2. Assessment of the Pacific Cod Stock in the Eastern Bering Sea

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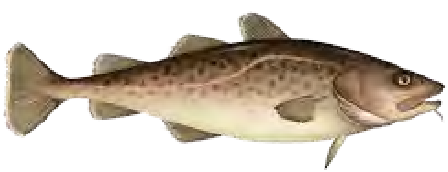

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EXECUTIVE SUMMARY

Summary of Changes in Assessment Inputs

Relative to the November edition of last year's BSAI SAFE report, the following substantive changes have been made in the eastern Bering Sea (EBS) Pacific cod stock assessment.

Changes in the Input Data

- Catches for 1991-2021 were updated, and a preliminary catch estimate for 2022 was incorporated.
- Commercial fishery size compositions for 1991-2021 were updated, and a preliminary size composition from the 2022 commercial fishery was incorporated.
- A new script was developed for pulling and processing data, the script included a change in weighting of catch for commercial fishery size compositions and was presented in September. Although the change in data processing did not lead to changes in model results it was deemed by the authors significant enough to trigger a change in model names for 2022.
- The VAST approach for the AFSC Bering Sea bottom trawl and winter longline fishery CPUE indices were used as in 2021, but with some adjustments and updated for both time series through 2022.
- The size composition from the 2022 EBS+NBS survey was incorporated
- The VAST approach was used to estimate the age compositions from the combined EBS+NBS survey time series through 2021.
- The seasonally corrected annual weight-at-length relationship adjustments were calculated using a new algorithm developed in R based on a Generalized Additive Modeling (GAM) approach presented in September.

Changes in the Assessment Methodology

The ensemble of models presented and accepted for use in 2021 were re-run with these new data as parameterized in last year's assessment. In addition, a set of models (22.x), deemed New Series, are presented with changes described in the September update (Appendix 2.1). The seasonally corrected annual weight-at-length adjustments were removed from the set of ensemble models. The post-2007 aging bias parameters were removed from the ensemble models to match recommendations from the Age and Growth Laboratory assuming no bias for the most recent ages, but retaining bias for those fish aged prior to 2008.

Summary of Results

The principal results of the present assessment, **based on the New Series ensemble**, are listed in the table below (biomass and catch figures are in units of t) and compared with the corresponding quantities as specified last year by the SSC:

Quantity	As estimated or *specified last* year for: 2022	2023	As estimated or *recommended this* year for: 2023*	2024*
M (natural mortality rate)	0.34	0.34	0.34	0.34
Tier	3b	3b	3b	3b
Projected total (age 0+) biomass (t)	879,978	848,615	844,578	831,566
Projected female spawning biomass (t)	259,789	254,585	245,594	242,911
$B_{100\%}$	686,761		668,477	
$B_{40\%}$	274,704		267,391	
$B_{35\%}$	240,366		233,467	
F_{OFL}	0.38	0.37	0.36	0.35
$maxF_{ABC}$	0.31	0.31	0.29	0.29
F_{ABC}	0.31	0.31	0.29	0.29
OFL (t)	183,012	180,909	172,495	166,814
maxABC (t)	153,383	151,709	144,834	140,159
ABC (t)	153,383	151,709	144,834	140,159
Status	As determined *last* year for: 2020	2021	As determined *this* year for: 2021	2022
Overfishing	No	n/a	No	n/a
Overfished	n/a	No	n/a	No
Approaching overfished	n/a	No	n/a	No

*Projections are based on assumed catches of 152,146 t, and 144,834 t in 2022 and 2023, respectively.

Note that the recommended 2023 and 2024 F_{ABC} and ABC values listed above may be subject to modification following consideration by the Plan Team and SSC. The summarized results of the risk analysis (see subsection in the “Harvest Recommendations” section) are shown below:

Assessment-related considerations	*Population dynamics considerations*	*Environmental/ ecosystem considerations*	*Fishery Performance considerations*
Level 1: Normal	Level 1: Normal	Level 1: Normal	Level 1: Normal

In the event that the 2023 F_{ABC} or ABC values are changed from those shown above, projected 2024 values of other non-constant quantities would need to change in response and would be reflected in the harvest specification tables.

Responses to SSC and Plan Team Comments on Assessments in General

December 2021 SSC

Assessment authors should evaluate the risk of the ABC exceeding the true (but unknown) OFL and whether a reduction from maximum ABC is warranted, even if past TACs or exploitation rates are low.

That has been and will continue to be the consideration of the authors for EBS Pacific cod.

The SSC recommends that groundfish, crab and scallop assessment authors do not change recommendations in documents between the Plan Team and the SSC meetings.

No changes will be made to the recommendations in the document prior to the SSC meeting.

November 2021 SSC

The Teams recommend that, for ESPs in general, when a fishery performance indicator may have ambiguous interpretations, no traffic light color coding should be assigned, but the scoring should be maintained.

For ambiguous performance indicators in the ESP no traffic light color has been assigned.

Responses to SSC and Plan Team Comments Specific to this Assessment

December 2021 SSC

Given that an ensemble model structure has been endorsed by the SSC in 2021, if the new authors choose to propose an ensemble in the future it may be prudent to minimize changes to the suite of models comprising the ensemble so that the potential benefits of a stable ensemble can be realized.

The authors presented a series of minor changes to the model and a major overhaul on how the data are pulled and processed this year. The Plan Team and SSC endorsed the proposed changes in data processing, removal of the annual weight-at-length adjustments and removal of the aging bias for post-2007. These model changes resulted in very minimal changes to the resulting model and are described in the document below. These changes are collated in the New Series ensemble and presented along with the Thompson Series for evaluation by the Plan Team and SSC.

If model ensembles are brought forward in the future, the authors should work with the BSAI GPT to define a process whereby GPT members themselves assign model scores based on the same, or an updated set, of scoring criteria.

In light of the above recommendation, model changes were kept to a minimum and the weighting criteria used for this year's ensemble were judged to rate the same as the weights generated by the CIE and endorsed by the SSC in 2021.

The SSC recommends that inclusion of [fishery age composition data] be fully explored in a later assessment cycle, either within a single model or multiple ensemble members, highlighting that it views this as a top priority for future research.

Given the already monumental task of taking this stock over from Dr. Thompson, the authors chose not to investigate the use of fishery age composition data. This also in light of the SSCs recommendation to minimize changes to the suite of models comprising the ensemble. The authors intend to investigate the use of fishery age composition data in the future.

INTRODUCTION

Pacific cod (*Gadus macrocephalus*) is a transoceanic species, ranging from Santa Monica Bay, California, northward along the North American coast; across the Gulf of Alaska and Bering Sea north to Norton Sound; and southward along the Asian coast from the Gulf of Anadyr to the northern Yellow Sea; and occurring at depths from shoreline to 500 m (Ketchen 1961, Bakkala et al. 1984). The southern limit of the species distribution is about 34° N latitude, with a northern limit of about 65° N latitude (Lauth 2011). Pacific cod is distributed widely over the eastern Bering Sea (EBS) as well as in the Aleutian Islands (AI) area. Tagging studies (e.g., Shimada and Kimura 1994) have demonstrated significant migration both within and between the EBS, AI, and Gulf of Alaska (GOA). The most recent genomic analysis of Pacific cod includes a new publication that used pooled whole genome sequencing (Pool-Seq), as well as a new study conducted during 2021 and 2022 that used low coverage whole genome sequencing (lcWGS). The Pool-Seq manuscript (Spies et al. 2022) is the culmination of several years of effort, while the lcWGS is more recent and provides a more powerful approach to gather individual-based sequence data from the whole genome. These two new studies contribute to our knowledge of the population structure of Pacific cod throughout Alaskan waters.

Low-coverage whole-genome sequencing analysis of 429 samples of Pacific cod from known spawning regions during spawning season indicated population structure similar to what was previously known, but with finer resolution and greater power owing to the larger number of markers. Using 1,922,927 polymorphic SNPs (Figure 2.1), the pattern of population structure mostly resembles isolation-by-distance, in which samples from proximate spawning areas are more genetically similar than samples from more distant areas. Isolation-by-distance was observed from western Gulf of Alaska (Kodiak and the Shumagin Islands) through Unimak Pass and the eastern Aleutian Islands. Previous studies have reported an isolation-by-distance pattern in Pacific cod using microsatellite markers (Cunningham et al. 2009 and Spies 2012) and reduced-representation sequencing (Drinan et al. 2018). Within the isolation-by-distance pattern, there were some distinct breaks in the population structure. The most significant genetic break occurs between western and eastern Gulf of Alaska (GOA) spawning samples (Figure 2.1), and was supported by previous research that highlighted the zona pellucida gene region (Spies et al. 2019).

A new finding from the lcWGS data was the documentation of a genetic break in samples taken from the western Bering Sea shelf, adjacent to Russia, and samples from all other regions. In other words, this study identified a new genetic group in the Bering Sea represented by samples from Russia along the western Bering Sea shelf. In addition, a subset of samples collected from Pervenets Canyon in the eastern Bering Sea appeared genetically similar to the western Bering Sea shelf group (Figure 2.1 bottom right where light blue points, Pervenets Canyon, mix with dark blue points, Russia). The majority of samples from the eastern Bering Sea were genetically more similar to Aleutian Islands and western Gulf of Alaska samples which was a significant deviation from the isolation-by-distance pattern found with the rest of the samples (Figure 2.1 center where light blue points mix with green squares, Aleutian Islands, and pink circles, western Gulf of Alaska). This result suggests an unresolved combination of isolation-by-distance. More specifically, at neutral markers Aleutian Island populations seem to follow the subtle IBD pattern documented throughout much of the western GOA. However, Aleutian Island populations are highly diverged at a few genomic regions that we believe are adaptively significant (Spies et al. 2022, Figure 2.2). These adaptive differences provide further support for the Aleutian Island management unit that was established as distinct from the Bering Sea in 2013.

Recent satellite tagging research on Pacific cod (S. McDermott, P.I.) indicates seasonal connectivity between the western Gulf of Alaska (GOA), the eastern Bering Sea (EBS), the northern Bering Sea (NBS), Russia, and the Chukchi Sea (CS). Pacific cod tagging research was initiated in 2019 and consists of an inter-agency collaboration between NOAA scientists and the Aleutians East Borough, the Freezer Longline Coalition, the Native Village of Savoonga, Norton Sound Economic Development Corporation, and Pacific Cod Harvesters. Satellite tags record depth, temperature, light intensity, and acceleration while tagged fish are at liberty. The tags are programmed to “pop up” from the fish at a specific time and provide a recovery location when they reach the surface and begin to transmit archived data to the Argos satellite network. Movement paths between the release and recovery locations can be reconstructed based on the archived data using a hidden Markov model for geolocation. Location probabilities for multiple tagged fish can be combined to visualize location probability for all tagged fish combined during different time periods. Results from satellite-tagged fish released in the NBS during summer foraging in 2019 (n = 38) indicate that tagged fish were located mostly in the NBS and Russia through November. By the peak spawning period (February 15 – March 31), all 12 tagged fish with winter location information had moved to traditional spawning areas in the EBS (77.1% of location probability for all tags combined), Russia (16.3%), and the Gulf of Alaska (6.6%; Figure 2.3). Most fish with year-long deployments (3 of 4 tagged fish with annual location information) were located in the NBS the following summer. Satellite tag releases in the NBS (n = 17) during the summer of 2021 provided similar results to 2019, as most tagged fish were located in the NBS and Russia during the summer and all 3 tagged fish with winter location information moved to traditional spawning areas in the EBS (Figure 2.4). Both fish with year-long deployments returned to the NBS the following summer. Satellite-tagged fish released in the EBS during the summer of 2021 (n = 8) remained in the EBS during the summer. During the winter, tagged fish either remained in the EBS (3 of 4) or likely moved to the WGOA (1 of 4). To understand movement from winter spawning areas in the WGOA to summer foraging areas, 25 satellite-tagged fish were released from the WGOA in March, 2021. More than half of the tagged fish (n = 10 of 17 tagged fish with location information during the summer) had moved into the EBS or farther north into the NBS, Russia, or the Chukchi Sea (Figure 2.4). In April 2022, another 27 satellite-tagged fish were released from similar locations to the 2021 release in the WGOA. Some movement into the EBS during the summer months was observed (3 of 23 tagged fish with summer location information), but most tagged fish remained in closer proximity to their release locations compared to 2021. Genetic information has been collected from all tagged fish and genetic analyses of these results is in progress. Results to date indicate some degree of seasonal connectivity between the GOA and BS management areas that may vary by year or with environmental conditions. Results also indicate the presence of resident and migratory fish in the western GOA and EBS, but not the NBS. Northward movement of fish into the NBS, Russia, and the arctic appears to be associated with summer foraging and not year-round occupation.

Additional information on the biology of Pacific cod, including early life history, can be found in the Ecosystem and Socioeconomic Profile (Appendix 2.2).

FISHERY

Description of the Directed Fishery

During the early 1960s, a Japanese longline fishery harvested EBS Pacific cod for the frozen fish market. Beginning in 1964, the Japanese trawl fishery for walleye pollock (*Gadus chalcogrammus*) expanded and cod became an important bycatch species and an occasional target species when high concentrations were detected during pollock operations. By the time that the Magnuson Fishery Conservation and Management Act went into effect in 1977, foreign catches of Pacific cod had consistently been in the 30,000-70,000 t range for a full decade. In 1981, a U.S. domestic trawl fishery and several joint venture fisheries began operations in the EBS. The foreign and joint venture sectors dominated catches through 1988, but by 1989 the domestic sector was dominant and by 1991 the foreign and joint venture sectors had been displaced entirely.

Presently, the Pacific cod stock is exploited by a multiple-gear fishery, including trawl, longline, pot, and jig components (although catches by jig gear are very small in comparison to the other three main gear types, with an average annual catch of less than 200 t since 1991). The breakdown of catch by gear during the most recent complete five-year period (2017-2021) is as follows: longline gear accounted for an average of 49.3% of the catch, trawl gear accounted for an average of 29.9%, and pot gear accounted for an average of 20.8%.

In the EBS, Pacific cod are caught throughout much of the continental shelf, with National Marine Fisheries Service (NMFS) statistical areas 509, 513, 517, 519, 521, and 524 each accounting for at least 5% of the total catch over the most recent 5-year period (2017-2021). In that time period Pacific cod catch from areas 521 (26%) and 509 (25%) have made up more than 50% of the total eastern Bering Sea catch.

Catches of Pacific cod taken in the EBS for the periods 1964-1980, 1981-1990, and 1991-2021 are shown in Table 2.1, Table 2.2, and Table 2.3, respectively; and the time series for the overall fishery (1977-2021) and by gear type (1988-2021) are shown in Figure 2.5. The catches in Table 2.1 and Table 2.2 are broken down by fleet sector (foreign, joint venture, domestic annual processing). The catches in Table 2.2 are also broken down by gear to the extent possible. The catches in Table 2.3 are broken down by gear.

Annual cummulative catch for 2016 through 2022 are shown in Figure 2.6. The start of fishing in the trawl sector was later than 2016-2020, but at a similar time as the 2021 fishery. Catch rate (tons per week) in the trawl sector in 2022 appears to have been faster than in 2021. The the longline sector catch rates in 2022 remained stable throughout the year unlike 2020 and 2021 where rates dipped in the summer months. The pot sector catch rates in 2022 were high in the starting weeks but tapered off by mid-February, slower than what was observed in 2016-2020, but similar to 2021. As in previous years the pot sector halted fishing in April and did not resume again until August. While overall catch is higher in 2022 than in 2020-2021 catch rates were slower than in 2020.

Maps of fishing effort for 2020 through 2002 by fishing sector (Figure 2.7) and for all gear types (Figure 2.8) indicate a dramatic shift away from the north beginning in 2020 and 2021 and continuing in 2022 for the trawl and longline sectors. In 2021 and 2022 there were few longline sets north of St. Lawrence Island and in 2022 there were few longline sets north of St. Mathews Island. The 2022 observed and reportable pot cod fishery was restricted to along the north side of the Alaska Peninsula and Aleutian Islands and in the southern side of St. George Island in the Pribilof Islands. Figure 2.9 shows the distribution of observed hauls by latitude and bottom depth by gear type. The largest latitudinal shift in fishing distribution is observed in the longline fishery. Here we see a slight southward shift in 2008-2013, then a shift northward peaking in 2019 through 2021, then a sharp southward shift in the 2022 observations. The trawl and pot fisheries also show a northward shift, the trawl fishery in 2019 and the pot fishery in 2020 and 2021, although much more subtle than for the longline fishery. The raw CPUE indices based on the method presented by Thompson et al. 2021 (Figure 2.10) show a rather flat CPUE by number trend since 2015. However, the CPUE by weight shows an increasing trend from 2014-2020, then an overall decreasing trend in 2020-2021. This does not match the VAST winter (January-February) longline fishery number CPUE trend (Table 2.10 and Figure 2.13; see below for full description) which indicated a dropping CPUE from 2018-202l, and then a sharp increase in CPUE in 2022.

Catches of Pacific cod taken from the portion of the western Bering Sea under Russian jurisdiction during 2001 through 2021 are summarized in Table 2.4. For 2001-2008 the data were retrieved from Lajus et al. (2019). For 2009-2021 catch data from Russian Ministry of Fisheries annual reports are available for 2009-2021, РОССИЙСКАЯ ФЕДЕРАЦИЯ: СВЕДЕНИЯ ОБ УЛОВЕ РЫБЫ И ДОБЫЧЕ ДРУГИХ ВОДНЫХ БИОРЕСУРСОВ (translation: RUSSIAN FEDERATION: INFORMATION ABOUT THE CATCH OF FISH AND THE EXTRACTION OF OTHER WATER BIORESOURCES). The Russian Federation website where these reports were hosted was no longer active as of March 2022 and future availability of these data is questionable.

Discards

The catches shown in Table 2.1 and Table 2.2 include estimated discards. Proportion retained of Pacific cod in the EBS Pacific cod fisheries are shown for each year 1991-2022 in Table 2.3. Amendment 49, which mandated increased retention and utilization of Pacific cod, was implemented in 1998. From 1991-1997, discard rates in the Pacific cod fishery averaged about 14%. Since then, they have averaged about 2%. There was an increase in 2021 in the discard of Pacific cod in the trawl fisheries up to 5% from 1% in 2019. This pushed the overall discard rate for all gears to 3% in 2021, the highest rate since 1997.

Management History

The history of acceptable biological catch (ABC), overfishing level (OFL), and total allowable catch (TAC) levels is summarized and compared with the time series of aggregate (i.e., all-gear, combined area) commercial catches in Table 2.5. Note that, prior to 2014, this time series pertains to the combined BSAI region, so the catch time series differs from that shown in Table 2.3, which pertains to the EBS only.

From 1980 through 2022 TAC averaged about 85% of ABC (ABC was not specified prior to 1980), and from 1980 through 2022, commercial catch averaged about 82% of TAC. In 9 of these 42 years, TAC equaled ABC exactly, and in 17 of these 42 years, catch exceeded TAC. However in 10 of those overages TAC was reduced by various proportions to account for a small, state-managed fishery inside state of Alaska waters (such reductions have been made in all years since 2006; see text table below for recent formulae); thus, while the combined Federal and State catch exceeded the Federal TAC in 2006-2010 and 2016-2021 by up to 10%, the overall target catch (Federal TAC plus State GHL) was *not* exceeded.

Total catch has been less than OFL in every year since 1993 (inclusive).

Changes in ABC over time are typically attributable to three factors: 1) changes in resource abundance, 2) changes in management strategy, and 3) changes in the stock assessment model. Assessments conducted prior to 1985 consisted of simple projections of current survey numbers at age. In 1985, the assessment was expanded to consider all survey numbers at age from 1979-1985. From 1985-1991, the assessment was conducted using a bespoke separable age-structured model. In 1992, the assessment was conducted using the Stock Synthesis modeling software (Methot 1986, 1990) with age-based data. All assessments from 1993 through 2003 continued to use the Stock Synthesis modeling software, but with length-based data. Age data based on a revised ageing protocol were added to the model in the 2004 assessment. At about that time, a major upgrade in the Stock Synthesis architecture resulted in a substantially new product, at that time labeled “SS2” (Methot 2005). The assessment was migrated to SS2 in 2005. Changes to model structure were made annually through 2011, then the base model remained constant through 2015, and new base models were adopted in 2016, 2018, 2019, and 2020 (see Appendix 2.3 of Thompson et al. 2021). A note on software nomenclature: The label “SS2” was dropped in 2008. Since then, the program has been known simply as “Stock Synthesis” or “SS,” with several versions typically produced each year, each given a numeric or alpha-numeric label.

