

Stock Assessment for Pacific Stock of Japanese Anchovy (Fiscal Year 2022)

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

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Summary

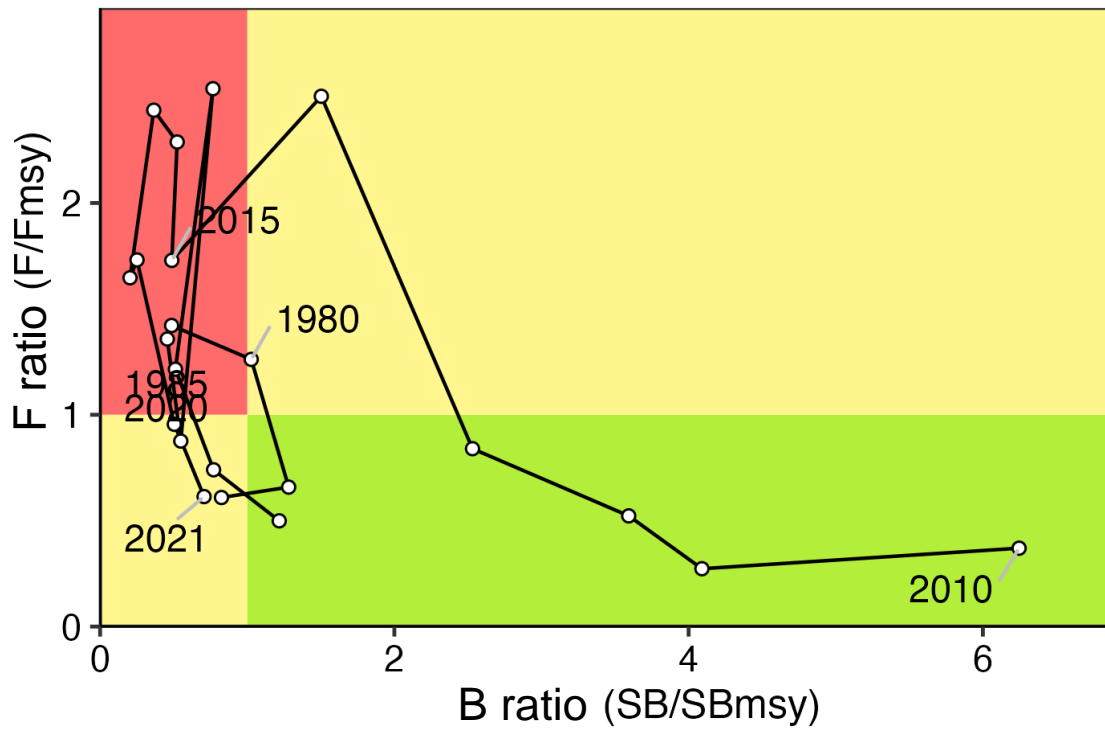
The biomass of this stock was estimated by cohort analysis (i.e., tuned VPA) using egg production and age 0 CPUE (catch per unit effort) from the Northward season surveys since 2010 as tuning indices. Biomass was less than 500,000 tons from 1978 to 1988, but increased rapidly to exceed 1 million tons in 1989, surpassed 2 million tons in 1998, and achieved a record high of 2.91 million tons in 2002. Since 2003, stock size has been in a decreasing trend, reaching a low of 95,000 tons in 2018, followed by another increase to reach 247,000 tons in 2021. SSB (spawning stock biomass) was 79,000 tons in 2021.

In the Research Institute Meeting held in September 2021, a normal recruitment period Beverton-Holt model was applied to the stock-recruitment relationship of this stock, and based on this, the maximum sustainable yield (MSY) was estimated, and the level of SSB required for MSY (SB_{msy}) was calculated to be 112,000 tons. Following these criteria, SSB of this stock in 2021 is below the level required for MSY. In addition, the fishing pressure for this stock in the 2021 fishing season was lower than the fishing pressure level required for MSY (F_{msy}). Based on trends seen in the previous 5 years (2017 to 2021 fishing seasons), SSB is judged to be in an “increasing” 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 Stakeholder meeting.

Summary Figures and Tables



MSY, SSB Levels and Trends, and ABC	
SSB required for MSY	112,000 tons
Level of SSB in 2021	Under the level required for MSY
Level of fishing pressure in 2021	Under the level required for MSY
Changes in SSB in 2021	Increase
Maximum sustainable yield (MSY)	81,000 tons
ABC for 2023	-
<p>Comments:</p> <ul style="list-style-type: none"> • ABC is estimated after Harvest Control Rules (HCRs) for this stock are compiled by the Stakeholder meeting, and set through the Fishery Policy Council. • Although stock assessment methodology was updated this year, values for recruitment and SSB since 2018 (based on 2020 assessment) used to estimate the stock-recruitment relationship are largely unchanged, so the impact of the methodology update is minor. 	

Recent Stock Biomass, SSB, Catch, Fishing Pressure, and Exploitation Rate					
Year	Biomass (thousand tons)	SSB (thousand tons)	Catch (thousand tons)	F/Fmsy	Exploitation Rate (%)
2017	124	41	54	2.45	43
2018	95	23	29	1.66	30
2019	125	28	44	1.74	35
2020	235	57	57	0.96	24
2021	247	79	40	0.62	16
2022	352	156	45	0.34	13
2023	395	191	-	-	-

• The values for 2022 and 2023 are estimates based on future projections.
 • The average of catch in weight in the previous 5 years (2017 to 2021) was used as catch in weight for 2022.

1. Data Sets

The data sets used for this stock assessment are as follows:

Data Sets	Basic Information & Related Surveys
Catch in number at age and by year	Annual Statistics of Fishery and Aquaculture Production (Ministry of Agriculture, Forestry and Fisheries) Landings at major ports (Hokkaido to Kagoshima (18 prefectures), relevant prefectures) Length composition surveys, precision measurement surveys (Japan Fisheries Research and Education Agency, Hokkaido to Kagoshima (18 prefectures), etc.) Catch Performance Report for Large to Medium-Scale Purse Seine Fisheries
Stock abundance index <ul style="list-style-type: none"> • Fishing effort for North Pacific large to medium-scale purse seine fisheries • Egg production* • CPUE of Northward Migration Season Trawl Surveys* • CPUE of Autumn Trawl Survey • Winter/Spring Catch in Joban-Boso Region • Stock abundance indices for North Pacific purse seine catches, March to June • Average CPUE of three two-boat purse seine vessels (large to medium-scale, medium-scale), February to June 	Distribution/Migration Status Analysis Surveys (JAFIC) Surveys on eggs, juveniles, and plankton (February to March, Japan Fisheries Research and Education Agency, monthly, Aomori to Kagoshima (18 prefectures)): NORPAC nets, CTD, etc. Northwest Pacific Ocean Northward Migration Season Pelagic Fish Stock Surveys (May to July, Japan Fisheries Research and Education Agency) Northwest Pacific Ocean Autumn Pelagic Fish Stock Survey (September to October, Japan Fisheries Research and Education Agency) Landings at major ports (Chiba, Ibaraki, and Fukushima Prefectures), length composition surveys Distribution/Migration Status Analysis Surveys (JAFIC) Catch status of two-boat purse seine vessels off Boso coast (Chiba Prefectural Fisheries Research Center)
Natural mortality (M)	1.0 for fish age 0 to 1, 1.6 for fish age 2, and 1.9 for fish age 3 (see Appendix 2).

* Indicates the tuning index for cohort analysis

For tuning, egg production was used as an index value for SSB (weight), and age 0 CPUE (ind./net) from the Northward Migration Season Trawl Surveys (hereinafter referred to as “Northward season surveys”) was used as an index value for recruitment (individuals). The age 0 CPUE from the Northward season surveys was calculated under a rough assumption that individuals with a standard

(scaled) body length of less than 10.5 cm are age 0, due to the fact that age data for individuals collected during the survey was not available at the time of calculation.

2. Ecology

(1) Distribution / Migration

The distribution area extends throughout coastal waters along the Pacific coast from Kyushu to Hokkaido, to the offshore Kuroshio region, the Kuroshio extension region, the Kuroshio-Oyashio transition region, and the Oyashio region, reaching a longitude of 170° East (Fig. 2-1).

(2) Age / Growth

Life span is assumed to be 4 years based on the results of scale readings, but it has been noted that the lifespan of this stock may be 1 to 2 years shorter when stock levels are low (Tsuruta 2001). Based on previous reports and recent analysis in the northern Pacific region, this species has a standard (scaled) body length of approx. 10 to 12 cm at age 1, reaching approx. 13 cm by age 2, while some reports mentioned fast-growing individuals which reached 13 cm at age 1 (Hayashi and Kondo 1957, Mitani 2001, Yasumi et al. 2007, Yukami et al. 2008) (Fig. 2-2). Length-weight relationships are expressed using the following regression equation (average parameters for 1998 to 2007).

$$\text{Weight (g)} = 0.010 \times \text{length}^{3.00} \text{ (cm)}$$

(3) Maturation / Spawning

Spawning occurs on a roughly annual basis. In the Pacific region, the mature length of this species is reported to be approx. 6 cm in the Sagami Bay region (Funamoto 2001), but mature individuals of such a small size are only a small percentage of all mature individuals, and are believed to only be found immediately adjacent to the coast, inside of bays, or within inland seas (Funakoshi 1990). The length of spawning stock is 9 cm or more in spring, and 7 to 12 cm in late spring through autumn, in waters off the Boso Peninsula to the Enshu-nada Sea (Funakoshi 1990), 12 cm or more in June to August in waters east of Hokkaido to off the Kuril islands (Mihara 2000, Suhara et al. 2013), and 11 cm or more in May to June in the Kuroshio-Oyashio transition region (Tsuruta and Takahashi 1997), which leads us to assume that age 0 is immature, and age 1 is mature (Fig. 2-3). During low-level periods of this stock (corresponding to the normal recruitment period), distribution is limited to inside of bays and coastal waters, and spawning primarily occurs in summer, but during high-level periods, distribution expands to offshore waters, and peak spawning season is longer, extending from early spring until autumn (Zenitani and Kimura 1997, Zenitani 2001). According to changes in egg production by month in Ocean Areas I to IV in the Pacific region, in recent years, the spawning season has been from April to August (Supplementary Fig. 7-2).

(4) Predator-Prey Relationships

This species feeds on zooplankton and other organisms. Meanwhile, it is preyed upon by medium-to-large size pelagic fish and cetaceans (Konishi et al. 2017).

(5) Special Remarks

The Pacific stock of Japanese anchovy is known to undergo large fluctuations that coincide with changes in the structure of the atmosphere-marine ecosystem, on a global scale and spanning decades (known as “regime shift”), the phases of which are opposite to those of the Pacific stock of Japanese pilchard (Kawasaki 1992, Klyashtorin 1998, Chavez et al. 2003). For example, high stock levels of Japanese pilchard are seen when the Pacific decadal oscillation index (PDO index) is positive, and high stock levels of Japanese anchovy are seen when it is negative, and these species are said to replace each other (Takasuka et al. 2008). Changes in the marine environment impact both the carrying capacity of the environment and recruitment rates (Tanaka 2003, Yatsu et al. 2005), so the possibility of variation in the stock-recruitment relationship was considered, and the stock-recruitment relationship of this stock was divided into normal recruitment periods and high recruitment periods (Kinoshita et al. 2021b, FRA-SA2021-BRP03-1). In recent years recruitment volume has remained low, so the stock-recruitment relationship of normal recruitment periods was used to calculate future projections based on proposed harvest control rules (HCRs) and other estimates.

3. Fishery Status

(1) Fishery Overview

Juveniles of this stock are caught in the late larval stage (also known as whitebait or “shirasu”) from spring to autumn by shirasu boat seine nets in coastal waters from Miyagi to Kagoshima Prefectures. Immature and mature fish are also caught in set nets and purse seine nets throughout every region. The fishing season for large to medium-scale purse seine fisheries in Joban-Boso is from December to June of the following year. In years when abundance is high, this species is caught in large numbers from September to November around east of Hokkaido to Sanriku, and from January to May around the Kumano-nada and Hyuga-nada regions. Fish populations distributed in offshore areas, such as the Kuroshio-Oyashio transition region, are generally not catch targets. From 1999 to 2004, 30 to 35% of the catch of immature and mature fish was from large to medium-scale purse seine fisheries in Joban-Boso, but this percentage has since decreased, and has stayed under 10% since 2012.

In recent years, age 0 fish have been the mainstay of catches. In the 1990s and 2000s, the population levels of this stock increased, coinciding with a decrease of the population levels of the Pacific stock of Japanese pilchard. High volumes were caught in purse seine nets, but abundance has been in a decreasing trend since the 2010s. During high stock level periods (corresponding to high recruitment periods), distribution of this stock extended to offshore waters, but in recent years, offshore distribution has been low, and fishing grounds have been established in coastal areas.

(2) Trends in Catch in Weight

The catch of this stock remained between 43,000 and 90,000 tons up to 1989, and then increased rapidly to exceed 200,000 tons in 1990 in the northern Pacific region (Aomori to Ibaraki Prefectures) (Fig. 3-1, Table 3-1). Subsequently, catch fluctuated widely from year to year while showing a generally increasing trend, reaching a record high of 408,000 tons in 2003. Since 2004, catch has been

in a decreasing trend, ranging from 144,000 to 160,000 tons in 2011 to 2014, from 29,000 to 78,000 tons in 2015 to 2020, and 40,000 tons in 2021. Catch by sea shows the majority of catch in weight is in the Central Pacific region (Chiba to Mie Prefectures), with smaller catches in the South Pacific region (Wakayama to Miyazaki Prefectures) and Hokkaido Pacific region. In the northern Pacific region, catch has declined significantly since 2012 (Fig. 3-1, Table 3-1). After 1990, the percentage of catch in the Joban-Boso region (Chiba, Ibaraki, and Fukushima Prefectures) remained high, ranging from 40 to 70%, but it has decreased and ranged under 10% since 2015. Meanwhile, the percentage of catch in the Tokai region (Mie to Kanagawa Prefectures) has been in an increasing trend, starting from approximately 20% from 1988 to 2007, and shifting to over 50% since 2015.

(3) Fishing Effort

Although it is difficult to accurately determine fishing effort for this stock, the number of nets in large to medium-scale purse seine fisheries in the North Pacific region in high abundance years can be used as one index. Accordingly, the number of nets was at a high level (around 2,000 nets) from 2001 to 2004, and then declined since 2005, and was around 500 nets from 2008 to 2011 (Supplementary Fig. 11-1, Supplementary Table 11-1). Subsequently, further decline was seen in 2012, and the number of nets has been 0 to 1 since 2016.

4. Stock Status

(1) Stock Assessment Methods

The abundance of this stock was estimated by cohort analysis based on the catch in number at age up to FY 2021. However, in the FY 2021 assessment, this species was identified as a candidate for TAC control, and the report discussed the need for application of tuning in cohort analysis in preparation for the possibility of catch limits to be enforced, and the need for measures to help reduce uncertainty, including addressing the possibility that the impact of predation by chub mackerel is not adequately reflected in the natural mortality (M) of this stock (Kinoshita et al. 2021b, 2022). Therefore, in this year's stock assessment (FY 2022), abundance (population size) was estimated by cohort analysis using abundance indices as tuning indices (hereinafter referred to as "Tuned VPA"). Catch in number at age, which is basic data for cohort analysis, is shown in Fig. 3-2. Egg production was used as an index value for SSB (weight), and age 0 CPUE (ind./net) from the Northward season surveys (May to July, ocean regions 39 to 46° N, 144° E to 165° W) was used as an index value for recruitment volume (individuals). The age 0 CPUE was calculated under a rough assumption that individuals with a standard (scaled) body length of less than 10.5 cm are age 0, due to the fact that age data for individuals collected during the survey was not available at the time of calculation. Trial calculation results for stock abundance using cohort analysis that includes predation pressure by mackerel species are shown in Appendix 12. In addition, stock assessment for this stock was performed without including larva (shirasu) in population estimates.

(2) Trends in Abundance Indices

The tuning indices used to adjust fishing mortality (F) are shown in Fig. 4-1 and Supplementary

Table 2-2.

Egg production in Pacific ocean areas (Area I to IV) was estimated based on aggregated values from surveys on eggs, juveniles, and plankton which reported the egg distribution volume in each 30-minute square in the latitude/longitude grid, and these estimates were used as a basis for calculating other total values. Annual egg production increased rapidly in 1991, followed by a trend of gradual decline until 1996. Later, egg production surged to 10 quadrillion (10^{16}) eggs in 1999, and remained at high levels, around 10 quadrillion, until 2012. It was in a decreasing trend since 2013, followed by an increasing trend since 2019, and was 3.014 quadrillion eggs in 2021 (Fig. 4-1a). Ocean areas described in surveys on eggs, juveniles, and plankton, and changes in egg production by area and by month since 2013, are shown in Appendix 7. Egg production in Area I (Kuroshio-Oyashio transition region north of Choshi) was low from 2015 to 2019, but has increased since 2020, with a peak period from June to August (Supplementary Fig. 7-2). In 2021, egg production increased in Area II (region south of Honshu, between south of Choshi and east of Shionomisaki) and Area IV (region from Satsunan (South Kagoshima) to southern East China Sea).

The age 0 CPUE from the Northward season surveys (ind./net, converted to value per hour of towing) was calculated based on the results of catch surveys performed by the Japan Fisheries Research and Education Agency in May to July since 2001 in the Kuroshio-Oyashio transition region to the Oyashio region using midwater trawl nets (mouth 30 m wide, codend mesh size 17 mm). The age 0 CPUE from the Northward season surveys reached a record high at 1,826 ind./net in 2002, and then fluctuated significantly year to year from 2003 to 2008, ranging from 80 to 869 ind./net (Fig. 4-1a). From 2009 to 2011, CPUE remained stable at around 900 ind./net, but declined sharply in 2012, and remained at 116 to 150 ind./net until 2014. In 2015 it decreased further to 12 ind./net, followed by another decline, and a record low of 0.1 ind./net in 2018. Then CPUE shifted to an increasing trend since 2019, and was 44 ind./net in 2021.

Abundance indices not used for Tuned VPA are shown in Appendix 11.

(3) Trends in Biomass and Fishing Pressure

Stock abundance (biomass) estimated using Tuned VPA was less than 500,000 tons from 1978 to 1988, but surged to exceed 1 million tons in 1989, and 2 million tons in 1998 (Fig. 4-2, Table 4-1). Since then, it has been in a decreasing trend, with a record high of 2.91 million tons in 2002, and a record low of 95,000 tons in 2018. Subsequently, it started to increase again and was estimated to be 247,000 tons in 2021.

SSB was in an increasing trend from 1978 to 1991 (876,000 tons), followed by a decline of approx. 300,000 tons, and then fluctuated around 600,000 tons from 1992 to 1997 (Fig. 4-2, Table 4-1). Thereafter, it showed an increasing trend again, reaching a record high of 1.431 million tons in 2003. Since 2004, it has been in a decreasing trend, reaching a record low of 23,000 tons in 2018, followed by another increase to reach 79,000 tons in 2021.

For reference, estimates using the egg production method based on egg production (Watanabe 1983) showed that SSB remained around 100,000 tons from 1982 to 1988, surged sharply from 1989 to reach 731,000 tons in 1991, and then declined around 200,000 tons, and fluctuated around 500,000 tons

from 1992 to 1996 (Supplementary Fig. 7-3, Supplementary Table 7-1). Then SSB started to increase again, reaching 1.924 million tons in 1999, with a record high of 2.556 million tons in 2003, with significant year to year fluctuations during this period. Since 2004, it has been in a decreasing trend, and remained around 1 million tons until 2012, followed by sharp decline, reaching a record low of 71,000 tons in 2018. Since 2019, it has been in an increasing trend, and was estimated to be 381,000 tons in 2021. Prior to 1998, when SSB started to increase to reach a record high, estimated values for SSB levels were similar whether performed using cohort analysis or the egg production method, but after the stock expanded offshore in 1999, estimated values using cohort analysis have continued to be low for many years, and the fluctuation range is more narrow compared to SSB using the egg production method (Supplementary Fig. 7-3).

Fish age 0 accounted for 58 to 90% of the numbers at age, and fish age 0 to 1 accounted for 90.5 to 99.8%, representing the majority of this stock (Fig. 4-3 and Supplementary Table 9-1). In 2021, stock population was higher than 2020 levels for all age groups, with a total of 51.9 billion fish in all age groups.

Fish age 0 accounted for 37 to 77% of the stock weight at age, and fish age 0 to 1 accounted for 79.6 to 99.2%, representing the majority of this stock (Fig. 4-4 and Supplementary Table 9-1). In 2021, stock weight was lower than 2020 levels for fish age 0 by 10,000 tons, but higher than 2020 levels for fish age 1 to 3.

Recruitment volume remained around 15.3 billion to 46.2 billion until 1987, and then increased rapidly from 1988, reaching a record high of 201 billion fish in 2001 (Fig. 4-5, Table 4-1). It was in a decreasing trend since 2002, reaching a second-lowest value of 17.1 billion fish in 2018. Since 2019, it has been in an increasing trend, with 42.7 billion fish in 2021.

Recruitment per spawning tended to be higher in years with low stock levels, and lower in years with high stock levels (Fig. 4-5, Table 4-1). From 1978, until recruitment volume surpassed 100 billion fish for the first time in 1989, recruitment per spawning fluctuated in the range of 132 to 713 ind./kg, with an average of 433 ind./kg during this period. Thereafter, including the periods when SSB exceeded 800,000 tons for the first time in 1990, when SSB reached a record high in 2003, and until SSB fell below 200,000 tons in 2014, recruitment per spawning remained low, ranging from 85 to 226 ind./kg. Since the period when SSB fell below 60,000 tons in 2015, recruitment per spawning has remained high, ranging from 499 to 1,194 ind./kg, and was 538 ind./kg in 2021 (Fig. 4-5, Table 4-1).

Results of sensitivity analysis with natural mortality (M) varied to 0.5 times, 1.0 times (reference value), and 1.5 times are shown in Fig. 4-6. Looking at estimated values for the most recent year, if M is 0.5 times, then abundance (biomass) is 64%, SSB is 87%, and recruitment volume is 52% of the reference value (Fig. 4-6). If M is 1.5 times, then abundance (biomass) is 250%, SSB is 206%, and recruitment volume is 271% of the reference value.

Changes in fishing mortality (F) at age over time are shown in Fig. 4-7 and Supplementary Table 9-1. After F for fish age 0 reached a high of 0.77 in 1984, it declined and remained below 0.2 from 1987 to 2011. Subsequently it increased from 2012 to 2014 to reach a record high of 1.22, and then fluctuated above 0.4 from 2015 to 2020, and was 0.31 in 2021. Meanwhile, F for fish age 1 was similar to fish age 0, and reached a high of 2.56 in 1984, and then declined and remained around 0.20 to 0.74

from 1987 to 2011. It was in an increasing trend from 2012 to 2018, reaching a record high of 2.60, and then declined and was 0.36 in 2021. After F for fish age 2 to 3 reached a high of 2.67 in 1984, it declined and remained below 1.4 from 1987 to 2011. It was in an increasing trend from 2012 to 2018, reaching a record high of 3.03, followed by a decreasing trend, and declined sharply to reach 0.14 in 2021.

The exploitation rate has been 21% on average for the past 44 years, but remained at high levels around 40% from 2014 to 2019, and then declined to 16% in 2021 (Fig. 4-8, Table 4-1).

Compared to the FY 2021 stock assessment, estimated values are not significantly different to those prior to 2018, but biomass, SSB, and recruitment volume from 2017 to 2020 have been revised upward (Supplementary Table 10-1). These revisions were made due to upward revisions for catch in number at age in 2020, and upward revisions for recruitment volume in the recruitment periods of 2014 to 2020 cohorts driven by the application of Tuned VPA.

(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. Lower fishing pressure means higher %SPR levels. In 1984, %SPR was low at 21%, but it increased and remained high at over 60% from 1987 to 2012. Following a sharp decline since 2013 and a record low of 17% in 2014, it fluctuated around 25% until 2019, and then increased to reach 60% in 2021 (Supplementary Table 9-1). Calculations showed that %SPR was 41% using the average F value of the 3 previous years (2019 to 2021) for the current fishing pressure.

The relationship between current fishing pressure and YPR and %SPR is shown in Fig. 4-10. The selectivity of F was defined as the value used to estimate the level of F required for maximum sustainable yield (F_{msy}) (Kinoshita et al. 2021b) at the Research Institute Meeting held in September 2021. In addition, the values used to calculate F_{msy} were also used for average body weight at age and the maturity rate. F_{msy} is equivalent to 45% when converted to %SPR. The current fishing pressure ($F_{2019-2021}$) is below $F_{40\%SPR}$ and $F_{0.1}$, but above F_{msy} .

(5) Stock-Recruitment Relationship

The relationship (stock-recruitment relationship) between SSB (in weight) and recruitment volume (individuals) is shown in Fig. 4-11. In the above-mentioned Research Institute Meeting, a normal recruitment period Beverton-Holt model has been applied to the stock-recruitment relationship model of this stock (Kinoshita et al. 2021b). The data used to estimate the parameters of this stock-recruitment relationship was based on SSB and recruitment volume (excluding data for 2019) reported in the FY 2020 stock assessment (Kinoshita et al. 2021a), and the optimization method was the least squares method. First-order autocorrelation was not considered 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 catch in weight required for maximum sustainable yield, under current environmental conditions (2010 and onward), were defined as the values estimated at the aforementioned Research Institute Meeting (Kinoshita 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 2021 is shown in Supplementary Table 6-3. 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.

SSB of this stock exceeded the value required for MSY (SBmsy) in 1979 to 1980, 1987, and from 2010 to 2014, but was below SBmsy in 1978, 1981 to 1986, and in 2015 and onward, and SSB in 2021 was 0.71 times the value of SBmsy. In addition, the fishing pressure from 2014 to 2019 was higher than the fishing pressure required for MSY (Fmsy), but was below Fmsy in 2020 and onwards, and in 2021 it was 0.62 times the value of Fmsy. The trend in SSB was determined to be an increase based on the trend over the previous 5 years (2017 to 2021).

5. Summary of Stock Assessment

Starting from this year, abundance (biomass) was estimated using Tuned VPA. Biomass was less than 500,000 tons from 1978 to 1988, but surged to exceed 1 million tons in 1989, and 2 million tons in 1998. After reaching a record high of 2.91 million tons in 2002, it has been in a decreasing trend, falling to a record low of 95,000 tons in 2018. Afterwards, biomass started to increase again and it was 247,000 tons in 2021. SSB has also increased since 2019, and it was 79,000 tons in 2021.

6. Additional Comments

In this year's stock assessment, the method used to estimate abundance (population size) was changed from VPA without tuning, which was used up to 2021, to Tuned VPA (ridge VPA). In addition, tuning indices included egg production used as an index value for SSB (weight), and age 0 CPUE from the Northward season surveys used as an index value for recruitment volume (individuals), but no standardization was implemented for these tuning indices. Age 0 CPUE from the Northward season surveys is an index value from research vessel surveys in offshore regions, so it is possible that this data does not adequately describe the current situation in which distribution of this stock is almost exclusive to coastal areas. Therefore, the Tuned VPA for this stock needs additional consideration of tuning methods in addition to exploration and standardization of abundance indices. Furthermore, it should be noted that because the stock assessment model includes data from offshore regions, estimated values for abundance (population size) and other information also include offshore regions.

In addition, the FY 2021 "Response to Matters Identified in the 2nd Stock Control Method Study Group on the Pacific Stock of Japanese Anchovy (FRA-SA2022-BRP01)" stated that "...there appears

to be significant uncertainty regarding VPA with mackerel predation, so it is necessary to study the matter further while setting a variety of conditions.” Accordingly, the results of further investigation of mackerel species predation VPA are shown in Appendix 12.

7. References

- Chavez, F.P., J. Ryan, S.E. Lluch-Cota, C.M. Niquen (2003) From anchovies to sardines and back: multidecadal change in the Pacific Ocean. *Science*, 299, 217-221.
- Funakoshi, S. (1990) Studies on the reproduction mechanisms of Japanese anchovy in the Enshu-nada Sea, Ise/Mikawa Bay, and surrounding waters. Aichi Fisheries Research Institute Performance Report Volume B, 10, 1-208. (in Japanese)
- Funamoto, T. (2001) Maturation and spawning of Japanese anchovy. *Fish. Sci.*, 67, 1129-1130. (in Japanese)
- Hayashi, S. and K. Kondo (1957) Growth of the Japanese Anchovy-IV. Age determination with the use of scales. *Bull. Tokai Reg. Fish. Res. Lab.*, 17, 31-64, pls.1-4.
- Kawasaki, T. (1992) Climate-dependent fluctuations in far eastern sardine population and their impacts on fisheries and society. In: *Climate variability, climate change and fisheries*, ed. Glantz, M.H., Cambridge University press, Cambridge, pp. 325-354.
- Kinoshita, J., Kamimura, Y., Yasuda, T. (2021a) Stock Assessment for Pacific Stock of Japanese Anchovy (Fiscal Year 2020). FRA-SA2020-SC02-1 (in Japanese)
- Kinoshita, J., Yasuda, T., Watanabe, C., Kamimura, Y. (2021b) Materials for the Research Institute Meeting on Reference Points of Pacific stock of Japanese anchovy (FY 2021). FRA-SA2021-BRP03-1 (in Japanese)
- Kinoshita, J., Yasuda, T., Watanabe, C., Kamimura, Y. (2022) Stock Assessment for Pacific Stock of Japanese Anchovy (Fiscal Year 2021). FRA-SA2021-SC02-1 (in Japanese)
- Klyashtorin, L. B. (1998) Long-term climate change and main commercial fish production in the Atlantic and Pacific. *Fish. Res.*, 37, 115-125.
- Konishi, K., T. Isoda and T. Tamura (2017) Overview of stomach content analyses for sei, Bryde’s and common minke whales under the offshore component of JARPNII, and temporal changes in feeding habits. *TEPER-ICR*, 1, 44-57.
- Mihara, Y. (2000) Maturation of the Japanese Anchovy, *Engraulis japonicus*, off Southeastern Hokkaido and Adjacent Waters. *Bull. Jpn. Soc. Fish. Oceanogr.*, 64, 10-17. (in Japanese with English abstract)
- Mitani, I. (2001) Growth of Japanese Anchovy. *Fish. Sci.*, 67, 1131-1132. (in Japanese)
- Suhara, M., Mori, Y., Mihara, Y., Yamamoto, M., Kawabata, A., Takahashi, M., Katsukawa, Y., Katayama, S., Yamashita, Y., Kawamura, T. and Watanabe, Y. (2013) Comparison of reproductive traits of Japanese anchovy *Engraulis japonicus* among sea areas around Japan. *Fish. Sci.*, 79, 813-822. (in Japanese with English abstract)
- Fisheries Resources Institute (2022) Response to Matters Identified in the 2nd Stock Control Method Study Group on the Pacific Stock of Japanese Anchovy. FRA-SA2022-BRP01. (in Japanese)
- Takasuka, A., Y. Oozeki and H. Kubota (2008) Multi-species regime shifts reflected in spawning

- temperature optima of small pelagic fish in the western North Pacific. Mar. Ecol. Prog. Ser., 360, 211-217.
- Tanaka, E. (2003) A method for estimating dynamics of carrying capacity using time series of stock and recruitment. Fish. Sci., 69, 677-686.
- Tsuruta, Y. and Takahashi, S. (1997) Reproductive ecology of the Japanese anchovy (*Engraulis japonicus* H.) in the Kuroshio Extension and the Mixed Water Region. Bull. Hokkaido Natl. Fish. Res. Inst., 61, 9-15. (in Japanese with English abstract)
- Tsuruta, Y. (2001) Life History Strategy of Japanese Anchovy. Fish. Sci., 67, 1133-1134. (in Japanese)
- Watanabe, T. (1983) Egg production method from Analysis and Assessment of Fisheries Stock: Methods and Applications. Edited by Takeo Ishii, Kouseisha Kouseikaku, Tokyo, 9-29. (in Japanese)
- Yasumi, N., Hirano, K., Mori, Y. and Nagashima, H. (2007) Reconsideration of growth and longevity of Japanese anchovy *Engraulis japonica*. Fisheries biology and oceanography in the Kuroshio, 8, 67-78. (in Japanese)
- Yatsu, A., T. Watanabe, M. Ishida, H. Sugisaki, L.D. Jacobsen (2005) Environmental effects on recruitment and productivity of Japanese sardine *Sardinops melanostictus* and chub mackerel *Scomber japonicus* with recommendations for management. Fish. Oceanogr., 14, 263-278.
- Yukami R., I. Aoki and I. Mitani (2008) Daily age of adult Japanese anchovy *Engraulis japonicus* off eastern Honshu, Japan by otolith daily increment. Fish. Sci., 74, 1348-1350.
- Zenitani H., and Kimura, R. (1997) Increase in Late Winter Egg Production of the Japanese Anchovy as Related to Recovery of the Stock Size along the Pacific Coast of Japan. Fish. Sci., 63, 665-671. (in Japanese with English abstract)
- Zenitani H. (2001) History and Character of Stock Fluctuation in Japanese Anchovy. Fish. Sci., 67, 1125-1126. (in Japanese)

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Fig. 2-1 Distribution and Migration Map of Pacific Stock of Japanese Anchovy

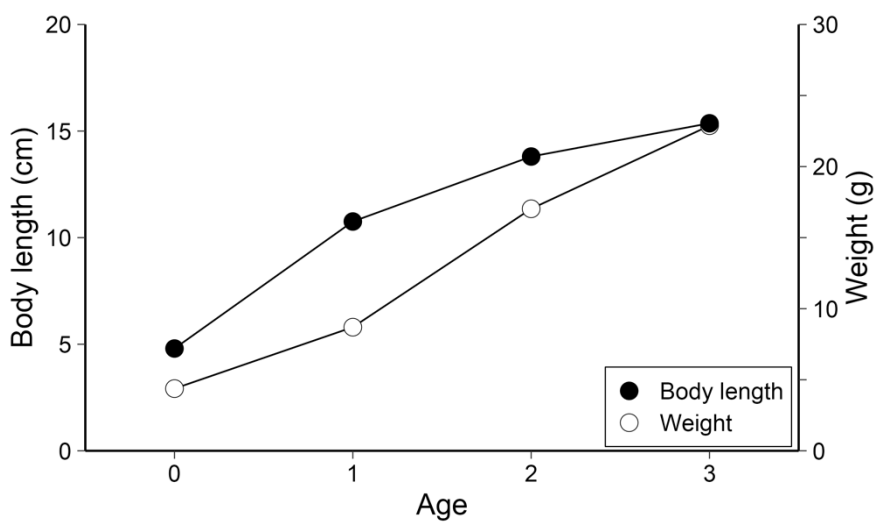


Fig. 2-2. Age and growth

Body weights are averages of average weight at age from 1978 to 1988 and 2015 to 2021 (normal recruitment period).

