Material for the Research Institute Meeting on Reference Points of Japanese Sardine 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. Because the S-R relationship of this stock has potentially undergone a great change with the ocean environment and other elements, we excluded the high recruitment period (1976-1987), chose as a candidate the S-R relationship of the normal recruitment period (1988-2018) that is considered to reflect the recent recruitment status and applied the hockey stick (HS) model to the information of the spawning biomass and recruitment which are estimated in the stock assessment. We used the least squares method for estimation of parameters of the S-R relationship without considering autocorrelation of recruitment residuals. As the target reference point, we propose SBmsy (1.097 million tons), which is the spawning biomass that produces the maximum sustainable yield (MSY) as calculated based on the S-R relationship. We propose SB0.6msy (47 thousand tons), which is the spawning biomass that produces 60% of MSY as the limit reference point, and SB0.1msy (66 thousand tons), which produces 10% of MSY as the fishing ban level. Fishing mortality that produces MSY (Fmsy) is 0.99 times the current fishing mortality (average fishing mortality during the period from 2014 to 2018).

Spawning biomass (thousand tons)	Ratio to the current spawning biomass (2018)	Ratio to the initial spawning biomass (2.885 million tons)	Expected average catch (thousand tons)	*Ratio to the current fishing mortality (2014-2018)*	Explanation
Proposed target reference point					
1,097	0.67	0.38	368	0.99	Spawning biomass that produces MSY (SBmsy)
Proposed limit reference point					
471	0.29	0.16	221	1.43	Spawning biomass that produces 60% of MSY (SB0.6msy)
Proposed fishing ban level					
66	0.04	0.02	37	1.73	Spawning biomass that produces 10% of MSY (SB0.1msy)
2018					
1,629	1.00	0.56	451**	-	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 at age under the current fishing mortality

**Actual catch in 2018

1. Stock-recruitment relationship

1-1) Data set to be used

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

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

1-2) Examination of S-R relationship

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 chose the least squares method and the least absolute value method as a candidate for optimization. We also compared a model with consideration of residual autocorrelation and a model without such consideration. To enable comparison with a model that assumes different S-R relationships depending on the period as described later, we used the simultaneous estimation method (autocorrelation parameter is incorporated into the model for simultaneous estimation of the S-R relationship and autocorrelation parameters) (for details, see "Model Diagnostics in Estimation of Stock-recruitment Relationship: FRA-SA2020-BRP01-5"). As data, we used the recruitment and spawning biomass for the whole period from 1976 to 2018, which were estimated in the stock assessment. Information of 2018 is also used to include the latest information. Because the small-sample-size-corrected version of Akaike information criterion (AICc) is lower in the model that is not based on the S-R relationship and that considers autocorrelation in residuals (Appendix Table 1-1), the model was a candidate for examination of the S-R relationship. Candidates for examination of the S-R relationship are shown in Table 1.

The biomass of Japanese sardine Pacific stock is known to change dramatically in synchronization with the interdecadal global shift in the structure of systems including the atmospheric system and marine ecosystems (regime shift) (Kawasaki 1992, Klyashtorin 1998, Chavez et al. 2003). The biomass increased synchronously with the 1976/77 regime shift (Yasunaka and Hanawa 2002), and then remained high at over 10 million tons in the 1980s.

After that, the recruitment per spawning successively declined from 1988 to 1991 in synchronization with the 1988/89 regime shift (Watanabe et al. 1995), resulting in a sharp decline in recruitment and biomass. The changes in the ocean environment and other elements are likely to have affected the environmental carrying capacity and recruitment success (Tanaka 2003, Yatsu et al. 2005), and have also changed the S-R relationship. Autocorrelation is found in recruitment residuals when the same S-R relationship is applied to the data of the whole period. This can be attributed to the varying S-R relationships depending on the period. For this reason, assuming that the S-R relationship can be divided into two types – the type of the normal recruitment period (1988-2018) and the type of the high recruitment period (1976-1987) based on the recruitment level during the period from 1976 to 2018, we considered models for all S-R types (Appendix 1; See also "Model Diagnostics in estimation of S-R relationship (FRA-SA2020-BRP01-5)). Autocorrelation is not considered when the S-R relationship is divided into two types. The timing of the switch of the S-R relationship is determined based on AICc by reference to past literature (Yatsu et al. 2005; Takahashi et al. 2009 and; Kurota et al. 2020). Candidates for examination of the S-R relationship divided into two types are shown in Table 1.

1-3) S-R relationship

Regardless of the model of the S-R relationship, the small-sample-size-corrected version of AICc is lower when the S-R relationship divided into two types compared with the models where the same relationship is applied to the data of the whole period. When the S-R relationship divided into two types, AICc estimated with the least absolute value method is lower. However, because parameter estimation is unstable with this method and the estimated parameters have no significant difference with the parameters estimated using the least squares method, the least squares method was chosen as a recommendation candidate for the estimation method. When the least squares method is used, the model that assumes an HS S-R relationship has the smallest AICc. For this reason, as the S-R relationship of this stock we apply the HS S-R relationship based on the least squares method when the S-R relationship is divided into normal and high recruitment periods. This stock has been continuing favorable recruitment in recent years and can be moving into a high recruitment period. However, because this cannot be clearly determined yet, we use the S-R relationship estimated for the normal recruitment period including 2018 (1988-2018) for calculation of the spawning biomass that produces MSY (SBmsy) and future projection.

Estimates of the parameters of the S-R relationship are shown in Appendix 1 (Appendix Table 1-2) 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.; Appendix Table 1-2) 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)").

Because it is deemed that a high abundance period is a short-term phenomenon under specific environmental conditions and not sustainable (Ito 1961 and 1991), we considered it is adequate to use the S-R relationship of the normal recruitment period rather than the high recruitment period for calculation of long-term SBmsy. As reference, we show also the results of the HS-model S-R relationship where the data of the whole period is used (least squares method, simultaneous estimation for autocorrelation) (Appendix 2).

Compared with the model where the S-R relationship is applied to the data of the whole period, the fishing mortality that produces MSY based on the S-R relationship of the normal recruitment period is slightly optimistic (Table 3 and Appendix Table 2-1). For this reason, the use of the S-R relationship of the normal recruitment period could have a risk of over-prediction of catch and biomass depletion in the case where the actual S-R relationship is not clearly divided but uniform throughout the periods. Therefore, we assessed the risk of biomass depletion by applying the S-R relationship of the normal recruitment period by conducting simplified Management Strategy Evaluation (MSE) for the model that assumes the S-R relationship of the normal recruitment while the real S-R relationship is one relationship to be applied to the data of the whole period (Appendix 3; for details of MSE, see "Comparison of robustness of multiple reference points and examination of HCRs using simplified MSE (FRA-SA2020-BRP01-7)"). As a result of simplified MSE, when safety coefficient β is 0.5 and under, the probability of exceeding the true (one S-R relationship to be applied to the data of the whole period) limit reference point after 10 years was over 90%. Judging from AICc, etc. the model that divides the S-R relationship into two types is considered to be more plausible, but we cannot dismiss the possibility of one S-R relationship throughout the whole period. For this reason it is thought that we should not raise β unduly from the standard value. We can reduce the risk of biomass depletion by lowering β toward 0.5.

On the other hand, the application of the S-R relationship of the normal recruitment period poses a risk of losing fishing opportunity if the stock is actually in a high-recruitment period. In order to assess this risk, we conducted simplified MSE for control assuming the S-R relationship of the normal recruitment period when recruitment changed due to the S-R relationship of the high recruitment period (Appendix 4). The result indicates that the catch is smaller compared with the model correctly applying the S-R relationship of the high recruitment period, and that the closer β is to 1, the smaller is the decrease of catch. We also made a comparison with the past high-recruitment period for reference: it is predicted that when β is 0.7 or higher, the average catch in 2021 and after is higher than the catch of the past high-recruitment period (1976 and after).

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 for one-stock biomass of the "2020 Basic Guidelines for the Harvest Control Rules and the Estimation of the Allowable Biological Catch (ABC) (FRA-SA2020-ABCWG01-01)" and using the S-R relationship presented in 1-3) above and the settings used for future projection in the Marine fisheries stock assessment and evaluation for Japanese waters (fiscal year 2019/2020; Fisheries Agency of Japan and FRA). Namely, we used for conditioning of simulation: the HS model S-R relationship of the normal recruitment period based on the recruitment and spawning biomass from 1976 to 2018 as estimated by the stock assessment; natural mortality; maturity rate; average body weight at age, and; selectivity of fishing. Here, the current fishing mortality (Fcurrent, Figure 2) is the average of fishing mortality (F) during the period from 2014 to 2018 (Table 2). For this stock, assuming equilibrium after the simulation years that are 20 times as long as the average generation time (3.66 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.

2-2) Proposed reference points and fishing ban level

We propose: SBmsy (1.097 million tons), which is the spawning biomass that produces the MSY under the normal S-R relationship for the target reference point; SB0.6msy (471 thousand tons), which is the spawning biomass that produces 60% of MSY for the limit reference point; and SB0.1msy (66 thousand tons), which produces 10% of MSY for the fishing ban level. The ratios of the proposed reference points and fishing ban level to the initial spawning biomass assuming no catch (SB0), the average catch at equilibrium under the corresponding fishing mortality and the ratio of the corresponding fishing mortality to the current fishing mortality are shown in Table 3. SBmsy, which is proposed as the target reference point is equivalent to 38% of SB0 and the average catch expected with this spawning biomass (MSY) is 368 thousand tons. The ratio of the fishing mortality corresponding to the proposed target reference point (fishing mortality that produces MSY: Fmsy) to the current (2014-2018) fishing mortality (Fmsy/Fcurrent) is 0.99 and the exploitation rate (Umsy) in this case is 21%. SB0.6msy, which is proposed as the limit reference point corresponds to 16% of SB0 and the average catch expected at this spawning biomass is 221 thousand tons. The ratio of the fishing mortality corresponding to SB0.6msy to the current fishing mortality is 1.43 and the exploitation rate is 27% in this case. SB0.1msy proposed as the fishing ban level corresponds to 2% of SB0 and the average catch expected with this spawning biomass is 37 thousand tons. Ratio of the fishing mortality corresponding to SB0.1msy to the current fishing mortality is 1.73 and the exploitation rate is 30% in this case. Average spawning biomass at equilibrium when F is changed variously and the corresponding average catch at age are shown in Figure 3.

We assumed constant body weight at age when calculating SBmsy. However, because it is reported that growth speed and body fatness of this stock change according to the stock status (Wada and Kashiwai 1991; Kawabata et al. 2011), body weight at age can change according to the stock status. For this reason, we considered the influence on SBmsy from changes in body weight at age according to the stock status (Appendix 5). When we changed body weight at age according to the stock status, SBmsy and MSY became slightly lower compared with the calculation when body weight is fixed, but there is no significant change.

2-3) Proposed target reference point and exploitation rate

The proposed target reference point (SBtarget) and Kobe plot that is based on the fishing mortality (Fmsy) or exploitation rate (Umsy) corresponding to the proposal are shown in Figure

4. Fishing mortality of this stock greatly exceeded the MSY level in 1990s and 2000s but decreased in the 2010s and has remained at the level of MSY. A similar trend is found in calculation based on the exploitation rate. The current spawning biomass (1.629 million tons in 2018) is over the proposed target reference point. The ratios of the proposed target reference point, the proposed limit reference point and the proposed fishing ban level to the current spawning biomass is 0.67, 0.29 and 0.04, respectively.

2-4) Proposed harvest control rule

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

2-5) Future projection based on the proposed HCRs

(1) When Safety Coefficient β 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 uses standard values for the proposed limit reference point and proposed fishing ban level, and sets β to 0.8 (Figure 5) are shown in Figure 6. This future projection assumes that fishing based on the proposed HCRs starts in 2021 and catch of 2019 and 2020 are assumed based on the predicted biomass and Fcurrent.

Because predicted spawning biomass in 2021 is above the proposed target reference point, fishing will start with βFmsy according to the proposed HCRs. When β is 0.8, the fishing mortality at 0.8Fmsy is about 80% of the current fishing effort. In medium- to long-term, it is projected that continued fishing at 0.8 Fmsy will keep catch and spawning biomass at the MSY level.

(2) When safety coefficient β is changed

In the future projection based on the proposed HCRs that uses 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, and changes in the average spawning biomass and average catch when β is changed between 0.0 and 1.0 are shown in Table 4 to 7.

This stock exceeded the proposed target reference point in 2018. When 0.8, which is the standard value, is used, it is predicted that the stock will also exceed the proposed target reference point with a probability of 65% in 2031, 10 years after starting fishing based on the proposed HCRs (Table 4). When β is set to 0.9 or lower, it is predicted that spawning biomass will be maintained over the proposed target reference point with a probability of over 50% in 2031. When β is 1, on the other hand, the probability for spawning biomass to exceed the proposed target reference point in 2031 is below 50%, while the probability of its exceeding the proposed limit reference point is 99% (Table 5). In 2022 and after, the lower β is, the larger future spawning biomass will be (Table 6). When β is 0.6 or larger, the catch in 2021 is larger than the current level (451 thousand tons in 2018) (Table 7).

3. Summary

AICc of the S-R relationship model of this stock is lower when different S-R relationships are used for the normal recruitment period and the high recruitment period, compared with applying the same relationship to the data of the whole period. Among the former, the model that assumes the HS S-R relationship has the smallest AICc. For this reason, we apply the HS S-R relationship to the S-R relationship of this stock based on the least squares method when different S-R relationships are used depending on the period. We determined the normal recruitment period including 2018 (1988-2018) to be the present state and used the S-R relationship estimated in the normal recruitment period for calculation of spawning biomass that produces MSY (SBmsy) and future projection.

We presented SBmsy estimated from the S-R relationship as the target reference point and SB0.6msy and SB0.1msy as the proposed limit reference point and proposed fishing ban level, respectively.

The current spawning biomass of this stock is over the proposed target reference point. Its fishing mortality and exploitation rate decreased in the 2010s and are currently at a similar level with or lower than Fmsy and Umsy. In the future projection based on this proposed target reference point, when β is 0.9 or lower, the probability of exceeding the proposed target reference point can be maintained at 50% or higher 10 years after applying the HCRs (Table 8). Considering the possible loss of fishing opportunity in the case where this stock moves to a high recruitment period, it is thought to be better to avoid adopting an unduly small value for β. However, considering that we cannot dismiss the possibility of the S-R relationship having no clear difference depending on the period but almost the same throughout the whole period, we cannot recommend β higher than 0.8, which is the standard value. For the reasons above, it is desirable to set β to 0.8, which is the standard value.

4. Future considerations

We applied a model that assumes different S-R relationships for the high recruitment period (1976-1987) and the normal recruitment period (1988-2018) and applied the S-R relationship of the normal recruitment period that is thought to reflect the present state. However, as this stock has been experiencing relatively good recruitment in recent years, there is a possibility of its moving to a high recruitment period. Because a method to determine the regime of current recruitment has not been established, and it is difficult to predict a regime, we think at present it is appropriate to use the S-R relationship of the normal recruitment period. With advancement of study on determination and prediction of the regime in the future, it is expected that we will be able to adequately use the S-R relationships of normal and high recruitment periods for future prediction suitable to the actual situation.

It is reported that biological characterization of this stock including growth speed and body fatness changes according to the stock status (Wada and Kashiwai 1991, Kawabata et al. 2011). It is necessary to continue study on whether changes in the biological characterization should be incorporated into the calculation of spawning biomass that produces MSY and future projection, and what relationship to assume if the changes are to be incorporated.

