Stock Assessment for Honshu Northern Pacific Stock of Pacific Cod (Fiscal Year 2022)

Fisheries Stock Assessment Center, Fisheries Resources Institute, Japan Fisheries Research and Education Agency

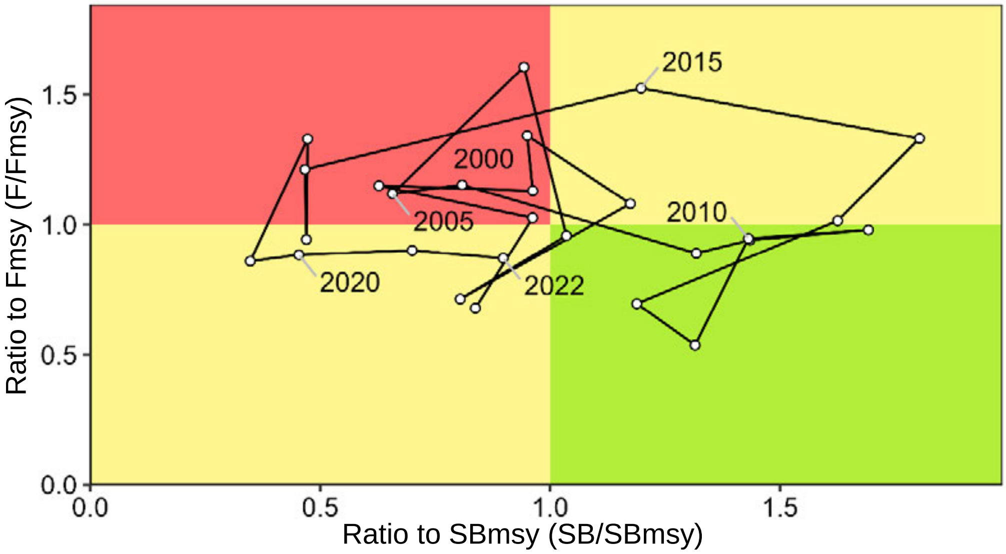
Participating Organizations: Aomori Prefectural Industrial Technology Research Center Fisheries Institute, Iwate Prefectural Fisheries Technology Center, Miyagi Prefecture Fisheries Technology Institute, Fukushima Prefectural Fisheries and Marine Science Research Center, Fukushima Prefectural Research Institute of Fisheries Resources, Ibaraki Prefectural Fisheries Research Institute, and Marine Ecology Research Institute

Summary

The biomass of this stock was estimated by cohort analysis using the bottom-trawl survey results as tuning indices. Stock biomass (total weight of fish age 1 and older) ranged from 23,000 to 60,000 tons during the 1996 to 2010 fishing seasons (April to March of the following year) and increased to 66,000 to 84,000 tons during the 2012 to 2013 fishing seasons following the Great East Japan Earthquake (hereinafter referred to as “Earthquake”). Since the 2014 fishing season, this stock has been in a decreasing trend, and the biomass was 17,000 tons in the 2022 fishing season. The SSB (spawning stock biomass) remained relatively stable in the range of 7,000 to 13,000 tons from the 1996 to 2006 fishing seasons, but has increased while fluctuating in cycles since the 2007 fishing season, reaching 20,000 tons in the 2014 fishing season. It has been declining since the 2015 fishing season, but has increased again to 10,000 tons in the 2022 fishing season. Recruitment size (stock population of age 1 fish) ranged from 11 million to 63 million fish in the 1996 to 2014 fishing seasons. On the other hand, since the 2015 fishing season, recruitment size has been low, ranging from 3 million to 17 million fish, and reached a record low of 3 million fish in the 2022 fishing season.

In March and August 2021, the Research Institute Meeting applied a Ricker model for stock-recruitment relationships to the stock-recruitment relationship model of this stock The SSB required for maximum sustainable yield (SBmsy) was estimated at 10,900 tons based on the applied stock-recruitment relationship. Following these criteria, SSB of this stock in 2021 is below SBmsy. In addition, the catch pressure in 2022 isbelow the level required for MSY. Based on trends seen in the previous 5 years (2018 to 2022), SSB is judged to be in a “increase” trend.

In this stock, the reference points, future projections, and other items are provisional values as proposed at the Research Institute Meeting, which will be finalized based on discussions of the Stock Management Policy Commission.



Summary Figures and Tables

MSY, Levels and Trends in SSB, and ABC	
SSB required for MSY	10,900 tons
Level of SSB for the 2022 fishing season	Under the level required for MSY
Level of fishing pressure for the 2022 fishing season	Under the level required for MSY
Trends in SSB in 2022	Increase
Maximum Sustainable Yield (MSY)	20,200 tons
ABC for the 2024 fishing season	-
Comments: ・ABC is estimated after Harvest Control Rules (HCRs) for this stock are compiled by the Stock Management Policy Commission, and set through the Fishery Policy Council. ・ It should be noted that the biomass remains low due to the fact that recruitment size in recent years has consistently been below the average value expected based on the stock-recruitment relationship.	

Recent Biomass, Catch, Fishing Pressure, and Exploitation Rate					
Fishing year	Biomass (thousand tons)	SSB (thousand tons)	Catch (thousand tons)	F/Fmsy	Exploitation rate (%)
2018	22.5	5.1	10.4	1.33	46
2019	18.9	3.8	6.6	0.86	35
2020	22.4	4.9	7.1	0.88	32
2021	23.8	7.6	7.3	0.89	30
2022	17.4	9.9	6.5	0.85	37
2023	17.6	10.7	7.9	0.90	45
2024	16.8	4.8	-	-	-
・The values for 2023 and 2024 are estimates based on future projections.					

1. Data Sets

Data Sets	Basic Information & Related Surveys
Catch in weight and number at age and by year	・ Fishery catch statistics by prefecture (Ministry of Agriculture, Forestry and Fisheries, and prefectural fishery experimental stations) ・ Catch performance report for Bottom-Trawl Fishing in Offshore Waters, Northern Pacific region (Fisheries Agency) ・ Body length composition of catches based on market measurements (Hachinohe, Miyako, Ishinomaki) ・ ALK using bottom-trawl survey catches (April and October to November) and market catches (prepared in six month periods for each year)
Stock abundance index ・ Abundance indices ・ SSB	・Standing stock based on demersal species stock abundance survey (Fisheries Resources Institute, bottom-trawl survey (October to November))* ・ Maturity ratio at age by year using precision-measured data from bottom-trawl surveys (October to November) and market catches (December to March of the following year)
Natural mortality (M)	Assuming M = 0.357 per year (Tanaka 1960)

* Indicates the tuning index for cohort analysis.

The fishing season for the stock is April through March of the following year, and the starting date for age is April 1.

2. Ecology

(1) Distribution / Migration

Pacific cod is widely found around coastal areas in the North Pacific and is distributed around Japan from the Sea of Japan to the northern East China Sea, the Pacific Ocean of northern Japan, and the Sea of Okhotsk (Bakkala et al. 1984). The southern limit of its distribution in the Pacific Ocean is considered to be off the coast of Ibaraki Prefecture (Mishima 1984, Fig. 2-1).

It is thought that there are more than 10 subpopulations of Pacific cod in and around Asia alone. The range of travel for individual subpopulations is limited and there is little interaction between them (Bakkala et al. 1984). However, mitochondrial DNA analysis of Pacific cod distributed in Japan shows no clear genetic differences, except for schools distributed in the San'in region (Suda et al. 2017). Spawning schools of Pacific cod form in Mutsu Bay in Aomori Prefecture. Tagged releases have shown that many individuals from these schools migrate to the Pacific coast of Hokkaido after spawning and return to Mutsu Bay once again during the spawning season (Fukuda et al. 1985, Miura et al. 2019). In addition, fishery catch statistics show no relationship between trends in catches off the

Pacific coast of the Tohoku region and those in the Mutsu Bay area. Therefore, we determined that the schools spawning in Mutsu Bay and migrating to the Pacific side of Hokkaido were a separate subpopulation to the Honshu North Pacific schools. For this assessment, we included individuals caught south and east of Omazaki, Aomori prefecture in this stock.

Distribution depths range from 40 to 550 m except for juveniles and during spawning migrations (Hattori et al. 2002, Narimatsu et al. 2015a), with seasonal shallow and deep migrations (Hashimoto 1974, Narimatsu et al. 2015b). The North-South migration is not clear.

(2) Age / Growth

Various hard tissue such as scales and dorsal fin rays has been used to determine the age of Pacific cod. In the Tohoku area, age determination has been conducted using sagittal otoliths (Hattori et al. 1992). Pacific cod grow quickly, reaching a length of 90 cm and a weight of 10 kg at the maximum age of 8 years (Fig. 2-2). Growth varies from year to year and is thought to be affected by distribution density and springtime inflow intensity of the Oyashio 1st branch (Narimatsu 2006, Narimatsu et al. 2010). A slowdown in growth has been observed since the Earthquake (Appendix 8). The relationship between standard body length, age, and weight is shown in the equation below.

$$SL = 1255.2(1 - \exp(-0.16(t - 0.036)))$$
$$BW = 7.07 \times 10^{-6} \times SL^{3.12}$$

In these equations, SL is standard length (mm), t is age (age starting date is January 1), and BW is body weight (g). Since it has been confirmed that there are no sex differences in growth (Hattori et al. 1992), sex differences were not taken into account.

(3) Maturation / Spawning

Based on the migration of spawners and the appearance of juveniles, spawning grounds for this stock are thought to be in Sendai Bay (Miyagi Prefecture), off Hachinohe (Aomori Prefecture), and on a small scale throughout the Sanriku coast (Kodama et al. 1990, Hattori et al. 1999). From summer to fall, this stock inhabits areas of 200 m or more in depth. In winter, spawners migrate to depths of 100 m or less (Narimatsu et al. 2015b), where they lay eggs in sandy muddy areas in male-female pairs or in groups of several males per female (Sakurai and Hattori 1996). Females spawn once per breeding season, and the number of eggs laid ranges from 500,000 (individuals around 40 cm in length) to 4,000,000 (individuals around 80 cm in length) (Hattori et al. 1995). After maturity, they are thought to spawn annually.

Since the late 1990s, the 50% mature body length in northern Tohoku is 46.2 cm for males and 48.3 cm for females. Age at first maturity is 3 or 4 year of age, and like growth, the maturity rate of age 3 fish is negatively related to stock status (Narimatsu et al. 2010). Although almost all individuals age 4 and older had been considered mature (Narimatsu 2006, Narimatsu et al. 2010), a trend toward late maturity was observed after the Earthquake (Supplementary Fig. 8-2). The average maturity rate for 1996 to 2022 was 28% at age 3 and 75% at age 4.

(4) Predator-Prey Relationships

Prey includes copepod larvae, fish eggs, and decapod larvae during the planktonic stage; krill during the juvenile stage; and fish, cephalopods, and large crustaceans during the adult stage (Yamamura 1993, Takatsu et al. 1995, 2002, Ito et al. 2014). Smaller individuals have also been shown to be preyed upon by large Pacific cod (Hashimoto 1974).

3. Fishery Status

(1) Fishery Overview

The catch of this species is the largest in offshore trawl fisheries, and since the 2000 fishing season, the percentage of offshore bottom trawl accounting for total catch has ranged from 39 to 76% (Table 3-1). The next largest catches are from longline, gillnet, and small bottom trawl fisheries. While these fisheries catch fish year-round except during the closed season, large individuals that come ashore to spawn in the winter are caught in set nets. The catch targets are mainly fish aged 1 year and older.

(2) Trends in Catch in Weight

Looking at annual changes in the total catch of all kind of fisheries for the fishing year (April to March of the following year) (Fig. 3-1, Table 3-1), the catch gradually increased from the 1980 fishing season and reached the 10,000-ton level in the 1986 to 1990 fishing seasons. Thereafter, it declined, falling to the 3,000-ton level of the early 1980s in 1993 and 1994. After the 1995 fishing season, the catch amount began to increase again, reaching 24,000 tons in the 1998 fishing season. Thereafter, it has increased over the long term with repeated fluctuations, reaching 26,000 tons in the 2010 fishing season. The 2011 and 2012 fishing seasons saw a decrease from pre-disaster levels as a result of the Earthquake, but the 2013 and 2014 fishing seasons recorded around 31,000 tons despite negligible catches in Fukushima and Ibaraki prefectures. However, this has since declined, reaching 10,000 tons in the 2016 fishing season, 7,000 tons in the 2020 fishing season, and 6,000 tons in the 2022 fishing season, although this figure is still provisional.

Comparing catches by kind of fisheries, offshore bottom trawl catches were the largest in most years, followed by longline, gillnetting, small bottom trawlers, and set net catches (Fig. 3-1, Table 3-1). Fish were caught in a wide range of offshore areas from Aomori Prefecture to Ibaraki Prefecture in offshore bottom trawls in 2020; in particular, Catch amount was higher from off Aomori prefecture to off Miyagi prefecture (Fig. 3-2). Catch amount was large in Iwate and Miyagi Prefectures, and recently also large in Aomori Prefecture (Table 3-2).

The catch in number at age is shown in Supplementary Table 2-1. Overall, the catch in number aged 1 and 2 tended to be high. In the 2012 to 2015 fishing seasons following the Earthquake, relatively large numbers of individuals age 3 to 6 were also caught. After the 2016 fishing season, the catch in number in each age group declined, and by the 2022 fishing season, the catch of 4 to 6+ years old fish was relatively high while that of 1-3 years old fish was low, with age 2 in particular having the lowest catch since the 1996 fishing season.

(3) Fishing Effort

As an indicator of fishing effort, the non-zero catches (the total number of hauls per vessel on the days when Pacific cod were caught) by ocean area for offshore bottom trawls, where the catch of this stock was the highest in each fishing method, was determined (Fig. 3-3). Non-zero catches in the Shiriyazaki area have been gradually increasing over a long period since 1972, and exceeded 21,000 hauls in 2008. After that, non-zero catches remained stable at around 15,000 hauls; however, these remained at around 10,000 hauls from 2018 to 2020, and 7,900 thousand hauls in 2022. Non-zero catches in the Iwate area peaked at 6,000 hauls in 1993; however, this has been on a downward trend since then. In recent years, non-zero catches have remained at between 2,000 to 2,600 hauls per year from 2012 to 2020 after reaching 1,600 hauls in 2011. Non-zero catches in the Kinkasan area were as high as 15,000 to 20,000 hauls from 1992 to 2004, and then declined slowly until the Earthquake. Non-zero catches declined for about three years following the Earthquake, but have stabilized at 10,000 to 11,000 hauls since 2014, although this is less than before the Earthquake. Non-zero catches in the Joban area were recorded at more than 30,000 hauls from 1989 to 1991, but then declined with repeated fluctuations until the Earthquake. Since 2011, non-zero catches have remained very low due to operational regulations and self-imposed operational restraints, these remained 2,800 and 3,100 hauls in 2021 and 2022, respectively

4. Stock Status

(1) Stock Assessment Methods

April through March of the following year as the fishing year, and fish biomass was estimated by VPA with tuning (cohort analysis) using Pope's (1972) approximation equation (Appendix 2). The catch in number at age used in the VPA was determined by dividing the fishing year into the first half (April to September) and the second half (October to March of the following year), and cohort slicing the length composition obtained at major ports in Aomori, Iwate and Miyagi prefectures using the age-length key determined for each year and half-year. Cohort slicing was for fish age 1 to 6 and older, with fish age 0 not included because of low catches in recent years and fish age 7 and older not included because these do not appear in surveys or catches very often. Natural mortality (M) was set at 0.357 based on the Tauchi-Tanaka equation (Tanaka 1960), using the regularly seen upper age limit (7 years) as life expectancy. The standing stock by age determined by trawl surveys (Appendix 7, Supplementary Table 2-1) was used as the abundance index for the tuning indices.

(2) Trends in Abundance Indices

Trawl survey results show that standing stock population is highest in age 1 fish and tends to decrease with age (Fig. 4-1 and Supplementary Table 7-1). The number of age 1 fish varied widely from year to year, ranging from 370,000 to 69,000,000 fish in the 1996 to 2022 fishing seasons. There were relatively large numbers in the 2011 to 2015 fishing seasons, and the overall number of fish was high. The standing stock, determined by multiplying the standing stock population by weight by fishing year and weight by age, also showed significant annual changes, ranging from 6,000 to 90,000 tons from 1996 to 2022, with the lowest value in the 2001 fishing season and the highest value in the 2012 fishing season (Fig. 4-2 and Supplementary Table 7-2). However, this declined after the 2013 fishing season, falling below 30,000 tons after the 2017 fishing season to 6,000 tons in the 2022 fishing season.

Time series variation in offshore bottom trawl CPUE (catch per unit effort) was determined for each small sea area as the abundance index based on fishery information. The CPUE was higher in the late 1990s than before, except for Danish seine fishing in the Shiriyazaki area; however, this then declined until 2002 (Fig. 4-3). CPUE was high in all ocean areas from 2012 to 2014, but has since decreased in all ocean areas, with low values since 2017. It should be noted that the operation mode for offshore bottom trawls is thought to have changed since the Earthquake.

Of the above abundance indices, the trawl survey results were used as tuning indices for the VPA because the trawl survey results provide age-specific information and because the fishery information shows changes in operation modes before and after the Earthquake.

(3) Trends in Biomass and Fishing Pressure

Stock population at age, biomass at age, SSB, and recruitment per spawning (RPS, recruitment (age 1) per kg of spawners), estimated by cohort analysis, are shown in Fig. 4-4, Fig. 4-5, Fig. 4-6, and Table 4-1 (see Appendix 2 for details). The proportion of age 1 and 2 fish making up the stock population is high, and the stock consists mainly of young fish. Recruitment (age 1 stock population) in the 2004 fishing season was 63 million fish, the highest among the 1996 to 2022 fishing seasons; however, this has since declined while fluctuating in cycles, reaching a record low of 3 million fish in the 2022 fishing season. The 2022 fishing season not only had fewer age 1 fish, but also had fewer fish age 2 and older, so the total for all ages was 10 million fish, the lowest number of fish since the 1996 fishing season.

Biomass remained between 23,000 and 61,000 tons during the 1996 to 2010 fishing seasons, but increased after the Earthquake, reaching 84,000 tons in 2013. It has decreased since 2014, reaching around 20,000 tons in the 2016 to 2022 fishing seasons. When looking at the results by age, the 2022 fishing season's biomass of age 1 fish was 1,100 tons, the lowest in the past 27 years (the average was 8,100 tons), and the biomass of age 2 fish was also the lowest in the past 27 years. Fish age 4 to 6 and more are relatively high.

SSB has increased while fluctuating in cycles since the 1996 fishing season, peaking at 20,000 tons in the 2014 fishing season. Since then, it has declined, reaching 4,000-5,000 tons in the 2016-2022 fishing seasons and has recovered to 10,000 tons until the 2022 fishing season. SSB is relatively high but biomass of age 1 and 2 fish is low, so the total biomass will decrease in near future.

Recruitment per spawning (RPS, recruitment of age 1 fish/SSB) was as high as 4.3 to 5.6 ind./kg in the 2003 to 2007 fishing seasons; however, this declined to 0.7 to 2.8 ind./kg in the 2008 to 2016 fishing seasons. There was a slight recovery of 2.7 to 3.8 ind./kg in the 2017 to 2020 fishing seasons; however, SSB was generally low and did not result in significant recruitment. It was also low at 1.0 and 0.4 ind./kg in the 2021 and 2022 fishing seasons, respectively.