Standard (scaled) body length is converted from body weight using the following equation:

$$\text{weight (g)} = 0.010 \times \text{body length (cm)}^3.$$

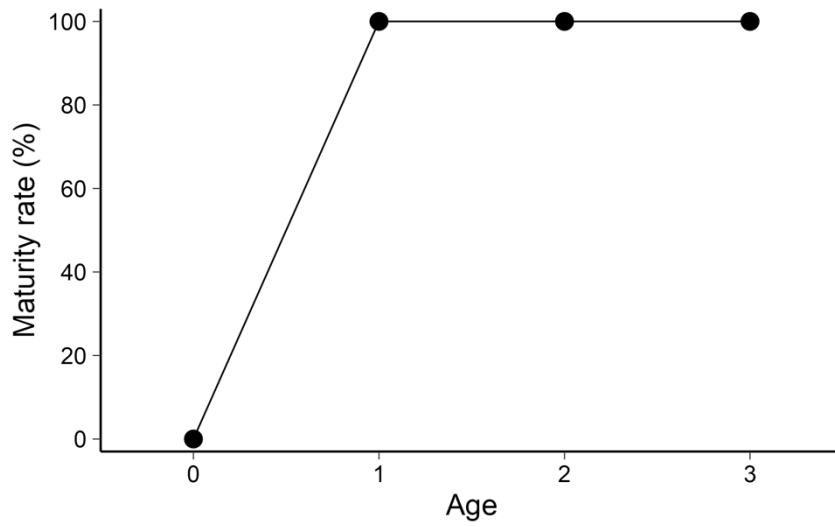


Fig. 2-3. Maturity rate at age

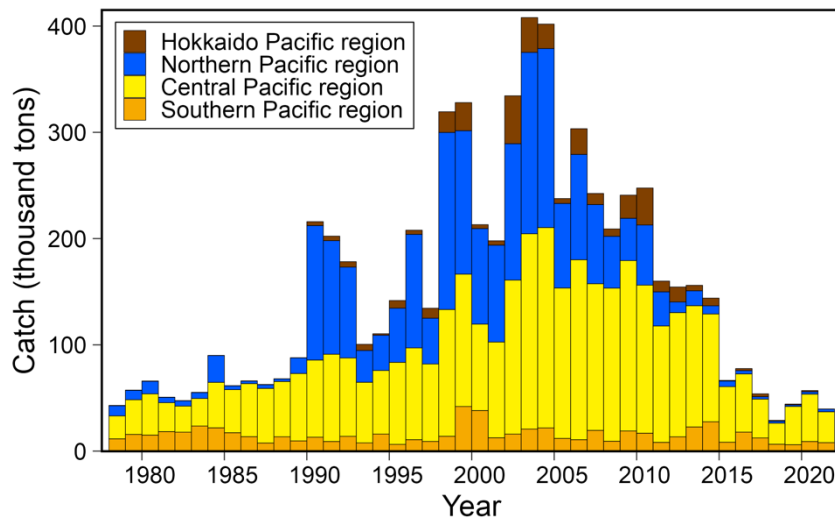


Fig. 3-1. Trends in catch in weight

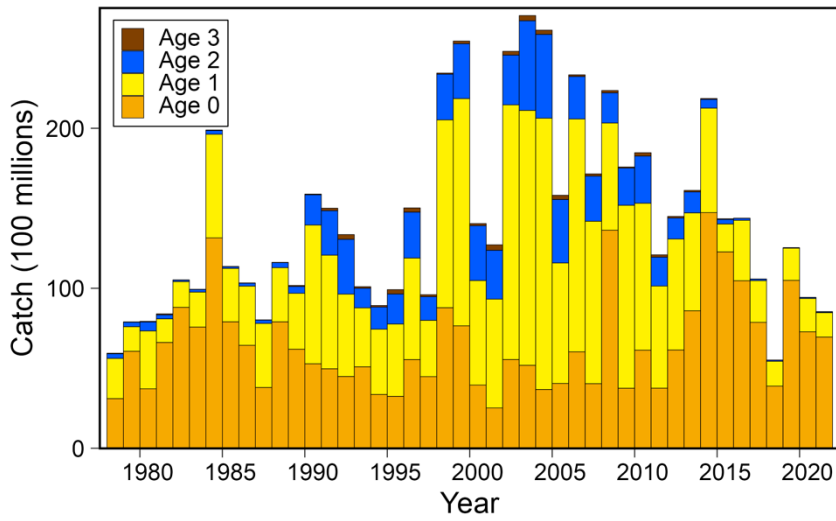


Fig. 3-2. Trends in catch in number at age

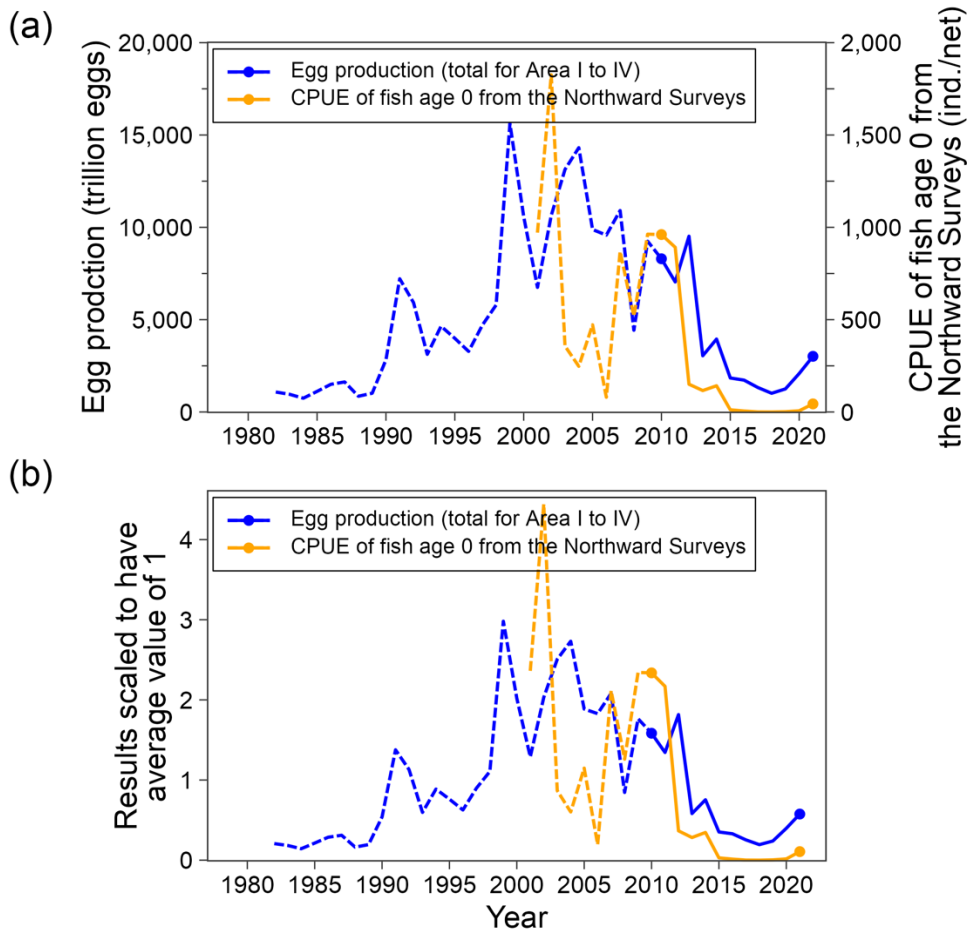


Fig. 4-1. Trends in stock abundance index (tuning indices)

In this chart, (a) shows observed values and (b) shows scaled values. The solid line indicates the years used for tuning.

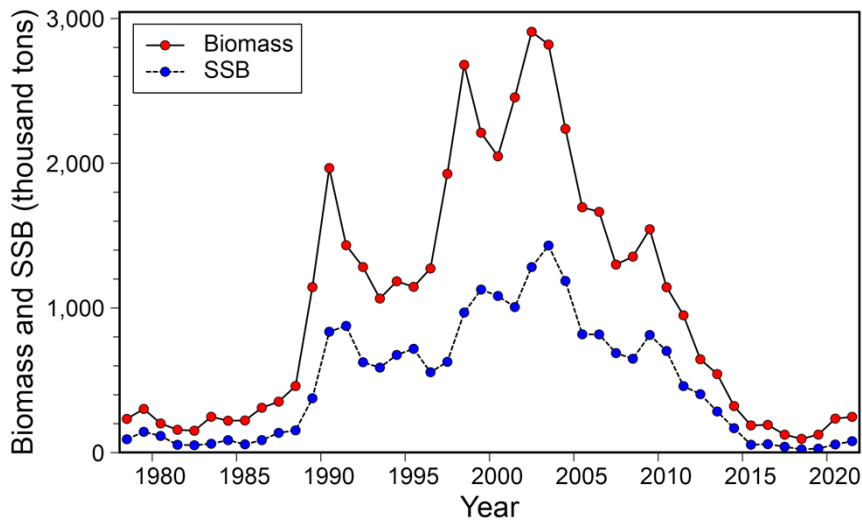


Fig. 4-2. Trends in biomass and SSB

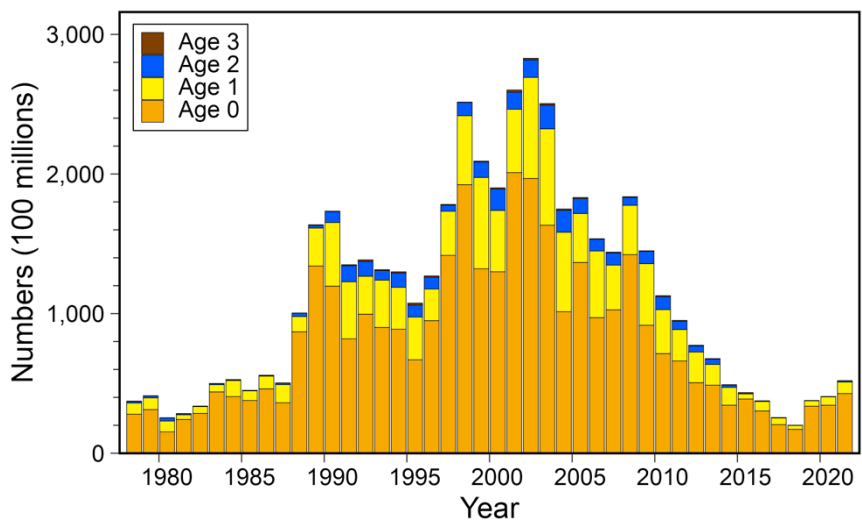


Fig. 4-3. Trends in stock population at age

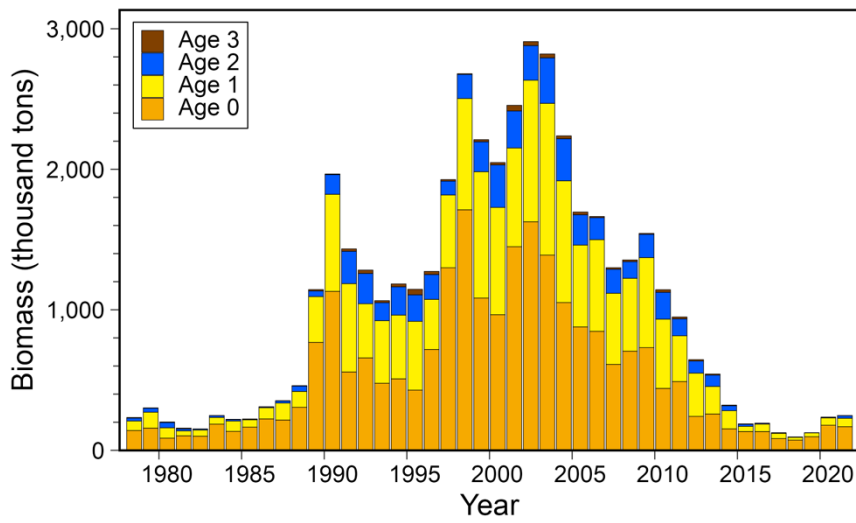


Fig. 4-4. Trends in stock weight at age

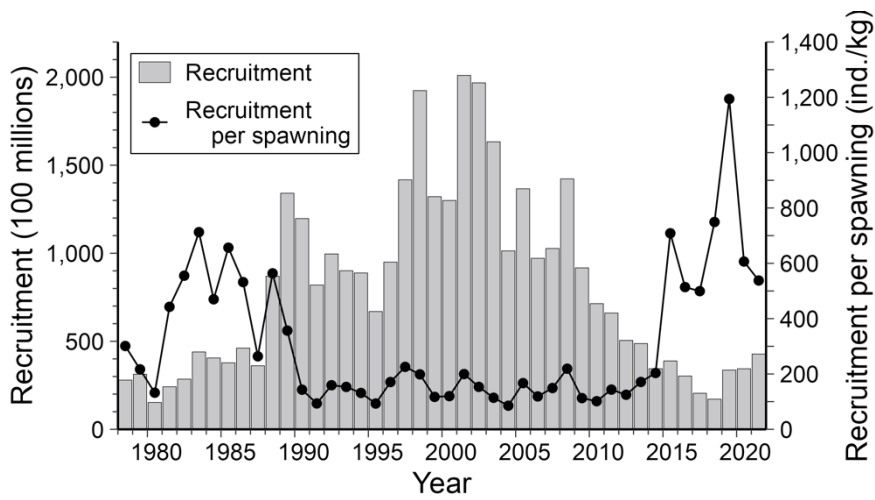


Fig. 4-5. Trends in recruitment volume and recruitment per spawning

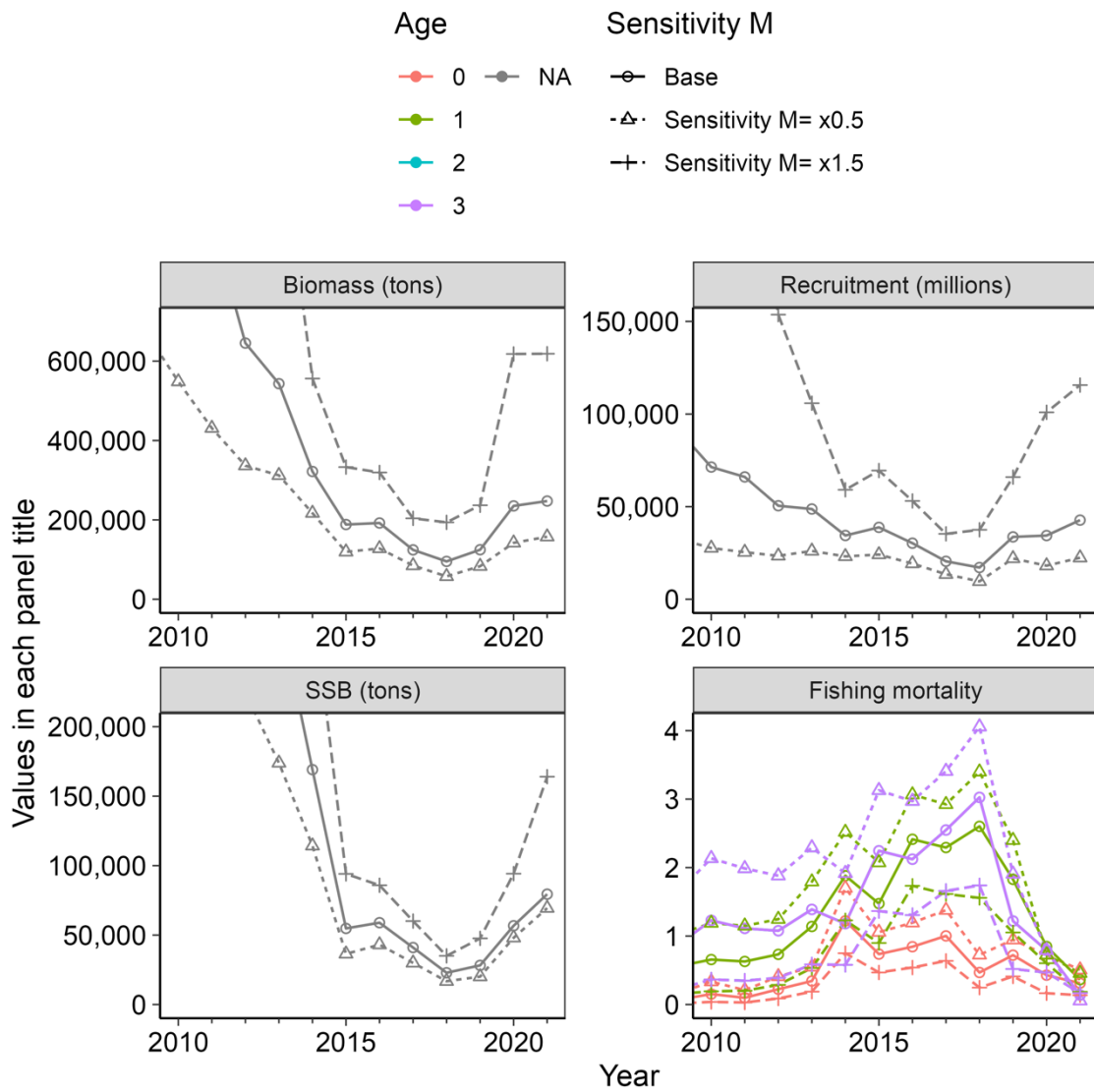


Fig. 4-6. Effects of natural mortality (M) on estimates of biomass, SSB, recruitment volume, and fishing mortality

Base indicates the reference scenario.

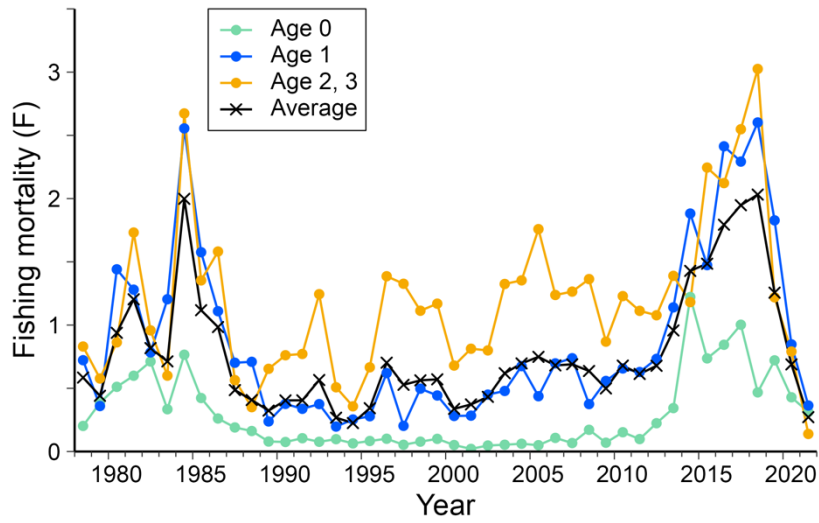


Fig. 4-7. Trends in fishing mortality F at age

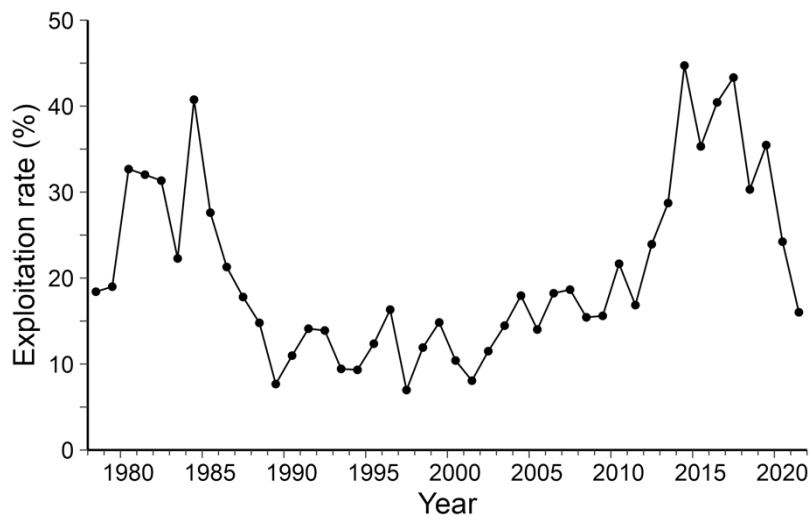


Fig. 4-8. Trends in exploitation rate

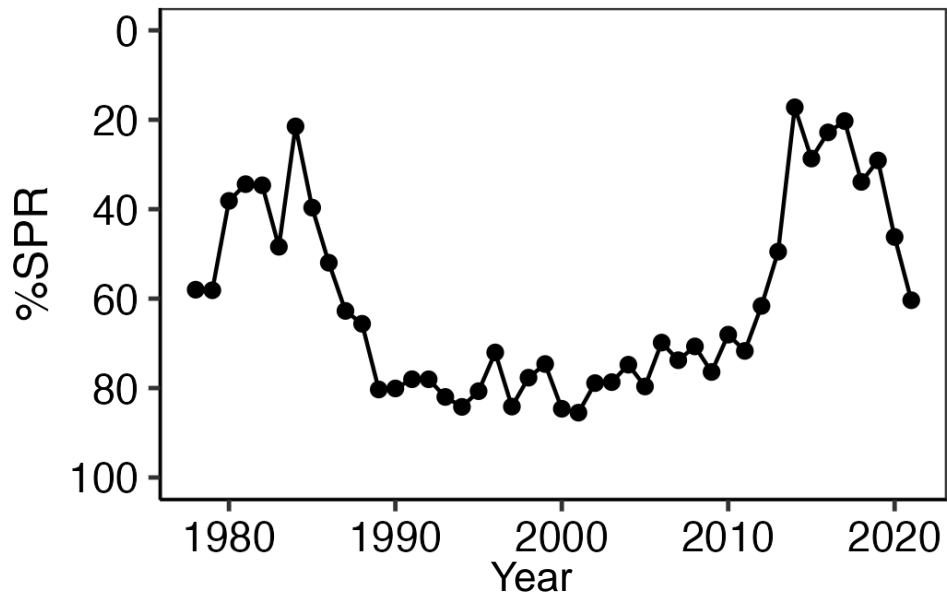


Fig. 4-9. Trends in %SPR of F by year

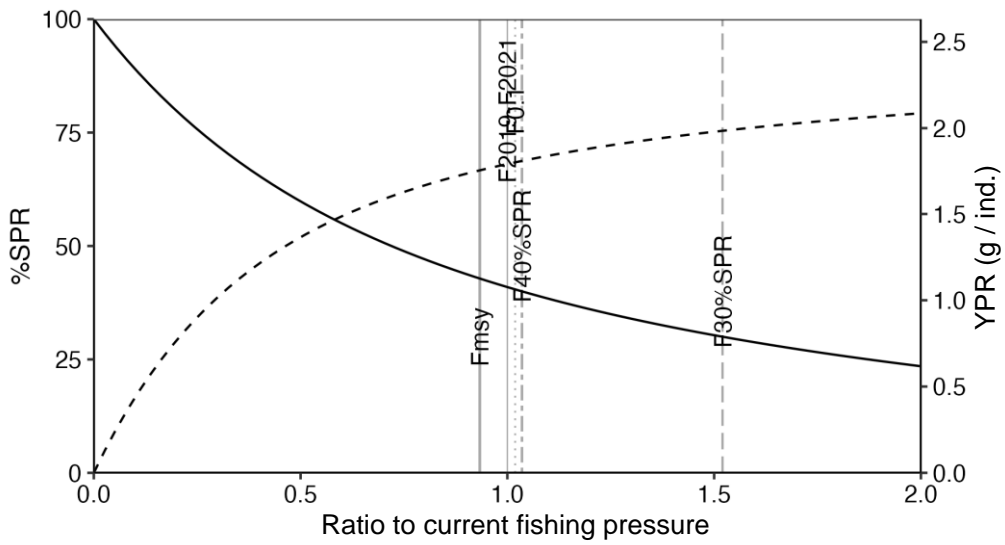


Fig. 4-10. Relationship of YPR and %SPR to current fishing pressure

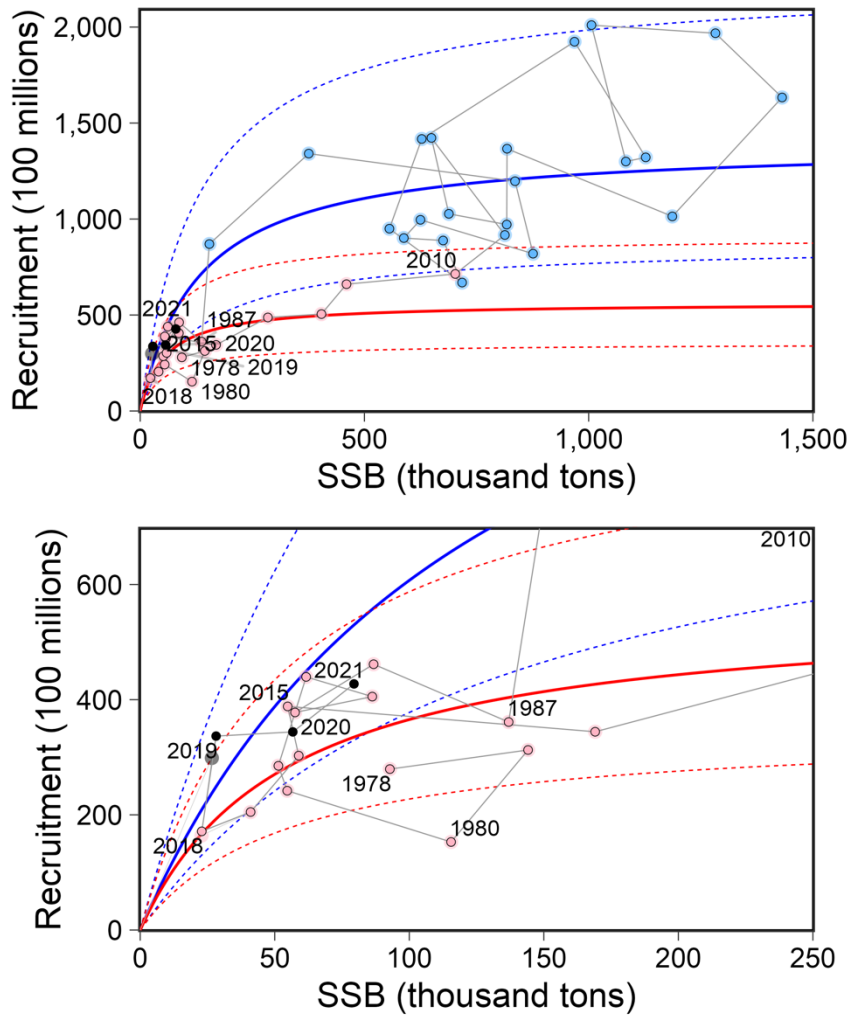


Fig. 4-11. Relationship between SSB and recruitment volume (stock-recruitment relationship)
 Stock-recruitment relationship model showing normal recruitment period (solid red line) and high recruitment period (solid blue line) proposed at the Research Institute Meeting held in September, 2021. The dotted lines above and below the stock-recruitment relationship model (red: normal recruitment period, blue: high recruitment period) indicate the range estimated to contain 90% of all observed data in the assumed stock-recruitment relationship model. The solid lines and circles plot the stock-recruitment relationship obtained from the FY 2022 stock assessment (1978 to 2021). The bottom figure is an enlargement of a portion of the top figure.

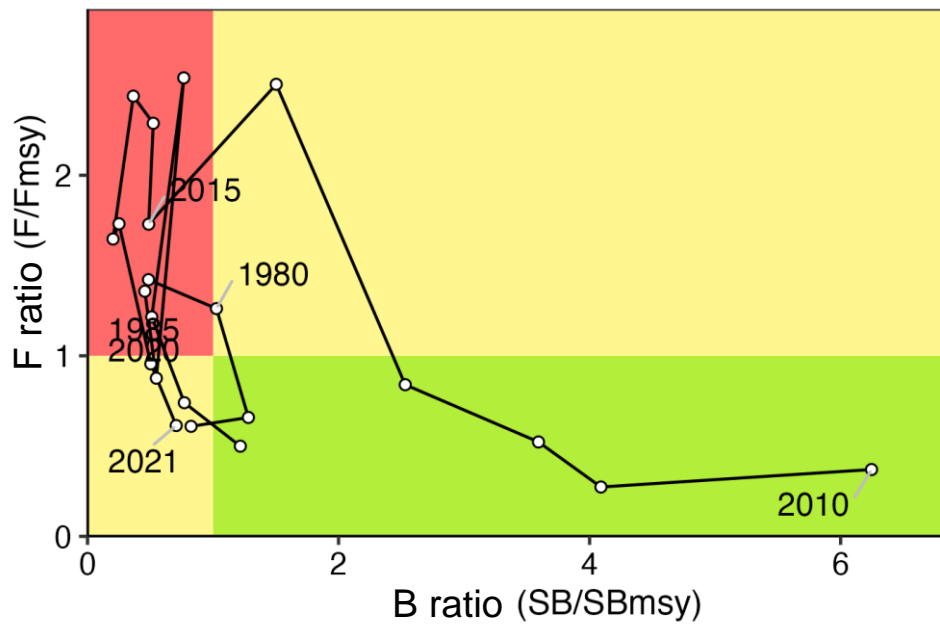


Fig. 4-12. Relationship of SSB and fishing pressure (Kobe plot)

Circles indicate results for years when normal recruitment period was assumed (1978 to 1987 and 2010 to 2021).

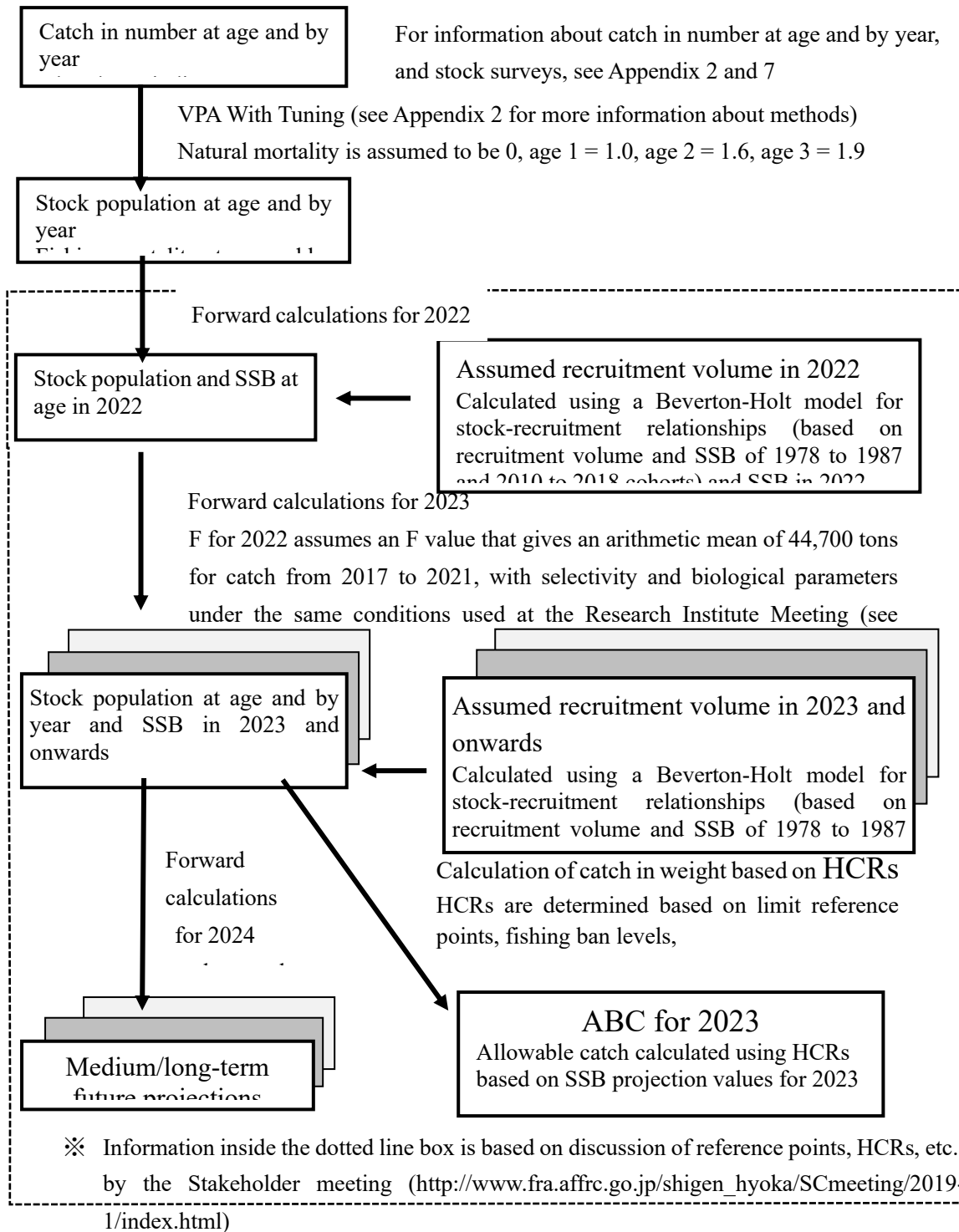
Table 3-1. Catch

Year	Catch (tons)					Catch in weight at major ports
	Southern Pacific region	Central Pacific region	Northern Pacific region	Hokkaido Pacific region	Pacific Total	
1978	11,557	21,626	9,512	303	42,998	
1979	15,725	32,644	8,856	201	57,426	
1980	15,095	38,782	11,814	268	65,959	
1981	18,354	27,218	4,988	47	50,607	
1982	17,804	24,572	5,085	81	47,542	
1983	23,585	25,957	5,640	46	55,228	
1984	21,947	42,780	25,226	54	90,007	
1985	17,311	40,506	3,601	17	61,435	
1986	13,575	49,941	2,448	98	66,062	
1987	7,618	51,406	3,450	259	62,733	
1988	13,461	52,080	2,496	51	68,088	
1989	9,581	63,455	14,723	45	87,804	
1990	13,082	72,619	126,560	3,680	215,941	
1991	9,069	82,142	106,812	4,296	202,319	
1992	13,875	73,791	85,489	5,121	178,276	
1993	7,712	57,101	29,931	5,743	100,487	
1994	16,002	59,842	33,209	1,375	110,428	73,573
1995	6,314	77,267	50,943	7,192	141,716	85,814
1996	10,741	86,365	106,913	3,871	207,890	151,860
1997	9,105	72,876	43,125	9,358	134,464	104,132
1998	13,938	119,330	166,652	19,451	319,371	240,982
1999	41,964	124,592	135,000	26,441	327,997	277,756
2000	38,181	81,333	89,937	3,665	213,116	192,638
2001	12,538	90,150	91,145	4,095	197,928	185,604
2002	15,998	144,967	128,358	45,076	334,399	304,895
2003	20,741	183,802	170,717	32,749	408,009	393,874
2004	21,816	188,584	168,461	23,004	401,865	407,431
2005	11,954	141,565	79,545	4,627	237,691	211,760
2006	10,722	169,385	99,111	24,210	303,428	270,406
2007	19,513	138,030	74,488	10,437	242,468	221,308
2008	9,301	144,075	48,815	6,891	209,082	180,061
2009	18,933	160,340	39,854	21,765	240,892	222,692
2010	16,882	139,307	56,581	34,859	247,629	234,049
2011	8,240	109,571	32,119	10,050	159,980	139,566
2012	13,439	116,920	9,975	14,125	154,459	141,674
2013	22,744	114,105	14,030	5,151	156,030	135,100
2014	27,585	101,488	7,688	7,223	143,984	120,144
2015	8,372	52,293	5,323	521	66,509	52,962
2016	17,853	54,792	3,140	1,908	77,693	65,153
2017	12,380	36,608	2,236	2,691	53,915	43,731
2018	6,488	19,850	1,896	673	28,907	22,947
2019	6,035	36,030	1,407	797	44,269	37,731
2020	9,059	44,591	2,248	1,102	57,000	50,065
2021	7,984	29,012	2,610	32	39,638	35,731

Table 4-1. Stock Analysis Results (Results of Tuned VPA)

Year	Biomass (thousand tons)	SSB (thousand tons)	Recruitment (100 millions)	Recruitment per spawning (ind. / kg)	Exploitation rate (%)	%SPR	F/Fmsy
1978	233.5	92.8	279.4	301.2	18.4	58.0	0.61
1979	302.2	144.1	312.6	216.9	19.0	58.1	0.66
1980	201.9	115.5	152.9	132.3	32.7	38.1	1.26
1981	158.0	54.6	241.9	442.7	32.0	34.4	1.42
1982	151.7	51.4	285.1	555.3	31.3	34.7	1.36
1983	247.9	61.7	439.5	712.7	22.3	48.4	0.88
1984	220.9	86.3	405.3	469.9	40.8	21.5	2.54
1985	222.6	57.5	377.8	656.6	27.6	39.7	1.22
1986	310.3	86.7	461.5	532.0	21.3	52.0	0.74
1987	352.5	136.9	361.2	263.8	17.8	62.7	0.50
1988	460.4	154.2	869.7	563.9	14.8	65.6	0.44
1989	1,144.1	375.8	1,340.9	356.8	7.7	80.3	0.20
1990	1,966.8	835.8	1,197.0	143.2	11.0	80.1	0.18
1991	1,433.5	876.0	819.5	93.6	14.1	78.0	0.23
1992	1,282.7	625.0	995.9	159.4	13.9	78.0	0.20
1993	1,065.2	587.9	900.9	153.2	9.4	82.0	0.20
1994	1,184.3	675.5	888.1	131.5	9.3	84.2	0.15
1995	1,146.1	717.8	669.1	93.2	12.4	80.7	0.19
1996	1,273.3	555.7	949.7	170.9	16.3	72.0	0.27
1997	1,927.0	627.8	1,417.1	225.7	7.0	84.1	0.13
1998	2,680.2	968.4	1,923.6	198.6	11.9	77.7	0.19
1999	2,210.9	1,127.2	1,321.2	117.2	14.8	74.6	0.26
2000	2,048.0	1,082.9	1,299.6	120.0	10.4	84.6	0.14
2001	2,455.3	1,006.3	2,010.1	199.8	8.1	85.5	0.14
2002	2,908.8	1,282.7	1,967.9	153.4	11.5	78.9	0.15
2003	2,820.6	1,431.3	1,633.2	114.1	14.5	78.7	0.14
2004	2,238.1	1,186.6	1,013.7	85.4	18.0	74.8	0.17
2005	1,696.0	818.0	1,366.3	167.0	14.0	79.6	0.14
2006	1,664.2	817.3	971.2	118.8	18.2	69.8	0.30
2007	1,299.8	688.3	1,027.2	149.2	18.7	73.8	0.18
2008	1,354.9	649.4	1,422.6	219.1	15.4	70.7	0.36
2009	1,543.8	813.2	916.9	112.8	15.6	76.4	0.19
2010	1,143.2	702.6	713.9	101.6	21.7	68.1	0.37
2011	949.1	460.1	660.5	143.6	16.9	71.7	0.27
2012	645.4	404.1	504.9	124.9	23.9	61.6	0.52
2013	543.2	284.7	487.3	171.2	28.7	49.5	0.84
2014	322.0	169.1	344.3	203.6	44.7	17.2	2.50
2015	188.3	54.8	388.3	708.6	35.3	28.7	1.73
2016	192.2	58.9	302.8	514.0	40.4	22.8	2.29
2017	124.5	41.0	204.9	499.4	43.3	20.3	2.44
2018	95.4	22.9	171.4	749.2	30.3	33.9	1.65
2019	124.8	28.2	336.8	1,194.2	35.5	29.1	1.73
2020	235.2	56.7	344.0	606.5	24.2	46.2	0.96
2021	247.5	79.5	427.4	537.8	16.0	60.4	0.61

Appendix 1 Stock Assessment Flow



Appendix 2 Calculation Methods

(1) Data Collection

Experimental stations and research institutes in prefectures along the Pacific coast surveyed data on landings at major ports and biological data (body length composition, precision measurement results, etc.), and the results are input into the Fishery Resource Conversation (FRESCO) system. We calculated information including length-weight relationships and maturity indices based on the data that was input into the FRESCO system.