This stock showed continued decline in recruitment per spawning from 1988 to 1991 (Watanabe et al. 1995), which was accompanied with a drastic fall in recruitment and biomass. It is pointed out that the high fishing mortality due to failure to reduce fishing effort at the time caused a shift to an extremely low level of biomass and catch in 2000s (Yatsu and Kaeriyama 2005). There is a considerable probability of decline in recruitment per spawning for several consecutive years. Against this possibility, it is necessary to study whether it is possible to take measures to mitigate the sharp decline in biomass and catch, and, if possible, the conditions under which such measures should be taken.

5. References

ABCWG (2020) Technical Note on Estimation of stock-recruitment relationship, reference point calculation and future prediction simulation (2020 Research Institute Meeting Version). FRA-SA2020-ABCWG01-02.

Chavez, F.P., J. Ryan, S.E. Lluch-Cota, C.M. Niquen (2003) From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science 299, 217–221.

Ichinokawa M. (2020) Kani teki MSE wo mochiita fukusuu no kanri kijunchi no gankensei no hikaku / HCR no kentou (Comparison of robustness of multiple reference points using simplified MSE and study of HCRs). FRA-SA2020-BRP01-7.

Ito S. (1961) Nihon kinkai ni okeru maiwashi no gyogyo seibutsugakuteki kenkyu (Fishery biological study on Japanese sardines in waters near Japan). JSNFRI annual report, (9), 1-227.

Ito S. (1991) Nihon no maiwashi: sono seikatsu to shigen (Japanese sardines in Japan: life and stock). "Gyoyu to maiwashi" (Fish oil and Japanese sardines) S. Matsushita ed., Kouseisha, Tokyo, 191-255.

Kawabata, A., H. Yamaguchi, S. Kubota and M. Nakagami (2011) Growth and fatness of 1975-2002 year classes of Japanese sardine in the Pacific waters around northern Japan. Fish. Sci., 77, 291-299.

Kawasaki, T. (1992) Climate-dependent fluctuations in far eastern sardine population and their impacts on fisheries and society. In: Climate variability, climate change and fisheries, ed. Glantz, M.H., Cambridge University press, Cambridge, pp. 325-354.

Klyashtorin, L. B. (1998) Long-term climate change and main commercial fish production in the Atlantic and Pacific. Fish. Res., 37, 115-125.

Japan Fisheries Research and Education Agency (2020) 2020 Basic Guidelines for the Harvest Control Rules and the Estimation of the Allowable Biological Catch (ABC). FRA-SA2020-ABCWG01-01.

Kurota, H., C.S. Szuwalski, M. Ichinokawa (2020) Drivers of recruitment dynamics in Japanese major fisheries resources: Effects of environmental conditions and spawner abundance. Fish. Res. 221, 105353.

Nishijima S., M. Ichinokawa and H. Okamura (2020) Saiseisan kankei suitei ni okeru moderu shindan syuhou (Model diagnostics in estimation of stock-recruitment relationship). FRA-SA2020-BRP01-5.

Takahashi, M., Y. Watanabe, A. Yatsu, H. Nishida (2009) Contrasting responses in larval and juvenile growth to a climate-ocean regime shift between anchovy and sardine. Can. J. Fish. Aquat. Sci. 66, 972–982.

Tanaka E (2003) A method for estimating dynamics of carrying capacity using time series of stock and recruitment. Fish. Sci., 69, 677-686.

Wada, T. and M. Kashiwai (1991) Changes in growth and feeding ground of Japanese sardine with fluctuation in stock abundance. In: Long-term variability of pelagic fish populations and their environment, ed. Kawasaki, T. et al., Pergamon, Oxford, pp. 181-190.

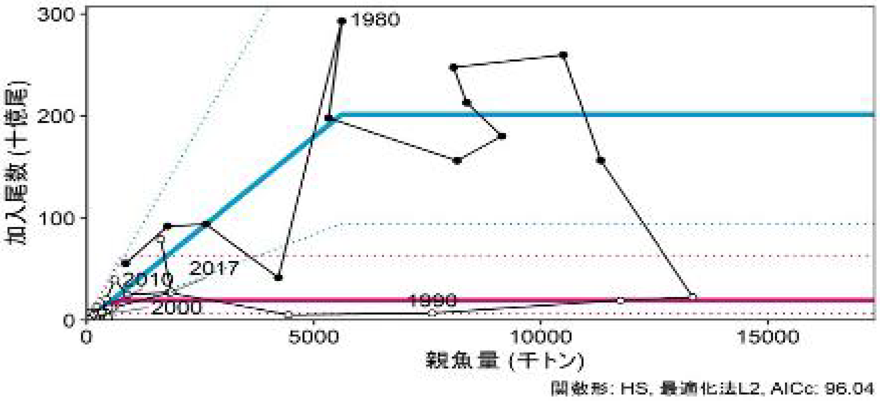
Watanabe, Y., H. Zenitani and R. Kimura (1995) Population decline of the Japanese sardine *Sardinops melanostictus* owing to the recruitment failures. Can. J. Fish. Aquat. Sci., 52, 1609-1616.

Yasunaka, S. and K. Hanawa (2002) Regime shifts found in the northern hemisphere SST field. J. Meteor. Soc. Japan, 80, 119-135.

Yatsu, A. and M. Kaeriyama (2005) Linkages between coastal and open-ocean habitats and dynamics of Japanese stocks of chum salmon and Japanese sardine. Deep-Sea Res. II, 52, 727-737.

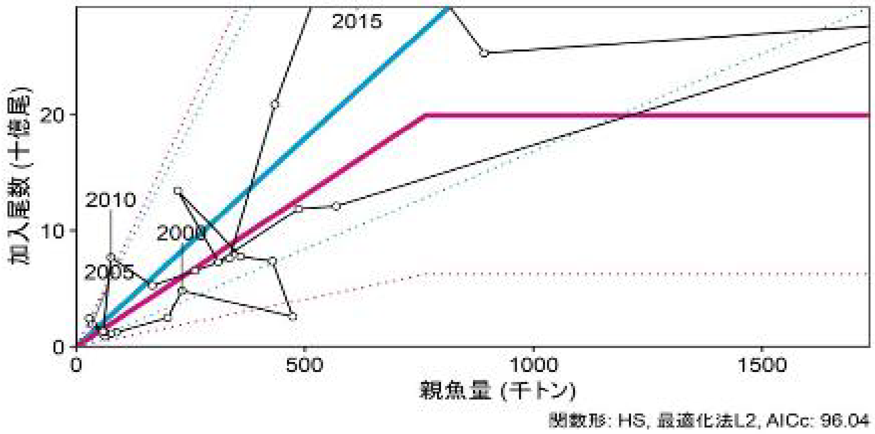
Yatsu, A., T. Watanabe, M. Ishida, H. Sugisaki, L.D. Jacobsen (2005) Environmental effects on recruitment and productivity of Japanese sardine *Sardinops melanostictus* and chub mackerel *Scomber japonicus* with recommendations for management. Fish. Oceanogr. 14, 263–278.

(Authors: Sho Furuichi, Ryuji Yukami, Yasuhiro Kamimura, Akira Hayashi, Sayoko Isu, Ryosuke Watanabe)



加入尾数（十億尾）	Recruitment (billion individuals)
親魚量（千トン）	Spawning biomass (thousand tons)
関数形：HS，最適化法 LS2，AICc: 96.04	Model: HS; optimization method: LS2, AICc: 96.04

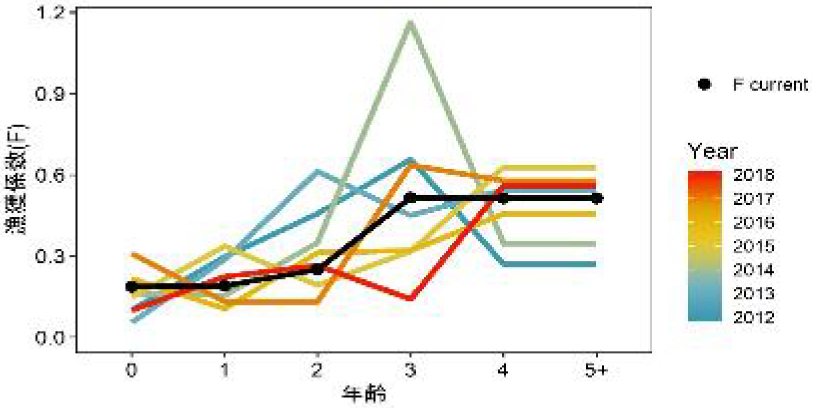
Enlarged view



加入尾数（十億尾）	Recruitment (billion individuals)
親魚量（千トン）	Spawning biomass (thousand tons)
関数形：HS，最適化法 L2，AICc: 96.04	Model: HS; optimization method: L2, AICc: 96.04

Figure 1. S-R relationship

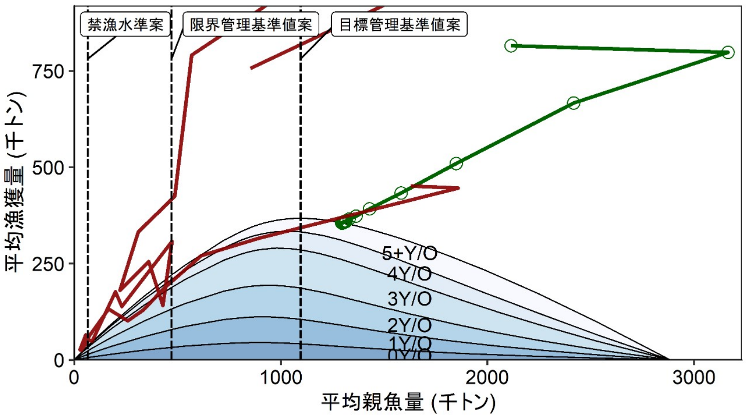
We used the HS S-R relationship with divided periods for the S-R relationship and conducted parameter estimation using the least squares method. The blue line represents the S-R relationship of the high recruitment period (1976-1987) and the red line represents the S-R relationship of the normal recruitment period (1988-2018). Circles represent the spawning biomass and recruitment used for the analysis (1976-2018). The black circles represent values of the high recruitment period, while the white circles represent values of the normal recruitment period. Dotted lines over and below the S-R relationships show the range supposed to include 90% of the observed data of the respective S-R relationship. Numbers in the figure indicate the class of recruited group (birth year).



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 2014 to 2018.

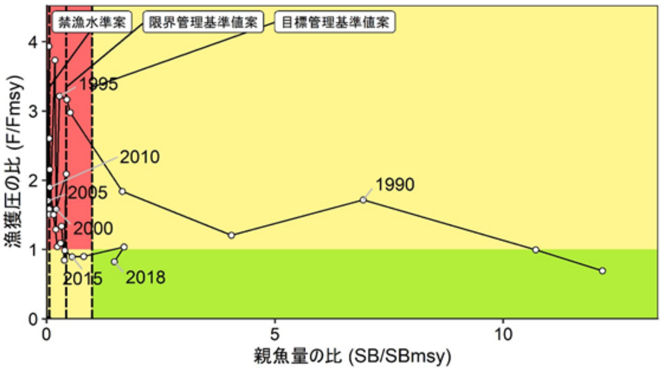


平均漁獲量（千トン）	Average catch (thousand tons)
平均親魚量（千トン）	Average spawning biomass (thousand tons)
禁漁水準案	Proposed fishing ban level
限界管理基準値案	Proposed limit reference point
目標管理基準値案	Proposed target reference point

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

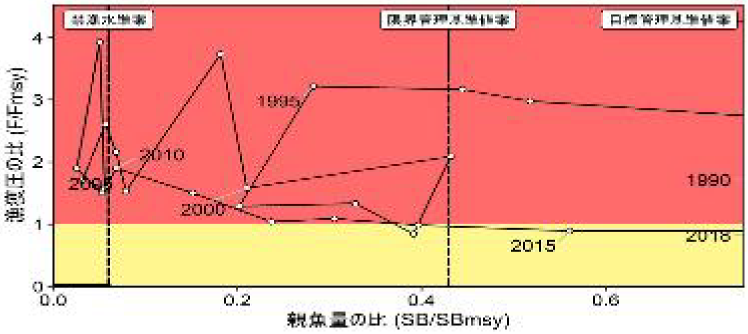
The figure shows the relationship of average catch at age corresponding to the average spawning biomass, with the proposed reference points and fishing ban level at equilibrium in the future projection simulation when the S-R relationship of the normal recruitment period is applied. The red line represents changes in the spawning biomass and catch, which are estimated by the stock assessment, while the green line represents the average spawning biomass and average catch in the future projection assuming fishing conducted based on the proposed HCRs. Safety coefficient β used in the proposed HCRs is 0.8. The initial spawning biomass assuming no catch (SB0) is 2.885 million tons. Here, past spawning biomass and part of catch are outside the scope (maximum value of spawning biomass: 19.542 million tons; maximum value of catch: 2.916 million tons).

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



漁獲圧の比	F/Fmsy
親魚量の比	SB/SBmsy
禁漁水準案	Proposed SBban
限界管理基準値案	Proposed SBlimit
目標管理基準値案	Proposed SBtarget

Enlarged view

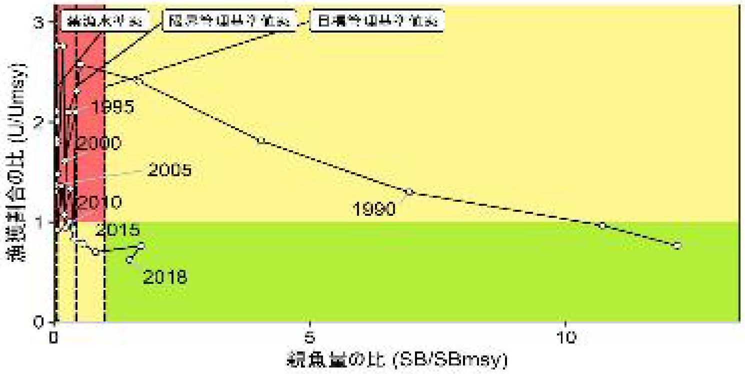


漁獲圧の比	F/Fmsy
親魚量の比	SB/SBmsy
禁漁水準案	Proposed SBban
限界管理基準値案	Proposed SBlimit
目標管理基準値案	Proposed SBtarget

Figure 4. Kobe plot (Four sections)

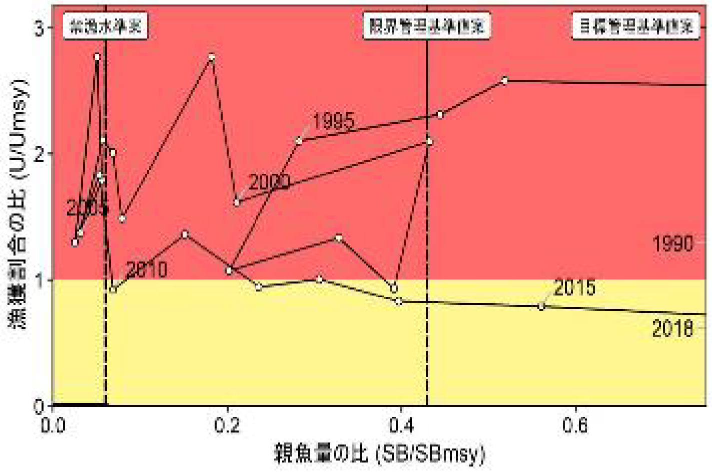
The figure shows a Kobe plot based on the S-R relationship of the normal recruitment period (a) when the ratio of fishing mortality is put on the vertical axis and (b) when the ratio of exploitation rate is put on the vertical axis. Only the plot of the normal recruitment period is shown here. The proposed target reference point (SBtarget), proposed limit reference point (SBlimit), and proposed fishing ban level (SBban) in the figure are set to SBmsy, SB0.6msy, and SB0.1msy，respectively.