Beginning with the 2014 fishery, the Board of Fisheries for the State of Alaska has established guideline harvest levels (GHLs) in State waters between 164 and 167 degrees west longitude in the EBS subarea (these have supplemented GHLs that had been set aside for the Aleutian Islands subarea since 2006). The table below shows the formulas that have been used to set the State GHL for the EBS (including the formula anticipated for setting the 2023 GHL):

Year	Formula
2014	0.030 × (EBS ABC +AI ABC)
2015	0.030 × (EBS ABC +AI ABC)
2016	0.064 × EBS ABC

2017	0.064 × EBS ABC
2018	0.064 × EBS ABC
2019	0.084 × EBS ABC
2020	0.090 × EBS ABC
2021	0.100 × EBS ABC
2022	0.110 × EBS ABC
2023	0.110 × EBS ABC

For 2020, 2021, 2022, and 2023, the Board of Fisheries established an additional GHL of 45 t for vessels using jig gear within State waters.

Table 2.6 lists all implemented amendments to the BSAI Groundfish FMP that reference Pacific cod explicitly.

In addition to those, the following rulemaking became effective for 2021 on permit requirements: https://www.federalregister.gov/documents/2020/12/03/2020-26593/fisheries-of-the-exclusive-economic-zone-off-alaska-pacific-cod-in-the-bering-sea-and-aleutian. In this rule, NMFS modified Federal permit conditions and imposed participation requirements for certain federally permitted vessels when fishing for Pacific cod in State of Alaska waters (state waters) adjacent to the Exclusive Economic Zone (EEZ) of the Bering Sea and Aleutian Islands (BSAI). The state waters portion of the Pacific cod fishery that runs concurrent with the Federal Pacific cod fishery is commonly known as the State's parallel fishery. The "parallel fisheries" in this preamble refer to the State waters Pacific cod parallel fisheries in the State of Alaska Bering Sea-Aleutian Islands Area, which presently is in the Dutch Harbor Subdistrict of the Bering Sea and within the Aleutian Islands Subdistrict of the Aleutian Islands, respectively. This rule prohibits (1) a hook-and-line, pot, or trawl gear vessel named on a Federal Fisheries Permit (FFP) or License Limitation Program (LLP) license from being used to catch and retain BSAI Pacific cod in State of Alaska (State) waters adjacent to the BSAI during the State's parallel Pacific cod fishery unless the vessel is named on an FFP and LLP license that have the required endorsements; (2) a hook-and-line, pot, or trawl gear vessel named on an FFP or LLP license from catching and retaining Pacific cod in state waters adjacent to the BSAI EEZ during the State's parallel fishery when NMFS has closed the EEZ to directed fishing for Pacific cod by the sector to which the vessel belongs; (3) the holder of an FFP with certain endorsements from modifying those endorsements during the effective period of the FFP; and (4) the reissuance of a surrendered FFP with certain endorsements for the remainder of the three-year term, or cycle, of FFPs.

For the third consecutive year the Bering Sea non-CDQ Pacific cod directed fishing closed for all non-CDQ sectors. The non-CDQ sectors have BSAI allocations and there was less fishing in the Aleutian Islands until after the Bering Sea non-CDQ sectors closed. In 2020, the closure was November 18, 2020. Directed fishing in 2021 closed for the Pacific cod non-CDQ sectors on September 17 and in 2022 on October 7. The closures were to prevent exceeding the non-CDQ allocation of the 2021 total allowable catch of Pacific cod in the Bering Sea subarea of the BSAI. After the closures there was still fishing by the CDQ groups and incidental catch of Pacific cod in other targets. https://www.fisheries.noaa.gov/bulletin/ib-22-48-nmfs-prohibits-directed-fishing-non-community-development-quota-pacific-cod

DATA

The first two subsections below describe fishery and survey data that are used in the current stock assessment models. The third subsection describes data that are not used in the current stock assessment models, but that may help to provide some context for the data that are used.

The following table summarizes the sources, types, and years of data included in the data file for at least one of the stock assessment models:

Source	Type	Years
Fishery	Catch biomass	1977-2022
Fishery	Catch size composition	1977-2022
Fishery	Catch per unit effort (VAST)	1996-2022
EBS+NBS trawl survey	Survey numerical abundance (VAST)	1982-2019, 2021-2022
EBS+NBS trawl survey	Survey age composition (VAST)	1994-2019, 2021

All data used in the 2022 models are provided in zip files in the following appendices:

- Appendix 2.3 Thompson Series Models SS files.zip (0.3 MB)
    - https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/APPENDICES/APPENDIX_2.3_THOMPSON__MODELS.zip
- Appendix 2.4 New Series Models SS files.zip (0.3MB)
    - https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/APPENDICES/APPENDIX_2.4_NEW_MODELS.zip
- Appendix 2.5 Data and results for all models and ensembles.xlsx (2.6 MB)
    - https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/APPENDICES/Appendix_2.5_Data_and_results.xlsx

Fishery Data Used in the Models

Catch Biomass
Catch estimates for the period 1977-2022 are shown in Table 2.1, Table 2.2, Table 2.3, and Table 2.5. However, the estimate for 2022 is complete only through October 9. The 2022 year-end catch in the model was set at the 5-year average proportion of the ABC that was harvested (99.2% or 152,146 t).

The catches shown in Table 2.1, Table 2.2, Table 2.3, and Table 2.5 consist of “official” data from the NMFS Alaska Region. However, other removals of Pacific cod are known to have occurred over the years, including removals due to subsistence fishing, sport fishing, scientific research, and fisheries managed under other FMPs. Estimates of such other removals are shown in Table 2.7 .

The catch estimates for the years 1977-1980 shown in Table 2.1 may or may not include discards.

Size Composition
Figure 2.11 shows the fishery size compositions from 1977 through 9 October 2022, which are parsed into 1-cm bins for use in the assessment models. The size composition were computed by using haul/vessel/month/gear/area catch proportions to create a weighted average for each year's record as described in Appendix 2.1, with a minimum sample size of 30 fish for any month/gear/area combination. The total number of Pacific cod measured in the fishery 1977-2022 are provided in Table 2.8.

The length distributions are generally unimodal, with a few years bimodal when larger than average year classes were encountered Figure 2.11. The peaks of the length composition in the fishery tends to be between 50 and 70 cm. The size of fish in the fishery has remained relatively stable over time, however the mean length in the fishery tends to decrease somewhat when there are large new recruitments then slowly increase as these fish age and grow (Figure 2.12). From 1977 through 1991 there was an increasing trend in mean length with the greatest mean length in 1991. There were also fewer data for this time period leading to higher uncertainty in the estimated distribution. In 1992 with the advancement of the domestic observer program and increased sampling uncertainty in the distributions was lower. For this period (1991-2022) the highest mean length occurred in 2021 following a period of low recruitment in 2014-2017. On average Pacific cod were slightly smaller in 2022 in part due to the influx of a large 2018 year class entering the fishery. It should be noted that the fishery length composition is made up of data from several gear types (trawl, longline, and pot) and the individual selectivity of these gear likely differs, therefore the length distributions will vary from year to year due to the proportion of catch from each of the gear types differing (Table 2.3 and Figure 2.9).

The nominal sample sizes (number of sampled hauls) for the size compositions and input sample sizes are shown in Table 2.9.

Catch per Unit Effort
Fishery catch-per-unit-effort (CPUE) data was analyzed to:

1. provide contextual information regarding wintertime habitat utilization and resulting indices of distribution shift and area expansion/contraction;
2. develop a standardized CPUE index that controls for inter-annual differences in fishery locational choice, for potential inclusion as an abundance index.

Analyzing CPUE data to develop standardized abundance indices has a long history in fisheries, but there are also many theoretical and case-study examples of why fishery CPUE indices can be biased relative to well-designed survey indices. In particular, spatial targeting can cause an arithmetic average of CPUE to be unrepresentative of population density (Walters 2003). In contrast, recent spatio-temporal methods address this issue explicitly through use of high-resolution spatial and timing information. Recent methods implicitly impute or predict the CPUE that would have arisen in unsampled locations, interpreting that CPUE as proportional to density after controlling for variables affecting catchability, weighting densities based on area, and integrating area-weighted uncertainty across poor- and well-sampled areas. This imputation occurs either structurally (Carruthers et al. 2011), via post-stratification and area-weighting of CPUE in different strata (Campbell 2016), or using area-weighting within spatio-temporal statistical models (Thorson 2019a). Relative to explicit imputation approaches (e.g., Carruthers et al. 2011), spatio-temporal methods extrapolate densities based on spatial correlations in predicted density as well as correlations across time either via a spatial component (which affects estimates of leverage for observations based on location) or an autocorrelated spatio-temporal component. Spatio-temporal models for fishery CPUE data have been tested using operating models mimicking fishery-dependent CPUE data that were developed independently and do not match the estimation model (Grüss et al. 2019; Thorson et al. 2017a). In particular, testing using SEAPODYM as the operating model and

VAST as the estimation model suggests that trends in abundance can be accurately reconstructed even when the spatial footprint of fishing has expanded or contracted over time (Ducharme-Barthe et al. 2022).

To do so, the longline fishery catch and effort data were obtained from the AFSC Fisheries Management Division database NORPAC on May 12, 2022. Sets were restricted to those occurring in Jan-Feb. from 1996-2022, and also to those occurring within the eastern Bering Sea shelf bottom-trawl survey area. An extrapolation area was then defined by manually identifying a polygon that includes all included sets. A spatio-temporal generalized linear mixed model was then fitted using log-link and gamma distribution, using catch of Pacific cod in numbers as response, total hook pots as effort offset, and integrated CPUE estimates across the extrapolation area. This implies that the resulting index has units $\#km^2/hook$; the resulting catchability coefficient fitted in the assessment model has units $hooks/km^2$, representing the the inverse of effective area fished per hook. This was specifically fitted using the VAST package. Both spatial and spatio-temporal model components were included with a first-order autoregressive process for the spatio-temporal component over time, estimated geometric anisotropy, and treated annual intercepts as fixed effects. No covariates were included representing fishery targeting behavior or technology, and therefore systematic variation could not be controlled.

The estimated CPUE index resulting from this analysis shows relatively little variation over time (Table 2.10). Comparing it with the estimate from 2021 assessment shows that the two estimates are highly correlated, although the 2022 update has somewhat higher scale perhaps due to updates in the extrapolation area made since that assessment (Figure 2.13). The estimated wintertime center-of-gravity varied significantly from 1996-2022, showing a southeastern distribution from 2011-2013 and a northwestern distribution in 2006-2008 and again 2015-2018 (Figure 2.14). Similarly, the estimated “effective area occupied” was higher in years with a northwestern distribution, but has also shown a trend upward from 2007 onward. Fine-scale interpretation of these trends can be seen by inspecting estimated CPUE maps (Figure 2.15)

Survey Data Used in the Models

Overview of Survey Areas and Frequency

The areas covered by the eastern Bering Sea (EBS) shelf and northern Bering Sea (NBS) bottom trawl surveys are shown in Figure 2.16. Prior to 2020, in the EBS, strata 10-62 had been surveyed annually since 1982 and strata 82 and 90 had been surveyed annually since 1987. However, the EBS bottom trawl survey was cancelled in 2020 due to the COVID-19 pandemic. In the NBS, strata 70, 71, and 81 in the NBS were surveyed fully in 2010, 2017, 2019, and 2021. Less extensive surveys of the NBS were conducted in 1982, 1985, 1988, 1991, and 2018. The NBS was also scheduled to be surveyed in 2020, but, like the EBS survey, the 2020 NBS survey was cancelled due to the COVID-19 pandemic. Both the EBS and NBS were once again surveyed with a full, standard sampling design in 2022.

VAST Estimates of Abundance from the EBS Shelf and NBS Bottom Trawl Surveys

The software versions of dependent programs used to generate VAST estimates were:

- Microsoft R Open (4.0.2)
- INLA (21.11.22)
- TMB (1.9.0)
- TMBhelper (1.4.0)
- VAST (3.9.0)
- FishStatsUtils (2.11.0)

VAST abundance

For model-based indices in the Bering Sea, observations of numerical abundance or biomass per unit area (where the use of abundance or biomass varied by stock at the request of assessors) were fitted from all grid cells and corner stations in the 83-112 bottom trawl survey of the EBS, 1982-2022, including exploratory northern extension samples in 2001, 2005, and 2006, as well as 83-112 samples available in the NBS in 1982, 1985, 1988, 1991, 2010, and 2017-2021. NBS samples collected prior to 2010 and in 2018 did not follow the 20 nautical mile sampling grid that was used in 2010, 2017, 2019, 2021 and 2022 surveys. Note that the 1982-1986 surveys did not include the NW expanded region which became part of the standard survey in 1987. Assimilating these data as well as the NMS data therefore required extrapolating into unsampled areas. This extrapolation was facilitated by including a spatially varying response to cold-pool extent (Thorson 2019). This spatially varying response was estimated for both linear predictors of the delta-model, and detailed comparison of results for EBS pollock has shown that it has a small but notable effect on these indices and resulting stock assessment outputs (O'Leary et al. 2020). For example, the NBS was not sampled between 2010 and 2017, and the cold-pool extent started to decrease substantially around 2014; therefore including this covariate results in estimates that depart somewhat from a "Brownian bridge" between 2010 and 2017, and instead indicates that population densities of walleye pollock in the NBS increased progressively after 2014 when cold-pool-extent declined prior to 2017. All environmental data used as covariates were computed within the R package *coldpool* (https://github.com/afsc-gap-products/coldpool; Rohan et al., in review).

A Poisson-link delta-model (Thorson 2019) involving two linear predictors was used, and a gamma distribution was used to model positive catch rates. Population density was extrapolated to the entire EBS and NBS in each year, using extrapolation grids that are available within FishStatsUtils, which were updated since 2021 assessment cycle based on new shape files developed by J. Conner (https://github.com/James-Thorson-NOAA/FishStatsUtils). These extrapolation grids are defined using 3705 m (2 nmi) × 3705 m (2 nmi) cells; this results in 36,690 extrapolation-grid cells for the eastern Bering Sea and 15,079 in the northern Bering Sea. A bilinear interpolation was used to interpolate densities from 750 "knots" to these extrapolation grid cells; knots were approximately evenly distributed over space, in proportion to the dimensions of the extrapolation grid. The geometric anisotropy (how spatial autocorrelation declines with differing rates over distance in some cardinal directions than others) was extrapolated, and included a spatial and spatio-temporal term for both linear predictors. To facilitate interpolation of density between unsampled years, the spatio-temporal fields were structured over time were specified as an AR(1) process (where the magnitude of autocorrelation was estimated as a fixed effect for each linear predictor). However, no temporal correlation for intercepts was included. Intercepts were treated as fixed effects for each linear predictor and year. Finally, an epsilon bias-correction was used to correct for retransformation bias (Thorson and Kristensen 2016).

The model fits were checked for evidence of non-convergence by confirming that (1) the derivative of the marginal likelihood with respect to each fixed effect was sufficiently small and (2) that the Hessian matrix was positive definite. Evidence of model fit was then checked by computing Dunn-Smyth randomized quantile residuals (Dunn and Smyth 1996) and visualizing these using a quantile-quantile plot within the DHARMa R package. The distribution of these residuals was also evaluated over space in each year, and inspected them for evidence of residual spatio-temporal patterns.

The resulting set of estimates is shown in Table 2.10, together with their respective log-scale standard deviations ("Sigma"), and compared with those used in the 2020 and 2021 assessments in Figure 2.19 (R2 = 0.985 and R^2 = 0.999). The VAST population abundance estimates closely resemble the design-based estimates (Table 2.10 and Figure 2.18 ; R^2 = 0.928), however the variance of the VAST estimates are on average 39% lower than the design-based estimates.

The VAST estimates of abundance show that population numbers were at an all-time high in 2014 at 1,231×10^6 fish. Abundance dropped rapidly through 2017 down to 521×10^6 fish before rebounding to 763×10^6 fish in 2019. Abundance once again dropped in 2021 to 609×10^6 fish and continued to drop to 554×10^6 fish in 2022, a drop of 9% from 2021 and a drop of 55% since the 2014 high. Maps of log density are shown in Figure 2.20 and in Figure 2.21 VAST derived estimates of centers of abundance, abundance by region (NBS and EBS) and effective area occupied. The most apparent shift is the move northward in the center of gravity since 2010 and shifting southward after 2019. With this change we observe a larger proportion of the stock residing in the NBS and a reversal of that trend starting in 2021.

A comparison of the standardized VAST bottom trawl survey abundance and VAST winter longline CPUE index is provided in Figure 2.22. Overall the two indices are not correlated (R^2 =-0.11) with the 2022 values divergent, the CPUE index increased from 2021 while the bottom trawl survey index decreased. The VAST bottom trawl survey index is more variable than the VAST CPUE index (CV=0.32 and CV=0.13, respectively).

Size Composition
Design-based estimates of the size compositions (in 1-cm bins) from the combined EBS and NBS bottom trawl surveys for the years 1982-2022 are shown in Figure 2.23 (VAST estimates of size composition are not available, so design-based estimates were used for all models). The number of lengths measured and otoliths collected and aged are provided in Table 2.8. Sample sizes for the survey size and age composition data, in units of sampled hauls, are shown in Table 2.9. The survey size composition mean length are shown in Figure 2.25.

The survey size composition distributions are multi-model, unlike the fisheries size composition distributions. Smaller fish (<40cm) are captured by the survey and individual cohorts can be observed in the data. Particularly large cohorts (e.g. 2007, 2018) reduce the mean length, while strings of poor recruitment (2014-2017) do the opposite. The size compositions from 2012-2014 show clear indications of incoming year classes that are larger than the long-term mean, the 2015-2018 size compositions indicate a string of poor recruitments. In 2019, 2021, and 2022 bottom trawl survey size composition distributions revealed a strong 2018 year class, with a strong mode in the 40-50 cm range in 2021 and 50-60 cm mode in 2022.

VAST age composition
For model-based estimation of age compositions in the Bering Sea, observations of numerical abundance-at-age were fit at each sampling location. This was made possible by applying a year-specific, region-specific (EBS and NBS) age-length key to records of numerical abundance and length-composition. These estimates were computed in VAST, assuming a Poisson-link delta-model (Thorson 2019) involving two linear predictors, and a gamma distribution to model positive catch rates. Density covariates were not included in estimation of age composition for consistency with models used in the previous assessment, and due to computational limitations. The same extrapolation grid was used as implemented for abundance indices, but here the spatial and spatiotemporal fields were modeled with a mesh with coarser spatial resolution than the index model, here using 50 “knots”. This reduction in the spatial resolution of the model, relative to that used abundance indices, was necessary due to the increased computational load of fitting multiple age categories and using epsilon bias-correction. The same diagnostics were used to check convergence and model fit as those used for abundance indices.

Updated VAST age compositions from the combined EBS and NBS surveys for 1994-2022 are shown in Figure 2.24. The age-length keys used to produce these estimates include newly read samples from the 2020 and 2021 surveys. Sample sizes for the survey age composition data, in units of read otoliths, are shown in Table 2.8 (but note that the sample sizes actually specified in the models are in units of sampled hauls (Table 2.9)). The mean age over time for the VAST derived survey age composition is shown in

Figure 2.25. The age composition matches the same patterns as observed in the size composition data, verifying that the 2018 year class continued to be a large portion of the population continuing into 2021.

Data Provided for Context Only

Design-Based Index Estimates from the EBS Shelf and NBS Bottom Trawl Surveys
The design-based area-swept estimates for population abundance (numbers of fish) are given in Table 2.10 and the biomass in Table 2.11. The population numbers for 2022 (501×10^6) have continued to decline since 2019 (730×10^6) and less than half of the number observed in 2014 ($1{,}134\times10^6$). Despite an increase in the eastern Bering Sea from 616×10^3 t in 2021 to 647×10^3 t in 2022, there was an overall decline in biomass Bering Sea-wide (Table 2.11) as biomass in the NBS dropped from 228×10^3 t in 2021 to 154×10^3 t in 2022, an overall drop of 43×10^3 t or -5%. The distribution of cod for 2010 through 2022 from the survey are provided in Figure 2.17 and population numbers with confidence intervals in Figure 2.18. The distribution of the survey shows a decline in Pacific cod in the NBS in 2021 and shift southward and towards the shelf edge. For 2016-2022 the inshore distribution of Pacific cod south of Nunivak Islands observed in 2010-2015 was at much lower abundance.

AFSC Longline Survey
The domestic longline survey began biennial sampling of the eastern BS in 1997 (Rutecki *et al.* 1997). Figure 2.26 shows the locations of the Bering Sea stations sampled by the AFSC longline survey. A Relative Population Number (RPN) index of Pacific cod abundance for the 1997 through 2021 Eastern Bering Sea survey area is available from this survey (Table 2.11and Figure 2.27). Details about these data and a description of the methods for the AFSC sablefish longline survey can be found in Hanselman *et al.* (2016) and Echave *et al.* (2012). The 2021 estimate is a 13% increase over the 2019 estimate. The 2019 index value was the lowest in the time series. 2021 index was 47% lower than the 1997 highest value and 24% below the series mean. The index has been below the long-term average since 2017.

ANALYTIC APPROACH

General Model Structure

Although Pacific cod in the EBS and AI were managed on a BSAI-wide basis through 2013, the stock assessment model has always been configured for the EBS stock only. Since 1992, the assessment model has always been developed under some version of the SS modeling framework (technical details given in Methot and Wetzel 2013; see especially Appendix A to that paper). Beginning with the 2005 assessment, the EBS Pacific cod models have all used versions of SS based on the ADMB software package (Fournier et al. 2012). A history of previous model structures, including all SS-based models that have been fully vetted since 2005, is given in Appendix 2.3 of Thompson et al. (2021). Female spawning stock biomass from the accepted models from 1999 to present is provided in Figure 2.28.

