is estimated simultaneously in the RI and BH S-R relationships

When autocorrelation is estimated simultaneously in the RI model (least squares method)



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

When autocorrelation is estimated simultaneously in the BH model (least squares method)

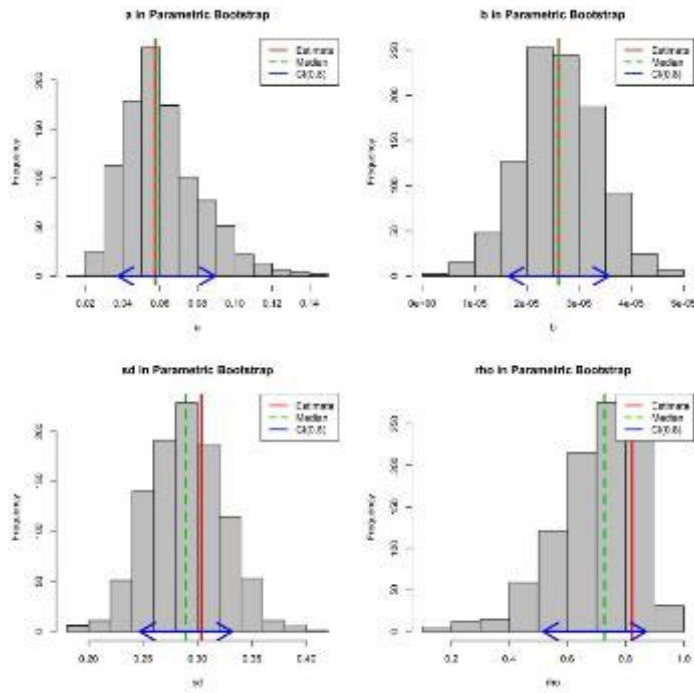


加入尾数 (百万尾)	Recruitment (million individuals)
親魚量 (トン)	Spawning biomass (tons)

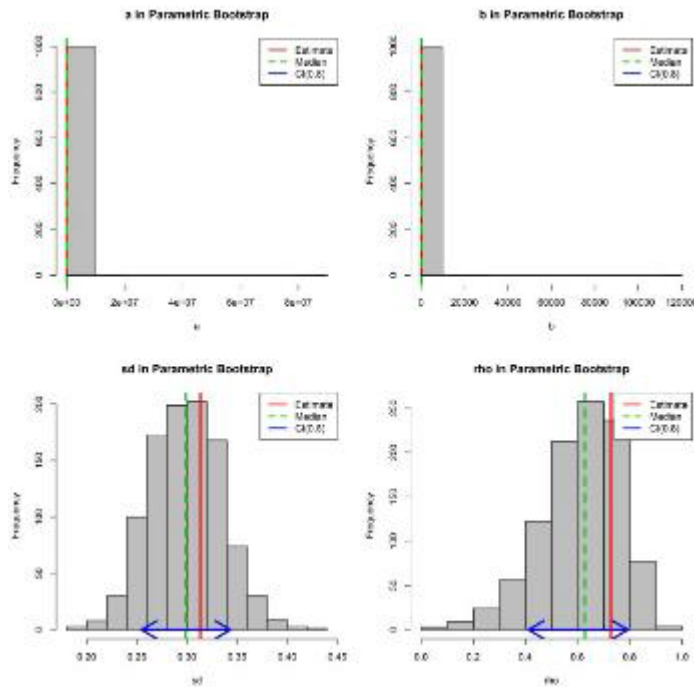
Appendix Figure 1-6. Results of residual bootstrap analysis when autocorrelation is estimated simultaneously in the RI and BH S-R relationships

The red line expresses the estimates with the original data, while the blue line expresses the estimates with nonparametric bootstrapping. Circles show the spawning biomass and recruitment, which are used for the analysis. The black circle shows the last year of the data period (2017).

When autocorrelation is estimated simultaneously in the RI model (least squares method)



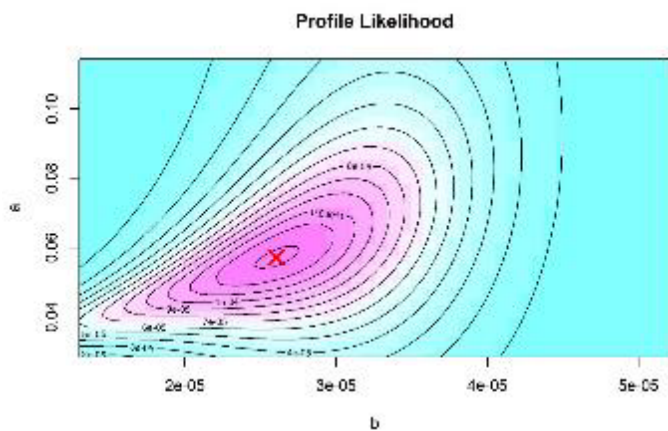
When autocorrelation is estimated simultaneously in the BH model (least squares method)



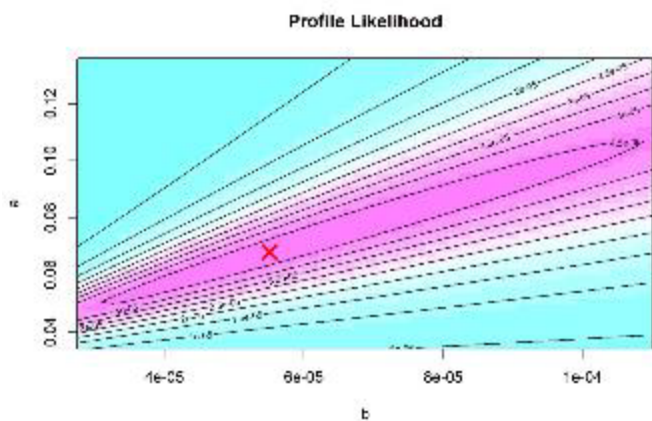
Appendix Figure 1-7. Median (green dotted lines) and the 80% confidence interval (blue lines) of residual bootstrap analysis of the RI and BH S-R relationships

Red lines express point estimates of the parameter.