A summary of surveys on eggs, juveniles, and plankton, and research vessel surveys including Northward season surveys, is shown in Appendix 7 and 10.

(2) Stock Calculation Methods Using Tuned VPA

Length-weight relationships obtained from data on landings at major ports along the Pacific coast, and precision measurement results such as body length composition, were used to find catch in number by length class, and catch in number at age at major ports was calculated based on age-length relationships by month. Assuming a life span of 4 years (death at the end of age 3), population ratios by age were stretched to fit values from the Annual Statistics of Fishery and Aquaculture Production, and catch in number at age was calculated for the entire stock (Supplementary Table 2-3).

Catch in number at age and by year was estimated assuming an age composition of age 0, age 1, age 2, and age 3, and stock population at age and by year was calculated using a regression method following Pope's approximation formula (Pope 1972). The following equation (1) was used to calculate data up to the year prior to the most recent year (2020).

$$N_{a,t} = N_{a+1,t+1}e^{M_a} + C_{a,t}e^{\frac{M_a}{2}} \quad (a = 0, 1, 2) \quad (1a)$$

$$N_{3,t} = N_{2,t} \frac{C_{3,t}}{C_{2,t}} e^{\frac{(M_3 - M_2)}{2}} \quad (1b)$$

In this equation, $N_{a,t}$ is the stock population of fish age a in year t , and $C_{a,t}$ is the catch in number of fish age a in year t , and M_a is the M of fish age a .

The following equation was used to calculate the fishing mortality $F_{a,t}$ for fish age a in year t up to the year prior to the most recent year.

$$F_{a,t} = -\ln \left\{ 1 - \frac{C_{a,t}e^{\frac{M_a}{2}}}{N_{a,t}} \right\} \quad (a = 0, 1, 2) \quad (2)$$

The fishing mortality for the oldest fish ($F_{3,t}$) was assumed to be equal to F for age 2 in all years.

$$F_{3,t} = F_{2,t} \quad (3)$$

The following equation was used to calculate the stock population $N_{a,T}$ of fish age a in the most recent year T ($T = 2021$).

$$N_{a,T} = C_{a,T}e^{\frac{M_a}{2}} \frac{1}{1 - e^{-F_{a,T}}} \quad (a = 0, 1, 2, 3) \quad (4)$$

In this equation, $C_{a,T}$ is the catch in number of fish age a in the most recent year. Meanwhile, $F_{a,T}$ indicates the fishing mortality of fish age a in the most recent year (terminal F), and if exploratory

estimates of $F_{a,T}$ are made, then estimates for the previous stock population at age and by year can be calculated retrospectively using equation (1) and (2).

Maturity rates and M at age used for stock calculations are shown in Supplementary Table 2-1. Body weight at age and by year was found by dividing the catch in weight at age and by year at major ports by the catch in number at age and by year.

(3) Estimated $F_{a,T}$ Using Tuned VPA

Tuned VPA was used to estimate $F_{a,T}$. Tuning indices used* annual egg production (eggs) along the Pacific coast (Supplementary Fig. 7-1, Area I to IV) as an index value for SSB (weight), and age 0 CPUE (ind./net) from the Northward season surveys (Supplementary Fig. 7-4, ocean regions 39°N to 46°N, 144°E to 165°W) as an index value for recruitment volume (individuals). The age 0 CPUE was calculated under a rough assumption that individuals with a standard (scaled) body length of less than 10.5 cm are age 0, due to the fact that age data for individuals collected during the survey was not available at the time of calculation.

Ridge VPA (Okamura et al. 2017) was applied to stabilize estimated values for terminal F . Terminal F values. This method is used to find terminal F by minimizing the function that adds penalties to the residual sum of squares, and the size of penalties are determined by minimizing retrospective bias (Mohn's ρ , Mohn 1999). The ridge VPA penalties are the sum of squares of the difference between F at age in the most recent year and the average of F at age in the previous three years (2019 to 2021), as shown in equation (5) (all F estimation method).

$$(1 - \lambda) \sum_{k=1}^p \sum_t \left[\frac{\{\ln(I_{k,t}) - \ln(q_k X_{k,t}^{b_k})\}^2}{2\sigma_k^2} - \ln\left(\frac{1}{\sqrt{2\pi}\sigma_k}\right) \right] + \lambda \sum_{a=0}^2 \left(F_{a,2021} - \frac{1}{3} \sum_{t=2019}^{2021} \hat{F}_{a,t} \right)^2 \quad (5)$$

In this equation, λ indicates the size of the ridge regression penalty, and which is assumed to be 0 or higher, but less than 1. During this step, λ was initially varied between 0 and 0.9 in increments of 0.1, and calculations were also performed for $\lambda = 0.9999$. Next, additional calculations were performed for scenarios ($\lambda = 0.1, 0.2, 0.7, 0.8, 0.9999$) which fulfilled the retrospective bias criteria described on the next page (within $\pm 20\%$ for all five items), with λ varied within a range of ± 0.05 in increments of 0.01 (Supplementary Table 2-4). In this equation, $I_{k,t}$ is the value of index values k in year t . In addition, q_k is the proportionality constant for k , while $X_{k,t}$ is the value of k (SSB or recruitment volume) in year t when calculated based on cohort analysis, b_k is the coefficient that describes nonlinearity in the relationship of k and values estimated using VPA, and σ_k^2 is the variance of difference between $\ln(I_{k,t})$ and $\ln(q_k X_{k,t}^{b_k})$ (Hashimoto et al. 2018). Finally, p indicates the number of index values used, and $p = 2$ in this equation because egg production and age 0 CPUE from the Northward season surveys were used. Next, steps to find terminal F involved performing calculations with an initial value of 1 (1 for all fish age 0 to 2), followed by a jitter analysis (10 iterations) with 10 initial values between 0.01 and 2 (0.01, 0.02, 0.03, 0.06, 0.11, 0.19, 0.34, 0.62, 1.11, 2.00), which diagnosed whether maximum likelihood estimates were obtained when the initial value was 1. Furthermore, for models in which it was judged that maximum likelihood estimates were not obtained, we derived the combination of maximum initial values obtained from the log-likelihood function, and the estimated terminal F , while

also removing cases when any terminal F converged/diverged into 0 or infinity. Then, we compared tendencies in initial values for maximum likelihood estimation against estimated terminal F values. Results showed that the combination of initial values for maximum likelihood estimation provided estimates for the equivalent terminal F values, so Tuned VPA was performed again with these estimated terminal F values as the initial values.

In addition, q_k and b_k were estimated using the equations (6) and (7), respectively.

$$q_k = \exp \left\{ \frac{1}{n_k} \sum_t \ln \left(\frac{I_{k,t}}{X_{k,t}^{b_k}} \right) \right\} \quad (6)$$

$$b_k = \frac{\text{Cov}[\ln(\mathbf{I}_k), \ln(\mathbf{X}_k)]}{V[\ln(\mathbf{X}_k)]} \quad (7)$$

In these equations, n_k is the number of years that k was used for tuning, V is variance, and Cov is covariance. Nonlinearity ($b_k \neq 1$) was assumed for both egg production ($k = 1$) and age 0 CPUE from the Northward season surveys ($k = 2$). Values for n_k used data from 2010 and onwards, which was determined to be a normal recruitment period in the Materials from the Research Institute Meeting on the Pacific stock of Japanese anchovy (FY 2021) (Kinoshita et al. 2021).

Mohn's ρ is the average of the relative values for estimates from calculations that use the full data up to the most recent year T (2021), and estimates from calculations that use data from the most recent year with data for a certain number of years i excluded ($T - i$). The number of years for retrospective data was set to 5 ($i = 1, 2, \dots, 5$). With retrospective bias within $\pm 20\%$ ($\rho = \pm 0.2$) for five items, which are averages of abundance (biomass), stock population, recruitment volume, SSB, and fishing mortality, the total of absolute values for Mohn's ρ was extremely low, and below values from VPA without tuning, in models where $\lambda = 0.98, 0.99, 0.9999$. However, because these results are due to a lack of tuning effect, the second lowest value for the total of absolute values for Mohn's ρ , a model where $\lambda = 0.66$, was applied as the Tuned VPA for this stock (Supplementary Table 2-4). We believe that the reason for the small retrospective bias of the VPA without tuning is that although this stock is composed of four age classes (age 0 to 3), in years when stock levels are low, as in recent years, age 0 fish compose the majority of catches, and the catch in number of fish age 1 or older is extremely low. Therefore, even if additional data for fish age 1 and older is included, the impact on estimated results will be minor.

The robustness of the statistical validity of the Tuned VPA and assumptions used for this stock assessment were diagnosed according to the Stock Assessment Model Diagnostic Procedures and Data Provision Guidelines (FY 2021) (FRA-SA2021-ABCWG02-03). No distinct retrospective patterns for abundance (biomass), recruitment volume, SSB, and other indices were seen in the results of 5-year retrospective analysis (Supplementary Fig. 2-1). In residual plots, egg production ($\sigma = 0.22$) had a smaller σ and relatively higher weight of index values compared to age 0 CPUE from the Northward season surveys ($\sigma = 0.97$) (Supplementary Fig. 2-2). The estimated nonlinear coefficient b was 0.624 for egg production, with tendencies of hyper stability, and age 0 CPUE from the Northward season surveys was 6.689, with tendencies of hyper depletion. Meanwhile, the results of jackknife analysis also suggest that because estimate terminal F for fish age 1 to 3 changes if either of the index values

are excluded (Supplementary Fig. 2-3), then information for both of these index values is contributing to estimated SSB. However, because terminal F for fish age 1 decreases when index values for age 0 CPUE from the Northward season surveys are excluded, and because it increases when egg production is excluded, we believe that egg production is contributing to higher SSB, while age 0 CPUE from the Northward season surveys is contributing to lower SSB (Supplementary Fig. 2-3).

(4) Natural mortality M

The calculation method for M has been revised since the 2005 stock assessment, adopting empirical equations (Pauly 1980) that find M using asymptotic length L_{∞} and growth rate constant K based on the von Bertalanffy growth function, and average M according to water temperature. These equations were revised further to produce the following equation (Quinn and Deriso 1999), which was used to estimate M.

$$\ln(M) = -0.0152 - 0.279 \times \ln(L_{\infty}) + 0.6543 \times \ln(K) + 0.4634 \times \ln(T)$$

Based on assumptions for the age-length relationship, L_{∞} was 17.0 cm, K was 0.67, and average water temperature T was 21.1°C, which was the average water temperature in the Kuroshio region (November to May of the following year) and the Kuroshio-Oyashio transition region (June to October) from 1950 to 2000. Small pelagic fish such as the Pacific stock of Japanese anchovy continue to be subject to strong predation pressure by larger fish such as bonito, and marine mammals such as cetaceans, even at advanced ages, and M increases rapidly in older fish due to exhaustion and senility following reproductive activities. Therefore, the trend of change in M with growth is thought to follow a typical bathtub curve. Accordingly, we distributed average M values calculated from practical approximation data across each age group, following the example of Chen and Watanabe (1989). The value used for age 0 to 1 was 1.0, which is the estimated value for early to late adult individuals in reports by Butler et al. (1993) which studied M in North American anchovy at different developmental stages. Based on a bathtub curve, M of shirasu stage fish should be higher than age 0 fish, but this report does not include the shirasu stage in the stock assessment, so M of age 0 fish is assumed to be lower than values based on a bathtub curve.

References

- Butler, J.L., P.E. Smith and N.C.H. Lo (1993) The effect of natural variability of life-history parameters on anchovy and sardine population growth. *CalCOFI Rep.*, **34**, 104-111.
- Chen, S. and S. Watanabe (1989) Age dependence of natural mortality coefficient in Fish population dynamics. *Nippon Suisan Gakkaishi*, **55**, 205-208.
- Hashimoto, M., H. Okamura, M. Ichinokawa, K. Hiramatsu and T. Yamakawa (2018) Impacts of the nonlinear relationship between abundance and its index in a tuned virtual population analysis. *Fish. Sci.*, **84**, 335-347.
- Kinoshita, J., Yasuda, T., Watanabe, C., Kamimura, Y. (2021) Materials for the Research Institute

Meeting on Reference Points of Pacific stock of Japanese anchovy (FY 2021). FRA-SA2021-BRP03-1 (in Japanese)

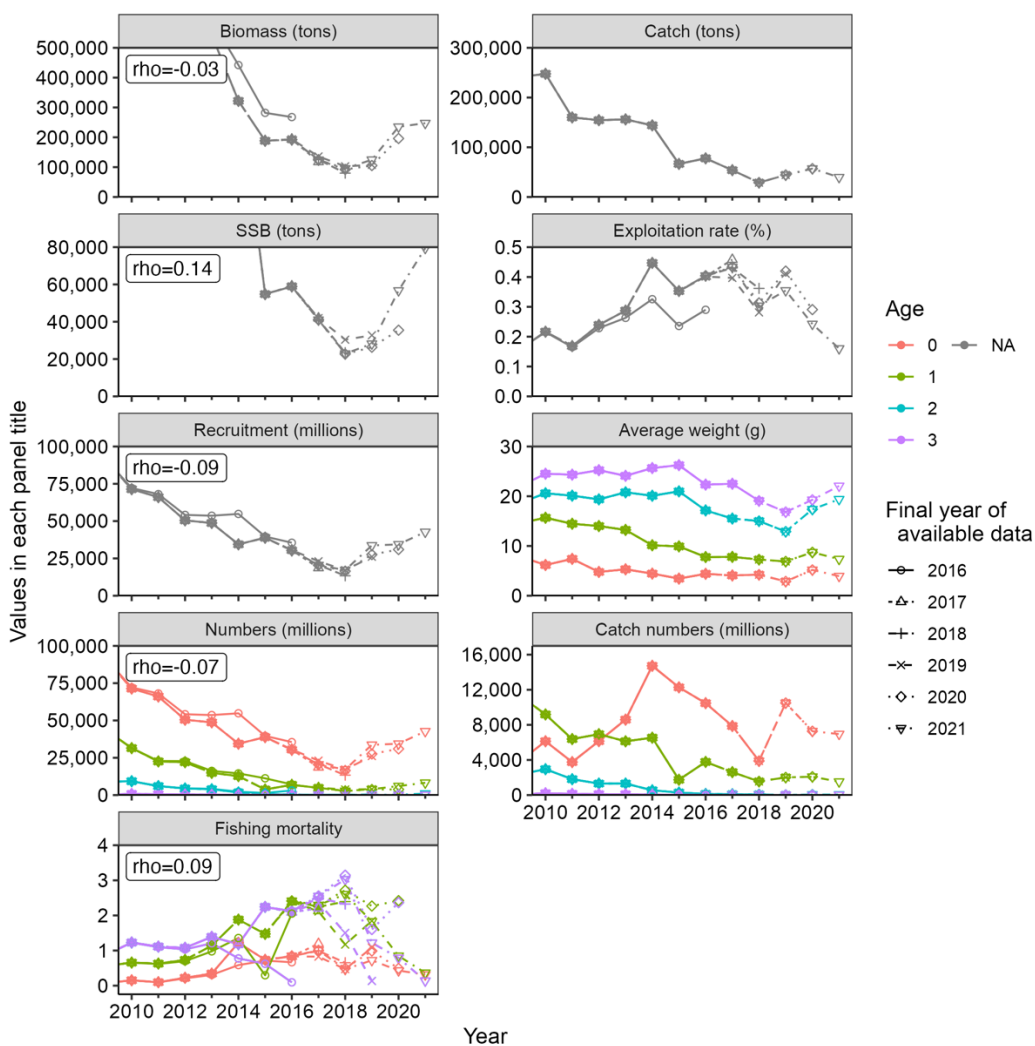
Mohn, R (1999) The retrospective problem in sequential population analysis: An investigation using cod fishery and simulated data. *ICES J. Mar. Sci.*, **56**, 473-488.

Okamura, H., Y. Yamashita and M. Ichinokawa (2017) Ridge virtual population analysis to reduce the instability of fishing mortalities in the terminal year. *ICES J. Mar. Sci.*, **74**, 2427-2436.

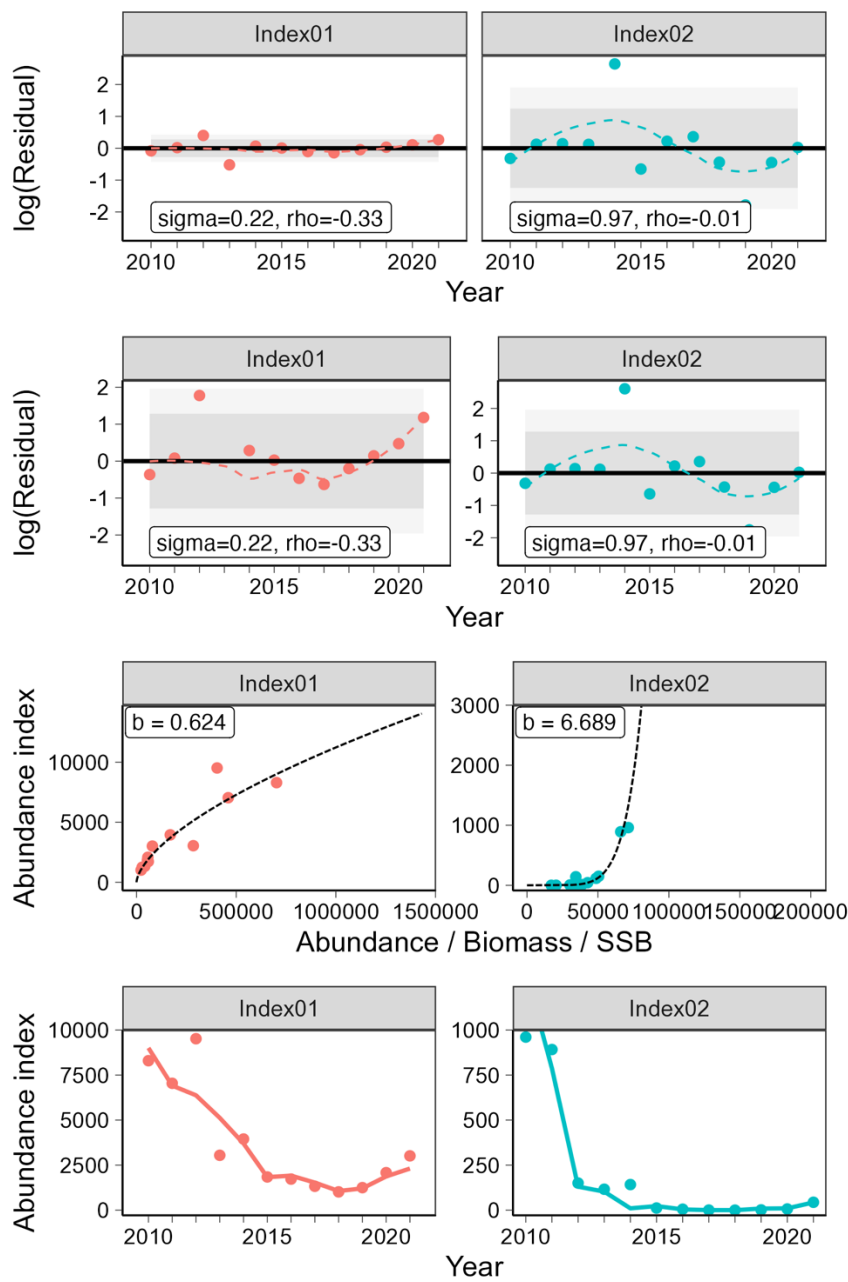
Pauly, D. (1980) On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. *J. Cons. Int. Explor. Mer.*, **39**, 175-192.

Pope, J.G. (1972) An investigation of the accuracy of virtual population analysis using cohort analysis. *Inst. Comm. Northwest Atlant. Fish. Res. Bull.*, **9**, 65-74.

Quinn, T.J.II and R.B. Deriso (1999) *Quantitative Fish Dynamics*. Oxford University Press, New York., 542 pp.



Supplementary Fig. 2-1. Retrospective analysis results for Tuned VPA ($\lambda = 0.66$, all F estimation method)



Supplementary Fig. 2-2. Residual plots

Top row: Time series plot of log residuals of abundance indices and projected values

2nd row: Time series plot of standardized log residuals of abundance indices and projected values

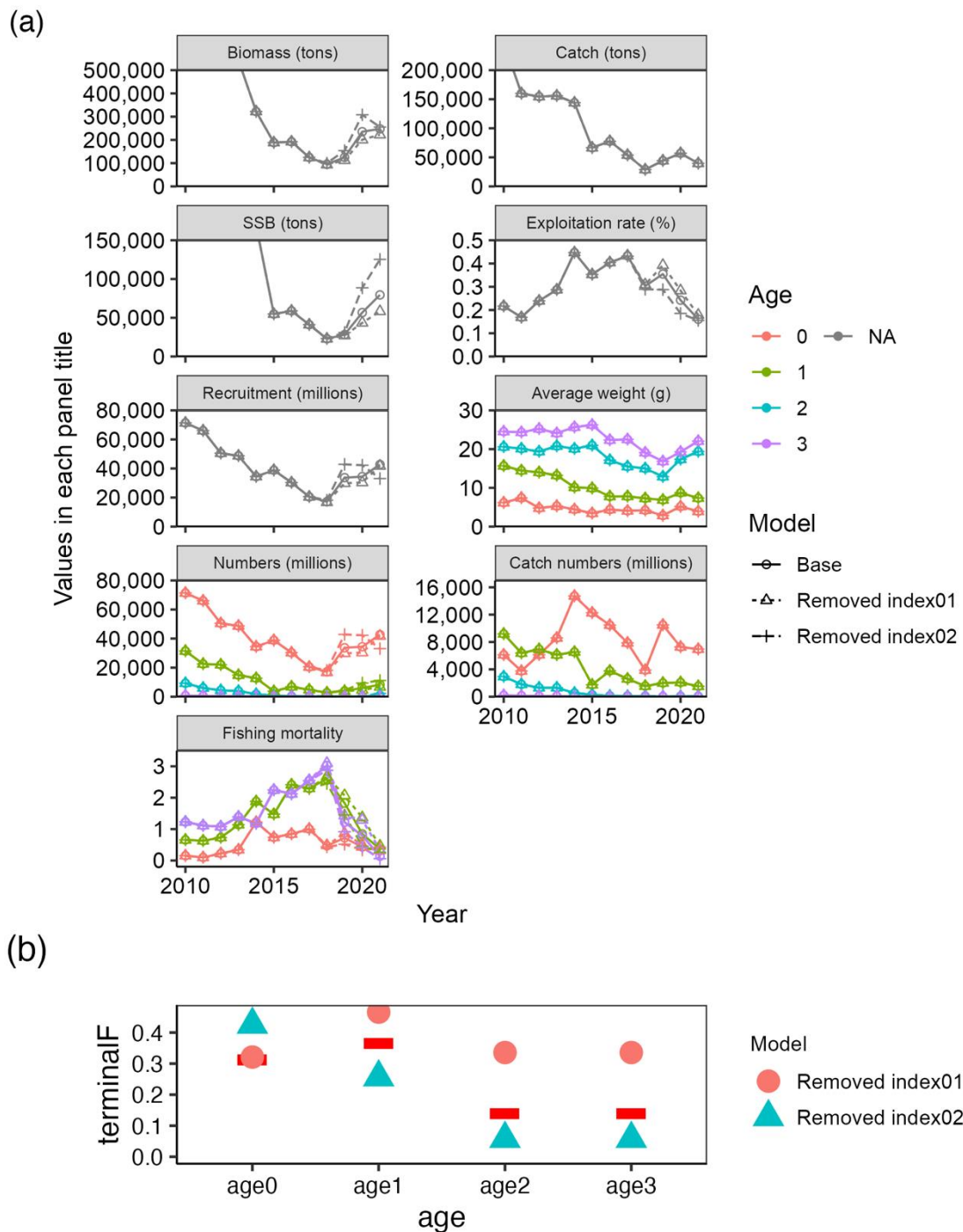
3rd row: Regression relationship of abundance indices and projected values

Bottom row: Time series plot of observed (circles) and predicted (line) abundance indices

Index values (Index 01: egg production, Index 02: estimated age 0 CPUE from the Northward season surveys)

In the top row, sigma is the observation error, and rho is the first-order autocorrelation coefficient (marked with an asterisk * if significant at 5% probability), the dark gray area indicates the 80% interval for observed values (1.28σ), and the light gray area indicates the 95% interval (1.96σ).

In the 3rd row panels, b is the nonlinear coefficient between the observed and predicted values of abundance indices.



Supplementary Fig. 2-3. Jackknife analysis of SSB, abundance (biomass), exploitation rate, recruitment in number, and fishing mortality: (a) trends in each abundance estimate, (b) estimated terminal F

The red horizontal bars in (b) indicate results with both index values included, i.e., base model estimates for (a).

Index values (index 01: egg production, index 02: estimated age 0 CPUE from the Northward season surveys)

Supplementary Table 2-1. Maturity rates and natural mortality M at age used in stock calculations

Age	Maturity Rate	M
Age 0	0	1.0
Age 1	1.0	1.0
Age 2	1.0	1.6
Age 3	1.0	1.9

Supplementary Table 2-2. Tuning indices

Abundance indices used for Tuned VPA applied are shown in bold.

Year	Egg production (trillion eggs)	CPUE of fish age 0 from the Northward Surveys (ind./net)
1978		
1979		
1980		
1981		
1982	1,081.6	
1983	958.5	
1984	745.7	
1985	1,116.1	
1986	1,498.7	
1987	1,627.5	
1988	852.7	
1989	1,016.6	
1990	2,826.9	
1991	7,214.6	
1992	5,924.7	
1993	3,122.7	
1994	4,644.0	
1995	3,988.2	
1996	3,282.1	
1997	4,704.2	
1998	5,797.1	
1999	15,622.5	
2000	10,581.9	
2001	6,749.7	971.4
2002	10,642.6	1,826.0
2003	13,134.1	357.0
2004	14,313.2	247.5
2005	9,882.0	472.0
2006	9,579.4	79.8
2007	10,909.2	869.1
2008	4,427.1	518.3
2009	9,246.3	963.0
2010	8,296.7	960.8
2011	7,042.0	891.8
2012	9,518.2	150.4
2013	3,045.7	116.1
2014	3,948.6	142.0
2015	1,842.1	11.7
2016	1,725.0	5.3
2017	1,325.9	0.4
2018	1,014.1	0.1
2019	1,249.4	1.5
2020	2,081.9	6.4
2021	3,014.1	43.8

Supplementary Table 2-3. Details of input values used for cohort analysis

Year	Catch numbers at age (millions)				Total	Average weight at age (g)			
	Age 0 fish	Age 1 fish	Age 2 fish	Age 3 fish		Age 0 fish	Age 1 fish	Age 2 fish	Age 3 fish
1978	3,105.2	2,512.6	288.3	34.2	5,940.3	5.0	8.4	18.2	25.5
1979	6,060.4	1,538.7	283.7	17.0	7,899.8	5.1	13.5	19.8	23.9
1980	3,713.1	3,622.8	560.0	36.5	7,932.5	5.6	9.5	17.4	22.6
1981	6,613.8	1,476.4	252.0	58.4	8,400.7	4.3	10.4	21.2	27.6
1982	8,807.7	1,610.6	95.5	5.8	10,519.6	3.5	9.1	18.4	24.9
1983	7,577.0	2,185.6	166.4	4.7	9,933.7	4.2	9.3	16.0	21.0
1984	13,149.4	6,474.5	237.6	32.8	19,894.3	3.3	6.4	18.0	25.9
1985	7,905.9	3,336.6	110.2	2.3	11,355.0	4.4	7.5	15.3	17.8
1986	6,433.4	3,701.7	188.3	5.3	10,328.7	4.8	8.7	12.5	27.8
1987	3,799.8	4,000.7	214.1	3.7	8,018.2	6.0	9.2	14.3	23.5
1988	7,903.6	3,384.0	316.9	14.5	11,619.0	3.5	10.3	16.1	21.8
1989	6,191.5	3,493.4	428.7	62.9	10,176.5	5.7	12.0	20.3	28.1
1990	5,282.6	8,673.2	1,889.1	43.0	15,887.9	9.4	15.2	17.7	22.5
1991	4,969.5	7,101.2	2,779.9	154.7	15,005.3	6.8	15.4	20.0	23.0
1992	4,488.2	5,146.4	3,426.6	295.6	13,356.8	6.6	14.2	20.1	22.5
1993	5,091.7	3,683.9	1,227.8	96.0	10,099.3	5.3	13.1	18.7	22.6
1994	3,360.9	4,080.9	1,383.7	96.9	8,922.4	5.7	15.1	19.6	24.9
1995	3,246.4	4,521.9	1,874.7	272.0	9,915.0	6.4	16.0	22.0	27.2
1996	5,542.8	6,348.1	2,873.0	258.2	15,022.0	7.6	15.8	20.7	24.8
1997	4,476.7	3,520.1	1,478.9	122.3	9,598.0	9.2	16.4	22.0	25.4
1998	8,787.4	11,740.1	2,860.6	62.3	23,450.5	8.9	16.0	18.1	21.5
1999	7,652.1	14,207.3	3,425.6	167.6	25,452.6	8.2	13.7	19.3	23.8
2000	3,950.7	6,535.6	3,425.8	132.3	14,044.4	7.4	17.4	19.6	24.2
2001	2,519.2	6,804.1	3,052.6	340.2	12,716.2	7.2	15.5	21.6	25.3
2002	5,546.0	15,920.1	3,112.1	232.8	24,811.1	8.3	13.9	19.6	25.7
2003	5,186.8	15,932.9	5,603.3	324.1	27,047.1	8.5	15.6	19.1	23.9
2004	3,674.2	16,955.5	5,243.0	261.5	26,134.2	10.4	15.2	19.0	22.6
2005	4,050.8	7,534.5	3,965.4	262.6	15,813.4	6.4	16.6	20.2	23.7
2006	6,026.8	14,556.2	2,657.1	101.8	23,341.9	8.7	13.6	18.7	23.4
2007	4,040.2	10,151.2	2,823.8	135.3	17,150.6	6.0	15.8	19.5	22.8
2008	13,629.0	6,703.6	1,886.8	143.7	22,363.1	5.0	14.7	21.0	24.0
2009	3,754.0	11,432.9	2,330.4	65.4	17,582.8	8.0	14.5	18.6	21.9
2010	6,130.7	9,186.7	2,948.9	207.0	18,473.2	6.2	15.7	20.6	24.5
2011	3,756.5	6,382.0	1,809.3	142.3	12,090.1	7.4	14.5	20.1	24.3
2012	6,143.4	6,937.0	1,310.6	101.6	14,492.5	4.8	14.0	19.4	25.2
2013	8,591.2	6,125.1	1,313.4	88.2	16,117.9	5.3	13.2	20.8	24.1
2014	14,727.6	6,537.3	544.1	52.5	21,861.6	4.4	10.1	20.1	25.7
2015	12,275.3	1,745.2	286.2	37.4	14,344.2	3.4	9.9	21.0	26.3
2016	10,471.3	3,777.2	124.4	5.2	14,378.0	4.4	7.8	17.1	22.3
2017	7,868.5	2,611.2	93.3	2.7	10,575.7	4.1	7.8	15.5	22.5
2018	3,883.8	1,553.3	76.1	1.3	5,514.5	4.2	7.3	15.0	19.1
2019	10,494.6	2,009.9	23.9	0.5	12,528.8	2.9	6.9	12.9	16.8
2020	7,277.4	2,087.7	57.3	1.0	9,423.4	5.2	8.7	17.4	19.3
2021	6,952.3	1,525.2	55.4	1.1	8,534.0	3.9	7.4	19.4	22.1

Supplementary Table 2-4. List of retrospective biases for all F estimation method model

The retrospective bias values (Mohn's ρ) when λ is varied in the F estimation method model. The scenario titled Plain indicates VPA without tuning, and allF indicates the all F estimation method. Green cells indicate scenarios where the absolute value of Mohn's ρ is less than 0.2. Green titles indicate scenarios where Mohn's ρ is less than 0.2 for all index values. The scenario marked with a box is the adopted scenario. The lower section of this table is results from calculations in increments of 0.1.