SS V3.30.20.00 was used to run all of the models in this final assessment. The user manual is available at https://nmfs-stock-synthesis.github.io/doc/.

Parameter Estimation

SS requires that prior distributions be associated with all internally estimated time-invariant parameters and the base values of all internally estimated time-varying parameters. For the models presented in this assessment, uniform prior distributions were used for estimation of all such parameters, with bounds set at values sufficiently extreme that:

- they were non-constraining (with two exceptions; see "Results" section below), or
- extending the bounds to even more extreme values would have no practical impact (because, when the parameter is back-transformed to the natural scale, the resulting quantity is indistinguishable from a logical constraint; e.g., selectivity cannot fall outside the (0,1) range).

To simplify terminology, such parameters will be referred to here as being "freely estimated." With two exceptions (discussed in the "Results" section below), in the rare instances where parameter estimates are pinned against either bound, those parameters are fixed in the final run of that model at the values estimated in the penultimate model run.

On the other hand, for each parameter that varies randomly on an annual basis, SS estimates a vector of annual deviations that are either added to, or multiplied by, the base value of the parameter. In the case of log recruitment, the deviations are constrained by a $N(0,\sigma^2)$ distribution. The deviations in every other vector are constrained by a $N(0,1)$ distribution, and then the vector is multiplied by a σ term specific to that vector. In 2021 for all the models in the assessment, each σ was tuned iteratively as follows:

- For a vector of deviations associated with log catchability, σ was tuned to set the root-mean-squared-standardized-residual (RMSSR) equal to unity.
- For the vector of deviations associated with log-scale recruitment, σ was tuned to match the square root of the variance of the estimates plus the sum of the estimates' variances (Methot and Taylor 2011).
- For all other vectors of deviations, σ was tuned to set the variance of the estimates plus the sum of the estimates' variances equal to unity.

The sigma values obtained in 2021 were used in this year's assessment in the corresponding models and provided in Table 2.19.

All models were run using the "-hess_step" option in ADMB. This resulted in all model gradients equaling 0 in the final pass. As an additional check on convergence, the final versions of all models successfully passed a "jitter" test of 50 runs with the jitter rate set at 0.1.

Description of Ensemble Models

Names of Models

Beginning with the final 2015 assessment (Thompson 2015), model numbering has followed the protocol given by Option A in the SAFE chapter guidelines. Names of all final models adopted between the 2005 assessment (when an ADMB-based version of SS was first used) and the 2015 assessment were translated according to that protocol in Table 2.11 of the 2015 assessment. The goal of the protocol is to make it easy to distinguish between major and minor changes in models and to identify the years in which major model changes were introduced. Names of models constituting *minor* changes from the original form of the current base model get linked to the name of that model (e.g., Model 19.12a, is a minor modification of Model 19.12, which was the base model adopted at the conclusion of the 2019 assessment cycle), while names of models constituting *major* changes get linked to the year that they are introduced (e.g., when Model 19.12 was adopted at the conclusion of the 2019 assessment cycle, it constituted a major change from the previous base model (Model 16.6i).

For 2022 as the lead authorship has changed and the way the data are pulled and processed have been substantially changed from previous years (Appendix 2.1), all new models presented this year will be numbered as a 22.X series to reflect that change in data processing, despite the model structures remaining relatively the same.

The Ensembles

For this year we are presenting two sets of ensemble models. The first set deemed the Thompson Series ensemble is the base ensemble used for 2021, the second will be deemed the New Series ensemble which were developed based on the Plan Team and SSC recommendations from September 2022 described in Appendix 2.1.

The Thompson Series ensemble consists of Models 19.12a (the 2020 base model), 19.12, 21.1, and 21.2. The structures of these models were described in the "Models" section of Appendix 2.1 in Thompson et al. (2021).

Following the procedure developed during the 2021 CIE review, the Thompson Series ensemble is "anchored" by Model 19.12A, and then alternative models are constructed by adding features, one per alternative, to the base model as follows:

Thompson Series models	M 19.12	M 19.12A	M 21.1	M 21.2
New Series models	M 22.1	M 22.2	M 22.3	M 22.4
Feature 1: Allow catchability to vary?	yes	no	no	no
Feature 2: Allow domed survey selectivity?	no	no	yes	no
Feature 3: Use fishery CPUE?	no	no	no	yes

Incorporating the above features into the alternative models involves adding the following parameters:

- Model 19.12: 39 constrained deviations
- Model 21.1: 3 survey selectivity parameters
- Model 21.2: 1 fishery catchability parameter

The New Series models presented for consideration this year are based on the Thompson Series models and their development is described in Appendix 2.1. The New Series models have two changes from the Thompson Series consistent across all four models:

- Removal of the annually varying seasonally corrected weight-at-length adjustments
- Removal of the post-2007 aging bias (-2 aging bias parameters)

In short, the annually varying seasonally corrected weight-at-length adjustments were removed because they did not improve fit of any of the model configurations. The ageing bias post-2007 was removed on recommendation from the Age and Growth laboratory indicating that there was no available evidence to suggest that the current aging method was biased.

Parameters Estimated Outside the Assessment Model

Variability in Estimated Age
Variability in estimated age was modeled as the standard deviation of estimated age between "reader" and "tester" age determinations (note that this is not the same as ageing *bias*, which is estimated internally in the assessment models). Weighted least squares regression, without an intercept, has been used in the past several assessments to estimate a proportional relationship between standard deviation and age. The regression has traditionally been computed over ages 1 through 13, yielding a slope parameter that is used to estimate standard deviation at age as the product of slope and age. To maintain consistency between models, only EBS survey age data have been used to estimate the slope parameter.

For the current data set, the estimated slope is 0.083, giving a weighted R^2 of 0.97. This regression corresponds to a standard deviation at age 1 of 0.083 and a standard deviation at age 20 of 1.669.

Weight at Length
Using the functional form weight = $\alpha\times\text{length}^{\beta}$, where weight is measured in kg and length is measured in cm, the long-term base values for the parameters were estimated this year (using fishery data from 1974 through 2021) as α = 5.40706E-06 (mean-unbiased) and β = 3.19601.

The Thompson series models allow inter-annual, externally estimated, variability in weight-length parameters. Values of annual additive offsets from the base α and β values are shown in Table 2.12.

Prior to the 2016 assessment, the EBS Pacific cod assessment models were seasonally structured, and seasonal adjustments to α and β were applied. Beginning with the 2012 assessment (Thompson and Lauth 2012, Annex 2.1.2), an explicit phenological model of intra-annually varying weight at length was used to estimate the α and β parameters, wherein α and β were modeled as trigonometric functions of time (within the calendar year), with time rescaled linearly so as to permit asymmetry in intra-annual rates of change. The simple functional forms enabled closed-form integration over any period within the year, so that seasonal averages could be computed straightforwardly. Although not documented in the 2020 assessment, the phenological model (specifically, the "unconstrained" version of the model described by Thompson and Lauth) was brought back into use in that assessment, not to provide seasonally varying estimates of α and β per se, but to use the estimated intra-annual patterns to extrapolate year-end values of α and β for the current year, for which only partial data are available. This model had been developed in a now outdated version of MathCad. This effort was duplicated using a GAM described in Appendix 2.1 and the GAM derived seasonal adjustments to α and β were used in the Thomson Series models and provided in Table 2.12. These adjustments were not used in the New Series ensemble models.

Maturity
A detailed history and evaluation of parameter values used to describe the maturity schedule for BSAI Pacific cod was presented in the 2005 assessment (Thompson and Dorn 2005). A length-based maturity schedule was used for many years. The parameter values used for the length-based maturity schedule in the 2005 and 2006 assessments were set on the basis of a study by Stark (2007) at the following values: length at 50% maturity = 58 cm and slope of linearized logistic equation = –0.132. However, in 2007, changes in SS allowed for use of either a length-based or an age-based maturity schedule. Beginning with the 2007 assessment, the accepted model has used an age-based schedule with intercept = 4.88 years and slope = –0.965 (Stark 2007). The use of an age-based rather than a length-based schedule followed a recommendation from the maturity study's author (James Stark, AFSC, *pers. commun.*), and the age-based parameters were retained through the 2018 assessment. However, because all assessments since 2009 have estimated some amount of ageing bias, all models beginning with the 2019 assessment have returned to using the length-based schedule.

Stock-Recruitment "Steepness"
Following the standard Tier 3 approach, all models assume that there is no relationship between stock and recruitment, so the "steepness" parameter is set at 1.0 in each.

Parameters Estimated Inside the Assessment Models

Except for the addition of some annual deviations necessitated by extending the terminal year through 2022, the parameters estimated by the assessment models are enumerated in Table 2.1.8 (Appendix 2.1 of Thompson et al. 2021).

For all parameters estimated within individual SS runs, the estimator used was the minimum negative log likelihood.

In addition to the above, the full set of fishing mortality rates was also estimated internally, but not in the same sense as the above parameters. The fishing mortality rates are determined (almost) exactly as functions of other model parameters, because SS assumes that the input total catch data are true values rather than estimates, so the fishing mortality rates can be computed algebraically given the other parameter values and the input catch data. An option does exist in SS for treating the fishing mortality rates as full parameters, but previous explorations have indicated that adding these parameters has almost no effect on other model output (Methot and Wetzel 2013).

Objective Function Components

All models in this assessment include likelihood components for catch, initial (equilibrium) catch, trawl survey relative abundance, fishery and survey size composition, survey age composition, recruitment, initial recruitment, "softbounds" (analogous to a very weak prior distribution designed to keep parameters from hitting bounds), and parameter deviations.

In SS, emphasis factors are specified to determine which likelihood components receive the greatest attention during the parameter estimation process. As in previous assessments, all likelihood components were given an emphasis of 1.0 here.

Use of Size Composition Data in Parameter Estimation
Size composition data are assumed to be drawn from a multinomial distribution specific to a particular year and fleet (fishery or survey). In the parameter estimation process, SS weights a given size composition observation according to the emphasis associated with the respective likelihood component and the sample size specified (and perhaps adjusted by a multiplier) for the multinomial distribution from which the data are assumed to be drawn. In developing the model upon which SS was originally based,

Fournier and Archibald (1982) suggested truncating the multinomial sample size at a value of 400 in order to compensate for contingencies which cause the sampling process to depart from the process that gives rise to the multinomial distribution. Over the years, assessments of EBS Pacific cod have used a variety of approaches to specify multinomial sample sizes that are roughly consistent with this recommendation (summarized most recently by Thompson and Thorson 2019).

The models in the present assessment all set input sample sizes for size composition data as follows:

- Input sample size for a survey is equal to the number of sampled hauls from that survey.
- Input sample size for the fishery is equal to the number of sampled hauls from the fishery, rescaled so that the mean for the time series is equal to the mean number of sampled hauls from the combined EBS+NBS survey time series.

Input sample sizes for size composition data (survey and fishery) are shown in Table 2.9.

Use of Age Composition Data in Parameter Estimation
Like the size composition data, the age composition data are assumed to be drawn from a multinomial distribution specific to a particular year. Because only survey age composition data are used here, input sample size is set equal to the number of hauls in the respective survey (Table 2.9), just as with the survey size composition data.

Note that the age compositions are used in the marginal form, not in conditional-age-at-length form.

Use of Survey Relative Abundance Data in Parameter Estimation
For each index, each year's abundance estimate or where relevant RPN index (for the winter longline fishery CPUE index) are assumed to be drawn from a lognormal distribution specific to that year. The point estimates and lognormal "sigma" terms are shown in Table 2.10.

Use of Recruitment Deviation "Data" in Parameter Estimation
The likelihood component for recruitment is different from traditional likelihoods because it does not involve "data" in the same sense that traditional likelihoods do. Instead, the log-scale recruitment deviation plays the role of the datum in a normal distribution with mean zero and specified standard deviation; but, of course, the deviations are parameters, not data.

RESULTS

Model Evaluation

Individual Model Goodness of Fit
Table 2.13 and Table 2.14 show the objective function value for each data component in each model for the Thompson Series and New Series respectively, along with the number of parameters in each model, where the latter is broken down into "true" (unconstrained) parameters and constrained deviations. With few exceptions, objective function values are not truly comparable across models, and attempts to apply information-theoretic statistics such as the Akaike information criterion may be misleading, because:

- The total parameter counts overestimate the number of "effective" parameters, as these counts include parameters with prior distributions and constrained deviations.
- The models sometimes use different data files (e.g., Model 21.2 and 22.4 use a different data file than the other models, as they include the fishery CPUE time series).
- The data are weighted differently between models, due to previous tuning of the "sigma" terms for devs.

However, within a model set, e.g. Model 19.12 and Model 22.1, data and tuning remain the same and therefore comparisons can be made (Figure 2.29). For all models the likelihoods by data component and fleet are provided in Table 2.15.

The RMSSRs for the index data and the correlations between model estimates and the index data are shown for all models below:

Index:	**Survey**				**Fishery**
Thompson Series	**M19.12**	**M19.12A**	**M21.1**	**M21.2**	**M21.2**
RMSSR	0.989	2.345	2.351	2.499	1.580
Correlation	0.982	0.883	0.883	0.865	0.891
New Series	**M22.1**	**M22.2**	**M22.3**	**M22.4**	**M22.4**
RMSSR	0.987	2.332	2.335	2.498	1.619
Correlation	0.983	0.887	0.887	0.867	0.884

Ideally, RMSSR values should equal 1.0, and this was the standard that was used to tune the sigma terms for the log catchability devs in Model 19.12 and Model 22.1. Models 19.12a and 21.1 underfit the survey index data to similar extents as did Models 22.2 and 22.3. Differences in RMSSR between counterpart models of the two series are minor. Model 21.2 and Model 22.4 fit the survey index data a bit worse than the other models in their respective series, because they had the added task of having to fit the fishery CPUE index, which they fit more successfully than they fit the survey index.

Fits to the bottom trawl survey abundance data are shown for all models for both series in Figure 2.30 and to the winter longline fishery CPUE index for Model 21.2 and 22.4 in Figure 2.32.

Individual model diagnostics and residuals for the index fits can be found in the r4ss library (Taylor et al. 2021) output provided on the AFSC-assessments public github repository:

Thompson Series			
Model 19.12	**Model 19.12A**	**Model 21.1**	**Model 21.2**
https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL19.12/plots/_SS_output_Index.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL19.12A/plots/_SS_output_Index.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL21.1/plots/_SS_output_Index.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL21.2/plots/_SS_output_Index.html
New Series			
Model 22.1	**Model 22.2**	**Model 22.3**	**Model 22.4**
https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL22.1/plots/_SS_output_Index.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL22.2/plots/_SS_output_Index.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL22.3/plots/_SS_output_Index.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL22.4/plots/_SS_output_Index.html

Effective sample sizes implied by the models' fits to the size composition and age composition data are compared with the corresponding input sample sizes in Table 2.16. Input sample sizes are expressed as arithmetic means. Two formulations of effective sample size are shown:

- The formulation popularized by McAllister and Ianelli (1997), which has been used in many previous assessments, is expressed as a harmonic mean. Ideally, the harmonic mean of this formulation of effective sample size should equal the arithmetic mean of the input sample size, which typically requires iterative tuning.
- The formulation of Thorson et al. (2017), which uses the Dirichlet-multinomial distribution to model compositional data, is expressed as a function of an internally estimated parameter ($\ln(\theta)$), so iterative tuning is not required.

Individual figures for selectivities for each model can be found here:

Thompson Series			
Model 19.12	**Model 19.12A**	**Model 21.1**	**Model 21.2**
https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL19.12/plots/_SS_output_Sel.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL19.12A/plots/_SS_output_Sel.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL21.1/plots/_SS_output_Sel.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL21.2/plots/_SS_output_Sel.html
New Series			
Model 22.1	**Model 22.2**	**Model 22.3**	**Model 22.4**
https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL22.1/plots/_SS_output_Sel.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL22.2/plots/_SS_output_Sel.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL22.3/plots/_SS_output_Sel.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL22.4/plots/_SS_output_Sel.html

Size composition: By the McAllister-Ianelli measure, both the fishery and survey size composition data were *over*fit by all of the models. The Dirichlet-multinomial parameter was constrained by the upper bound for both the fishery and survey size composition data in all models, meaning that, by the Thorson et al. measure, the effective sample size was equal to the average input sample size. Fits to the mean length are shown for all models for both series in Figure 2.33. Model fits to the size composition data and residuals can be found in the r4ss library (Taylor et al. 2021) output provided on the AFSC-assessments public github repository:

Thompson Series			
Model 19.12	**Model 19.12A**	**Model 21.1**	**Model 21.2**
https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL19.12/plots/_SS_output_LenComp.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL19.12A/plots/_SS_output_LenComp.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL21.1/plots/_SS_output_LenComp.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL21.2/plots/_SS_output_LenComp.html
New Series			
Model 22.1	**Model 22.2**	**Model 22.3**	**Model 22.4**
https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL22.1/plots/_SS_output_LenComp.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL22.2/plots/_SS_output_LenComp.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL22.3/plots/_SS_output_LenComp.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL22.4/plots/_SS_output_LenComp.html

Age composition: By the McAllister-Ianelli measure, the age composition data were *under*fit by all of the models. The effective sample sizes for the Thorson et al. (2017) formulation were of the same magnitude and rank order as, but larger than, the effective sample sizes for the McAllister-Ianelli formulation. By both measures, the Thompson Series of models fit the age composition data better and within each series Model 19.12 and Model 22.1 exhibited slightly better fits than the other models. Fits to the mean age are shown for all models for both series in Figure 2.34. Model fits to the age composition data and residuals can be found in the r4ss library (Taylor et al. 2021) output provided on the AFSC-assessments public github repository:

Thompson Series			
Model 19.12	**Model 19.12A**	**Model 21.1**	**Model 21.2**
https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL19.12/plots/_SS_output_AgeComp.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL19.12A/plots/_SS_output_AgeComp.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL21.1/plots/_SS_output_AgeComp.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL21.2/plots/_SS_output_AgeComp.html
New Series			
Model 22.1	**Model 22.2**	**Model 22.3**	**Model 22.4**
https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL22.1/plots/_SS_output_AgeComp.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL22.2/plots/_SS_output_AgeComp.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL22.3/plots/_SS_output_AgeComp.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL22.4/plots/_SS_output_AgeComp.html

Carvalho et al. (2021) Model Diagnostics from ss3diags R Library (Winker et al. 2022)

Residual runs test: The residual runs test is a nonparametric hypothesis test for randomness in the residual sequence that calculates the 2-sided p-value to estimate the number of runs (i.e., sequences of values of the same sign) above and below the mean. This checks for the presence of systematic drifts in the residual mean through time. The results of the runs test for each data component and model are provided in Table 2.17.

None of the models passed all of the runs tests for all data components. Model 19.12 was the best behaved in only failing the fishery length composition runs test. All of the models for both ensemble series passed the survey index runs test, while neither of the models with the winter longline fishery CPUE index passed. Only Model 19.12 passed the residual runs test for the either length composition component. All of the Thompson Series models passed the age composition runs test, while only Model 22.1 passed of the New Series models. By eye the residuals from the length and age composition data appear to be acceptable, however the runs test results suggest that there is significant autocorrelation in the residuals. Further exploration of the use of the runs test is warranted as well as exploration of model configurations that will reduce this autocorrelation should be pursued in future models.

Mean absolute scaled error (MASE): The MASE diagnostic builds on the principle of evaluating the prediction skill of a model relative to a naïve baseline prediction. A prediction is said to have 'skill' if it improves the model forecast compared to the baseline. MASE uses as a baseline the 'persistence algorithm' that takes the observation at the previous time step to predict the expected outcome at the next time step as a random walk of naïve in-sample predictions. The MASE score scales the mean absolute error (MAE) of forecasts to MAE of a naïve in-sample prediction. A MASE score > 1 indicates that the average model forecasts are worse than a random walk. Conversely, a MASE score of 0.5 indicates that the model forecasts twice as accurately as a naïve baseline prediction; thus, the model has prediction skill. The MASE for each data component and model are provided in Table 2.18. For all models for both series the models performed better than a random walk for both the bottom trawl survey and winter longline fishery CPUE indices. For the fishery length composition all performed well and conversely none of the models performed better than a random walk for the survey length composition predictions with values all exceeding 1.0.