When autocorrelation is estimated simultaneously in the RI model (least squares method)



When autocorrelation is estimated simultaneously in the BH model (least squares method)



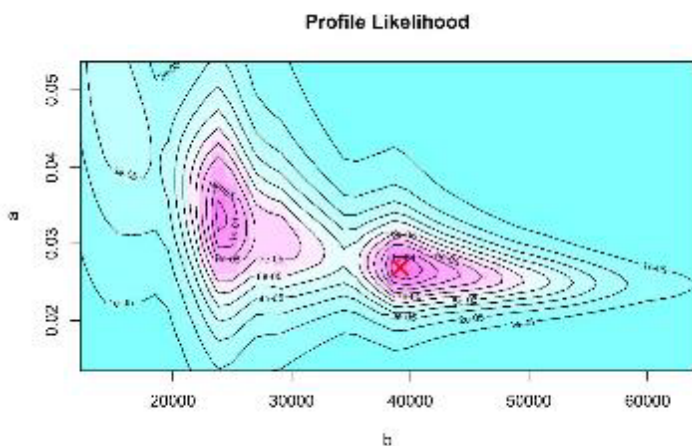
Appendix Figure 1-8. Profile likelihood of the estimated parameters when autocorrelation is estimated simultaneously in the RI and BH S-R relationships

The × mark represents the parameter value of the maximum likelihood estimation

**Appendix 2. Instability of HS model where autocorrelation is estimated simultaneously**

When the difference in autocorrelation coefficient is especially big between the two-stage estimation and the simultaneous estimation, it is recommended to use the result of the simultaneous estimation after confirming the stability of the estimated parameters (FRA-SA2020-BRP01-6).

Appendix Figure 1-8 shows a single peak of profile likelihood of the estimated S-R relationship parameters of the RI and BH models where autocorrelation is estimated simultaneously. On the other hand, two peaks of similar height of likelihood are found in the HS model where autocorrelation is estimated simultaneously (Appendix Figure 2-1).



Appendix Figure 2-1. Profile likelihood of the estimated parameters of the HS S-R relationship where autocorrelation is estimated simultaneously

The × mark represents the parameter value estimated with the maximum likelihood method.

### Appendix 3. Proposed reference points of RI and BH models where autocorrelation is estimated simultaneously

The table below shows: average spawning biomass when simulation is made until equilibrium by using the proposed reference points calculated based on the respective S-R relationships; ratio to the initial spawning biomass that assumes no catch (SB0); average catch; %SPR-converted fishing mortality; exploitation rate; ratio of fishing effort to the Fcurrent; and fishing mortality at age at the fishing mortality that produces MSY (Fmsy).

Appendix Table 3-1. Proposed reference points of RI model (simultaneous estimation)

管理基準値案	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	SB <sub>msy</sub>	44	0.39	34	0.17	0.39	0.89
限界管理基準値案	SB <sub>0.6msy</sub>	13	0.12	21	0.08	0.51	1.54
禁漁水準案	SB <sub>0.1msy</sub>	1.5	0.01	3.4	0.05	0.57	2.00
MSY を実現する 漁獲圧	F <sub>msy</sub>	(0 歳, 1 歳, 2 歳, 3 歳以上) = (0.49, 0.70, 0.93, 0.93)					

管理基準値案	Proposed reference points
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) = (0.49, 0.70, 0.93, 0.93)	(Ages 0, 1, 2, 3 and above) = (0.49, 0.70, 0.93, 0.93)

Appendix Table 3-2. Proposed reference points of BH model (simultaneous estimation)

管理基準値案	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	132	0.31	53	0.34	0.26	0.46
限界管理基準値案	SB0.6msy	26	0.06	32	0.10	0.47	1.28
禁漁水準案	SB0.1msy	2.4	0.01	5.3	0.05	0.57	2.00
MSY を実現する 漁獲圧	Fmsy	(0 歳, 1 歳, 2 歳, 3 歳以上) = (0.26, 0.36, 0.49, 0.49)					

管理基準値案	Proposed reference points
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) = (0.26, 0.36, 0.49, 0.49)	(Ages 0, 1, 2, 3 and above) = (0.26, 0.36, 0.49, 0.49)

For reference, the results of the HS model when autocorrelation is estimated in two stages are shown in the table below (the results of the RI and BH models with two-stage method are not shown because they form a linear relationship and produce unrealistic proposed reference points).

Appendix Table 3-3. Proposed reference points of HS model (two-stage estimation)

管理基準値案	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	124	0.26	65	0.26	0.31	0.62
限界管理基準値案	SB0.6msy	39	0.08	39	0.13	0.43	1.10
禁漁水準案	SB0.1msy	5.8	0.01	6.5	0.11	0.46	1.23
MSY を実現する 漁獲圧	Fmsy	(0 歳, 1 歳, 2 歳, 3 歳以上) = (0.34, 0.48, 0.65, 0.65)					

管理基準値案	Proposed reference points
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) = (0.34, 0.48, 0.65, 0.65)	(Ages 0, 1, 2, 3 and above) = (0.34, 0.48, 0.65, 0.65)

\* 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

#### **Appendix 4. Evaluation of S-R relationship with simplified MSE**

We evaluated the robustness of the three S-R relationships that are considered as candidate models (RI, BH and weighted average models) against uncertainty, and the influence of wrong selection of the respective S-R relationship (risk of decrease in catch and spawning mass) by using simplified MSE (Punt 2001). For the calculation method of the simplified MSE, see "Comparison of robustness of multiple reference points and examination of HCRs using simplified MSE (FRA-SA2020-BRP01-7)."

Catch calculation procedure of MSE is as follows:

- (1) Stock assessment is made every year.
- (2) Proposed HCRs are formulated and future projection is made based on the S-R relationship chosen for calculation of the spawning biomass that produces MSY, and the average catch after two years is calculated based on the proposed HCRs.
- (3) Fishing is conducted with the catch calculated in (2) under the future projection based on the true S-R relationship.