Fishing mortality F fluctuates from year to year and with age, and tends to be higher the older the individual (Fig. 4-7). F for age 1 was low in the 2008 to 2019 fishing seasons; but it was slightly higher in the 2020 - 2022 fishing seasons. F for age 2 to 4 tended to be similar.

Biomass for the 1996 to 2022 fishing seasons when M is adjusted between 0.3 and 0.4 is estimated at 16,000 to 78,000 tons when M = 0.3, and 18,000 to 89,000 tons when M = 0.4, which is 90 to 94% for the former and 105 to 108% for the latter when compared to when M = 0.357 (Fig. 4-8).

(4) Yield Per Recruit (YPR), Spawning Per Recruit (SPR), and Current Fishing Pressure

In order to compare fishing pressures with consideration for selectivity, we compared findings for spawning per recruit (SPR) in scenarios with and without fishing pressure. Fig. 4-9 shows changes in the SPR ratio (%SPR), which compares SPR in a scenario without fishing pressure against SPR in a scenario with fishing for each year. The %SPR tended to be low, ranging from 1.9% to 13.7%, and the %SPR was 7.7% when calculated using the average F value over the recent 3 years (the 2019 to 2021 fishing seasons) as the current fishing pressure.

The relationship between current fishing pressure and YPR and %SPR is shown in Fig. 4-10. The selection probability of F was defined as the value used to estimate the level of F required for maximum sustainable yield (Fmsy) (Narimatsu et al. 2021a) at the Research Institute Meeting held in August 2020. In addition, the values used to calculate Fmsy were also used for average body weight at age and the maturity rate (Supplementary Table 5-1). Fmsy is equivalent to 5.9% when converted to %SPR. The current fishing pressure (F2019-2021) is above Fmax and F30%SPR but below Fmsy.

(5) Stock-Recruitment Relationship

The relationship (stock-recruitment relationship) between SSB (in weight) and recruitment size (individuals) is shown in Figure 4-11. The above-mentioned Research Institute Meeting applied a Ricker model for stock-recruitment relationships to the stock-recruitment relationship model of this stock (Narimatsu et al. 2021a). The data used to estimate the parameters of the stock-recruitment relationship model was SSB and recruitment volume based on stock assessments for the 2020 fiscal year (Narimatsu et al. 2021b), and the optimization method was the minimum absolute value method. We believe there is autocorrelation regarding residuals in recruitment volume. The parameters of the stock-recruitment relationship model are shown in Supplementary Table 6-1.

(6) Levels Required for MSY Under Current Environmental Conditions

The SSB required for maximum sustainable yield (SBmsy) and the fishing pressure required for maximum sustainable yield (Fmsy), under current environmental conditions (1996 and onward), were defined as the values estimated at the aforementioned Research Institute Meeting (Narimatsu et al. 2021b), and are shown in Supplementary Table 6-2.

(7) Stock Levels/Trends and Fishing Pressure Levels

Reference values for SSB and fishing pressure required for MSY are shown in a Kobe plot in Fig. 4-12. In addition, a summary of SSB and fishing pressure in 2022 is shown in Supplementary Table 6-3. SSB of this stock in the 2022 fishing season was below the SSB required for MSY (SBmsy), SSB in the 2022 fishing season was 0.9 times the value of SBmsy. In addition, the fishing pressure in the

2022 fishing season was lower than the fishing pressure required for MSY (Fmsy), specifically, it was 0.85 times the value of Fmsy. The F ratios (F/Fmsy) shown in the Kobe plot are the ratio between F values in each year, and the value of F that gives the fishing pressure of Fmsy under the selectivity of F in each year, converted to %SPR. Based on trends seen in the previous 5 years (2018 to 2022), the SSB is judged to be in a “increase” trend. SSB for this stock exceeded SBmsy during the 2007 to 2015 fishing seasons, but has remained at a level below SBmsy since the 2016 fishing season due to increased fishing pressure and decreased recruitment.

5. Summary of Stock Assessment

The biomass of this stock increased from 23,000 to 84,000 tons between the 1996 and 2013 fishing seasons, but then decreased to 23,000 tons in the 2016 fishing season. Afterwards, biomass did not increase due to the lack of major recruitment, and it was 17,000 tons in the 2022 fishing season. Similar to biomass, SSB also increased between the 1996 fishing season and the 2014 fishing season, fluctuating between 7,000 and 20,000 tons. However, it then declined sharply to 13,000 tons in the 2015 fishing season and 5,000 tons in the 2016 fishing season. The level has remained between 4,000 and 5,000 tons in 2016 – 2020 fishing seasons, and has increased until 10,000 tons in the 2022 fishing season.

SSB in the 2022 fishing season was below the level required for MSY, and the trend was determined to be increased based on the past five years (the 2018 to 2022 fishing seasons). Fishing pressure in the 2022 fishing season was below the fishing pressure required for MSY (Fmsy).

6. Additional Comments

Although there has been a slight slowdown in recent years, the growth of Pacific cod is fast. Furthermore, since recovery of stock has been observed in the past in a relatively short period of time, it is expected that the SSB will increase quickly if there is a certain degree of recruitment, and if not subjected to excessively high fishing pressure.

7. References

Bakkala, R., S. Westrheim, S. Mishima, C. Zhang and E. Brown (1984) Distribution of Pacific cod (*Gadus macrocephalus*) in the North Pacific Ocean. Int. North Pac. Fish. Comm. Bull., **42**, 111-115.

Fukuda, S., Yokoyama, K. and Hayakawa, Y. (1985) Tagged Releases of Mature Pacific Cod at Mutsu Bay Mouth in Aomori Prefecture Technical Reports of Japanese Sea Ranching Program, **14**, 71-77.

Hashimoto, R. (1974) Investigation of Feeding Habits and Variation of Inhabiting Depths with Cod (*Gadus Macrocephalus*) Distributed on the Northeastern Fishing Ground in Japan. Bull. Tohoku Reg. Fish. Res. Lab., **33**, 51-67.

Hattori T., Sakurai Y., Shimazaki K. (1992) Age Determination by Sectioning of Otoliths and Growth Pattern of Pacific Cod. Fish. Sci., **58**, 1203-1210.

Hattori T., Sakurai Y., Shimazaki K. (1995) Fecundity of Spawning Pacific Cod (Gadus macrocephalus) in Mutsu Bay, Japan. Bull. Tohoku Reg. Fish. Res. Lab., **57**, 1-5.

Hattori, T., Kitagawa, D., Imamura, H. and Nobetsu, T. (1999) Results of the 1998 Demersal Species Stock Abundance Survey. Tohoku Demersal Fish Research, **19**, 77-91.

Hattori, T., Kitagawa, D., Narimatsu, Y., Saeki, M., Katayama, S., Fujiwara, K., Odani, K., Honda, G. (2002) Results of the 2001 Demersal Species Standing Stock Survey.Tohoku Demersal Fish Research, **22**, 82-98.

Ito, M., Hattori, T., Narimatsu, Y. & Shibata, Y. (2014) Predation on Snow Crab by Pacific Cod in the Pacific off Tohoku. Tohoku Demersal Fish Research, **34**, 123-132.

Kodama, J., Nagashima, H., and Izumi, Y. (1990) Pacific Cod Inhabiting the Kinkasan Area. Tohoku Ocean Area Demersal Fish Research Team Meeting Report, Tohoku Regional Fisheries Research Laboratory, **11**, 43-46.

Mishima, S. (1984) Stock assessment and biological aspects of Pacific cod (*Gadus macrocephalus* Tilesius) in Japanese waters. Int. North Pac. Fish. Comm. Bull., **42**, 180-199.

Miura, T., Yoshida, M., Yamada, Y., Noro, K., Ito, K. and Azuma, N. (2019) Distribution and migration of the Pacific cod, Gadus macrocephalus, Mutsu Bay local spawning population. Aquacult. Sci., 67, 19-24.

Narimatsu, Y. (2006) Reproductive Biology of Pacific Cod, a Review Especially Referring to Interannual Variations of Biomass, Age and Size at Maturity and Fecundity. Bull. Fish. Res. Agen., Supplement **4**, 137-146.

Narimatsu, Y., S. Kakehi, S. Ito, Y. Okazaki, R. Inagawa and T.Yano (2015a) Impact of the Great East Japan Earthquake tsunami on growth and survival of Pacific cod, *Gadus macrocephalus*. Can. J. Fish. Aquat. Sci., **72**, 1629-1638.

Narimatsu, Y., T. Sohtome, M. Yamada, Y. Shigenobu, Y. Kurita, T. Hattori and R. Inagawa (2015b) Why do the radionuclide concentrations of Pacific cod depend on the body size? In: Impact of the Fukushima nuclear accident on fish and fishing grounds, ed. K. Nakata and H. Sugisaki, Springer Japan, Tokyo, pp. 123-138.

Narimatsu, Y., Suzuki, H., Morikawa, E., Tokioka, S., Misawa, R., Kanamori, Y., Togashi, H., Shibata, Y. (2021a) Materials for the Research Institute Meeting on Reference Points of Honshu Northern Pacific Stock of Pacific Cod (Fiscal Year 2021). Japan Fisheries Research and Education Agency, 1-50. FRA-SA2021-BRP02-1. https://www.fra.affrc.go.jp/shigen_hyoka/SCmeeting/2019-1/detail_madara_pacN_RIM_quickVer_20210930.pdf (last accessed 21 July 2022).

Narimatsu, Y., Suzuki, H., Morikawa, E., Tokioka, S., Misawa, R., Kanamori, Y., Togashi, H., Shibata, Y. (2021b) Stock Assessment Report, 1 to 31. FRA-SA2021-RC05-2. http://abchan.fra.go.jp/digests2021/details/202134.pdf

Narimatsu, Y., Y. Ueda, T. Okuda, T. Hattori, K. Fujiwara and M. Ito (2010) The effect of temporal changes in life-history traits on reproductive potential in an exploited population of Pacific cod, *Gadus macrocephalus*. ICES J. Mar. Sci., **67**, 1659-1666.

Sakurai, Y. and T. Hattori (1996) Reproductive behavior of Pacific cod in captivity. Fish. Sci., **62**, 222-228.

Suda, A., N. Nagata, A. Sato, Y. Narimatsu, H. H. Nadiatul and M. Kawata (2017) Genetic variation and local differences in Pacific cod *Gadus macrocephalus* around Japan. J. Fish Biol., **90**, 61-79.

Takatsu, T., T. Nakatani, T. Mutoh and T. Takahashi (1995) Feeding habits of Pacific cod larvae and juveniles in Mutsu bay, Japan. Fish. Sci., **61**, 415-422.

Takatsu, T., T. Nakatani, T. Miyamoto, K. Kouka and T. Takahashi (2002) Spatial distribution and feeding habits of Pacific cod (*Gadus macrocephalus*) larvae in Mutsu Bay, Japan. Fish. Oceanogr., **11**, 90-101.

Tanaka, S (1960) Population Dynamics of fishery organisms and fishery resource management. Bull. Tokai Reg. Fish. Re. Lab., **28**, 1-200.

Yamamura, O. (1993) Stock Partitioning in Demersal Fish Subpopulations off Sendai Bay. Reports of the Demersal Fish Subcommittee, Scientific Council on the Fisheries Resources, **26**, 61-70.

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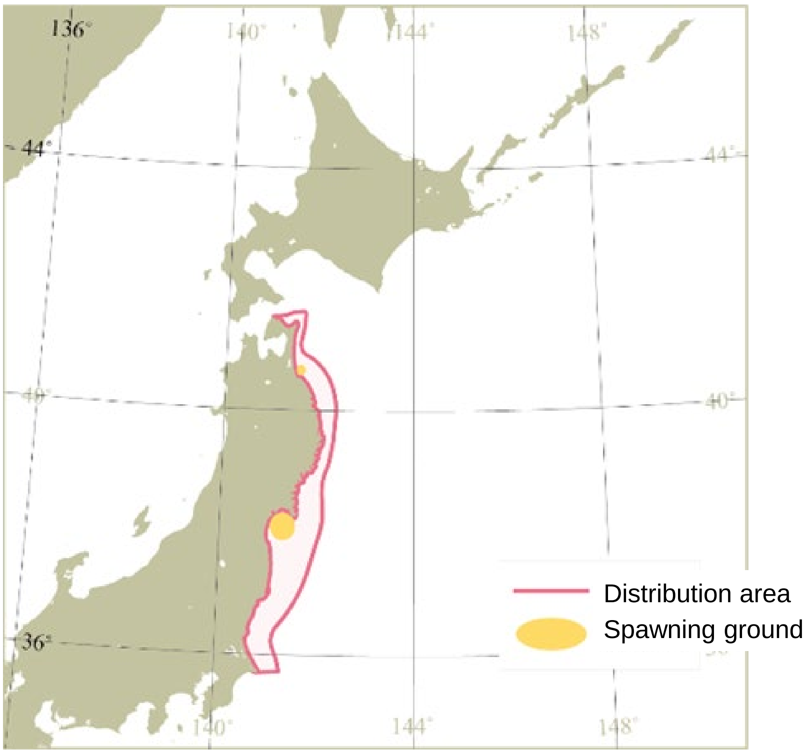


Fig. 2-1. Distribution area of Pacific Cod in the North Pacific off Honshu Island of Japan

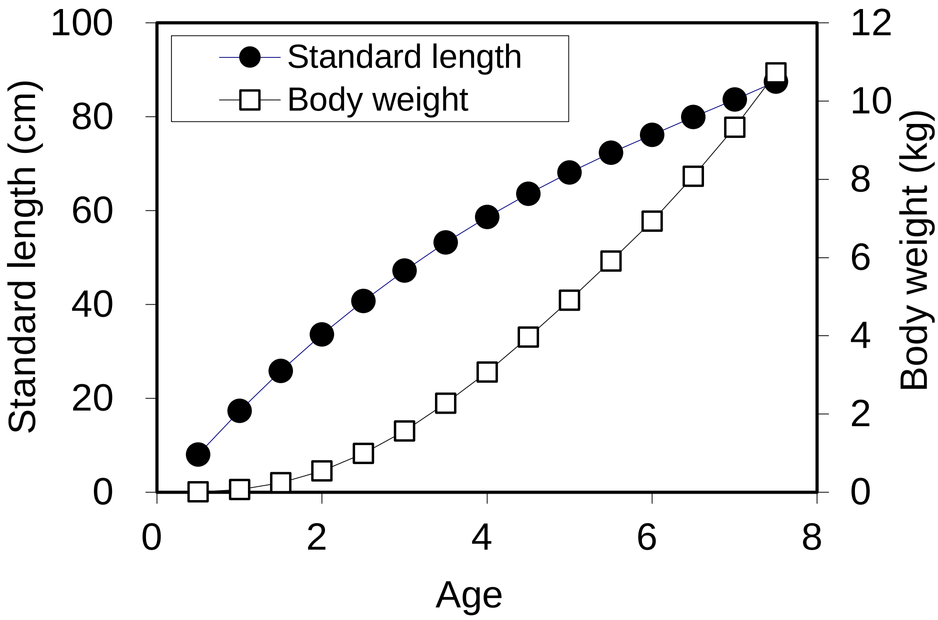


Fig. 2-2. Growth of Pacific Cod in the North Pacific off Honshu Island of Japan

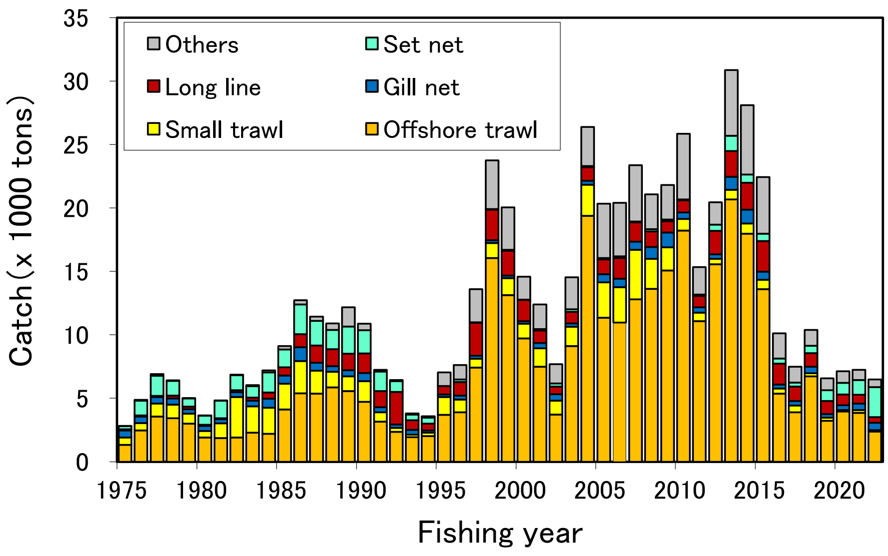


Fig. 3-1. Catches of Pacific Cod in the North Pacific off Honshu Island of Japan by Fishery Type. Values for 2022 fishing season are provisional.

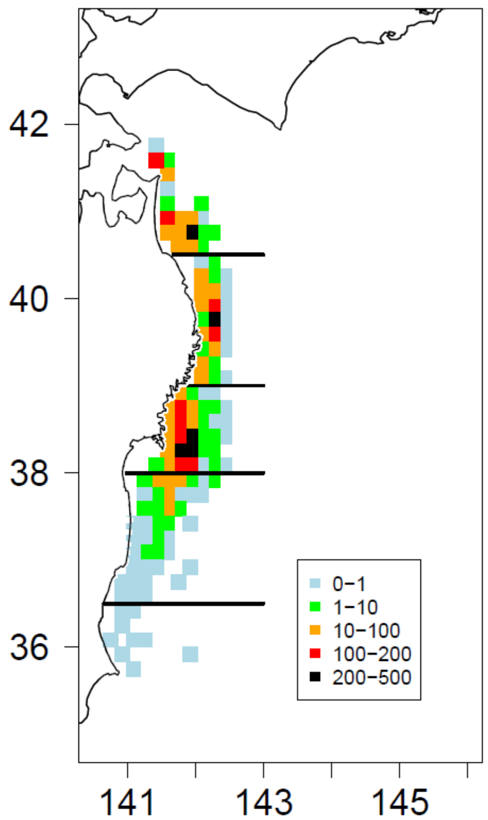
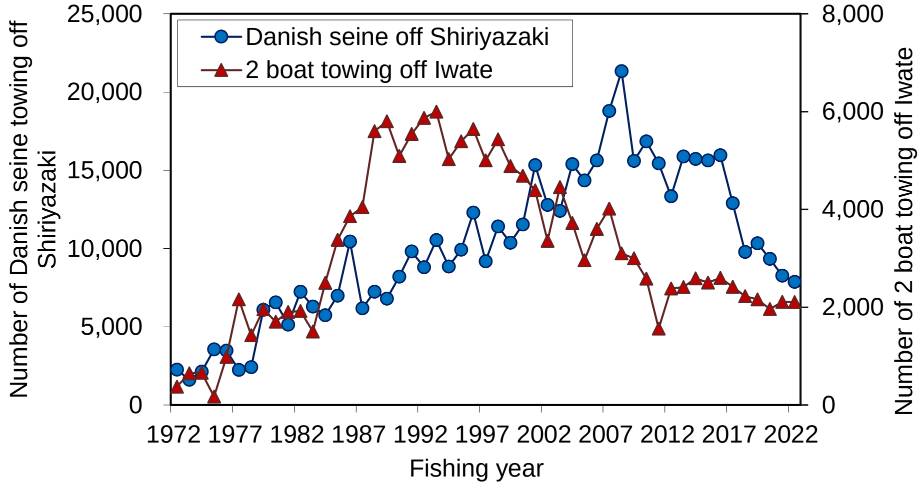


Fig. 3-2. Distribution of Catches (Tons) in 2021 by Offshore Bottom Trawl



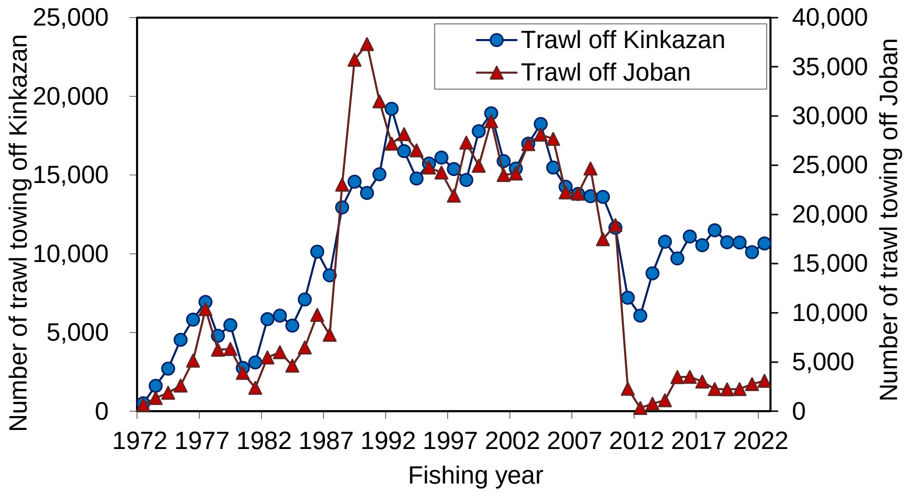


Fig. 3-3. Trends in Non-Zero Catches by Offshore Bottom Trawl

Top: Two-Boat and Danish Seine, Bottom: Trawl. Values for 2022 are provisional.