b-1) 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

Enlarged view

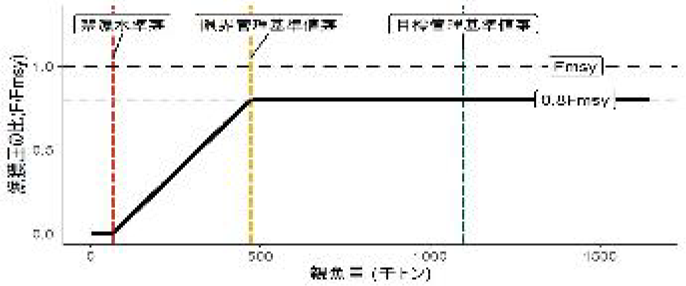


漁獲割合の比	F/Fmsy
親魚量の比	SB/SBmsy
禁漁水準案	Proposed SBban
限界管理基準値案	Proposed SBlimit
目標管理基準値案	Proposed SBtarget

Figure 4 (continued). Kobe plot (four sections)

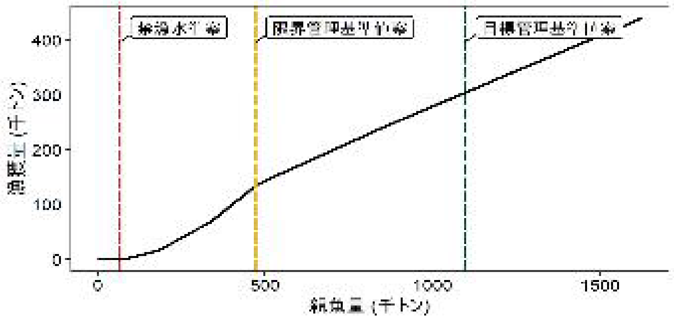
The figure shows a Kobe plot based on the S-R relationship of the normal recruitment period (a) when the ratio of fishing mortality is put on the vertical axis and (b) when the ratio of exploitation rate is put on the vertical axis. Only the plot of the normal recruitment period is shown here. The proposed target reference point (SBtarget), proposed limit reference point (SBlimit), and proposed fishing ban level (SBban) in the figure are set to SBmsy, SB0.6msy, and SB0.1msy, respectively.

a) When 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 vertical axis is catch

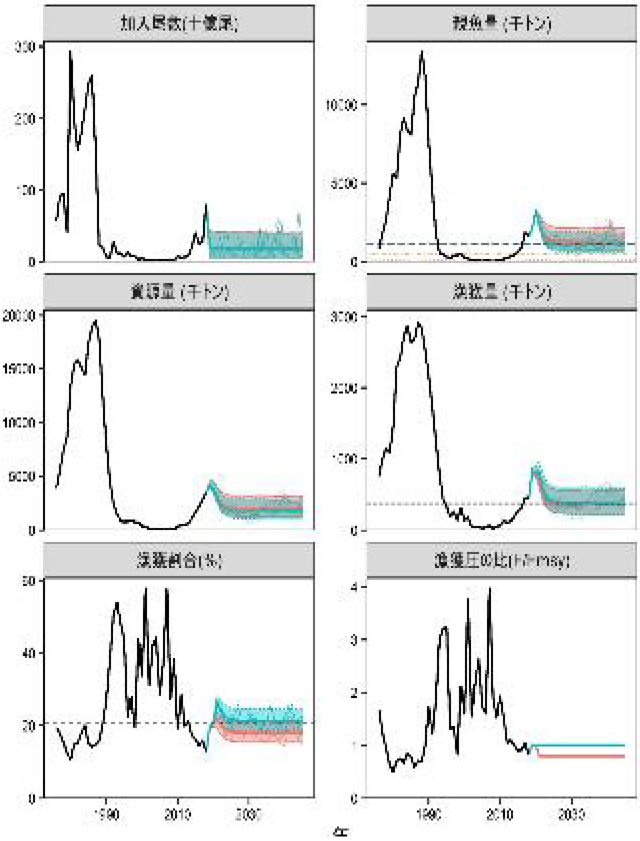


漁獲量（千トン）	Catch (thousand tons)
親魚量（千トン）	Spawning biomass (thousand tons)
禁漁水準案	Proposed SBban
限界管理基準値案	Proposed SBlimit
目標管理基準値案	Proposed SBtarget

Figure 5. Proposed HCRs

The proposed target reference point (SBtarget), proposed limit reference point (SBlimit), and proposed fishing ban level (SBban) in the figure are set to SBmsy, SB0.6msy, and SB0.1msy, respectively. Estimation is made based on the S-R relationship of the normal recruitment period. Safety coefficient β is set to 0.8, which is the standard value. The black dashed line represents

Fmsy; the grey dashed line represents 0.8Fmsy; the black thick line represents the proposed HCRs; the red dashed line represents the proposed fishing ban level; the yellow dashed line represents the proposed limit reference point; and the green dashed line represents the proposed target reference point. In a) the ratio of fishing mortality is put on the vertical axis, while in b) the catch is put on the vertical axis. Regarding b), the catch varies a little depending on the age composition of the fishing year but here we show the catch of average age composition at equilibrium.



加入尾数（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

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) when the S-R relationship of the normal recruitment period is applied

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 Umsy. The catch in 2019 and 2020 are assumed based on the projected biomass and Fcurrent, while the catch in 2021 and after is based on the proposed HCRs (Figure 5). Safety coefficient β is set to 0.8.

Table 1. Candidates for S-R relationship: the S-R relationship to be applied is in thick line

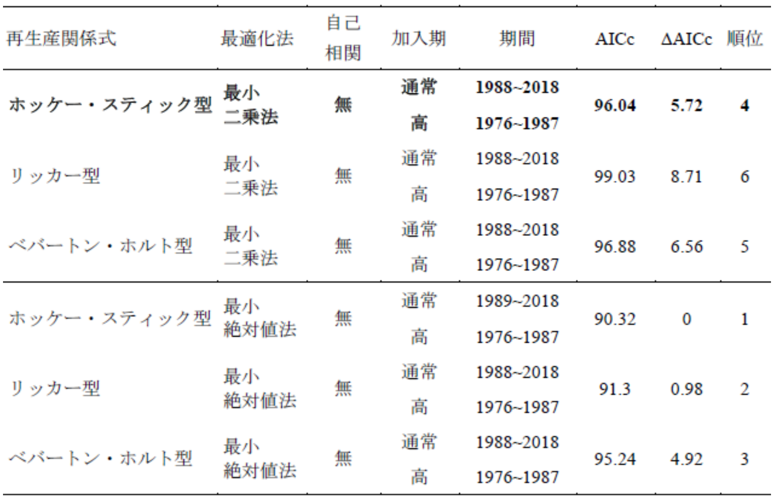
When applied to the whole period

再生産関係式	最適化法	自己相関	期間	AICc	ΔAICc	順位
ホッケー・スティック型	最小二乗法	有	1976~2018	108.30	0	1
リッカー型	最小二乗法	有	1976~2018	109.11	0.81	2
ベバートン・ホルト型	最小二乗法	有	1976~2018	109.54	1.24	3
ホッケー・スティック型	最小二乗法	無	1976~2018	122.93	14.63	8
リッカー型	最小二乗法	無	1976~2018	122.27	13.97	7
ベバートン・ホルト型	最小二乗法	無	1976~2018	123.18	14.88	9
ホッケー・スティック型	最小絶対値法	無	1976~2018	118.09	9.79	4
リッカー型	最小絶対値法	無	1976~2018	120.02	11.72	5
ベバートン・ホルト型	最小絶対値法	無	1976~2018	120.16	11.86	6

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

For estimation of autocorrelation, we used the simultaneous estimation method where autocorrelation is estimated simultaneously with the parameters of the S-R relationship. Because it is more appropriate to assume the normality of residuals in this case, we used the least squares method for optimization.

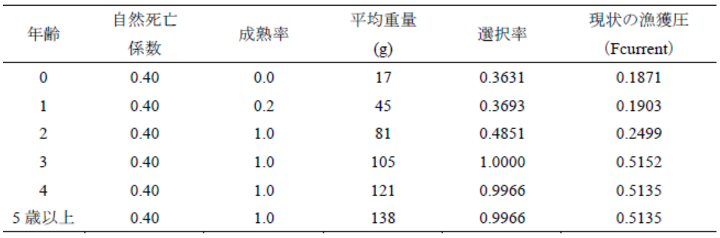
When divided into two periods



再生産関係式	最適化法	自己相関	加入期	期間	AICc	ΔAICc	順位
ホッケー・スティック型	**最小二乗法**	**無**	**通常**	**1988~2018**	**96.04**	**5.72**	**4**
			高	**1976~1987**			
リッカー型	最小二乗法	無	通常	1988~2018	99.03	8.71	6
			高	1976~1987			
ベバートン・ホルト型	最小二乗法	無	通常	1988~2018	96.88	6.56	5
			高	1976~1987			
ホッケー・スティック型	最小絶対値法	無	通常	1989~2018	90.32	0	1
			高	1976~1987			
リッカー型	最小絶対値法	無	通常	1988~2018	91.3	0.98	2
			高	1976~1987			
ベバートン・ホルト型	最小絶対値法	無	通常	1988~2018	95.24	4.92	3
			高	1976~1987			

再生産関係式	S-R relationship
最適化法	Optimization method
自己相関	Autocorrelation
加入期	Recruitment period
期間	Period
順位	Rank
ホッケー・スティック型	Hockey stick
リッカー型	Ricker
ベバートン・ホルト型	Beverton-Holt
最小二乗法	Least squares method
最小絶対値法	Least absolute value method
無	No
通常	Normal
高	High

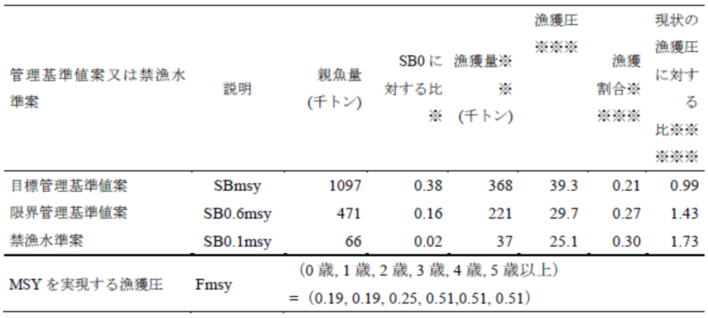
Table 2 Settings used for calculation of the spawning biomass that produces MSY and future projection



年齢	自然死亡係数	成熟率	平均重量 (g)	選択率	現状の漁獲圧 (Fcurrent)
0	0.40	0.0	17	0.3631	0.1871
1	0.40	0.2	45	0.3693	0.1903
2	0.40	1.0	81	0.4851	0.2499
3	0.40	1.0	105	1.0000	0.5152
4	0.40	1.0	121	0.9966	0.5135
5 歳以上	0.40	1.0	138	0.9966	0.5135

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
5 歳以上	Age 5 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	1097	0.38	368	39.3	0.21	0.99
限界管理基準値案	SB0.6msy	471	0.16	221	29.7	0.27	1.43
禁漁水準案	SB0.1msy	66	0.02	37	25.1	0.30	1.73
MSYを実現する漁獲圧	Fmsy	（0歳, 1歳, 2歳, 3歳, 4歳, 5歳以上） =（0.19, 0.19, 0.25, 0.51,0.51, 0.51）					

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	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, 4歳, 5歳以上）＝（0.19, 0.19, 0.25, 0.51,0.51, 0.51）	(Ages 0, 1, 2, 3, 4, 5 and above) = (0.19, 0.19, 0.25, 0.51,0.51, 0.51)

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

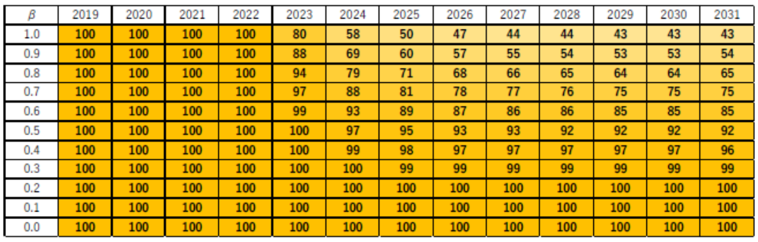
** Average catch at equilibrium under the fishing mortality corresponding to the proposed reference points and fishing ban level

*** %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

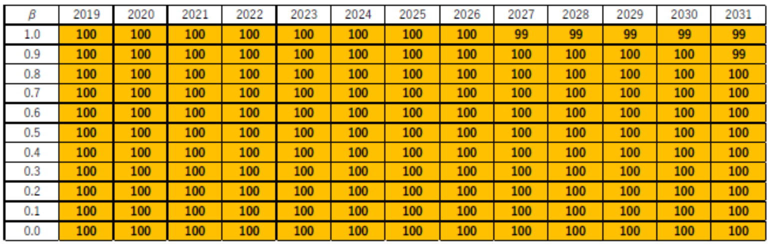
Table 4. Probability for future spawning biomass to exceed the proposed target reference point (%)



β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
1.0	100	100	100	100	80	58	50	47	44	44	43	43	43
0.9	100	100	100	100	88	69	60	57	55	54	53	53	54
0.8	100	100	100	100	94	79	71	68	66	65	64	64	65
0.7	100	100	100	100	97	88	81	78	77	76	75	75	75
0.6	100	100	100	100	99	93	89	87	86	86	85	85	85
0.5	100	100	100	100	100	97	95	93	93	92	92	92	92
0.4	100	100	100	100	100	99	98	97	97	97	97	97	96
0.3	100	100	100	100	100	100	99	99	99	99	99	99	99
0.2	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
0.0	100	100	100	100	100	100	100	100	100	100	100	100	100

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

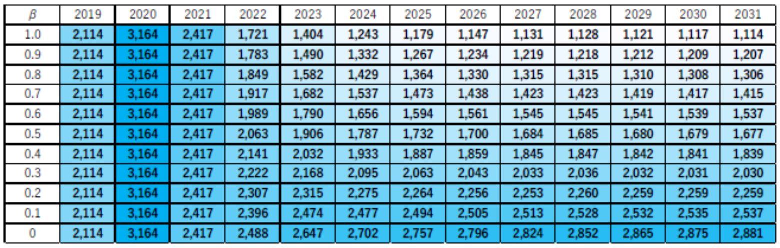
Table 5. Probability for the future spawning biomass to exceed the proposed limit reference point (%)



β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
1.0	100	100	100	100	100	100	100	100	99	99	99	99	99
0.9	100	100	100	100	100	100	100	100	100	100	100	100	99
0.8	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
0.6	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
0.4	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
0.2	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
0.0	100	100	100	100	100	100	100	100	100	100	100	100	100