Combination scenarios of the S-R relationships for MSE are as follows:

- (1) The true S-R relationship is the RI model, while catch calculation is based on the BH model
- (2) The true S-R relationship is the BH model, while catch calculation is based on the RI model
- (3) The true S-R relationship is the RI model, while catch calculation is based on the weighted average model
- (4) The true S-R relationship is the BH model, while catch calculation is based on the weighted average model

Results of using the proposed HCRs with  $\beta$  set to 0.8 for calculation of catch:

Scenario 1 (the true S-R relationship is the RI model, while catch calculation is based on the BH model): the probability of exceeding the proposed target reference point (SBtarget) and the proposed limit reference point (SBlimit) after 10 years is 92% and 100%, respectively, and the catch in 2021 is 6.3 thousand tons, a significant decrease from the catch in 2018 (19 thousand tons) (Appendix Figure 4-1); Scenario 2 (the true S-R relationship is the BH model, while catch calculation is based on the RI model): the probability of exceeding the proposed SBtarget and the proposed SBlimit after 10 years is 24% and 92%, respectively, and the catch in 2021 is 14 thousand tons (Appendix Figure 4-2). Scenario 3 (the true S-R relationship is the RI model, while catch calculation is based on the weighted average model): the probability of exceeding the proposed SBtarget and proposed SBlimit after 10 years is 70% and 99%, respectively, and the catch in 2021 is 11 thousand tons (Appendix Figure 4-3). Scenario 4 (the true S-R relationship is the BH model, while catch calculation is based on the weighted average model): the probability of exceeding the proposed SBtarget and proposed SBlimit after 10 years is 32% and 97%, respectively, and the catch in 2021 is 13 thousand tons (Appendix

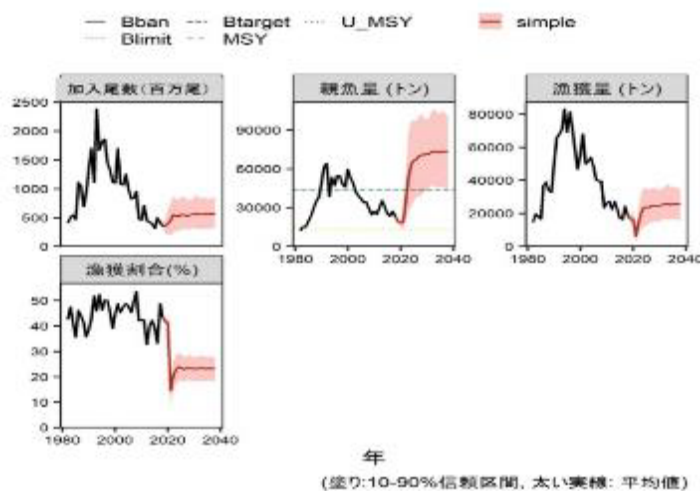
Figure 4-4).

Based on the above, when the harvest is controlled under the proposed HCRs based on the S-R relationship of the weighted average model, the probability of exceeding the proposed target reference point (SB<sub>target</sub>) and the proposed limit reference point (SB<sub>limit</sub>) after 10 years is lower by 22% and 1%, respectively, compared with the scenario where the true S-R relationship is the RI model and catch calculation is based on the BH model, while the risk of drastic reduction of the catch in 2021 is smaller (reduction with catch calculation based on the BH model is larger by 4.7 thousand tons compared with the weighted average model). Similarly, the probability of exceeding the proposed SB<sub>target</sub> and SB<sub>limit</sub> after 10 years is higher by 8% and 5%, respectively, compared with the scenario where the true S-R relationship is the BH model and catch calculation is based on the RI model, while the catch in 2021 is almost the same (reduction with catch calculation based on the weighted average model is 1 thousand tons greater compared with calculation based on the RI model). For the reasons above, we propose as a candidate for this stock the S-R relationship of the weighted average model that shows intermediate values for risk of spawning biomass decrease and does not involve a great reduction in catch compared with selecting either the RI or BH S-R relationship.

The proposed weighted average model assumes that the actual S-R relationship is either the BH or RI model. Therefore, in order to assess the influence when the true S-R relationship is different from the weighted average model, we conducted MSE with varying  $\beta$  values for Scenarios 3 and 4.

The spawning biomass, catch, probability of exceeding the proposed target reference point and probability of exceeding the proposed limit reference point when the catch is calculated with the weighted average model are shown in Appendix Tables 4-1 and 4-2. The year of recovery to the true proposed target reference point with a probability of 50%, when  $\beta$  is set to 0.8, is 2025 (58%) when the true S-R relationship is the RI model. The probability does not reach 50% within 10 years when the true S-R relationship is the BH model (32% in 2031). The probability of recovery to the true proposed target reference point within 10 years is over 50% when  $\beta$  is set to 0.9 (63%) if the true S-R relationship is the RI model, while the probability is over 50% when  $\beta$  is set to 0.6 (54%) if the true S-R relationship is the BH model. For this reason, it is thought that when the weighted average model is chosen for ABC calculation, in order to achieve the (true) proposed target reference point after 10 years with a probability of 50% or higher, it is necessary to lower  $\beta$  to 0.6 if the true relationship is the BH model, but this can be achieved with  $\beta$  set to 0.9 if the true relationship is the RI model.

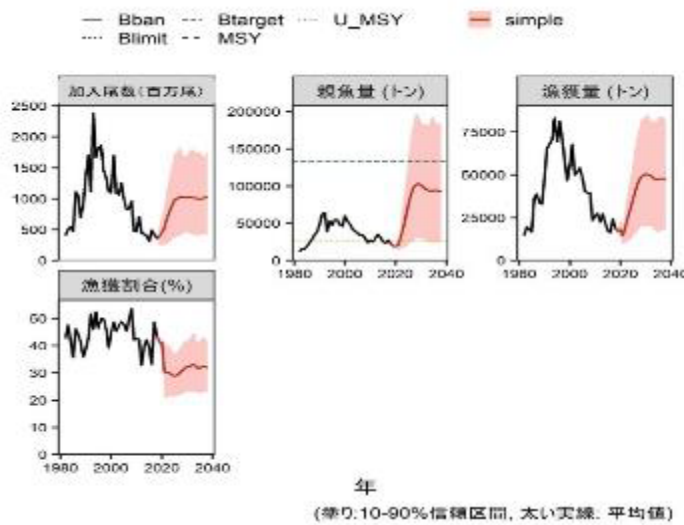
Based on the result above, if the possibility of the BH model being the true S-R relationship is weighed heavily, it is desirable to set  $\beta$  to a value smaller than 0.8.