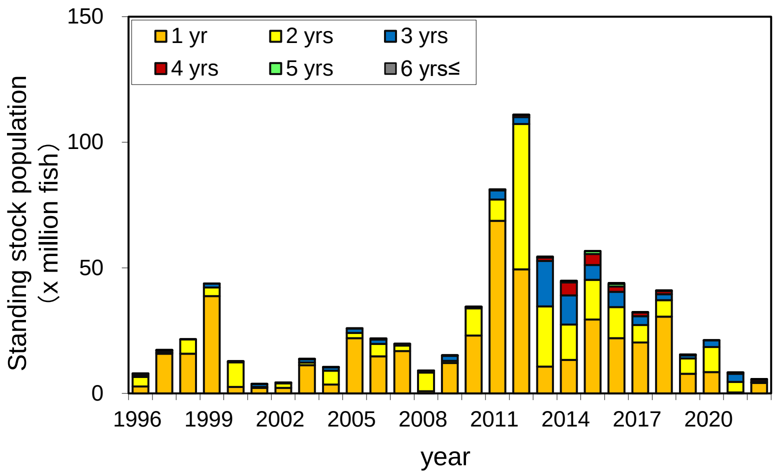


Fig. 4-1. Trends in Standing Stock Population by Age Estimated by Trawl Surveys

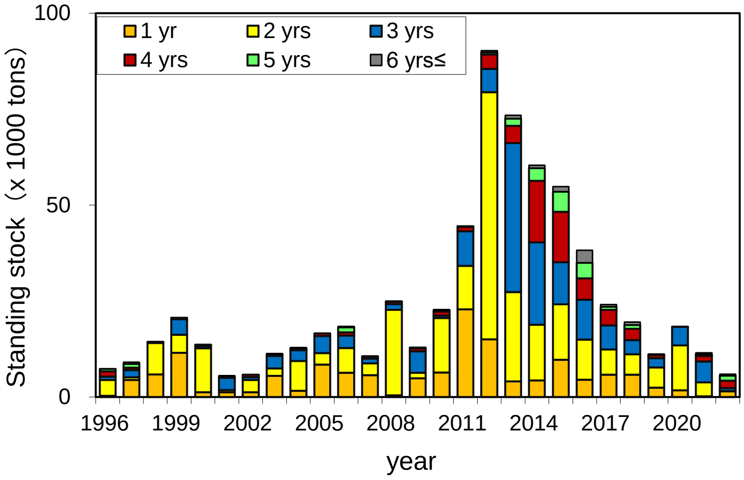


Fig. 4-2. Trends in Standing Stock by Age (Abundance Indices) Estimated by Trawl Surveys

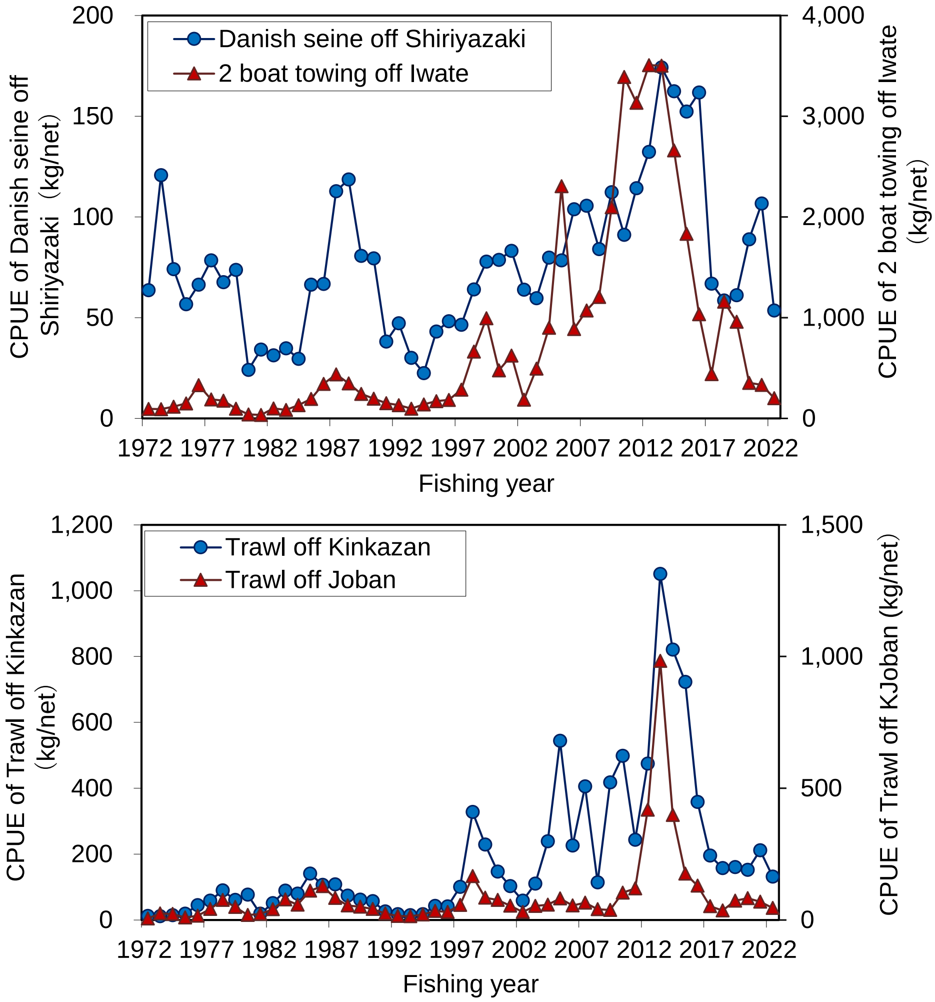


Fig. 4-3. Trends in CPUE of Offshore Bottom Trawl

Top: Two-Boat and Danish Seine, Bottom: Trawl. Values for 2021 are provisional.

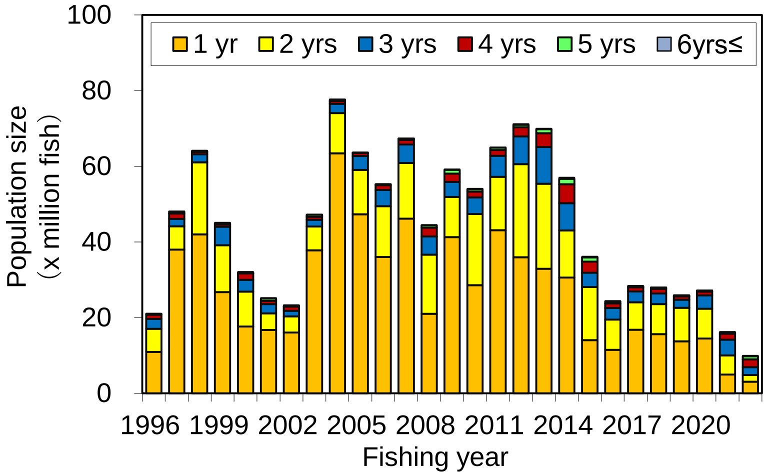


Fig. 4-4. Trends in Stock Population at Age Estimated by VPA

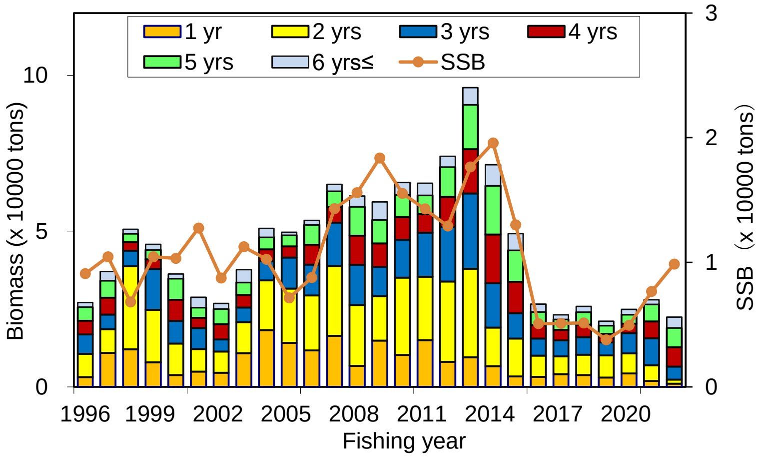


Fig. 4-5. Trends in Biomass and SSB by Age Estimated by VPA

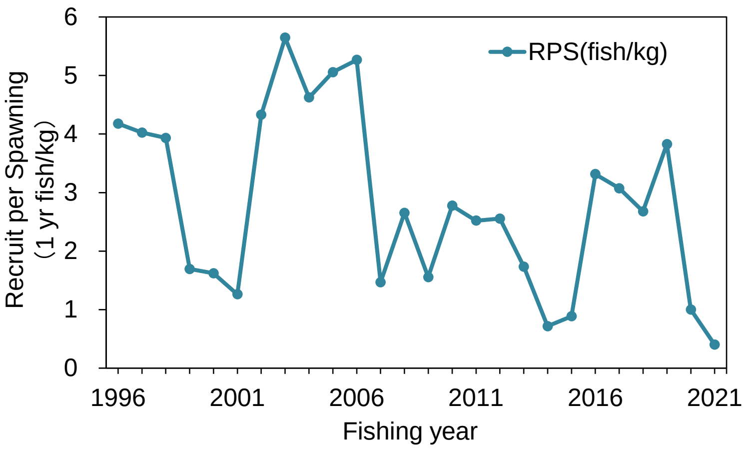


Fig. 4-6. Trends in Recruitment Per Spawning

The fishing years in which age 1 fish were recruited are shown here, and the SSB is the value for the previous fishing year.

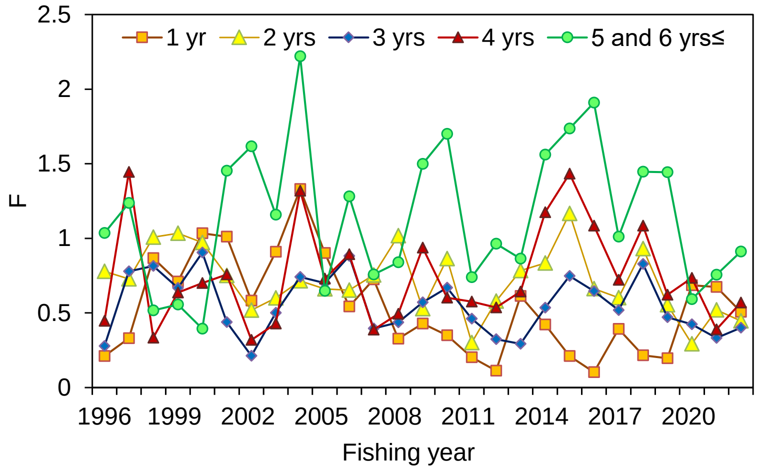


Fig. 4-7. Trends in fishing mortality F

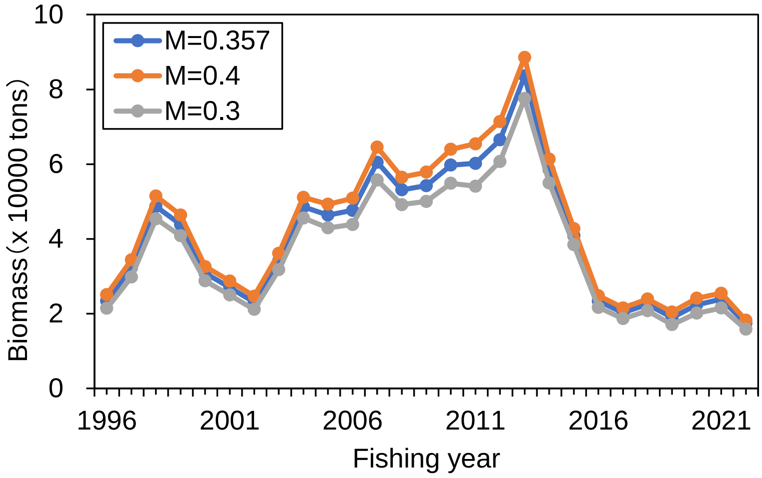


Fig. 4-8. Changes in Biomass when M is Adjusted

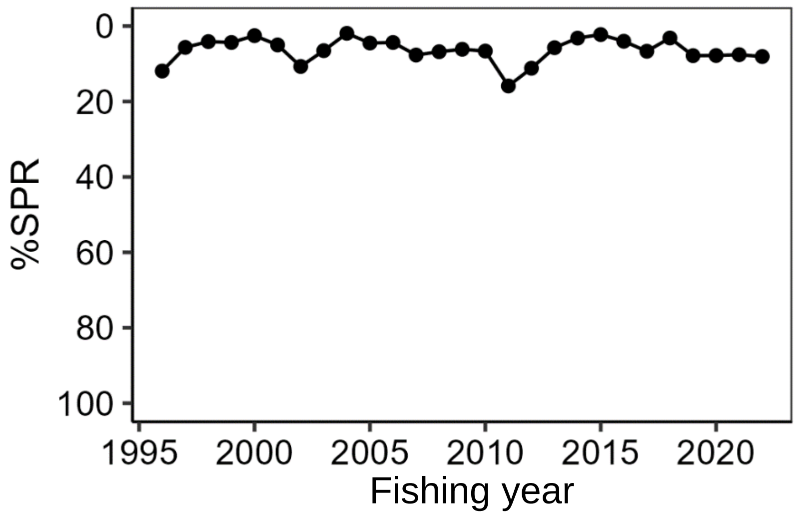


Fig. 4-9. Trends in %SPR

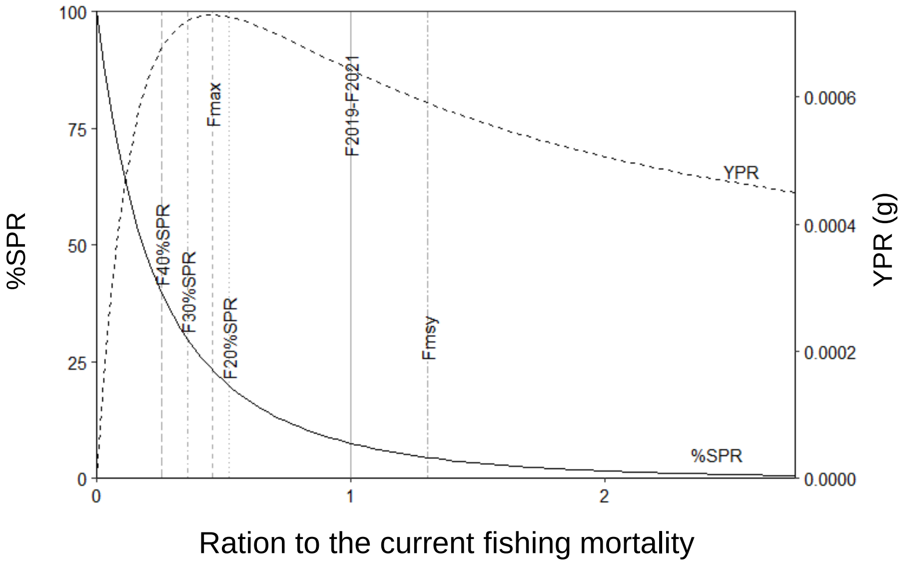


Fig. 4-10. Relationship of YPR and %SPR to current fishing pressure

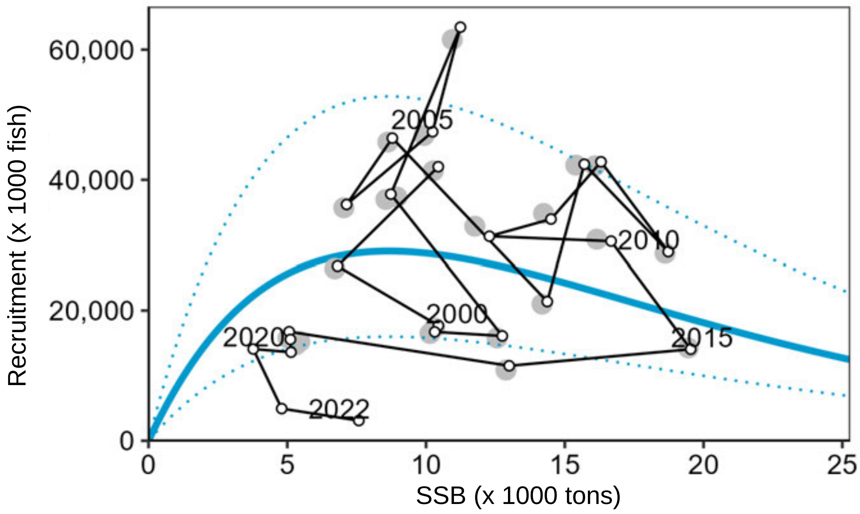


Fig. 4-11. Relationship between SSB and Recruitment Size (Number of Age 1 Fish) (Stock-Recruitment Relationship)

The gray circles and blue line are the stock-recruitment relationship model proposed at the Research Institute Meeting held in August 2021 (Narimatsu et al. 2021). The dotted line indicates the range estimated to contain 90% of the observed data. White circles indicate biomass and recruitment size data in the FY2023 stock assessment.