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

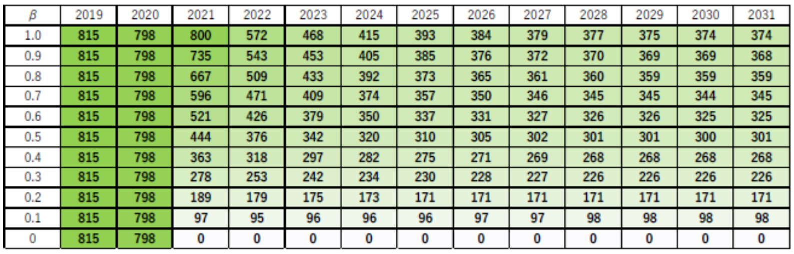
Table 6. Changes in future average spawning biomass (thousand tons)



β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
1.0	2,114	3,164	2,417	1,721	1,404	1,243	1,179	1,147	1,131	1,128	1,121	1,117	1,114
0.9	2,114	3,164	2,417	1,783	1,490	1,332	1,267	1,234	1,219	1,218	1,212	1,209	1,207
0.8	2,114	3,164	2,417	1,849	1,582	1,429	1,364	1,330	1,315	1,315	1,310	1,308	1,306
0.7	2,114	3,164	2,417	1,917	1,682	1,537	1,473	1,438	1,423	1,423	1,419	1,417	1,415
0.6	2,114	3,164	2,417	1,989	1,790	1,656	1,594	1,561	1,545	1,545	1,541	1,539	1,537
0.5	2,114	3,164	2,417	2,063	1,906	1,787	1,732	1,700	1,684	1,685	1,680	1,679	1,677
0.4	2,114	3,164	2,417	2,141	2,032	1,933	1,887	1,859	1,845	1,847	1,842	1,841	1,839
0.3	2,114	3,164	2,417	2,222	2,168	2,095	2,063	2,043	2,033	2,036	2,032	2,031	2,030
0.2	2,114	3,164	2,417	2,307	2,315	2,275	2,264	2,256	2,253	2,260	2,259	2,259	2,259
0.1	2,114	3,164	2,417	2,396	2,474	2,477	2,494	2,505	2,513	2,528	2,532	2,535	2,537
0	2,114	3,164	2,417	2,488	2,647	2,702	2,757	2,796	2,824	2,852	2,865	2,875	2,881

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

Table 7. Changes in future average catch (thousand tons)

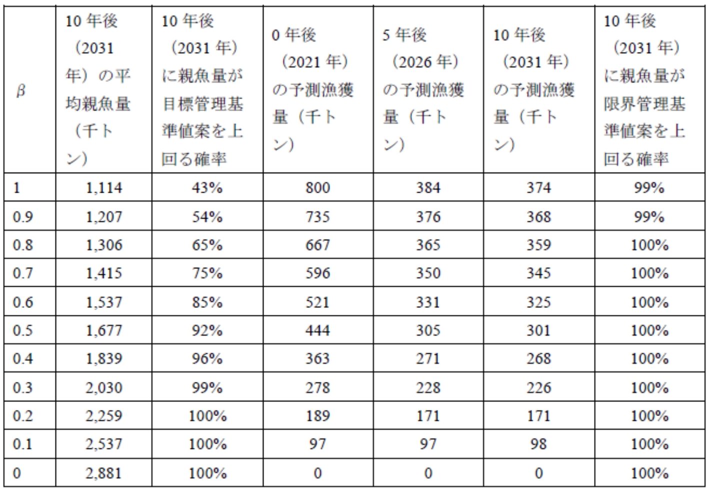


β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
1.0	815	798	800	572	468	415	393	384	379	377	375	374	374
0.9	815	798	735	543	453	405	385	376	372	370	369	369	368
0.8	815	798	667	509	433	392	373	365	361	360	359	359	359
0.7	815	798	596	471	409	374	357	350	346	345	345	344	345
0.6	815	798	521	426	379	350	337	331	327	326	326	325	325
0.5	815	798	444	376	342	320	310	305	302	301	301	300	301
0.4	815	798	363	318	297	282	275	271	269	268	268	268	268
0.3	815	798	278	253	242	234	230	228	227	226	226	226	226
0.2	815	798	189	179	175	173	171	171	171	171	171	171	171
0.1	815	798	97	95	96	96	96	97	97	98	98	98	98
0	815	798	0	0	0	0	0	0	0	0	0	0	0

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

Table 8. Summary of the projected spawning biomass, catch and the probability for spawning biomass to exceed the proposed limit reference point

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



β	10 年後（2031 年）の平均親魚量（千トン）	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	1,114	43%	800	384	374	99%
0.9	1,207	54%	735	376	368	99%
0.8	1,306	65%	667	365	359	100%
0.7	1,415	75%	596	350	345	100%
0.6	1,537	85%	521	331	325	100%
0.5	1,677	92%	444	305	301	100%
0.4	1,839	96%	363	271	268	100%
0.3	2,030	99%	278	228	226	100%
0.2	2,259	100%	189	171	171	100%
0.1	2,537	100%	97	97	98	100%
0	2,881	100%	0	0	0	100%

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

Appendix 1. Diagnosis result of S-R relationship models

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

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

Here, R_y represents recruitment in year y and B_y represents the spawning biomass of year y. In 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 S.D. of the recruitment from the estimated S-R curve.

When using the whole-period (1976-2018) data, we applied HS, RI and BH S-R relationships using the least squares method and the least absolute value method. For comparison with a model that assumes a different S-R relationship depending on the period, we used the simultaneous estimation method where autocorrelation parameter ρ is incorporated into the model to simultaneously estimate the parameters of the S-R relationship and autocorrelation (for details, see "Technical Note on estimation of S-R relationship, reference point calculation and future prediction simulation (FRA2020-ABCWG01-02)"). Because it is more appropriate to assume the normality of residuals in this case, we used the least squares method for optimization. Estimated S-R relationship parameters are shown in Appendix Table 1-1. The small-sample-size-corrected version of AICc is lower in the model that is not based on the S-R relationship and considers autocorrelation in residuals.

The biomass of Japanese sardine Pacific stock is known to change dramatically in synchronization with the interdecadal global shift in the structure of systems including the atmospheric system and marine ecosystems (regime shift) (Kawasaki 1992, Klyashtorin 1998, Chavez et al. 2003). The changes in the ocean environment and other elements are likely to affect the environmental carrying capacity and recruitment success (Tanaka 2003, Yatsu et al. 2005), and have also changed the S-R relationship. Autocorrelation of recruitment residuals, which is found when the S-R relationship is applied to data of the whole period, may be attributable to different S-R relationships depending on the period. For this reason, we assumed two types of S-R relationship – normal-recruitment-period type and high-recruitment-period type – based on the S-R level from 1976 to 2018, and we assumed a shift from the high-recruitment period to normal-recruitment period. We considered years from 1987 to 1990 for switching of the S-R relationship based on the past references (Yatsu et al. 2005, Takahashi et al. 2009 and Kurota et al. 2020). We examined models of all combinations of switching year and all models of the S-R relationship.

For each S-R relationship and estimation method, we selected the combination with the lowest AICc for examination of the S-R relationship divided into different periods (Appendix Table 1-2). Regardless of the model of the S-R relationship, AICc is lower when the S-R relationship is divided into normal and high recruitment periods than AICc when one relationship is applied to the data of the whole period. When the S-R relationship is divided into two types, AICc estimated with the least absolute value method is lower. However, because parameter estimation is unstable in this case and there is no significant difference from the parameters estimated using the least squares method, we chose the least squares method as a candidate for the estimation method. When the least squares method is used, the model that assumes the HS S-R relationship had the smallest AICc.

We diagnosed the model of the HS S-R relationship that is applied as the S-R relationship of this stock and that is based on the least squares method when the S-R relationship is divided (for details, see "Model diagnosis method in estimation of S-R relationship (FRA-SA2020-BRP01-5)"). Residual trend and autocorrelation plot are shown in Appendix Figure 1-2. Significant autocorrelation is not found. It is believed that division of the S-R relationship could adequately handle the autocorrelation of recruitment. When we place the focus on time series of residuals, recruitment residuals in recent years lean to the positive side, which leads to an interpretation that recruitment higher than the recruitment projected based on the S-R relationship of the normal recruitment period is continuing. We examined the normality of residuals for the S-R relationship models with the Shapiro-Wilk test and Kolmogorov-Smirnov test. As a result, significant deviation was not found (Appendix Figure 1-3). The influence of individual data on parameter estimation was examined by Jack-knife analysis where data of one year is removed in turn. We had not much data of the high recruitment period, but we found one piece of data (1979) with significant influence in the parameter estimation of the S-R relationship of the high-recruitment period (Appendix Figures 1-4 and 1-5). In the S-R relationship of the normal recruitment period, no significant change was found in the estimates of the parameters and the estimated S-R relationship was robust (Appendix Figures 1-4 and 1-5). When we conducted nonparametric bootstrapping of residuals 1,000 times, little bias was found in all parameters (Appendix Figures 1-6 and 1-7). In addition, it is confirmed that profile likelihood is maximum at the estimated value when parameters a and b are changed (Appendix Figure 1-8).

References

ABCWG (2020) Technical Note on Estimation of stock-recruitment relationship, reference point calculation and future prediction simulation (2020 Research Institute Meeting Version). FRA-SA2020-ABCWG01-02.

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

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

Chavez, F. P., J. Ryan, S. E. Lluch-Cota, C. M. Niquen (2003) From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science 299, 217–221.

Kawasaki, T. (1992) Climate-dependent fluctuations in far eastern sardine population and their impacts on fisheries and society. In: Climate variability, climate change and fisheries, ed. Glantz, M.H., Cambridge University press, Cambridge, pp. 325-354.

Klyashtorin, L. B. (1998) Long-term climate change and main commercial fish production in the Atlantic and Pacific. Fish. Res., 37, 115-125.

Kurota, H., C.S. Szuwalski, M. Ichinokawa (2020) Drivers of recruitment dynamics in Japanese major fisheries resources: Effects of environmental conditions and spawner abundance. Fish. Res. 221, 105353.

Nishijima S., M. Ichinokawa and H. Okamura (2020) Saiseisan kankei suitei ni okeru moderu shindan syuhou (Model diagnostics in estimation of stock-recruitment relationship). FRA-SA2020-BRP01-5.

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

Takahashi, M., Y. Watanabe, A. Yatsu, H. Nishida (2009) Contrasting responses in larval and juvenile growth to a climate-ocean regime shift between anchovy and sardine. Can. J. Fish. Aquat. Sci. 66, 972–982.

Tanaka E (2003) A method for estimating dynamics of carrying capacity using time series of stock and recruitment. Fish. Sci., 69, 677-686.

Yatsu, A., T. Watanabe, M. Ishida, H. Sugisaki, L.D. Jacobsen (2005) Environmental effects on recruitment and productivity of Japanese sardine *Sardinops melanostictus* and chub mackerel *Scomber japonicus* with recommendations for management. Fish. Oceanogr. 14, 263–278.

Appendix Table 1-1. Estimated values of the parameters in the S-R relationships based on the data of the whole period

再生産関係式	最適化法	自己相関	推定法	a	b	S.D.	ρ	データ数	AICc
ホッケー・スティック型	最小二乗法	有	同時	0.034	1,629,150	0.763	0.604	43	108.30
リッカー型	最小二乗法	有	同時	0.032	1.52e-07	0.775	0.554	43	109.54
ベバートン・ホルト型	最小二乗法	有	同時	0.040	5.00e-07	0.771	0.601	43	109.11
ホッケー・スティック型	最小二乗法	無	-	0.027	2,732,831	0.936	0	43	122.93
リッカー型	最小二乗法	無	-	0.029	1.27e-07	0.929	0	43	122.27
ベバートン・ホルト型	最小二乗法	無	-	0.030	2.33e-07	0.938	0	43	123.18
ホッケー・スティック型	最小絶対値法	無	-	0.024	6,478,416	0.990	0	43	118.09
リッカー型	最小絶対値法	無	-	0.025	3.17e-08	1.008	0	43	120.02
ベバートン・ホルト型	最小絶対値法	無	-	0.024	2.97e-08	1.014	0	43	120.16

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
データ数	Data quantity
ホッケー・スティック型	Hockey stick
リッカー型	Ricker
ベバートン・ホルト型	Beverton-Holt
最小二乗法	Least squares method
最小絶対値法	Least absolute value method
有	Yes
無	No
同時	Simultaneous

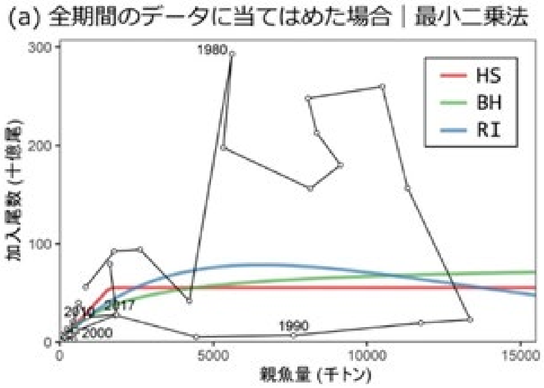
S.D. is an index expressing magnitude of dispersion of recruitment, which is the standard deviation of log residuals (square root of mean square error).

Appendix Table 1-2. Estimated values of the parameters in the model where the S-R relationship is applied separately to two periods

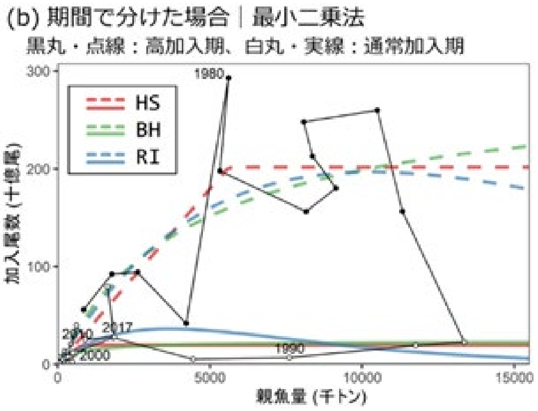
再生産関係式	最適化法	期間	加入期	a	b	S.D.	ρ	データ数	AICc
ホッケー・スティック型	最小二乗法	1988~2018	通常	0.026	764,253	0.705	0	31	96.04
		1976~1987	高	0.036	5,612,630	0.460	0	12	
リッカー型	最小二乗法	1988~2018	通常	0.027	2.73e-07	0.755	0	31	99.03
		1976~1987	高	0.052	9.68e-08	0.436	0	12	
ベバートン・ホルト型	最小二乗法	1988~2018	通常	0.036	1.54e-06	0.734	0	31	96.88
		1976~1987	高	0.064	2.23e-07	0.429	0	12	
ホッケー・スティック型	最小絶対値法	1988~2018	通常	0.023	1,005,619	0.717	0	31	90.32
		1976~1987	高	0.038	5,613,207	0.462	0	12	
リッカー型	最小絶対値法	1988~2018	通常	0.024	2.29e-07	0.770	0	31	91.30
		1976~1987	高	0.063	1.08e-07	0.454	0	12	
ベバートン・ホルト型	最小絶対値法	1988~2018	通常	0.033	1.38e-06	0.736	0	31	95.21
		1975~1987	高	0.075	2.34e-07	0.448	0	12	

再生産関係式	S-R relationship
最適化法	Optimization method
期間	Period
加入期	Recruitment period
データ数	Data quantity
ホッケー・スティック型	Hockey stick
リッカー型	Ricker
ベバートン・ホルト型	Beverton-Holt
最小二乗法	Least squares method
最小絶対値法	Least absolute value method
通常	Normal
高	High

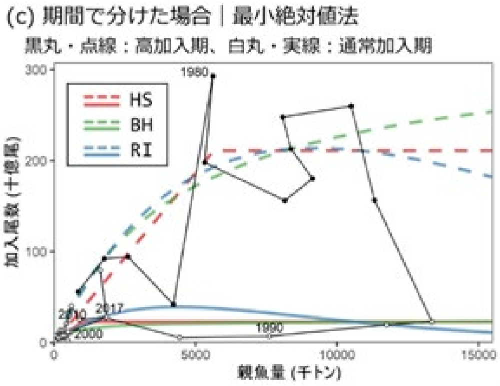
S.D. is an index expressing magnitude of dispersion of recruitment, which is the standard deviation of log residuals (square root of mean square error).