加入尾数 (百万尾)	Recruitment (million individuals)
親魚量 (トン)	Spawning biomass (tons)
漁獲量 (トン)	Catch (tons)
漁獲割合	Exploitation rate
年	Year
(塗り: 10-90%信頼区間, 太い実線: 平均値)	(Shaded: 10-90% prediction interval; thick solid line: average value)

Appendix Figure 4-1. MSE future projection of Scenario 1 (when the RI model is assumed to be the true S-R relationship and the proposed HCRs of the BH model are used)

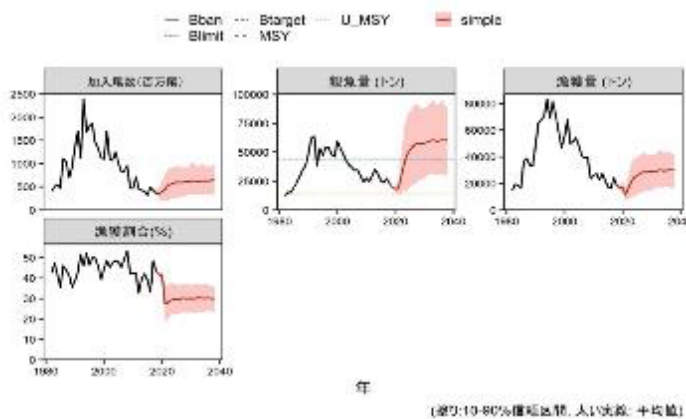
The thick solid lines represent average values. The shaded areas show the 80% prediction intervals that cover 80% of simulation results. The dashed lines in the spawning biomass chart represent the proposed reference points of the RI model (green: proposed target reference point; yellow: proposed limit reference point). The catch in 2019 and 2020 are assumed based on the projected biomass and  $F_{current}$ , while the catch in 2021 and after is based on the proposed HCRs (Figure 5). Safety coefficient  $\beta$  is set to 0.8.



加入尾数 (百万尾)	Recruitment (million individuals)
親魚量 (トン)	Spawning biomass (tons)
漁獲量 (トン)	Catch (tons)
漁獲割合	Exploitation rate (%)
年	Year
(塗り: 10-90%信頼区間, 太い実線: 平均値)	(Shaded: 10-90% prediction interval; thick solid line: average value)

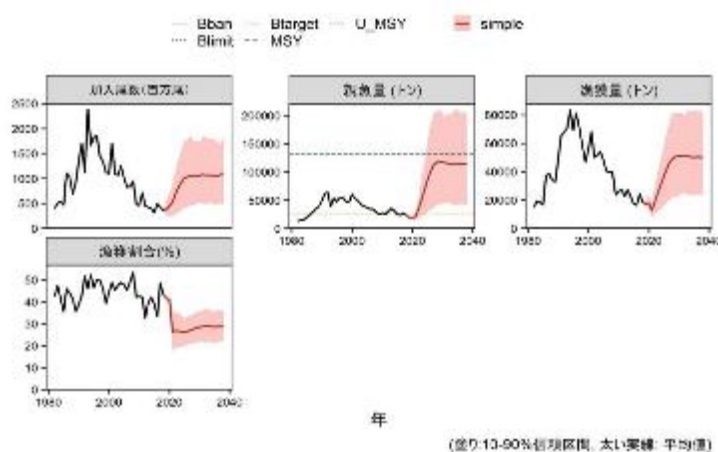
Appendix Figure 4-2. MSE future projection of Scenario 2 (when the BH model is assumed to be the true S-R relationship and the proposed HCRs of the RI model are used)

The thick solid lines represent average values. The shaded areas show the 80% prediction intervals that cover 80% of simulation results. The dashed lines in the spawning biomass chart represent the proposed reference points of the BH model (green: proposed target reference point; yellow: proposed limit reference point). The Catch in 2019 and 2020 are assumed based on the projected biomass and  $F_{current}$ , while the catch in 2021 and after is based on the proposed HCRs (Figure 5). Safety coefficient  $\beta$  is set to 0.8.



加入尾数（百万尾）	Recruitment (million individuals)
親魚量（トン）	Spawning biomass (tons)
漁獲量（トン）	Catch (tons)
漁獲割合	Exploitation rate (%)
年	Year
（塗り：10-90%信頼区間，太い実線：平均値）	(Shaded: 10-90% prediction interval; thick solid line: average value)

Appendix Figure 4-3. MSE future projection of Scenario 3 (when the RI model is assumed to be the true S-R relationship and the proposed HCRs of the weighted average model are used) The thick solid lines represent average values. The shaded areas show the 80% prediction intervals that cover 80% of simulation results. The dashed lines in the spawning biomass chart represent the proposed reference points of the RI model (green: proposed target reference point; yellow: proposed limit reference point). The catch in 2019 and 2020 are assumed based on the projected biomass and  $F_{current}$ , while the catch in 2021 and after is based on the proposed HCRs (Figure 5). Safety coefficient  $\beta$  is set to 0.8.



加入尾数（百万尾）	Recruitment (million individuals)
親魚量（トン）	Spawning biomass (tons)
漁獲量（トン）	Catch (tons)
漁獲割合	Exploitation rate (%)
年	Year
（塗り：10-90%信頼区間，太い実線：平均値）	(Shaded: 10-90% prediction interval; thick solid line: average value)

Appendix Figure 4-4. MSE future projection of Scenario 4 (when the BH model is assumed to be the true S-R relationship and the proposed HCRs of the weighted average model are used) The thick solid lines represent average values. The shaded areas show the 80% prediction intervals that cover 80% of simulation results. The dashed lines in the spawning biomass

chart represent the proposed reference points of the BH model (green: proposed target reference point; yellow: proposed limit reference point). The catch in 2019 and 2020 are assumed based on the projected biomass and  $F_{current}$ , while the catch in 2021 and after is based on the proposed HCRs (Figure 5). Safety coefficient  $\beta$  is set to 0.8.