Plots from the ss3diags library (Winker et al. 2022) analysis as described in Carvalho et al. (2021) are available on the AFSC-assessment github repository and linked here:

Thompson Series			
Model 19.12	**Model 19.12A**	**Model 21.1**	**Model 21.2**
https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/SS3DIAGS/SS3DIAGS_M19.12.pdf	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/SS3DIAGS/SS3DIAGS_M19.12A.pdf	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/SS3DIAGS/SS3DIAGS_M121.1.pdf	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/SS3DIAGS/SS3DIAGS_M21.2.pdf

New Series			
Model 22.1	**Model 22.2**	**Model 22.3**	**Model 22.4**
https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/SS3DIAGS/SS3DIAGS_M22.1.pdf	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/SS3DIAGS/SS3DIAGS_M22.2.pdf	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/SS3DIAGS/SS3DIAGS_M22.3.pdf	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/SS3DIAGS/SS3DIAGS_M22.4.pdf

Model Weights
The 2021 CIE review resulted in a set of model weights for the five models in the reviewers' recommended ensemble (Table 2.1.14 of Appendix 2.1 of Thompson et al. 2021). These weights were developed from a procedure that was based on the procedures used in the 2019 and 2020 assessments, with some modifications (see "Model weights" section in Appendix 2.1 of Thompson et al. 2021). In brief, model weights were computed by normalizing the emphasis-weighted averages of reviewer-averaged scores (0, 1, or 2) for a set of criteria. Because the SSC's ensemble omits one model from the CIE reviewers' ensemble (Model 21.3), the weights determined by the CIE panel were renormalized, giving the weights shown in Table 2.20.

The model weights in Table 2.20 were used to augment the model-specific results for both the Thompson Series and New Series ensembles.

Retrospective Performance
Retrospective analyses were conducted for all models and both ensemble series. Mohn's ρ values (Mohn 1999) for all individual models and ensembles are provided in Table 2.21 and shown in Figure 2.35. For the spawning stock biomass retrospective analysis all models, including the ensembles for both series, have values of ρ within their respective acceptable ranges as suggested by Hurtado-Ferro et al. (2015). In both series the model fitting the winter fisheries CPUE index (Model 21.2 and Model 22.4) perform the least well of all models, however still well within acceptable bounds (-0.21 to 0.29 across all models). Values for recruitment, fishing mortality, and the biomass ratio are also provided. However acceptable ranges for these have yet to be determined. For all models there is a consistent positive bias in spawning biomass, recruitment and the biomass ratio and a consistent negative bias in fishing mortality. The spawning stock biomass retrospective plots for the New Series models were produced using ss3diags library (Winker et al. 2022) are shown in Figure 2.36 and the spawning biomass retrospective plot for the New Series ensemble is shown in Figure 2.37.

Parameter Estimates
All parameter estimates with their standard deviations for the New Series and Thompson Series models as well as their ensembles are provided in an Excel file as Appendix 2.5 (https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/APPENDICES/Appendix_2.5_%20Data_and_results.xlsx).

Individual figures for these parameters for each model can be found here:

Thompson Series			
Model 19.12	**Model 19.12A**	**Model 21.1**	**Model 21.2**
https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL19.12/plots/_SS_output_Pars.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL19.12A/plots/_SS_output_Pars.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL21.1/plots/_SS_output_Pars.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL21.2/plots/_SS_output_Pars.html

New Series			
Model 22.1	**Model 22.2**	**Model 22.3**	**Model 22.4**
https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL22.1/plots/_SS_output_Pars.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL22.2/plots/_SS_output_Pars.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL22.3/plots/_SS_output_Pars.html	https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/R4SS_FIGURES/MODEL22.4/plots/_SS_output_Pars.html

Table 2.23 provides the estimates and standard deviations for the parameter estimates that are shared for all models for both the Thompson Series and New Series ensembles.

Distribution plots of all fit parameters for Thompson ensembles are provided in a pdf (9.2 MB; pages 403-536 here:

https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/ENSEMBLE_FIGURES/THOMPSON_ENSEMBLE.pdf

Distribution plot of parameters for the New Series ensemble are provided in a pdf (9.0 MB; pages 383-513) here:

https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/FIGURES/ENSEMBLE_FIGURES/NEW_ENSEMBLE.pdf

All parameters appear to be well estimated, however in Model 19.12 and Model 19.12A the parameter for fishery selectivity double normal defining descending slope was within 1.5% of the upper bound (10) and in Model 22.3 the same parameter for the survey selectivity was within 1.5% of its lower bound (-10). In Models 19.12 and 19.12A this creates a tapered dome-shaped selectivity (Figure 2.38). In the case of Model 22.3 this results in an asymptotic survey selectivity up to a knife edge drop after the maximum size of cod observed (Figure 2.38). This knife edge becomes more dome-shaped in the selectivity at age as interpreted through the age-length key, but at ages with few observations in the survey.

As noted under "Goodness of fit" above, the Dirichlet-multinomial parameters for both fishery and survey size composition ended up being pinned near the upper bound (=10.0) for all models, so those parameters were fixed in the final run of each model. The range of estimates of natural mortality were much greater for the Thompson Series models (Table 2.13) ranging from 0.349 (Model 21.1) to 0.415 (Model 19.15A), compared to 0.333 (Model 22.1) to 0.351 (Model 22.4) in the New Series (Table 2.14). The overall ensemble mean natural mortality was relatively close for the two ensembles at 0.347 for the Thompson Series ensemble and 0.343 for the New Series ensemble.

For the all of the Thompson Series models the sign of the ageing bias (Table 2.22) flips from all positive (pre-2008) to very near zero at age 1 but negative at older ages (post-2007). Aging bias for pre-2008 in the New Series, although not exact, matches that found for the Thompson Series. For all models without the CPUE index aging bias for pre-2008 was at 0.9 for age 20 fish and 0.8 for the two models fit with the CPUE index (Model 21.2 and Model 22.4). Aging bias for pre-2008 at age 1 ranged between 0.34 and 0.35 for all models. In the Thompson Series models aging bias for post-2007 at age 20 ranged between -1.3 to -1.5.

The AFSC bottom trawl survey catchability was higher on average in the Thompson Series models with an ensemble value of 0.978 versus 0.969 in the New Series models (Table 2.13 and Table 2.14). In both series of models the model fit with the winter longline CPUE index (Model 21.2 and Model 22.4) had the lowest trawl survey catchability values, both at 0.89. Model 19.12 and Model 22.1 fit with annually varying bottom trawl survey catchability, had base values of 1.03 and closely matching time series (Figure 2.31).

For the Thompson Series models asymptotic length ($L\infty$) ranged from 111.848 cm (Model 19.12A) to 144.934 cm (Model 21.1) and the Brody growth coefficient (K) ranged from 0.064 (Model 21.1) to 0.118 (Model 19.12A; Table 2.13). In the New Series the ranges of L_∞ and K were much smaller, between 112 and 115 for $L\infty$ and 0.110 and 0.115 for K (Table 2.14).

Initial fishing mortality ranges from 0.085 (Model 21.1) to 0.135 (Model 22.1). Initial fishing mortality for the New Series models were all higher for each model pair than those from the Thompson Series models and therefore the New Series ensemble value for initial fishing mortality (0.125) was slightly higher than for the Thompson Series ensemble (0.110).

Derived Quantities
Table 2.24 contains selected management reference points for the Thompson Series and New Series ensembles. Static quantities include $B_{100\%}$, $B_{40\%}$, $B_{35\%}$, $F_{40\%}$, and $F_{35\%}$. Quantities shown for each of the first two projection years (2023 and 2024) consist of female spawning biomass, relative spawning biomass, the probability that the ratio of spawning biomass to $B_{100\%}$ will fall below 0.2, maxFABC, maxABC, catch, FOFL, OFL, and the probability that maxABC exceeds the true-but-unknown OFL.

The values of 2022 female spawning biomass, relative spawning biomass, maxFABC, and maxABC projected by the Thompson Series ensemble and New Series ensemble shown in Table 2.24 don't differ markedly from last year's projections of those same quantities from last year's ensemble, as shown below:

Year	Quantity	Last Year	Thompson Series	Change	New Series	Change	Thompson vs. New
2023	Female spawning biomass	254,585	245,934	-3.4%	245,594	-3.5%	0.1%
2023	Relative spawning biomass	0.370	0.367	-0.8%	0.367	-0.8%	0.0%
2023	$maxF_{ABC}$	0.310	0.291	-6.1%	0.293	-5.5%	0.7%
2023	maxABC	151,709	142,539	-6.0%	144,834	-4.5%	1.6%

The difference from last year can be attributed to the lower 2022 bottom trawl survey abundance estimate (-9%) than expected by last year's ensemble, which had projected a smaller decrease in abundance (-1%).

Choice of Ensemble
There is little difference (Figure 2.39) in the sets of models from the two ensembles presented. The removal of the weight-at-length adjustments make nearly no change to the model (Appendix 2.1). The major difference in objective function is due to the removal of the post-2007 aging bias resulting in a poorer fit to the age composition in the New Ensemble models. However, the New Series models provide a slightly better fit the length composition data, which doesn't fully make up for the weaker fit to the age composition data. In the end results from both series of models are plausible, however in consideration of advice from the AFSC Age and Growth Laboratory (Appendix 2.1) and lack of evidence for bias in the new aging methods the New Series models would be the best available science at this time. As described in September the annual weight-at-length adjustment does not improve model fits while adding undue complexity to the models. We therefore recommend the use of the NEW Series models.

Time Series Results

The biomass estimates presented here will be defined in two ways: 1) age 0+ biomass, consisting of the biomass of all fish aged 0 years or greater in January of a given year; and 2) spawning biomass, consisting of the biomass of all spawning females in January of a given year. The recruitment estimates presented here will be defined as numbers of age 0 fish in a given year.

Results tables including estimated time series, numbers at age and length, and selectivity from all models and ensembles are provided in Excel tables in Appendix 2.5.

https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/APPENDICES/Appendix_2.5_%20Data_and_results.xlsx

Table 2.25 provides the time series of female spawning biomass (t) since 1977 as estimated last year's ensemble, the Thompson Series ensemble, and the New Series ensemble. The estimated spawning biomass time series are accompanied by their respective standard deviations. Figure 2.40 shows the time series of female spawning biomass annual ensemble distributions for the New Series ensemble and point estimates for each model within the ensemble. Figure 2.41 shows a timeseries of the ratio of the spawning stock biomass to unfished spawning biomass annual ensemble distributions for the New Series ensemble and point estimates for each model within the ensemble. In general, all of the models agree on the trends in the time series with the highest spawning biomass in the 1980s dropping through the 1990s and into the 2000s with the lowest spawning biomass in 2010 which reached a low of $B_{21\%}$. With the large 2006, 2008, 2011, and 2013 year classes the stock rebounded to $B_{51\%}$ by 2018 to a spawning biomass of 338,863 t. The stock has been declining since and is estimated to be at $B_{37.4\%}$ in 2022 at 250,144 t and is projected to be at 245,583 t in 2023, status dropping slightly to $B_{36.7\%}$.

Table 2.26 provides the time series of age 0+ biomass since 1978 as estimated last year's ensemble, the Thompson Series ensemble, and the New Series ensemble (point estimates only). The age 0+ biomass follows a similar trend to the spawning biomass with peak biomass estimated greater than 900,000 t from 1982-1991 with the highest biomass in 1988 at 1.332 million t. After the peak in 1989 age 0+ biomass leveled showed a dropping trend with occasional peaks down to a low of 570,000 t (a 57% drop from the 1989 peak) in 2008. The age 0+ rose again to a peak of 1.205 million tons in 2016 (90% of the peak 1989 biomass) before dropping to 0.853 million ton in 2022. 2023 total age 0+ biomass is expected to be at 63% of the peak 1989 age 0+ biomass.

Table 2.27 provides the time series of recruitment (1000s of fish) for the years since 1978 as estimated last year's ensemble, the Thompson Series ensemble, and the New Series ensemble. The estimated time series are accompanied by their respective standard deviations. The correlation between last year's estimated recruitment time series and this year's is 0.997 and 0.995 for the Thompson and New Series ensembles. Figure 2.42 shows the time series of age-0 recruitment (1000s of fish) annual ensemble distributions for the New Series ensemble and point estimates for each model within the ensemble. For the time series as a whole, the 2008 and 2013 cohorts are currently estimated to be the largest. Other recent year classes that exceed the time series average by at least 50% are the 2006, 2010, 2011, and 2018 cohorts. In last year's assessment, the 2018 year class ranked 11th in the time series, with an estimated size of 749,239,000 fish. In this year's assessment, the 2018 year class ranked 9th in the time series, and the estimated size increased to 807,998,000 fish. Although the confirmed strength of the 2018 year class is a positive sign, it should also be noted that six of the last seven year classes have been below average, including four of the bottom ten in the overall time series, and seven of the last ten year classes have also been below average. By way of context, there has been one previous seven-year string in which six year classes have been below average, and three previous nine-year strings in which seven year classes have been below average.

Table 2.28 provides the time series of instantaneous apical fishing for the years since 1977 as estimated last year's ensemble, the Thompson Series ensemble, and the New Series ensemble. The estimated time series are accompanied by their respective standard deviations. Figure 2.43 shows time series of instantaneous apical fishing annual ensemble distributions for the New Series ensemble and point estimates for each model within the ensemble. Fishing mortality increased throughout the 1980s and into the 1990's with an initial high peak in the New Series ensemble in 1997 at 0.506. This then drops to 0.347 in 2001 before rising again up to a maximum of 0.605 in 2011 and dropping down to a new low of 0.261 in 2021. 2022 is expected to have an increase in fishing mortality to 0.325. The years from 1994 to 1998 and from 2004 to 2017 had estimated fishing mortality values exceeding the $F_{35\%}$ of 0.389. All the models are in general agreement with the overall trends, however Model 22.4, which fit the winter longline fishery CPUE index, estimates a lower fishing mortality rate from the mid-1990s through 2012 and higher values from 2014 to 2020.

Figure 2.44 plots the estimated/projected trajectory of relative fishing mortality ($F/F_{35\%}$) and relative female spawning biomass ($B/B_{35\%}$) from 1977 through 2023 based on apical fishing mortality, overlaid with the current harvest control rules. Models prior to 2016 featured dome-shaped survey selectivity, while models since 2016 have forced survey selectivity to be asymptotic, which changed the appearance of the trajectory considerably, so that, in hindsight, the stock was being subjected to fishing mortality rates in excess of the retroactively calculated F_{OFL} values (but not the official F_{OFL} values that were calculated at the time) in all years from the early 1990s through 2017.

Harvest Recommendations

Results presented in this section pertain primarily to the New Series ensemble only, however results for the Thompson Series or any one specific model can be made available.

Amendment 56 Reference Points

Amendment 56 to the BSAI Groundfish Fishery Management Plan (FMP) defines the "overfishing level" (OFL), the fishing mortality rate used to set OFL (F_{OFL}), the maximum permissible ABC, and the fishing mortality rate used to set the maximum permissible ABC. The fishing mortality rate used to set ABC (F_{ABC}) may be less than this maximum permissible level, but not greater. Because reliable estimates of reference points related to maximum sustainable yield (MSY) are currently not available but reliable estimates of reference points related to spawning per recruit are available, Pacific cod in the EBS have generally been managed under Tier 3 of Amendment 56. Tier 3 uses the following reference points: $B_{40\%}$, equal to 40% of the equilibrium spawning biomass that would be obtained in the absence of fishing; $F_{35\%}$, equal to the fishing mortality rate that reduces the equilibrium level of spawning per recruit to 35% of the level that would be obtained in the absence of fishing; and $F_{40\%}$, equal to the fishing mortality rate that reduces the equilibrium level of spawning per recruit to 40% of the level that would be obtained in the absence of fishing. The following formulae apply under Tier 3:

3a) Stock status: $B/B_{40\%} > 1$

$F_{OFL} = F_{35\%}$

$F_{ABC} \leq F_{40\%}$

3b) Stock status: $0.05 < B/B_{40\%} \leq 1$

$F_{OFL} = F_{35\%} \times (B/B_{40\%} - 0.05) \times 1/0.95$

$F_{ABC} \leq F_{40\%} \times (B/B_{40\%} - 0.05) \times 1/0.95$

3c) Stock status: $B/B_{40\%} \leq 0.05$

$F_{OFL} = 0$

$F_{ABC} = 0$

The weighted average estimate of $F_{35\%}$ from the ensemble is 0.389; and the weighted average estimate of $F_{40\%}$ from the ensemble is 0.320 (Table 2.24).

The weighted average estimate of $B_{100\%}$ from the ensemble is 668,477 t. The distribution of each model from the New Series and ensemble are shown in Figure 2.45; the weighted average estimate of $B_{40\%}$ from the ensemble is 267,391 t; and the weighted average estimates of $B_{35\%}$ from the ensemble is 233,967 t (Table 2.24).

Means and standard deviations of the ABC and OFL distributions for 2023 and 202 are shown for each model and for the ensemble in Table 2.24, and the distribution for the maxABCs are shown in Figure 2.47.

Specification of OFL and Maximum Permissible ABC
Given the assumptions of Scenario 2 (below), female spawning biomass for 2023 is estimated by the ensemble to be 245,594 t; and female spawning biomass for 2024 is estimated to be 242,911 t. Both of these projected values are below $B_{40\%}$, thereby placing Pacific cod in Tier 3b for both 2023 and 2024. Given this, the estimates of OFL, maximum permissible ABC, and the associated fishing mortality rates for 2023 and 2024 as follows (from Table 2.24):

Year	F_{OFL}	maxF_{ABC}	OFL (t)	maxABC (t)
2023	0.356	0.293	172,495	144,834
2024	0.352	0.290	166,814	140,159

The age 0+ biomass projections for 2023 and 2024 from the ensemble are 844,578 t and 831,566 t, respectively (Table 2.26).

Standard Harvest Scenarios, Projection Methodology, and Projection Results
A standard set of projections is required for each stock managed under Tiers 1, 2, or 3 of Amendment 56. This set of projections encompasses seven harvest scenarios designed to satisfy the requirements of Amendment 56, the National Environmental Policy Act, and the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA). Prior to the 2018 assessment, the standard harvest scenarios were made using the AFSC's "Proj" program. Beginning with the 2018 assessment, however, the projections have been made within SS. Point estimates of all time-varying parameters used in the projections are set at their respective time series means, except for annual deviations governing length at age of year classes currently in the population, as these propagate into the future. Year-end catch for 2022 was estimated to be 152,146 t, equal to the proportion of end of year catch to ABC for the previous five years times the 2022 ABC. In the event that catch is likely to be less than the recommended ABC in either of the first two projection years, Scenario 2 must be conducted, using the best estimates of catch in those two years (otherwise, Scenario 2 can be omitted if the author's recommended ABCs for the next two years are equal to the maximum permissible ABCs). The following relationship between ABC and catch was described under "Management History" in the "Fishery" section: For ABC≥198,000 t, catch = 89,000 t + 0.55×ABC; for ABC<198,000 t, catch = ABC. Because the recommended ABCs for both of the first two projection years are less than 198,000 t, no adjustment is necessary.

In each subsequent year, the fishing mortality rate is prescribed on the basis of the spawning biomass in that year and the respective harvest scenario.

Five of the seven standard scenarios are sometimes used in an Environmental Assessment prepared in conjunction with the final SAFE. These five scenarios, which are designed to provide a range of harvest alternatives that are likely to bracket the final TACs for 2022 and 2023, are as follow ("*max* F_{ABC}" refers to the maximum permissible value of F_{ABC} under Amendment 56):

> *Scenario 1*: In all future years, F is set equal to *max* F_{ABC}. (Rationale: Historically, TAC has been constrained by ABC, so this scenario provides a likely upper limit on future TACs.)

Scenario 2: In all future years, *F* is set equal to a constant fraction ("author's F") of *max* F_{ABC}, where this fraction is equal to the ratio of the F_{ABC} value for 2023 recommended in the assessment to the *max* F_{ABC} for 2023, and where catches for 2023 and 2024 are estimated at their most likely values given the 2023 and 2024 recommended ABCs under this scenario. (Rationale: When F_{ABC} is set at a value below *max* F_{ABC}, it is often set at the value recommended in the stock assessment; also, catch tends not to equal ABC exactly.)

Scenario 3: In all future years, *F* is set equal to the 2017-2021 average *F*. (Rationale: For some stocks, TAC can be well below ABC, and recent average *F* may provide a better indicator of F_{TAC} than F_{ABC}.)

Scenario 4: In all future years, the upper bound on F_{ABC} is set at $F_{60\%}$. (Rationale: This scenario provides a likely lower bound on F_{ABC} that still allows future harvest rates to be adjusted downward when stocks fall below reference levels.)

Scenario 5: In all future years, *F* is set equal to zero. (Rationale: In extreme cases, TAC may be set at a level close to zero.)

Two other scenarios are needed to satisfy the MSFCMA's requirement to determine whether a stock is currently in an overfished condition or is approaching an overfished condition. These two scenarios are as follow (for Tier 3 stocks, the MSY level is defined as $B_{35\%}$):

Scenario 6: In all future years, *F* is set equal to F_{OFL}. (Rationale: This scenario determines whether a stock is overfished. If the stock is 1) above its MSY level in 2022 or 2) above 1/2 of its MSY level in 2022 and expected to be above its MSY level in 2032 under this scenario, then the stock is not overfished.)

Scenario 7: In 2023, *F* is set equal to *max* F_{ABC}, and in all subsequent years, *F* is set equal to F_{OFL}. (Rationale: This scenario determines whether a stock is approaching an overfished condition. If the stock is 1) above its MSY level in 2024 or 2) above 1/2 of its MSY level in 2023 and expected to be above its MSY level in 2034 under this scenario, then the stock is not approaching an overfished condition.)