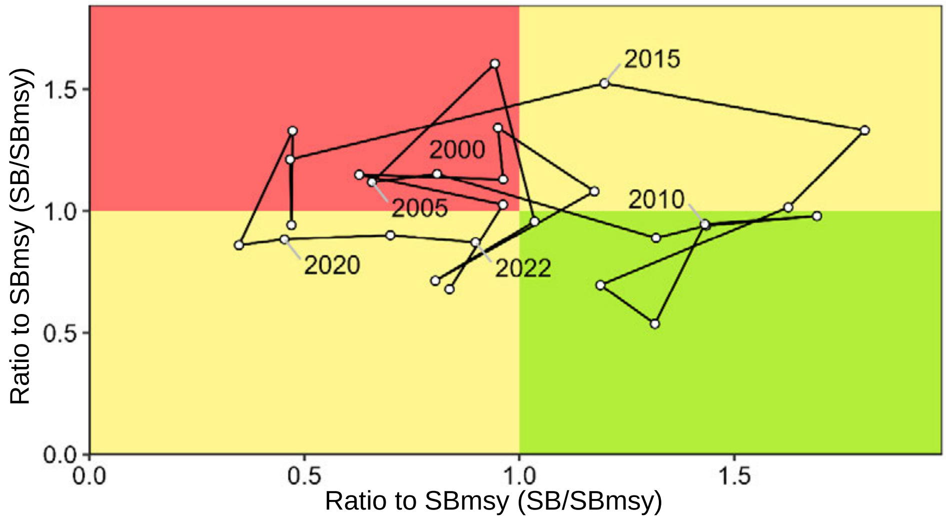


Fig. 4-12. Relationship of SSB required for MSY (SBmsy) and fishing pressure required for MSY (Fmsy) against levels of SSB and fishing pressure (Kobe plot)

Table 3-1. Trends in Catch by Kind of Fisheries (Fishing Year Aggregate: Tons)

	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Offshore trawl	1,337	2,472	3,567	3,431	2,992	1,919	1,855	1,902	2,284	2,202	4,117	5,399	5,371
Small trawl	574	583	1,028	1,070	795	506	1,166	3,208	2,068	2,054	2,032	2,541	1,793
Gill net	546	511	498	478	351	388	329	373	453	702	635	1,086	642
Long line	107	72	106	229	205	103	76	160	260	494	666	1,029	1,358
Set net	230	1,178	1,573	1,160	645	709	1,377	1,178	885	1,579	1,403	2,347	1,935
Others	7	70	138	56	26	15	17	37	76	156	266	317	330
Total	2,801	4,886	6,909	6,424	5,014	3,641	4,821	6,857	6,026	7,186	9,119	12,719	11,428

	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Offshore trawl	5,860	5,568	4,727	3,160	2,349	1,935	2,013	3,690	3,899	7,413	16,055	13,119	9,716
Small trawl	1,227	1,169	1,630	735	318	189	278	1,400	990	706	1,172	1,347	1,154
Gill net	450	487	632	397	280	379	166	213	323	242	235	191	215
Long line	1,336	1,285	1,535	1,274	2,546	762	546	639	1,068	2,575	2,397	1,971	1,661
Set net	1,522	2,142	1,848	1,548	857	447	462	29	193	43	51	59	36
Others	497	1,523	501	116	99	92	106	1,080	1,154	2,623	3,837	3,357	1,796
Total	10,892	12,174	10,873	7,229	6,447	3,805	3,571	7,051	7,627	13,602	23,747	20,045	14,577

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Offshore trawl	7,477	3,712	9,109	19,365	11,355	10,976	12,786	13,628	15,070	18,215	11,068	15,552	20,661
Small trawl	1,467	1,088	1,511	2,453	2,773	2,778	3,912	2,353	1,838	921	678	431	773
Gill net	415	516	281	317	644	674	642	940	1,144	510	430	359	1,027
Long line	981	610	909	1,069	1,173	1,619	1,532	1,229	900	959	879	1,849	2,028
Set net	117	236	198	105	101	131	63	172	131	74	131	503	1,200
Others	1,928	1,514	2,526	3,061	4,279	4,216	4,435	2,741	2,733	5,166	2,160	1,752	5,179
Total	12,385	7,677	14,535	26,370	20,325	20,395	23,369	21,062	21,817	25,846	15,344	20,447	30,868

	2014	2015	2016	2017	2018	2019	2020	2021	2022
Offshore trawl	17,963	13,600	5,364	3,887	6,729	3,219	3,953	3,853	2,376
Small trawl	803	731	406	544	253	241	119	221	102
Gill net	1,089	658	320	351	500	304	384	502	580
Long line	2,129	2,408	1,643	1,151	1,069	1,024	853	703	454
Set net	657	569	407	294	580	840	910	1,161	2,361
Others	5,449	4,465	1,978	1,255	1,262	939	918	810	603
Total	28,091	22,431	10,117	7,482	10,393	6,567	7,137	7,250	6,476

Table 3-2. Trends in catch amount in each kind of fishery in each prefecture

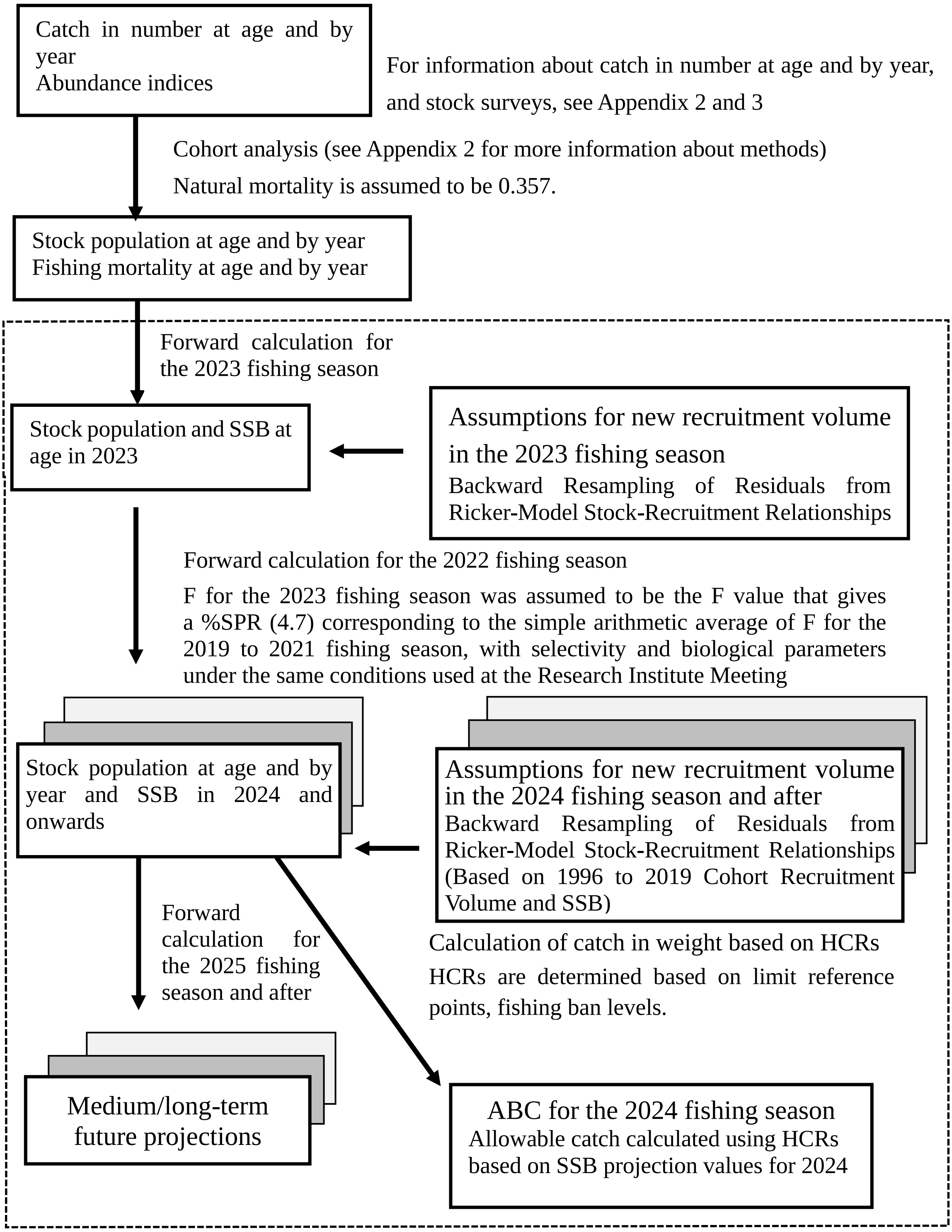
		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Aomori	Offshore trawl	1,375	1,439	791	1,228	1,406	1,274	2,210	2,595	2,216	1,636	2,199	1,529	2,318	3,271	2,275	3,203	1,343	714	708	626	978	981	729
	Small trawl	424	521	581	439	614	480	915	1,170	437	713	641	414	337	608	278	308	115	52	60	73	54	126	48
	Gill net	0	0	53	81	86	146	167	121	337	420	0	0	0	0	1	0	0	0	0	0	0	0	0
	Long line	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
	Set net	10	14	42	147	14	11	21	14	70	75	18	33	48	69	89	71	61	66	60	48	77	283	1,201
	Others	356	342	214	133	136	146	195	394	461	543	847	1,130	493	1,903	2,020	1,622	929	513	617	557	508	367	407
Iwate	Offshore trawl	3,150	2,247	614	2,565	8,161	3,377	3,998	4,310	6,414	8,237	9,426	5,992	8,613	8,136	6,802	4,273	1,856	1,284	3,828	990	861	660	614
	Small trawl																							
	Gill net	75	266	379	87	39	128	153	238	283	371	248	170	207	227	340	141	125	143	258	199	217	271	419
	Long line	1,559	896	553	784	762	948	1,488	1,315	1,118	809	846	838	1,847	2,006	2,099	2,352	1,629	1,139	1,062	1,019	851	702	453
	Set net	12	10	191	29	64	22	28	9	57	50	23	32	224	529	198	162	46	45	215	381	479	293	958
	Others	182	146	117	62	128	144	15	55	18	10	4	17	30	34	65	43	30	23	34	22	23	25	24
Miyagi	Offshore trawl	4,490	3,114	1,381	3,826	8,527	5,099	3,751	4,603	4,419	4,034	5,982	3,528	4,620	9,254	8,789	5,889	2,034	1,796	2,105	1,512	1,986	2,144	981
	Small trawl	615	904	465	902	1,689	2,114	1,798	2,695	1,826	1,035	229	236	92	165	477	375	270	478	180	158	63	92	50
	Gill net	94	130	48	65	76	234	222	233	261	329	261	259	152	799	749	517	195	207	240	101	165	221	161
	Long line	0	0	0	0	0	0	0	0	0	13	30	16	1	21	18	22	13	8	7	5	2	1	1
	Set net	13	93	3	22	28	68	82	40	44	6	34	67	231	602	370	337	299	183	306	411	354	585	202
	Others	1,211	1,422	1,180	2,306	2,743	3,979	4,003	3,982	2,259	2,178	4,314	1,012	1,230	3,242	3,363	2,797	1,019	718	608	360	388	418	172
Fukushima	Offshore trawl	693	674	923	1,478	1,256	1,591	1,009	1,271	565	1,145	579	0	0	0	45	144	94	76	86	90	127	67	52
	Small trawl	81	34	33	91	70	99	46	37	70	71	25	0	0	0	0	0	0	4	4	5	1	3	4
	Gill net	46	19	37	49	115	137	131	50	59	24	1	0	0	0	0	0	0	1	3	4	3	10	0
	Long line	32	47	38	73	128	130	63	114	63	61	52	0	0	0	0	0	0	0	0	0	0	0	0
	Set net	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Others	46	18	3	24	52	10	3	3	2	3	1	0	0	0	0	0	0	0	3	0	0	0	0
Ibaraki	Offshore trawl	8	4	3	12	15	13	9	8	14	18	29	18	0	0	52	91	37	17	2	1	1	1	0
	Small trawl	34	8	9	80	80	81	19	10	19	19	26	28	2	0	48	48	21	11	9	6	1	0	0
	Gill net	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Long line	69	38	19	53	179	95	68	102	48	17	30	24	1	0	12	33	1	3	0	0	0	0	0
	Set net	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Others	0	0	0	2	2	1	0	0	0	0	1	0	0	0	1	3	0	1	0	0	0	0	0

Table 4-1. Results of Stock Analysis of Honshu Northern Pacific Stock of Pacific Cod

Fishing year	Catch (x 100 tons)	Biomass (x 100 tons)	SSB (x 100 tons)	Recruitment (1 yr fish, x million fish)	Exploitation rate(%)	Average F	RPS (fish/kg)	F/Fmsy	%SPR
1996	76	234	91	11	33	0.63		0.68	11.9
1997	136	322	104	38	42	0.96	4.2	1.03	5.7
1998	237	487	68	42	49	0.68	4.0	1.15	4.1
1999	200	439	104	27	46	0.69	3.9	1.13	4.4
2000	146	309	103	18	47	0.73	1.7	1.34	2.5
2001	124	270	127	17	46	0.98	1.6	1.08	5.0
2002	77	230	87	16	33	0.81	1.3	0.71	10.7
2003	145	341	112	38	43	0.79	4.3	0.96	6.5
2004	264	486	102	63	54	1.42	5.7	1.61	1.9
2005	203	464	71	47	44	0.71	4.6	1.12	4.5
2006	204	476	88	36	43	0.92	5.1	1.15	4.4
2007	234	605	143	46	39	0.63	5.3	0.89	7.7
2008	211	531	156	21	40	0.66	1.5	0.94	6.8
2009	218	542	184	41	40	0.91	2.7	0.98	6.2
2010	258	597	155	29	43	0.98	1.6	0.95	6.6
2011	153	602	143	43	25	0.50	2.8	0.54	15.9
2012	204	665	129	36	31	0.58	2.5	0.70	11.2
2013	309	836	176	33	37	0.68	2.6	1.01	5.7
2014	281	585	196	31	48	1.01	1.7	1.33	3.2
2015	224	408	130	14	55	1.17	0.7	1.52	2.3
2016	101	234	51	12	43	1.05	0.9	1.21	4.0
2017	75	202	51	17	37	0.71	3.3	0.94	6.7
2018	104	225	51	16	46	0.99	3.1	1.33	3.2
2019	66	189	38	14	35	0.79	2.7	0.86	7.8
2020	71	224	49	14	32	0.55	3.8	0.88	7.8
2021	73	238	76	5	30	0.57	1.0	0.89	7.6
2022	65	174	99	3	37	0.62	0.4	0.85	8.1

RPS is estimated as number of 1 year old fish by the SSB in the previous year.

Appendix 1 Stock Assessment Flow



※ Information inside the dotted line box is based on discussion of reference points, HCRs, etc., by the Stock Management Policy Commission. (http://www.fra.affrc.go.jp/shigen_hyoka/SCmeeting/2019-1/index.html)

Appendix 2 Calculation Methods

(1) Stock Calculation Methods

Cohort analysis was used to estimate the stock population, fishing mortality, and biomass by fishing year for age 1 to 6+ (ages 6+ are collectively referred to as the 6+ (plus group)) from 1996 to 2022. Age-length keys were created by year and half-year using the samples caught by bottom-trawl surveys and Pacific cod bought at fish market since 1996. In addition, the fishing year was set from April to March of the following year, with the first half of the year from April to September and the second half from October to March of the following year. Standard length composition of Pacific cod landings in Aomori and Miyagi prefectures from 1996 to 2015, and in Aomori, Iwate, and Miyagi prefectures from 2016 onward, was determined and combined with age-length key results to estimate the catch in number at age by half year (Supplementary Table 2-1). The obtained catch in number at age was used to estimate the stock population at age by year using the VPA shown below. Although Pacific cod in the Tohoku area have been reported to live up to about age 8, we have designated age 6 and older as a plus group here because there are very few individuals age 7 and older. Life expectancy was assumed to be 7 years, and the natural mortality was constant at 2.5/7 = 0.357 based on the Tauchi-Tanaka formula (Tanaka 1960). Additionally, the standing stocks by age obtained from bottom-trawl surveys was used as an index value for tuning.

Calculation of stock population using Pope’s approximation equation (Step 1)

The stock population at each age and year Na, y were calculated using the following Pope’s (1972) approximation equation below.

$$N_{a,y} = N_{a+1,y+1}\, exp(M) + C_{a,y}\, exp(M/2) \qquad (1)$$

In these equations, $N_{a,y}$ is the stock population of fish age *a* in year *y*, and $C_{a,y}$ is the catch in number of fish age *a* in year *y*. The stock population for the most recent year (the 2022 fishing season), the oldest fish (age 6, plus group) and the oldest fish - age 1 fish, respectively, were determined using the following equations.

$$N_{a,2021} = C_{a,2022}\, exp(M/2)/(1 - exp(-F_{a,2022})) \qquad (2)$$

$$N_{6+,y} = C_{6+,y}/(C_{6+,y} + C_{5,y}) \times N_{6+,y+1} \times exp(M) + C_{6+,y} \times exp(M/2) \qquad (3)$$

$$N_{5,y} = C_{6,y}/(C_{6+,y} + C_{5,y}) \times N_{6+,y+1} \times exp(M) + C_{5,y} \times exp(M/2) \qquad (4)$$

Calculation of fishing mortality (F), excluding the terminal F, was determined using equation (5).

$$F_{a,y} = -ln(1 - C_{a,y}\, exp(M/2)/N_{a,y})) \qquad (5)$$

The F of the oldest fish was determined to be equal to the F of the oldest fish - age 1 fish. F for the 2021 fishing season, the most recent year in the cohort analysis, was first set as the average F for the three most recent years (the 2019 to 2021 fishing seasons) for fish age 1 to 5. F for the plus group (the oldest group), was sought exploratively so as to equal the oldest - age 1 fish. Next, we further adjusted F in the most recent year following the methods in Step 2.

Adjustment of F in the most recent year (Step 2)

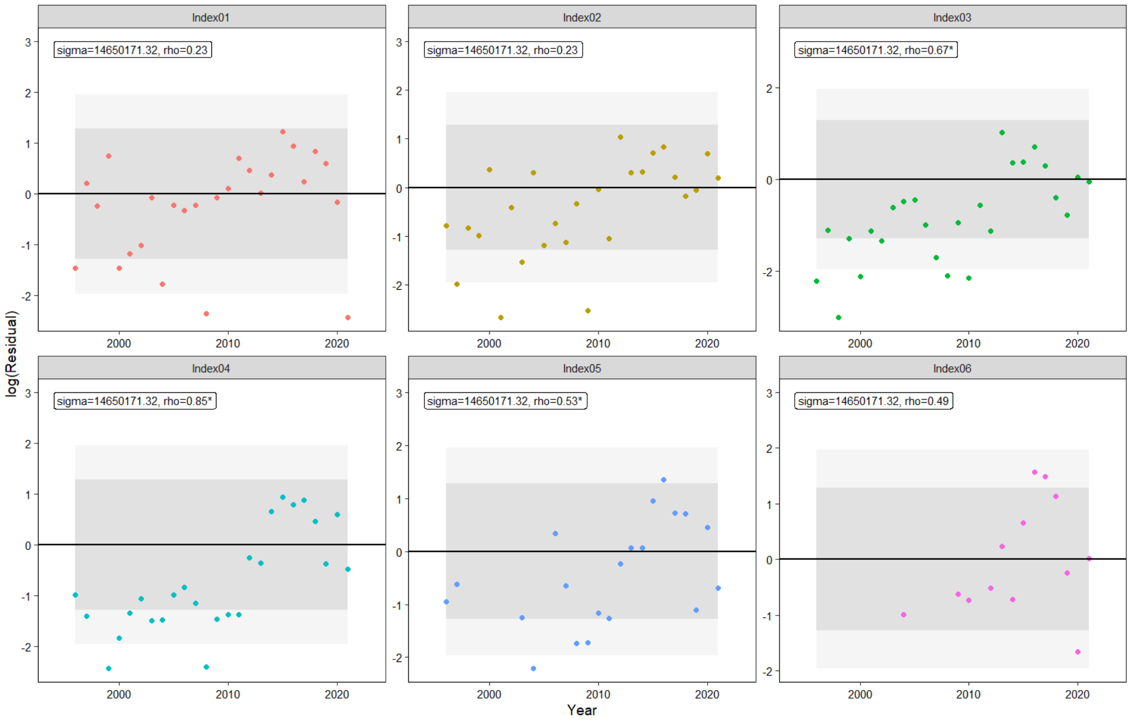
The abundance index values by age, which were used as tuning indices, were calculated by multiplying the standing stock population of age 1 to 6 and older in October of each year (Supplementary Table2-1) obtained from bottom trawl surveys by the weight of each age group in each year.