Appendix Table 4-1. MSE result of Scenario 3 with varying  $\beta$  values (the true S-R relationship is the RI model, while ABC calculation is based on the weighted average model)

The table shows the results of the future projection based on the proposed HCRs (Figure 5) when safety coefficient  $\beta$  is changed from 0.6 to 0.9 in 0.1 intervals. The projection assumes  $F_{current}$  catch for 2019 and 2020 and a catch corresponding to the proposed HCRs for 2021 and after.

(a) Probability for future spawning biomass to exceed the proposed target reference point (%)

$\beta$	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0.9	0	0	0	11	30	41	49	56	59	60	61	64	63
0.8	0	0	0	13	33	49	58	63	68	68	70	70	70
0.7	0	0	0	16	37	56	66	71	74	76	77	78	77
0.6	0	0	0	17	45	67	75	79	82	85	86	87	87

(b) Probability for future spawning biomass to exceed the proposed limit reference point (%)

$\beta$	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0.9	100	100	87	90	92	92	94	95	95	97	97	97	98
0.8	100	100	87	92	94	95	97	97	98	97	98	99	99
0.7	100	100	87	95	97	97	98	98	98	99	99	99	100
0.6	100	100	87	97	98	99	99	99	99	100	100	100	100

(c) Future spawning biomass (thousand tons)

$\beta$	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0.9	19	18	19	28	37	44	47	50	52	52	52	53	54
0.8	19	18	19	29	40	48	52	55	57	57	57	58	59
0.7	19	18	19	30	44	53	57	60	62	62	62	63	64
0.6	19	18	19	32	47	59	63	65	67	67	68	68	69

(d) Future catch (thousand tons)

$\beta$	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0.9	17	17	13	17	22	25	26	28	29	29	29	30	30
0.8	17	17	11	16	21	24	26	27	28	28	28	29	29
0.7	17	17	10	15	21	24	25	26	27	27	27	28	28
0.6	17	17	9	14	19	23	24	25	25	25	26	26	26

Appendix Table 4-2. MSE result of Scenario 4 with varying  $\beta$  values (the true S-R relationship is the BH model, while ABC calculation is based on the weighted average model)

The table shows the results of the future projection based on the proposed HCRs (Figure 5) when safety coefficient  $\beta$  is changed from 0.6 to 0.9 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.

(a) Probability for future spawning biomass to exceed the proposed target reference point (%)

$\beta$	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0.9	0	0	0	0	2	7	12	20	24	25	25	26	24
0.8	0	0	0	0	2	7	15	24	29	33	33	31	32
0.7	0	0	0	0	2	9	20	30	37	41	41	40	42
0.6	0	0	0	0	4	13	26	39	49	50	52	54	54

(b) Probability for future spawning biomass to exceed the proposed limit reference point (%)

$\beta$	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0.9	0	1	14	57	74	83	87	91	92	93	94	96	95
0.8	0	1	14	62	81	88	91	94	96	97	97	98	97
0.7	0	1	14	65	88	91	95	96	98	98	99	99	99
0.6	0	1	14	70	90	95	98	98	98	99	100	100	100

(c) Future spawning biomass (thousand tons)

$\beta$	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0.9	19	19	21	32	46	62	76	89	99	103	104	103	101
0.8	19	19	21	34	50	68	85	101	112	117	118	118	116
0.7	19	19	21	35	54	75	96	114	127	133	135	135	133
0.6	19	19	21	37	59	84	108	128	143	151	154	155	154

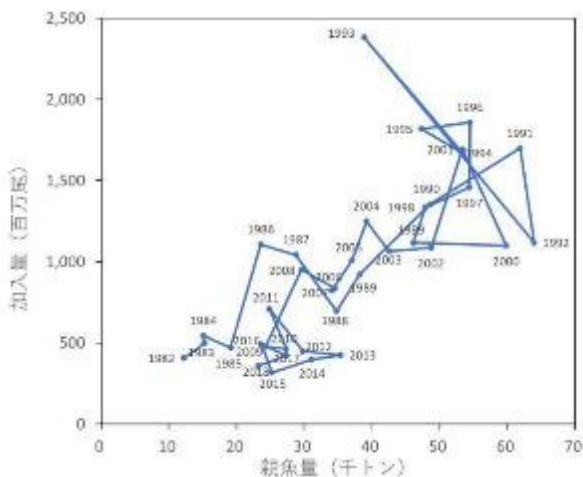
(d) Future catch (thousand tons)

$\beta$	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0.9	17	18	14	20	26	31	37	42	47	49	50	50	50
0.8	17	18	13	19	25	31	37	42	47	49	51	51	51
0.7	17	18	11	18	24	30	36	42	47	49	51	51	51
0.6	17	18	10	16	22	29	35	40	45	48	50	51	51

**Appendix 5. Recruitment residuals in future projection**

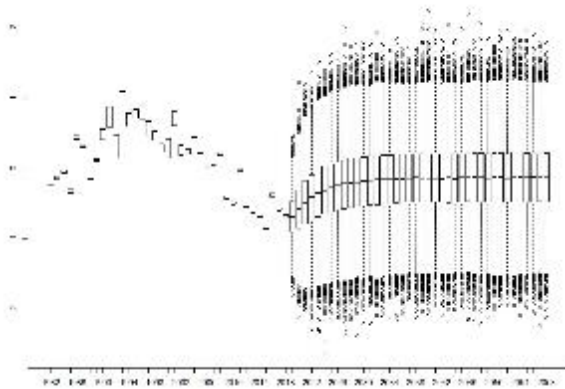
This stock has been experiencing low-abundance recruitment since 2009 (Appendix Figure 5-1). Because its S-R relationship has a tendency that residuals of the recruitment observation values (stock assessment values) against the predicted values lean to the negative side (Figure 1), it is assumed that low-abundance recruitment to the spawning biomass is continuing.