Projections (means and standard deviations) of female spawning biomass (B), full selection fishing mortality (F), and catch (C) corresponding to the standard scenarios are shown for all models and both the weighted and unweighted ensemble averages in Table 2.30. Female spawning stock biomass trajectories for all scenarios for the New Series ensemble are presented in Figure 2.48.

In addition to the seven standard harvest scenarios, Amendments 48/48 to the BSAI and GOA Groundfish Fishery Management Plans require projections of the likely OFL two years into the future. While Scenario 6 gives the best estimate of OFL for 2023, it does not provide the best estimate of OFL for 2024, because the mean 2024 catch under Scenario 6 is predicated on the 2023 catch being equal to the 2023 OFL, whereas the actual 2023 catch will likely be less than the 2023 OFL. Table 2.24 contains the appropriate one- and two-year ahead projections for both ABC and OFL.

Risk Table and ABC Recommendation

<u>Overview</u>
The following template is used to complete the risk table:

	Assessment-related considerations	*Population dynamics considerations*	*Environmental/ecosystem considerations*	*Fishery Performance*
Level 1: Normal	Typical to moderately increased uncertainty/minor unresolved issues in assessment.	Stock trends are typical for the stock; recent recruitment is within normal range.	No apparent environmental/ecosystem concerns	No apparent fishery/resource-use performance and/or behavior concerns
Level 2: Substantially increased concerns	Substantially increased assessment uncertainty/ unresolved issues.	Stock trends are unusual; abundance increasing or decreasing faster than has been seen recently, or recruitment pattern is atypical.	Some indicators showing adverse signals relevant to the stock but the pattern is not consistent across all indicators.	Some indicators showing adverse signals but the pattern is not consistent across all indicators
Level 3: Major Concern	Major problems with the stock assessment; very poor fits to data; high level of uncertainty; strong retrospective bias.	Stock trends are highly unusual; very rapid changes in stock abundance, or highly atypical recruitment patterns.	Multiple indicators showing consistent adverse signals a) across the same trophic level as the stock, and/or b) up or down trophic levels (i.e., predators and prey of the stock)	Multiple indicators showing consistent adverse signals a) across different sectors, and/or b) different gear types
Level 4: Extreme concern	Severe problems with the stock assessment; severe retrospective bias. Assessment considered unreliable.	Stock trends are unprecedented; More rapid changes in stock abundance than have ever been seen previously, or a very long stretch of poor recruitment compared to previous patterns.	Extreme anomalies in multiple ecosystem indicators that are highly likely to impact the stock; Potential for cascading effects on other ecosystem components	Extreme anomalies in multiple performance indicators that are highly likely to impact the stock

The table is applied by evaluating the severity of four types of considerations that could be used to support a scientific recommendation to reduce the ABC from the maximum permissible. These considerations are stock assessment considerations, population dynamics considerations, environmental/ecosystem considerations, and fishery performance. Examples of the types of concerns that might be relevant include the following:

1. Assessment considerations—data-inputs: biased ages, skipped surveys, lack of fishery-independent trend data; model fits: poor fits to fits to fishery or survey data, inability to simultaneously fit multiple data inputs; model performance: poor model convergence, multiple minima in the likelihood surface, parameters hitting bounds; estimation uncertainty: poorly-estimated but influential year classes; retrospective bias in biomass estimates.

2. Population dynamics considerations—decreasing biomass trend, poor recent recruitment, inability of the stock to rebuild, abrupt increase or decrease in stock abundance.

3. Environmental/ecosystem considerations—adverse trends in environmental/ecosystem indicators, ecosystem model results, decreases in ecosystem productivity, decreases in prey abundance or availability, increases or increases in predator abundance or productivity.

4. Fishery performance—fishery CPUE is showing a contrasting pattern from the stock biomass trend, unusual spatial pattern of fishing, changes in the percent of TAC taken, changes in the duration of fishery openings.

Development of the risk table in this assessment follows the approach described by Thompson (2021), which is an explicit attempt to view the risk table in the context of the probability that ABC exceeds the true-but-unknown OFL. The approach partitions this probability into *internal* and *external* components. The *internal* probability is that which is routinely computed from the stock assessment model; for example, Table 2.24 indicates that, if the 2023 catch were to equal the 2023 maxABC, the internal probability for the ensemble is approximately 0.33 (see the line in the table labeled "Pr(maxABC>truOFL)"). The *external* probability is that which cannot be computed from the stock assessment model, because it involves factors that are external to the stock assessment model, and hence is evaluated using the risk table. The approach also includes an option whereby the integer levels in the risk table template can be supplemented by specifying an *intralevel* fraction between 0 and 1. The intralevel fraction describes where the stock falls within the assigned level. For example, does the stock barely qualify for the assigned level, does it lie squarely in the middle of the assigned level, or does it nearly qualify for the next higher level? The intralevel fractions, like the integer risk levels, are based on "subjective but well-informed interpretation of the available data."

<u>Assessment Considerations</u>

Recognizing the SSC's recommendation that, "Risk scores should be specific to a given stock or stock complex", the assessment considerations will be limited to a comparison of the present assessment with previous assessments of the same stock. As a point of departure, the assessment considerations category was assigned a risk level of 1 in each of the three previous assessments.

Recent range expansion of the stock into the NBS made assessment modeling more difficult for a few years. However, with the development of the VAST method (Thorson and Barnett 2017), it has become possible to treat the combined EBS and NBS surveys in a coherent fashion, eliminating the need to treat those surveys separately, either with or without explicit movement between areas. Spatial distribution concerns have now shifted to some extent toward movement between American and Russian jurisdictions. Although harvests in Russian waters have the potential to impact harvests in American waters if there is significant mixing between the two areas, the available data suggest that recent harvest rates in Russian waters do not appear to be particularly high (Table 2.4). Note that this concern may heighten if data on that fishery are no longer available.

This year, an ensemble model is proposed once again. As suggested in previous assessments, use of an ensemble approach gives some confidence that alternative explanations of the data are considered, and mitigates, at least to some extent, concerns that may exist regarding any individual model.

Assessment considerations were once again rated as level 1 (normal).

Population Dynamics Considerations

Population dynamics considerations were assigned a risk level of 1 in each of the two previous assessments, and last year's assessment included the additional suggestion that "within level 1, the degree of concern is nearer the bottom end of the level than the upper end" (Thompson et al. 2020).

As noted above under "Time Series Results," six out of the seven most recent cohorts are estimated to have been below average, as have seven out of the last nine. Although neither of these occurrences is unprecedented (there was one previous six-out-of-seven string and three previous seven-out-of-nine strings in the time series), they are at least somewhat concerning, as they may be harbingers of a long-term change in mean recruitment. While the time series of recruitment estimates are already part of the stock assessment model, and therefore should not be considered as a reason for a risk table adjustment, the possibility of a long-term change in mean recruitment is not part of the stock assessment model.

The ensemble estimate of age 0+ biomass for 2023 is only 0.22 standard deviations removed from the pre-2023 time series mean, and the ensemble estimate of female spawning biomass for 2023 is only 0.06 standard deviations removed from the pre-2023 time series mean. The estimated rate of change in age 0+ biomass from 2022 to 2023 is -3.8%. The estimated rate of change in female spawning biomass from 2022 to 2023 is -1.8%. None of this suggests that abundance is "increasing or decreasing faster than has been seen recently".

Population dynamics considerations were once again rated as level 1 (normal).

Environmental/Ecosystem Considerations

Appendix 2.2 provides a detailed look at environmental/ecosystem considerations specific to this stock within the ecosystem and socioeconomic profile (ESP). Broad-scale information on environmental and ecosystem considerations are provided by the Eastern Bering Sea Ecosystem Status Report (ESR; Siddon, 2022). The text below summarizes ecosystem information related to EBS Pacific cod provided from both the ESP and ESR.

Environmental processes:

The extended warm phase experienced in the eastern Bering Sea (EBS) that began in approximately 2014 has largely relaxed to normal conditions over the past year (August 2021 - August 2022). The North Pacific Index (NPI) has been positive during 5 out of the last 6 winters, with the exception being the winter of 2018-19. Positive values mean a weak Aleutian Low Pressure System (ALPS) and generally calmer conditions. Spring to summer sea surface temperature (SST) was slightly above the long term average (see Appendix 2.2: Spring Summer Temperature Surface SEBS Satellite indicator by M. Callahan) and marine heatwaves were relatively weak and short-lived compared to recent years. Estimates of bottom temperature derived from the ROMS model suggest that bottom temperatures in the northern Bering Sea (NBS) over the past year were within normal ranges while the southeastern Bering Sea (SEBS) was significantly cooler than average (see Appendix 2.2: Summer Temperature Bottom SEBS Model indicator by K. Kearney). The Bering Sea ice extent was generally higher than average throughout much of the 2021-2022 winter, particularly for the ice advance season (Dec-Feb) which had been well below average since 2014, prior to the onset of the marine heatwaves (see Appendix 2.2: Winter and Spring Sea Ice Advance and Retreat BS Satellite indicator by M. Wang). Ice advanced rapidly in November, though there was an abrupt springtime retreat beginning in mid-April and the ice retreat season (Mar-May) was very just slightly below average. These cool-to-normal winter conditions were favorable to cold pool formation, though not to the areal extent in the years preceding 2014. The 2022 cold pool was near the historical average and resembled other average-to-cool years, most similar to 2017 (Hennon et al. 2022). While the cold pool is included as a covariate of the spatiotemporal estimates of biomass used in the main stock assessment model, the dynamics are an important consideration and relevant to understanding the overall health of the EBS ecosystem.

The ecosystem ‘red flags’ that occurred in the NBS in 2021, notably the crab population declines (Richar 2021) and salmon run failures in the Arctic-Yukon-Kuskokwim region (Liller 2021), continued into 2022 (Richar 2022; Whitehouse 2022). However, the center of gravity estimate for Pacific cod has shifted from 2021 with the population center moving further south and east in 2022. The area occupied in the NBS has continued a downward trend seen in 2021, decreasing to below 2010 levels (Figure 2.21), while the area occupied in the SEBS was slightly above average (see Appendix 2.2: Summer Pacific Cod Center Gravity and Area Occupied indicators by L. DeFilippo and J. Conner). Therefore, concerns about the food web dynamics and carrying capacity in the NBS may have less impact on the EBS Pacific cod population as its center of gravity shifts south and population contracts in the NBS and expands in the SEBS.

Prey:

Overall peak timing of the spring bloom in the SEBS was earlier than past two years (see Appendix 2.2: Spring Chlorophyll A Peak SEBS Satellite indicator by J. Nielsen 2022). Regionally in the EBS, spring bloom peak timing suggests that 2022 was average in the south inner, south middle, and south outer shelf regions. For the south middle shelf region, there was evidence of 2 peaks (Nielsen et al., 2022), while chlorophyll-a biomass varied spatially over the shelf. Persistently low chlorophyll-a biomass within the outer shelf region has occurred since 2015 (Nielsen et al. 2022). The Rapid Zooplankton Assessment (Kimmel et al. 2022) noted reduced overall zooplankton productivity in the EBS in spring and summer 2022, though euphausiid abundances were higher than recent years, supporting the hypothesis that increased euphausiid abundances during warm years may compensate for lower large copepod abundances (Duffy-Anderson et al. 2017). The acoustic euphausiid survey documented an increase in euphausiid density from 2018 (last available estimate), but the 2022 value still remains below the time series average (Ressler 2022). The biomass of motile epifauna, as measured over the southeastern Bering Sea (SEBS) shelf, peaked in 2017 and remains above their long-term mean in 2022. Trends in motile epifauna biomass indicate benthic productivity, although individual species and/or taxa may reflect varying time scales of productivity. Brittle stars, sea stars, and other echinoderms are well above their long-term means, while king crabs, tanner crab, and snow crab are all below their long-term means (Whitehouse 2022). Pacific cod (all sizes) were generally in above-average condition over the southern shelf, but below-average condition over the northern shelf (Rohan et al. 2022). That said, juvenile Pacific cod condition was closer to the long-term average while adult fish were in slightly better condition (see Appendix 2.2: Summer Pacific Cod Condition Adult and Juvenile EBS Model indicators by S. Rohan).

Competitors:

Competitors of Pacific cod prey resources include arrowtooth flounder, juvenile sablefish, and gray whales (e.g., benthic amphipods). Arrowtooth flounder biomass has been increasing steadily since 2000 and remains at a high level in recent years (see Appendix 2.2: Arrowtooth flounder total biomass from the most recent stock assessment model in the EBS by S. K. Shotwell). In the SEBS, the biomass of the apex predator guild increased from 2021 to 2022 to nearly equal to their long term mean (Whitehouse 2022). The impacts of recent large year classes of sablefish to the EBS ecosystem (as prey, predators, and competitors) remains largely unknown at this time. The large 2019 year class of sablefish (see Goethel et al. 2021) may compete with Pacific cod for prey resources as juveniles, but may also be prey for larger, adult Pacific cod. Gray whale life history includes annual migrations of up to 20,000 km from summer feeding grounds in the northern Bering and Chukchi seas to southern Baja California to mate and calve. Following several years of high numbers of stranded gray whales (an Unusual Mortality Event was declared in 2019; Savage 2020), fewer gray whales were reported in 2022 (as of Sept. 15, 17 whales had been reported in 2022) (K. Savage, pers. comm.).

Predators:

Pacific cod are cannibalistic and rates of cannibalism might be expected to increase as the abundance of older, larger fish increases concurrently with increases in juvenile abundance. With the center of gravity shifting south in 2022, and the area occupied in the NBS decreasing, the potential spatial overlap of adult and juvenile Pacific cod may lead to increased cannibalism. Other predators of Pacific cod include northern fur seals, Steller sea lions, various whale species, and tufted puffin, but unfortunately, no direct measurements of population trends for these species are available.

Summary for Environmental/Ecosystem considerations:

- Environment: The extended warm phase experienced by the EBS that began in approximately 2014 has largely relaxed to normal conditions over the past year (August 2021 - August 2022).
- Prey: Abundance trends of prey for Pacific cod are mixed, though largely average or below average for 2022. However, fish condition for both juvenile and adult Pacific cod over the southern shelf (larger portion of the population) is above average.
- Competitors: Trends in competitors of Pacific cod are mixed: ATF abundance remains high while the impact of increased juvenile sablefish remains unknown. Gray whale strandings have continued to decrease from the peak in 2019 combined with the Pacific cod distribution shifting southward in 2022.
- Predators: The above-average condition of adult Pacific cod in 2022, combined with the potential increase in spatial overlap between adults and juveniles over the SEBS, may reflect increased predation (i.e., cannibalism) pressure on younger age classes of Pacific cod.

Together, the most recent data available suggest an ecosystem risk Level 1 – Normal: “No apparent environmental/ecosystem concerns.”

Fishery Performance Considerations

Fishery performance considerations were assigned a risk level of 1 in each of the three previous assessments. Figure 2.10 shows simple annual averages of catch (in weight and number) per unit effort for all gears. CPUE by number has been relatively stable over the previous 9 years and CPUE by weight although dropping in the past two years remains well above the average. The winter longline fishery CPUE index indicated an increasing trend in numbers for that fishery and season for 2022. Catch rates throughout the season and for all gears were near average conditions (Figure 2.6).

Fishery performance considerations were once again rated as level 1 (normal).

Summary and ABC Recommendation

The risk levels and intralevel fractions assigned to the four categories are summarized below:

Assessment-related considerations	*Population dynamics considerations*	*Environmental/ ecosystem considerations*	*Fishery Performance considerations*
Level 1: Normal	Level 1: Normal	Level 1: Normal	Level 1: Normal

The score of level 1 for each category suggests that setting the ABC below the maximum permissible is not warranted at this time.

Status Determination
Under the MSFCMA, the Secretary of Commerce is required to report on the status of each U.S. fishery with respect to overfishing. This report involves the answers to three questions: 1) Is the stock being subjected to overfishing? 2) Is the stock currently overfished? 3) Is the stock approaching an overfished condition?

Is the stock being subjected to overfishing? The official catch estimate for the most recent complete year (2021) is 121,734 t. This is less than the 2021 OFL of 147,949 t. Therefore, the EBS Pacific cod stock is not being subjected to overfishing.

Harvest Scenarios #6 and #7 are intended to permit determination of the status of a stock with respect to its minimum stock size threshold (MSST). Any stock that is below its MSST is defined to be *overfished*. Any stock that is expected to fall below its MSST in the next two years is defined to be *approaching* an overfished condition. Harvest Scenarios #6 and #7 are used in these determinations as follows:

Is the stock currently overfished? This depends on the stock's estimated spawning biomass in 2022:

a. If spawning biomass for 2022 is estimated to be below ½ $B_{35\%}$, the stock is below its MSST.
b. If spawning biomass for 2022 is estimated to be above $B_{35\%}$, the stock is above its MSST.
c. If spawning biomass for 2022 is estimated to be above ½ $B_{35\%}$ but below $B_{35\%}$, the stock's status relative to MSST is determined by referring to harvest Scenario #6 (Table 2.30). If the mean spawning biomass for 2032 is below $B_{35\%}$, the stock is below its MSST. Otherwise, the stock is above its MSST.

Is the stock approaching an overfished condition? This is determined by referring to harvest Scenario #7 (Table 2.30):

a. If the mean spawning biomass for 2024 is below ½ $B_{35\%}$, the stock is approaching an overfished condition.
b. If the mean spawning biomass for 2024 is above $B_{35\%}$, the stock is not approaching an overfished condition.
c. If the mean spawning biomass for 2024 is above 1/2 $B_{35\%}$ but below $B_{35\%}$, the determination depends on the mean spawning biomass for 2034. If the mean spawning biomass for 2034 is below $B_{35\%}$, the stock is approaching an overfished condition. Otherwise, the stock is not approaching an overfished condition.

Based on the above criteria and Table 2.30, the stock is not overfished and is not approaching an overfished condition.

To fulfill reporting requirements for the Species Information System, each model was used to reverse-engineer the fishing mortality rate corresponding to the specified OFL for the last complete year (2021). These reverse-engineered F_{OFL} values (*RE* F_{OFL}) are shown below:

Model	M22.1	M22.2	M22.3	M22.4	Ensemble
2021 RE F_{OFL}	0.329	0.320	0.325	0.324	0.324

ECOSYSTEM CONSIDERATIONS

Ecosystem considerations are addressed in Appendix 2.2 and in the Ecosystem Status Report.

DATA GAPS AND RESEARCH PRIORITIES

Significant improvements in the quality of this assessment could be made if future research were directed toward closing certain data gaps. At this point, the most critical needs pertain to the effects of the large and potentially unprecedented movements of Pacific cod between the major subregions of the Bering Sea (eastern, northern, and western) and western Gulf of Alaska that appear to have taken place in the last few years, including: 1) to understand the factors determining these movements, 2) to understand whether/how these movements change over time, 3) to obtain accurate estimates of these movements, 4) to understand the extent to which reciprocal movements occur, and 5) to understand the spawning contributions fish in each subregion to the overall stock. Continued surveying of the NBS is strongly encouraged, as are genetic analyses and tagging studies. Ageing also continues to be an issue, as the assessment models consistently estimate a positive ageing bias, at least for otoliths read prior to 2008. The removal of the post-2007 aging bias results in a worse fit to the models and given assertions that aging bias is no longer an issue may suggest potential changes in growth that should be explored further. Maturity is also an important factor that needs to be better understood. Currently the model employs a static relationship developed from data prior to 2007. Another need is development of methods to quantify input sample sizes based on the among-sample variance in compositional measurements, using bootstrapping or model-based methods. Longer-term biological research needs include improved understanding of: 1) the ecology of Pacific cod in the EBS, including spatial dynamics, trophic and other interspecific relationships, and the relationship between climate and recruitment; 2) ecology of species taken as bycatch in the Pacific cod fisheries, including estimation of biomass, carrying capacity, and resilience; and 3) ecology of species that interact with Pacific cod, including estimation of interaction strengths, biomass, carrying capacity, and resilience.

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TABLES

Table 2.1. Summary of 1964-1980 catches (t) of Pacific cod in the EBS by fleet sector. "For." = foreign, "JV" = joint venture processing, "Dom." = domestic annual processing. Catches by gear are not available for these years. Catches may not always include discards.

Year	For.	JV	Dom.	Total
1964	13,408	0	0	13,408
1965	14,719	0	0	14,719
1966	18,200	0	0	18,200
1967	32,064	0	0	32,064
1968	57,902	0	0	57,902
1969	50,351	0	0	50,351
1970	70,094	0	0	70,094
1971	43,054	0	0	43,054
1972	42,905	0	0	42,905
1973	53,386	0	0	53,386
1974	62,462	0	0	62,462
1975	51,551	0	0	51,551
1976	50,481	0	0	50,481
1977	33,335	0	0	33,335
1978	42,512	0	31	42,543
1979	32,981	0	780	33,761
1980	35,058	8,370	2,433	45,861

Table 2.2. Summary of 1981-1990 catches (t) of Pacific cod in the EBS by fleet sector, and gear type. All catches include discards. "LLine" = longline, "Subt." = sector subtotal. Breakdown of domestic annual processing by gear is not available prior to 1988.