Scenario name	Initial value	Mohn's ρ (5-year retrospective)					Sum of absolute values
		Biomass	Numbers	Recruitment	SSB	Fishing mortality	
1 Plain	1	0.025	0.022	0.014	0.054	-0.069	0.184
2 AEP&NSage0-2010-allF- λ 0.05	1	-0.046	-0.087	-0.108	0.102	0.209	0.553
3 AEP&NSage0-2010-allF- λ 0.06	1	-0.046	-0.087	-0.108	0.103	0.204	0.547
4 AEP&NSage0-2010-allF- λ 0.07	1	-0.045	-0.086	-0.107	0.103	0.199	0.541
5 AEP&NSage0-2010-allF- λ 0.08	1	-0.045	-0.086	-0.107	0.104	0.196	0.537
6 AEP&NSage0-2010-allF- λ 0.09	1	-0.044	-0.086	-0.107	0.104	0.193	0.534
7 AEP&NSage0-2010-allF- λ 0.1	1	-0.044	-0.085	-0.106	0.105	0.191	0.531
8 AEP&NSage0-2010-allF- λ 0.11	1	-0.044	-0.085	-0.106	0.105	0.190	0.529
9 AEP&NSage0-2010-allF- λ 0.12	1	-0.043	-0.085	-0.106	0.105	0.189	0.528
10 AEP&NSage0-2010-allF- λ 0.13	0.315, 0.364, 0.291	-0.141	-0.152	-0.167	-0.073	0.371	0.903
11 AEP&NSage0-2010-allF- λ 0.14	0.315, 0.364, 0.287	-0.043	-0.084	-0.105	0.105	0.189	0.526
12 AEP&NSage0-2010-allF- λ 0.15	0.315, 0.364, 0.283	-0.140	-0.152	-0.167	-0.073	0.372	0.904
13 AEP&NSage0-2010-allF- λ 0.16	1	-0.042	-0.084	-0.105	0.105	0.190	0.526
14 AEP&NSage0-2010-allF- λ 0.17	1	-0.042	-0.084	-0.104	0.105	0.191	0.526
15 AEP&NSage0-2010-allF- λ 0.18	1	Inf	Inf	Inf	-0.075	0.101	-
16 AEP&NSage0-2010-allF- λ 0.19	1	-0.042	-0.083	-0.104	0.104	0.193	0.527
17 AEP&NSage0-2010-allF- λ 0.2	1	-0.042	-0.083	-0.104	0.104	0.195	0.528
18 AEP&NSage0-2010-allF- λ 0.21	1	-0.042	-0.083	-0.104	0.104	0.196	0.529
19 AEP&NSage0-2010-allF- λ 0.22	0.315, 0.364, 0.260	-0.140	-0.152	-0.166	-0.077	0.386	0.920
20 AEP&NSage0-2010-allF- λ 0.23	1	-0.041	-0.083	-0.103	0.104	0.200	0.531
21 AEP&NSage0-2010-allF- λ 0.24	1	-0.041	-0.083	-0.103	0.104	0.202	0.533
22 AEP&NSage0-2010-allF- λ 0.25	1	-0.041	-0.083	-0.103	0.103	0.204	0.534
23 AEP&NSage0-2010-allF- λ 0.65	1	-0.143	-0.155	-0.170	-0.077	0.442	0.986
24 AEP&NSage0-2010-allF- λ 0.66	0.312, 0.364, 0.139	-0.025	-0.073	-0.093	0.145	0.094	0.430
25 AEP&NSage0-2010-allF- λ 0.67	0.312, 0.364, 0.137	-0.025	-0.073	-0.093	0.146	0.098	0.435
26 AEP&NSage0-2010-allF- λ 0.68	0.312, 0.365, 0.134	-0.025	-0.072	-0.092	0.147	0.103	0.440
27 AEP&NSage0-2010-allF- λ 0.69	0.312, 0.365, 0.131	-0.025	-0.072	-0.092	0.148	0.108	0.445
28 AEP&NSage0-2010-allF- λ 0.7	0.312, 0.365, 0.129	-0.024	-0.072	-0.092	0.149	0.113	0.451
29 AEP&NSage0-2010-allF- λ 0.71	0.312, 0.366, 0.126	-0.024	-0.072	-0.092	0.151	0.118	0.456
30 AEP&NSage0-2010-allF- λ 0.72	0.312, 0.366, 0.124	-0.024	-0.072	-0.092	0.152	0.124	0.463
31 AEP&NSage0-2010-allF- λ 0.73	0.312, 0.367, 0.121	-0.023	-0.072	-0.091	0.153	0.130	0.469
32 AEP&NSage0-2010-allF- λ 0.74	0.312, 0.367, 0.118	-0.023	-0.072	-0.091	0.155	0.136	0.476
33 AEP&NSage0-2010-allF- λ 0.75	0.312, 0.368, 0.116	-0.023	-0.072	-0.091	0.156	0.142	0.483
34 AEP&NSage0-2010-allF- λ 0.76	0.312, 0.369, 0.113	-0.023	-0.071	-0.090	0.157	0.149	0.491
35 AEP&NSage0-2010-allF- λ 0.77	0.311, 0.370, 0.110	-0.022	-0.071	-0.090	0.159	0.156	0.499
36 AEP&NSage0-2010-allF- λ 0.78	0.311, 0.371, 0.107	-0.022	-0.071	-0.090	0.161	0.164	0.508
37 AEP&NSage0-2010-allF- λ 0.79	0.311, 0.372, 0.105	-0.022	-0.071	-0.089	0.163	0.172	0.517
38 AEP&NSage0-2010-allF- λ 0.8	0.311, 0.373, 0.102	-0.021	-0.071	-0.089	0.165	0.181	0.527
39 AEP&NSage0-2010-allF- λ 0.81	0.3113, 0.3747, 0.0988	-0.021	-0.071	-0.089	0.167	0.191	0.538
40 AEP&NSage0-2010-allF- λ 0.82	0.3113, 0.3765, 0.0958	-0.020	-0.071	-0.088	0.169	0.201	0.549
41 AEP&NSage0-2010-allF- λ 0.83	0.3112, 0.3787, 0.0928	-0.020	-0.070	-0.088	0.172	0.211	0.561
42 AEP&NSage0-2010-allF- λ 0.84	0.3113, 0.3813, 0.0897	-0.019	-0.070	-0.087	0.175	0.223	0.574
43 AEP&NSage0-2010-allF- λ 0.85	0.3113, 0.3845, 0.0865	-0.003	-0.059	-0.079	0.214	-0.229	0.584
44 AEP&NSage0-2010-allF- λ 0.95	0.3298, 0.6008, 0.0483	0.261	0.100	0.044	0.942	-0.540	1.888
45 AEP&NSage0-2010-allF- λ 0.96	0.3408, 0.6460, 0.0442	0.351	0.150	0.078	1.209	-0.567	2.356
46 AEP&NSage0-2010-allF- λ 0.97	0.3579, 0.6689, 0.0395	0.556	0.262	0.148	1.827	-0.613	3.405
47 AEP&NSage0-2010-allF- λ 0.98	1	0.031	0.031	0.031	0.029	-0.008	0.130
48 AEP&NSage0-2010-allF- λ 0.99	1	0.025	0.025	0.023	0.030	-0.009	0.112
49 AEP&NSage0-2010-allF- λ 0.9999	0.961, 2.261, 1.883	0.022	0.023	0.020	0.031	-0.010	0.106
Increments of 0.1							
AEP&NSage0-2010-allF- λ 0	0.316, 0.365, 0.343	-0.151	-0.161	-0.174	-0.087	1.1E+42	1.1E+42
AEP&NSage0-2010-allF- λ 0.1	1	-0.044	-0.085	-0.106	0.105	0.191	0.531
AEP&NSage0-2010-allF- λ 0.2	1	-0.042	-0.083	-0.104	0.104	0.195	0.528
AEP&NSage0-2010-allF- λ 0.3	1	-0.041	-0.082	-0.102	0.102	0.215	0.543
AEP&NSage0-2010-allF- λ 0.4	0.314, 0.363, 0.206	-0.041	-0.082	-0.101	0.101	0.242	0.567
AEP&NSage0-2010-allF- λ 0.5	1	-0.041	-0.082	-0.101	0.098	0.276	0.597
AEP&NSage0-2010-allF- λ 0.6	1	-0.142	-0.154	-0.170	-0.074	0.413	0.953
AEP&NSage0-2010-allF- λ 0.7	0.312, 0.365, 0.129	-0.024	-0.072	-0.092	0.149	0.113	0.451
AEP&NSage0-2010-allF- λ 0.8	0.311, 0.373, 0.102	-0.021	-0.071	-0.089	0.165	0.181	0.527
AEP&NSage0-2010-allF- λ 0.9	0.3127, 0.4184, 0.0691	0.010	-0.050	-0.068	0.253	-0.246	0.627
AEP&NSage0-2010-allF- λ 0.9999	0.961, 2.261, 1.883	0.022	0.023	0.020	0.031	-0.010	0.106

Appendix 3 Proposed Reference Points and Proposed Fishing Ban Level

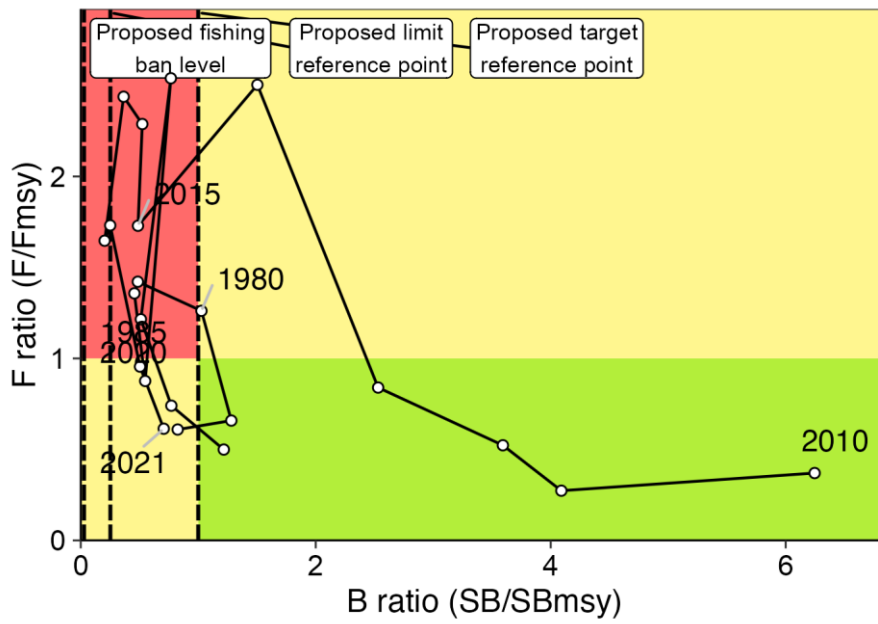
The Research Institute Meeting held in September 2021 proposed adoption of the following: SSB required for MSY (SB_{msy}: 112,000 tons) as a target reference point (SB_{target}), SSB required for 60% MSY (SB_{0.6msy}: 28,000 tons) as a limit reference point (SB_{limit}), and SSB required for 10% MSY (SB_{0.1msy}: 3,000 tons) as a fishing ban level (SB_{ban}) (Kinoshita 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 2021 (SB₂₀₂₁: 79,000 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 of this stock since 2014 was above the fishing pressure required for MSY (F_{msy}), but was determined to be lower than F_{msy} from 2020 to 2021 (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 0 and age 1 fish. However, the proportion of older fish tends to increase in correlation with increase of SSB.

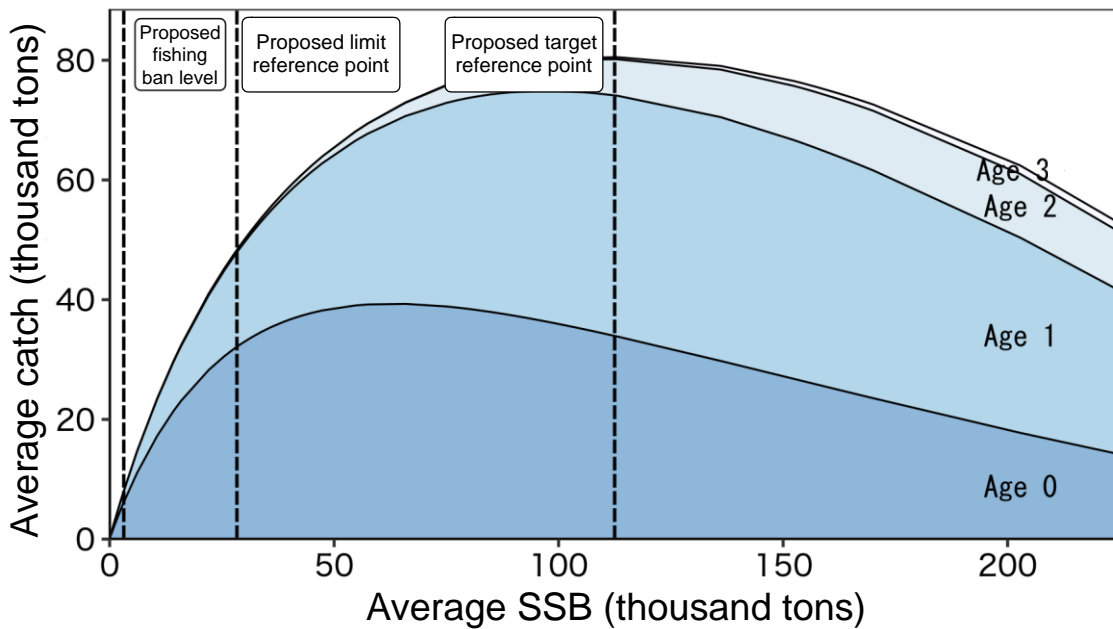
References

Kinoshita, J., Yasuda, T., Watanabe, C., Kamimura, Y. (2021) Materials for the Research Institute Meeting on Reference Points of Pacific stock of Japanese anchovy (FY 2021). FRA-SA2021-BRP03-1 (in Japanese)



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

White circles indicate results for years when normal recruitment period was assumed (1978 to 1987 and 2010 to 2021).



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 projection calculations were performed for the 2022 to 2053 fishing seasons using a progression method for cohort analysis applied to estimates for stock abundance in 2021 (Appendix 5). Recruitment volume in future projections was forecast based on SSB in each year using the stock-recruitment relationship model. Calculations were replicated 10,000 times assuming errors which follow log-normal distribution to account for uncertainty in recruitment. Catch in 2022 was assumed to be the average of the most recent 5-year period under recent fishing conditions or the previous year's fishing conditions (44,700 tons from 2017 to 2021). The current fishing pressure is the F value that gives the %SPR corresponding to fishing pressure from 2019 to 2021 in this assessment, under the same selectivity and biological parameters (average body weight, etc.) as the calculations for proposed reference points. Fishing pressure in 2023 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 Harvest Control Rules

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 Basic Guidelines for Harvest Control Rules and 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 F_{msy} multiplied by adjustment coefficient β when SSB is above the limit reference point. Supplementary Fig. 4-1 shows the proposed 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 0.9, then there is a 50% or higher probability that values will exceed proposed target reference points in 10 years.”

(3) Projected Values for 2023

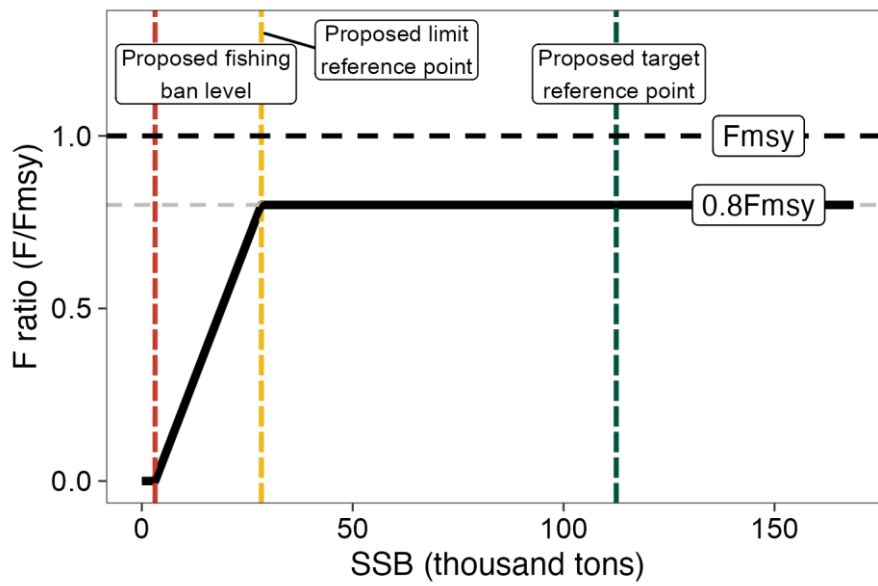
The average catch in 2023, as calculated based on proposed HCRs, will be 101,000 tons if β is set to 0.8, and 116,000 tons if β is set to 1.0 (Supplementary Table 6-4). Projected SSB in 2023 is forecast to be an average of 191,000 tons, which exceeds limit reference points in replicated calculations using both values.

(4) Projections for 2024 and Onwards

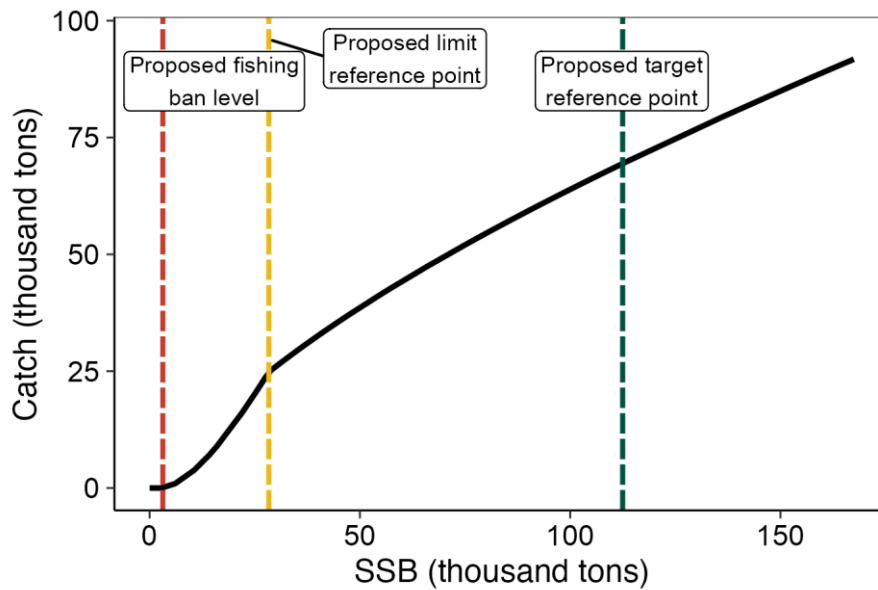
Results of future projections, including 2024 and onwards, are shown in Supplementary Fig. 4-2 and Supplementary Tables 4-1 and 4-2. If management based on these proposed HCRs is continued for 10 years, then projected values for average SSB in 2033 will be 137,000 tons if β is set to 0.8 (90% prediction interval: 87,000 to 203,000 tons), and 113,000 tons if β is set to 1.0 (90% prediction interval: 70,000 to 171,000 tons) (Supplementary Table 6-5). If β is 0.9 or lower, then there is a 50% or higher probability that the projected value will exceed the proposed target reference point in 2033 (Supplementary Table 4-1). Meanwhile, if β is 1.0 or lower, then there is a 100% probability that the

value will exceed the proposed limit reference point in 2033. If the current fishing pressure (F2019 to 2021) is continued, then projected values for average SSB in 2033 will be 99,000 tons (90% prediction interval of 60,000 to 151,000 tons), with a 27% probability that the value will exceed the proposed target reference point, and a 100% probability that it will exceed the proposed limit reference point (Supplementary Table 6- 5).

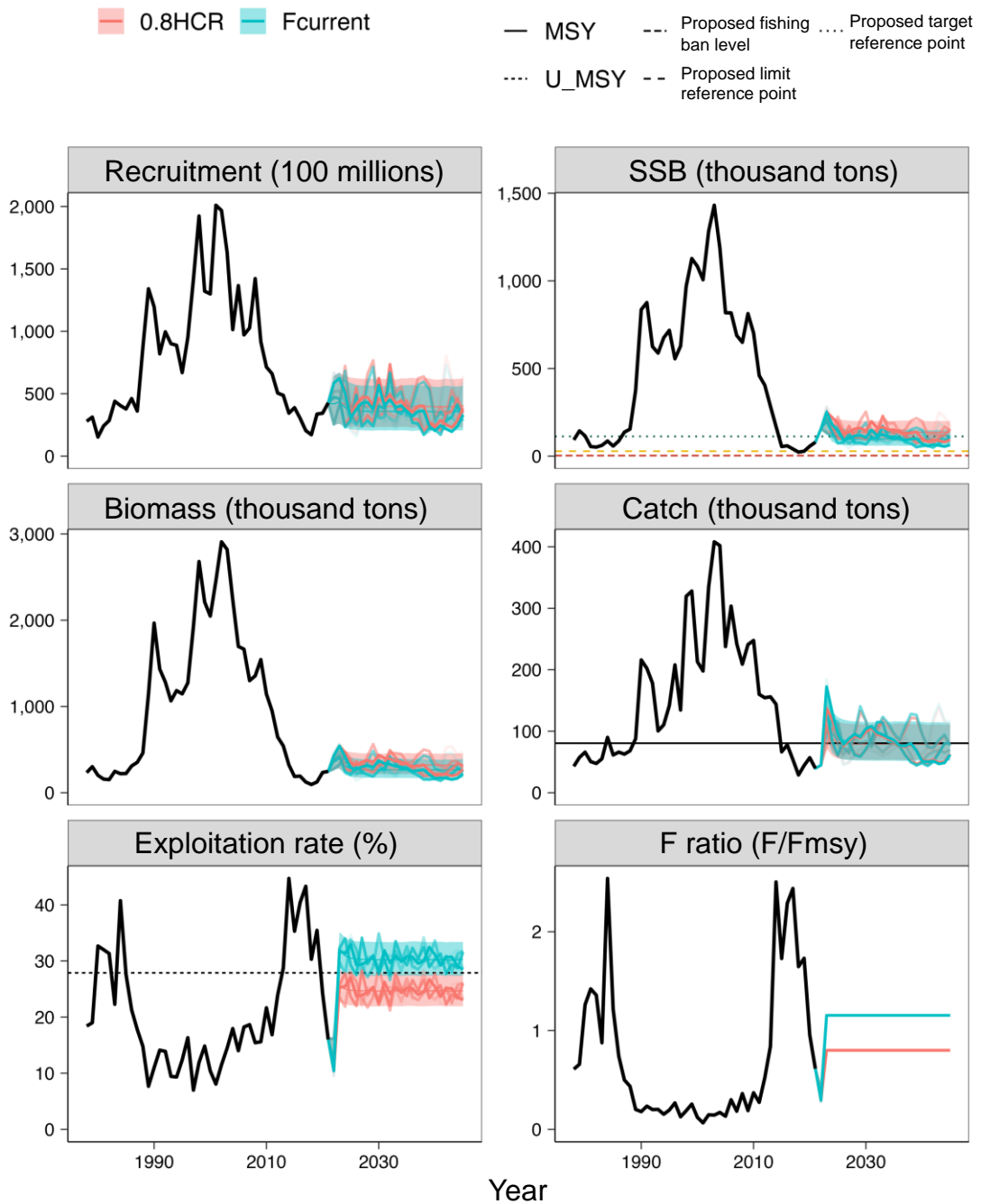
a) When the vertical axis is fishing pressure



b) When the vertical axis is catch in weight



Supplementary Fig. 4-1. Proposed HCRs ($\beta = 0.8$), (a) is the scenario when the vertical axis shows fishing pressure, and (b) is the scenario when the vertical axis shows catch in weight



(Shaded areas: 5 to 95% prediction interval, thin solid lines: average value, thick solid lines: some of simulation results)

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

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

horizontal line indicates MSY. These graphs use results for constant fishing pressure and adjustment coefficient $\beta = 0.8$. F for 2022 was set to a value that gives the average catch for the most recent 5-year period (44,700 tons from 2017 to 2021).

Supplementary Table 4-1. 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. These tables show results with β varied from 0.0 to 1.0 in 2023 and onwards, and future projections if the current fishing pressure (F2019 to 2021) is continued.

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

β	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2043	2053
1.0	0	100	99	76	58	51	47	46	45	45	45	46	45	45	45
0.9	0	100	99	83	69	64	61	61	59	59	59	60	60	59	59
0.8	0	100	99	89	80	76	74	74	73	73	74	74	73	73	73
0.7	0	100	99	93	88	86	86	85	85	85	85	85	85	84	85
0.6	0	100	99	96	94	93	93	93	93	93	93	93	93	93	93
0.5	0	100	99	98	98	97	98	97	97	98	98	98	97	97	97
0.4	0	100	99	99	99	99	99	99	99	99	99	99	99	99	99
0.3	0	100	99	100	100	100	100	100	100	100	100	100	100	100	100
0.2	0	100	99	100	100	100	100	100	100	100	100	100	100	100	100
0.1	0	100	99	100	100	100	100	100	100	100	100	100	100	100	100
0.0	0	100	99	100	100	100	100	100	100	100	100	100	100	100	100
F2019-2021	0	100	99	64	41	32	29	28	27	26	27	27	27	26	27

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

β	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2043	2053
1.0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.9	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.8	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.7	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.6	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.5	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.4	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.3	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.2	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
F2019-2021	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

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Supplementary Table 4-2. Trends in future average SSB and catch in weight

Values in bold indicate values in the target year, which is 10 years after starting management based on proposed HCRs. These tables show results with β varied from 0.0 to 1.0 in 2023 and onwards, and future projections if the current fishing pressure (F2019 to 2021) is continued.

a) Trends in average SSB (thousand tons)

β	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2043	2053
1.0	79	156	191	138	122	117	115	114	113	113	113	113	113	113	113
0.9	79	156	191	146	132	128	126	125	124	124	124	124	124	124	124
0.8	79	156	191	155	143	139	137	137	136	136	136	136	137	136	136
0.7	79	156	191	165	155	152	151	150	150	150	150	150	150	149	149
0.6	79	156	191	175	169	167	166	166	165	165	166	165	166	165	165
0.5	79	156	191	187	184	184	183	183	183	183	183	183	183	182	183
0.4	79	156	191	199	201	203	203	203	203	203	203	203	204	202	203
0.3	79	156	191	213	221	225	226	227	226	226	227	227	227	226	226
0.2	79	156	191	228	243	250	252	254	253	253	254	254	254	253	253
0.1	79	156	191	244	269	280	284	285	285	285	286	286	286	284	285
0.0	79	156	191	262	299	314	320	322	322	322	323	323	324	322	323
F2019-2021	79	156	191	127	109	103	101	99	99	98	99	98	99	98	98

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b) Trends in average catch (thousand tons)

β	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2043	2053
1.0	40	45	116	93	85	83	82	81	81	81	81	81	81	80	80
0.9	40	45	109	90	84	82	81	81	80	80	80	80	80	80	80
0.8	40	45	101	87	82	81	80	79	79	79	79	79	79	79	79
0.7	40	45	92	83	79	78	78	77	77	77	77	77	77	77	77
0.6	40	45	82	77	75	75	74	74	74	74	74	74	74	74	74
0.5	40	45	72	70	70	70	70	69	69	69	69	69	69	69	69
0.4	40	45	60	62	62	63	63	63	63	63	63	63	63	63	63
0.3	40	45	47	51	53	53	53	53	53	53	54	54	54	53	53
0.2	40	45	33	38	40	40	41	41	41	41	41	41	41	41	41
0.1	40	45	17	21	22	23	23	23	23	23	24	24	24	23	23
0.0	40	45	0	0	0	0	0	0	0	0	0	0	0	0	0
F2019-2021	40	45	126	95	86	83	81	81	80	80	80	80	80	80	80

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Appendix 5 Future Projection Methods

Future projections were performed based on proposed HCRs using the SSB estimates. The values used for recruitment volume projections for 2022 and onwards were values estimated using the Beverton-Holt model for relationships ($a = 1.039$, $b = 1.843e-05$, $SD = 0.288$) proposed at the Research Institute Meeting held in September 2021 (Kinoshita et al. 2021b). The data used to estimate the parameters of the stock-recruitment relationship was SSB and recruitment volume in normal recruitment periods based on the FY 2020 stock assessment (Kinoshita et al. 2021a), and the optimization method was the least squares method. In addition, autocorrelation was not considered regarding residuals in recruitment.

The fishing mortality F used in the future projections were values estimated based on control rules for Stock Group 1 according to Basic Guidelines for Harvest Control Rules and ABC Calculation at FY 2022 (FRA-SA2022-ABCWG02-01). We used the same values for selectivity and average body weight in catches as were used to estimate the various proposed reference points which were proposed at the Research Institute Meeting (Supplementary Table 5-1). These values are based on the FY 2020 stock assessment, same as for the stock-recruitment relationship.

Fishing pressure in 2022 (F2022) was assumed to be the value that makes catch in 2022 equal to 44,700 tons, which was the average catch of the most recent 5-year period (2017 to 2021). We believe that average catch from 2017 to 2021 is an appropriate assumption because if current fishing pressure (F2019 to 2021) is assumed for F in 2022, then catch in 2022 would be 110,000 tons, and this does not align with landings at major ports in the Pacific block in recent months up to June 2022 (about the same as in 2021, and somewhat lower than the average from 2017 to 2021).

Projections for stock population were made using progression method cohort analysis.

$$N_{a+1,t+1} = N_{a,t} \exp(-F_{a,t} - M_a) \quad (a = 0, 1, 2) \quad (8)$$

Catch in number was determined using the equation below (9) with catch in number results from the equation above (8) and F value assumptions based on each catch strategy.

$$C_{a,t} = N_{a,t} \{1 - \exp(-F_{a,t})\} \exp\left(-\frac{M_a}{2}\right) \quad (a = 0, 1, 2, 3) \quad (9)$$

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

	Selectivity (Note 1)	Fmsy (Note 2)	F2019 to 2021 (Note 3)	Average weight (g)	Natural mortality	Maturity rate
Age 0	0.27	0.38	0.13	4.7	1.0	0.0
Age 1	0.89	1.23	0.42	10.0	1.0	1.0
Age 2	1.00	1.39	0.47	17.8	1.6	1.0
Age 3	1.00	1.39	0.47	23.6	1.9	1.0

Note 1: Selectivity used to estimate the level required for MSY at the FY 2021 Research Institute Meeting (i.e., selectivity of $F_{current}$ in the FY2020 stock assessment)

Note 2: Fmsy estimated at the FY 2021 Research Institute Meeting (i.e., $F_{msy}/F_{current}$ multiplied by $F_{current}$ in the FY2020 stock assessment)

Note 3: F was assumed to be the value that makes catch in 2022 equal to the average catch of the most recent 5-year period (44,700 tons from 2017 to 2021) based on the abundance (biomass) in 2021 as estimated in this stock assessment, under the selectivity described above

References

Kinoshita, J., Kamimura, Y., Yasuda, T. (2021a) Stock Assessment for Pacific Stock of Japanese Anchovy (Fiscal Year 2020). FRA-SA2020-RC02-1. Marine fisheries stock assessment and evaluation for Japanese waters (Fiscal Year 2020), Japan Fisheries Research and Education Agency, Fisheries Agency (in Japanese)

Kinoshita, J., Yasuda, T., Watanabe, C., Kamimura, Y. (2021b) Materials for the Research Institute Meeting on Reference Points of Pacific stock of Japanese anchovy (FY 2021). FRA-SA2021-BRP03-1 (in Japanese)

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
Beverton-Holt	Least squares method	No	1.039	1.843×10^{-5}	0.288	-

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)	112,000 tons	A proposed target reference point. SSB required for MSY (SBmsy)
SBlimit (proposed)	28,000 tons	A proposed limit reference point. SSB required for catch of 60% of MSY (SB0.6msy)
SBban (proposed)	3,000 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 0, Age 1, Age 2, Age 3) = (0.38, 1.23, 1.39, 1.39)	
%SPR (Fmsy)	45%	%SPR corresponding to Fmsy
MSY	81,000 tons	Maximum Sustainable Yield

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

Item	Value	Description
SB2021	79,000 tons	SSB in 2021
F2021	Fishing pressure in 2021 (fishing mortality F) (Age 0, Age 1, Age 2, Age 3) = (0.31, 0.36, 0.14, 0.14)	
U2021	16%	Exploitation rate in 2021
%SPR (F2021)	60.4%	%SPR in 2021
%SPR (F2019 to 2021)	40.9%	%SPR corresponding to current fishing pressure (2019 to 2021 fishing seasons)*
Compared against proposed reference points		
SB2021 / SB _{msy} (SB _{target})	0.71	B ratio required for MSY (proposed target reference point) to SSB in 2021 fishing season
F2021 / F _{msy}	0.62	F ratio required for MSY to fishing pressure in 2021*
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 F converted to %SPR, which gives the fishing pressure of F_{msy} under the selectivity of 2021

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

SSB in 2023 (average projected value): 191,000 tons			
Item	Catch (thousand tons) in 2023	Ratio to current fishing pressure (F/F2019 to 2021)	Exploitation rate in 2023 (%)
$\beta = 1.0$	116	0.87	29
$\beta = 0.8$	101	0.69	26
$\beta = 0.6$	82	0.52	21
$\beta = 0.4$	60	0.35	15
$\beta = 0.2$	33	0.17	8
$\beta = 0$	0	0	0
F2019 to 2021	126	1.00	32

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

Uncertainty under consideration: recruitment					
β	SSB in 2033 (thousand tons)	90% prediction interval (thousand tons)	Probability (%) that SSB will exceed the following proposed reference points in 2033		
			SBtarget (proposed)	SBlimit (proposed)	SBban (proposed)
$\beta = 1.0$	113	70 – 171	45	100	100
$\beta = 0.8$	137	87 – 203	73	100	100
$\beta = 0.6$	166	108 – 242	93	100	100
$\beta = 0.4$	204	137 – 292	99	100	100
$\beta = 0.2$	254	175 – 356	100	100	100
$\beta = 0$	324	228 – 444	100	100	100
F2019 to 2021	99	60 – 151	27	100	100

Appendix 7 Summary of R/V Survey Results

Abundance Survey

Surveys on eggs, juveniles, and plankton were conducted by experimental stations and research institutes in prefectures along the coast year-round, and by the Japan Fisheries Research and Education Agency in February to March (Kuroshio region) and May to June (Kuroshio-Oyashio transition region). Samples were vertically hauled using improved NORPAC nets (mouth 45 cm wide, cylindrical-conical shape, mesh size 0.335 mm), and the obtained data was input into the Fishery Resource Conversation (FRESCO) system. Based on this data, egg distribution density was found for each collection site according to egg collection volume, cable length, cable tilt angle, water filter rotation speed, and water temperature, and monthly egg production was calculated by stretching results according to the surface area of each ocean region (Mori et al. 1988, Kikuchi and Konishi 1990, Ishida and Kikuchi 1992, Zenitani et al. 1995, Kubota et al. 1999).