Residuals of recruitment in the future projection of the weighted average model are shown in Appendix Figure 5-2. This S-R relationship is the result of weighted averaging of the BH and RI models with high autocorrelation coefficient according to the ratio of Akaike weight. The trend of the recruitment residuals indicates the negative trend of recruitment residuals for three to four years after starting the future projection. For this reason, it is thought that residuals for three to four years after starting the future projection reflect the recent low-abundance recruitment.



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

Appendix Figure 5-1. Relationship between spawning biomass and recruitment in the 2019 stock assessment



Appendix Figure 5-2. Recruitment residuals in the future projection of the weighted average model

## Appendix 6. Future projection of the low-recruitment scenario

In the S-R relationship of this stock, there has been a tendency that the residuals of observation values against the projected values of recruitment lean to the negative side in recent years. This may indicate continuing low-level recruitment to the spawning biomass. For this reason, we examined two scenarios that assume continuing low-level recruitment in the future and made future projection accordingly. Following the 2019 stock assessment that used RPS of the past five years excluding the latest year (2013-2017) for the future projection scenarios, we decided to conduct resampling of the recruitment residuals for the period of 2013-2017. Our assumptions are as follows:

[Scenario 1] Recruitment will gradually increase after five years of continued low recruitment

[Scenario 2] Low recruitment will continue in the future

[Scenario 1] Recruitment will gradually increase after five years of continued low recruitment

Recruitment in the future projection is given by random resampling of the residuals between the values predicted based on the S-R relationship and the past observation values. We conducted this random resampling of residuals as follows by retrospectively dividing periods (backward resampling; Appendix Figure 6-1)

(1) The 1st to the 5th years of the future projection: resampling allowing duplication from the residuals of the stock assessment of the latest five years (2013-2017)

(2) The 6th to the 10th years of the future projection: resampling allowing duplication from either the residuals of the stock assessment of the latest five years (2013-2017) or the residuals of the five years before 2013 (2008-2012)

(3) The 11th year of the future projection and after: add a further five years to the resampling option following the procedure above

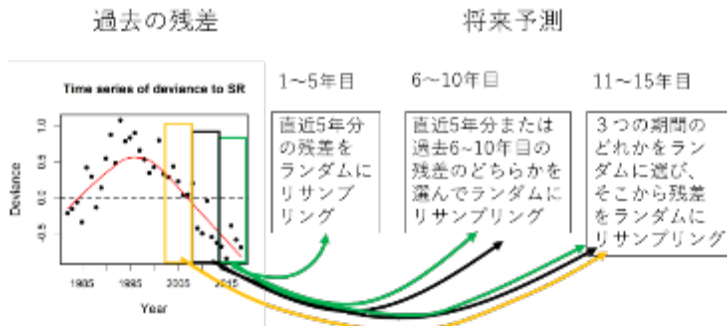
Future projection result of Scenario 1 when  $\beta$  is set to 0.8 is shown in Appendix Figure 6-2. The probability of exceeding the proposed target reference point in 2031 is 22%, and catch is 24 tons (Appendix Table 6-1).

[Scenario 2] Low recruitment will continue in the future

We continued to give recruitment of the future projection through resampling of the recruitment residuals in the period of 2013-2017. The results of the future projection of Scenario 2 when  $\beta$  is set to 0.8 are shown in Appendix Figure 6-3. The probability of exceeding the proposed target reference point in 2031 is 0%, and the catch is 21 tons (Appendix Table 6-2).

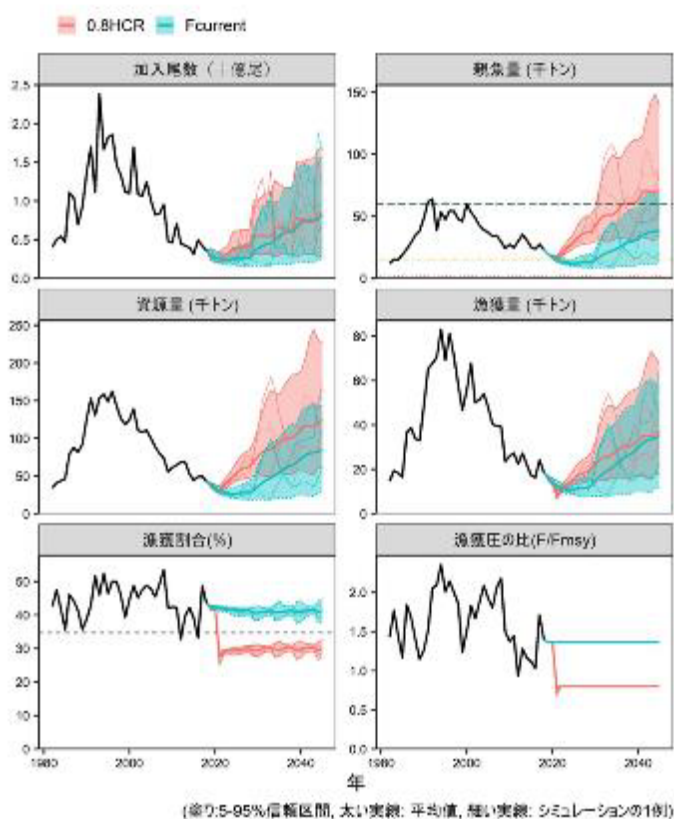
In conventional future projection (when average recruitment continues, namely neither backward resampling nor residual resampling is conducted) with  $\beta$  set to 0.8, the probability of exceeding the proposed target reference point in 2031 is 57%, and the catch is 36 thousand tons. (Figure 6, Tables 4 and 6) The result suggests that, if the low-level recruitment of the two

scenarios above continues, it will take many years for spawning biomass to recover to the proposed target reference point and the catch will remain low for a long period of time compared with the scenario where average recruitment continues.