	Foreign			Joint Venture		Domestic Annual Processing				
Year	Trawl	LLine	Subt.	Trawl	Subt.	Trawl	LLine	Pot	Subt.	Total
1981	30,347	5,851	36,198	7,410	7,410	n/a	n/a	n/a	12,899	56,507
1982	23,037	3,142	26,179	9,312	9,312	n/a	n/a	n/a	25,613	61,104
1983	32,790	6,445	39,235	9,662	9,662	n/a	n/a	n/a	45,904	94,801
1984	30,592	26,642	57,234	24,382	24,382	n/a	n/a	n/a	43,487	125,103
1985	19,596	36,742	56,338	35,634	35,634	n/a	n/a	n/a	51,475	143,447
1986	13,292	26,563	39,855	57,827	57,827	n/a	n/a	n/a	37,923	135,605
1987	7,718	47,028	54,746	47,722	47,722	n/a	n/a	n/a	47,435	149,903
1988	0	0	0	106,592	106,592	93,706	2,474	299	96,479	203,071
1989	0	0	0	44,612	44,612	119,631	13,935	145	133,711	178,323
1990	0	0	0	8,078	8,078	115,493	47,114	1,382	163,989	172,067

Table 2.3. Summary of 1991-2022 catches (t) and percent retained (%) of Pacific cod in the EBS by gear type. Catches for 2022 are through October 14.

	Catch (t)					Percent retained (%)			
Year	Longline	Pot	Trawl	Other	Total	Longline	Pot	Trawl	Other
1991	77,506	3,342	129,394	0	210,242	98	100	88	0
1992	79,404	7,510	77,291	1	164,206	98	99	72	100
1993	49,297	2,094	81,793	2	133,186	95	99	65	100
1994	78,557	8,036	84,934	730	172,257	96	98	69	100
1995	97,664	19,277	110,954	600	228,495	96	99	68	100
1996	88,881	28,003	91,912	266	209,062	97	99	76	100
1997	117,010	21,490	93,924	171	232,595	97	100	82	96
1998	84,328	13,229	60,775	193	158,525	97	100	98	100
1999	81,470	12,397	51,897	100	145,864	98	100	97	100
2000	81,643	15,849	53,847	39	151,378	97	100	98	100
2001	90,365	16,472	35,649	53	142,539	98	100	98	100
2002	100,272	15,050	51,064	165	166,551	98	99	97	100
2003	108,670	19,936	46,673	155	175,434	98	99	98	100
2004	108,474	17,242	57,793	231	183,740	98	100	99	100
2005	113,127	17,096	52,600	104	182,927	98	100	99	100
2006	96,567	18,960	53,213	83	168,823	98	100	98	100
2007	77,136	17,237	45,672	82	140,127	98	100	99	100
2008	88,918	17,367	33,490	20	139,795	98	99	99	100
2009	96,595	13,611	36,954	12	147,172	98	100	99	100
2010	81,616	19,678	41,201	344	142,839	98	100	97	100
2011	116,762	27,995	63,926	506	209,189	98	100	99	100
2012	128,300	28,725	75,505	86	232,616	99	100	99	100
2013	124,814	30,249	81,614	14	236,691	97	100	98	100
2014	127,256	39,196	72,261	2	238,715	98	100	99	100
2015	128,191	37,937	66,665	28	232,821	98	100	99	100
2016	127,917	47,078	72,574	48	247,617	98	100	99	100
2017	122,774	46,182	68,876	13	237,845	98	100	99	100
2018	100,209	39,684	59,958	0	199,851	98	100	99	0
2019	88,780	41,056	49,018	49	178,903	98	100	99	100
2020	72,088	32,967	50,564	38	155,657	98	100	98	100
2021	57,256	25,693	38,765	20	121,734	98	100	95	100
2022	63,513	36,301	41,013	28	140,855	98	100	98	100

Table 2.4. Pacific cod catch in the western Bering Sea Russian EEZ for 2001-2021. 2001-2008 from Lajus et al. (2019). 2009-2021 catch data from from Russian Ministry of Fisheries annual reports, РОССИЙСКАЯ ФЕДЕРАЦИЯ: СВЕДЕНИЯ ОБ УЛОВЕ РЫБЫ И ДОБЫЧЕ ДРУГИХ ВОДНЫХ БИОРЕСУРСОВ (translation: RUSSIAN FEDERATION: INFORMATION ABOUT THE CATCH OF FISH AND THE EXTRACTION OF OTHER WATER BIORESOURCES) for 2009 through 2021. The Russian Federation website where these reports were hosted was no long active as of March 2022, future availability of these data is questionable.

Year	**Catch(t)**	**Year**	**Catch(t)**
2001	13,300	2012	15,397
2002	12,600	2013	18,065
2003	18,900	2014	23,068
2004	22,200	2015	19,799
2005	14,900	2016	21,420
2006	14,600	2017	31,664
2007	13,700	2018	45,793
2008	15,100	2019	NA
2009	11,124	2020	92,680
2010	16,252	2021	85,364
2011	16,260		

Table 2.5. History of BSAI (1977-2013) and EBS (2014-2022) Pacific cod catch, TAC, Alaska State GHL (2016-2022), ABC, and OFL (t). Catch for 2022 is through October 9. Note that specifications through 2013 were for the combined BSAI region, so BSAI catch is shown rather than the EBS catches from Table 2.3 for the period 1977-2013. Source for historical specifications: NPFMC staff.

Year	Catch	TAC	ABC	OFL	Year	Catch	TAC	GHL	ABC	OFL
1977	35,597	58,000			2000	191,060	193,000		193,000	240,000
1978	45,838	70,500			2001	176,749	188,000		188,000	248,000
1979	39,354	70,500			2002	197,356	200,000		223,000	294,000
1980	51,649	70,500	148,000		2003	207,900	207,500		223,000	324,000
1981	63,941	78,700	160,000		2004	212,621	215,500		223,000	350,000
1982	69,501	78,700	168,000		2005	205,633	206,000		206,000	265,000
1983	103,231	120,000	298,000		2006	193,029	189,768		194,000	230,000
1984	133,084	210,000	291,000		2007	174,484	170,720		176,000	207,000
1985	150,384	220,000	347,000		2008	171,030	170,720		176,000	207,000
1986	142,511	229,000	249,000		2009	175,756	176,540		182,000	212,000
1987	163,110	280,000	400,000		2010	171,850	168,780		174,000	205,000
1988	208,236	200,000	385,300		2011	220,089	227,950		235,000	272,000
1989	182,865	230,681	370,600		2012	250,840	261,000		314,000	369,000
1990	179,608	227,000	417,000		2013	250,301	260,000		307,000	359,000
1991	220,038	229,000	229,000		2014	238,715	246,897		255,000	299,000
1992	207,278	182,000	182,000	188,000	2015	232,821	240,000		255,000	346,000
1993	167,391	164,500	164,500	192,000	2016	247,617	238,680	16,320	255,000	390,000
1994	193,802	191,000	191,000	228,000	2017	237,845	223,704	15,296	239,000	284,000
1995	245,033	250,000	328,000	390,000	2018	199,851	188,136	12,864	201,000	238,000
1996	240,676	270,000	305,000	420,000	2019	178,903	166,475	15,204	181,000	216,000
1997	257,765	270,000	306,000	418,000	2020	155,657	141,799	14,074	155,873	191,386
1998	193,256	210,000	210,000	336,000	2021	121,734	111,380	12,426	123,805	147,949
1999	173,998	177,000	177,000	264,000	2022*	140,855	136,466	16,917	153,383	183,012

Table 2.6. Amendments to the BSAI Fishery Management Plan (FMP) that reference Pacific cod explicitly (excerpted from Appendix A of the FMP, except that Amendment 113, which is listed in Appendix A of the FMP, is omitted here, due to the fact that the final rule implementing that amendment was vacated by the U.S. District Court for the District of Columbia on March 21, 2019).

Amendment 2, implemented January 12, 1982:

For Pacific cod, decreased maximum sustainable yield to 55,000 t from 58,700 t, increased equilibrium yield to 160,000 t from 58,700 t, increased acceptable biological catch to 160,000 t from 58,700 t, increased optimum yield to 78,700 t from 58,700 t, increased reserves to 3,935 t from 2,935 t, increased domestic annual processing (DAP) to 26,000 t from 7,000 t, and increased DAH to 43,265 t from 24,265 t.

Amendment 4, implemented May 9, 1983, supersedes Amendment 2:

For Pacific Cod, increased equilibrium yield and acceptable biological catch to 168,000 t from 160,000 t, increased optimum yield to 120,000 t from 78,700 t, increased reserves to 6,000 t from 3,935 t, and increased TALFF to 70,735 t from 31,500 t.

Amendment 10, implemented March 16, 1987:

Established Bycatch Limitation Zones for domestic and foreign fisheries for yellowfin sole and other flatfish (including rock sole); an area closed to all trawling within Zone 1; red king crab, C. bairdi Tanner crab, and Pacific halibut PSC limits for DAH yellowfin sole and other flatfish fisheries; a C. bairdi PSC limit for foreign fisheries; and a red king crab PSC limit and scientific data collection requirement for U.S. vessels fishing for Pacific cod in Zone 1 waters shallower than 25 fathoms.

Amendment 24, implemented February 28, 1994, and effective through December 31, 1996:

1. Established the following gear allocations of BSAI Pacific cod TAC as follows: 2 percent to vessels using jig gear; 44.1 percent to vessels using hook-and-line or pot gear, and 53.9 percent to vessels using trawl gear.
2. Authorized the seasonal apportionment of the amount of Pacific cod allocated to gear groups. Criteria for seasonal apportionments and the seasons authorized to receive separate apportionments will be set forth in regulations.

Amendment 46, implemented January 1, 1997, superseded Amendment 24:

Replaced the three year Pacific cod allocation established with Amendment 24, with the following gear allocations in BSAI Pacific cod: 2 percent to vessels using jig gear; 51 percent to vessels using hook-and-line or pot gear; and 47 percent to vessels using trawl gear. The trawl apportionment will be divided 50 percent to catcher vessels and 50 percent to catcher processors. These allocations as well as the seasonal apportionment authority established in Amendment 24 will remain in effect until amended.

Amendment 49, implemented January 3, 1998:

Implemented an Increased Retention/Increased Utilization Program for pollock and Pacific cod beginning January 1, 1998 and rock sole and yellowfin sole beginning January 1, 2003.

Amendment 64, implemented September 1, 2000, revised Amendment 46:

Allocated the Pacific cod Total Allowable Catch to the jig gear (2 percent), fixed gear (51 percent), and trawl gear (47 percent) sectors.

Amendment 67, implemented May 15, 2002, revised Amendment 39:

Established participation and harvest requirements to qualify for a BSAI Pacific cod fishery endorsement for fixed gear vessels.

Amendment 77, implemented January 1, 2004, revised Amendment 64:

Implemented a Pacific cod fixed gear allocation between hook and line catcher processors (80%), hook and line catcher vessels (0.3%), pot catcher processors (3.3%), pot catcher vessels (15%), and catcher vessels (pot or hook and line) less than 60 feet (1.4%).

(Continued on next page.)

Table 2.5. (Cont.) Amendments to the BSAI Fishery Management Plan (FMP) that reference Pacific cod explicitly (excerpted from Appendix A of the FMP).

Amendment 77, implemented January 1, 2004, revised Amendment 64:

Implemented a Pacific cod fixed gear allocation between hook and line catcher processors (80%), hook and line catcher vessels (0.3%), pot catcher processors (3.3%), pot catcher vessels (15%), and catcher vessels (pot or hook and line) less than 60 feet (1.4%).

Amendment 85, partially implemented March 5, 2007, superseded Amendments 46 and 77:

Implemented a gear allocation among all non-CDQ fishery sectors participating in the directed fishery for Pacific cod. After deduction of the CDQ allocation, the Pacific cod TAC is apportioned to vessels using jig gear (1.4 percent); catcher processors using trawl gear listed in Section 208(e)(1)-(20) of the AFA (2.3 percent); catcher processors using trawl gear as defined in Section 219(a)(7) of the Consolidated Appropriations Act, 2005 (Public Law 108-447) (13.4 percent); catcher vessels using trawl gear (22.1 percent); catcher processors using hook-and-line gear (48.7 percent); catcher vessels ≥60' LOA using hook-and-line gear (0.2 percent); catcher processors using pot gear (1.5 percent); catcher vessels ≥60' LOA using pot gear (8.4 percent); and catcher vessels <60' LOA that use either hook-and-line gear or pot gear (2.0 percent).

Amendment 99, implemented January 6, 2014 (effective February 6, 2014):

Allows holders of license limitation program (LLP) licenses endorsed to catch and process Pacific cod in the Bering Sea/Aleutian Islands hook-and-line fisheries to use their LLP license on larger newly built or existing vessels by:

1. Increasing the maximum vessel length limits of the LLP license, and
2. Waiving vessel length, weight, and horsepower limits of the American Fisheries Act.

Amendment 103, implemented November 14, 2014:

Revise the Pribilof Islands Habitat Conservation Zone to close to fishing for Pacific cod with pot gear (in addition to the closure to all trawling).

Amendment 109, implemented May 4, 2016:

Revised provisions regarding the Western Alaska CDQ Program to update information and to facilitate increased participation in the groundfish CDQ fisheries (primarily Pacific cod) by:

1. Exempting CDQ group-authorized catcher vessels greater than 32 ft LOA and less than or equal to 46 ft LOA using hook-and-line gear from License Limitation Program license requirements while groundfish CDQ fishing,
2. Modifying observer coverage category language to allow for the placement of catcher vessels less than or equal to 46 ft LOA using hook-and-line gear into the partial observer coverage category while groundfish CDQ fishing, and
3. Updating CDQ community population information, and making other miscellaneous editorial revisions to CDQ Program-related text in the FMP.

Amendment 120, implemented December 20, 2019:

1. Limits the number of catcher/processors (C/Ps) eligible to operate as motherships receiving and processing Pacific cod from catcher vessels (CVs) directed fishing in the BSAI non-Community Development Quota Program Pacific cod trawl fishery.
2. Prohibits replaced Amendment 80 C/Ps from receiving and processing Pacific cod harvested and delivered by CVs directed fishing for Pacific cod in the BSAI and GOA.

Table 2.7 Non-commercial catch of Pacific cod (kg) in the Bering Sea 2012-2021.

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Grand Total
AFSC Annual Longline Survey		27,179		32,797		26,260		29,028		26,629	165,433
Aleutian Island Bottom Trawl Survey	1,187		2,167		1,940		2,814				10,479
Bait for Crab Fishery	1,551,360	1,383,450	1,750,993	2,013,221	1,424,231	864,191	885,990	864,204	1,323,011	957,800	14,451,943
Bering Sea Acoustic Survey											8
BS Bottom Trawl Survey											37,773
BS Slope Survey	871				874						3,303
Blue King Crab Pot Survey							3,438				3,438
Bristol Bay Red King Crab Tagging									729		729
BSAI Trawl Salmon Excluder Device EFP 2018-03-02										2,041	2,041
Eastern Bering Sea Bottom Trawl Survey	51,773	33,345	38,500	39,268	35,590	24,072	18,859	18,544		22,500	324,739
EBS Walleye Pollock Acoustic-Trawl Survey							342				342
Gulf of Alaska Bottom Trawl Survey		0		134				22			391
IPHC Annual Longline Survey	17,414	28,887	52,417	58,812	47,227	36,527	33,603	46,065		26,513	398,732
Large-Mesh Trawl Survey	1,543	573	1,041	1,137	830	1,007	467	285		373	8,885
NBS Bottom Trawl Survey						8,800	6,394	11,535		7,616	35,233
Pollock EFP 11-01	307,037										317,813
Pribilof Island Tanner Tagging								66			66
Pribilof Islands Crab Survey					4,557						9,434
Sport Fishery					1,630	1,844	3,712		902		8,088
St. Matthews Crab Survey						5,415					14,039
Summer EBS Survey with Russia	62										62
Grand Total	1,931,247	1,473,435	1,845,118	2,145,369	1,516,880	968,117	955,620	969,750	1,324,642	1,043,473	15,792,972

Table 2.8. Number of otoliths and fish lengthed from the bottom trawl survey and fishery.

Year	Otoliths				Lengths	
	Survey Collected	Survey Aged	Fishery Collected	Fishery Aged	Survey	Fishery
1977						1,324
1978						11,683
1979						17,031
1980						17,939
1981						23,955
1982					10,863	9,658
1983					13,143	33,200
1984	782	316			12,133	45,635
1985					17,150	66,940
1986					15,872	58,257
1987					9,483	129,226
1988	639	639			6,950	111,065
1989	703	703			4,246	58,625
1990	793	793	4,500	1,073	5,428	39,698
1991	659	659	6,085	658	7,069	374,227
1992	717	717	2,333	368	10,129	344,923
1993	653	635	1,229		10,500	248,967
1994	731	715	7,050		12,931	359,147
1995	625	571	5,500	1	9,820	344,794
1996	733	711	2,087		9,348	445,217
1997	737	719	1,818		9,591	474,908
1998	694	635	1,433		9,574	438,746
1999	878	860	2,691		11,183	186,233
2000	883	860	3,797		12,170	199,708
2001	948	920	3,857		19,078	210,419
2002	889	870	3,871		12,365	230,802
2003	1,278	1,263	4,272		11,835	288,854
2004	1,017	995	3,668		10,968	237,487
2005	1,313	1,279	3,341		11,753	228,664
2006	1,316	1,300	3,714		12,530	179,782
2007	1,477	1,441	2,793	964	13,441	140,663
2008	1,229	1,213	10,243	1,324	15,328	164,860
2009	1,427	1,412	4,656	1,207	23,737	147,875
2010	1,475	1,467	5,501	1,176	21,223	131,514
2011	1,266	1,253	6,211	1,735	25,150	172,269
2012	1,307	1,301	15,182	983	30,177	192,273
2013	1,424	1,418	16,529	988	19,902	211,962
2014	1,441	1,420	17,758	987	29,204	234,476
2015	1,827	1,819	16,433	994	19,880	213,888
2016	1,634	1,624	14,100	987	19,507	182,980
2017	1,764	1,744	12,271	995	15,020	157,482
2018	1,352	1,339	9,729	985	8,806	124,004
2019	1,940	1,824	7,105		23,408	86,800
2020			5,511	414		65,301
2021	1,810	1,757	4,244	409	17,397	55,858
2022	1,806		3,355		16,677	38,644

Table 2.9. Number of hauls and input composition sample sizes (survey includes EBS and NBS; units = hauls). For the survey the input sample size is the number of hauls, fishery input sample sizes are scaled to the mean survey number of hauls.

Year	**Survey hauls/inputs**	**Fishery hauls**	**Fishery input**	**Year**	**Survey hauls/inputs**	**Fishery hauls**	**Fishery input**
1977		92	6	2000	355	9,966	651
1978		147	10	2001	366	10,581	691
1979		181	12	2002	402	11,607	758
1980		187	12	2003	363	14,477	946
1981		212	14	2004	422	12,144	793
1982	313	106	7	2005	360	11,641	761
1983	255	393	26	2006	354	9,078	593
1984	264	471	31	2007	368	7,119	465
1985	369	710	46	2008	381	8,429	551
1986	349	725	47	2009	360	7,465	488
1987	339	1,328	87	2010	451	6,652	435
1988	370	1,353	88	2011	368	8,739	571
1989	293	626	41	2012	400	9,342	610
1990	329	643	42	2013	354	11,094	725
1991	330	5,267	344	2014	373	12,129	792
1992	332	5,195	339	2015	354	11,200	732
1993	363	3,080	201	2016	412	9,498	621
1994	364	4,839	316	2017	481	8,317	543
1995	347	5,258	344	2018	364	6,390	418
1996	359	6,797	444	2019	479	4,605	301
1997	369	7,216	471	2020		3,526	230
1998	362	6,898	451	2021	476	2,894	189
1999	336	9,171	599	2022	481	2,123	139

Table 2.10. VAST estimates of bottom trawl survey population estimates, VAST winter longline CPUE index, and designed-based bottom trawl survey population number estimates. Note that the design-based estimates are not used in any assessment model.