（a）全期間のデータに当てはめた場合｜最小二乗法	(a) When applied to the data of the whole periods; least squares method
加入尾数（十億尾）	Recruitment (billion individuals)
親魚量（千トン）	Spawning biomass (thousand tons)



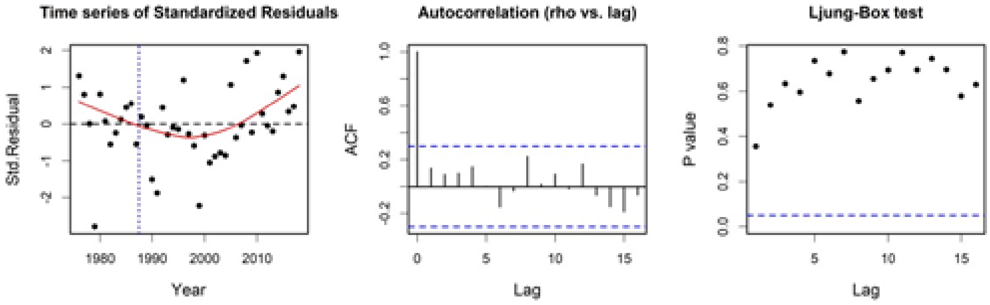
（b）期間で分けた場合｜最小二乗法	(b) When data is divided by period; least squares method
黒丸・点線：高加入期、白丸・実線：通常加入期	Black circles and dotted lines for the high-recruitment period; white circles and solid lines for the normal recruitment period
加入尾数（十億尾）	Recruitment (billion individuals)
親魚量（千トン）	Spawning biomass (thousand tons)



（c）期間で分けた場合｜最小絶対値法	(c) When data is divided by period; least absolute value method
黒丸・点線：高加入期、白丸・実線：通常加入期	Black circles and dotted lines for high-recruitment period; white circles and solid lines for normal recruitment period

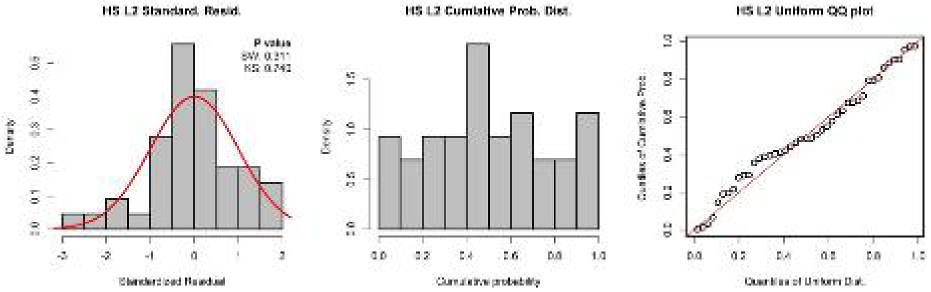
Appendix Figure 1-1. S-R relationship of each model

(a) When applied to the data of the whole period (simultaneous estimation of autocorrelation), (b) when data is divided by period and optimized by the least squares method, and (c) when data is divided by period and optimized by the least absolute value method. The S-R relationships of the HS model, RI model and BH model are shown. Circles represent the spawning biomass and recruitment (1976-2018) which are used for the analysis. Numbers in the figures represent the class (birth year) of the recruited group.



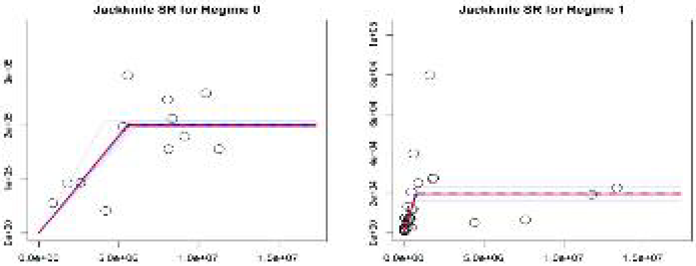
Appendix Figure 1-2. Time-series trend of standardized residuals (left), correlogram (center) and P value of Ljung-Box test (right) in the model where the HS model is assumed and the S-R relationship is divided by period

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.



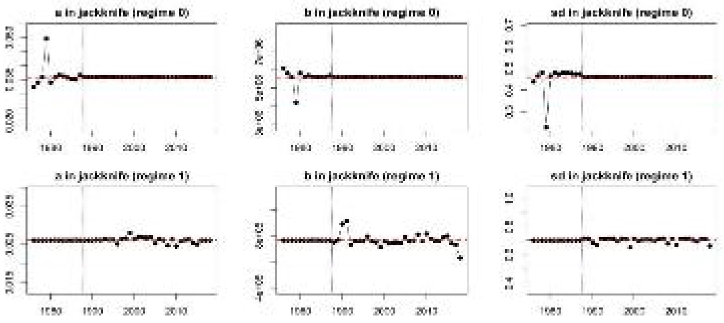
Appendix Figure 1-3. Histogram of standardized residuals and normality test results (left), histogram of residual cumulative probability density (center) and QQ plot assuming uniform distribution (right) in the model where the HS model is assumed and the S-R relationship is divided by period

The upper-right numbers of the residual histogram represent the results of the 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.



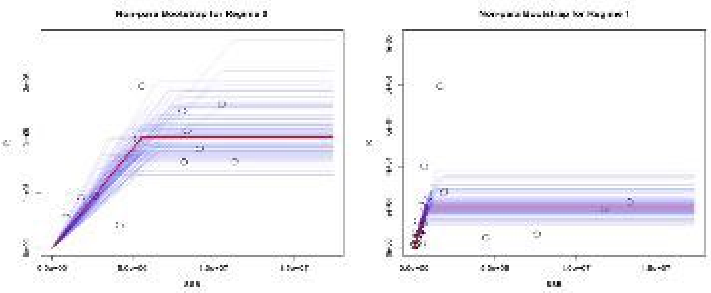
Appendix Figure 1-4. Estimated results of Jack Knife analysis in the model where the HS model is assumed and the S-R relationship is divided by period

The red line expresses the estimates of all data, while the blue line expresses the estimates when the data of the respective year is removed. Circles show the spawning biomass and recruitment, which are used for the analysis. The left figure shows the results of the high-recruitment period (Regime 0), while the right figure shows the results of the normal recruitment period (Regime 1).



Appendix Figure 1-5. Influence by parameter in Jack Knife analysis in the model where the HS model is assumed and the S-R relationship is divided by period

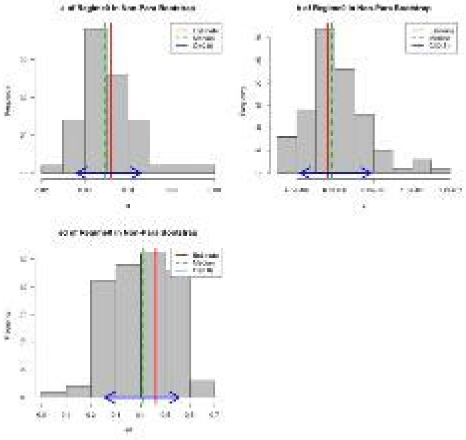
The upper charts show the results of the high-recruitment period (Regime 0) and the lower charts are results of the normal recruitment period (Regime 1). The blue dotted line indicates the switching points of the S-R relationship.



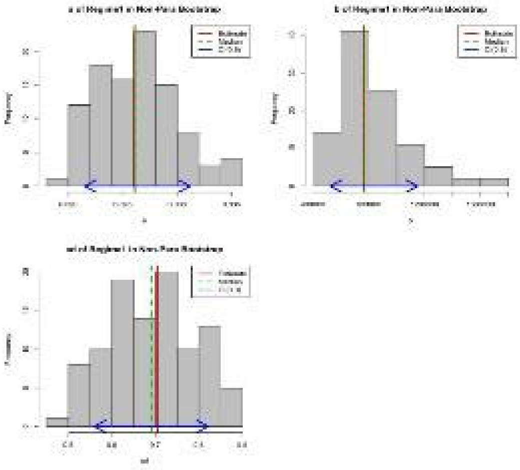
Appendix Figure 1-6. Results of bootstrap analysis of residuals in the model where the HS model is assumed and the S-R relationship is divided by period

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 left figure shows the results of the high-recruitment period (Regime0), while the right figure shows the results of the normal recruitment period (Regime1).

High-recruitment period

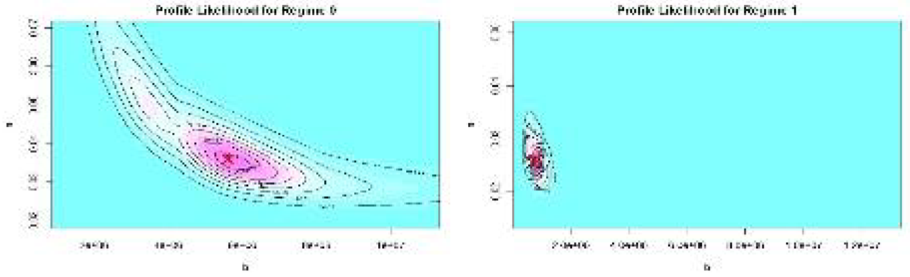


Normal recruitment period



Appendix Figure 1-7. Median (green dotted line) and 80% confidence interval (blue line) of bootstrap analysis of residuals in the model where the HS model is assumed and the S-R relationship is divided by period

The solid red line indicates the point estimates. The red line in the upper charts show the results of the high-recruitment period (Regime 0) while the lower charts are results of the normal recruitment period (Regime 1).

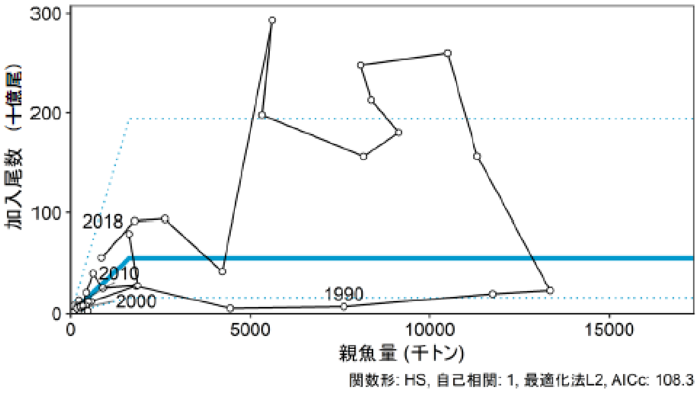


Appendix Figure 1-8. Profile likelihood of estimated parameters in the model where the HS model is assumed and the S-R relationship is divided by period

The × marks correspond to the likelihood at the estimated parameter values. The left figure shows the results of the high-recruitment period (Regime 0) while the right figure shows the results of the normal recruitment period (Regime 1).

Appendix 2. Results of S-R relationship when the data of the whole period (1976-2018) are used

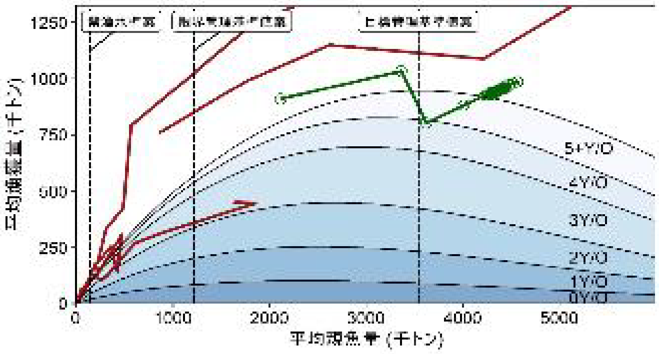
The figure shows the result of the HS S-R relationship when data of the whole period is used (the least squares method; simultaneous estimation of autocorrelation)



加入尾数（十億尾）	Recruitment (billion individuals)
親魚量（千トン）	Spawning biomass (thousand tons)
関数形：HS，自己相関：1，最適化法 L2，AICc: 108.3	Model: HS; autocorrelation: 1; optimization method: L2; AICc: 108.3

Appendix Figure 2-1. HS S-R relationship when data of the whole period is used

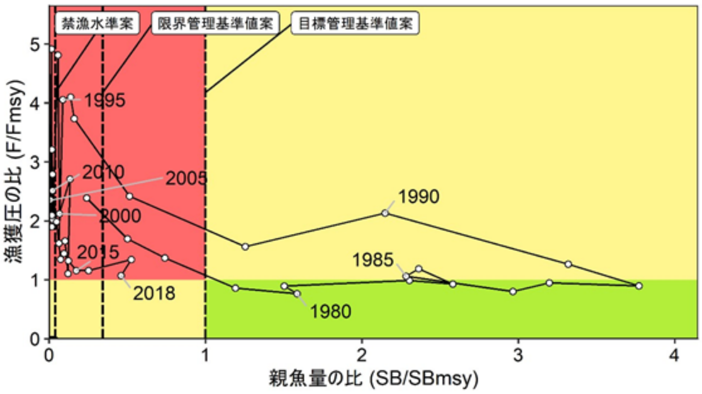
The solid blue line expresses the S-R relationship, while white circles represent the spawning biomass and recruitment (1976-2018) used for the analysis. The dotted lines over and below the S-R relationship show the estimated range that contains 90% of observation data under the assumed S-R relationship. Numbers in the figure denote the year class.



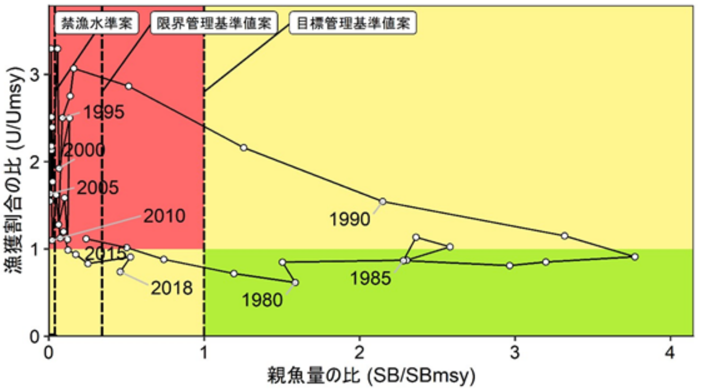
平均漁獲量（千トン）	Average catch (thousand tons)
平均親魚量（千トン）	Average spawning biomass (thousand tons)
禁漁水準案	Proposed fishing ban level
限界管理基準値案	Proposed limit reference point
目標管理基準値案	Proposed target reference point

Appendix Figure 2-2. Relationship of the proposed reference points / fishing ban level with curves of catch at age (when the HS S-R relationship is applied using data of the whole period)

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 when the HS S-R relationship is applied using data of the whole period. 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 harvest control rules (HCRs). Safety coefficient β used in the proposed HCRs is 0.8. The initial spawning biomass assuming no catch (SB0) is 10.791 million tons.