The fishing mortality F for each age group in the most recent year (2022 fishing season) was tuned as follows to estimate the stock population and F. For selectivity by age for F of fish age 1 to 6 and older in the most recent year, we used the 2019 to 2021 average estimated based on the VPA without tuning (Step 1). Based on Hiramatsu (2001), q and Ft for the most recent year which minimize equation (6) were determined analytically and exploratively, respectively.

$$\sum_a \sum_y (I_{a,y} - q_a B_{a,y})^2 \qquad (6)$$

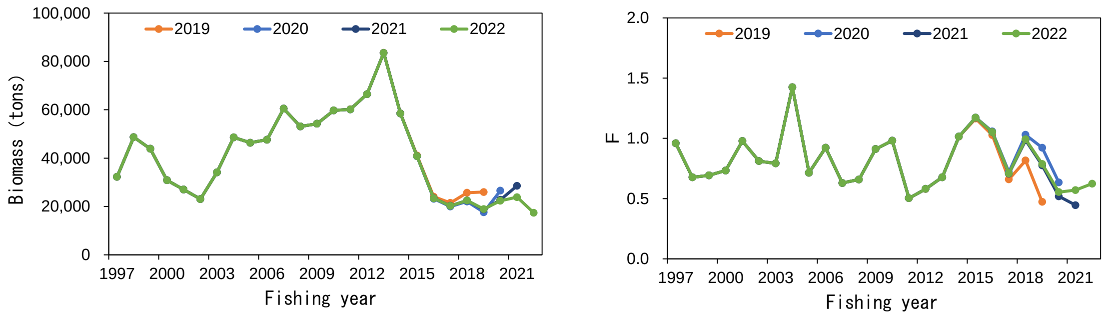
Here, a is age, y is year, I is the standing stock based on trawl surveys for the 1996 to 2022 fishing seasons, and B is the biomass based on the VPA.

The robustness of the statistical validity of the VPA with tuning and assumptions used for this stock assessment were diagnosed according to the Stock Assessment Model Diagnostic Procedures and Data Provision Guidelines (FY 2023) (FRA-SA2023-ABCWG02-03). The residuals of observed values of indices and projected values showed large yearly fluctuations for each age group, and the residuals tended to be large (Supplementary Fig. 2-1). Retrospective analysis examining the impact of adding and updating data for each fishing year showed that there was a large divergence in both biomass and F value in the 2018 fishing year; however, this stabilized thereafter (Supplementary Fig. 2-2).



Supplementary Fig. 2-1. Residual Plots Showing the Difference Between Observed Abundance Indices and Projections in the Model

Index 01 to Index 06 show fish age 1 to age 6 or older, respectively.



Supplementary Fig. 2-2. Results of Retrospective Analysis of Biomass (Left) and F (Right)

Supplementary Table 2-1. Data used for Cohort Analysis (1996 to 2010 Fishing Seasons)

Catch at age（x 1000 fish）

age	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
1	1,745	8,938	20,378	11,396	9,537	8,905	5,951	18,878	39,039	23,528	12,633	19,932	4,898	12,051	7,069
2	2,753	2,684	10,145	6,658	4,790	1,946	1,442	2,374	4,551	4,747	5,388	6,495	8,362	3,643	9,104
3	534	884	977	1,986	1,530	724	233	584	1,058	1,536	2,080	1,339	1,428	1,442	1,784
4	335	892	149	256	737	387	252	239	460	349	627	330	752	1,112	593
5	140	296	78	112	66	390	191	321	280	56	164	161	277	639	409
6+	42	50	40	52	50	129	89	33	101	15	40	29	67	142	129
total	5,548	13,743	31,766	20,460	16,710	12,481	8,157	22,430	45,489	30,231	20,931	28,286	15,784	19,031	19,087

Weight at age（g）

age	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
1	287	287	288	296	216	294	283	287	287	299	326	355	320	359	358
2	1,229	1,229	1,396	1,365	1,094	1,645	1,595	1,584	1,498	1,484	1,309	1,526	1,249	1,346	1,318
3	2,381	2,381	2,371	2,676	2,372	2,752	2,679	2,653	2,560	2,732	2,336	2,844	2,673	2,371	2,788
4	3,930	3,930	4,379	4,765	3,882	3,784	4,459	4,900	5,091	4,474	5,012	4,109	4,050	3,462	4,614
5	5,825	5,825	5,841	5,591	5,980	5,475	6,054	7,247	7,721	6,606	5,504	6,059	5,913	5,854	6,509
6+	8,110	8,110	7,286	8,174	7,769	7,573	8,869	8,982	11,099	8,174	8,110	7,929	8,174	11,035	7,300

Maturity at age

age	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0.44	0.41	0.50	0.35	0.24	0.73	0.43	0.66	0.41	0.25	0.18	0.50	0.16	0.39	0.33
4	0.96	0.90	0.77	0.93	0.84	0.92	0.84	0.89	0.86	0.94	0.78	0.91	0.95	0.86	0.86
5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
6+	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

F

age	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
1	0.21	0.33	0.87	0.71	1.03	1.01	0.58	0.91	1.33	0.90	0.54	0.73	0.33	0.43	0.35
2	0.78	0.73	1.01	1.03	0.97	0.75	0.52	0.60	0.71	0.66	0.65	0.75	1.02	0.53	0.86
3	0.28	0.78	0.81	0.67	0.90	0.44	0.21	0.50	0.74	0.70	0.88	0.40	0.44	0.57	0.67
4	0.45	1.45	0.33	0.64	0.70	0.76	0.32	0.43	1.32	0.73	0.89	0.39	0.49	0.94	0.60
5	1.04	1.24	0.52	0.56	0.39	1.45	1.62	1.16	2.22	0.65	1.28	0.76	0.84	1.50	1.70
6+	1.04	1.24	0.52	0.56	0.39	1.45	1.62	1.16	2.22	0.65	1.28	0.76	0.84	1.50	1.70
ave	0.63	0.96	0.68	0.69	0.73	0.98	0.81	0.79	1.42	0.71	0.92	0.63	0.66	0.91	0.98

Tuning index

age	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
1	301	4,451	5,895	11,509	1,212	1,272	1,262	5,530	1,591	8,434	6,285	5,661	448	4,882	6,362
2	4,141	692	8,191	4,663	11,485	539	3,146	1,914	7,763	3,033	6,462	3,098	22,259	1,446	14,211
3	869	1,843	330	4,096	588	3,190	795	3,220	2,828	4,415	3,292	1,233	1,507	5,573	655
4	1,371	662		374	367	326	615	362	300	693	812	439	592	762	1,071
5	635	978						81	177		1,307	219	110	240	203
6+		467				250		188	225		263				262

Population size estimated by tuning VPA (x 1000 fish)

age	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
1	10,952	37,970	42,010	26,787	17,692	16,725	16,101	37,797	63,456	47,382	36,209	46,410	21,381	42,394	28,960
2	6,082	6,205	19,094	12,351	9,211	4,403	4,254	6,289	10,657	11,748	13,475	14,771	15,803	10,864	19,585
3	2,631	1,953	2,096	4,875	3,073	2,439	1,453	1,771	2,415	3,651	4,250	4,922	4,903	4,064	4,555
4	1,112	1,395	627	650	1,750	870	1,101	822	751	805	1,269	1,234	2,325	2,236	1,637
5	259	498	230	314	241	608	285	560	375	141	272	364	587	997	635
6+	78	84	118	145	184	201	132	58	136	39	66	66	141	222	200
total	21,114	48,104	64,175	45,122	32,151	25,245	23,326	47,296	77,789	63,765	55,541	67,766	45,140	60,778	55,571

Biomass estimated by tuning VPA (tons)

age	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
1	3,148	10,914	12,103	7,920	3,827	4,921	4,563	10,864	18,240	14,157	11,802	16,498	6,841	15,236	10,377
2	7,474	7,625	26,655	16,865	10,075	7,242	6,786	9,962	15,960	17,429	17,639	22,542	19,741	14,623	25,820
3	6,264	4,650	4,971	13,044	7,289	6,712	3,892	4,698	6,183	9,973	9,928	14,001	13,104	9,633	12,699
4	4,369	5,482	2,747	3,097	6,794	3,294	4,908	4,027	3,823	3,600	6,362	5,069	9,414	7,741	7,552
5	1,506	2,900	1,343	1,756	1,439	3,328	1,728	4,056	2,894	929	1,495	2,206	3,473	5,839	4,132
6+	635	678	861	1,187	1,433	1,519	1,174	521	1,507	317	533	521	1,156	2,451	1,457
total	23,397	32,249	48,680	43,870	30,857	27,015	23,050	34,129	48,607	46,405	47,759	60,836	53,729	55,524	62,037

Supplementary Table 2-1. Data used for Cohort Analysis (2011 to 2022 Fishing Seasons)

Catch at age（x 1000 fish）

age	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
1	6,606	3,232	12,656	8,815	2,231	949	4,568	2,545	2,042	6,010	2,029	1,023
2	3,063	9,067	10,212	5,903	8,092	3,232	2,749	4,020	3,150	1,680	1,729	531
3	1,720	1,691	2,056	2,490	1,671	1,218	972	1,312	687	1,028	977	586
4	575	851	1,467	2,913	1,873	696	482	663	330	416	439	754
5	262	319	485	897	751	349	158	244	181	120	142	385
6+	44	121	110	240	174	118	36	59	50	22	65	77
total	12,269	15,280	26,986	21,258	14,792	6,562	8,965	8,843	6,441	9,276	5,381	3,356

Weight at age（g）

age	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
1	349	224	288	218	241	284	243	243	220	302	387	345
2	1,445	1,045	1,266	990	867	850	789	819	804	813	985	750
3	2,541	2,411	2,503	1,979	2,128	1,791	1,776	2,040	1,908	1,832	2,093	1,971
4	3,827	3,916	3,855	3,108	3,436	3,422	3,027	3,345	3,186	3,106	3,356	2,999
5	6,443	5,633	5,460	4,996	4,913	5,021	4,828	4,798	4,813	5,089	4,718	4,398
6+	8,110	8,627	7,748	7,762	6,891	6,636	7,044	7,022	7,033	7,689	8,797	8,005

Maturity at age

age	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0.31	0.09	0.02	0.06	0.04	0.01	0.20	0.08	0.06	0.18	0.17	0.17
4	0.87	0.61	0.70	0.59	0.55	0.34	0.64	0.54	0.60	0.57	0.62	0.73
5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
6+	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

F

age	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
1	0.20	0.11	0.61	0.42	0.21	0.10	0.39	0.22	0.20	0.69	0.67	0.51
2	0.30	0.58	0.78	0.83	1.17	0.66	0.60	0.93	0.56	0.29	0.52	0.45
3	0.46	0.32	0.29	0.54	0.75	0.65	0.52	0.83	0.47	0.42	0.33	0.40
4	0.58	0.54	0.64	1.17	1.43	1.09	0.72	1.08	0.62	0.73	0.39	0.57
5	0.74	0.96	0.86	1.56	1.74	1.91	1.01	1.45	1.44	0.59	0.76	0.91
6+	0.74	0.96	0.86	1.56	1.74	1.91	1.01	1.45	1.44	0.59	0.76	0.91
ave	0.50	0.58	0.68	1.01	1.17	1.05	0.71	0.99	0.79	0.55	0.57	0.62

Tuning index

age	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
1	22,846	15,017	4,046	4,303	9,692	4,513	5,794	5,836	2,441	1,744	149	1,495
2	11,287	64,404	23,311	14,498	14,432	10,462	6,559	5,275	5,248	11,682	3,636	81
3	9,018	6,054	38,816	21,478	10,967	10,341	6,300	3,707	2,410	4,837	5,455	711
4	1,127	3,748	4,445	16,033	13,142	5,576	4,082	2,917	837	23	1,445	1,948
5	217	601	1,907	3,332	5,251	4,115	780	1,001	107		417	1,309
6+		443	854	722	1,304	3,235	549	761	178		426	422

Population size estimated by tuning VPA (x 1000 fish)

age	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
1	42,765	33,967	31,333	30,583	14,063	11,517	16,752	15,569	13,605	14,092	4,938	3,093
2	13,950	23,877	21,158	12,461	14,045	7,975	7,265	7,888	8,766	7,787	5,093	1,758
3	5,572	6,957	9,386	7,170	3,793	3,061	2,878	2,777	2,158	3,460	4,117	2,117
4	1,594	2,325	3,503	5,030	2,939	1,257	1,124	1,198	846	926	1,606	2,064
5	616	589	940	1,355	1,089	490	298	382	284	311	318	757
6+	103	223	213	362	252	166	68	93	78	58	146	151
total	64,601	67,938	66,533	56,961	36,182	24,467	28,385	27,906	25,736	26,635	16,217	9,940

Biomass estimated by tuning VPA (tons)

age	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
1	14,923	7,612	9,027	6,659	3,383	3,268	4,069	3,782	2,986	4,256	1,911	1,068
2	20,157	24,949	26,776	12,342	12,174	6,781	5,735	6,463	7,051	6,331	5,016	1,318
3	14,159	16,773	23,491	14,191	8,073	5,482	5,111	5,664	4,116	6,339	8,616	4,173
4	6,098	9,105	13,503	15,636	10,100	4,302	3,402	4,008	2,694	2,878	5,389	6,189
5	3,969	3,317	5,132	6,768	5,350	2,462	1,437	1,831	1,368	1,585	1,501	3,327
6+	838	1,926	1,649	2,808	1,740	1,098	480	653	552	446	1,282	1,210
total	60,143	63,682	79,578	58,404	40,821	23,395	20,235	22,402	18,768	21,834	23,716	17,285

References

Hiramatsu, K. (2001) VPA (Virtual Population Analysis). “Fiscal Year 2000 Report on Establishment and Promotion of the Stock Assessment System”. Japan Fisheries Resource Conservation Association, 104-129.

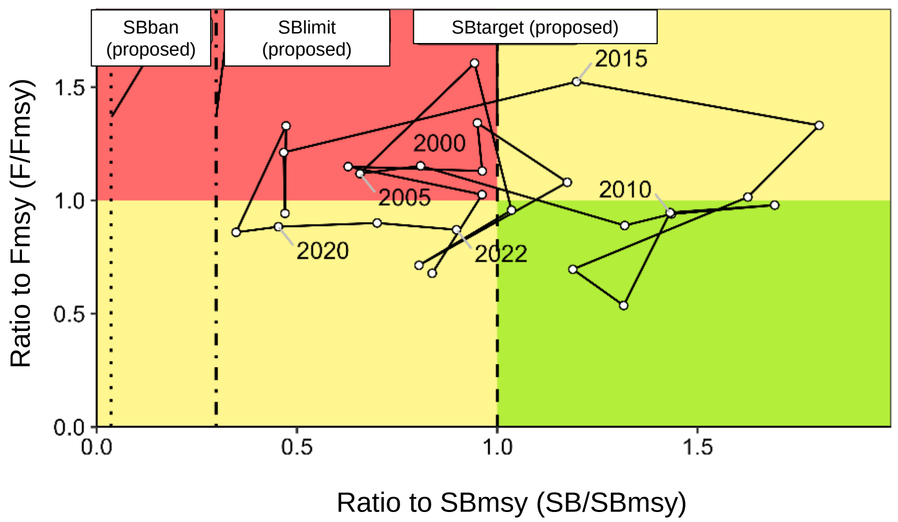
Pope, J. G (1972) An investigation of accuracy of virtual population analysis using cohort analysis. Res. Bull. int. comm. Northw. Atlant. Fish., 9, 65-74.

Tanaka, S (1960) Population Dynamics of fishery organisms and fishery resource management. Bull. Tokai Reg. Fish. Res. Lab., **28**, 1-200.

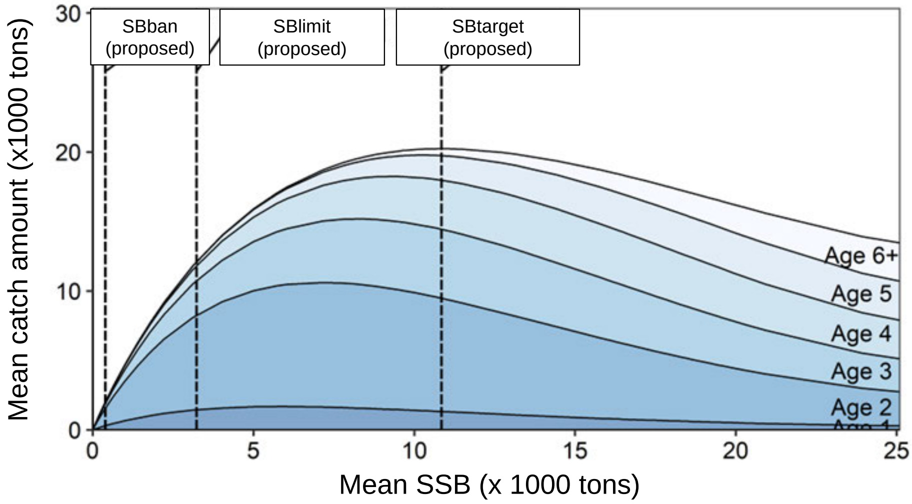
Appendix 3 Proposed Reference Points and Proposed Fishing Ban Level

The Research Institute Meeting held in August 2020 proposed adoption of the following: SSB required for MSY (SBmsy: 10,900 tons) as a target reference point (SBtarget), SSB required for 60% MSY (SB0.6msy: 3,200 tons) as a limit reference point (SBlimit), and SSB required for 10% MSY (SB0.1msy: 400 tons) as a fishing ban level (SBban)(Narimatsu et al. 2021, Supplementary Table 6-2).

The proposed target reference points and fishing pressure (F) required for MSY are shown in the Kobe plot in Supplementary Fig. 3-1. SSB in 2022 (SB2022: 9,900 tons) obtained from cohort analysis is lower than the proposed target reference points, but above the proposed limit reference point and proposed fishing ban level. Fishing pressure for this stock for the 2018 to 2021 fishing seasons is determined to have exceeded the fishing pressure required for MSY (Supplementary Table 6-3).
The relationship of average SSB and average catch in weight at age at equilibrium is shown in Supplementary Fig. 3-2. When average SSB is below the limit reference point, catches are dominated by age 3 and younger. However, the proportion of older fish tends to increase in correlation with increase of SSB.



Supplementary Fig. 3-1. Relationship of proposed reference points and SSB/fishing pressure (Kobe plot)



Supplementary Fig. 3-2. Relationship of average SSB and average catch in weight at age at equilibrium (catch in weight curve)

Appendix 4. Future Projections Based on Proposed HCRs

(1) Setting Future Projections

Future forecast calculations were performed for the 2023 to 2054 fishing seasons using a progression method for cohort analysis applied to stock abundance in the 2022 fishing season estimated in stock assessment reports (see Appendix 5).

It is known that the maturity ratio of this stock varies by age, and the relationship to stock status has been pointed out (Narimatsu et al. 2010). Since a negative correlation between stock population at age and maturity ratio has been observed in recent data (Appendix 5), in future projections, SSB was calculated by taking into account changes in maturity ratio at age due to fluctuations in biomass. However, the maximum and minimum maturity ratio at age were each assumed to be within the range of values observed in the past.