SSB was calculated by applying an egg production method, which considers water temperature and gonadal weight index, to egg production calculated according to surveys on eggs, juveniles, and plankton. Because Takasuka et al. (2005) were able to clearly distinguish between the spawning ecology of coastal spawning stock and offshore spawning stock, we calculated SSB by ocean area, assuming Area I to be offshore spawning stock, and Area II to IV to be coastal spawning stock. The estimated SSB for each year was set as the total SSB in the month with the highest levels (Supplementary Table 7-1, Supplementary Fig. 7-3). Water temperatures by month and by ocean area are the temperatures weighted by egg count found from ocean observation results at the time of surveys on eggs, juveniles, and plankton. Gonadal weight index was the average value in individuals 8 cm or more in length, based on precision measurement results by month and by ocean area.

$$\text{Monthly SSB} = (\text{monthly egg production} / \text{batch fecundity per 1 g}) \times \text{spawning interval} / \text{number of days in the month} / \text{percentage of females}$$

Sex ratio = 1:1, batch fecundity = number of eggs laid per spawning per 1 individual female

Offshore area (Area I, Water temperature range: 8.0 to 20.2°C):

$$\text{Batch fecundity per 1 g} = -30.4 + 11.7 \times \text{water temperature} + 23.5 \times \text{gonadal weight index}$$

$$\text{Spawning interval} = 5.30 - 0.182 \times \text{water temperature}$$

Coastal area (Area II to IV, Water temperature range: 15.0 to 26.7°C)

$$\text{Batch fecundity per 1 g} = -338.7 + 27.4 \times \text{water temperature} + 87.3 \times \text{gonadal weight index}$$

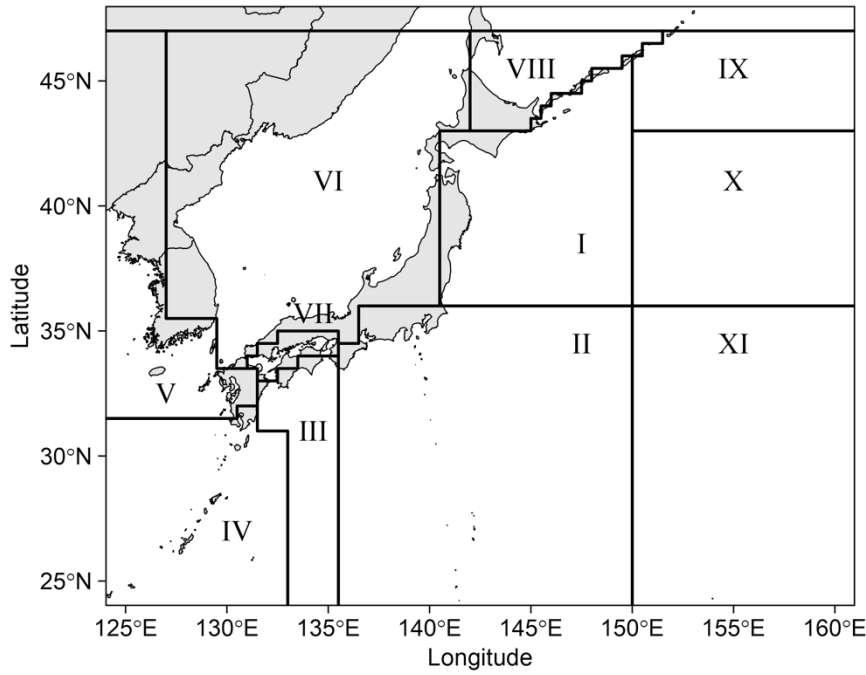
$$\text{Spawning interval} = 7.65 - 0.234 \times \text{water temperature}$$

The Northward season surveys (a combination of surveys on the western North Pacific stock of Pacific saury and the Northwestern Pacific Ocean Northward Migration Season Pelagic Fish Stock Surveys) estimated the distribution volume of Japanese anchovy based on the results of catch surveys performed by the Japan Fisheries Research and Education Agency in May to July since 2001 in the Kuroshio-Oyashio transition region to the Oyashio region using midwater trawl nets (mouth 30 m wide, codend mesh size 17 mm). Average CPUE of Japanese anchovy at all measurement sites are

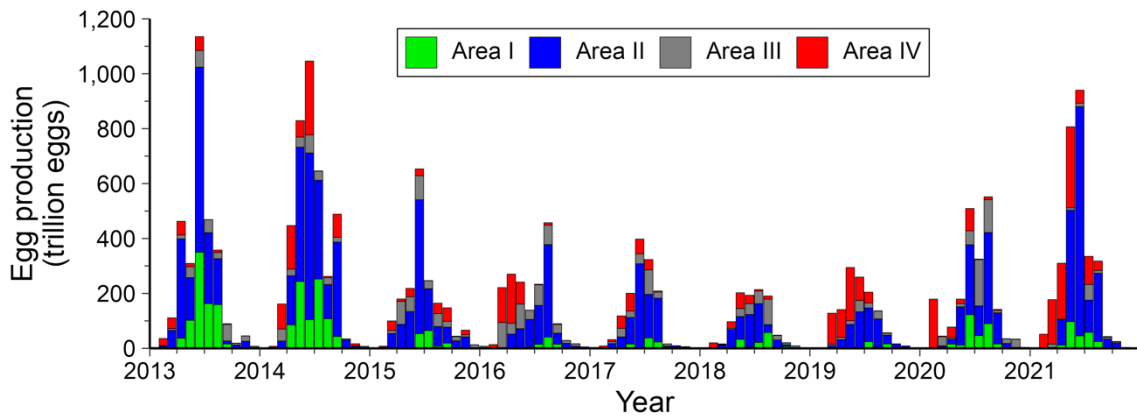
shown in Supplementary Fig. 7-4 and Supplementary Table 7-1, and the percentage of sites with Japanese anchovy in annual surveys is shown in Supplementary Fig. 7-5.

References

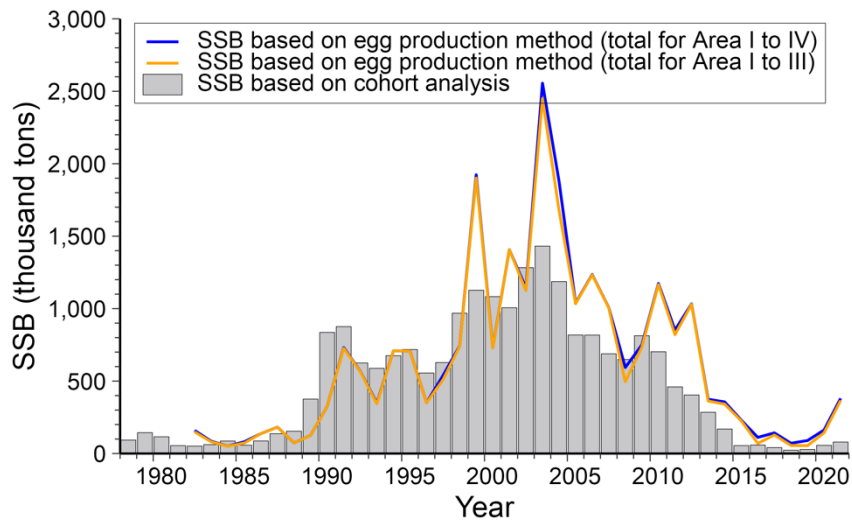
- Ishida, M. and Kikuchi, H. (1992) Spawning status of Japanese pilchard, Japanese anchovy and mackerel species by month and area along the Pacific coast of Japan (ocean regions between Joban and Satsunan (South Kagoshima)): January 1989 to December 1990. Nansei National Fisheries Research Institute and National Fisheries Research Institute, 86 pp. (in Japanese)
- Kikuchi, H. and Konishi, Y. (1990) Spawning status of Japanese pilchard, Japanese anchovy and mackerel species by month and area along the Pacific coast of Japan (ocean regions between Joban and Satsunan (South Kagoshima)): January 1987 to December 1988. Central Fisheries Research Institute (Former Tokai Regional Fisheries Research Laboratory) and Nansei National Fisheries Research Institute, 72 pp. (in Japanese)
- Kubota, H., Oozeki, Y., Ishida, M., Konishi, Y., Goto, T., Zenitani, H. and Kimura, R. (1999) Distribution status by month of eggs and juveniles of Japanese pilchard, Japanese anchovy, mackerel species, red-eyed round herring, and Japanese jack mackerel, and larva of Japanese common squid, in ocean regions surrounding Japan: January 1994 to December 1996. National Research Institute of Fisheries Science, 352 pp. (in Japanese)
- Mori K., Kuroda K., and Konishi Y. (1988) Spawning status of Japanese pilchard, Japanese anchovy and mackerel species by month and area along the Pacific coast of Japan (ocean regions between Joban and Satsunan (South Kagoshima)): January 1978 to December 1986. Tokai Fisheries Research Institute, 321 pp. (in Japanese)
- Takasuka, A., Y. Oozeki, H. Kubota, Y. Tsuruta and T. Funamoto (2005) Temperature impacts on reproductive parameters for Japanese anchovy: Comparison between inshore and offshore waters. *Fish. Res.*, **76**, 475-482.
- Zenitani, H., Ishida, M., Konishi, Y., Goto, T., Watanabe, Y., Kimura, R. (1995) Distribution status by month of eggs and juveniles of Japanese pilchard, Japanese anchovy, mackerel species, red-eyed round herring, and Japanese jack mackerel, and larva of Japanese common squid, in ocean regions surrounding Japan: January 1991 to December 1993. National Research Institute of Fisheries Science, 368 pp. (in Japanese)



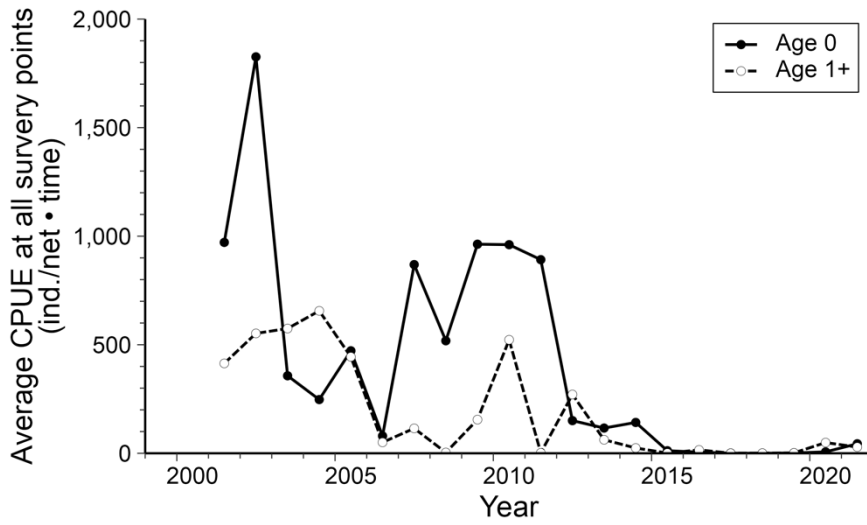
Supplementary Fig. 7-1. Ocean areas in surveys on eggs, juveniles, and plankton



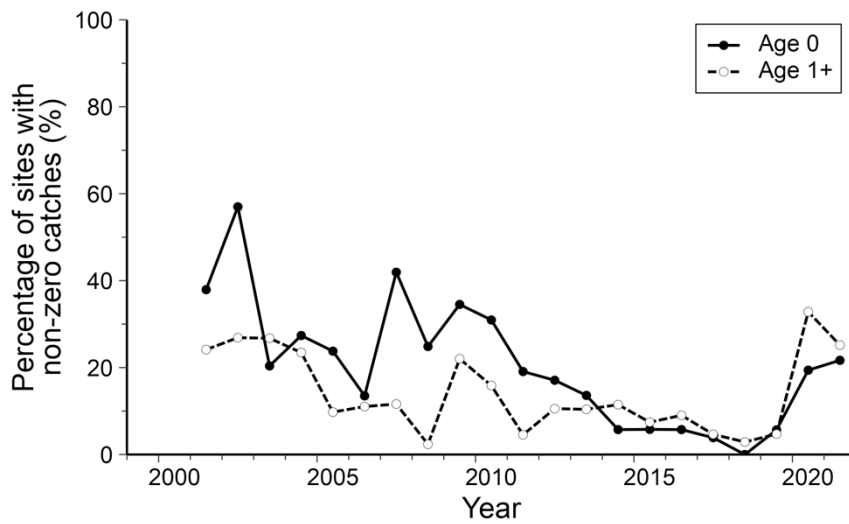
Supplementary Fig. 7-2. Egg production of Japanese anchovy by area and by month since 2013



Supplementary Fig. 7-3. SSB based on egg production method and SSB based on cohort analysis



Supplementary Fig. 7-4. Average CPUE of fish age 0 and fish age 1 and older at all measurement sites from the Northward season surveys



Supplementary Fig. 7-5. Percentage of sites with fish age 0 and fish age 1 and older from the Northward season surveys

Supplementary Table 7-1. Egg production in surveys on eggs, juveniles, and plankton, estimated SSB according to the egg production method, and average CPUE at all measurement sites from the Northward season surveys

Year	Egg production and estimated SSB based on egg production method			Average CPUE at all survey points from the Northward season surveys	
	Egg production (trillion eggs) Area I to IV	SSB (thousand tons) Area I to IV	SSB (thousand tons) Area I to III	Age 0 fish (ind./net)	Age 1+ (ind./net)
1982	1,081.6	159.6	149.4		
1983	958.5	84.9	80.6		
1984	745.7	51.1	50.6		
1985	1,116.1	81.3	72.5		
1986	1,498.7	137.4	137.3		
1987	1,627.5	182.2	182.2		
1988	852.7	73.5	73.4		
1989	1,016.6	125.6	125.3		
1990	2,826.9	324.9	324.8		
1991	7,214.6	731.1	725.9		
1992	5,924.7	567.8	565.9		
1993	3,122.7	349.1	342.8		
1994	4,644.0	708.6	708.5		
1995	3,988.2	707.9	707.2		
1996	3,282.1	350.9	350.0		
1997	4,704.2	539.6	510.1		
1998	5,797.1	742.5	739.6		
1999	15,622.5	1,923.9	1,901.1		
2000	10,581.9	732.1	727.2		
2001	6,749.7	1,407.0	1,407.0	971.40	413.99
2002	10,642.6	1,142.7	1,124.0	1,826.03	552.08
2003	13,134.1	2,555.8	2,449.6	356.99	574.68
2004	14,313.2	1,878.4	1,678.1	247.45	655.99
2005	9,882.0	1,037.9	1,033.8	472.02	444.22
2006	9,579.4	1,235.9	1,232.9	79.77	50.33
2007	10,909.2	1,007.6	1,005.4	869.07	114.69
2008	4,427.1	594.0	495.8	518.32	3.62
2009	9,246.3	749.8	735.0	962.97	154.96
2010	8,296.7	1,173.5	1,166.3	960.82	522.74
2011	7,042.0	852.3	819.9	891.80	1.98
2012	9,518.2	1,033.0	1,030.1	150.38	270.81
2013	3,045.7	374.7	362.6	116.13	62.19
2014	3,948.6	356.2	340.5	142.02	24.34
2015	1,842.1	230.5	225.5	11.73	0.83
2016	1,725.0	111.4	70.1	5.32	15.48
2017	1,325.9	142.6	127.7	0.45	0.41
2018	1,014.1	71.1	55.7	0.06	0.74
2019	1,249.4	89.7	54.3	1.46	1.87
2020	2,081.9	162.4	143.2	6.41	49.21
2021	3,014.1	380.9	366.0	43.79	28.54
CV	0.80	0.92	0.92	1.20	1.24

Supplementary Table 7-2. Estimated SSB by ocean area according to the egg production method and summary of biological parameters used for estimation

This table shows a yearly summary of monthly data that was published in stock assessment reports up to FY 2021.

Year	Egg production (trillion eggs)				SSB based on egg production method (thousand tons)				Annual highs on GSI			
	I	II	III	IV	I	II	III	IV	I	II	III	IV
1982	186.4	556.6	135.6	202.9	76.2	69.0	9.6	16.8	4.0	4.0	4.0	4.0
1983	5.6	650.4	175.9	126.6	2.6	69.1	15.8	23.5	4.0	4.0	4.0	4.0
1984	11.9	590.3	123.9	19.7	1.7	47.8	7.3	3.0	4.0	4.0	4.0	4.0
1985	19.4	840.1	122.2	134.4	7.4	61.6	4.2	8.8	4.0	4.0	4.0	4.0
1986	3.3	1,295.5	151.6	48.2	1.9	125.6	12.7	5.2	4.0	4.0	4.0	4.0
1987	110.9	1,431.9	27.6	57.1	12.5	169.3	1.8	10.0	4.0	4.0	4.0	4.0
1988	232.9	541.3	39.3	39.3	48.3	61.4	2.3	3.5	4.0	4.0	4.0	4.0
1989	161.4	788.3	41.2	25.6	52.4	119.2	1.8	5.5	4.0	4.0	4.0	4.0
1990	525.9	2,148.6	143.5	8.9	125.2	190.5	11.6	1.1	4.0	4.0	4.0	4.0
1991	2,478.6	4,178.8	192.3	365.0	460.3	258.0	15.0	80.0	4.0	4.0	4.0	4.0
1992	1,100.3	3,977.8	517.8	328.7	315.6	313.1	61.7	45.1	4.0	4.0	4.0	4.0
1993	275.7	2,198.0	476.4	172.7	95.0	315.3	52.3	51.0	4.0	4.0	4.0	4.0
1994	595.2	3,711.7	123.9	213.2	162.2	567.1	9.4	56.0	4.0	4.0	4.0	4.0
1995	858.1	2,885.8	235.2	9.2	314.2	386.0	22.1	1.0	4.0	4.0	4.0	4.0
1996	106.6	2,354.9	431.7	388.9	28.6	315.4	67.6	96.2	4.0	4.0	4.0	4.0
1997	891.1	3,158.8	267.4	386.8	211.4	285.6	23.3	58.8	4.0	4.0	4.0	4.0
1998	1,232.2	4,185.0	288.8	91.1	241.7	483.0	28.3	16.4	4.3	4.7	4.7	4.7
1999	5,201.1	7,655.3	1,818.2	948.0	1,400.8	644.9	208.5	106.4	3.1	4.8	4.8	4.8
2000	2,825.3	6,029.8	1,382.6	344.2	525.2	448.0	100.6	29.6	5.5	5.9	5.9	5.9
2001	4,544.3	2,002.8	201.6	1.0	1,197.7	207.4	23.9	0.1	6.2	6.1	6.1	6.1
2002	3,074.0	6,423.7	458.9	685.9	787.3	423.6	43.0	61.3	6.9	4.5	4.5	4.5
2003	3,693.6	6,490.9	1,819.3	1,130.3	1,448.5	848.3	406.6	207.9	4.6	3.8	3.8	3.8
2004	2,459.1	7,757.0	2,665.9	1,431.1	816.3	746.7	578.0	200.3	4.8	4.5	4.5	4.5
2005	1,283.7	5,448.6	2,193.0	956.7	221.4	760.9	294.0	174.7	8.6	4.2	5.2	5.2
2006	4,151.4	4,936.3	283.9	207.8	699.9	520.2	43.5	32.6	6.0	5.0	5.0	5.0
2007	2,907.7	4,991.6	622.3	2,387.5	378.6	605.3	33.1	348.2	6.8	4.7	4.7	4.7
2008	1,149.6	2,159.6	272.4	845.5	199.5	279.0	31.6	98.2	7.3	5.2	5.2	5.2
2009	2,448.2	4,985.4	1,482.3	330.3	297.4	479.7	135.6	32.2	5.6	4.7	4.7	4.7
2010	3,014.0	4,262.6	891.1	128.9	469.2	650.4	69.3	11.3	5.6	5.0	5.0	5.0
2011	2,059.1	3,929.7	259.3	793.9	441.2	375.1	31.5	70.5	5.3	5.2	5.2	5.2
2012	3,076.6	5,827.8	521.3	92.4	455.2	774.1	26.8	44.3	4.7	4.3	4.3	4.3
2013	832.8	1,737.4	285.9	189.6	154.1	194.7	13.8	23.2	6.3	5.0	5.0	5.0
2014	841.8	2,162.9	262.5	681.4	136.7	198.5	21.3	73.8	5.2	4.9	4.9	4.9
2015	151.3	1,112.4	370.7	207.7	28.3	171.5	33.0	21.1	5.9	4.6	4.6	4.6
2016	79.4	768.0	465.3	412.3	10.6	52.3	48.5	62.0	6.0	4.9	4.9	4.9
2017	90.3	791.1	222.3	222.2	9.1	115.3	19.2	22.0	6.2	5.0	5.0	5.0
2018	133.2	482.3	245.5	153.2	17.2	41.3	10.9	19.5	4.9	5.4	5.4	5.4
2019	55.6	532.8	125.7	535.4	7.0	42.2	10.4	52.5	5.6	4.7	4.7	4.7
2020	312.8	986.5	448.8	333.8	49.2	81.2	37.0	68.0	5.4	4.3	4.3	4.3
2021	244.0	1,750.5	118.5	901.1	46.6	340.0	10.1	79.1	5.4	5.1	5.1	5.1
CV	1.10	0.73	1.21	1.15	1.26	0.74	1.80	1.20	0.24	0.13	0.13	0.13

Supplementary Table 7-2. (continued)

Year	Annual mean of batch fecundity (eggs / g BW)				Annual mean of spawning interval (days)				Annual mean of weighted water temperature (°C)				Annual mean of GSI			
	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
1982	264.2	553.1	589.5	612.4	3.7	3.1	2.7	3.8	17.5	19.6	21.1	22.0	4.0	4.0	4.0	4.0
1983	259.7	565.0	588.1	590.8	4.5	3.3	2.7	3.9	16.8	20.3	21.1	21.3	4.0	4.0	4.0	4.0
1984	289.8	563.3	589.8	621.3	3.7	3.4	2.7	4.2	21.0	19.9	21.3	22.3	4.0	4.0	4.0	4.0
1985	285.7	570.0	605.5	620.3	4.4	3.3	3.0	3.3	20.1	20.4	21.8	22.4	4.0	4.0	4.0	4.0
1986	272.5	565.0	589.1	609.0	4.8	3.3	2.7	4.7	17.9	20.3	21.2	22.1	4.0	4.0	4.0	4.0
1987	287.4	563.9	583.9	570.8	3.8	3.3	2.8	5.3	19.8	20.2	21.0	20.5	4.0	4.0	4.0	4.0
1988	283.3	564.3	591.3	589.8	3.2	2.9	2.7	3.5	20.0	20.2	21.3	21.2	4.0	4.0	4.0	4.0
1989	279.3	544.8	603.3	574.1	3.0	3.1	2.6	4.1	18.9	19.5	21.7	20.6	4.0	4.0	4.0	4.0
1990	273.0	573.4	586.5	619.4	3.6	2.8	3.1	4.6	19.1	20.6	21.1	22.4	4.0	4.0	4.0	4.0
1991	282.3	556.3	591.8	593.4	2.9	3.5	2.7	3.5	19.6	19.6	21.3	21.4	4.0	4.0	4.0	4.0
1992	267.1	560.7	608.6	601.6	3.2	3.0	2.5	3.0	17.5	20.1	21.9	21.6	4.0	4.0	4.0	4.0
1993	262.7	540.6	593.1	562.9	3.7	3.1	2.7	4.1	17.2	19.4	21.3	20.2	4.0	4.0	4.0	4.0
1994	273.0	569.9	629.3	531.0	3.3	2.9	3.2	5.8	19.1	20.5	22.9	19.0	4.0	4.0	4.0	4.0
1995	277.1	549.4	616.3	590.1	3.0	3.1	2.9	3.9	19.1	19.6	22.1	21.2	4.0	4.0	4.0	4.0
1996	262.9	545.0	596.4	605.0	3.5	3.5	2.6	3.0	17.5	19.5	21.5	21.8	4.0	4.0	4.0	4.0
1997	266.6	564.2	612.5	586.8	3.1	3.3	2.9	3.6	18.2	20.2	22.2	21.1	4.0	4.0	4.0	4.0
1998	218.2	520.7	572.6	560.3	2.9	3.1	2.3	3.4	18.0	21.1	23.0	22.1	2.4	3.3	3.3	3.3
1999	231.9	482.9	506.8	510.8	2.4	2.7	2.5	2.4	19.2	21.3	22.3	22.3	1.8	2.7	2.7	2.7
2000	240.4	528.0	548.2	601.5	2.6	2.8	2.6	3.2	17.7	20.9	21.7	22.6	2.7	3.4	3.4	3.4
2001	257.3	442.8	548.8	491.3	2.8	2.9	3.7	6.1	18.2	20.2	22.8	20.8	2.7	2.6	2.6	2.6
2002	264.7	527.6	562.9	578.8	3.3	3.6	2.9	3.7	19.0	20.7	22.2	22.9	2.7	3.2	3.2	3.2
2003	243.7	492.3	545.2	544.8	2.9	2.9	2.4	2.4	17.9	20.2	22.4	22.4	2.4	3.2	3.2	3.2
2004	242.0	498.2	529.6	554.3	3.3	2.8	2.5	3.7	18.6	20.8	22.0	22.5	1.9	3.1	3.1	3.1
2005	259.5	458.0	510.3	524.3	3.1	3.3	2.6	3.3	18.3	20.3	21.8	22.2	2.8	2.8	2.9	2.9
2006	251.0	483.8	523.9	531.3	3.3	3.4	2.5	4.2	19.3	20.0	22.1	22.6	2.0	3.0	3.0	3.0
2007	247.3	482.7	521.5	540.9	2.5	3.2	2.4	3.2	18.8	20.6	22.4	22.9	2.6	2.9	2.9	2.9
2008	260.7	444.5	494.8	521.3	2.8	3.4	2.4	3.3	19.0	19.8	22.4	22.6	2.9	2.6	2.6	2.6
2009	258.3	475.0	519.7	521.8	3.3	2.9	2.5	2.9	18.8	20.3	22.1	22.3	2.3	3.0	3.0	3.0
2010	268.4	472.5	535.2	576.4	3.0	3.0	2.4	3.7	19.2	20.1	22.7	22.6	3.0	3.0	3.0	3.0
2011	266.8	470.6	498.7	521.9	3.0	3.3	2.5	2.9	18.8	20.1	21.8	22.3	2.9	2.8	2.8	2.8
2012	241.8	505.1	516.0	539.7	2.8	3.2	2.5	3.3	18.6	20.8	21.9	22.5	2.3	3.0	3.0	3.0
2013	251.0	467.8	479.3	505.6	2.9	3.2	2.6	3.7	17.8	20.7	21.6	22.6	3.0	2.6	2.6	2.6
2014	251.9	441.1	480.5	515.7	2.7	3.4	2.6	2.8	19.1	19.8	21.7	22.8	2.4	2.6	2.6	2.6
2015	251.0	438.8	459.5	483.6	3.3	3.3	2.6	2.8	18.9	20.5	21.8	22.4	2.1	2.3	2.3	2.3
2016	262.7	482.8	520.1	559.1	3.1	3.1	2.4	4.0	20.7	21.1	22.7	23.4	2.6	2.8	2.8	2.8
2017	245.3	440.6	477.1	502.4	2.3	3.3	2.5	3.3	17.9	20.2	22.0	22.2	2.9	2.5	2.5	2.5
2018	261.4	528.9	499.3	520.1	2.6	3.5	2.7	2.9	20.3	21.3	21.4	22.4	2.5	2.9	2.9	2.9
2019	261.7	519.3	529.8	575.9	3.2	3.1	2.4	3.7	20.4	21.1	22.3	22.6	2.4	3.1	3.1	3.1
2020	252.2	506.0	498.3	523.3	2.8	3.5	2.5	2.8	18.9	21.5	22.0	22.7	2.5	2.7	2.7	2.7
2021	260.9	458.1	493.1	510.9	2.9	2.8	2.5	2.3	19.8	20.9	22.2	23.0	2.4	2.6	2.6	2.6
CV	0.06	0.09	0.09	0.07	0.17	0.08	0.10	0.23	0.05	0.03	0.02	0.04	0.25	0.18	0.18	0.18

Appendix 8 Tuning Period and Terminal F Estimation Method for tuned VPAs

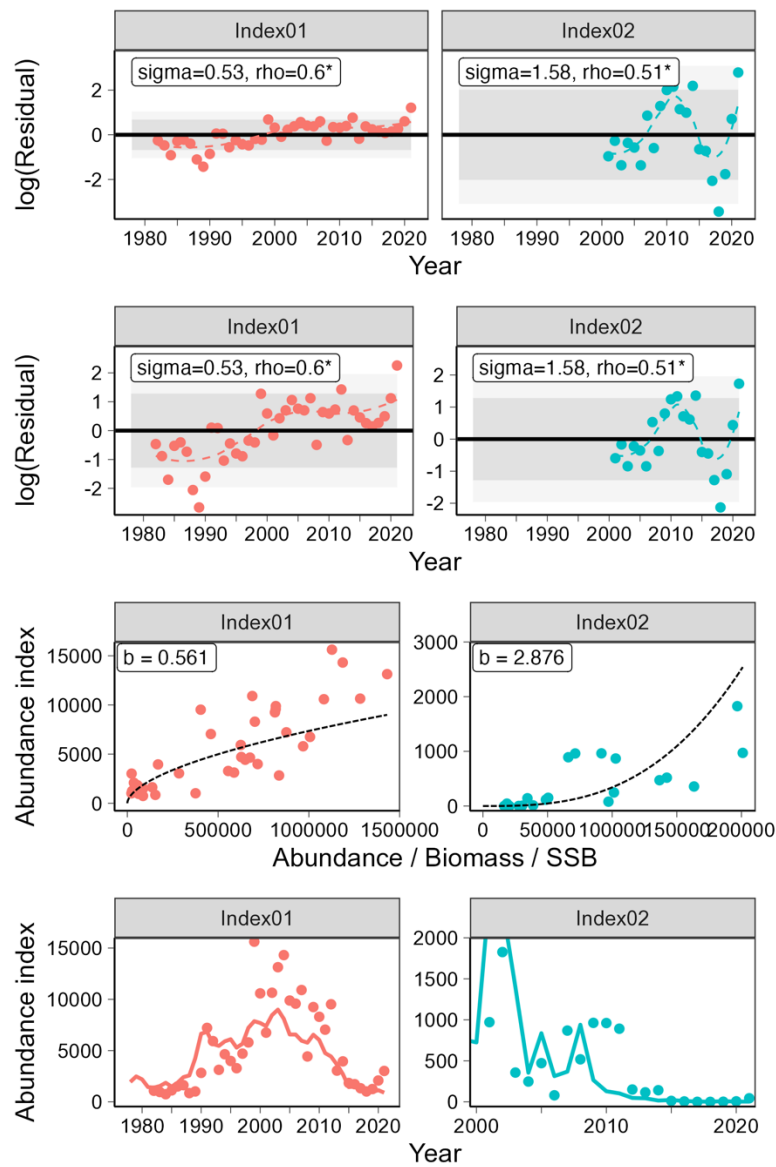
For Tuned VPA, the tuning period was set as the normal recruitment period since 2010, and the terminal F estimation method was the all F estimation method. However, investigations were also made for a tuning period scenario which used all available data starting from 1982 (egg production) and 2001 (age 0 CPUE from the Northward season surveys), and for a scenario which used a two-step selectivity method for the estimation method.

Results for Mohn's ρ in the tuning period scenario which used all available data starting from 1982 (egg production) and 2001 (age 0 CPUE from the Northward season surveys), and for the scenario which used data starting from 2010, are shown in Supplementary Table 8-1. When data from all available years was included, only one model ($\lambda = 0.9999$) showed a retrospective bias within $\pm 20\%$ ($\rho = \pm 0.2$) for all five items, which are averages of abundance (biomass), stock population, recruitment volume, SSB, and fishing mortality. In addition, this model showed significant first-order autocorrelation in residuals (Supplementary Fig. 8-1). Therefore, we believe that the normal recruitment period since 2010 is an appropriate tuning period.

Results for Mohn's ρ when the tuning period scenario was set as the normal recruitment period since 2010, and for a scenario which used a two-step selectivity method for the terminal F estimation method, are shown in Supplementary Table 8-2. When a two-step selectivity method was used, all models except one ($\lambda = 0.0$) showed a retrospective bias within $\pm 20\%$ ($\rho = \pm 0.2$) for all five items, which are averages of abundance (biomass), stock population, recruitment volume, SSB, and fishing mortality. In this scenario, the models with $\lambda = 0.9999$ and 0.9 produced extremely low values for the total of absolute values of Mohn's ρ , and the abundance estimation results of these models were similar to estimation results from VPA without tuning. Models with $\lambda = 0.1$ to 0.8 all showed similar results for abundance estimates, and that estimated SSB in 2021 was similar to 2020. We noted that although egg production in research vessel surveys has increased from 2020 to 2021, the estimated number of eggs per batch (Appendix 7) based on GSI and water temperature has not increased much (Supplementary Table 7-2). Accordingly, we judged that it was more appropriate to use the all F estimation method ($\lambda = 0.66$), which gives a higher value for SSB in 2021 than 2020, than the two-step selectivity method. However, the Tuned VPA for this stock needs additional consideration of tuning methods in addition to exploration and standardization of abundance indices.

When we applied the two-step method, we used the same equation (5) for minimizing the function as the all F estimation method.

Selectivity was the average values of fishing mortality estimated using VPA without tuning (Age 0, Age 1, Age 2, Age 3) = (0.39, 1, 0.88, 0.88) for the most recent 3-year period (2019 to 2021).



Supplementary Fig. 8-1. Residual plots for scenario titled “spawning-volume&northward-age0-allyears-allF- λ 0.9999” in Supplementary Table 8-1

Top row: Time series plot of log residuals of abundance indices and projected values

2nd row: Time series plot of standardized log residuals of abundance indices and projected values

3rd row: Regression relationship of abundance indices and projected values

Bottom row: Time series plot of observed (circles) and predicted (line) abundance indices

Index values (index 01: egg production, index 02: estimated age 0 CPUE from the Northward season surveys)

In the top row, sigma is the observation error, and rho is the first-order autocorrelation coefficient (marked with an asterisk * if significant at 5% probability), the dark gray area indicates 80% of the range of observed values (1.28σ), and the light gray area indicates 95% of the range (1.96σ). In the 3rd row panels, b is the nonlinear coefficient between the observed and predicted values of abundance indices.

Supplementary Table 8-1. List of retrospective bias values (Mohn's ρ) when tuning period and λ are varied while tuning the all F estimation method

The scenario titled Plain indicates VPA without tuning. Titles including allF indicate that Tuned VPA was the all-age terminal F estimation method. Green cells indicate scenarios where the absolute value of Mohn's ρ is less than 0.2, and green titles indicate scenarios where Mohn's ρ is less than 0.2 for all five index values.

Scenario name	Initial value	Mohn's ρ (5-year retrospective)					Sum of absolute values
		Biomass	Numbers	Recruitment	SSB	Fishing mortality	
1 Plain	1	0.025	0.022	0.014	0.054	-0.069	0.184
2 AEP&NSage0-2010-allF- λ 0	0.316, 0.365, 0.343	-0.151	-0.161	-0.174	-0.087	1.1E+42	1.1E+42
3 AEP&NSage0-2010-allF- λ 0.1	1	-0.044	-0.085	-0.106	0.105	0.191	0.531
4 AEP&NSage0-2010-allF- λ 0.2	1	-0.042	-0.083	-0.104	0.104	0.195	0.528
5 AEP&NSage0-2010-allF- λ 0.3	1	-0.041	-0.082	-0.102	0.102	0.215	0.543
6 AEP&NSage0-2010-allF- λ 0.4	0.314, 0.363, 0.206	-0.041	-0.082	-0.101	0.101	0.242	0.567
7 AEP&NSage0-2010-allF- λ 0.5	1	-0.041	-0.082	-0.101	0.098	0.276	0.597
8 AEP&NSage0-2010-allF- λ 0.6	1	-0.142	-0.154	-0.170	-0.074	0.413	0.953
9 AEP&NSage0-2010-allF- λ 0.7	0.312, 0.365, 0.129	-0.024	-0.072	-0.092	0.149	0.113	0.451
10 AEP&NSage0-2010-allF- λ 0.8	0.311, 0.373, 0.102	-0.021	-0.071	-0.089	0.165	0.181	0.527
11 AEP&NSage0-2010-allF- λ 0.9	0.3127, 0.4184, 0.0691	0.010	-0.050	-0.068	0.253	-0.246	0.627
12 AEP&NSage0-2010-allF- λ 0.9999	0.961, 2.261, 1.883	0.022	0.023	0.020	0.031	-0.010	0.106
13 AEP&NSage0-allyears-allF- λ 0	0.230, 0.267, 0.114	-0.139	-0.320	-0.433	0.603	6.103	7.598
14 AEP&NSage0-allyears-allF- λ 0.1	1	-0.115	-0.283	-0.393	0.571	0.358	1.720
15 AEP&NSage0-allyears-allF- λ 0.2	1	NaN	NaN	NaN	NaN	Inf	-
16 AEP&NSage0-allyears-allF- λ 0.3	1	-0.193	-0.290	-0.360	0.214	0.660	1.718
17 AEP&NSage0-allyears-allF- λ 0.4	1	-0.184	-0.278	-0.345	0.211	0.715	1.733
18 AEP&NSage0-allyears-allF- λ 0.5	0.2316, 0.3039, 0.0677	-0.024	-0.204	-0.313	0.724	0.202	1.467
19 AEP&NSage0-allyears-allF- λ 0.6	0.2328, 0.3228, 0.0596	0.022	-0.169	-0.282	0.823	-0.375	1.672
20 AEP&NSage0-allyears-allF- λ 0.7	0.2354, 0.3577, 0.0513	0.071	-0.132	-0.247	0.928	-0.412	1.790
21 AEP&NSage0-allyears-allF- λ 0.8	0.2423, 0.4393, 0.0426	0.151	-0.073	-0.190	1.109	-0.456	1.979
22 AEP&NSage0-allyears-allF- λ 0.9	0.2656, 0.5596, 0.0333	0.329	0.046	-0.085	1.557	-0.529	2.546
23 AEP&NSage0-allyears-allF- λ 0.9999	1	0.022	0.023	0.020	0.031	-0.010	0.106

Supplementary Table 8-2. List of retrospective bias values (Mohn's ρ) when tuning method (all F estimation method and two-step selectivity method) and λ are varied

Color indicators are the same as in Supplementary Table 8-1. Titles including allF indicate the all F estimation method, and titles with maxF indicate the two-step selectivity method.