	VAST				Design-based	
Year	Survey population	Survey sigma	CPUE Index	CPUE sigma	Survey population	Survey sigma
1987	827,910,820	0.058			698,609,300	0.064
1988	547,101,763	0.044			512,360,645	0.070
1989	360,136,669	0.058			301,283,394	0.066
1990	473,699,475	0.052			439,009,229	0.084
1991	514,740,296	0.052			498,850,467	0.103
1992	558,668,040	0.057			587,304,176	0.117
1993	828,313,265	0.057			817,857,214	0.122
1994	1,176,240,822	0.050			1,260,690,441	0.122
1995	722,896,871	0.049			764,228,127	0.099
1996	613,729,432	0.060	61,555	0.044	615,809,466	0.143
1997	523,444,143	0.056	66,186	0.051	494,486,664	0.143
1998	619,360,780	0.072	54,007	0.044	524,149,999	0.090
1999	524,679,967	0.055	47,852	0.040	542,810,224	0.100
2000	520,732,683	0.057	57,484	0.045	489,723,433	0.090
2001	1,012,604,304	0.056	42,951	0.044	977,116,905	0.094
2002	632,552,438	0.071	57,874	0.049	545,304,209	0.099
2003	626,822,759	0.080	44,034	0.029	517,535,040	0.120
2004	494,053,564	0.083	44,302	0.028	405,251,779	0.085
2005	506,513,065	0.073	42,042	0.028	465,249,132	0.137
2006	441,760,136	0.047	48,206	0.042	407,949,965	0.059
2007	597,084,961	0.052	49,488	0.034	758,497,682	0.261
2008	484,226,694	0.051	49,345	0.034	494,359,348	0.101
2009	714,576,551	0.046	50,719	0.039	724,773,831	0.087
2010	752,333,289	0.049	57,249	0.037	908,910,258	0.130
2011	862,264,620	0.048	56,278	0.044	847,967,416	0.094
2012	1,051,417,095	0.059	57,626	0.042	996,959,215	0.092
2013	760,764,997	0.056	55,745	0.038	764,239,270	0.165
2014	1,231,901,647	0.068	44,066	0.038	1,134,482,392	0.127
2015	1,083,986,346	0.067	43,285	0.041	989,903,729	0.115
2016	944,269,500	0.094	52,806	0.035	662,134,411	0.093
2017	520,888,531	0.044	46,191	0.028	500,634,050	0.073
2018	528,569,516	0.063	56,880	0.035	249,081,430	0.071
2019	762,871,107	0.051	48,238	0.048	730,701,587	0.092
2021	608,971,280	0.056	42,389	0.048	551,453,352	0.072
2022	554,472,678	0.049	48,827	0.051	511,194,737	0.064

Table 2.11. Designed-based biomass estimate for the AFSC bottom trawl survey 1987-2022 and relative population number (RPN) estimates for the AFSC longline survey Bering Sea region 1997-2021. Note that these are not used in any assessment model.

Year	EBS		NBS		Total		AFSC Longline	
	Biomass (t)	sigma	Biomass (t)	sigma	Biomass (t)	sigma	RPN	sigma
1987	1,064,504	0.060			1,064,504	0.060		
1988	975,197	0.079			975,197	0.079		
1989	866,777	0.072			866,777	0.072		
1990	727,806	0.072			727,806	0.072		
1991	530,731	0.073			530,731	0.073		
1992	539,064	0.083			539,064	0.083		
1993	670,773	0.080			670,773	0.080		
1994	1,379,428	0.179			1,379,428	0.179		
1995	1,010,002	0.091			1,010,002	0.091		
1996	910,374	0.096			910,374	0.096		
1997	627,118	0.109			627,118	0.109	204,250	20,290
1998	551,408	0.078			551,408	0.078		
1999	618,730	0.091			618,730	0.091	139,390	14,690
2000	537,449	0.080			537,449	0.080		
2001	827,408	0.088			827,408	0.088	168,872	22,719
2002	597,450	0.106			597,450	0.106		
2003	625,549	0.099			625,549	0.099	203,096	25,236
2004	578,018	0.058			578,018	0.058		
2005	638,154	0.068			638,154	0.068	109,534	23,052
2006	543,533	0.053			543,533	0.053		
2007	450,305	0.078			450,305	0.078	119,105	16,525
2008	427,423	0.065			427,423	0.065		
2009	430,461	0.082			430,461	0.082	95,553	21,171
2010	872,777	0.118	29,126	0.226	901,904	0.114		
2011	913,952	0.073			913,952	0.073	143,786	26,141
2012	899,909	0.113			899,909	0.113		
2013	813,804	0.092			813,804	0.092	171,225	41,944
2014	1,098,193	0.140			1,098,193	0.140		
2015	1,111,980	0.135			1,111,980	0.135	157,996	30,499
2016	986,239	0.078			986,239	0.078		
2017	644,508	0.078	287,551	0.127	932,060	0.066	124,913	18,391
2018	507,316	0.058			507,316	0.058		
2019	517,141	0.044	365,005	0.147	882,146	0.066	94,496	13,340
2020								
2021	616,380	0.049	227,582	0.178	843,962	0.060	108,312	23,361
2022	647,400	0.065	153,735	0.130	801,135	0.058		

Table 2.12. Annual weight length parameter offsets.

Year	α offset	β offset	Year	α offset	β offset
1974	-1.40E-06	0.099	2000	5.49E-06	-0.165
1975	-3.52E-06	0.299	2001	5.04E-06	-0.155
1976	-1.70E-06	0.119	2002	2.33E-06	-0.085
1977	8.16E-07	-0.020	2003	7.00E-07	-0.030
1978	-1.16E-06	0.062	2004	2.15E-06	-0.079
1979	1.48E-06	-0.052	2005	4.36E-07	-0.016
1980	-2.81E-07	0.014	2006	1.81E-06	-0.068
1981	2.74E-07	-0.010	2007	2.50E-06	-0.089
1982	2.62E-06	-0.083	2008	8.32E-07	-0.037
1983	3.45E-06	-0.118	2009	2.00E-06	-0.080
1984	8.20E-06	-0.228	2010	2.94E-06	-0.113
1985	1.12E-06	-0.039	2011	1.26E-06	-0.060
1986	-3.30E-07	0.022	2012	2.03E-07	-0.018
1987	4.02E-06	-0.130	2013	6.21E-07	-0.033
1988	1.95E-07	-0.001	2014	-7.02E-07	0.026
1989	1.62E-06	-0.055	2015	-1.08E-06	0.041
1990	2.73E-06	-0.084	2016	-8.30E-07	0.032
1991	1.11E-06	-0.039	2017	-7.80E-07	0.031
1992	-1.02E-06	0.054	2018	7.93E-07	-0.038
1993	2.05E-06	-0.053	2019	3.54E-07	-0.015
1994	7.58E-07	-0.023	2020	8.88E-07	-0.039
1995	-1.58E-06	0.093	2021	1.06E-06	-0.046
1996	4.91E-06	-0.142	2022	-6.02E-07	0.023
1997	7.06E-07	-0.031			
1998	8.57E-07	-0.037			
1999	1.72E-06	-0.063			

Table 2.13. Objective function values (negative log likelihood) and parameter counts as well as selected results for Thompson Series models and Thompson Series ensemble.

Label	Model 19.12	Model 19.12A	Model 21.1	Model 21.2	Ensemble
# parameters	348	306	310	307	
TOTAL like	10,764.5	10,854.4	10,858.2	10,896.7	
Survey like	-95.134	-4.742	-4.104	-43.204	
Length comp like	9,960.95	9,991.01	10,010.4	10,066.8	
Age comp like	786.738	794.939	784.932	796.359	
$LN(R_0)$	13.074	13.260	12.987	13.253	13.142
Natural mortality (M)	0.342	0.363	0.324	0.359	0.347
$L\infty$	116.345	111.848	144.934	115.542	121.411
VonBert K	0.107	0.118	0.064	0.103	0.100
Bratio 2021	0.374	0.415	0.349	0.368	0.380
SPRratio 2020	0.583	0.538	0.603	0.564	0.570
Q Bottom trawl survey	1.033	0.917	1.067	0.890	0.978
$B_{100\%}$ (10^6 t)	0.654	0.639	0.789	0.647	0.679
$F_{40\%}$	0.301	0.349	0.278	0.353	0.320
$F_{35\%}$	0.367	0.425	0.331	0.429	0.388
maxABC 2023	127,161	169,418	116,160	154,362	142,539
maxABC 2024	127,073	153,741	122,787	150,321	138,417

$LN(R_0)$ = the natural log of the equilibrium virgin recruits at age-0
$B_{100\%}$ = equilibrium unfished female spawning biomass
$F_{40\%}$ = fishing mortality that reduces equilibrium spawning per recruit to 40% of unfished
$F_{35\%}$ = fishing mortality that reduces equilibrium spawning per recruit to 35% of unfished
maxABC = maximum permissible ABC under Tier 3

Table 2.14. Objective function values (negative log likelihood) and parameter counts as well as selected results for New Series models and New Series ensemble.

Label	Model 22.1	Model 22.2	Model 22.3	Model 22.4	Ensemble
# parameters	346	304	308	305	
TOTAL like	10,779.7	10,875.3	10,874.2	10,916.6	
Survey like	-95.205	-5.956	-5.703	-41.63	
Length comp like	9,950.94	9,990.46	9,989.69	10,058.5	
Age comp like	809.631	817.846	817.250	818.604	
LN(R_0)	13.041	13.156	13.139	13.225	13.131
Natural mortality (M)	0.333	0.347	0.345	0.351	0.343
L_∞	114.768	112.387	113.007	112.786	113.274
VonBert K	0.110	0.115	0.113	0.110	0.112
Bratio 2021	0.380	0.404	0.398	0.374	0.391
SPRratio 2020	0.583	0.556	0.562	0.564	0.566
Q Bottom trawl survey	1.030	0.960	0.971	0.892	0.969
$B_{100\%}$ (10^6 t)	0.681	0.662	0.665	0.665	0.669
$F_{40\%}$	0.304	0.326	0.322	0.335	0.320
$F_{35\%}$	0.369	0.396	0.3911	0.407	0.389
maxABC 2023	127,755	152,783	147,835	154,758	144,857
maxABC 2024	127,728	144,694	142,025	150,221	140,185

LN(R_0) = the natural log of the equilibrium virgin recruits at age-0
$B_{100\%}$ = equilibrium unfished female spawning biomass
$F_{40\%}$ = fishing mortality that reduces equilibrium spawning per recruit to 40% of unfished
$F_{35\%}$ = fishing mortality that reduces equilibrium spawning per recruit to 35% of unfished
maxABC = maximum permissible ABC under Tier 3

Table 2.15. Likelihoods by fleet for all models.

Label	All	Fishery	Survey	Model
Age_like	786.738	0	786.738	Model 19.12
Age_like	794.939	0	794.939	Model 19.12A
Age_like	784.932	0	784.932	Model 21.1
Age_like	796.359	0	796.359	Model 21.2
Age_like	809.631	0	809.631	Model 22.1
Age_like	817.846	0	817.846	Model 22.2
Age_like	817.25	0	817.250	Model 22.3
Age_like	818.604	0	818.604	Model 22.4
Catch_like	3.557e-11	3.557e-11	0	Model 19.12
Catch_like	1.599e-11	1.599e-11	0	Model 19.12A
Catch_like	3.540e-11	3.540e-11	0	Model 21.1
Catch_like	1.214e-11	1.214e-11	0	Model 21.2
Catch_like	2.507e-11	2.507e-11	0	Model 22.1
Catch_like	1.578e-11	1.578e-11	0	Model 22.2
Catch_like	1.916e-11	1.916e-11	0	Model 22.3
Catch_like	3.542e-12	3.542e-12	0	Model 22.4
Init_equ_like	2.161e-03	2.161e-03	0	Model 19.12
Init_equ_like	1.042e-03	1.042e-03	0	Model 19.12A
Init_equ_like	4.347e-04	4.347e-04	0	Model 21.1
Init_equ_like	1.035e-03	1.035e-03	0	Model 21.2
Init_equ_like	2.581e-03	2.581e-03	0	Model 22.1
Init_equ_like	1.609e-03	1.609e-03	0	Model 22.2
Init_equ_like	1.492e-03	1.492e-03	0	Model 22.3
Init_equ_like	1.199e-03	1.199e-03	0	Model 22.4
Length_like	9960.95	4500.37	5,460.58	Model 19.12
Length_like	9991.01	4499.95	5,491.07	Model 19.12A
Length_like	10010.4	4516.47	5,493.94	Model 21.1
Length_like	10066.8	4552.03	5,514.75	Model 21.2
Length_like	9950.94	4494.86	5,456.08	Model 22.1
Length_like	9990.46	4502.49	5,487.98	Model 22.2
Length_like	9989.69	4501.63	5,488.06	Model 22.3
Length_like	10058.5	4550.38	5,508.16	Model 22.4
Surv_like	-95.134	0	-95.134	Model 19.12
Surv_like	-4.742	0	-4.742	Model 19.12A
Surv_like	-4.104	0	-4.104	Model 21.1
Surv_like	-43.204	-53.422	10.218	Model 21.2
Surv_like	-95.205	0	-95.205	Model 22.1
Surv_like	-5.956	0	-5.956	Model 22.2
Surv_like	-5.703	0	-5.703	Model 22.3
Surv_like	-41.63	-51.776	10.145	Model 22.4

Table 2.16. Fits to size composition and age composition data. Note that the “Nave” values for the size composition data do not equal those for the age composition data due to the fact that the time series are of different length.

				Effective N		Ratios	
Model	**Data**	**log(theta)**	**Nave**	**Harmonic mean**	**Dirichlet**	**McAllister-Ianelli**	**Dirichlet**
Model 19.12	Fishery Length	9.990	369	609	369	1.65	1.00
Model 19.12A	Fishery Length	9.989	369	608	369	1.65	1.00
Model 21.1	Fishery Length	9.989	369	597	369	1.62	1.00
Model 21.2	Fishery Length	9.989	369	607	369	1.64	1.00
Model 22.1	Fishery Length	9.990	369	608	369	1.65	1.00
Model 22.2	Fishery Length	9.989	369	606	369	1.64	1.00
Model 22.3	Fishery Length	9.989	369	613	369	1.66	1.00
Model 22.4	Fishery Length	9.989	369	605	369	1.64	1.00
Model 19.12	Survey Length	9.985	369	631	369	1.71	1.00
Model 19.12A	Survey Length	9.984	369	604	369	1.64	1.00
Model 21.1	Survey Length	9.985	369	592	369	1.60	1.00
Model 21.2	Survey Length	9.983	369	577	369	1.56	1.00
Model 22.1	Survey Length	9.985	369	636	369	1.72	1.00
Model 22.2	Survey Length	9.984	369	605	369	1.64	1.00
Model 22.3	Survey Length	9.985	369	604	369	1.64	1.00
Model 22.4	Survey Length	9.983	369	586	369	1.59	1.00
Model 19.12	Survey Age	0.021	350	108	178	0.31	0.51
Model 19.12A	Survey Age	-0.183	350	101	160	0.29	0.46
Model 21.1	Survey Age	0.104	350	106	185	0.30	0.53
Model 21.2	Survey Age	-0.385	350	93	143	0.27	0.41
Model 22.1	Survey Age	-0.393	350	79	142	0.23	0.41
Model 22.2	Survey Age	-0.472	350	72	135	0.21	0.39
Model 22.3	Survey Age	-0.453	350	72	137	0.21	0.39
Model 22.4	Survey Age	-0.679	350	69	119	0.20	0.34

Table 2.17. Residual runs test (Carvalho et al. 2021) for fit to survey and fishery CPUE indices for all models and versions. The p-value is a test of whether the observed residual distribution is further than three standard deviations away from the expected residual process average of 0.

Model	Type	Index	p-value	Test	Sigma3 lo	Sigma3 hi
M19.12	cpue	Survey	0.266	Passed	-0.159	0.159
M19.12A	cpue	Survey	0.280	Passed	-0.383	0.383
M21.1	cpue	Survey	0.100	Passed	-0.369	0.369
M21.2	cpue	Fishery	0.093	Passed	-0.126	0.126
M21.2	cpue	Survey	0.027	Failed	-0.376	0.376
M22.1	cpue	Survey	0.266	Passed	-0.159	0.159
M22.2	cpue	Survey	0.280	Passed	-0.383	0.383
M22.3	cpue	Survey	0.100	Passed	-0.369	0.369
M22.4	cpue	Fishery	0.093	Passed	-0.126	0.126
M22.4	cpue	Survey	0.027	Failed	-0.376	0.376
M19.12	len	Fishery	0.010	Failed	-0.026	0.026
M19.12	len	Survey	0.102	Passed	-0.072	0.072
M19.12A	len	Fishery	0.009	Failed	-0.024	0.024
M19.12A	len	Survey	0.001	Failed	-0.078	0.078
M21.1	len	Fishery	0.001	Failed	-0.027	0.027
M21.1	len	Survey	0.005	Failed	-0.077	0.077
M21.2	len	Fishery	0.000	Failed	-0.036	0.036
M21.2	len	Survey	0.000	Failed	-0.079	0.079
M22.1	len	Fishery	0.001	Failed	-0.024	0.024
M22.1	len	Survey	0.028	Failed	-0.068	0.068
M22.2	len	Fishery	0.002	Failed	-0.024	0.024
M22.2	len	Survey	0.000	Failed	-0.077	0.077
M22.3	len	Fishery	0.002	Failed	-0.024	0.024
M22.3	len	Survey	0.000	Failed	-0.077	0.077
M22.4	len	Fishery	0.000	Failed	-0.033	0.033
M22.4	len	Survey	0.000	Failed	-0.079	0.079
M19.12	age	Survey	0.724	Passed	-0.152	0.152
M19.12A	age	Survey	0.494	Passed	-0.151	0.151
M21.1	age	Survey	0.447	Passed	-0.151	0.151
M21.2	age	Survey	0.451	Passed	-0.161	0.161
M22.1	age	Survey	0.724	Passed	-0.142	0.142
M22.2	age	Survey	0.039	Failed	-0.160	0.160
M22.3	age	Survey	0.039	Failed	-0.145	0.145
M22.4	age	Survey	0.039	Failed	-0.164	0.164

Table 2.18. Mean absolute scaled error (MASE) values for model data components for all models and versions. Values greater than 1.0 indicated prediction fits worse than a random walk.

	Index		**Lengths**		**Age**
Model	**Fishery**	**Survey**	**Fishery**	**Survey**	**Survey**
Model 19.12		0.19	0.31	1.23	0.71
Model 19.12A		0.44	0.33	1.22	0.71
Model 21.1		0.44	0.34	1.21	0.68
Model 21.2	0.41	0.47	0.42	1.28	0.71
Model 22.1		0.20	0.31	1.22	0.76
Model 22.2		0.45	0.32	1.20	0.76
Model 22.3		0.45	0.32	1.19	0.75
Model 22.4	0.42	0.47	0.42	1.28	0.77

Table 2.19. "Sigma" terms for vectors of annual random deviations other than those associated with catchability. Deviations are ~normal(0,σ^2) for ln(Recruits), ~normal(0,1) for others.

	Model 19.12			Model 19.12A			Model 21.1			Model 21.2		
Parameter	**var_dev**	**ave_var**	**sigma**	**var_dev**	**ave_var**	**sigma**	**var_dev**	**ave_var**	**sigma**	**var_dev**	**ave_var**	**sigma**
ln(Recruits)	0.4581	0.0122	0.6642	0.4581	0.0122	0.6651	0.4581	0.0122	0.6681	0.4581	0.0122	0.6452
Length_at_1.5	0.8532	0.1165	0.1746	0.8532	0.1165	0.1804	0.8532	0.1165	0.1725	0.8532	0.1165	0.1749
Sel_fsh_lnSD1	0.8699	0.2596	0.1593	0.8699	0.2596	0.1639	0.8699	0.2596	0.1817	0.8699	0.2596	0.1903
Sel_fsh_logitEnd	0.0084	0.9947	0.7615	0.0084	0.9947	0.7726	0.0084	0.9947	0.6754	0.0084	0.9947	1.3903
Sel_srv_PeakStart	0.7381	0.1433	0.2258	0.7381	0.1433	0.2092	0.7381	0.1433	0.2065	0.7381	0.1433	0.2028
Sel_srv_lnSD1	0.6354	0.2479	0.8414	0.6354	0.2479	0.7710	0.6354	0.2479	0.7573	0.6354	0.2479	0.7390

	Model 22.1			Model 22.2			Model 22.3			Model 22.4		
Parameter	**var_dev**	**ave_var**	**sigma**	**var_dev**	**ave_var**	**sigma**	**var_dev**	**ave_var**	**sigma**	**var_dev**	**ave_var**	**sigma**
ln(Recruits)	0.4489	0.0124	0.6642	0.4586	0.0121	0.6651	0.4589	0.0119	0.6681	0.4433	0.0122	0.6452
Length_at_1.5	0.8419	0.1181	0.1746	0.7890	0.1142	0.1804	0.8528	0.1184	0.1725	0.8141	0.1194	0.1749
Sel_fsh_lnSD1	0.8166	0.2613	0.1593	0.8186	0.2522	0.1639	0.7537	0.2266	0.1817	1.0124	0.1840	0.1903
Sel_fsh_logitEnd	0.1696	0.7675	0.7615	0.1925	0.7328	0.7726	0.1764	0.7837	0.6754	0.3970	0.4238	1.3903
Sel_srv_PeakStart	0.7715	0.1391	0.2258	0.7513	0.1549	0.2092	0.7610	0.1503	0.2065	0.7756	0.1559	0.2028
Sel_srv_lnSD1	0.6428	0.2425	0.8414	0.6500	0.2764	0.7710	0.6597	0.2725	0.7573	0.6560	0.2822	0.7390

Table 2.20. Computation of model weights.