Catch in weight in the 2023 was assumed based on forecasted stock abundance and current fishing pressure (F2019-2021). Fishing pressure in 2024 and onwards was set as the fishing pressure established in the following proposed HCRs, which are based on SSB projections for each year.

(2) Proposed HCRs

Proposed HCRs guidelines which aim for better results than proposed target reference points in consideration of the probability of success for both maintenance and recovery of SSB, which set fishing pressure (F) and other factors that correspond to SSB. The HCRs and Basic Guidelines for ABC Calculation describe linear reduction of fishing pressure down to the proposed fishing ban level when SSB falls below the proposed limit reference point, and an upper limit for fishing pressure equal to Fmsy multiplied by adjustment coefficient β when SSB is above the limit reference point. Supplementary Fig. 4-1 shows the HCRs from the Research Institute Meeting for this stock. This figure includes an example showing when the adjustment coefficient β is set to 0.8. The Research

Institute Meeting proposals state that “when β is lower than 0.8, then there is a 50% or higher probability that values will exceed proposed target reference points in 10 years.”

(3) Projected Values for the 2024 Fishing Season

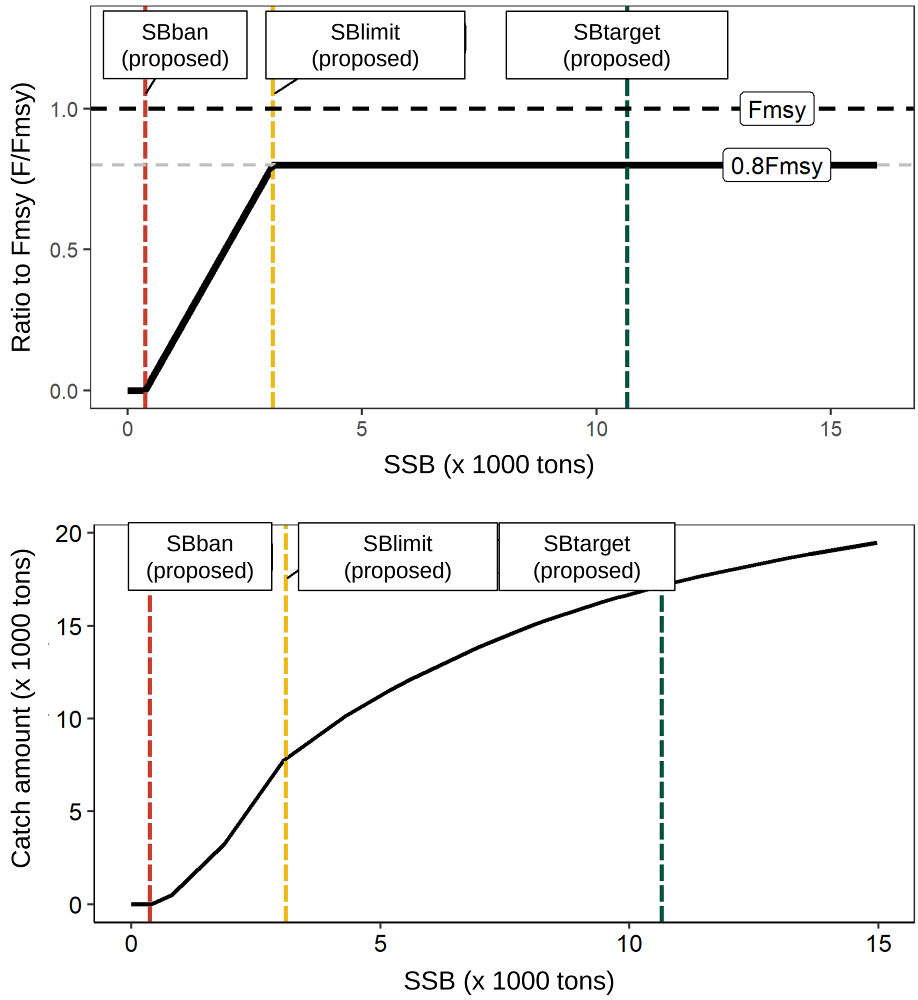
The average catch in 2024, as calculated based on proposed HCRs, will be 6,300 tons if β is set to 0.8, and 7,300 tons if β is set to 1.0 (Supplementary Table 6-4). The projected SSB for the 2024 fishing season exceeded the limit reference point and is expected to average 4,800 tons.

(4) Forecast for the 2025 Fishing Season and After

Results of future projections, including 2025 and onwards, are shown in Supplementary Figure 4-2 and Supplementary Tables 4-2 and 4-3. If management based on these proposed HCRs is continued for 10 years, then projected values for average SSB in 2034 will be 10,400 tons if β is set to 0.8 (90% prediction interval: 4,100 to 18,800 tons), and 6,900 tons if β is set to 1.0 (90% prediction interval: 2,700 to 12,800 tons) (Supplementary Table 6-5). If β is 0.75 or lower, then there is a 50% or higher probability that the projected value will exceed the proposed target reference point. The probability of exceeding the proposed limit reference point is greater than 50%, even if β is 1. If the current fishing pressure (F2019-2021) is continued, then projected values for SSB in 2034 will be 8,200 tons (90% prediction interval of 3,000 to 15,200 tons), with a 24% probability that the value will exceed the proposed target reference point, and a 93% probability that it will exceed the proposed limit reference point.

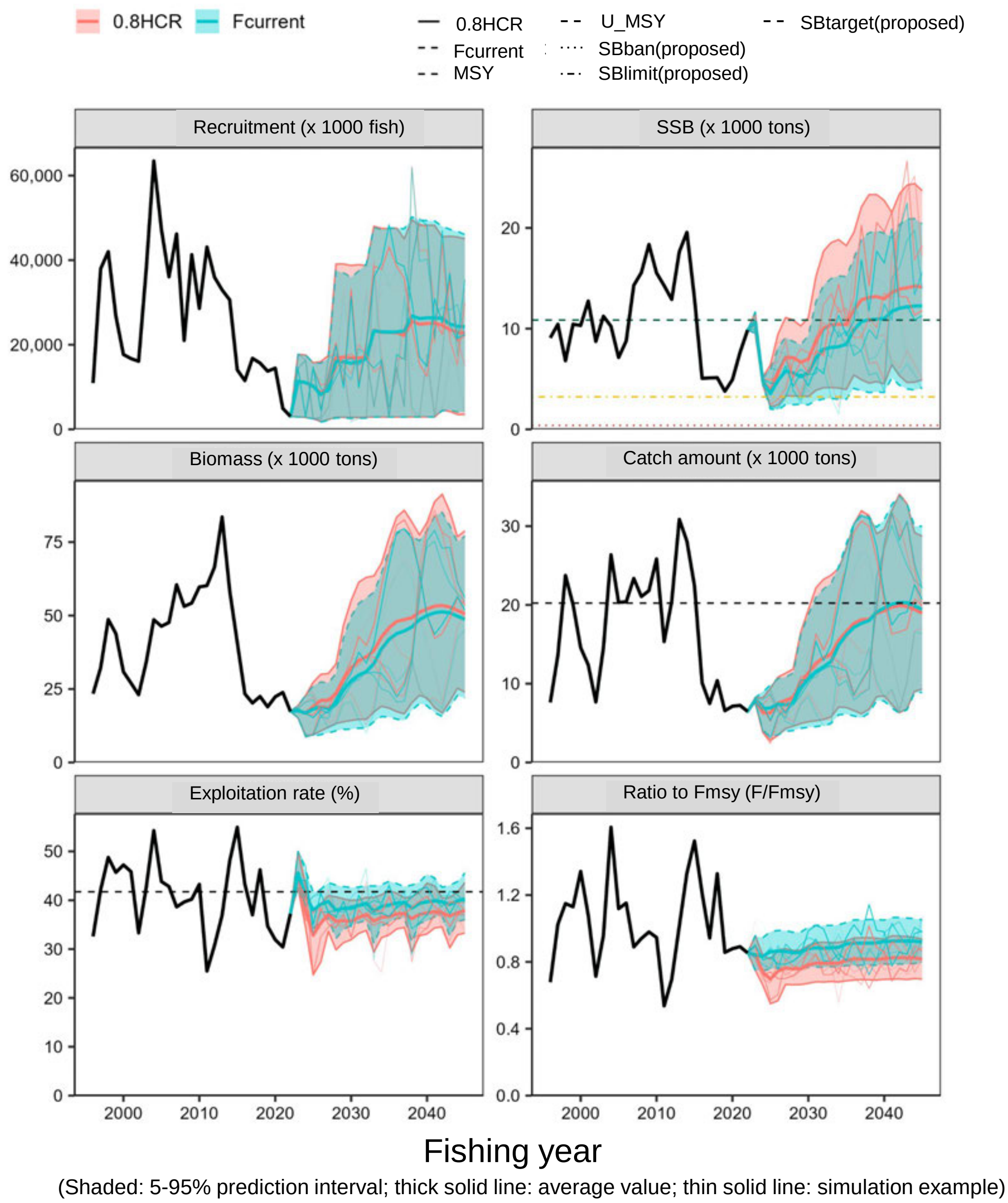
If management continues under the proposed HCRs, the fishing year in which the SSB would have a greater than 50% probability of exceeding the proposed target reference point is projected to be the 2044 fishing year and onwards if β is set at 0.8 (Supplementary Table 6-5). The fishing year with a greater than 50% probability of exceeding the limit reference point is projected to be the 2024 fishing season. Even if catch pressure is reduced to zero (β = 0), it is projected that SSB will not exceed the proposed target reference points with more than 50% probability until the 2025 fishing season.

In future projections based on the FY2021 stock assessment results, the probability that the projected values for SSB 10 years from now will exceed the target reference points when β is set at 0.8 is 56%, which is higher thanlast year's (48%) and this year’s results (41%). This may be attributed to a decrease in the estimated number of age 1 fish due to the addition of data.



Supplementary Fig. 4-1. Proposed Harvest Control Rules (HCRs)

The proposed target reference points (SBtarget) are the SBmsy values calculated based on a Ricker stock-recruitment model. Standard values are used for the proposed limit reference point (SBlimit) and the proposed fish ban level (SBban), respectively. The standard value of 0.8 was used for the adjustment coefficient β. The black dashed line indicates Fmsy, the gray dashed line is 0.8 Fmsy, the black thick line is HCR, the red dashed line is proposed fish ban level, the yellow dashed line is proposed limit reference point, and the green dashed line is proposed target reference points. Graph (a) is the scenario when the vertical axis shows fishing pressure, and graph (b) is the scenario when the vertical axis shows catch in weight. In (b), while catch in weight varies slightly depending on the age composition in the year of catch, the catch in weight for the average age composition at equilibrium is shown here.



Supplementary Fig. 4-2. Future projections based on proposed HCRs (red line), and future projections if the current fishing is continued (green line).

The solid line indicates average values, the shaded area indicates the prediction interval which contains 90% of simulation results, and the thin lines indicate 5 future projections. In the SSB graph, the green dashed line is the target reference point, the yellow dotted line is the limit reference point, and the red dotted line is the fishing ban level. In the exploitation rate graph, the dashed line indicates Umsy.

Supplementary Table 4-1. Parameter values used to estimate the level of realization of Maximum Sustainable Yield (MSY) (Narimatsu et al. 2021)

age	M	Mean maturity rate	Mean body weight (g)	Selectivity*	Fcurrent**
1	0.357	0	285	0.16	0.23
2	0.357	0	1,239	0.53	0.74
3	0.357	0.22	2,402	0.48	0.68
4	0.357	0.73	3,999	0.66	0.93
5	0.357	1.00	5,788	1.00	1.40
6+	0.357	1.00	8,065	1.00	1.40

*The selectivity used to estimate level of realization of MSY is the selectivity of Fcurrent in FY 2021 (selectivity of average F from 2017 to 2019 fishing years)

**Fcurrent in the FY2021 (average F from 2017 to 2019 fishing years)

Supplementary Table 4-2. Probability (%) that future SSB will exceed proposed target/limit reference points. Values in bold indicate values in the target year, which is 10 years after starting management based on HCRs.

a) Probability of exceeding the proposed target reference point (%)

β	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	**2034**	2044	2054
1.0	0	42	0	0	0	1	0	0	1	8	13	12	**13**	49	44
0.95	0	42	0	0	0	1	0	0	1	10	17	18	**18**	55	51
0.9	0	42	0	0	1	2	1	0	2	14	23	25	**25**	60	57
0.85	0	42	0	0	1	3	2	1	3	18	30	33	**33**	64	62
0.8	0	42	0	0	1	6	5	3	6	24	38	41	**41**	66	66
0.75	0	42	0	0	2	11	11	7	11	32	45	50	**50**	69	71
0.7	0	42	0	0	3	17	20	15	19	41	55	59	**59**	71	74
0.65	0	42	0	0	5	25	31	27	30	52	64	67	**67**	74	76
0.6	0	42	0	0	8	35	44	40	43	63	72	73	**74**	75	77
0.55	0	42	0	0	12	43	55	54	56	74	79	79	**80**	77	78
0.5	0	42	0	0	16	51	67	68	68	83	86	84	**85**	78	79
0.4	0	42	0	0	28	71	83	88	88	94	94	92	**90**	79	78
0.3	0	42	0	1	42	83	92	96	97	99	98	96	**92**	81	81
0.2	0	42	0	1	54	88	97	99	100	100	100	99	**95**	91	95
0.1	0	42	0	3	62	94	99	100	100	100	100	100	**99**	100	99
0.0	0	42	0	5	70	99	100	100	100	100	100	100	**100**	100	100
F2019-2021	0	42	0	0	0	1	0	0	2	11	20	22	**24**	59	56

b) Probability of exceeding the proposed limit reference point (%)

β	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	**2034**	2044	2054
1.0	100	100	100	42	77	87	87	79	81	89	91	91	**90**	96	97
0.95	100	100	100	45	79	90	90	85	85	92	93	93	**93**	97	97
0.9	100	100	100	49	80	93	92	89	89	94	95	95	**95**	98	98
0.85	100	100	100	53	82	94	94	92	92	96	96	97	**97**	98	99
0.8	100	100	100	57	83	95	96	94	95	97	97	98	**98**	99	99
0.75	100	100	100	62	85	96	97	96	97	98	99	99	**99**	99	99
0.7	100	100	100	69	87	97	98	98	98	99	99	99	**99**	99	99
0.65	100	100	100	75	90	98	99	99	99	99	100	100	**100**	99	99
0.6	100	100	100	81	92	98	99	100	100	100	100	100	**100**	99	99
0.55	100	100	100	90	96	100	100	100	100	100	100	100	**100**	99	99
0.5	100	100	100	99	99	100	100	100	100	100	100	100	**100**	100	100
0.4	100	100	100	100	100	100	100	100	100	100	100	100	**100**	100	100
0.3	100	100	100	100	100	100	100	100	100	100	100	100	**100**	100	100
0.2	100	100	100	100	100	100	100	100	100	100	100	100	**100**	100	100
0.1	100	100	100	100	100	100	100	100	100	100	100	100	**100**	100	100
0.0	100	100	100	100	100	100	100	100	100	100	100	100	**100**	100	100
F2019-2021	100	100	100	49	76	89	89	86	86	92	93	93	**93**	97	98

Supplementary Table 4-3. Trends in future SSB and average catch in weight Values in bold indicate values in the target year, which is 10 years after starting management based on proposed HCRs.

a) Trends in average SSB (thousand tons)

β	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	**2034**	2044	2054
1.0	9.9	10.7	4.8	3.3	4.8	5.6	5.2	4.6	5.0	6.4	7.0	6.9	**6.9**	10.6	10.3
0.95	9.9	10.7	4.8	3.4	5.0	5.9	5.6	5.0	5.4	6.9	7.6	7.6	**7.7**	11.5	11.1
0.9	9.9	10.7	4.8	3.5	5.2	6.3	6.0	5.5	5.9	7.5	8.4	8.5	**8.5**	12.3	12.0
0.85	9.9	10.7	4.8	3.7	5.4	6.7	6.5	6.1	6.4	8.1	9.2	9.4	**9.4**	13.3	12.9
0.8	9.9	10.7	4.8	3.8	5.7	7.1	7.1	6.7	7.0	8.8	10.0	10.4	**10.4**	14.2	13.8
0.75	9.9	10.7	4.8	4.0	6.0	7.6	7.8	7.4	7.6	9.6	11.0	11.5	**11.6**	15.2	14.8
0.7	9.9	10.7	4.8	4.1	6.3	8.2	8.5	8.2	8.4	10.4	12.1	12.7	**12.9**	16.3	15.9
0.65	9.9	10.7	4.8	4.3	6.7	8.8	9.3	9.1	9.3	11.4	13.3	14.0	**14.2**	17.4	17.0
0.6	9.9	10.7	4.8	4.5	7.0	9.5	10.3	10.1	10.3	12.5	14.6	15.4	**15.7**	18.7	18.2
0.55	9.9	10.7	4.8	4.6	7.4	10.3	11.3	11.3	11.5	13.8	15.9	16.9	**17.2**	20.1	19.5
0.5	9.9	10.7	4.8	4.8	7.9	11.2	12.5	12.7	13.0	15.2	17.5	18.4	**18.7**	21.7	21.0
0.4	9.9	10.7	4.8	5.2	8.8	13.2	15.5	16.2	16.6	18.7	20.9	21.5	**21.5**	25.3	24.5
0.3	9.9	10.7	4.8	5.6	10.0	15.7	19.4	20.9	21.6	23.4	24.9	24.6	**23.6**	29.7	29.4
0.2	9.9	10.7	4.8	6.1	11.2	18.8	24.6	27.5	29.0	30.2	30.3	27.9	**24.7**	36.0	38.9
0.1	9.9	10.7	4.8	6.6	12.7	22.6	31.5	36.9	39.9	40.6	38.4	32.8	**26.6**	49.9	59.0
0.0	9.9	10.7	4.8	7.1	14.3	27.3	40.8	50.6	56.7	57.7	53.1	44.1	**34.3**	80.3	64.8
F2019-2021	9.9	10.7	4.8	3.5	4.9	5.8	5.6	5.2	5.6	7.1	8.0	8.1	**8.2**	12.3	11.9

b) Trends in average catch (thousand tons)

β	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	**2034**	2044	2054
1.0	6.5	7.9	7.3	6.2	7.7	7.5	7.6	9.2	10.3	11.3	11.7	12.3	**14.4**	19.9	19.8
0.95	6.5	7.9	7.1	6.3	7.6	7.6	7.7	9.5	10.6	11.7	12.1	12.7	**14.8**	19.9	19.8
0.9	6.5	7.9	6.8	6.3	7.6	7.7	7.9	9.7	10.9	12.0	12.5	13.1	**15.1**	19.8	19.7
0.85	6.5	7.9	6.6	6.3	7.6	7.8	8.1	9.9	11.1	12.3	12.9	13.4	**15.3**	19.7	19.5
0.8	6.5	7.9	6.3	6.3	7.5	7.9	8.3	10.0	11.4	12.6	13.3	13.8	**15.5**	19.4	19.3
0.75	6.5	7.9	6.0	6.2	7.4	8.0	8.4	10.2	11.5	12.8	13.6	14.0	**15.6**	19.1	18.9
0.7	6.5	7.9	5.8	6.2	7.4	8.0	8.6	10.3	11.6	13.0	13.8	14.2	**15.6**	18.6	18.4
0.65	6.5	7.9	5.5	6.1	7.3	8.1	8.7	10.3	11.7	13.0	13.9	14.2	**15.4**	18.1	17.9
0.6	6.5	7.9	5.1	5.9	7.1	8.1	8.8	10.4	11.7	13.0	13.9	14.1	**15.2**	17.5	17.3
0.55	6.5	7.9	4.8	5.7	7.0	8.1	8.8	10.3	11.5	12.8	13.7	13.9	**14.7**	15.1	16.9
0.5	6.5	7.9	4.5	5.5	6.8	8.0	8.9	10.2	11.3	12.5	13.3	13.4	**14.1**	16.2	15.9
0.4	6.5	7.9	3.7	4.9	6.2	7.7	8.7	9.9	10.6	11.4	12.0	11.9	**12.3**	14.5	14.3
0.3	6.5	7.9	2.9	4.0	5.4	7.0	8.2	9.1	9.5	9.8	9.9	9.6	**9.6**	12.0	12.3
0.2	6.5	7.9	2.0	3.0	4.2	5.7	7.0	7.7	7.9	7.8	7.5	6.8	**6.4**	9.1	10.3
0.1	6.5	7.9	1.1	1.7	2.5	3.6	4.5	5.1	5.2	5.0	4.5	3.9	**3.3**	6.0	7.7
0.0	6.5	7.9	0	0	0	0	0	0	0	0	0	0	**0**	0	0
F2019-2021	6.5	7.9	6.8	6.9	7.4	7.3	7.6	9.4	10.6	11.5	12.1	12.8	**14.9**	19.9	19.8

Appendix 5. Future Projection Methods

Future projections were performed based on proposed HCRs using the SSB estimates. The projected recruitment volume after 2023 is based on a Ricker-model stock-recruitment relationship (a = 9,116, b = $1.15*10^{-4}$, SD = 0.36) based on the 1996 to 2019 cohort recruitment volume and SSB proposed at the Research Institute Meeting held in August 2021. However, recruitment continues to be lower than projected from stock-recruitment relationships based on 2014 cohort recruitment volume (recruitment of age 1 fish in the 2015 fishing season) (Fig. 4-11). Since the same trend is projected to continue in the future, we have made future projections incorporating the recent recruitment situation. Backward resampling, in which the residuals in the observed values and the stock-recruitment relationship model are resampled retroactively every five years, was employed when projecting recruitment for the 2022 fishing season and onwards (Supplementary Fig. 5-1). Using this method, we assumed that in the short term, recruitment would reflect the most recent environmental conditions, and in the medium-to-long term, recruitment would reflect conditions in the past

・ 1st to 5th years of future projection: Resample, allowing overlap only from the residuals for the past 5 years (the 2018 to 2022 fishing seasons).