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



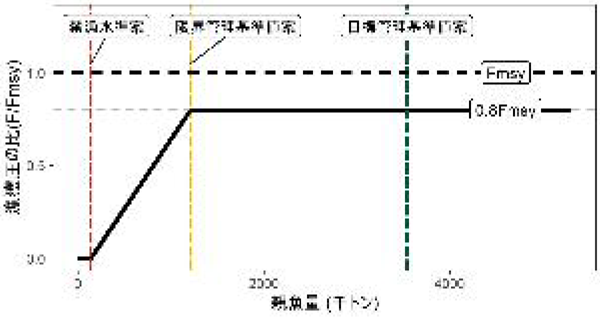
漁獲割合の比	F/Fmsy
親魚量の比	SB/SBmsy
禁漁水準案	Proposed SBban

限界管理基準値案	Proposed SBlimit
目標管理基準値案	Proposed SBtarget

Appendix Figure 2-2. Kobe plot (when the HS S-R relationship is applied using data of the whole period)

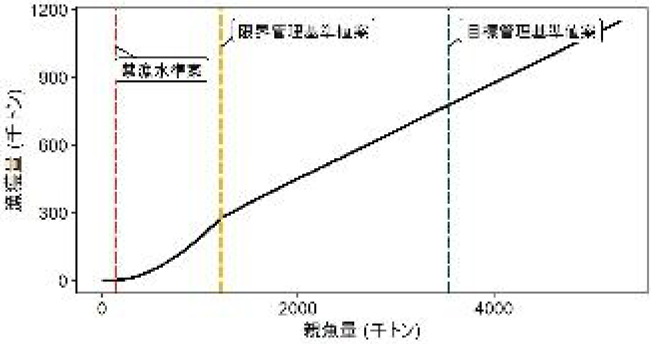
The upper chart shows the case where the ratio of fishing mortality is put on the vertical axis. The lower chart shows the case where the ratio of exploitation rate is put on the vertical axis. The proposed target reference point (SBtarget), proposed limit reference point (SBlimit), and proposed fishing ban level (SBban) in the figure are set to 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

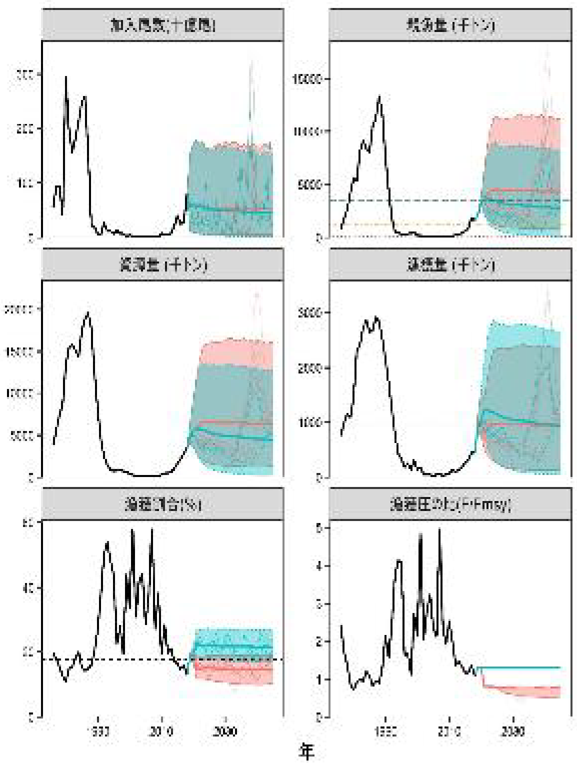
b) When the vertical axis is catch



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

Appendix Figure 2-3. Proposed HCRs (when the HS S-R relationship is applied using data of the whole period)

The proposed target reference point (SBtarget), proposed limit reference point (SBlimit), and proposed fishing ban level (SBban) in the figure are set to SBmsy, SB0.6msy, and SB0.1msy, respectively. Estimation is made by applying the S-R relationship using data of the whole period. For safety coefficient β, 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.

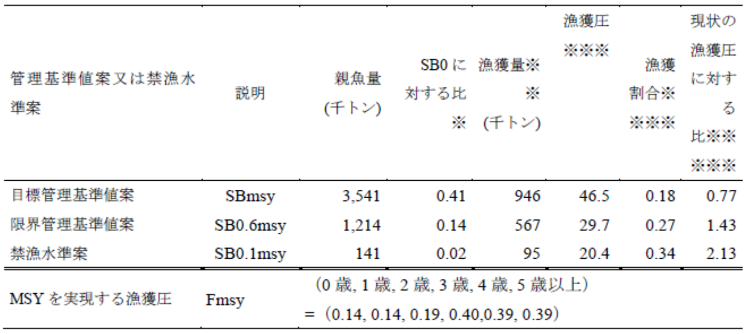


加入尾数（十億尾）	Recruitment (billion individuals)
資源量（千トン）	Stock biomass (thousand tons)
漁獲割合	Exploitation rate (%)
親魚量（千トン）	Spawning biomass (thousand tons)
漁獲量（千トン）	Catch (thousand tons)
漁獲圧の比	Ratio of the fishing mortality to MSY
年	Year

Appendix Figure 2-4. Comparison of the future projection based on the proposed HCRs (in red) with the future projection assuming fishing continued at the current fishing mortality level (in green) (HS S-R relationship using data of the whole period is applied)

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 Umsy. The catch in 2019 and 2020 are assumed based on the projected biomass and Fcurrent, while the catch in 2021 and after is based on the proposed HCRs (Figure 5). Safety coefficient β is set to 0.8.

Appendix Table 2-1. 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	3,541	0.41	946	46.5	0.18	0.77
限界管理基準値案	SB0.6msy	1,214	0.14	567	29.7	0.27	1.43
禁漁水準案	SB0.1msy	141	0.02	95	20.4	0.34	2.13
MSY を実現する漁獲圧	Fmsy	（0 歳, 1 歳, 2 歳, 3 歳, 4 歳, 5 歳以上） ＝（0.14, 0.14, 0.19, 0.40,0.39, 0.39）					

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	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, 4 歳, 5 歳以上）＝（0.14, 0.14, 0.19, 0.40,0.39, 0.39）	(Ages 0, 1, 2, 3, 4, 5 and above) = (0.14, 0.14, 0.19, 0.40,0.39, 0.39)

Results of application of HS S-R relationship using data of the whole period

* 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

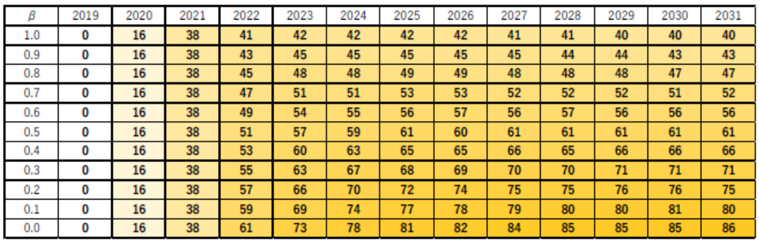
*** %SPR-converted value of fishing mortality corresponding to the proposed reference points and fishing ban level

**** 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 Table 2-2. Probability for future spawning biomass to exceed the proposed target reference point (%)

(Result of application of HS S-R relationship using data of the whole period)

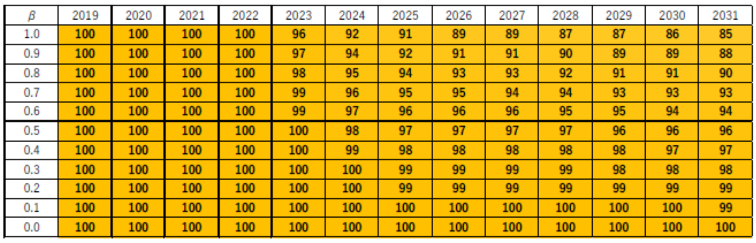


β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
1.0	0	16	38	41	42	42	42	42	41	41	40	40	40
0.9	0	16	38	43	45	45	45	45	45	44	44	43	43
0.8	0	16	38	45	48	48	49	49	48	48	48	47	47
0.7	0	16	38	47	51	51	53	53	52	52	52	51	52
0.6	0	16	38	49	54	55	56	57	56	57	56	56	56
0.5	0	16	38	51	57	59	61	60	61	61	61	61	61
0.4	0	16	38	53	60	63	65	65	66	65	66	66	66
0.3	0	16	38	55	63	67	68	69	70	70	71	71	71
0.2	0	16	38	57	66	70	72	74	75	75	76	76	75
0.1	0	16	38	59	69	74	77	78	79	80	80	81	80
0.0	0	16	38	61	73	78	81	82	84	85	85	85	86

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

Appendix Table 2-3. Probability for the future spawning biomass to exceed the proposed limit reference point (%)

(Result of application of HS S-R relationship using data of the whole period)

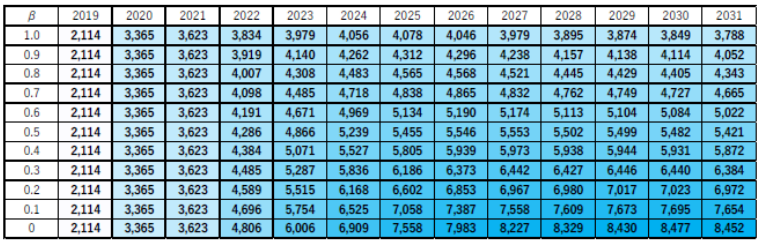


β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
1.0	100	100	100	100	96	92	91	89	89	87	87	86	85
0.9	100	100	100	100	97	94	92	91	91	90	89	89	88
0.8	100	100	100	100	98	95	94	93	93	92	91	91	90
0.7	100	100	100	100	99	96	95	95	94	94	93	93	93
0.6	100	100	100	100	99	97	96	96	96	95	95	94	94
0.5	100	100	100	100	100	98	97	97	97	97	96	96	96
0.4	100	100	100	100	100	99	98	98	98	98	98	97	97
0.3	100	100	100	100	100	100	99	99	99	99	98	98	98
0.2	100	100	100	100	100	100	99	99	99	99	99	99	99
0.1	100	100	100	100	100	100	100	100	100	100	100	100	99
0.0	100	100	100	100	100	100	100	100	100	100	100	100	100

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

Appendix Table 2-4. Changes in future average spawning biomass (thousand tons)

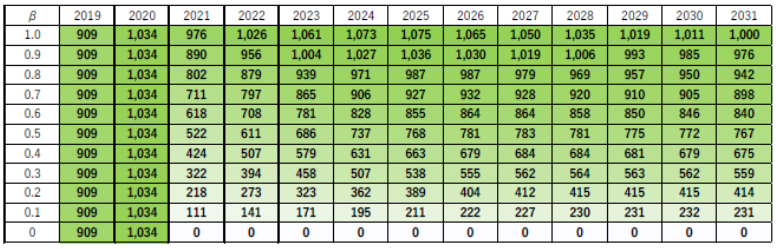
(Result of application of HS S-R relationship using data of the whole period)



β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
1.0	2,114	3,365	3,623	3,834	3,979	4,056	4,078	4,046	3,979	3,895	3,874	3,849	3,788
0.9	2,114	3,365	3,623	3,919	4,140	4,262	4,312	4,296	4,238	4,157	4,138	4,114	4,052
0.8	2,114	3,365	3,623	4,007	4,308	4,483	4,565	4,568	4,521	4,445	4,429	4,405	4,343
0.7	2,114	3,365	3,623	4,098	4,485	4,718	4,838	4,865	4,832	4,762	4,749	4,727	4,665
0.6	2,114	3,365	3,623	4,191	4,671	4,969	5,134	5,190	5,174	5,113	5,104	5,084	5,022
0.5	2,114	3,365	3,623	4,286	4,866	5,239	5,455	5,546	5,553	5,502	5,499	5,482	5,421
0.4	2,114	3,365	3,623	4,384	5,071	5,527	5,805	5,939	5,973	5,938	5,944	5,931	5,872
0.3	2,114	3,365	3,623	4,485	5,287	5,836	6,186	6,373	6,442	6,427	6,446	6,440	6,384
0.2	2,114	3,365	3,623	4,589	5,515	6,168	6,602	6,853	6,967	6,980	7,017	7,023	6,972
0.1	2,114	3,365	3,623	4,696	5,754	6,525	7,058	7,387	7,558	7,609	7,673	7,695	7,654
0	2,114	3,365	3,623	4,806	6,006	6,909	7,558	7,983	8,227	8,329	8,430	8,477	8,452

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

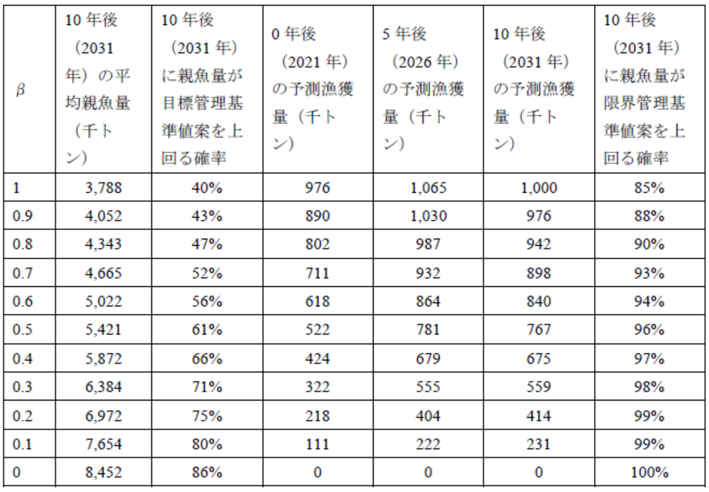
Appendix Table 2-5. Changes in future average catch (thousand tons)
(Result of application of HS S-R relationship using data of the whole period)



β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
1.0	909	1,034	976	1,026	1,061	1,073	1,075	1,065	1,050	1,035	1,019	1,011	1,000
0.9	909	1,034	890	956	1,004	1,027	1,036	1,030	1,019	1,006	993	985	976
0.8	909	1,034	802	879	939	971	987	987	979	969	957	950	942
0.7	909	1,034	711	797	865	906	927	932	928	920	910	905	898
0.6	909	1,034	618	708	781	828	855	864	864	858	850	846	840
0.5	909	1,034	522	611	686	737	768	781	783	781	775	772	767
0.4	909	1,034	424	507	579	631	663	679	684	684	681	679	675
0.3	909	1,034	322	394	458	507	538	555	562	564	563	562	559
0.2	909	1,034	218	273	323	362	389	404	412	415	415	415	414
0.1	909	1,034	111	141	171	195	211	222	227	230	231	232	231
0	909	1,034	0	0	0	0	0	0	0	0	0	0	0

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

Appendix Table 2-6. Summary of the projected spawning biomass, catch and the probability for spawning biomass to exceed the proposed limit reference point
The table shows results of future projection when safety coefficient β is changed from 0.0 to 1.0 in 0.1 intervals.