Scenario name	Initial value	Mohn's ρ (5-year retrospective)					Sum of absolute values
		Biomass	Numbers	Recruitment	SSB	Fishing mortality	
1 Plain	1	0.025	0.022	0.014	0.054	-0.069	0.184
2 AEP&NSage0-2010-allF- λ 0	0.316, 0.365, 0.343	-0.151	-0.161	-0.174	-0.087	1.1E+42	1.1E+42
3 AEP&NSage0-2010-allF- λ 0.1	1	-0.044	-0.085	-0.106	0.105	0.191	0.531
4 AEP&NSage0-2010-allF- λ 0.2	1	-0.042	-0.083	-0.104	0.104	0.195	0.528
5 AEP&NSage0-2010-allF- λ 0.3	1	-0.041	-0.082	-0.102	0.102	0.215	0.543
6 AEP&NSage0-2010-allF- λ 0.4	0.314, 0.363, 0.206	-0.041	-0.082	-0.101	0.101	0.242	0.567
7 AEP&NSage0-2010-allF- λ 0.5	1	-0.041	-0.082	-0.101	0.098	0.276	0.597
8 AEP&NSage0-2010-allF- λ 0.6	1	-0.142	-0.154	-0.170	-0.074	0.413	0.953
9 AEP&NSage0-2010-allF- λ 0.7	0.312, 0.365, 0.129	-0.024	-0.072	-0.092	0.149	0.113	0.451
10 AEP&NSage0-2010-allF- λ 0.8	0.311, 0.373, 0.102	-0.021	-0.071	-0.089	0.165	0.181	0.527
11 AEP&NSage0-2010-allF- λ 0.9	0.3127, 0.4184, 0.0691	0.010	-0.050	-0.068	0.253	-0.246	0.627
12 AEP&NSage0-2010-allF- λ 0.9999	0.961, 2.261, 1.883	0.022	0.023	0.020	0.031	-0.010	0.106
13 AEP&NSage0-2010-maxF- λ 0	1	-0.173	-0.201	-0.240	-0.001	806.0	806.7
14 AEP&NSage0-2010-maxF- λ 0.1	1	-0.073	-0.086	-0.106	0.018	0.116	0.400
15 AEP&NSage0-2010-maxF- λ 0.2	1	-0.063	-0.076	-0.094	0.020	0.069	0.321
16 AEP&NSage0-2010-maxF- λ 0.3	1	-0.058	-0.069	-0.085	0.021	0.039	0.272
17 AEP&NSage0-2010-maxF- λ 0.4	1	-0.054	-0.065	-0.080	0.020	0.019	0.237
18 AEP&NSage0-2010-maxF- λ 0.5	1	-0.052	-0.062	-0.076	0.019	0.003	0.212
19 AEP&NSage0-2010-maxF- λ 0.6	1	-0.051	-0.061	-0.074	0.017	-0.008	0.211
20 AEP&NSage0-2010-maxF- λ 0.7	1	-0.053	-0.062	-0.075	0.013	-0.014	0.218
21 AEP&NSage0-2010-maxF- λ 0.8	1	-0.068	-0.077	-0.089	0.002	0.001	0.237
22 AEP&NSage0-2010-maxF- λ 0.9	1	-0.041	-0.047	-0.056	0.009	-0.032	0.186
23 AEP&NSage0-2010-maxF- λ 0.9999	2.24	-0.030	-0.035	-0.042	0.016	-0.043	0.165

Appendix 9 Cohort Analysis Results

Supplementary Table 9-1. Detailed results of cohort analysis (Tuned VPA)

Year	Numbers at age (millions)				Total	Fishing mortality				%SPR	F/Fmsy
	Age 0	Age 1	Age 2	Age 3		Age 0	Age 1	Age 2	Age 3		
1978	27,944.1	8,054.5	1,137.5	156.6	37,292.7	0.20	0.72	0.83	0.83	58.0	0.61
1979	31,264.1	8,396.6	1,439.1	100.1	41,199.9	0.39	0.36	0.58	0.58	58.1	0.66
1980	15,287.7	7,825.6	2,155.7	163.1	25,432.0	0.51	1.44	0.86	0.86	38.1	1.26
1981	24,188.4	3,371.9	681.5	183.6	28,425.4	0.60	1.28	1.73	1.73	34.4	1.42
1982	28,514.5	4,886.9	344.9	24.4	33,770.7	0.71	0.78	0.96	0.96	34.7	1.36
1983	43,953.4	5,147.7	821.0	26.7	49,948.8	0.33	1.20	0.60	0.60	48.4	0.88
1984	40,531.9	11,573.9	568.1	91.0	52,764.8	0.77	2.56	2.67	2.67	21.5	2.54
1985	37,782.4	6,935.3	330.8	7.9	45,056.4	0.42	1.58	1.35	1.35	39.7	1.22
1986	46,150.7	9,104.2	527.6	17.3	55,799.7	0.26	1.11	1.58	1.58	52.0	0.74
1987	36,116.4	13,075.8	1,104.1	21.9	50,318.2	0.19	0.70	0.56	0.56	62.7	0.50
1988	86,971.8	10,981.8	2,383.8	126.7	100,464.1	0.16	0.71	0.35	0.35	65.6	0.44
1989	134,088.1	27,201.4	1,987.4	338.9	163,615.8	0.08	0.24	0.65	0.65	80.3	0.20
1990	119,695.3	45,572.9	7,888.0	208.7	173,364.8	0.08	0.38	0.76	0.76	80.1	0.18
1991	81,951.1	40,829.4	11,504.8	743.7	135,029.0	0.11	0.34	0.77	0.77	78.0	0.23
1992	99,594.3	27,134.0	10,713.2	1,073.7	138,515.2	0.08	0.37	1.24	1.24	78.0	0.20
1993	90,090.6	33,916.4	6,860.6	623.3	131,491.0	0.10	0.20	0.51	0.51	82.0	0.20
1994	88,806.3	30,054.2	10,242.8	833.5	129,936.8	0.06	0.25	0.36	0.36	84.2	0.15
1995	66,906.6	30,631.5	8,581.1	1,446.3	107,565.5	0.08	0.28	0.67	0.67	80.7	0.19
1996	94,966.6	22,644.5	8,526.0	890.1	127,027.2	0.10	0.62	1.39	1.39	72.0	0.27
1997	141,706.9	31,574.4	4,480.2	430.5	178,191.8	0.05	0.20	1.33	1.33	84.1	0.13
1998	192,364.1	49,415.8	9,480.5	240.0	251,500.4	0.08	0.50	1.11	1.11	77.7	0.19
1999	132,124.8	65,437.0	11,058.3	628.7	209,248.8	0.10	0.44	1.17	1.17	74.6	0.26
2000	129,961.4	43,964.7	15,455.8	693.4	190,075.4	0.05	0.28	0.68	0.68	84.6	0.14
2001	201,010.5	45,413.9	12,209.7	1,581.2	260,215.2	0.02	0.28	0.81	0.81	85.5	0.14
2002	196,793.6	72,419.6	12,579.9	1,093.5	282,886.7	0.05	0.45	0.80	0.80	78.9	0.15
2003	163,324.6	69,032.5	16,985.7	1,141.5	250,484.3	0.05	0.48	1.32	1.32	78.7	0.14
2004	101,369.3	56,937.8	15,731.9	911.6	174,950.6	0.06	0.68	1.35	1.35	74.8	0.17
2005	136,626.2	35,063.2	10,662.2	820.4	183,172.0	0.05	0.44	1.76	1.76	79.6	0.14
2006	97,120.8	47,805.0	8,329.1	370.9	153,625.8	0.11	0.70	1.24	1.24	69.8	0.30
2007	102,716.3	32,073.3	8,757.7	487.7	144,035.0	0.07	0.74	1.26	1.26	73.8	0.18
2008	142,260.3	35,336.7	5,642.1	499.3	183,738.4	0.17	0.38	1.36	1.36	70.7	0.36
2009	91,686.1	44,068.3	8,933.7	291.3	144,979.4	0.07	0.56	0.87	0.87	76.4	0.19
2010	71,385.5	31,452.5	9,277.4	756.6	112,872.0	0.15	0.66	1.23	1.23	68.1	0.37
2011	66,052.5	22,542.8	5,998.7	548.1	95,142.1	0.10	0.63	1.11	1.11	71.7	0.27
2012	50,488.7	22,020.9	4,422.2	398.1	77,329.9	0.22	0.73	1.08	1.08	61.6	0.52
2013	48,727.1	14,847.6	3,893.6	303.9	67,772.2	0.34	1.14	1.39	1.39	49.5	0.84
2014	34,426.3	12,714.9	1,747.1	195.9	49,084.2	1.22	1.88	1.18	1.18	17.2	2.50
2015	38,831.0	3,732.0	712.5	108.2	43,383.6	0.74	1.47	2.25	2.25	28.7	1.73
2016	30,281.7	6,839.7	314.4	15.2	37,451.1	0.84	2.41	2.12	2.12	22.8	2.29
2017	20,491.9	4,788.8	225.2	7.6	25,513.5	1.00	2.29	2.55	2.55	20.3	2.44
2018	17,136.6	2,766.1	177.9	3.6	20,084.1	0.47	2.60	3.03	3.03	33.9	1.65
2019	33,675.7	3,948.6	75.4	1.7	37,701.4	0.72	1.83	1.22	1.22	29.1	1.73
2020	34,400.5	6,023.3	233.5	4.5	40,661.8	0.43	0.85	0.79	0.79	46.2	0.96
2021	42,735.8	8,241.3	949.6	21.4	51,948.1	0.31	0.36	0.14	0.14	60.4	0.61

Supplementary Table 9-1. Detailed results of cohort analysis (Tuned VPA) (continued)

Year	Biomass at age (thousand tons)				Biomass (thousand tons)	SSB (thousand tons)	Catch (tons)	Exploitation rate (%)
	Age 0	Age 1	Age 2	Age 3				
1978	140.76	68.05	20.74	3.99	233.54	92.78	42,998	18.4
1979	158.10	113.22	28.54	2.40	302.25	144.15	57,426	19.0
1980	86.33	74.36	37.48	3.69	201.87	115.54	65,959	32.7
1981	103.39	35.15	14.43	5.06	158.03	54.64	50,607	32.0
1982	100.38	44.40	6.35	0.61	151.74	51.35	47,542	31.3
1983	186.21	47.96	13.15	0.56	247.88	61.67	55,228	22.3
1984	134.61	73.66	10.23	2.36	220.86	86.25	90,007	40.8
1985	165.01	52.33	5.07	0.14	222.55	57.55	61,435	27.6
1986	223.60	79.66	6.61	0.48	310.34	86.74	66,062	21.3
1987	215.57	120.62	15.79	0.52	352.49	136.93	62,733	17.8
1988	306.13	113.09	38.39	2.77	460.38	154.25	68,088	14.8
1989	768.28	325.99	40.30	9.53	1,144.11	375.83	87,804	7.7
1990	1,130.99	691.22	139.91	4.70	1,966.82	835.83	215,941	11.0
1991	557.55	628.90	229.96	17.13	1,433.54	875.99	202,319	14.1
1992	657.78	385.47	215.30	24.19	1,282.73	624.95	178,276	13.9
1993	477.29	445.60	128.23	14.06	1,065.17	587.88	100,487	9.4
1994	508.79	453.81	200.87	20.79	1,184.26	675.47	110,428	9.3
1995	428.37	489.58	188.83	39.37	1,146.15	717.78	141,716	12.4
1996	717.63	356.85	176.76	22.08	1,273.33	555.69	207,890	16.3
1997	1,299.19	518.30	98.55	10.93	1,926.97	627.79	134,464	7.0
1998	1,711.80	791.97	171.26	5.17	2,680.20	968.40	319,371	11.9
1999	1,083.66	899.01	213.24	14.96	2,210.89	1,127.22	327,997	14.8
2000	965.05	763.47	302.67	16.77	2,047.96	1,082.90	213,116	10.4
2001	1,449.04	702.92	263.43	39.93	2,455.31	1,006.28	197,928	8.1
2002	1,626.13	1,007.94	246.59	28.15	2,908.80	1,282.67	334,399	11.5
2003	1,389.22	1,080.25	323.85	27.23	2,820.56	1,431.33	408,009	14.5
2004	1,051.48	866.63	299.39	20.58	2,238.07	1,186.59	401,865	18.0
2005	878.05	583.04	215.49	19.45	1,696.04	817.99	237,691	14.0
2006	846.93	652.52	156.11	8.69	1,664.24	817.31	303,428	18.2
2007	611.50	506.53	170.62	11.11	1,299.76	688.26	242,468	18.7
2008	705.52	519.07	118.32	11.99	1,354.90	649.38	209,082	15.4
2009	730.64	640.95	165.84	6.37	1,543.80	813.16	240,892	15.6
2010	440.65	492.94	191.06	18.55	1,143.20	702.56	247,629	21.7
2011	489.00	326.05	120.68	13.34	949.08	460.07	159,980	16.9
2012	241.29	308.39	85.66	10.05	645.39	404.10	154,459	23.9
2013	258.47	196.41	80.94	7.33	543.16	284.68	156,030	28.7
2014	152.88	128.94	35.12	5.03	321.97	169.09	143,984	44.7
2015	133.54	37.01	14.95	2.84	188.34	54.80	66,509	35.3
2016	133.25	53.18	5.39	0.34	192.16	58.91	77,693	40.4
2017	83.42	37.37	3.49	0.17	124.45	41.03	53,915	43.3
2018	72.51	20.13	2.67	0.07	95.39	22.87	28,907	30.3
2019	96.62	27.20	0.97	0.03	124.82	28.20	44,269	35.5
2020	178.50	52.58	4.06	0.09	235.22	56.72	57,000	24.2
2021	167.99	60.58	18.41	0.47	247.45	79.46	39,638	16.0

Appendix 10 Results of Stock Assessment and Future Projections Under Different Assumptions

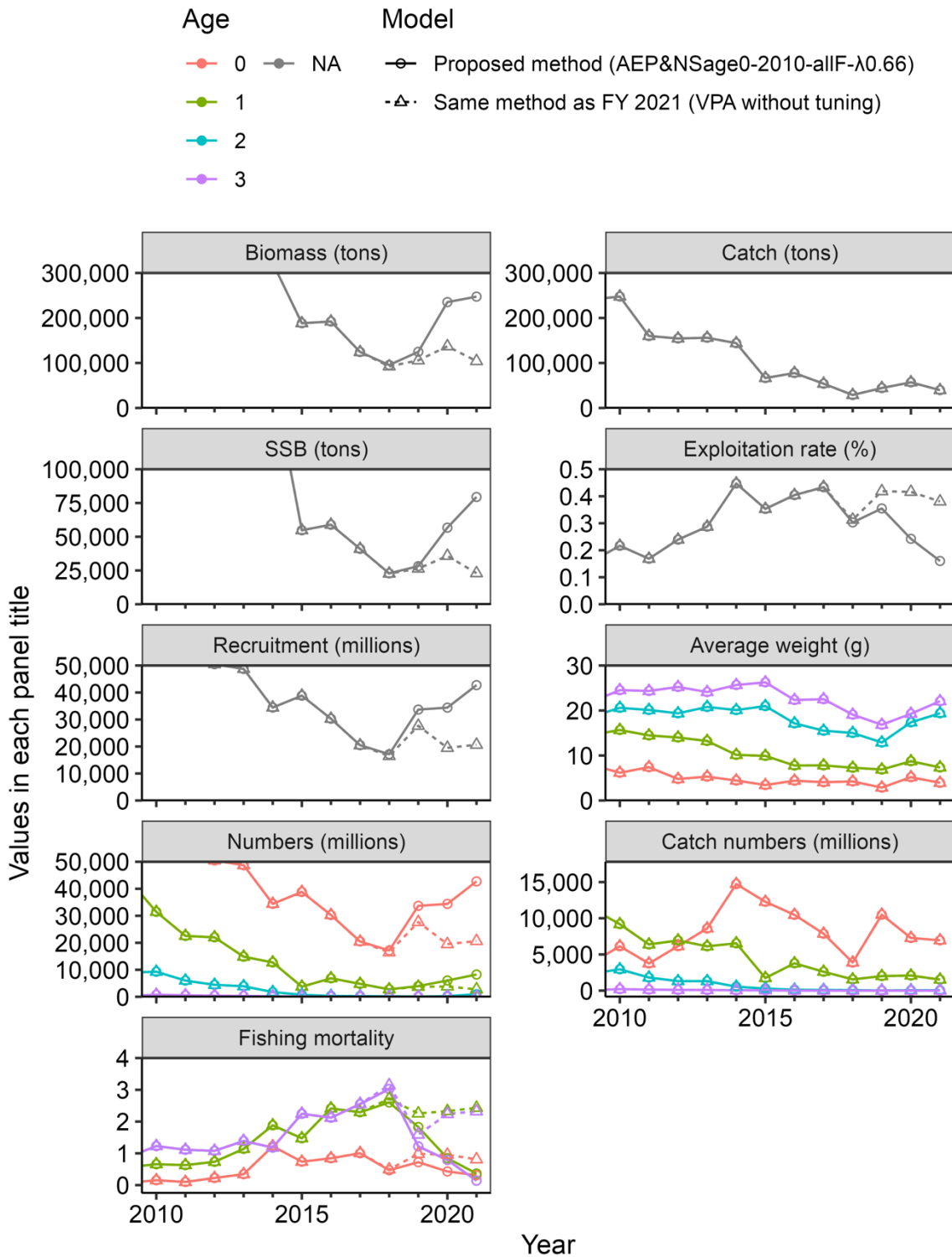
Tuned VPA was introduced for the first time in this year's Stock Assessment for Pacific Stock of Japanese Anchovy. For reference, this Appendix contains the results that would have been obtained if this stock assessment had been performed using the same methods as the FY 2021 stock assessment (VPA without tuning), and these results are shown against the stock assessment (Tuned VPA) for comparison. In the FY 2021 stock assessment using VPA without tuning, abundance (biomass) was estimated using equations (1) to (4), and in addition, the assumptions in the below equations (11) and (12) were used to find $F_{3,2021}$ for exploratory calculations.

$$F_{a,2021} = \frac{1}{3} \sum_{t=2018}^{2020} F_{a,t} \quad (a = 0, 1, 2) \quad (11)$$

$$F_{3,2021} = F_{2,2021} \quad (12)$$

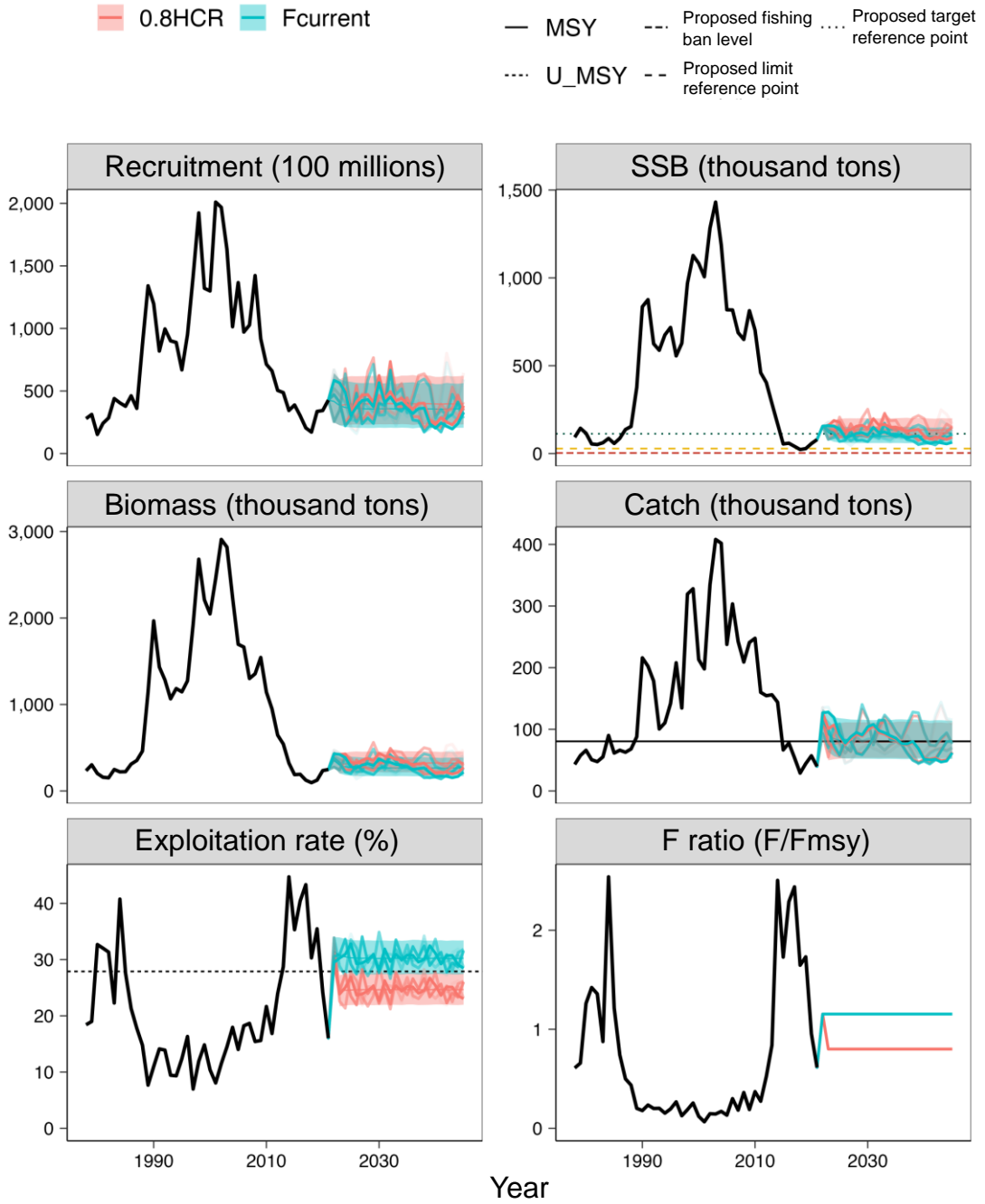
Trends in various estimates since 2010 for each model are shown in Supplementary Fig. 10-1, and values for the most recent 5-year period are shown in Supplementary Table 10-1. In the stock assessment performed using the same VPA without tuning as the FY 2021 stock assessment, only data for catch in number at age was used, so biomass and SSB in 2021 were lower compared to 2020, and recruitment volume was about the same as in 2020 (Supplementary Table 10-1).

In the stock assessment, F in 2022 was assumed to be the F that gives catch equal to 44,700 tons, which was the average catch of the most recent 5 year period (2017 to 2021). The reasoning for this choice is that if current fishing pressure (F2019 to 2021) is assumed for F in 2022, then catch in 2022 would be 110,000 tons, which is around twice the level of catch since 2017. Fishing conditions in the Pacific regions in recent months up to June 2022 were similar to landings at major ports year on year (January to June 2021), and somewhat lower than average levels of the most recent 5-year period (January to June in 2017 to 2021). Therefore, we believe that the F value which corresponds to the average catch in weight of the most recent 5-year period is an appropriate assumption for F in 2022. For reference, future projections for a scenario that uses current fishing pressure (F2019 to 2021) for F in 2022 are shown in Supplementary Fig. 10-2, Supplementary Table 10-2, and Supplementary Table 10-3.



Supplementary Fig. 10-1. Comparison of estimates using Tuned VPA and VPA without tuning

These graphs show an enlarged view of low values for biomass, SSB, recruitment volume, recruitment in number, and catch in weight. Up to 2018, both models showed nearly identical trends.



(Shaded areas: 5 to 95% prediction interval, thin solid lines: average value, thick solid lines: some of simulation results)

Supplementary Fig. 10-2. Future projection results for the scenario that uses current fishing pressure (F2019 to 2021) for F in 2022

Color indicators are the same as in Supplementary Fig. 4-2.

Supplementary Table 10-1. Comparison of abundance estimates for the most recent 5-year period (2017 to 2021) using different models

Green titles indicate models proposed in the stock assessment.

Item	Stock Assessment	2017	2018	2019	2020	2021
Biomass (thousand tons)	FY2021 (Published)	124.15	92.16	104.64	142.13	-
	FY2021 (Re-assessment)	124.16	92.27	105.40	145.83	-
	FY2022*	124.17	92.36	105.77	136.96	104.14
	FY2022 (tuned VPA, $\lambda 0.66$)	124.45	95.39	124.82	235.22	247.45
SSB (thousand tons)	FY2021 (Published)	41.01	22.67	26.26	34.58	-
	FY2021 (Re-assessment)	41.01	22.68	26.33	35.43	-
	FY2022*	41.01	22.69	26.39	35.82	22.98
	FY2022 (tuned VPA, $\lambda 0.66$)	41.03	22.87	28.20	56.72	79.46
Recruitment (millions)	FY2021 (Published)	20,423.6	16,420.7	27,318.4	20,726.7	-
	FY2021 (Re-assessment)	20,425.8	16,444.6	27,561.9	21,277.2	-
	FY2022*	20,427.9	16,466.7	27,668.9	19,491.6	20,646.8
	FY2022 (tuned VPA, $\lambda 0.66$)	20,491.9	17,136.6	33,675.7	34,400.5	42,735.8
Fishing mortality (Age 3, oldest)	FY2021 (Published)	2.554	3.150	1.625	2.443	-
	FY2021 (Re-assessment)	2.554	3.146	1.606	2.435	-
	FY2022*	2.554	3.141	1.589	2.238	2.323
	FY2022 (tuned VPA, $\lambda 0.66$)	2.548	3.025	1.219	0.791	0.139
Exploitation rate (%)	FY2021 (Published)	43.4	31.4	42.3	39.2	-
	FY2021 (Re-assessment)	43.4	31.3	42.0	39.1	-
	FY2022*	43.4	31.3	41.9	41.6	38.1
	FY2022 (tuned VPA, $\lambda 0.66$)	43.3	30.3	35.5	24.2	16.0
Catch numbers (millions, total of all ages)	FY2021 (Published)	10,575.7	5,514.5	12,528.8	9,215.6	-
	FY2021 (Re-assessment)	10,575.7	5,514.5	12,528.8	9,423.4	-
	FY2022	10,575.7	5,514.5	12,528.8	9,423.4	8,534.0
Catch (thousand tons)	FY2021 (Published)	53.9	28.9	44.3	55.7	-
	FY2021 (Re-assessment)	53.9	28.9	44.3	57.0	-
	FY2022	53.9	28.9	44.3	57.0	39.6

*Same method as FY 2021 (VPA without tuning)

Supplementary Table 10-2. Probability (%) that future SSB will exceed proposed target/limit reference points in the scenario that uses current fishing pressure (F2019 to 2021) for F in 2022

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

β	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2043	2053
1.0	0	100	53	50	47	46	45	46	45	44	45	45	45	45	45
0.9	0	100	53	58	59	59	59	60	59	59	59	60	60	59	59
0.8	0	100	53	66	70	72	73	73	73	73	73	74	73	73	73
0.7	0	100	53	74	80	83	84	85	84	84	85	85	85	84	85
0.6	0	100	53	81	88	91	92	93	93	93	93	93	93	93	93
0.5	0	100	53	87	94	96	97	97	97	98	98	98	97	97	97
0.4	0	100	53	92	98	99	99	99	99	99	99	99	99	99	99
0.3	0	100	53	95	99	100	100	100	100	100	100	100	100	100	100
0.2	0	100	53	97	100	100	100	100	100	100	100	100	100	100	100
0.1	0	100	53	99	100	100	100	100	100	100	100	100	100	100	100
0.0	0	100	53	100	100	100	100	100	100	100	100	100	100	100	100
F2019-2021	0	100	53	38	31	29	28	27	27	26	27	26	27	26	27

2

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

β	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2043	2053
1.0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.9	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.8	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.7	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.6	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.5	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.4	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.3	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.2	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
0.0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
F2019-2021	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

2

Supplementary Table 10-3. Trends in future average SSB and catch in weight in the scenario that uses current fishing pressure (F2019 to 2021) for F in 2022

a) Trends in average SSB (thousand tons)

β	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2043	2053
1.0	79	156	119	116	114	114	113	113	113	113	113	113	113	113	113
0.9	79	156	119	122	123	124	124	124	124	124	124	124	124	124	124
0.8	79	156	119	129	133	135	136	136	136	136	136	136	136	136	136
0.7	79	156	119	137	144	148	149	150	149	149	150	150	150	149	149
0.6	79	156	119	145	156	162	164	165	165	165	165	165	166	165	165
0.5	79	156	119	153	170	178	181	182	182	182	183	183	183	182	183
0.4	79	156	119	163	186	196	201	202	202	203	203	203	204	202	203
0.3	79	156	119	173	203	218	223	226	226	226	227	227	227	226	226
0.2	79	156	119	184	223	242	249	252	253	253	254	254	254	253	253
0.1	79	156	119	197	246	270	280	284	284	285	286	286	286	284	285
0.0	79	156	119	210	272	303	316	321	322	322	323	323	324	322	323
F2019-2021	79	156	119	107	102	100	99	99	98	98	98	98	99	98	98

□

b) Trends in average catch (thousand tons)

β	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2043	2053
1.0	40	110	84	82	81	81	81	81	80	81	81	81	81	80	80
0.9	40	110	78	80	80	80	80	80	80	80	80	80	80	80	80
0.8	40	110	72	76	78	79	79	79	79	79	79	79	79	79	79
0.7	40	110	66	72	75	77	77	77	77	77	77	77	77	77	77
0.6	40	110	59	67	71	73	74	74	74	74	74	74	74	74	74
0.5	40	110	51	61	66	68	69	69	69	69	69	69	69	69	69
0.4	40	110	43	53	59	61	62	63	63	63	63	63	63	63	63
0.3	40	110	33	44	49	52	53	53	53	53	54	54	54	53	53
0.2	40	110	23	32	37	39	40	41	41	41	41	41	41	41	41
0.1	40	110	12	18	21	23	23	23	23	23	24	24	24	23	23
0.0	40	110	0	0	0	0	0	0	0	0	0	0	0	0	0
F2019-2021	40	110	91	85	82	81	81	80	80	80	80	80	80	80	80

□

Appendix 11 Abundance Indices listed in the FY 2021 Stock Assessment (not used for tuning)

JAFIC released CPUE (catch per unit effort (catch per net)) of North Pacific large to medium-scale purse seining as part of Distribution/Migration Status Analysis Surveys, which showed that CPUE was 39 to 50 tons/net from 2001 to 2004, and increased due to a decrease of effort in 2005 (Supplementary Fig. 11-1, Supplementary Table 11-1). Levels from 2008 to 2011 were stable and similar to levels from 2001 to 2004, but declined significantly since 2013, and operations effort has flattened out to only 0 or 1 net since 2016. CPUE (catch in weight) in 2017 and 2020, when operations effort was 1 net, was 20 tons/net and 23 tons/net, respectively.

The Northwest Pacific Ocean Autumn Pelagic Fish Stock Survey expanded survey ocean regions since 2005, and it is clear that distribution of this stock had spread from the waters east of Hokkaido to off the Kuril Islands. In the same survey, the CPUE of fish less than 10.5 cm in length (ind./net, converted to value per 30 minutes of towing) was analyzed by the Chiba Prefecture Fisheries Research Agency, and they found a clear correlation between these results and catch of fish age 1 in early January in the studies on winter/spring catch in the Joban-Boso region, and a positive correlation between the CPUE of fish 10.5 cm in length or longer, and the catch of fish age 2 in early January (Hasegawa and Kawabata 2013). The CPUE of fish less than 10.5 cm in length was high in 2011 at 5,205 ind./net, but sharply decreased in 2012, similar to the age 0 CPUE from the Northward season surveys, and ranged around 0.1 to 4.4 ind./net from 2013 to 2018, and then surged to 1,000 ind./net since 2019, reaching a record high of 5,909 ind./net in 2021 (Supplementary Fig. 11-2, Supplementary Table 11-1). The CPUE of fish 10.5 cm in length or longer reached a record high of 4,587 ind./net in 2006, followed by a decreasing trend, reaching a record low of less than 1 ind./net in 2018. Since 2019, levels have increased, and it was 338 ind./net in 2021.

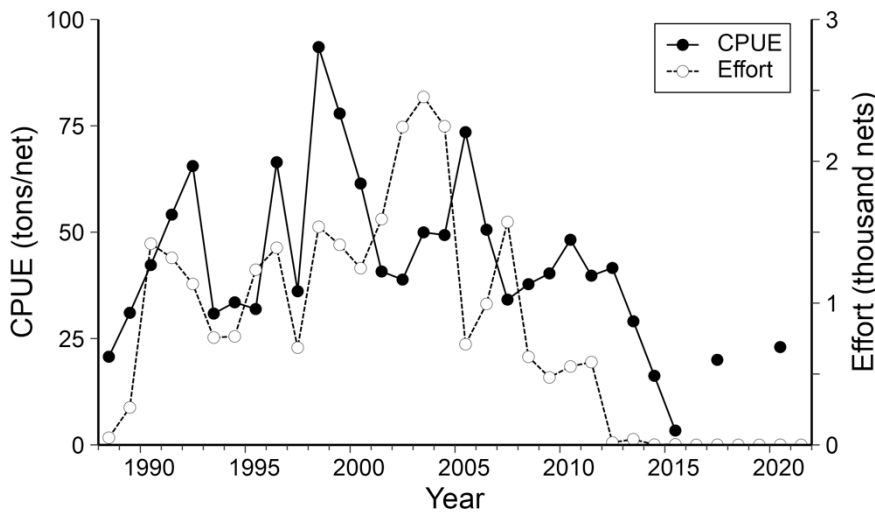
The main fishing season is usually winter/spring in the Joban-Boso region (waters off Chiba, Ibaraki, and Fukushima Prefectures), so we set the fishing season for these regions to be from November to June of the following year (i.e., the 2021 fishing season is from November 2020 to June 2021). Catches at the major ports in these regions showed a strong positive correlation between catch in weight of fish less than 12 cm in length and age 0 catch in weight in the year prior to each fishing season (i.e., in 2020 for the 2021 fishing season), and a strong positive correlation between catch in weight of fish 12 cm in length or longer and SSB in the same year as each fishing season (i.e., 2021 for the 2021 fishing season). Since 1999, catch in weight of fish less than and longer than 12 cm has been in a decreasing trend, despite reaching record highs in the 2003 fishing season (Supplementary Fig. 11-3, Supplementary Table 11-2). In the 2021 fishing season, catch of fish less than 12 cm in length was 3,700 tons, which was slightly higher than the record low of 3,200 tons seen in the 2019 fishing season. Likewise, in the 2021 fishing season, catch of fish 12 cm in length or longer was 1,400 tons, which was slightly higher than the record low of 14 tons seen in the 2019 fishing season (data from the 2022 fishing season (preliminary values) is shown in Supplementary Fig. 11-3 as a reference for the most recent fishing conditions). In addition, in the Joban-Boso region, there are many cases where fish age 1 and 2 are seen in catches in the first half of the fishing season (from November of the previous year to February of the fishing season year), but fish age 1 are the primary catch in the second half of the

fishing season (from March to June). Therefore, because this region is one of the fishing grounds of large to medium-scale purse seine fisheries in the North Pacific, the total abundance index for March to June (according to JAFIC) is considered to be an abundance index for age 0 fish in the previous year, but this index has been in a decreasing trend since peaking in 2003 (1129), and was 0 in 2021 (Supplementary Table 11-2).