過去の残差	Past residuals
将来予測	Future projection
1~5年目	The 1st to the 5th year
直近5年分の残差をランダムにリサンプリング	Random resampling of the residuals of the latest five years
6~10年目	The 6th to the 10th year
直近5年分または過去6~10年目の残差のどちらかを選んでランダムにリサンプリング	Random resampling of residuals of the latest five years or of the five years prior
11~15年目	The 11th to 15th year
3つの期間のどれかをランダムに選び、そこから残差をランダムにリサンプリング	Random resampling from the residuals of a randomly selected period among the three periods

Appendix Figure 6-1. Conceptual diagram of backward resampling

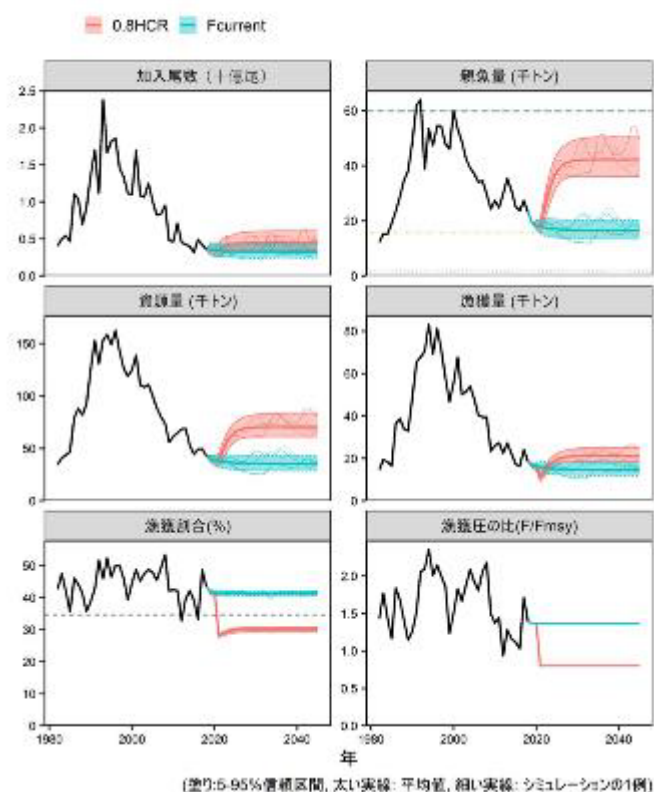


加入尾数 (十億尾)	Recruitment (billion individuals)
資源量 (千トン)	Stock biomass (thousand tons)
漁獲割合	Exploitation rate (%)
親魚量 (千トン)	Spawning biomass (thousand tons)
漁獲量 (千トン)	Catch (thousand tons)
漁獲圧の比	Ratio of the fishing mortality
年	Year
(塗り: 5-95%信頼区間, 太い実線: 平均値, 細い実線: シミュレーションの1例)	(Shaded: 5-95% prediction interval; thick solid line: average value; thin solid line: simulation example)

Appendix Figure 6-2. Comparison of the future projection using the proposed HCRs (in red) with the future projection when fishing is continued with the current fishing mortality (in green) in Scenario 1

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 figure 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 figure of exploitation rate shows  $U_{msy}$ . The catch in 2019 and 2020 are assumed based on the projected stock biomass and  $F_{current}$ , while the catch in 2021 and after is based on the proposed HCRs (Figure 5). Safety coefficient  $\beta$  is set to 0.8



加入尾数 (十億尾)	Recruitment (billion 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
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% prediction interval; thick solid line: average value; thin solid line: simulation example)

Appendix Figure 6-3. Comparison of the future projection using the proposed HCRs (in red) with the future projection when fishing is continued with the current fishing mortality (in green) in Scenario 2

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 figure 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 figure of exploitation rate shows Umsy. The catch in 2019 and 2020 are assumed based on the projected stock biomass and Fcurrent, while the catch in 2021 and after is based on the proposed HCRs (Figure 5). Safety coefficient  $\beta$  is set to 0.8

Appendix Table 6-1. Result of the future projection of Scenario 1 (recruitment will gradually increase after five years of continued low recruitment) with varying  $\beta$  values

The table shows the results of the future projection based on the proposed HCRs (Figure 5) when safety coefficient  $\beta$  is changed from 0.5 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.

(a) Probability for future spawning biomass to exceed the proposed target reference point (%)

$\beta$	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2041	2051
1.0	0	0	0	0	0	0	0	0	0	0	0	0	2	38	46
0.9	0	0	0	0	0	0	0	0	0	0	0	1	10	51	57
0.8	0	0	0	0	0	0	0	0	1	1	3	22	62	67	
0.7	0	0	0	0	0	0	0	0	2	4	6	12	36	67	73
0.6	0	0	0	0	0	0	0	4	10	13	16	27	46	72	80
0.5	0	0	0	0	0	0	2	17	31	35	35	48	58	78	87
0.4	0	0	0	0	0	0	16	43	54	54	51	65	67	86	94
0.3	0	0	0	0	0	7	54	83	86	83	81	88	88	96	98
0.2	0	0	0	0	0	35	94	100	100	99	99	100	100	100	100
0.1	0	0	0	0	2	81	100	100	100	100	100	100	100	100	100
0.0	0	0	0	0	11	99	100	100	100	100	100	100	100	100	100

(b) Probability for future spawning biomass to exceed the proposed limit reference point (%)

$\beta$	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2041	2051
1.0	100	100	42	95	99	100	100	100	100	100	100	100	100	100	100
0.9	100	100	42	100	100	100	100	100	100	100	100	100	100	100	100
0.8	100	100	42	100	100	100	100	100	100	100	100	100	100	100	100
0.7	100	100	42	100	100	100	100	100	100	100	100	100	100	100	100
0.6	100	100	42	100	100	100	100	100	100	100	100	100	100	100	100
0.5	100	100	42	100	100	100	100	100	100	100	100	100	100	100	100
0.4	100	100	42	100	100	100	100	100	100	100	100	100	100	100	100
0.3	100	100	42	100	100	100	100	100	100	100	100	100	100	100	100
0.2	100	100	42	100	100	100	100	100	100	100	100	100	100	100	100
0.1	100	100	42	100	100	100	100	100	100	100	100	100	100	100	100
0.0	100	100	42	100	100	100	100	100	100	100	100	100	100	100	100