β	10 年後（2031 年）の平均親魚量（千トン）	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	3,788	40%	976	1,065	1,000	85%
0.9	4,052	43%	890	1,030	976	88%
0.8	4,343	47%	802	987	942	90%
0.7	4,665	52%	711	932	898	93%
0.6	5,022	56%	618	864	840	94%
0.5	5,421	61%	522	781	767	96%
0.4	5,872	66%	424	679	675	97%
0.3	6,384	71%	322	555	559	98%
0.2	6,972	75%	218	404	414	99%
0.1	7,654	80%	111	222	231	99%
0	8,452	86%	0	0	0	100%

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

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

Result of application of HS S-R relationship using data of the whole period

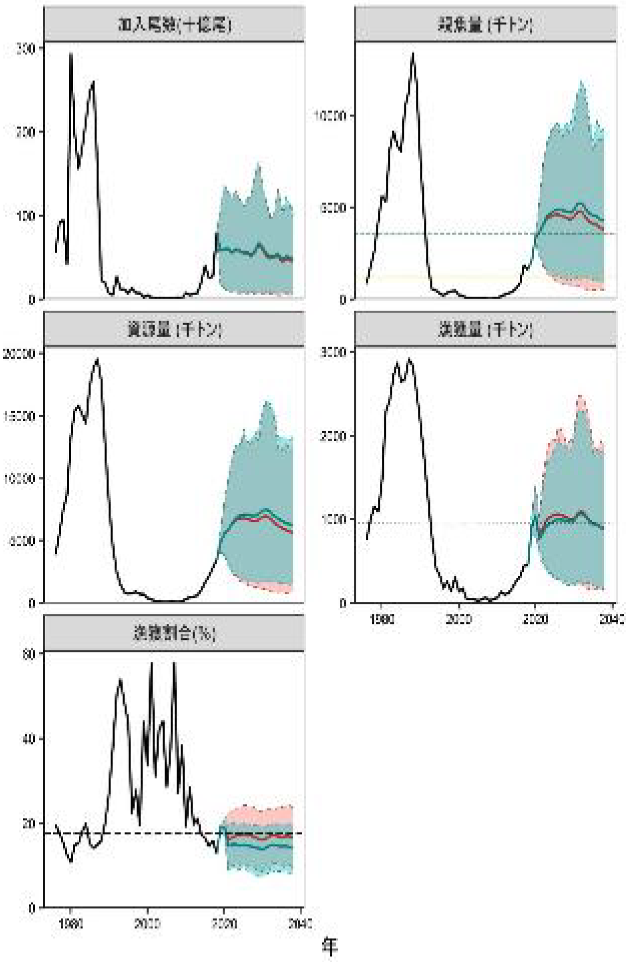
Appendix 3. Examination of risk of biomass depletion

Compared with the model where the S-R relationship is applied to the data of the whole period, the fishing mortality that produces MSY based on the S-R relationship of the normal recruitment period is slightly optimistic (Table 3 and Appendix Table 2-1). One possible reason is: because the distribution of recruitment residuals is larger when a single S-R relationship is applied to data of the whole period and also there is autocorrelation, variation of projected recruitment is larger and, therefore, the spawning biomass that produces MSY was estimated conservatively. For this reason, the use of the S-R relationship of the normal recruitment period could have a risk of over-prediction of catch and biomass depletion in the case where the actual S-R relationship is not clearly divided but uniform throughout the periods. Therefore, we assessed the risk of biomass depletion due to application of the S-R relationship of the normal recruitment period by conducting simplified MSE for the case applying the S-R relationship of the normal recruitment period when the real situation is a single S-R relationship applicable to data of the whole period (for details, see "Comparison of robustness of multiple reference points and examination of HCRs using simplified MSE (FRA-SA2020-BRP01-7)").

Results are shown in Appendix Figure 3 and Appendix Tables 3-1 to 3-4. With safety coefficient β set at 0.5 and under, the probability of exceeding the true (single S-R relationship applied to data of the whole period) limit reference point after 10 years was over 90% (Appendix Table 3-2). Judging from the small-sample-size-corrected version of AICc, etc. models that divide the S-R relationship by period are considered to be more plausible, but we cannot dismiss the possibility of a single S-R relationship throughout the whole period. For this reason, it is not recommended to set β higher than the standard value (0.8). We can reduce the risk of biomass depletion by lowering β toward 0.5.

References

Ichinokawa M. (2020) Kani teki MSE wo mochiita fukusuu no kanri kijunchi no gankensei no hikaku / HCR no kentou (Comparison of robustness of multiple reference points using simplified MSE and study of HCRs). FRA-SA2020-BRP01-7.



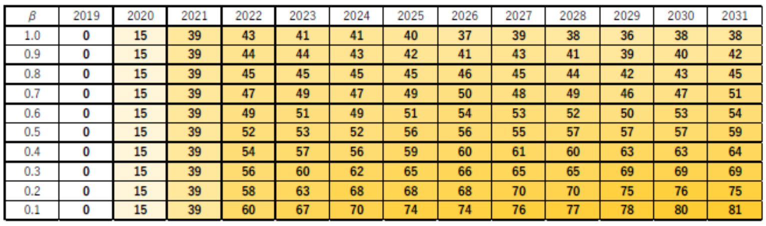
加入尾数（十億尾）	Recruitment (billion individuals)
資源量（千トン）	Stock biomass (thousand tons)
漁獲割合	Exploitation rate (%)
親魚量（千トン）	Spawning biomass (thousand tons)
漁獲量（千トン）	Catch (thousand tons)

Appendix Figure 3. Comparison of the future projection assuming control based on the S-R relationship of the normal recruitment period (in red) with the future projection assuming control based on the actual S-R relationship (a single S-R relationship is applied to data of the whole period) (in green)

The thick solid line expresses the average value, while the shaded area expresses the 90% prediction interval that contains 90% of the simulation results. In the spawning biomass chart, the green dashed line, the yellow dotted line and red line express the proposed target reference point, proposed limit reference point, and proposed fishing ban level, respectively. The dashed line in the catch chart expresses MSY, while the dashed line in the exploitation ratio chart expresses Umsy (both values are based on the true S-R relationship). The catch in 2019 and

2020 is assumed based on the projected biomass and Fcurrent, while the catch in 2021 and after is based on the proposed HCRs. Safety coefficient β is set to 0.8.

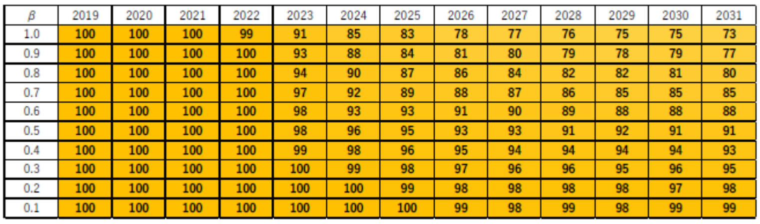
Appendix Table 3-1. Probability for future spawning biomass to exceed the proposed target reference point (of the true S-R relationship) (%)



β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
1.0	0	15	39	43	41	41	40	37	39	38	36	38	38
0.9	0	15	39	44	44	43	42	41	43	41	39	40	42
0.8	0	15	39	45	45	45	45	46	45	44	42	43	45
0.7	0	15	39	47	49	47	49	50	48	49	46	47	51
0.6	0	15	39	49	51	49	51	54	53	52	50	53	54
0.5	0	15	39	52	53	52	56	56	55	57	57	57	59
0.4	0	15	39	54	57	56	59	60	61	60	63	63	64
0.3	0	15	39	56	60	62	65	66	65	65	69	69	69
0.2	0	15	39	58	63	68	68	68	70	70	75	76	75
0.1	0	15	39	60	67	70	74	74	76	77	78	80	81

The true S-R relationship is the relationship applied to data of the whole period, but this is the result of control based on the S-R relationship of the normal recruitment period.

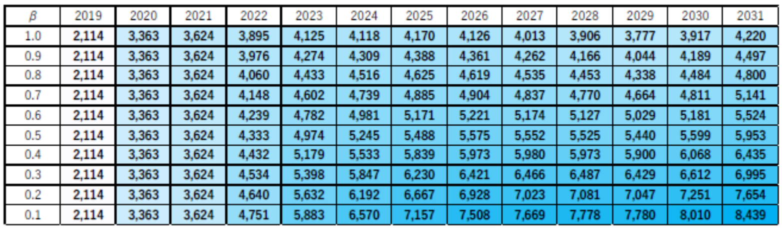
Appendix Table 3-2. Probability for future spawning biomass to exceed the proposed limit reference point (of the true S-R relationship) (%)



β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
1.0	100	100	100	99	91	85	83	78	77	76	75	75	73
0.9	100	100	100	100	93	88	84	81	80	79	78	79	77
0.8	100	100	100	100	94	90	87	86	84	82	82	81	80
0.7	100	100	100	100	97	92	89	88	87	86	85	85	85
0.6	100	100	100	100	98	93	93	91	90	89	88	88	88
0.5	100	100	100	100	98	96	95	93	93	91	92	91	91
0.4	100	100	100	100	99	98	96	95	94	94	94	94	93
0.3	100	100	100	100	100	99	98	97	96	96	95	96	95
0.2	100	100	100	100	100	100	99	98	98	98	98	97	98
0.1	100	100	100	100	100	100	100	99	98	99	98	99	99

The true S-R relationship is the relationship applied to data of the whole period, but this is the result of control based on the S-R relationship of the normal recruitment period.

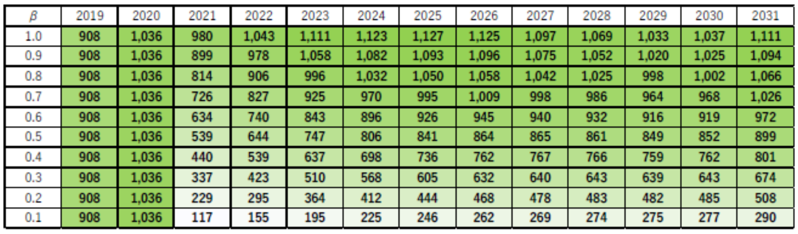
Appendix Table 3-3. Changes in future average spawning biomass (thousand tons)



β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
1.0	2,114	3,363	3,624	3,895	4,125	4,118	4,170	4,126	4,013	3,906	3,777	3,917	4,220
0.9	2,114	3,363	3,624	3,976	4,274	4,309	4,388	4,361	4,262	4,166	4,044	4,189	4,497
0.8	2,114	3,363	3,624	4,060	4,433	4,516	4,625	4,619	4,535	4,453	4,338	4,484	4,800
0.7	2,114	3,363	3,624	4,148	4,602	4,739	4,885	4,904	4,837	4,770	4,664	4,811	5,141
0.6	2,114	3,363	3,624	4,239	4,782	4,981	5,171	5,221	5,174	5,127	5,029	5,181	5,524
0.5	2,114	3,363	3,624	4,333	4,974	5,245	5,488	5,575	5,552	5,525	5,440	5,599	5,953
0.4	2,114	3,363	3,624	4,432	5,179	5,533	5,839	5,973	5,980	5,973	5,900	6,068	6,435
0.3	2,114	3,363	3,624	4,534	5,398	5,847	6,230	6,421	6,466	6,487	6,429	6,612	6,995
0.2	2,114	3,363	3,624	4,640	5,632	6,192	6,667	6,928	7,023	7,081	7,047	7,251	7,654
0.1	2,114	3,363	3,624	4,751	5,883	6,570	7,157	7,508	7,669	7,778	7,780	8,010	8,439

The true S-R relationship is the relationship applied to data of the whole period, but this is the result of control based on the S-R relationship of the normal recruitment period.

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



β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
1.0	908	1,036	980	1,043	1,111	1,123	1,127	1,125	1,097	1,069	1,033	1,037	1,111
0.9	908	1,036	899	978	1,058	1,082	1,093	1,096	1,075	1,052	1,020	1,025	1,094
0.8	908	1,036	814	906	996	1,032	1,050	1,058	1,042	1,025	998	1,002	1,066
0.7	908	1,036	726	827	925	970	995	1,009	998	986	964	968	1,026
0.6	908	1,036	634	740	843	896	926	945	940	932	916	919	972
0.5	908	1,036	539	644	747	806	841	864	865	861	849	852	899
0.4	908	1,036	440	539	637	698	736	762	767	766	759	762	801
0.3	908	1,036	337	423	510	568	605	632	640	643	639	643	674
0.2	908	1,036	229	295	364	412	444	468	478	483	482	485	508
0.1	908	1,036	117	155	195	225	246	262	269	274	275	277	290

The true S-R relationship is the relationship applied to data of the whole period, but this is the result of control based on the S-R relationship of the normal recruitment period.

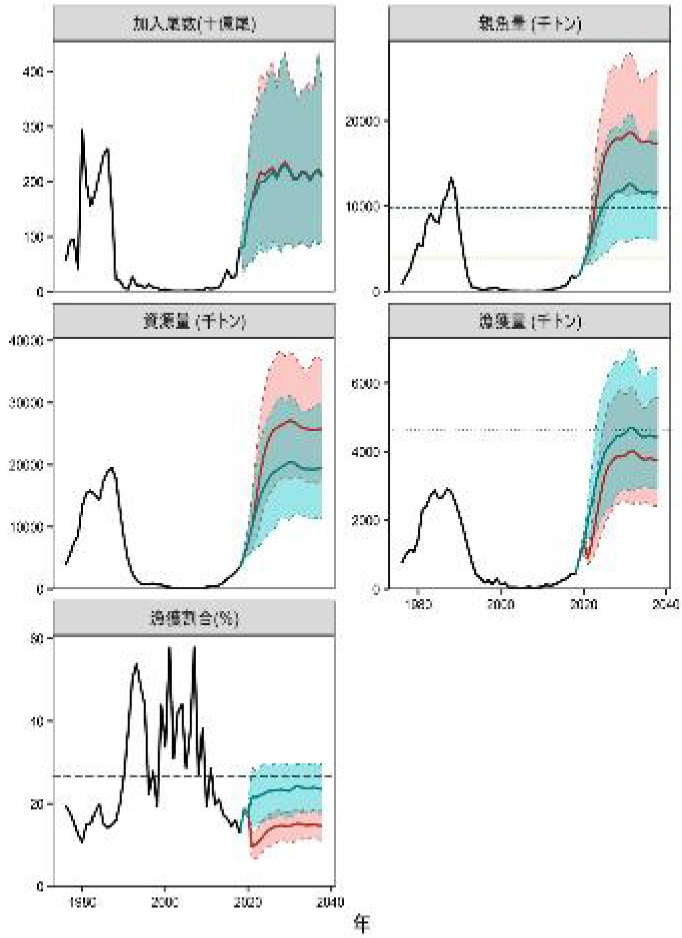
Appendix 4. Examination of risk of losing fishing opportunity

Application of the S-R relationship of the normal recruitment period poses a risk of losing fishing opportunity if the stock is actually in a high-recruitment period. In order to assess this risk, we conducted simplified MSE for control assuming the S-R relationship of the normal recruitment period even though true S-R relationship is that of a high-recruitment period (for details, see "Comparison of robustness of multiple reference points and examination of HCRs using simplified MSE (FRA-SA2020-BRP01-7)").

The results are shown in Appendix Figure 4 and Appendix Tables 4-1 to 4-4. Control based on the S-R relationship of the normal recruitment period when it is actually the high-recruitment period results in a catch over the current level (451 thousand tons in 2018) in many cases, but the catch was smaller compared with the case correctly applying the S-R relationship of the high recruitment period (Appendix Table 4-1). It is indicated that the closer β is to 1, the smaller the catch decrease . Compared with the past high-recruitment period, it is predicted that when β is 0.7 or higher, the average catch volume in 2021 and after will be higher than the catch of the past high-recruitment period (1976 and after).