・ 6th to 10th years of future projection: Residuals from either the last 5 years (the 2018 to 2022 fishing seasons) or from the 6th to 10th years (the 2013 to 2017 fishing seasons) were randomly selected and resampled, allowing for an overlap of 5 years' worth for the chosen residuals.

・ 11th year and onwards of the future projection: The above procedure was used to add a range for resampling the residuals every 5 years. Projections for 2043 and onwards will be made via resampling of all residual data.

The fishing mortality F used in the future projections were values estimated based on control rules for Stock Group 1 according to Harvest Control Rules and Basic Guidelines for ABC Calculation. The parameters used for future projections (Supplementary Table 5-1) were the values used to estimate the various reference points proposed at the Research Institute Meeting. As noted above, in future projections, SSB was calculated by taking into account changes in maturity ratio at age due to fluctuations in the stock population. However, the maximum and minimum age-specific maturity rates were assumed to be within the range of values observed in the past, respectively (Supplementary Fig. 5-2). Projections for stock population were made using progression method cohort analysis.

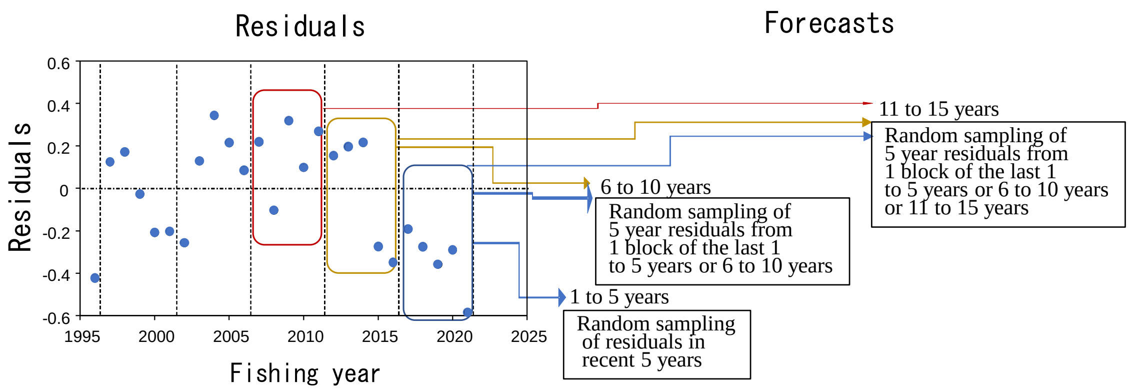
$$N_{a+1,y+1} = N_{a,y}\, exp(-F_{a,y} - M) \ \text{(Age 1 to 5)} \qquad (1)$$

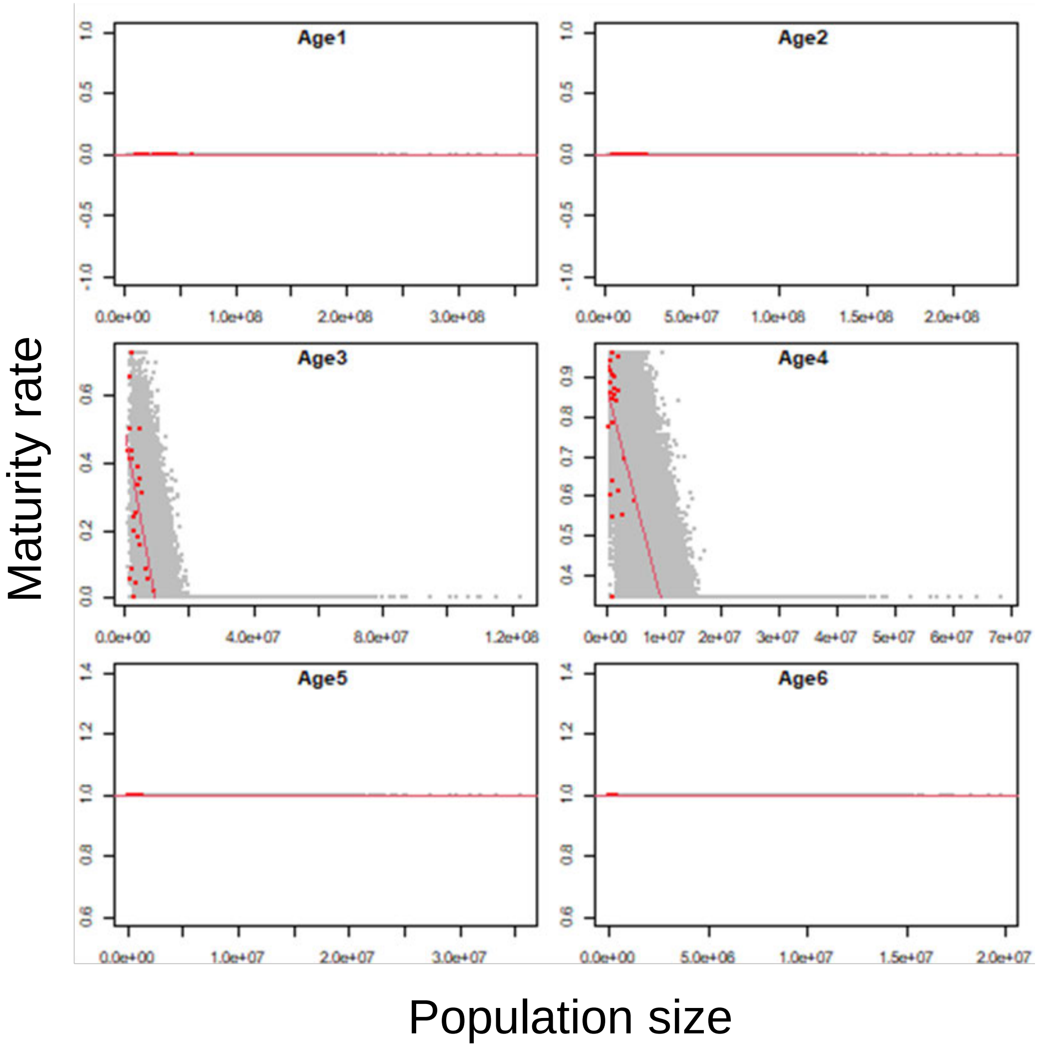
$$N_{6+,y+1} = (N_{6+,y} + N_{5,y})\, exp(-F_{5,y} - M) \ \text{(Age 6 and older)} \qquad (2)$$

Catch in number was determined using the equation below with catch in number results from the equation above and F value assumptions based on each catch strategy

$$C_{a,y} = N_{a,y}\{1 - exp(-F_{a,y})\}\, exp(-\frac{M}{2}) \qquad (3)$$

Supplementary Fig. 5-1. Schematic View of Backward Resampling





Supplementary Fig. 5-2. Relationship between Stock Population at Age and Maturity rate

The red dots are measured values, the red line is their regression, and the gray dots are estimated values in future projections.

Supplementary Table 5-1. Parameters used for future projection calculations

	Selectivity (Note 1)	Fmsy (Note 2)	F2017-2019 (Note 3)	Average weight (g)	Natural mortality coefficient	Maturity rate (Note 4)
Age 1	0.16	0.23	0.30	285	0.357	0
Age 2	0.53	0.75	0.96	1,239	0.357	0
Age 3	0.48	0.69	0.88	2,402	0.357	0.02-0.72
Age 4	0.66	0.95	1.22	3,999	0.357	0.34-0.96
Age 5	1.00	1.42	1.81	5,788	0.357	1
Age 6+	1.00	1.42	1.81	8,065	0.357	1

Note 1: Selectivity used to estimate the level required for MSY at the FY 2020 Research Institute Meeting (i.e., selectivity of Fcurrent in the FY2020 stock assessment).

Note 2: Fmsy estimated at the FY 2020 Research Institute Meeting (i.e., Fmsy/Fcurrent multiplied by Fcurrent in the FY2020 stock assessment).

Note 3: Under the selectivity above, an F value that gives the same fishing pressure as the average F value by age in the 2018 to 2021 fishing seasons estimated in this stock assessment was calculated by conversion to %SPR. This F value was used as the assumed catch for the 2022 fishing season.

Note 4: The maturity rates (Maa) of age 3 and 4 in future projections are based on the following equations, respectively. In addition, N

is the stock population at each age.

Age 3: $Maa=-5.24*10^{(-8)}N_{age3}+0.48$ $(0.72 \geq Maa \geq 0.02)$

Age 4: $Maa=-5.67*10^{(-8)}N_{age4}+0.87$ $(0.96 \geq Maa \geq 0.34)$

Appendix 6 Summary of Various Parameters and Assessment Results

Supplementary Table 6-1. Parameters for stock-recruitment relationship model

Stock-recruitment relationship model	Optimization method	Autocorrelation	a	b	S.D.	ρ
Ricker model	Least squares method	Yes	9,116	1.15×10^{-4}	0.36	0.63

In this table, a and b are the estimated parameters of the stock-recruitment relationship model, S.D. is the standard deviation of recruitment volume, and ρ is the autocorrelation coefficient.

Supplementary Table 6-2. Proposed reference points and MSY

Item	Value	Description
SBtarget (proposed)	10,900 tons	A proposed target reference point. SSB required for MSY (SBmsy).
SBlimit (proposed)	3,200 tons	A proposed limit reference point. SSB required for catch of 60% of MSY (SB0.6msy).
SBban (proposed)	400 tons	Proposed fishing ban level. SSB required for catch of 10% of MSY (SB0.1msy).
Fmsy	Fishing pressure required for MSY (fishing mortality F) (Age 1, Age 2, Age 3, Age 4, Age 5, Age 6 and older) = (0.23, 0.75, 0.69, 0.95, 1.42, 1.42)	
%SPR (Fmsy)	5.9%	%SPR corresponding to Fmsy
MSY	20,200 tons	Maximum Sustainable Yield

Supplementary Table 6-3. SSB and fishing pressure in most recent year

Item	Value	Description
SB2022	9,900 tons	SSB in 2022 fishing season
F2022	Fishing pressure in 2021 fishing season (fishing mortality F) (Age 1, Age 2, Age 3, Age 4, Age 5, Age 6 and older) = (0.51, 0.45, 0.40, 0.57, 0.91, 0.91)	
U2022	37%	Exploitation rate in 2022 fishing season (%)
%SPR (F2022)	8.1%	%SPR in 2022 fishing season
%SPR (F2019-2021)	7.7%	%SPR corresponding to current fishing pressure (2019 to 2021 fishing seasons)*
Compared against proposed reference points		
SB2022 / SBmsy (SBtarget)	0.91	B ratio required for MSY (proposed target reference points) to SSB in 2021 fishing season
F2022 / Fmsy	0.85	F ratio required for MSY to fishing pressure in 2022*
Level of SSB	Under the level required for MSY	
Level of fishing pressure	Under the level required for MSY	
Changes in SSB	Increase	

*Ratio calculated based on %SPR converted F, which reflects Fmsy fishing pressure at the selection probability of the 2022 fishing season.

Supplementary Table 6-4. Projected catch in weight and projected SSB

SSB in 2024 fishing season (average projected value): 4,800 tons			
Item	Catch in 2024 (thousand tons)	Ratio to current fishing pressure (F/F2019-2021)	Exploitation rate in 2024 fishing season (%)
β = 1.0	7.3	1.11	43
β = 0.9	6.8	1.00	41
β = 0.8	6.3	0.89	38
β = 0.75	6.0	0.83	36
β = 0.7	5.8	0.78	34
β = 0.6	5.1	0.67	31
β = 0.5	4.5	0.55	27
F2018-2020	6.8	1.00	41

Supplementary Table 6-5. Results of future projections using various β

Uncertainty under consideration: Recruitment volume					
β	SSB in the 2034 fishing season (thousand tons)	90% Prediction interval (thousand tons)	Probability (%) that SSB will exceed the proposed reference points below in the 2034 fishing season		
			SBtarget (proposed)	SBlimit (proposed)	SBban (proposed)
β=1.0	6.9	2.7 – 12.8	13	90	100
β=0.9	8.5	3.3 – 15.5	25	95	100
β=0.8	10.4	4.1 – 18.8	41	98	100
β=0.75	11.6	4.6 – 20.7	50	99	100
β=0.7	12.9	5.2 – 22.8	59	99	100
β=0.6	15.7	6.5 – 27.5	74	100	100
β=0.5	18.7	7.9 – 32.6	85	100	100
F2019-2021	8.2	3.0 – 15.2	24	93	100

Supplementary Table 6-5. Results of future projections using various β (continued)

Uncertainty under consideration: Recruitment volume			
β	Years in which SSB exceeds the proposed reference points by more than 50% (fishing year)		
	SBtarget (proposed)	SBlimit (proposed)	SBban (proposed)
β=1.0	2054 and onowards	2024	2024
β=0.9	2044	2024	2024
β=0.8	2044	2024	2024
β=0.75	2033	2024	2024
β=0.7	2032	2024	2024
β=0.6	2031	2024	2024
β=0.5	2027	2024	2024
F2019-2021	2044	2024	2024

Appendix 7 Summary of Survey Results

The abundance index for the Honshu northern Pacific stock of Pacific cod was determined by an area-density method using the results of bottom-trawl surveys conducted by research vessels in the Tohoku area. The survey area covers a range of 100 to 1000 m in depth off Aomori to Ibaraki prefectures, and covers the horizontal and vertical distribution of this stock (Supplementary Fig. 3-1). This stock are distributed from off Aomori to Ibaraki prefectures. However, considering that the number of nets off the coast of Fukushima has decreased significantly since the Earthquake, and only trial operation of fishery was conducted until March 2021, it is considered that there has been a bias in the number of fish caught by age since the Earthquake. Therefore, we used the standing stock value from off Aomori to Miyagi prefectures as an index value for tuning. The age of Pacific cod caught in the survey was assessed for all individuals based on body length composition (age 0 and 1) and otolith transparency zone readings (age 2 and older). The survey area was then divided into north-south at 38°50' N latitude, stratifying the area into 16 layers in 8 depth zones: 100 to 200 m, 200 to 300 m, 300 to 400 m, 400 to 500 m, 500 to 600 m, 600 to 700 m, 700 to 800 m and 800 to 1,000 m. The distance from the net reaching the bottom to the net leaving the bottom at each survey point (j) was determined for each layer (i) stratified into north-south and depth zones and then used as the trawl distance. Otter board spacing was measured with an otter recorder, and sleeve tip spacing was estimated using the ratio of otter board spacing to sleeve tip spacing (1:0.258) obtained from the gear configuration. The trawl area at layer i, point j (aij) was obtained by multiplying the trawl distance by the sleeve tip spacing. The catch in weight at age or the catch in number at age at layer i, point j (Cij) was divided by aij to calculate the density at layer i, point j (dij), and the average of the two was used as the density of layer i (di). Note that ni represents the number of survey sites in layer i.

$$d_{ij} = \frac{C_{ij}}{a_{ij}} \quad (1)$$

$$d_i = \frac{1}{n_i}\sum_{j=1}^{n_i} d_{ij} \quad (2)$$

Furthermore, the average density of layer i (di) was multiplied by the ocean area of layer i (Ai) to determine the standing stock or biomass in numbers of layer i (Bi), which was then totaled to obtain the standing stock or biomass in numbers of Pacific cod in the entire Tohoku area (B).

$$B_i = A_i \cdot d_i \quad (3)$$

$$B = \sum B_i \quad (4)$$

The standing stock population was calculated by body length in 1 cm increments to determine the body length composition by age of the entire stock.

The standard deviation of the density of layer i (SDdi) was obtained, and the standard error of the biomass or biomass in numbers in layer i (SEBi) was calculated using ni and Ai. The standard error (SE) and coefficient of variation (CV, %) of the stock for the entire survey area were obtained using the following equations. The CV obtained here is the value for the index values of standing stock and biomass in numbers, and does not include estimation errors in capture efficiency.

$$SE_{B_i} = \frac{A_i \cdot SD_{d_i}}{\sqrt{n_i}} \quad (5)$$

$$SE = \sqrt{\sum SE_{B_i}^2} \quad (6)$$

$$CV = \frac{SE}{B} \quad (7)$$

The upper and lower limits of the confidence intervals were determined by exp(log(N)-1.96×CV) and exp(log(N)+1.96×CV), respectively.

Capture efficiency by age in bottom trawls was determined based on the results of previous cohort analysis on the results of bottom-trawl surveys and the age and body length composition of catches (age 1: 0.64, age 2: 0.54, and age 3: 0.12, Ueda et al. 2006).

The height of the nets used in the survey was about 3 to 4 m during trawling, and individuals distributed above this height do not enter the nets. In addition, bottom trawl nets are difficult to haul over rocky reef areas, so the encounter rate with older fish that inhabit the vicinity of rocky reef areas is low. Therefore, the capture efficiency here was determined by including the encounter rate as well.

As a result, the standing stock population for the 1996 to 2022 fishing seasons ranged from 4 million to 111 million (Fig. 4-1 and Supplementary Table 7-1). Biomass used as an abundance index ranged from 6,000 to 90,000 tons, and after reaching 90,000 tons in 2012, it has been rapidly decreasing, and was 23,000 tons in 2021 (Fig. 4-2 and Supplementary Table 7-2).