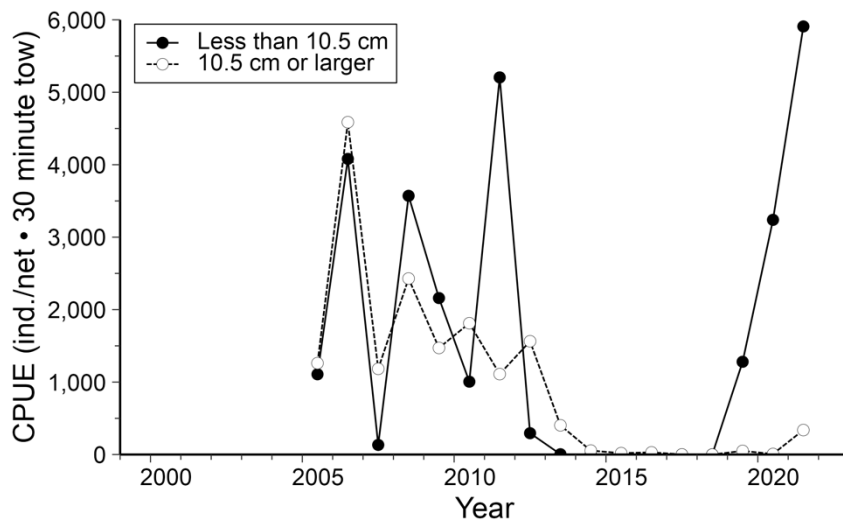
Recently, offshore distribution has declined significantly in parallel with the decrease in stock population, but offshore research vessel surveys have found signs of increase in the most recent 3-year period. However, because distribution is scattered and the distribution volume is low, the main distribution area of this stock is concentrated along the coast. It is believed that abundance indices for coastal stock should be introduced to replace abundance indices for offshore migratory stock, which is the main catch targets of large to medium-scale purse seine fisheries in the North Pacific. Accordingly, the average CPUE of fish presumed to be spawning stock according to commercial size category (8 to 10 cm, 10 to 12 cm, 12 to 13 cm, 13 to 15 cm) from three two-boat purse seine vessels (large to medium-scale, medium-scale) operating along the coast of Chiba from February to June has been used since the FY 2019 stock assessment. The CPUE ranged from around 30 to 40 tons/net from 2008 to 2013, and then declined sharply since 2014, and has remained under 11 tons/net since 2016, reaching a low of 8.3 tons/net in 2021, which was the third lowest level since 2008 (Supplementary Fig. 11-4, Supplementary Table 11-2).

References

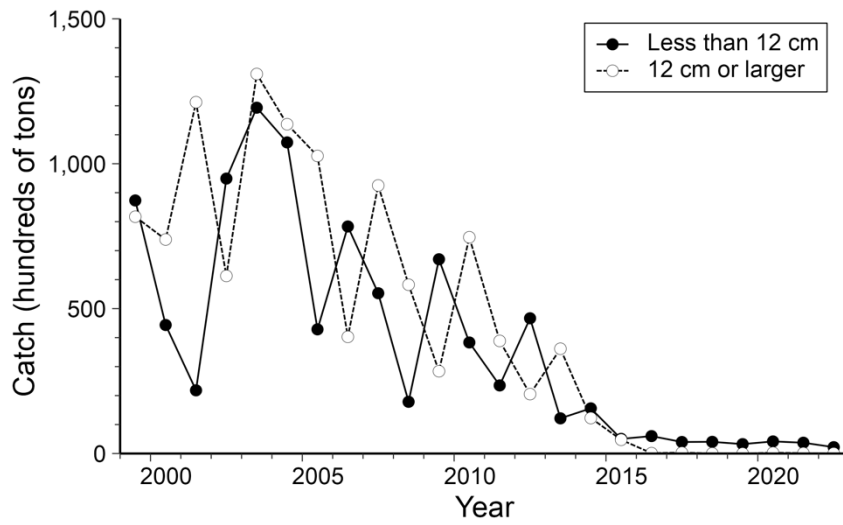
- Hasegawa, J. and Kawabata, A. (2013) Relationship between results of the Northwest Pacific Ocean Autumn Pelagic Fish Stock Surveys, and winter/spring fishing conditions of Japanese Anchovy migrating to the Boso region. 61st Research Institute Meeting on Stock of Pacific Saury and Small Pelagic Fish, Fisheries Research Agency, 237-238. (in Japanese)



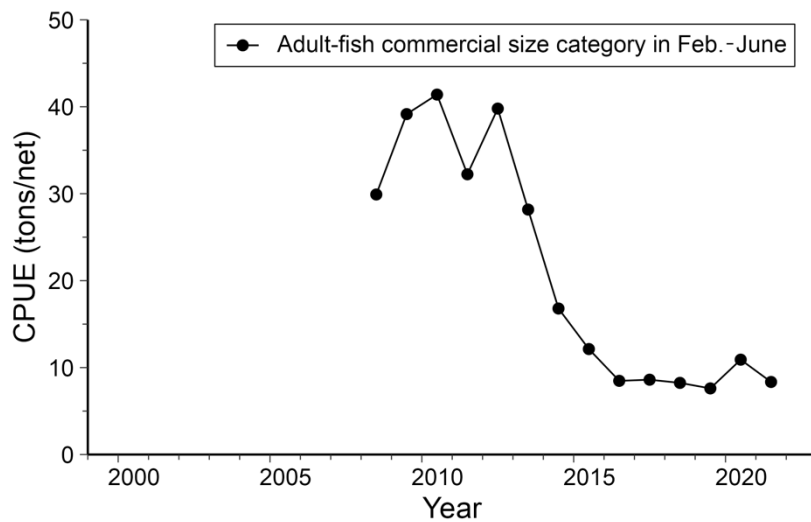
Supplementary Fig. 11-1. Trends in effort and CPUE (tons/net) of North Pacific large to medium-scale purse seine fisheries



Supplementary Fig. 11-2. Trends in CPUE (ind./net) in the Northwest Pacific Ocean Autumn Pelagic Fish Stock Survey



Supplementary Fig. 11-3. Trends in catch in weight in the Joban-Boso region from November of the previous year to June of the fishing season year



Supplementary Fig. 11-4. Average CPUE of fish presumed to be spawning stock according to commercial size category (8 to 10 cm, 10 to 12 cm, 12 to 13 cm, 13 to 15 cm) from three two-boat purse seine vessels (large to medium-scale, medium-scale) operating in Chiba Prefecture in the Boso region (February to June)

Supplementary Table 11-1. Abundance indices in the North Pacific region

Year	Catch, effort, CPUE of North Pacific purse seine fisheries, and total of abundance indices March to June				Average CPUE at all survey points from the Northwest Pacific Ocean Autumn Pelagic Fish Stock Survey	
	Catch (tons)	Effort (nets)	CPUE (tons/net)	Total of abundance indices March to June	Less than 10.5 cm (ind./net)	10.5 cm or larger (ind./net)
1988	1,057.0	51	20.7	73.3		
1989	8,198.0	264	31.1	147.0		
1990	59,993.0	1,419	42.3	53.9		
1991	71,394.0	1,319	54.1	287.8		
1992	74,394.0	1,135	65.5	208.7		
1993	23,366.0	757	30.9	620.3		
1994	25,636.5	765	33.5	353.3		
1995	39,439.0	1,235	31.9	135.9		
1996	92,344.0	1,390	66.4	241.1		
1997	24,775.5	686	36.1	160.0		
1998	143,807.5	1,538	93.5	436.5		
1999	109,905.2	1,411	77.9	608.1		
2000	76,550.0	1,246	61.4	396.7		
2001	64,887.5	1,592	40.8	712.1		
2002	87,135.9	2,242	38.9	823.9		
2003	122,550.0	2,453	50.0	1,129.2		
2004	110,835.5	2,247	49.3	680.8		
2005	52,187.0	710	73.5	551.2	1,107.7	1,261.1
2006	50,277.0	994	50.6	853.1	4,080.7	4,586.9
2007	53,686.4	1,572	34.2	604.2	132.9	1,183.1
2008	23,459.5	621	37.8	418.4	3,571.0	2,429.1
2009	19,189.0	476	40.3	630.2	2,159.7	1,471.4
2010	26,662.0	553	48.2	577.6	1,005.4	1,812.3
2011	23,234.5	584	39.8	392.5	5,205.4	1,110.1
2012	707.0	17	41.6	302.7	294.5	1,563.4
2013	1,162.0	40	29.1	117.8	4.4	403.2
2014	32.5	2	16.3	16.3	0.1	54.3
2015	13.5	4	3.4	1.0	0.1	19.2
2016	0.0	0		0.0	0.8	29.9
2017	20.0	1	20.0	20.0	0.3	1.9
2018	0.0	0		0.0	0.6	0.4
2019	0.0	0		0.0	1,280.3	49.9
2020	23.0	1	23.0	0.0	3,239.3	8.0
2021	0.0	0		0.0	5,908.6	337.8

Supplementary Table 11-2. Abundance indices in the Joban-Boso region

Year	Catch in the Joban-Boso region (Chiba, Ibaraki, and Fukushima prefectures) from November of the previous year to June of the fishing season year (total of major ports)		Average CPUE of adult-fish commercial size category (8 to 10 cm, 10 to 12 cm, 12 to 13 cm, 13 to 15 cm) from three two-boat purse seine vessels (large and medium type or medium type) operating in Chiba prefecture
	Less than 12 cm (hundred tons)	12 cm or larger (hundred tons)	CPUE (tons/net)
1999	873.3	817.2	
2000	443.5	738.4	
2001	218.1	1,212.3	
2002	948.7	612.9	
2003	1,193.3	1,309.6	
2004	1,073.6	1,136.3	
2005	428.5	1,026.9	
2006	783.5	402.6	
2007	553.1	925.0	
2008	178.5	582.5	29.9
2009	670.3	284.0	39.2
2010	383.2	746.3	41.4
2011	235.0	388.6	32.2
2012	466.7	205.1	39.8
2013	121.5	361.6	28.2
2014	155.9	122.5	16.8
2015	50.6	47.5	12.1
2016	60.2	1.3	8.5
2017	39.8	3.1	8.6
2018	40.4	0.5	8.2
2019	32.5	0.1	7.6
2020	41.8	2.7	10.9
2021	37.4	1.4	8.3

Appendix 12 Trial Application of Tuned VPA with Accounting for Predation by Two Japanese Mackerel Species

A paper which estimated predation mortality in the Pacific stock of Japanese anchovy due to predation by mackerel species (Tanaka 2022) was released ahead of print on November 26, 2021. This report discusses results for a scenario using Tuned VPA which adjusts the natural mortality (M) of this stock according to the abundance of mackerel species (chub mackerel and blue mackerel) in the Pacific region (hereinafter referred to as “VPA with mackerel predation”). Therefore, we also performed trial calculations for abundance and other information based on VPA with mackerel predation for this year’s stock assessment, as in FY 2021. Although this Appendix does not explore stock-recruitment relationships and proposed reference points based on results using VPA with mackerel predation, that data has been published in separate materials which discuss the scenario where trial calculations are performed using data from the FY 2021 stock assessment (“Response to Matters Identified in the 2nd Stock Control Group on the Pacific Stock of Japanese Anchovy” (Fisheries Resources Institute, FRA-SA2022-BRP01)).

1. Materials and Methods

Trial calculations were performed for abundance and other information using VPA with mackerel predation based on Tanaka’s (2022) method. Data for catch in number by age, body weight by age, and other parameters of this stock was the same data that was used in the stock assessment (1978 to 2021), and the tuning years were the same years that were used in the original paper (1995 and after). Meanwhile, data for abundance (biomass) of the Pacific stock of chub mackerel and the Pacific stock of blue mackerel was taken from FY 2021 stock assessment results (Yukami et al. 2022, FRA-SA2021-SC03-1, FRA-SA2021-SC03-2), and future projections. In addition, Tanaka (2022) used data published in FY 2019 stock assessments (1995 to 2018), and performed sensitive and analytical calculations for the base case (S0) and 12 scenarios. This Appendix shows trial calculations for an expanded range of years for the base scenario (S0), a scenario with high rates of predation on older fish (S7) and a scenario with high rates of predation on younger fish (S8). The trial calculations were performed using a program included in R version 4.2.1 (R core team 2022).

Details including formulas for VPA with mackerel predation are presented in the original paper, so this Appendix will only explain the main assumptions. VPA with mackerel predation separates M_t (M in year t) into predation by mackerel species $M2_t$ (1/year) and all other natural mortality $M1$ (1/year).

$$M_t = M1 + M2_t \quad (12.1)$$

The base case assumes that 1) $M1$ is constant for all years, 2) $M2_t$ is not age-dependent, and 3) $M2_t$ relative to combined abundance of mackerel species, with equal predation pressure per unit weight for both chub mackerel and blue mackerel. The relationship between M and abundance of mackerel species, based on these assumptions, is expressed by the following equations.

$$M2_t = \sum_{i=1}^2 m_{i,t} \quad (12.2)$$

$$m_{i,t} = \alpha \bar{P}_{i,t} \quad (12.3)$$

$$M_\mu = M1 + \overline{M2} \quad (12.4)$$

$$\overline{M2} = \frac{1}{T} \sum_{t=1}^T M2_t \quad (12.5)$$

In these equations, $m_{i,t}$ represents the annual rate of predation mortality by mackerel i , and $i = 1, 2$ indicates the Pacific stock of chub mackerel and the Pacific stock of blue mackerel, respectively. In addition, α represents the predation mortality per unit weight of mackerel species abundance (1/year · tons), and $\bar{P}_{i,t}$ represents the annual average abundance of mackerel i . Calculations to find $\bar{P}_{i,t}$ are required in order to compare against the Pacific stock of Japanese anchovy, which does stock calculations with the fishing year set to January to December, because the fishing year of the Pacific stock of both chub mackerel and blue mackerel is set from July to June. Estimates for $M2_t$ in 1994 and earlier, when stock assessment results for the Pacific stock of blue mackerel are not available, only use stock assessment results for the Pacific stock of chub mackerel. In addition, M_μ is 1.375, which is the average of M by age (Supplementary Table 2-1) as used in the current stock assessment for the Pacific stock of Japanese anchovy. If we set limiting conditions that define M_μ as equal to \bar{M} , which is the average of M_t for the number of years T used in the stock assessment for the Pacific stock of Japanese anchovy, then a correlation can be maintained with previous stock assessments for the Pacific stock of Japanese anchovy. $\bar{P}_{i,t}$ is calculated using the following equation.

$$\bar{P}_{i,t} = \bar{N}_{t,a} w_{t,a} \quad (12.6)$$

$$\bar{N}_{t,a} = \frac{N_{t,a}(1 - e^{-F_{t,a} - M_{t,a}})}{F_{t,a} + M_{t,a}} \quad (12.7)$$

In these equations, $\bar{N}_{t,a}$ is the annual average of numbers at age of mackerel i , $w_{t,a}$ is body weight at age, $N_{t,a}$ is the numbers at age in fishing year calculations, $F_{t,a}$ is fishing mortality at age, and $M_{t,a}$ is M at age. In addition, tuning was performed using the following equation, which assumes that observation error of SSB in VPA follows a lognormal distribution.

$$B_t = \sum_{a=0}^A r_a w_{t,a} N_{t,a} \quad (12.8)$$

$$\ln(B_t) = \ln(\widehat{B}_t) + \varepsilon_t \quad (12.9)$$

$$\varepsilon_t \sim N\left(-\frac{\sigma^2}{2}, \sigma^2\right) \quad (12.10)$$

In these equations, r_a is the maturity rate at age, B_t is SSB estimated directly using the egg

production method (Supplementary Table 7-1, Area I to IV in Supplementary Fig. 7-3), and \widehat{B}_t is SSB in VPA with mackerel predation. Assuming that residuals ε_t follow a lognormal distribution, we performed exploratory calculations using the maximum likelihood method to find α (unknown parameters), θ (ratio of F of oldest fish to F of oldest fish - age 1 fish), and terminal F ($F_{2,T}$ which is the F of oldest fish - age 1 fish in the most recent year of stock assessment). Based on the definitions above, the negative log-likelihood function to be minimized is shown in the following equation (12.11).

$$-\ln L(F_{2,T}, \theta, \alpha) = \frac{n}{2} \ln \left(2\pi\sigma^2 + \frac{1}{n} \sum_{t=1}^n \{ \ln(B_t) - \ln(\widehat{B}_t(F_{2,T}, \theta, \alpha)) \} + \frac{\sigma^2}{2} \right) + \frac{n}{2} \quad (12.11)$$

In addition, in scenarios with age-dependent predation pressure (S7 and S8), calculations were performed using the age-dependent value $M_{t,a}$, which is defined by the following equations, to replace M_t , which is calculated using equations (12.1) and (12.2).

$$M_{t,a} = M1 + M2_{t,a} \quad (12.12)$$

$$M2_{t,a} = \sum_{i=1}^2 \beta_a m_{i,t} \quad (a = 0, 1, 2, 3) \quad (12.13)$$

$$M_\mu = M1 + \frac{1}{(3+1)T} \sum_{a=0}^3 \sum_{t=1}^T M2_{t,a} \quad (12.14)$$

$$\beta_a = \begin{cases} 0.8^{3-a} \\ 0.8^a \end{cases} \quad (a = 0, 1, 2, 3) \quad (12.15)$$

In these equations, the parameter β_a represents age-dependence in predation mortality, and 0.8 times was assumed to be the exponents of base 0.8.

2. Results of Trial Calculations Using VPA With Mackerel Predation

Parameter estimates for each scenario using VPA with mackerel predation are shown in Supplementary Table 12-1. Both positive log-likelihood and c-AIC were not significantly different between scenarios, and similar to Tanaka (2022), we could not demonstrate significant improvement in likelihood under the assumption of an age gradient in predation pressure. Results for terminal F ($F_{2021,2}$) were lowest in S7, followed by S0, and highest in S8, while θ and M1 showed an inverse relationship with terminal F. Results for α were lowest in S0, followed by S7, and highest in S8.

Estimated SSB, recruitment volume, and other indices from results of VPA with mackerel predation, the estimation method used up to FY 2021 (VPA without tuning), and this year's stock assessment (Tuned VPA) are shown in Supplementary Fig. 12-1 and Supplementary Tables 12-2 to 12-4. Recruitment volume estimated using Tuned VPA and VPA without tuning was in a decreasing trend since the 2000s, and has remained at low levels in recent years, but recruitment volume in trial calculations using VPA with mackerel predation was at record high levels in 2019 in S0 and S8, and in 2008 in S7, and remained at relatively high levels in recent years in each scenario. In addition, SSB results from trial calculations using VPA with mackerel predation showed much higher levels than SSB from Tuned VPA and VPA without tuning from 2004 to 2014, and 2019 to 2021.

Numbers at age, biomass, natural mortality M , fishing mortality, and exploitation rate at age are shown in Supplementary Fig. 12-2. Numbers at age and biomass of fish age 1 and 2 from VPA with mackerel predation were relatively higher than estimates from VPA without tuning and Tuned VPA in 2004 and onwards, and levels of fish age 0 and 3 were high across most years. Estimates of natural mortality from VPA with mackerel predation were higher than estimated from VPA without tuning and Tuned VPA for fish age 0 to 1 across all years, and were higher for fish age 2 in 2013 and onwards, but were generally low and varied by scenario for fish age 3 (Supplementary Fig. 12-2, Supplementary Tables 12-2 to 12-4). Estimates for fishing mortality and exploitation rate from VPA without tuning and Tuned VPA were higher than estimates from VPA with mackerel predation for all ages, with a rather prominent difference in 2006 and after.

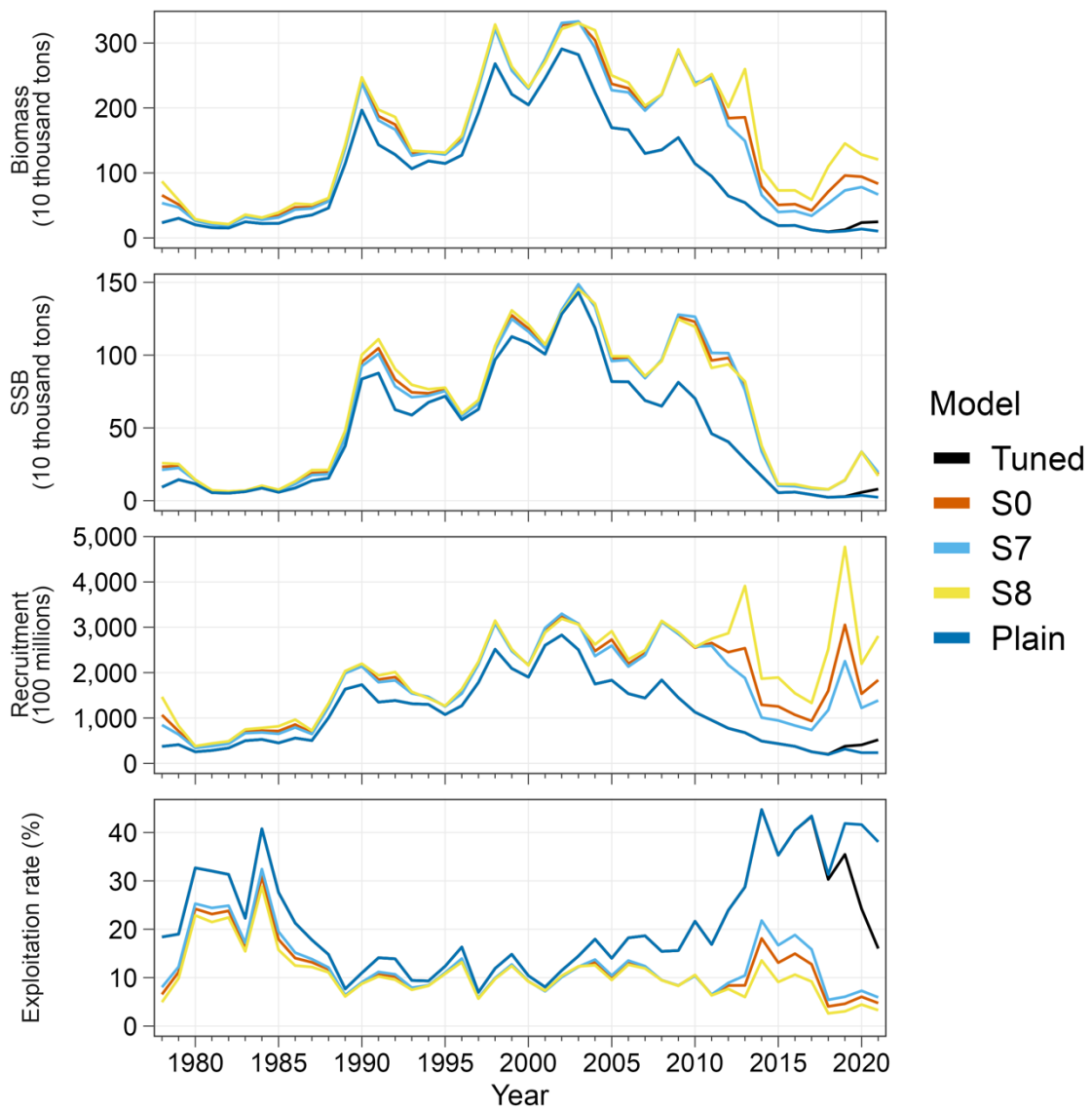
Results (residual plots) that show the fit of VPA with mackerel predation against index values (SSB according to the egg production method) are shown in Supplementary Fig. 12-3. First-order autocorrelation of residuals was not significant in any scenario. However, standardized residuals tended to be increasingly larger in recent years across all scenarios.

3. Summary

Results of trial calculations using VPA with mackerel predation are presented in this Appendix, but in order to determine the validity of the assumption in this VPA that M in this stock is proportional to the biomass of the Pacific stock of mackerel species, further research into biological findings regarding predation by mackerel species is required.

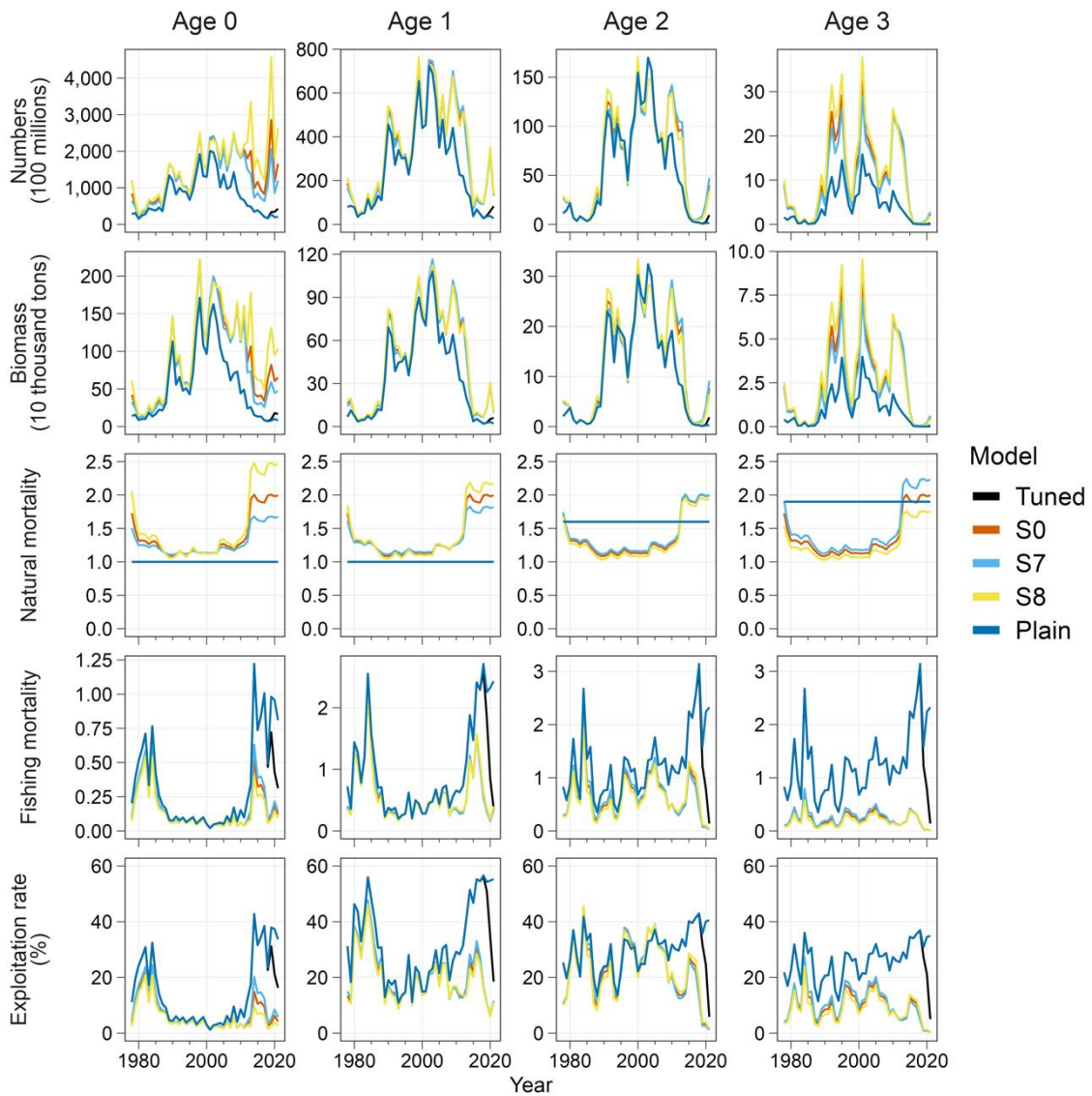
References

- R Core Team (2022) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>.
- Tanaka, E. (2022) Estimation of predation mortality rates of the Pacific stock of Japanese anchovy by the Pacific stocks of mackerel. *Fish. Sci.*, 88 (1), p.2-11. <https://doi.org/10.2331/suisan.20-00067> (in Japanese with English abstract)
- Fisheries Resources Institute (2022) Response to Matters Identified in the 2nd Stock Control Method Study Group on the Pacific Stock of Japanese Anchovy. FRA-SA2022-BRP01. (in Japanese)
- Yukami, R., Nishijima, S., Kamimura, Y., Furuichi, S., Watanabe, R. (2022) Stock Assessment for Pacific Stock of Chub Mackerel (Fiscal Year 2021). FRA-SA2021-SC03-1 (in Japanese)
- Yukami, R., Nishijima, S., Kamimura, Y., Furuichi, S., Watanabe, R. (2022) Stock Assessment for Pacific Stock of Blue Mackerel (Fiscal Year 2021). FRA-SA2021-SC03-2 (in Japanese)

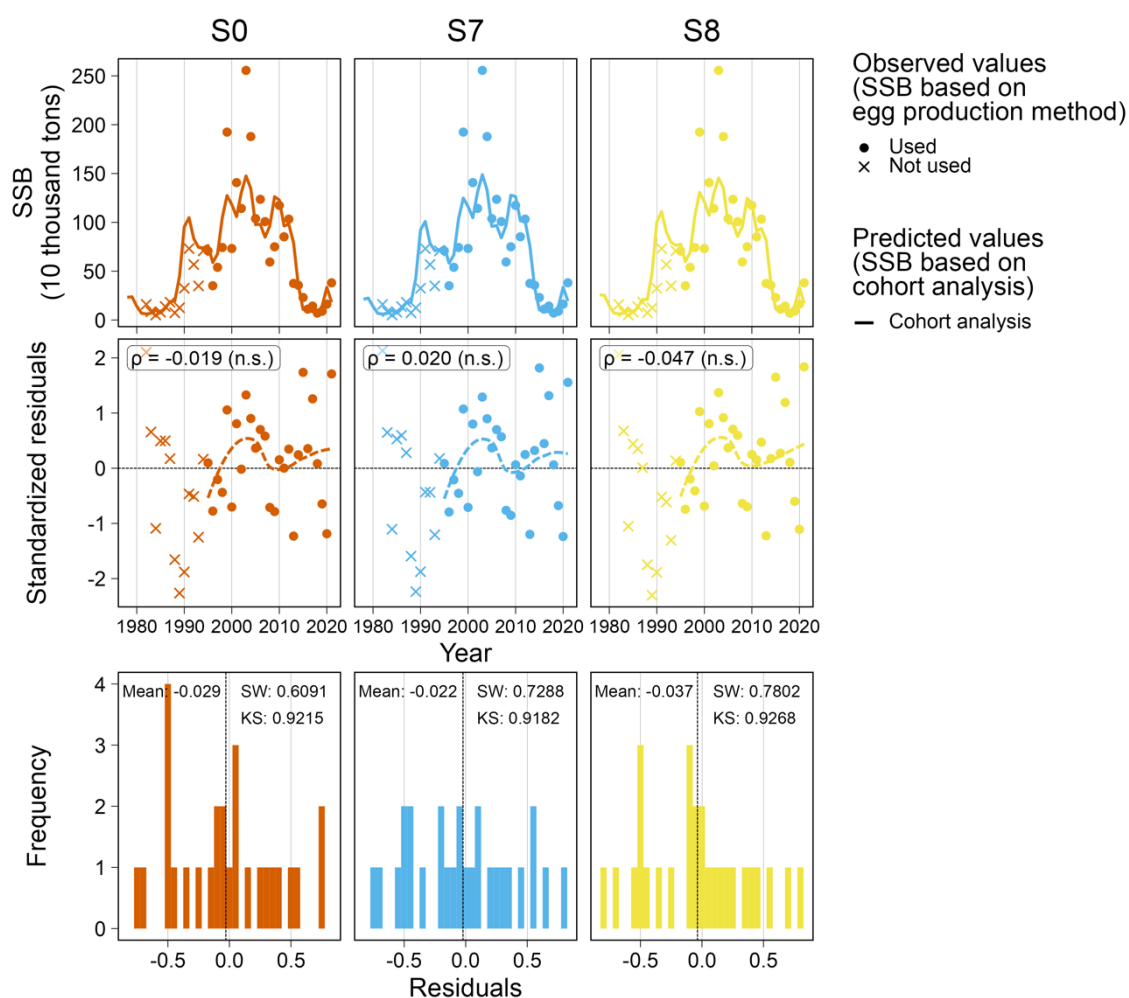


Supplementary Figure 12-1. Trends in biomass, SSB, recruitment volume, and exploitation rate from VPA with mackerel predation, VPA without tuning, and Tuned VPA

In these graphs, the colored lines represent different models. Tuned: Tuned VPA proposed this year, S0: Base case in VPA with mackerel predation, S7: Scenario with high rates of predation on older fish, S8: Scenario with high rates of predation on younger fish, Plain: Method used up to FY 2021 (VPA without tuning).



Supplementary Fig. 12-2. Trends in biomass, numbers at age, natural mortality, fishing mortality, and exploitation rate at age from VPA with mackerel predation, VPA without tuning, and Tuned VPA. In these graphs, the colored lines represent different models. Tuned: Tuned VPA proposed this year, S0: Base case in VPA with mackerel predation, S7: Scenario with high rates of predation on older fish, S8: Scenario with high rates of predation on younger fish, Plain: Method used up to FY 2021 (VPA without tuning).



Supplementary Fig. 12-3. Residual plots of VPA with mackerel predation

From left to right, these graphs show the base scenario (S0), a scenario with high rates of predation on older fish (S7) and a scenario with high rates of predation on younger fish (S8). In the top row, which shows trends in projected values and observed values, the solid line indicates trends in SSB estimates from cohort analysis, circles indicate data used for tuning, and \times marks indicate data not used for tuning. In the middle row, which shows standardized residual panels, the value in the upper left corner is the autocorrelation coefficient (AR1) of the standardized residuals, which was not significant in any of the scenarios for VPA with mackerel predation. The dashed lines represent the smoothing curves for the standardized residuals. In the bottom row, which shows histograms of residuals, the numbers in the upper right corners are P-Values from the Shapiro-Wilk test (SW) and the Kolmogorov-Smirnov test (KS). In all scenarios, the null hypothesis was found to follow a normal distribution.

Supplementary Table 12-1. Estimated parameters

M1 corresponds to the constrained parameters in Table 1 of the report by Tanaka (2022).