References

Ichinokawa M. (2020) Kani teki MSE wo mochiita fukusuu no kanri kijunchi no gankensei no hikaku / HCR no kentou (Comparison of robustness of multiple reference points using simplified MSE and study of HCRs). FRA-SA2020-BRP01-7.



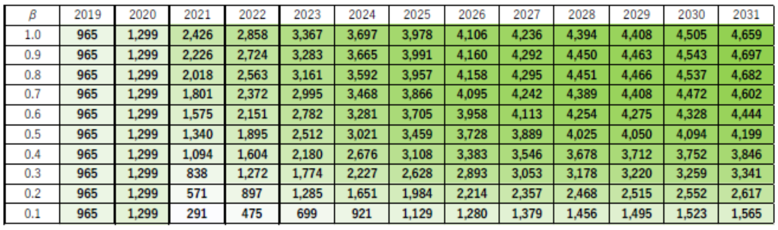
加入尾数（十億尾）	Recruitment (billion individuals)
資源量（千トン）	Stock biomass (thousand tons)
漁獲割合	Exploitation rate (%)
親魚量（千トン）	Spawning biomass (thousand tons)
漁獲量（千トン）	Catch (thousand tons)
加入尾数（十億尾）	Year

Appendix Figure 4. Comparison of the future projection assuming control based on the S-R relationship of the normal recruiting period (in red) with the future projection assuming control based on the true S-R relationship (the S-R relationship of the high recruitment period) (in green)

The thick solid line expresses the average value, while the shaded area expresses the 90% prediction interval that contains 90% of the simulation results. In the spawning biomass chart, the green dashed line, the yellow dotted line, and the red line express the proposed target reference point, proposed limit reference point, and proposed fishing ban level, respectively. The dashed line of the catch chart expresses MSY, while the dashed line of the exploitation ratio chart expresses Umsy (all values are based on the true S-R relationship). The catch in 2019 and 2020 is assumed based on the projected biomass and Fcurrent, while the catch in 2021 and after is based on the proposed HCRs. Safety coefficient β is set to 0.8.

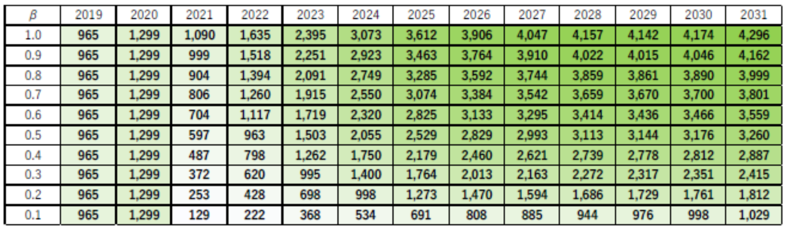
Appendix Table 4-1. Changes in future average catch (thousand tons)

●Assuming control based on the S-R relationship of the true high recruitment period



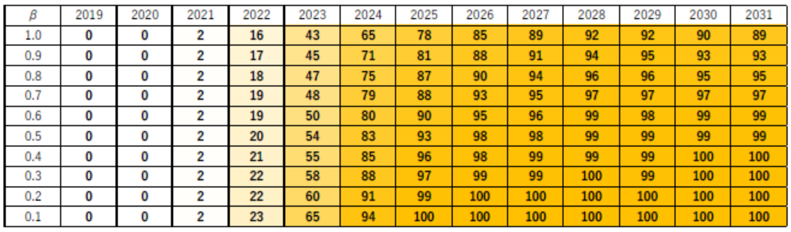
β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
1.0	965	1,299	2,426	2,858	3,367	3,697	3,978	4,106	4,236	4,394	4,408	4,505	4,659
0.9	965	1,299	2,226	2,724	3,283	3,665	3,991	4,160	4,292	4,450	4,463	4,543	4,697
0.8	965	1,299	2,018	2,563	3,161	3,592	3,957	4,158	4,295	4,451	4,466	4,537	4,682
0.7	965	1,299	1,801	2,372	2,995	3,468	3,866	4,095	4,242	4,389	4,408	4,472	4,602
0.6	965	1,299	1,575	2,151	2,782	3,281	3,705	3,958	4,113	4,254	4,275	4,328	4,444
0.5	965	1,299	1,340	1,895	2,512	3,021	3,459	3,728	3,889	4,025	4,050	4,094	4,199
0.4	965	1,299	1,094	1,604	2,180	2,676	3,108	3,383	3,546	3,678	3,712	3,752	3,846
0.3	965	1,299	838	1,272	1,774	2,227	2,628	2,893	3,053	3,178	3,220	3,259	3,341
0.2	965	1,299	571	897	1,285	1,651	1,984	2,214	2,357	2,468	2,515	2,552	2,617
0.1	965	1,299	291	475	699	921	1,129	1,280	1,379	1,456	1,495	1,523	1,565

●Assuming control based on the S-R relationship of the normal recruitment period rather than the true high recruitment period



β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
1.0	965	1,299	1,090	1,635	2,395	3,073	3,612	3,906	4,047	4,157	4,142	4,174	4,296
0.9	965	1,299	999	1,518	2,251	2,923	3,463	3,764	3,910	4,022	4,015	4,046	4,162
0.8	965	1,299	904	1,394	2,091	2,749	3,285	3,592	3,744	3,859	3,861	3,890	3,999
0.7	965	1,299	806	1,260	1,915	2,550	3,074	3,384	3,542	3,659	3,670	3,700	3,801
0.6	965	1,299	704	1,117	1,719	2,320	2,825	3,133	3,295	3,414	3,436	3,466	3,559
0.5	965	1,299	597	963	1,503	2,055	2,529	2,829	2,993	3,113	3,144	3,176	3,260
0.4	965	1,299	487	798	1,262	1,750	2,179	2,460	2,621	2,739	2,778	2,812	2,887
0.3	965	1,299	372	620	995	1,400	1,764	2,013	2,163	2,272	2,317	2,351	2,415
0.2	965	1,299	253	428	698	998	1,273	1,470	1,594	1,686	1,729	1,761	1,812
0.1	965	1,299	129	222	368	534	691	808	885	944	976	998	1,029

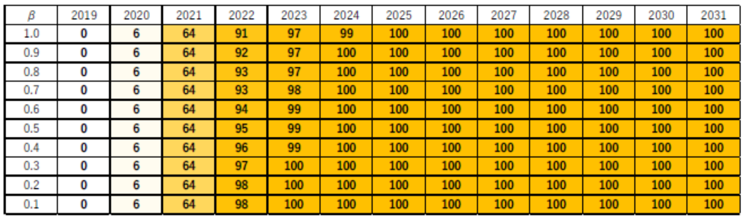
Appendix Table 4-2. Probability for future spawning biomass to exceed the proposed target reference point (of the true S-R relationship) (%)



β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
1.0	0	0	2	16	43	65	78	85	89	92	92	90	89
0.9	0	0	2	17	45	71	81	88	91	94	95	93	93
0.8	0	0	2	18	47	75	87	90	94	96	96	95	95
0.7	0	0	2	19	48	79	88	93	95	97	97	97	97
0.6	0	0	2	19	50	80	90	95	96	99	98	99	99
0.5	0	0	2	20	54	83	93	98	98	99	99	99	99
0.4	0	0	2	21	55	85	96	98	99	99	99	100	100
0.3	0	0	2	22	58	88	97	99	99	100	99	100	100
0.2	0	0	2	22	60	91	99	100	100	100	100	100	100
0.1	0	0	2	23	65	94	100	100	100	100	100	100	100

Results of control based on the S-R relationship of the normal recruitment period rather than the true high recruitment period

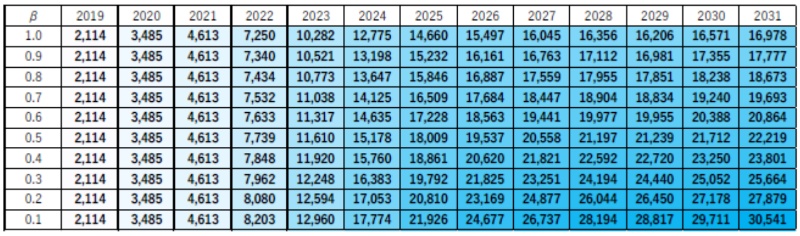
Appendix Table 4-3. Probability for future spawning biomass to exceed the proposed limit reference point (of the true S-R relationship) (%)



β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
1.0	0	6	64	91	97	99	100	100	100	100	100	100	100
0.9	0	6	64	92	97	100	100	100	100	100	100	100	100
0.8	0	6	64	93	97	100	100	100	100	100	100	100	100
0.7	0	6	64	93	98	100	100	100	100	100	100	100	100
0.6	0	6	64	94	99	100	100	100	100	100	100	100	100
0.5	0	6	64	95	99	100	100	100	100	100	100	100	100
0.4	0	6	64	96	99	100	100	100	100	100	100	100	100
0.3	0	6	64	97	100	100	100	100	100	100	100	100	100
0.2	0	6	64	98	100	100	100	100	100	100	100	100	100
0.1	0	6	64	98	100	100	100	100	100	100	100	100	100

Results of control based on the S-R relationship of the normal recruitment period rather than the true high recruitment period

Appendix Table 4-4. Changes in future average spawning biomass (thousand tons)



β	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
1.0	2,114	3,485	4,613	7,250	10,282	12,775	14,660	15,497	16,045	16,356	16,206	16,571	16,978
0.9	2,114	3,485	4,613	7,340	10,521	13,198	15,232	16,161	16,763	17,112	16,981	17,355	17,777
0.8	2,114	3,485	4,613	7,434	10,773	13,647	15,846	16,887	17,559	17,955	17,851	18,238	18,673
0.7	2,114	3,485	4,613	7,532	11,038	14,125	16,509	17,684	18,447	18,904	18,834	19,240	19,693
0.6	2,114	3,485	4,613	7,633	11,317	14,635	17,228	18,563	19,441	19,977	19,955	20,388	20,864
0.5	2,114	3,485	4,613	7,739	11,610	15,178	18,009	19,537	20,558	21,197	21,239	21,712	22,219
0.4	2,114	3,485	4,613	7,848	11,920	15,760	18,861	20,620	21,821	22,592	22,720	23,250	23,801
0.3	2,114	3,485	4,613	7,962	12,248	16,383	19,792	21,825	23,251	24,194	24,440	25,052	25,664
0.2	2,114	3,485	4,613	8,080	12,594	17,053	20,810	23,169	24,877	26,044	26,450	27,178	27,879
0.1	2,114	3,485	4,613	8,203	12,960	17,774	21,926	24,677	26,737	28,194	28,817	29,711	30,541

Results of control based on the S-R relationship of the normal recruitment period rather than the true high recruitment period

Appendix 5. Influence of changes in body weight at age according to stock status

We assumed constant body weight at age when calculating SBmsy. However, because it is reported that growth speed and body fatness of this stock change according to the stock status (Wada and Kashiwai 1991, Kawabata et al. 2011), body weight at age can change according to the stock status. For this reason, we considered the influence on SBmsy from changes in body weight at age according to the stock status. First, we conducted simple linear regression using the logarithm of the number of fish and body weight at each age. From the estimated regression formula of each age, body weight at age according to the number of fish was probabilistically produced (for details, see "Technical Note on estimation of S-R relationship, reference point calculation and future prediction simulation (FRA2020-ABCWG01-02)"). We applied the HS S-R relationship of the normal recruitment period (the least squares method without autocorrelation). Settings are the same as those of the body text excluding the setting of body weight at age.

The results of the regression analysis showed a negative relationship between the number of fish and body weight at age – body weight decreases with increase in the number of fish (Appendix Figure 5). When changes in body weight at age according to the stock status are incorporated into simulation by using this regression formula, SBmsy and MSY became slightly lower but there was no significant change (Appendix Table 5). This time we simply used the regression formula of the number of fish and body weight of each age, but it is necessary to continue to study how to incorporate the relationship between the number of fish and body weight into simulation.

References

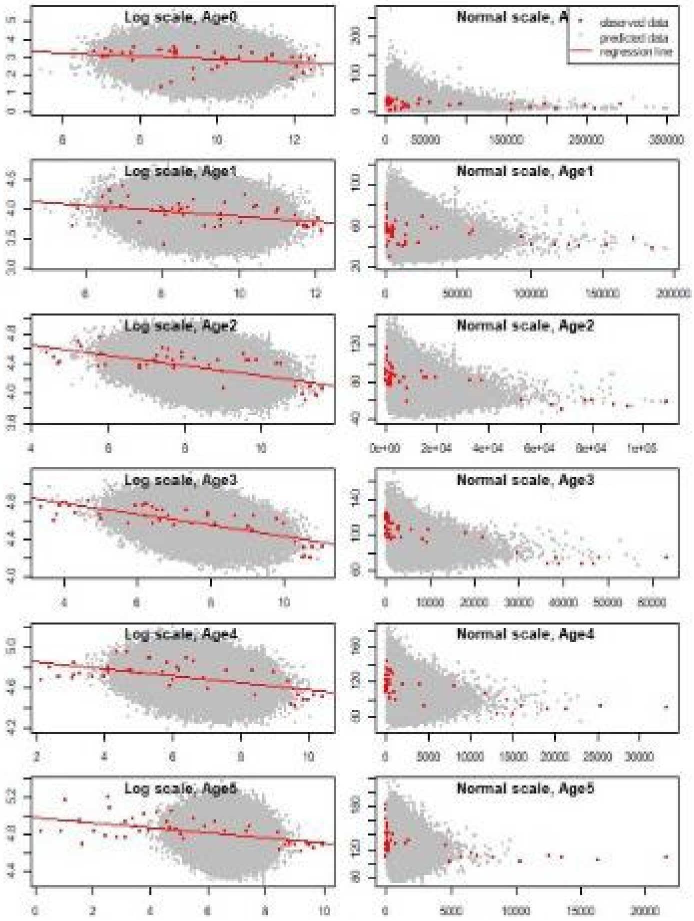
ABCWG (2020) Technical Note on Estimation of stock-recruitment relationship, reference point calculation and future prediction simulation (2020 Research Institute Meeting Version). FRA-SA2020-ABCWG01-02.

Kawabata, A., H. Yamaguchi, S. Kubota and M. Nakagami (2011) Growth and fatness of 1975-2002 year classes of Japanese sardine in the Pacific waters around northern Japan. Fish. Sci., 77, 291-299.

Wada, T. and M. Kashiwai (1991) Changes in growth and feeding ground of Japanese sardine with fluctuation in stock abundance. In: Long-term variability of pelagic fish populations and their environment, ed. Kawasaki, T. et al., Pergamon, Oxford, pp. 181-190.

Appendix Table 5. SBmsy, etc. when body weight at age is fixed and when changed according to the number of fish

	Body weight at age is fixed	Body weight is changed according to the number of fish
SBmsy (thousand tons)	1,097	1,004
MSY (thousand tons)	368	346
Umsy	0.21	0.20
Fmsy/Fcurrent	0.99	0.98



Appendix Figure 5. Relationship between the number of fish and body weight at each age

From above, the charts show the relationship between the number of fish and body weight at age 0, 1, 2, 3, 4, and 5 and above. Body weight is put to the vertical axis and the number of fish is put to the horizontal axis. A logarithmic scale is used for both axes in the left charts, while a normal scale is used in right charts. The red lines represent estimated regression formula, red dots represent actual values, and gray dots show the values used for the simulation.