The CV of standing stock population by age in the 2021 survey was 0.27 for age 1, 0.41 for age 2, and 0.22 for all ages combined (Supplementary Table 7-3).

References

Ueda, Y., Narimatsu, Y., Hattori, T., Ito, M., Kitagawa, D., Tomikawa, N. and Matsuishi, T. (2006) Fishing efficiency estimated based on the abundance from virtual population analysis and bottom-trawl surveys of Pacific cod Gadus macrocephalus in the waters off the Pacific coast of northern Honshu, Japan. Fish. Sci., **72**, 201-209.

Supplementary Table 7-1. Standing Stock Population by Age (thousands) Estimated From Trawl Surveys

Age	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
1	2,760	15,806	15,848	38,757	2,630	2,247	2,196	11,253	3,509	22,042	14,743	16,866	893	12,057	23,066
2	3,871	518	5,695	3,452	9,758	332	1,798	1,060	5,570	2,018	4,936	2,219	7,449	921	10,863
3	752	749	74	1,519	360	1,125	286	1,287	1,313	1,779	1,736	550	597	1,957	299
4	554	123	0	49	105	96	128	103	69	156	223	107	111	190	237
5	103	123	0	0	0	0	0	14	21	0	244	36	16	29	39
6+	0	62	0	0	0	25	0	18	24	0	20	0	0	0	25
total	8,040	17,381	21,618	43,777	12,853	3,826	4,407	13,734	10,508	25,995	21,901	19,779	9,066	15,155	34,529

Age	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
1	68,679	49,374	10,688	13,297	29,436	22,036	20,272	30,588	7,803	8,449	372	4,189
2	8,487	57,884	23,993	14,172	15,807	12,327	6,957	6,559	6,088	10,026	4,249	96
3	3,685	2,718	18,083	11,600	5,842	6,096	3,554	2,377	1,243	2,665	3,157	346
4	343	899	1,327	5,091	4,362	2,105	1,442	1,180	262	7	481	786
5	49	105	357	680	1,230	1,015	187	282	23	0	98	319
6+	0	40	97	111	189	476	82	111	33	0	81	67
total	81,243	111,019	54,546	44,949	56,866	44,055	32,493	41,098	15,453	21,148	8,437	5,802

Surveys were conducted in Oct to Nov.

Estimation by swept-area method

Catch efficiencies were adapted 0.54 in 1 year old fish, 0.12 in 2 and older fish.

Supplementary Table 7-2. Standing stock by Age (Tons) Estimated From Trawl Surveys

Age	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
1	301	4,451	5,895	11,509	1,212	1,272	1,262	5,530	1,591	8,434	6,285	5,661	448	4,882	6,362
2	4,141	692	8,191	4,663	11,485	539	3,146	1,914	7,763	3,033	6,462	3,098	22,259	1,446	14,211
3	869	1,843	330	4,096	588	3,190	795	3,220	2,828	4,415	3,292	1,233	1,507	5,573	655
4	1,371	662	0	374	367	326	615	362	300	693	812	439	592	762	1,071
5	635	978	0	0	0	0	0	81	177	0	1,307	219	110	240	203
6+	0	467	0	0	0	250	0	188	225	0	263	0	0	0	262
total	7,316	9,094	14,416	20,643	13,653	5,577	5,819	11,295	12,883	16,575	18,421	10,650	24,916	12,902	22,764

Age	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
1	22,846	15,017	4,046	4,303	9,692	4,513	5,794	5,836	2,441	1,744	149	1,495
2	11,287	64,404	23,311	14,498	14,432	10,462	6,559	5,275	5,248	11,682	3,636	81
3	9,018	6,054	38,816	21,478	10,967	10,341	6,300	3,707	2,410	4,837	5,455	711
4	1,127	3,748	4,445	16,033	13,142	5,576	4,082	2,917	837	23	1,445	1,948
5	217	601	1,907	3,332	5,251	4,115	780	1,001	107	0	417	1,309
6+	0	443	854	722	1,304	3,235	549	761	178	0	426	422
total	44,494	90,267	73,380	60,366	54,789	38,242	24,064	19,497	11,221	18,285	11,527	5,966

Surveys were conducted in Oct to Nov.

Estimation by swept-area method

Supplementary Table 7-3. Standing Stock Population and Coefficient of Variation (CV) of Pacific Cod Obtained from Trawl Surveys, and Annual Changes in Confidence Intervals

Year	1996	1997	1998	1999	2000	2001
Number of stations	22	36	37	35	50	55
Population size (x 1000 fish)	3,497	17,381	21,618	43,777	12,853	3,826
CV of population size	0.511	0.127	0.188	0.176	0.218	0.349
SE of population size (x 1000 fish)	1,787	2,205	4,059	7,720	2,799	1,335
95% confidence interval (lowest, x 1000 fish)	1,285	13,556	14,962	30,984	8,387	1,930
95% confidence interval (highest, x 1000 fish)	9,520	22,287	31,235	61,852	19,698	7,583

Year	2002	2003	2004	2005	2006	2007
Number of stations	47	56	80	80	79	81
Population size (x 1000 fish)	4,407	13,734	10,508	25,995	21,901	19,779
CV of population size	0.321	0.240	0.200	0.205	0.140	0.166
SE of population size (x 1000 fish)	1,417	3,300	2,100	5,337	3,061	3,291
95% confidence interval (lowest, x 1000 fish)	2,347	8,575	7,103	17,383	16,653	14,275
95% confidence interval (highest, x 1000 fish)	8,276	21,997	15,546	38,874	28,802	27,405

Year	2008	2009	2010	2011	2012	2013
Number of stations	81	71	67	66	60	64
Population size (x 1000 fish)	9,066	15,115	34,529	81,242	159,256	74,541
CV of population size	0.224	0.267	0.225	0.466	0.111	0.193
SE of population size (x 1000 fish)	2,034	4,042	7,761	37,862	17,725	14,349
95% confidence interval (lowest, x 1000 fish)	5,843	8,986	22,227	32,590	128,042	51,113
95% confidence interval (highest, x 1000 fish)	14,074	25,561	53,642	202,530	198,078	108,706

Year	2014	2015	2016	2017	2018	2019
Number of stations	61	65	64	60	62	60
Population size (x 1000 fish)	56,759	70,038	54,327	38,290	46,563	20,526
CV of population size	0.181	0.167	0.147	0.178	0.290	0.256
SE of population size (x 1000 fish)	10,284	11,695	8,009	6,801	13,516	5,251
95% confidence interval (lowest, x 1000 fish)	39,793	50,488	40,694	27,033	26,361	12,433
95% confidence interval (highest, x 1000 fish)	80,959	97,157	72,528	54,235	82,249	33,888

Year	2020	2021	2022
Number of stations	79	71	75
Population size (x 1000 fish)	29,503	11,977	5,882
CV of population size	0.239	0.420	0.331
SE of population size (x 1000 fish)	7,045	5,027	1,948
95% confidence interval (lowest, x 1000 fish)	18,476	5,261	3,073
95% confidence interval (highest, x 1000 fish)	47,111	27,266	11,258

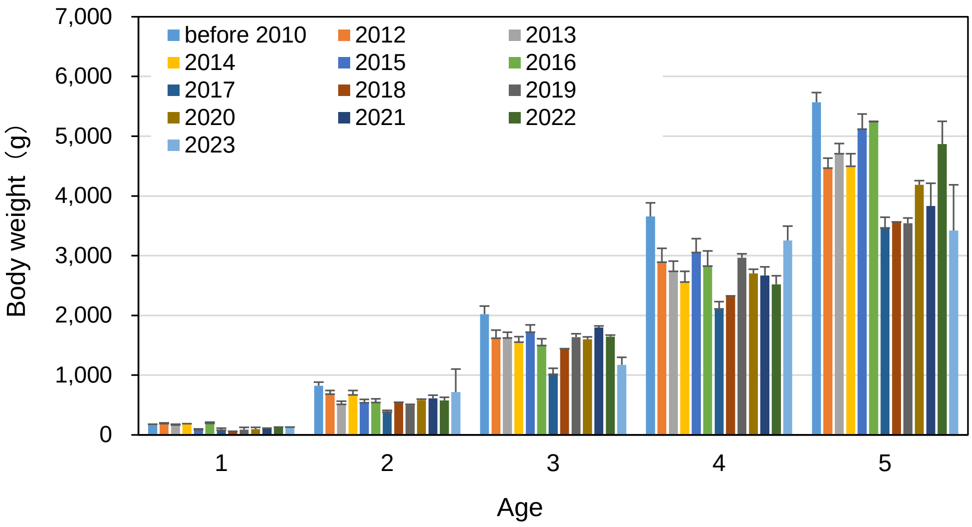
Note) CV, confidence interval derived from the population size in number and SE for each age group

Appendix 8. Slowdown in Growth and Changes in Maturity Rate Since the Earthquake

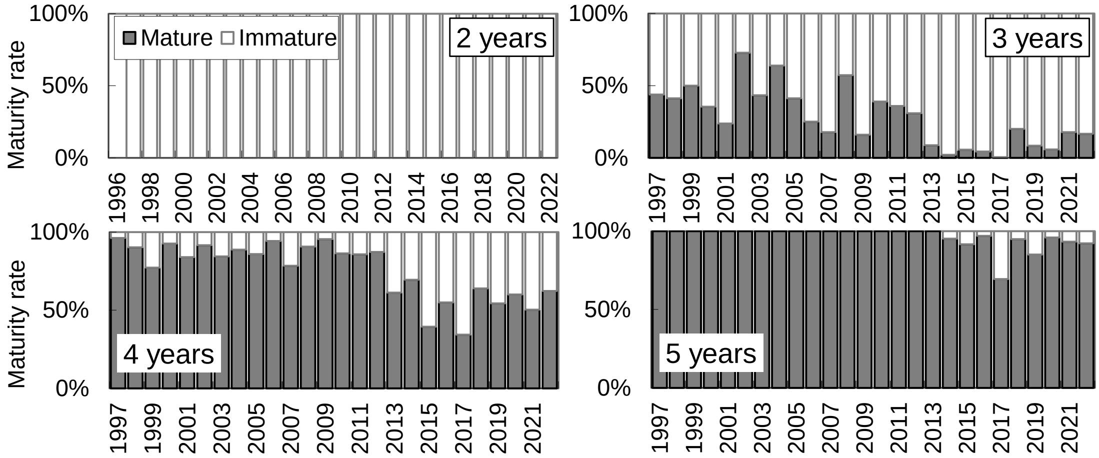
Since the Earthquake, a declining trend in Pacific cod growth has been observed. Since Pacific cod growth was shown to be negatively correlated with recruitment even before the Earthquake (Narimatsu et al. 2010), it is likely that growth slowed down in tandem with the rapid increase in stock following the Earthquake. In past stock assessments, biomass has been estimated by multiplying the average weight by age as of April for the most recent five years by the stock population. However, Pacific cod caught in surveys conducted in 2017 and April 2018 tended to be significantly lighter in body weight by age than Pacific cod caught in the post-Earthquake period from 2012 to 2016 (Supplementary Figure 4-1). In those years, certain age groups were found to have dropped to 30 to 40% of their pre-Earthquake weight. In 2022, age 3 and 4 body weight was still lower than pre-Earthquake levels; however, these had recovered overall compared to 2017 and 2018. Following the slowdown in growth, the maturity rate by age also declined, particularly in the age 3 and age 4 groups. (Supplementary Figure 4-2).

References

Narimatsu, Y., Y. Ueda, T. Okuda, T. Hattori, K. Fujiwara and M. Ito (2010) The effect of temporal changes in life-history traits on reproductive potential in an exploited population of Pacific cod, *Gadus macrocephalus*. ICES J. Mar. Sci., **67**, 1659-1666.



Supplementary Fig. 8-1. Time-Series Variation in Body Weight by Age of Pacific cod



Supplementary Fig. 8-2. Time-Series Variation in Maturity Rate of Pacific cod

Appendix 9. Monthly catch ratio

The catch of this stock is calculated from April to March of the following year in consideration of the biological characteristics of cod spawning in winter, and the stock is evaluated. On the other hand, if the fishing season and the closed season of the bottom trawl fishery are taken into account, it may be more appropriate to conduct stock management during a period different from April to March of the following year. Therefore, in order to examine the predicted catch when different aggregation periods are applied, the average value of the monthly catch for the 2024 fishing season and the 2025 fishing season was calculated using the monthly catch ratio for the last 5 and 3 years.

Supplementary Table 9-1 shows the monthly catch for the last 5 years according to the prefectural fisheries experimental station and the monthly percentage based on the catch. The proportion of fish caught by month was highest in January and February, at 44% of the total. Average monthly catches based on different betas are shown in Supplementary Table 9-2. At β=0.8, the predicted catch for the 2024 fishing season was 6300 tons for the year of the fishing season (April to March of the following year) and 6300 tons for the year of the offshore fishing season (September to August of the following year).

Similarly, when using monthly catch for the last 3 years and the monthly percentage based on them (Supplementary Table 9-3), the monthly percentage was highest in January to February, accounting for 51% of the total. The estimated catch for the 2024 fishing season at β=0.8 was 6300 tons for the year of the fishing season (April to March of the following year) and 6300 tons for the year of the offshore fishing season (September to August of the following year) (Supplementary Table 9-4).

Supplementary Table 9-1. Monthly catch (tons) in recent 5 years (2018 – 2022 fishing years)

Monthly catch	2018	2019	2020	2021	2022	Mean catch	Mean catch ratio
4	633	586	711	956	308	639	8%
5	1,042	584	771	634	295	665	9%
6	1,000	410	289	467	189	471	6%
7	231	280	153	105	55	165	2%
8	191	201	182	61	28	133	2%
9	507	465	236	99	79	277	4%
10	484	391	295	173	118	292	4%
11	635	244	304	288	126	320	4%
12	600	390	361	552	657	512	7%
1	2,084	1,166	1,399	2,086	2,895	1,926	25%
2	2,043	1,149	1,435	1,407	1,323	1,472	19%
3	944	699	1,002	422	405	694	9%
total	10,393	6,567	7,138	7,251	6,478	37,827	100%

Supplementary Table 9-2. Mean monthly catch with various beta values (using recent 5 years)

2024 fishing year

	Mean catch total catch（x 1000 tons）	Mean monthly catch（Apr 2024 - Mar 2025）											
		Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
β=1.00	7.3	0.62	0.64	0.45	0.16	0.13	0.27	0.28	0.31	0.49	1.86	1.42	0.67
β=0.80	6.3	0.53	0.55	0.39	0.14	0.11	0.23	0.24	0.27	0.43	1.60	1.23	0.58
β=0.75	6.0	0.51	0.53	0.37	0.13	0.11	0.22	0.23	0.25	0.41	1.53	1.17	0.55
β=0.70	5.8	0.49	0.51	0.36	0.13	0.10	0.21	0.22	0.24	0.39	1.48	1.13	0.53
β=0.60	5.1	0.43	0.45	0.32	0.11	0.09	0.19	0.20	0.22	0.35	1.30	0.99	0.47
F2019-2021	6.8	0.57	0.60	0.42	0.15	0.12	0.25	0.26	0.29	0.46	1.73	1.32	0.62
Monthly catch ratio (average in 5 years)		0.08	0.09	0.06	0.02	0.02	0.04	0.04	0.04	0.07	0.25	0.19	0.09

2025 fishing year

	Mean catch total catch（x 1000 tons）	Mean monthly catch（Apr 2024 - Mar 2025）											
		Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
β=1.00	6.2	0.52	0.55	0.39	0.14	0.11	0.23	0.24	0.26	0.42	1.58	1.21	0.57
β=0.80	6.3	0.53	0.55	0.39	0.14	0.11	0.23	0.24	0.27	0.43	1.60	1.23	0.58
β=0.75	6.2	0.52	0.55	0.39	0.14	0.11	0.23	0.24	0.26	0.42	1.58	1.21	0.57
β=0.70	6.2	0.52	0.55	0.39	0.14	0.11	0.23	0.24	0.26	0.42	1.58	1.21	0.57
β=0.60	6.1	0.52	0.54	0.38	0.13	0.11	0.22	0.24	0.26	0.41	1.55	1.19	0.56
F2019-2021	6.9	0.58	0.61	0.43	0.15	0.12	0.25	0.27	0.29	0.47	1.76	1.34	0.63
Monthly catch ratio (average in 5 years)		0.08	0.09	0.06	0.02	0.02	0.04	0.04	0.04	0.07	0.25	0.19	0.09

Supplementary Table 9-3. Monthly catch (tons) in recent 3 years (2020 – 2022 fishing years)

Monthly catch	2020	2021	2022	Mean catch	Mean catch ratio
4	711	956	308	658	9%
5	771	634	295	567	8%
6	289	467	189	315	5%
7	153	105	55	104	1%
8	182	61	28	90	1%
9	236	99	79	138	2%
10	295	173	118	195	3%
11	304	288	126	239	3%
12	361	552	657	523	8%
1	1,399	2,086	2,895	2,126	31%
2	1,435	1,407	1,323	1,388	20%
3	1,002	422	405	610	9%
total	7,138	7,251	6,478	20,867	100%

Supplementary Table 9-4. Mean monthly catch with various beta values (using recent 3 years)

2024 fishing year

	Mean catch total catch（x 1000 tons）	Mean monthly catch（Apr 2024 - Mar 2025）											
		Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
β=1.00	7.3	0.69	0.59	0.33	0.11	0.09	0.14	0.20	0.25	0.55	2.23	1.46	0.64
β=0.80	6.3	0.60	0.51	0.29	0.09	0.08	0.12	0.18	0.22	0.47	1.93	1.26	0.55
β=0.75	6.0	0.57	0.49	0.27	0.09	0.08	0.12	0.17	0.21	0.45	1.83	1.20	0.53
β=0.70	5.8	0.55	0.47	0.26	0.09	0.08	0.11	0.16	0.20	0.44	1.77	1.16	0.51
β=0.60	5.1	0.48	0.42	0.23	0.08	0.07	0.10	0.14	0.18	0.38	1.56	1.02	0.45
F2019-2021	6.8	0.64	0.55	0.31	0.10	0.09	0.13	0.19	0.23	0.51	2.08	1.36	0.60
Monthly catch ratio (average in 3 years)		0.09	0.08	0.05	0.01	0.01	0.02	0.03	0.03	0.08	0.31	0.20	0.09

2025 fishing year

	Mean catch total catch（x 1000 tons）	Mean monthly catch（Apr 2024 - Mar 2025）											
		Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
β=1.00	6.2	0.59	0.51	0.28	0.09	0.08	0.12	0.17	0.21	0.47	1.90	1.24	0.54
β=0.80	6.3	0.60	0.51	0.29	0.09	0.08	0.12	0.18	0.22	0.47	1.93	1.26	0.55
β=0.75	6.2	0.59	0.51	0.28	0.09	0.08	0.12	0.17	0.21	0.47	1.90	1.24	0.54
β=0.70	6.2	0.59	0.51	0.28	0.09	0.08	0.12	0.17	0.21	0.47	1.90	1.24	0.54
β=0.60	6.1	0.58	0.50	0.28	0.09	0.08	0.12	0.17	0.21	0.46	1.86	1.22	0.53
F2019-2021	6.9	0.65	0.56	0.31	0.10	0.09	0.14	0.19	0.24	0.52	2.11	1.38	0.60
Monthly catch ratio (average in 3 years)		0.09	0.08	0.05	0.01	0.01	0.02	0.03	0.03	0.08	0.31	0.20	0.09