Scenario Name	Positive log-likelihood	c-AIC	$F_{2021,2}$	θ	α ($\times 10^{(-6)}$ / tons / year)	M1 (/year)
S0	-14.7465	38.5187	0.0383	0.3328	0.2095	1.0531
S7	-14.8305	38.6866	0.0325	0.3649	0.2543	1.0866
S8	-14.8136	38.6529	0.0446	0.2953	0.3248	1.0066

Supplementary Table 12-2. Detailed results of S0 (base case) in VPA with mackerel predation

Year	Numbers at age (millions)				Fishing mortality at age				M2			
	Age 0	Age 1	Age 2	Age 3	Age 0	Age 1	Age 2	Age 3	Age 0	Age 1	Age 2	Age 3
1978	84,121.0	18,801.7	2,779.7	903.5	0.09	0.38	0.28	0.09	0.68	0.68	0.68	0.68
1979	54,783.3	13,621.4	2,278.4	371.9	0.26	0.27	0.30	0.10	0.42	0.42	0.42	0.42
1980	23,194.4	9,615.2	2,375.5	384.8	0.37	1.30	0.61	0.20	0.26	0.26	0.26	0.26
1981	34,970.8	4,298.6	702.8	347.2	0.46	1.09	1.18	0.39	0.27	0.27	0.27	0.27
1982	39,076.4	5,913.7	384.2	57.3	0.57	0.74	0.65	0.22	0.26	0.26	0.26	0.26
1983	63,168.8	5,962.0	758.1	54.0	0.26	1.17	0.53	0.18	0.21	0.21	0.21	0.21
1984	57,509.4	13,797.7	521.2	125.5	0.58	2.33	2.09	0.70	0.25	0.25	0.25	0.25
1985	62,185.6	8,715.4	364.6	17.4	0.28	1.33	0.87	0.29	0.25	0.25	0.25	0.25
1986	72,165.7	12,773.8	628.7	41.6	0.18	0.77	0.81	0.27	0.18	0.18	0.18	0.18
1987	48,124.5	17,582.1	1,727.7	81.7	0.15	0.53	0.25	0.08	0.12	0.12	0.12	0.12
1988	110,356.8	12,781.2	3,216.1	415.7	0.13	0.62	0.19	0.06	0.07	0.07	0.07	0.07
1989	165,368.2	31,500.6	2,238.0	868.6	0.07	0.21	0.40	0.13	0.04	0.04	0.04	0.04
1990	154,717.0	52,055.3	8,573.5	504.4	0.06	0.34	0.48	0.16	0.03	0.03	0.03	0.03
1991	121,487.8	49,089.1	12,512.5	1,793.4	0.07	0.29	0.49	0.16	0.05	0.05	0.05	0.05
1992	138,095.8	37,354.0	12,163.2	2,542.3	0.06	0.28	0.70	0.23	0.11	0.11	0.11	0.11
1993	103,995.0	40,816.5	8,837.9	1,897.0	0.09	0.17	0.28	0.09	0.07	0.07	0.07	0.07
1994	101,231.5	30,823.8	11,138.1	2,166.8	0.06	0.26	0.24	0.08	0.04	0.04	0.04	0.04
1995	83,320.3	31,837.8	7,928.0	2,917.3	0.07	0.29	0.54	0.18	0.08	0.08	0.08	0.08
1996	123,908.3	24,919.5	7,662.5	1,483.7	0.08	0.62	1.14	0.38	0.14	0.14	0.14	0.14
1997	181,104.1	34,630.2	4,078.4	746.1	0.04	0.20	1.04	0.34	0.10	0.10	0.10	0.10
1998	247,011.9	54,698.2	8,961.8	457.2	0.06	0.47	0.82	0.27	0.07	0.07	0.07	0.07
1999	162,010.5	75,025.9	11,038.9	1,275.2	0.09	0.41	0.79	0.26	0.08	0.08	0.08	0.08
2000	151,422.7	47,741.3	16,062.6	1,606.3	0.05	0.28	0.47	0.16	0.08	0.08	0.08	0.08
2001	232,673.4	46,715.6	11,720.7	3,245.8	0.02	0.30	0.61	0.20	0.07	0.07	0.07	0.07
2002	238,164.5	74,009.0	11,272.9	2,062.2	0.04	0.48	0.67	0.22	0.08	0.08	0.08	0.08
2003	218,001.8	73,445.3	14,772.2	1,860.4	0.04	0.48	1.10	0.37	0.07	0.07	0.07	0.07
2004	163,572.5	67,658.1	14,721.0	1,595.7	0.04	0.64	1.11	0.37	0.21	0.21	0.21	0.21
2005	216,844.8	44,422.3	10,155.1	1,382.1	0.04	0.39	1.33	0.44	0.22	0.22	0.22	0.22
2006	151,851.3	58,846.0	8,499.2	753.3	0.08	0.61	0.87	0.29	0.18	0.18	0.18	0.18
2007	191,442.3	40,838.7	9,241.3	1,035.8	0.04	0.61	0.83	0.28	0.17	0.17	0.17	0.17
2008	250,371.3	54,266.6	6,531.5	1,191.9	0.10	0.25	0.74	0.25	0.13	0.13	0.13	0.13
2009	202,813.0	68,962.9	12,874.7	952.7	0.04	0.37	0.41	0.14	0.19	0.19	0.19	0.19
2010	182,395.5	56,476.4	13,749.4	2,461.6	0.07	0.37	0.52	0.17	0.22	0.22	0.22	0.22
2011	204,607.7	47,614.4	10,894.8	2,276.3	0.04	0.30	0.39	0.13	0.26	0.26	0.26	0.26
2012	180,387.3	53,236.9	9,528.3	1,998.9	0.07	0.30	0.32	0.11	0.35	0.35	0.35	0.35
2013	200,993.1	41,442.1	9,685.9	1,699.3	0.12	0.49	0.44	0.15	0.89	0.89	0.89	0.89
2014	98,840.0	25,645.2	3,636.7	894.8	0.52	1.19	0.52	0.17	0.95	0.95	0.95	0.95
2015	116,210.5	7,904.3	1,054.2	290.0	0.32	0.86	1.24	0.41	0.87	0.87	0.87	0.87
2016	94,139.6	12,327.7	490.1	44.9	0.34	1.56	1.06	0.35	0.84	0.84	0.84	0.84
2017	82,788.7	10,085.6	388.1	25.4	0.28	1.09	0.96	0.32	0.83	0.83	0.83	0.83
2018	149,853.1	9,481.4	511.8	22.5	0.07	0.59	0.52	0.17	0.94	0.94	0.94	0.94
2019	285,585.7	18,999.2	719.3	41.7	0.11	0.34	0.09	0.03	0.95	0.95	0.95	0.95
2020	116,933.3	34,590.9	1,820.0	88.1	0.18	0.18	0.09	0.03	0.93	0.93	0.93	0.93
2021	165,925.1	13,429.7	3,996.9	229.8	0.12	0.37	0.04	0.01	0.94	0.94	0.94	0.94

Supplementary Table 12-2. (continued)

Year	Biomass at age (thousand tons)				Biomass (thousand tons)	SSB (thousand tons)	Catch (thousand tons)	Exploitation rate (%)
	Age 0	Age 1	Age 2	Age 3				
1978	423.7	158.9	50.7	23.0	656.3	232.6	43.0	6.6
1979	277.0	183.7	45.2	8.9	514.8	237.7	57.4	11.2
1980	131.0	91.4	41.3	8.7	272.4	141.4	66.0	24.2
1981	149.5	44.8	14.9	9.6	218.7	69.3	50.6	23.1
1982	137.6	53.7	7.1	1.4	199.8	62.2	47.5	23.8
1983	267.6	55.5	12.1	1.1	336.4	68.8	55.2	16.4
1984	191.0	87.8	9.4	3.3	291.5	100.5	90.0	30.9
1985	271.6	65.8	5.6	0.3	343.2	71.7	61.4	17.9
1986	349.6	111.8	7.9	1.2	470.4	120.8	66.1	14.0
1987	287.2	162.2	24.7	1.9	476.1	188.8	62.7	13.2
1988	388.4	131.6	51.8	9.1	580.9	192.5	68.1	11.7
1989	947.5	377.5	45.4	24.4	1,394.8	447.3	87.8	6.3
1990	1,461.9	789.5	152.1	11.4	2,414.9	953.0	215.9	8.9
1991	826.5	756.1	250.1	41.3	1,874.1	1,047.5	202.3	10.8
1992	912.1	530.7	244.4	57.3	1,744.4	832.4	178.3	10.2
1993	551.0	536.3	165.2	42.8	1,295.2	744.2	100.5	7.8
1994	580.0	465.4	218.4	54.0	1,317.9	737.9	110.4	8.4
1995	533.5	508.9	174.5	79.4	1,296.2	762.7	141.7	10.9
1996	936.3	392.7	158.9	36.8	1,524.7	588.4	207.9	13.6
1997	1,660.4	568.5	89.7	18.9	2,337.5	677.1	134.5	5.8
1998	2,198.1	876.6	161.9	9.8	3,246.5	1,048.4	319.4	9.8
1999	1,328.8	1,030.8	212.9	30.4	2,602.8	1,274.0	328.0	12.6
2000	1,124.4	829.1	314.6	38.8	2,306.9	1,182.4	213.1	9.2
2001	1,677.3	723.1	252.9	82.0	2,735.2	1,057.9	197.9	7.2
2002	1,968.0	1,030.1	221.0	53.1	3,272.1	1,304.1	334.4	10.2
2003	1,854.3	1,149.3	281.6	44.4	3,329.6	1,475.3	408.0	12.3
2004	1,696.7	1,029.8	280.1	36.0	3,042.7	1,346.0	401.9	13.2
2005	1,393.6	738.7	205.2	32.8	2,370.3	976.7	237.7	10.0
2006	1,324.2	803.2	159.3	17.6	2,304.4	980.2	303.4	13.2
2007	1,139.7	645.0	180.0	23.6	1,988.3	848.6	242.5	12.2
2008	1,241.7	797.1	137.0	28.6	2,204.4	962.7	209.1	9.5
2009	1,616.2	1,003.0	239.0	20.8	2,879.1	1,262.9	240.9	8.4
2010	1,125.9	885.1	283.2	60.4	2,354.5	1,228.7	247.6	10.5
2011	1,514.8	688.7	219.2	55.4	2,478.0	963.3	160.0	6.5
2012	862.1	745.6	184.6	50.4	1,842.7	980.6	154.5	8.4
2013	1,066.2	548.2	201.4	41.0	1,856.7	790.5	156.0	8.4
2014	438.9	260.1	73.1	23.0	795.1	356.1	144.0	18.1
2015	399.6	78.4	22.1	7.6	507.8	108.1	66.5	13.1
2016	414.2	95.9	8.4	1.0	519.5	105.3	77.7	15.0
2017	337.0	78.7	6.0	0.6	422.3	85.3	53.9	12.8
2018	634.1	69.0	7.7	0.4	711.2	77.1	28.9	4.1
2019	819.3	130.9	9.3	0.7	960.2	140.8	44.3	4.6
2020	606.8	302.0	31.6	1.7	942.0	335.3	57.0	6.1
2021	652.2	98.7	77.5	5.1	833.5	181.3	39.6	4.8

Supplementary Table 12-3. Detailed results of S7 (high rates of predation on older fish) in VPA with mackerel predation

Year	Numbers at age (millions)				Fishing mortality at age				M2			
	Age 0	Age 1	Age 2	Age 3	Age 0	Age 1	Age 2	Age 3	Age 0	Age 1	Age 2	Age 3
1978	64,374.6	16,698.7	2,668.9	858.6	0.11	0.41	0.30	0.11	0.42	0.53	0.66	0.82
1979	48,352.9	12,807.0	2,210.0	346.5	0.28	0.28	0.32	0.12	0.26	0.33	0.41	0.51
1980	21,606.4	9,450.2	2,350.7	359.9	0.39	1.31	0.63	0.23	0.16	0.20	0.26	0.32
1981	32,671.5	4,203.2	699.3	328.1	0.48	1.11	1.23	0.45	0.17	0.21	0.26	0.33
1982	36,990.2	5,795.4	378.6	53.3	0.59	0.75	0.68	0.25	0.16	0.20	0.25	0.31
1983	59,812.4	5,910.1	754.1	50.5	0.27	1.18	0.55	0.20	0.13	0.16	0.21	0.26
1984	53,805.8	13,564.3	521.7	119.8	0.61	2.38	2.18	0.80	0.16	0.20	0.25	0.31
1985	56,272.5	8,439.1	348.4	15.5	0.30	1.39	0.95	0.35	0.16	0.19	0.24	0.30
1986	66,510.9	12,002.9	585.7	35.5	0.19	0.84	0.93	0.34	0.11	0.14	0.17	0.22
1987	46,482.0	16,545.3	1,518.7	65.8	0.16	0.57	0.30	0.11	0.07	0.09	0.12	0.15
1988	108,234.3	12,430.7	2,868.0	338.8	0.14	0.66	0.22	0.08	0.04	0.05	0.06	0.08
1989	165,191.9	30,535.0	2,066.6	728.6	0.07	0.22	0.45	0.16	0.02	0.03	0.04	0.04
1990	154,401.6	50,937.5	8,015.7	428.5	0.06	0.35	0.53	0.19	0.02	0.03	0.03	0.04
1991	117,560.0	47,955.1	11,761.6	1,536.5	0.08	0.30	0.54	0.20	0.03	0.04	0.05	0.06
1992	133,584.2	35,546.1	11,489.7	2,196.5	0.06	0.30	0.78	0.28	0.07	0.08	0.10	0.13
1993	104,863.7	39,670.0	8,175.2	1,606.5	0.09	0.18	0.31	0.11	0.05	0.06	0.07	0.09
1994	103,342.9	30,915.0	10,564.6	1,880.7	0.06	0.26	0.26	0.10	0.03	0.03	0.04	0.05
1995	82,898.2	31,987.7	7,745.4	2,626.8	0.07	0.29	0.57	0.21	0.05	0.06	0.08	0.10
1996	120,302.9	24,727.1	7,576.1	1,365.2	0.09	0.63	1.20	0.44	0.09	0.11	0.13	0.17
1997	179,218.0	34,184.2	4,003.0	676.0	0.05	0.20	1.10	0.40	0.06	0.08	0.10	0.12
1998	244,944.6	54,325.0	8,709.8	407.8	0.07	0.48	0.88	0.32	0.05	0.06	0.07	0.09
1999	161,747.9	73,932.6	10,677.5	1,131.7	0.09	0.42	0.86	0.31	0.05	0.06	0.08	0.10
2000	152,912.5	47,529.2	15,412.1	1,414.8	0.05	0.28	0.51	0.18	0.05	0.06	0.07	0.09
2001	237,110.9	46,966.8	11,430.0	2,912.0	0.02	0.30	0.65	0.24	0.05	0.06	0.07	0.09
2002	241,776.7	75,004.9	11,127.8	1,880.4	0.04	0.47	0.70	0.25	0.05	0.06	0.08	0.10
2003	216,786.4	74,400.5	14,793.7	1,731.1	0.04	0.48	1.13	0.41	0.05	0.06	0.07	0.09
2004	153,458.6	66,892.6	14,701.5	1,504.2	0.04	0.64	1.14	0.41	0.13	0.16	0.20	0.25
2005	204,521.3	43,510.6	10,123.3	1,301.6	0.04	0.39	1.38	0.50	0.13	0.17	0.21	0.26
2006	145,983.5	58,154.5	8,392.5	696.2	0.08	0.62	0.91	0.33	0.11	0.14	0.18	0.22
2007	187,737.6	40,629.5	9,137.5	957.1	0.04	0.61	0.86	0.31	0.10	0.13	0.16	0.20
2008	249,613.4	54,829.6	6,506.3	1,107.0	0.10	0.25	0.76	0.28	0.08	0.10	0.13	0.16
2009	201,196.7	0.0	12,988.1	902.2	0.03	0.36	0.41	0.15	0.12	0.15	0.18	0.23
2010	182,215.3	58,248.8	14,187.7	2,408.2	0.06	0.35	0.51	0.19	0.14	0.17	0.22	0.27
2011	194,991.3	50,155.6	11,618.8	2,313.8	0.04	0.28	0.36	0.13	0.16	0.20	0.25	0.31
2012	150,096.8	54,047.5	10,500.8	2,125.7	0.08	0.29	0.29	0.11	0.22	0.27	0.34	0.42
2013	138,216.7	37,617.6	10,406.7	1,886.6	0.15	0.50	0.41	0.15	0.55	0.69	0.86	1.08
2014	72,811.2	23,092.3	3,853.4	988.6	0.63	1.22	0.49	0.18	0.59	0.74	0.92	1.16
2015	85,813.5	7,229.9	1,095.1	316.7	0.39	0.87	1.16	0.42	0.54	0.67	0.84	1.05
2016	71,328.3	11,439.3	519.5	50.0	0.40	1.55	0.97	0.35	0.52	0.65	0.82	1.02
2017	63,527.0	9,574.4	424.1	29.4	0.32	1.05	0.84	0.31	0.52	0.65	0.81	1.01
2018	107,600.2	9,236.3	592.8	27.5	0.09	0.54	0.43	0.16	0.58	0.73	0.91	1.14
2019	205,778.4	18,561.8	875.5	52.3	0.13	0.31	0.08	0.03	0.59	0.74	0.92	1.16
2020	86,043.4	33,876.1	2,181.7	108.4	0.22	0.17	0.07	0.03	0.58	0.72	0.90	1.13
2021	120,488.7	13,140.4	4,713.3	277.8	0.14	0.34	0.03	0.01	0.59	0.73	0.91	1.14

Supplementary Table 12-3. (continued)

Year	Biomass at age (thousand tons)				Biomass (thousand tons)	SSB (thousand tons)	Catch (thousand tons)	Exploitation rate (%)
	Age 0	Age 1	Age 2	Age 3				
1978	324.3	141.1	48.7	21.9	535.9	211.6	43.0	8.0
1979	244.5	172.7	43.8	8.3	469.3	224.8	57.4	12.2
1980	122.0	89.8	40.9	8.1	260.8	138.8	66.0	25.3
1981	139.7	43.8	14.8	9.0	207.3	67.7	50.6	24.4
1982	130.2	52.7	7.0	1.3	191.2	60.9	47.5	24.9
1983	253.4	55.1	12.1	1.1	321.6	68.2	55.2	17.2
1984	178.7	86.3	9.4	3.1	277.5	98.8	90.0	32.4
1985	245.8	63.7	5.3	0.3	315.1	69.3	61.4	19.5
1986	322.2	105.0	7.3	1.0	435.6	113.3	66.1	15.2
1987	277.4	152.6	21.7	1.6	453.3	175.9	62.7	13.8
1988	381.0	128.0	46.2	7.4	562.6	181.6	68.1	12.1
1989	946.5	365.9	41.9	20.5	1,374.8	428.4	87.8	6.4
1990	1,458.9	772.6	142.2	9.7	2,383.3	924.4	215.9	9.1
1991	799.8	738.7	235.1	35.4	1,809.0	1,009.1	202.3	11.2
1992	882.3	505.0	230.9	49.5	1,667.6	785.4	178.3	10.7
1993	555.6	521.2	152.8	36.2	1,265.8	710.2	100.5	7.9
1994	592.1	466.8	207.2	46.9	1,313.0	720.9	110.4	8.4
1995	530.8	511.3	170.4	71.5	1,284.0	753.2	141.7	11.0
1996	909.1	389.7	157.1	33.9	1,489.7	580.6	207.9	14.0
1997	1,643.1	561.1	88.1	17.2	2,309.5	666.4	134.5	5.8
1998	2,179.7	870.6	157.3	8.8	3,216.5	1,036.8	319.4	9.9
1999	1,326.6	1,015.7	205.9	26.9	2,575.2	1,248.6	328.0	12.7
2000	1,135.5	825.4	301.8	34.2	2,296.9	1,161.4	213.1	9.3
2001	1,709.3	727.0	246.6	73.5	2,756.4	1,047.1	197.9	7.2
2002	1,997.8	1,043.9	218.1	48.4	3,308.3	1,310.4	334.4	10.1
2003	1,844.0	1,164.3	282.1	41.3	3,331.6	1,487.6	408.0	12.2
2004	1,591.8	1,018.1	279.8	34.0	2,923.7	1,331.9	401.9	13.7
2005	1,314.4	723.5	204.6	30.9	2,273.4	959.0	237.7	10.5
2006	1,273.0	793.8	157.3	16.3	2,240.4	967.4	303.4	13.5
2007	1,117.7	641.7	178.0	21.8	1,959.1	841.5	242.5	12.4
2008	1,237.9	805.4	136.4	26.6	2,206.4	968.4	209.1	9.5
2009	1,603.3	1,017.4	241.1	19.7	2,881.5	1,278.2	240.9	8.4
2010	1,124.8	912.9	292.2	59.1	2,388.9	1,264.2	247.6	10.4
2011	1,443.6	725.4	233.7	56.3	2,459.1	1,015.5	160.0	6.5
2012	717.3	756.9	203.4	53.6	1,731.3	1,014.0	154.5	8.9
2013	733.2	497.6	216.3	45.5	1,492.6	759.4	156.0	10.5
2014	323.3	234.2	77.5	25.4	660.4	337.0	144.0	21.8
2015	295.1	71.7	23.0	8.3	398.1	103.0	66.5	16.7
2016	313.9	88.9	8.9	1.1	412.8	99.0	77.7	18.8
2017	258.6	74.7	6.6	0.7	340.6	82.0	53.9	15.8
2018	455.3	67.2	8.9	0.5	532.0	76.7	28.9	5.4
2019	590.4	127.9	11.3	0.9	730.4	140.0	44.3	6.1
2020	446.5	295.7	37.9	2.1	782.2	335.7	57.0	7.3
2021	473.6	96.6	91.4	6.1	667.7	194.1	39.6	5.9

Supplementary Table 12-4. Detailed results of S8 (high rates of predation on younger fish) in VPA with mackerel predation

Year	Numbers at age (millions)				Fishing mortality at age				M2			
	Age 0	Age 1	Age 2	Age 3	Age 0	Age 1	Age 2	Age 3	Age 0	Age 1	Age 2	Age 3
1978	121,518.5	21,264.4	2,898.5	994.7	0.07	0.35	0.26	0.08	1.05	0.84	0.67	0.54
1979	65,282.3	14,461.1	2,361.6	417.0	0.24	0.26	0.28	0.08	0.66	0.53	0.42	0.34
1980	25,555.3	9,730.7	2,409.3	427.8	0.35	1.29	0.58	0.17	0.41	0.33	0.26	0.21
1981	38,440.2	4,382.7	706.2	381.2	0.43	1.07	1.12	0.33	0.42	0.33	0.27	0.21
1982	42,176.6	6,020.7	392.6	64.4	0.55	0.73	0.61	0.18	0.40	0.32	0.26	0.20
1983	68,081.3	5,975.9	768.4	60.3	0.24	1.17	0.51	0.15	0.33	0.26	0.21	0.17
1984	63,352.4	14,016.7	520.0	136.9	0.54	2.25	1.95	0.58	0.39	0.32	0.25	0.20
1985	72,250.9	9,076.0	393.0	21.0	0.25	1.24	0.74	0.22	0.39	0.31	0.25	0.20
1986	81,641.0	13,980.7	705.0	53.2	0.16	0.67	0.66	0.19	0.28	0.22	0.18	0.14
1987	50,909.9	19,230.9	2,090.7	111.6	0.15	0.46	0.20	0.06	0.19	0.15	0.12	0.10
1988	114,403.3	13,360.3	3,812.9	556.5	0.13	0.57	0.15	0.05	0.10	0.08	0.07	0.05
1989	166,728.5	33,164.3	2,532.1	1,118.8	0.07	0.20	0.34	0.10	0.06	0.04	0.04	0.03
1990	155,571.5	53,976.5	9,524.4	638.3	0.06	0.32	0.41	0.12	0.05	0.04	0.03	0.03
1991	126,998.9	50,800.7	13,771.7	2,241.6	0.07	0.27	0.42	0.12	0.08	0.07	0.05	0.04
1992	144,955.0	39,895.9	13,238.5	3,139.9	0.06	0.26	0.60	0.18	0.16	0.13	0.11	0.08
1993	103,035.3	42,444.7	9,870.3	2,389.6	0.09	0.16	0.24	0.07	0.11	0.09	0.07	0.06
1994	98,088.2	30,711.8	12,038.9	2,639.0	0.06	0.26	0.22	0.06	0.07	0.06	0.04	0.04
1995	83,641.4	31,494.0	8,221.2	3,391.4	0.07	0.29	0.50	0.15	0.13	0.10	0.08	0.07
1996	129,190.7	25,045.9	7,790.0	1,679.9	0.08	0.61	1.06	0.31	0.21	0.17	0.14	0.11
1997	183,816.4	35,155.5	4,196.5	862.1	0.04	0.19	0.95	0.28	0.15	0.12	0.10	0.08
1998	249,564.6	55,093.1	9,359.2	538.8	0.06	0.46	0.74	0.22	0.11	0.09	0.07	0.06
1999	162,159.3	76,301.6	11,589.4	1,511.2	0.09	0.39	0.71	0.21	0.13	0.10	0.08	0.06
2000	149,173.9	47,859.4	17,029.9	1,916.6	0.05	0.27	0.42	0.13	0.12	0.09	0.08	0.06
2001	226,365.4	46,207.2	12,148.6	3,777.4	0.02	0.29	0.56	0.17	0.11	0.09	0.07	0.06
2002	232,574.5	72,412.5	11,490.4	2,349.2	0.04	0.48	0.63	0.19	0.13	0.10	0.08	0.06
2003	217,589.0	71,766.6	14,771.1	2,066.4	0.04	0.49	1.05	0.31	0.12	0.09	0.07	0.06
2004	177,615.5	67,909.3	14,721.0	1,749.8	0.04	0.63	1.06	0.31	0.32	0.26	0.21	0.16
2005	234,568.3	45,172.3	10,176.3	1,519.7	0.03	0.38	1.26	0.37	0.33	0.27	0.21	0.17
2006	160,386.1	59,317.6	8,653.3	849.2	0.07	0.61	0.81	0.24	0.28	0.23	0.18	0.15
2007	197,975.2	40,926.4	9,408.7	1,169.1	0.04	0.61	0.78	0.23	0.26	0.21	0.17	0.13
2008	252,554.8	53,616.7	6,614.0	1,339.9	0.10	0.25	0.70	0.21	0.21	0.16	0.13	0.11
2009	207,632.5	67,706.0	12,889.4	1,051.1	0.04	0.38	0.40	0.12	0.30	0.24	0.19	0.15
2010	185,954.0	54,531.2	13,398.4	2,618.0	0.07	0.39	0.52	0.15	0.35	0.28	0.22	0.18
2011	217,300.7	44,887.4	10,257.6	2,324.8	0.04	0.32	0.40	0.12	0.40	0.32	0.26	0.20
2012	224,806.2	51,428.9	8,633.1	1,941.3	0.06	0.32	0.35	0.10	0.54	0.43	0.34	0.28
2013	335,404.7	45,153.8	8,843.3	1,569.5	0.09	0.49	0.48	0.14	1.37	1.10	0.88	0.70
2014	154,063.2	28,404.6	3,359.5	829.7	0.40	1.16	0.56	0.17	1.48	1.18	0.94	0.76
2015	179,335.2	8,609.9	997.1	272.2	0.25	0.85	1.31	0.39	1.35	1.08	0.86	0.69
2016	140,764.3	13,284.3	456.7	41.5	0.27	1.58	1.15	0.34	1.31	1.04	0.84	0.67
2017	122,050.5	10,639.2	353.3	22.8	0.23	1.14	1.08	0.32	1.29	1.03	0.83	0.66
2018	241,402.9	9,748.4	440.8	19.2	0.06	0.64	0.61	0.18	1.46	1.17	0.93	0.75
2019	457,140.3	19,424.4	586.6	34.6	0.08	0.37	0.11	0.03	1.48	1.18	0.95	0.76
2020	182,882.6	35,125.3	1,505.3	74.3	0.15	0.19	0.11	0.03	1.44	1.15	0.92	0.74
2021	263,564.3	13,717.0	3,351.7	197.2	0.09	0.40	0.04	0.01	1.46	1.17	0.93	0.75

Supplementary Table 12-4. (continued)

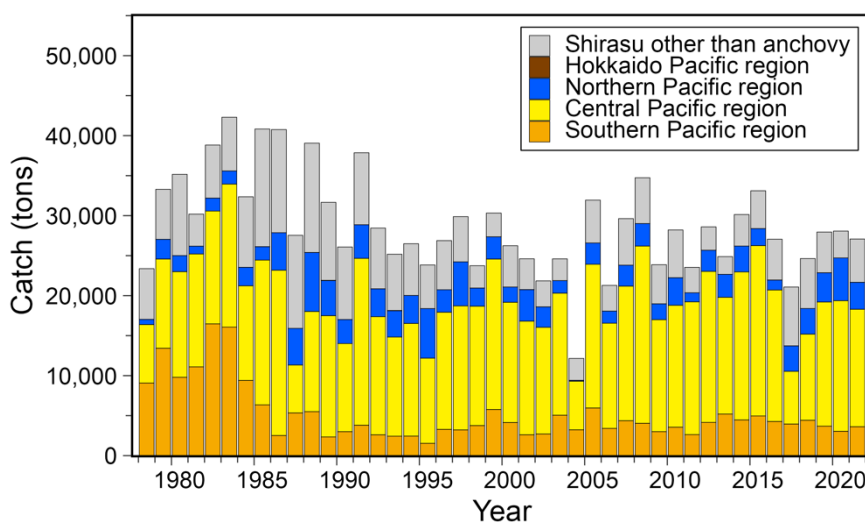
Year	Biomass at age (thousand tons)				Biomass (thousand tons)	SSB (thousand tons)	Catch (thousand tons)	Exploitation rate (%)
	Age 0	Age 1	Age 2	Age 3				
1978	612.1	179.7	52.8	25.4	870.0	257.9	43.0	4.9
1979	330.1	195.0	46.8	10.0	581.9	251.8	57.4	9.9
1980	144.3	92.5	41.9	9.7	288.4	144.0	66.0	22.9
1981	164.3	45.7	15.0	10.5	235.5	71.1	50.6	21.5
1982	148.5	54.7	7.2	1.6	212.0	63.5	47.5	22.4
1983	288.4	55.7	12.3	1.3	357.7	69.3	55.2	15.4
1984	210.4	89.2	9.4	3.5	312.5	102.1	90.0	28.8
1985	315.5	68.5	6.0	0.4	390.4	74.9	61.4	15.7
1986	395.5	122.3	8.8	1.5	528.2	132.6	66.1	12.5
1987	303.9	177.4	29.9	2.6	513.8	209.9	62.7	12.2
1988	402.7	137.6	61.4	12.1	613.8	211.1	68.1	11.1
1989	955.3	397.5	51.3	31.5	1,435.6	480.3	87.8	6.1
1990	1,470.0	818.7	168.9	14.4	2,472.0	1,002.0	215.9	8.7
1991	864.0	782.5	275.3	51.6	1,973.4	1,109.4	202.3	10.3
1992	957.4	566.8	266.1	70.7	1,860.9	903.6	178.3	9.6
1993	545.9	557.6	184.5	53.9	1,341.9	796.0	100.5	7.5
1994	562.0	463.7	236.1	65.8	1,327.6	765.7	110.4	8.3
1995	535.5	503.4	180.9	92.3	1,312.1	776.6	141.7	10.8
1996	976.3	394.7	161.5	41.7	1,574.1	597.9	207.9	13.2
1997	1,685.3	577.1	92.3	21.9	2,376.5	691.3	134.5	5.7
1998	2,220.8	883.0	169.1	11.6	3,284.4	1,063.6	319.4	9.7
1999	1,330.0	1,048.3	223.5	36.0	2,637.7	1,307.7	328.0	12.4
2000	1,107.7	831.1	333.5	46.3	2,318.7	1,210.9	213.1	9.2
2001	1,631.8	715.2	262.1	95.4	2,704.5	1,072.7	197.9	7.3
2002	1,921.8	1,007.8	225.2	60.5	3,215.3	1,293.5	334.4	10.4
2003	1,850.8	1,123.0	281.6	49.3	3,304.7	1,454.0	408.0	12.3
2004	1,842.4	1,033.6	280.1	39.5	3,195.6	1,353.3	401.9	12.6
2005	1,507.5	751.1	205.7	36.0	2,500.3	992.8	237.7	9.5
2006	1,398.6	809.7	162.2	19.9	2,390.4	991.7	303.4	12.7
2007	1,178.6	646.3	183.3	26.6	2,034.9	856.3	242.5	11.9
2008	1,252.5	787.6	138.7	32.2	2,211.0	958.5	209.1	9.5
2009	1,654.6	984.7	239.3	23.0	2,901.6	1,247.0	240.9	8.3
2010	1,147.9	854.6	275.9	64.2	2,342.6	1,194.8	247.6	10.6
2011	1,608.7	649.2	206.4	56.6	2,520.9	912.2	160.0	6.3
2012	1,074.4	720.2	167.2	49.0	2,010.8	936.5	154.5	7.7
2013	1,779.2	597.3	183.8	37.8	2,598.2	819.0	156.0	6.0
2014	684.2	288.1	67.5	21.3	1,061.0	376.9	144.0	13.6
2015	616.7	85.4	20.9	7.1	730.2	113.4	66.5	9.1
2016	619.4	103.3	7.8	0.9	731.4	112.0	77.7	10.6
2017	496.8	83.0	5.5	0.5	585.9	89.0	53.9	9.2
2018	1,021.5	71.0	6.6	0.4	1,099.4	77.9	28.9	2.6
2019	1,311.5	133.8	7.6	0.6	1,453.5	141.9	44.3	3.0
2020	949.0	306.6	26.1	1.4	1,283.2	334.2	57.0	4.4
2021	1,036.1	100.8	65.0	4.4	1,206.2	170.2	39.6	3.3

Appendix 13 Catch of Shirasu

Japanese anchovy are important catch targets in coastal fisheries, not only in catches of immature and mature fish, but also as juveniles in the late larval stage (known as whitebait or “shirasu”). Since 1978, the catch of shirasu in the Pacific region has ranged from 12,000 to 42,000 tons (Annual Statistics of Fishery and Aquaculture Production) (Supplementary Fig. 13-1, Supplementary Table 13-1).

In order to estimate the catch in weight of Japanese anchovy shirasu within the catch in weight of all shirasu, we aggregated catch in weight of shirasu by prefecture and by month (at major ports) and by-catch ratio data for Japanese anchovy shirasu, and used this data to calculate the annual catch in weight of Japanese anchovy shirasu, and by-catch ratio, by ocean area (at major ports). Next, we used the by-catch ratio by ocean area (at major ports), and the catch in weight of shirasu by ocean area in the Pacific region (Annual Statistics of Fishery and Aquaculture Production), to estimate the catch in weight of Japanese anchovy shirasu in the Pacific region.

Catch in weight of shirasu of this stock has ranged from 9,400 to 36,000 tons, and has generally remained stable around 23,000 tons (Supplementary Fig. 13-1, Supplementary Table 13-1). Shirasu fishing grounds compose a very narrow ocean region within the whole distribution area and spawning grounds of this stock, so it is believed that the impact of shirasu fisheries on the Pacific stock of Japanese anchovy is generally limited. However, the low distribution volume of this stock in offshore regions in recent years has boosted the importance of coastal spawning grounds and nursery grounds, so further monitoring of trends in shirasu stocks is required.



Supplementary Fig. 13-1. Trends in catch in weight of Japanese anchovy shirasu and other shirasu

Supplementary Table 13-1. Catch in weight of shirasu, estimated catch in weight of Japanese anchovy shirasu, and ratio of Japanese anchovy shirasu within the catch in weight of all shirasu

Year	Catch of shirasu (tons) from Annual Report on Fisheries and Aquaculture Production Statistics					Total of Major Ports	Pacific Total (estimated)	
	Southern Pacific region	Central Pacific region	Northern Pacific region	Hokkaido Pacific region	Pacific Total	Catch of Shirasu (tons)	Catch of Japanese anchovy's Shirasu (tons)	Percentage of Japanese anchovy's Shirasu (%)
1978	12,446	10,019	906	0	23,371	8,643	17,036	73
1979	16,518	13,732	3,040	0	33,290	12,384	27,041	81
1980	13,769	18,559	2,836	0	35,164	16,791	25,009	71
1981	12,793	16,264	1,132	0	30,189	14,880	26,186	87
1982	19,857	17,015	1,953	0	38,825	14,039	32,194	83
1983	18,406	21,879	2,020	0	42,305	26,069	35,588	84
1984	12,358	16,725	3,276	0	32,359	20,092	23,543	73
1985	14,937	23,692	2,205	0	40,834	31,951	26,126	64
1986	11,343	24,721	4,696	0	40,760	31,792	27,867	68
1987	11,672	11,274	4,592	0	27,538	18,945	15,910	58
1988	12,084	19,414	7,561	2	39,059	26,228	25,399	65
1989	10,322	16,344	4,953	43	31,619	25,025	21,915	69
1990	9,889	13,054	3,138	1	26,081	24,526	17,016	65
1991	11,628	21,929	4,303	1	37,860	35,500	28,865	76
1992	9,977	14,921	3,548	2	28,446	25,022	20,859	73
1993	8,255	13,553	3,332	37	25,140	23,119	18,146	72
1994	8,414	14,498	3,571	8	26,483	24,239	20,025	76
1995	6,176	10,833	6,828	1	23,837	23,099	18,384	77
1996	8,747	14,974	3,156	0	26,877	24,559	20,737	77
1997	7,808	15,679	6,388	0	29,875	26,104	24,225	81
1998	6,320	14,960	2,463	1	23,743	20,126	20,957	88
1999	8,395	18,877	3,050	2	30,322	29,440	27,357	90
2000	8,312	15,243	2,685	1	26,240	24,824	21,078	80
2001	4,496	14,570	5,528	14	24,594	23,546	20,762	84
2002	4,214	13,654	3,970	7	21,838	19,660	18,601	85
2003	7,214	15,507	1,876	3	24,597	24,594	21,882	89
2004	5,808	6,161	176	7	12,145	11,987	9,419	78
2005	9,142	18,067	4,725	4	31,934	26,429	26,585	83
2006	5,409	13,211	2,660	1	21,280	19,583	18,068	85
2007	7,397	17,008	5,218	6	29,623	27,640	23,808	80
2008	6,422	22,972	5,345	2	34,739	29,731	29,012	84
2009	5,538	14,268	4,062	3	23,868	21,648	18,981	80
2010	6,890	15,462	5,854	4	28,206	24,631	22,248	79
2011	5,064	17,335	1,136	3	23,535	21,216	20,359	87
2012	6,768	19,177	2,647	5	28,592	25,624	25,677	90
2013	7,059	14,928	2,895	1	24,882	22,515	22,663	91
2014	6,751	20,064	3,322	4	30,137	26,116	26,196	87
2015	7,315	23,606	2,190	3	33,111	27,693	28,386	86
2016	6,807	18,842	1,402	2	27,051	24,109	21,956	81
2017	6,009	10,891	4,173	3	21,073	19,024	13,728	65
2018	6,784	13,783	4,070	1	24,637	20,812	18,391	75
2019	6,395	17,634	3,920	1	27,949	22,909	22,865	82
2020	5,425	16,894	5,754	0	28,073	23,897	24,714	88
2021	6,288	16,669	4,123	1	27,080	25,569	21,668	80