(c) Future spawning biomass (thousand tons)

$\beta$	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2041	2051
1.0	19	17	15	18	19	20	22	24	26	27	27	30	35	55	61
0.9	19	17	15	19	21	23	26	28	30	32	32	36	41	62	68
0.8	19	17	15	20	23	26	30	33	36	37	38	42	47	69	75
0.7	19	17	15	21	26	30	35	39	42	43	44	48	54	77	84
0.6	19	17	15	22	28	34	40	45	49	50	51	55	61	86	94
0.5	19	17	15	23	31	39	46	52	56	58	58	62	70	96	106
0.4	19	17	15	24	35	45	53	61	65	66	67	71	79	108	119
0.3	19	17	15	26	38	51	62	70	74	76	76	81	90	122	134
0.2	19	17	15	27	43	58	71	80	85	87	87	92	102	138	153
0.1	19	17	15	29	47	66	82	93	98	100	100	106	117	157	176
0	19	17	15	31	52	76	95	107	113	115	116	122	135	182	207

(d) Future catch (thousand tons)

$\beta$	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2041	2051
1.0	16	14	10	12	13	14	15	16	17	17	19	21	23	35	38
0.9	16	14	9	11	13	14	15	17	18	18	20	22	24	35	38
0.8	16	14	8	11	13	14	16	17	18	19	20	22	24	35	38
0.7	16	14	8	10	12	14	16	18	19	19	20	22	24	34	37
0.6	16	14	7	9	12	14	16	18	19	19	20	22	24	33	35
0.5	16	14	6	9	11	13	15	17	18	18	19	21	22	30	33
0.4	16	14	5	7	10	12	14	16	16	17	18	19	20	27	30
0.3	16	14	4	6	8	11	12	14	14	15	15	16	17	23	26
0.2	16	14	2	4	6	8	10	11	11	11	12	12	13	18	20
0.1	16	14	1	2	3	5	6	6	6	7	7	7	8	10	12
0	16	14	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix Table 6-2. Result of the future projection of Scenario 2 (low recruitment will continue) with varying  $\beta$  values

The table shows the results of the future projection based on the proposed HCRs (Figure 5) when safety coefficient  $\beta$  is changed from 0.5 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.

(a) Probability for future spawning biomass to exceed the proposed target reference point (%)

$\beta$	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2041	2051
1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.7	0	0	0	0	0	0	0	0	1	2	3	4	4	5	5
0.6	0	0	0	0	0	0	2	8	14	18	21	23	23	25	25
0.5	0	0	0	0	0	3	26	44	45	42	41	43	43	42	42
0.4	0	0	0	0	0	29	82	89	85	79	77	79	80	80	80
0.3	0	0	0	0	2	79	100	100	100	99	99	99	99	99	99
0.2	0	0	0	0	17	99	100	100	100	100	100	100	100	100	100
0.1	0	0	0	0	49	100	100	100	100	100	100	100	100	100	100
0.0	0	0	0	0	85	100	100	100	100	100	100	100	100	100	100

(b) Probability for future spawning biomass to exceed the proposed limit reference point (%)

$\beta$	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2041	2051
1.0	100	100	96	100	100	100	100	100	100	100	100	100	100	100	100
0.9	100	100	96	100	100	100	100	100	100	100	100	100	100	100	100
0.8	100	100	96	100	100	100	100	100	100	100	100	100	100	100	100
0.7	100	100	96	100	100	100	100	100	100	100	100	100	100	100	100
0.6	100	100	96	100	100	100	100	100	100	100	100	100	100	100	100
0.5	100	100	96	100	100	100	100	100	100	100	100	100	100	100	100
0.4	100	100	96	100	100	100	100	100	100	100	100	100	100	100	100
0.3	100	100	96	100	100	100	100	100	100	100	100	100	100	100	100
0.2	100	100	96	100	100	100	100	100	100	100	100	100	100	100	100
0.1	100	100	96	100	100	100	100	100	100	100	100	100	100	100	100
0.0	100	100	96	100	100	100	100	100	100	100	100	100	100	100	100

(c) Future spawning biomass (thousand tons)

$\beta$	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2041	2051
1.0	19	18	18	22	25	27	29	30	31	31	31	31	32	32	32
0.9	19	18	18	23	27	31	33	35	36	36	36	36	37	37	37
0.8	19	18	18	24	30	35	38	40	41	41	42	42	42	42	42
0.7	19	18	18	25	33	39	44	46	47	47	48	48	48	48	48
0.6	19	18	18	27	36	44	50	52	54	54	54	55	55	55	55
0.5	19	18	18	29	40	50	57	60	61	61	62	62	63	63	63
0.4	19	18	18	30	44	57	65	68	69	70	70	71	71	72	72
0.3	19	18	18	32	49	65	74	78	79	79	80	81	82	82	82
0.2	19	18	18	34	54	73	85	89	89	90	91	93	94	94	94
0.1	19	18	18	36	60	83	98	102	102	102	104	107	109	109	110
0	19	18	18	38	67	95	113	118	117	117	120	124	127	128	129

(d) Future catch (thousand tons)

$\beta$	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2041	2051
1.0	17	16	13	15	16	18	19	19	19	20	20	20	20	20	20
0.9	17	16	12	14	16	18	19	20	20	20	21	21	21	21	21
0.8	17	16	11	14	16	18	20	20	21	21	21	21	21	21	21
0.7	17	16	10	13	16	18	20	20	21	21	21	21	21	21	21
0.6	17	16	8	12	15	18	19	20	20	20	21	21	21	21	21
0.5	17	16	7	11	14	17	18	19	19	19	20	20	20	20	20
0.4	17	16	6	9	13	15	17	17	18	18	18	18	18	18	18
0.3	17	16	5	7	10	13	14	15	15	15	15	16	16	16	16
0.2	17	16	3	5	8	10	11	11	12	12	12	12	12	12	12
0.1	17	16	2	3	4	6	6	7	7	7	7	7	7	7	7
0	17	16	0	0	0	0	0	0	0	0	0	0	0	0	0