Feature		M 19.12 M 22.1	M 19.12A M 22.2	M 21.1 M 22.3	M 21.2 M 22.4
Feature 1: Allow catchability to vary?		yes	no	no	no
Feature 2: Allow domed survey selectivity?		no	no	yes	no
Feature 3: Use fishery CPUE?		no	no	no	yes
Criterion	Emph.	M 19.12 M 22.1	M 19.12A M 22.2	M 21.1 M 22.3	M 21.2 M 22.4
General plausibility of the model	3	1	2	0.6667	1
Acceptable retrospective bias	3	2	2	1.3333	1
Uses properly vetted data	3	2	2	2	0
Acceptable residual patterns	3	2	2	2	2
Comparable complexity	2	1	2	1	2
Fits consistent with variances	2	2	1	1	0
Average emphasis:		1.6875	1.875	1.375	1
Model weight:		0.2842	0.3158	0.2316	0.1684

Table 2.21. Retrospective Mohn's rho values for spawning stock biomass (SSB), age-o recruitment (R), full selection fishing mortality (F), and biomass ratio (B Ratio) for all models and ensembles. The shaded values for R, F, and Bratio are provided here as a relative measure of bias among models, there has yet to be a set standard proposed for these values to evaluate model performance.

Thompson Series	**Model 19.12**	**Model 19.12A**	**Model 21.1**	**Model 21.2**	**Ensemble**
SSB	0.055	0.042	0.018	0.079	0.045
R	0.120	0.099	0.093	0.181	0.134
F	-0.060	-0.045	-0.043	-0.074	-0.054
B Ratio	0.094	0.053	0.056	0.085	-0.054
New Series	**Model 22.1**	**Model 22.2**	**Model 22.3**	**Model 22.4**	**Ensemble**
SSB	0.069	0.066	0.040	0.079	0.063
R	0.145	0.133	0.098	0.184	0.151
F	-0.071	-0.077	-0.050	-0.067	-0.067
B Ratio	0.108	0.083	0.057	0.085	0.084

Table 2.22. Aging bias parameters for all models.

	1977-2007		2008-2022	
	Age1	**Age20**	**Age1**	**Age20**
Thompson Series				
M19.12	0.343	0.997	0.009	-1.523
M19.12A	0.349	0.888	0.001	-1.299
M21.1	0.342	0.946	0.003	-1.380
M21.2	0.351	0.828	0.003	-1.339
New Series				
M22.1	0.344	0.930	0	0
M22.2	0.348	0.860	0	0
M22.3	0.347	0.862	0	0
M22.4	0.350	0.799	0	0

Table 2.23. Parameter values and standard deviation for the Thompson Series and New Series ensembles.

	Thompson Ensemble		New Ensemble	
Label	Est.	Stdev.	Est.	Stdev.
NatM	0.347	0.020	0.343	0.014
L_at_Amin	15.143	0.450	15.137	0.444
L_at_Amax	121.411	15.858	113.274	3.211
VonBert_K	0.100	0.024	0.112	0.009
Richards	1.519	0.074	1.482	0.043
SD_young	3.528	0.070	3.522	0.070
SD_old	10.379	1.224	9.880	0.407
Aging bias at age 1 1977- 2007	0.346	0.017	0.347	0.019
Aging bias at age 20 1977- 2007	0.922	0.226	0.870	0.241
LN(R0)	13.142	0.152	13.131	0.120
SR_regime_1976	-0.883	0.222	-0.932	0.192
Early_InitAge_20	-0.013	0.656	-0.018	0.658
Early_InitAge_19	-0.007	0.660	-0.010	0.658
Early_InitAge_18	-0.012	0.659	-0.015	0.654
Early_InitAge_17	-0.018	0.658	-0.023	0.652
Early_InitAge_16	-0.028	0.654	-0.035	0.652
Early_InitAge_15	-0.043	0.649	-0.052	0.650
Early_InitAge_14	-0.065	0.642	-0.078	0.637
Early_InitAge_13	-0.098	0.633	-0.114	0.630
Early_InitAge_12	-0.146	0.620	-0.164	0.617
Early_InitAge_11	-0.212	0.604	-0.229	0.601
Early_InitAge_10	-0.297	0.588	-0.312	0.585
Early_InitAge_9	-0.400	0.569	-0.409	0.564
Early_InitAge_8	-0.512	0.550	-0.514	0.548
Early_InitAge_7	-0.617	0.529	-0.611	0.531
Early_InitAge_6	-0.677	0.518	-0.667	0.517
Early_InitAge_5	-0.617	0.516	-0.601	0.513
Early_InitAge_4	-0.296	0.524	-0.276	0.524
Early_InitAge_3	0.182	0.484	0.201	0.484
Early_InitAge_2	0.152	0.530	0.177	0.534
Early_InitAge_1	0.625	0.573	0.658	0.587
Main_RecrDev_1977	1.032	0.223	1.039	0.219
Main_RecrDev_1978	0.582	0.236	0.556	0.242
Main_RecrDev_1979	0.675	0.112	0.663	0.112
Main_RecrDev_1980	-0.811	0.209	-0.864	0.216
Main_RecrDev_1981	-0.742	0.143	-0.741	0.144
Main_RecrDev_1982	0.934	0.050	0.939	0.050
Main_RecrDev_1983	-0.544	0.169	-0.555	0.168
Main_RecrDev_1984	0.842	0.054	0.852	0.054
Main_RecrDev_1985	0.018	0.085	0.022	0.085
Main_RecrDev_1986	-0.574	0.106	-0.582	0.108
Main_RecrDev_1987	-1.712	0.216	-1.718	0.219
Main_RecrDev_1988	-0.290	0.086	-0.268	0.086
Main_RecrDev_1989	0.390	0.060	0.420	0.060

Table 2.23. Parameter values and standard deviation for the Thompson Series and New Series ensembles.

	Thompson Ensemble		New Ensemble	
Label	Est.	Stdev.	Est.	Stdev.
Main_RecrDev_1990	0.385	0.066	0.403	0.067
Main_RecrDev_1991	-0.081	0.095	-0.068	0.096
Main_RecrDev_1992	0.833	0.066	0.847	0.066
Main_RecrDev_1993	-0.155	0.076	-0.187	0.080
Main_RecrDev_1994	-0.312	0.078	-0.328	0.077
Main_RecrDev_1995	-0.426	0.082	-0.430	0.085
Main_RecrDev_1996	0.775	0.047	0.789	0.043
Main_RecrDev_1997	-0.145	0.084	-0.148	0.080
Main_RecrDev_1998	-0.328	0.095	-0.356	0.098
Main_RecrDev_1999	0.545	0.049	0.535	0.051
Main_RecrDev_2000	0.252	0.053	0.255	0.054
Main_RecrDev_2001	-0.679	0.110	-0.735	0.117
Main_RecrDev_2002	-0.112	0.088	-0.096	0.087
Main_RecrDev_2003	-0.264	0.088	-0.270	0.088
Main_RecrDev_2004	-0.572	0.092	-0.577	0.089
Main_RecrDev_2005	-0.313	0.091	-0.259	0.087
Main_RecrDev_2006	0.721	0.061	0.698	0.060
Main_RecrDev_2007	-0.245	0.100	-0.174	0.098
Main_RecrDev_2008	1.110	0.053	1.063	0.054
Main_RecrDev_2009	-0.782	0.164	-0.738	0.153
Main_RecrDev_2010	0.609	0.068	0.609	0.071
Main_RecrDev_2011	0.933	0.060	0.908	0.064
Main_RecrDev_2012	0.120	0.100	0.215	0.093
Main_RecrDev_2013	1.111	0.053	1.060	0.055
Main_RecrDev_2014	-0.626	0.132	-0.657	0.130
Main_RecrDev_2015	-0.234	0.088	-0.275	0.085
Main_RecrDev_2016	-0.623	0.110	-0.664	0.109
Main_RecrDev_2017	-0.973	0.177	-0.802	0.174
Main_RecrDev_2018	0.710	0.059	0.688	0.061
Main_RecrDev_2019	-0.895	0.183	-0.932	0.191
Main_RecrDev_2020	-0.140	0.119	-0.137	0.119
InitF	0.110	0.037	0.125	0.039
LnQ BT Survey	-0.023	0.097	-0.031	0.081
Size_DblN_peak_Fishery(1)	74.456	1.117	74.970	0.360
Size_DblN_top_logit_Fishery(1)	-9.287		-8.602	
Size_DblN_ascend_se_Fishery(1)	6.032	0.057	6.058	0.035
Size_DblN_descend_se_Fishery(1)	-0.142		-9.192	
Size_DblN_end_logit_Fishery(1)	-0.052	3.077	1.801	0.278
Size_DblN_peak_Survey(2)	20.937	0.846	21.065	0.795
Size_DblN_ascend_se_Survey(2)	3.516	0.159	3.554	0.151
ln(DM_theta) Age	-0.093	0.262	-0.480	0.183
L_at_Amin_Fem_GP_1_DEVmult_1977	0.537	0.949	0.499	0.928
L_at_Amin_Fem_GP_1_DEVmult_1978	-0.003	0.945	0.014	0.948

Table 2.23. Parameter values and standard deviation for the Thompson Series and New Series ensembles.

Label	Thompson Ensemble Est.	Thompson Ensemble Stdev.	New Ensemble Est.	New Ensemble Stdev.
L_at_Amin_Fem_GP_1_DEVmult_1979	0.234	0.952	0.271	0.953
L_at_Amin_Fem_GP_1_DEVmult_1980	0.084	0.904	0.083	0.901
L_at_Amin_Fem_GP_1_DEVmult_1981	-1.097	0.376	-1.105	0.374
L_at_Amin_Fem_GP_1_DEVmult_1982	-1.020	0.240	-1.012	0.241
L_at_Amin_Fem_GP_1_DEVmult_1983	0.601	0.599	0.646	0.591
L_at_Amin_Fem_GP_1_DEVmult_1984	0.029	0.212	0.053	0.208
L_at_Amin_Fem_GP_1_DEVmult_1985	-1.626	0.340	-1.607	0.340
L_at_Amin_Fem_GP_1_DEVmult_1986	-0.045	0.231	0.008	0.229
L_at_Amin_Fem_GP_1_DEVmult_1987	-0.617	0.387	-0.567	0.379
L_at_Amin_Fem_GP_1_DEVmult_1988	-0.971	0.365	-0.972	0.366
L_at_Amin_Fem_GP_1_DEVmult_1989	-0.826	0.241	-0.831	0.244
L_at_Amin_Fem_GP_1_DEVmult_1990	-0.259	0.278	-0.218	0.273
L_at_Amin_Fem_GP_1_DEVmult_1991	0.134	0.222	0.168	0.222
L_at_Amin_Fem_GP_1_DEVmult_1992	-0.043	0.204	-0.023	0.203
L_at_Amin_Fem_GP_1_DEVmult_1993	0.369	0.313	0.399	0.312
L_at_Amin_Fem_GP_1_DEVmult_1994	-0.390	0.257	-0.328	0.255
L_at_Amin_Fem_GP_1_DEVmult_1995	-0.419	0.321	-0.410	0.321
L_at_Amin_Fem_GP_1_DEVmult_1996	-0.250	0.240	-0.198	0.237
L_at_Amin_Fem_GP_1_DEVmult_1997	-0.616	0.532	-0.296	0.286
L_at_Amin_Fem_GP_1_DEVmult_1998	-0.874	0.284	-0.817	0.272
L_at_Amin_Fem_GP_1_DEVmult_1999	-1.276	0.233	-1.249	0.233
L_at_Amin_Fem_GP_1_DEVmult_2000	0.597	0.222	0.603	0.218
L_at_Amin_Fem_GP_1_DEVmult_2001	0.120	0.246	0.195	0.246
L_at_Amin_Fem_GP_1_DEVmult_2002	0.453	0.215	0.479	0.216
L_at_Amin_Fem_GP_1_DEVmult_2003	0.063	0.264	0.081	0.265
L_at_Amin_Fem_GP_1_DEVmult_2004	1.074	0.228	1.101	0.224
L_at_Amin_Fem_GP_1_DEVmult_2005	-0.318	0.249	-0.385	0.248
L_at_Amin_Fem_GP_1_DEVmult_2006	-0.454	0.199	-0.443	0.200
L_at_Amin_Fem_GP_1_DEVmult_2007	-1.134	0.275	-1.255	0.273
L_at_Amin_Fem_GP_1_DEVmult_2008	-1.124	0.223	-1.088	0.220
L_at_Amin_Fem_GP_1_DEVmult_2009	-0.887	0.358	-0.935	0.365
L_at_Amin_Fem_GP_1_DEVmult_2010	0.134	0.203	0.149	0.200
L_at_Amin_Fem_GP_1_DEVmult_2011	-1.205	0.244	-1.186	0.247
L_at_Amin_Fem_GP_1_DEVmult_2012	0.147	0.302	0.060	0.297
L_at_Amin_Fem_GP_1_DEVmult_2013	-0.399	0.213	-0.378	0.213
L_at_Amin_Fem_GP_1_DEVmult_2014	0.038	0.374	-0.062	0.388
L_at_Amin_Fem_GP_1_DEVmult_2015	1.303	0.203	1.297	0.206
L_at_Amin_Fem_GP_1_DEVmult_2016	1.443	0.308	1.414	0.314
L_at_Amin_Fem_GP_1_DEVmult_2017	1.391	0.254	1.303	0.254
L_at_Amin_Fem_GP_1_DEVmult_2018	2.030	0.188	2.004	0.188
L_at_Amin_Fem_GP_1_DEVmult_2019	0.605	0.995	0.058	1.089
L_at_Amin_Fem_GP_1_DEVmult_2020	1.189	0.226	1.179	0.223
L_at_Amin_Fem_GP_1_DEVmult_2021	0.441	0.233	0.448	0.232
L_at_Amin_Fem_GP_1_DEVmult_2022	2.834	0.274	2.852	0.269

Table 2.24. Management reference point for last year's ensemble and the Thompson and New Series ensembles with weighted estimate and coefficient of variation (cv).

	Last Year	Thompson Series		New Series	
	Est.	Est.	cv	Est.	cv
$B_{100\%}$	686,761	679,221	0.10	668,477	0.04
$B_{40\%}$	274,704	271,688	0.10	267,391	0.04
$B_{35\%}$	240,366	237,727	0.10	233,967	0.04
$F_{40\%}$	0.330	0.320	0.11	0.320	0.06
$F_{35\%}$	0.410	0.388	0.11	0.389	0.06
2023 Female spawning biomass	254,585	245,934	0.10	245,594	0.08
2023 Relative spawning biomass	0.370	0.364	0.04	0.368	0.03
2023 Pr(B/B100%<0.2)	0	0		0	
2023 maxF_{ABC}	0.310	0.291	0.20	0.293	0.14
2023 maxABC	151,709	142,539	0.23	144,834	0.19
2023 Catch	151,709	142,539	0.23	144,834	0.19
2023 F_{OFL}	0.370	0.353	0.20	0.356	0.14
2023 OFL	180,909	169,477	0.13	172,495	0.11
2023 Pr(max(ABC>truOFL)	0.24	0.35		0.33	
2024 Female spawning biomass		244,597	0.10	242,911	0.05
2024 Relative spawning biomass		0.362	0.03	0.364	0.02
2024 Pr(B/B100%<0.2)		0		0	
2024 maxF_{ABC}		0.288	0.19	0.290	0.10
2024 maxABC		138,417	0.19	140,159	0.12
2024 Catch		138,417	0.15	140,159	0.12
2024 F_{OFL}		0.349	0.19	0.352	0.10
2024 OFL		164,445	0.10	166,814	0.08
2024 Pr(max(ABC>truOFL)		0.26		0.22	

Legend:
$B_{100\%}$ = equilibrium unfished female spawning biomass
$B_{40\%}$ = 40% of B100% (the inflection point of the harvest control rules in Tier 3)
$B_{35\%}$ = 35% of B100% (the BMSY proxy for Tier 3)
$F_{40\%}$ = fishing mortality that reduces equilibrium spawning per recruit to 40% of unfished
$F_{35\%}$ = fishing mortality that reduces equilibrium spawning per recruit to 35% of unfished
Relative spawning biomass = ratio of female spawning biomass to B100%
Pr($B/B_{100\%}$<0.2) = probability that relative spawning biomass is less than 0.2
maxF_{ABC} = maximum permissible ABC fishing mortality rate under Tier 3
maxABC = maximum permissible ABC under Tier 3
Catch = estimated catch conditional on ABC=maxABC
F_{OFL} = OFL fishing mortality rate under Tier 3
OFL = OFL under Tier 3
Pr(maxABC>truOFL) = probability that maxABC is greater than the "true" OFL

Table 2.25. Female spawning biomass (t) time series comparison for last year's ensemble and this year's Thompson and New ensembles.

		Thompson Ensemble		New Ensemble				Thompson Ensemble		New Ensemble	
Year	Last Year Est.	Est.	Stdev.	Est.	Stdev.	Year	Last Year Est.	Est.	Stdev.	Est.	Stdev.
1978	125,487	109,564	60,398	92,044	35,818	2002	242,144	228,810	32,828	225,637	30,503
1979	127,244	112,923	55,633	97,050	35,947	2003	247,157	234,097	30,636	231,808	27,706
1980	151,143	136,885	54,430	122,928	38,789	2004	251,658	240,290	29,157	236,729	25,723
1981	212,676	200,189	56,258	185,999	45,109	2005	247,993	235,394	28,346	229,320	24,506
1982	320,765	302,771	65,107	275,117	54,746	2006	223,741	210,419	26,927	206,468	24,262
1983	420,010	377,676	68,442	363,545	61,548	2007	200,913	183,319	26,735	179,467	25,566
1984	422,817	409,944	67,866	413,484	62,555	2008	178,378	159,536	26,585	158,405	27,015
1985	476,765	441,036	72,483	418,440	58,828	2009	160,199	139,145	26,088	140,741	28,043
1986	467,389	434,887	71,103	407,576	53,792	2010	154,528	135,038	25,160	140,093	28,612
1987	454,223	419,208	64,701	406,821	49,012	2011	178,230	159,771	24,128	167,289	27,922
1988	479,036	432,740	65,734	407,882	44,994	2012	204,105	187,020	22,748	195,628	25,832
1989	465,941	412,344	61,653	390,624	41,220	2013	229,364	208,834	21,728	216,628	23,466
1990	420,038	391,743	58,759	362,261	35,954	2014	232,837	215,478	22,554	224,639	22,833
1991	339,391	329,154	53,235	310,868	30,071	2015	238,823	225,278	25,341	239,766	25,341
1992	253,190	254,793	48,092	237,377	25,489	2016	273,517	259,729	31,224	273,885	30,026
1993	240,330	234,587	42,430	205,240	23,454	2017	315,904	300,437	37,263	314,229	35,467
1994	236,669	230,217	35,489	214,054	23,448	2018	345,828	327,017	40,534	338,863	38,217
1995	247,259	243,826	35,574	224,322	25,534	2019	349,927	331,289	40,822	332,967	36,835
1996	243,780	243,177	36,167	224,530	30,090	2020	313,835	295,078	37,600	298,700	33,190
1997	237,741	235,819	38,588	228,854	34,984	2021	251,897	257,131	34,880	260,990	29,537
1998	214,034	212,756	40,107	208,245	37,189	2022	256,927	245,485	33,137	250,144	27,033
1999	208,789	202,953	40,303	196,566	37,055	2023	253,076	245,934	33,521	245,583	26,699
2000	219,489	202,064	38,298	197,523	35,990						
2001	227,593	215,182	35,564	211,132	33,728						

Table 2.26. Total biomass (t) time series comparison for last year's ensemble and this year's Thompson and New ensembles.

		Thompson Ensemble	New Ensemble			Thompson Ensemble	New Ensemble
Year	Last Year Est.	Est.	Est.	Year	Last Year Est.	Est.	Est.
1978	396,115	366,584	311,287	2002	916,414	887,764	867,059
1979	424,820	386,914	349,054	2003	908,216	880,833	873,251
1980	560,456	511,542	460,879	2004	885,340	857,966	841,038
1981	770,008	721,876	690,028	2005	821,638	787,497	771,437
1982	1,015,307	979,123	938,766	2006	733,216	694,262	680,907
1983	1,287,369	1,243,839	1,137,687	2007	661,297	612,652	597,525
1984	1,400,287	1,292,753	1,244,891	2008	616,269	571,794	570,430
1985	1,341,386	1,304,068	1,290,343	2009	648,714	603,682	603,301
1986	1,442,943	1,367,008	1,306,132	2010	739,571	696,878	699,709
1987	1,429,514	1,366,961	1,305,338	2011	853,813	814,895	835,008
1988	1,441,967	1,381,348	1,332,026	2012	891,828	856,252	884,407
1989	1,468,123	1,363,440	1,305,319	2013	947,478	909,149	931,227
1990	1,346,997	1,220,042	1,166,113	2014	972,731	949,925	991,125
1991	1,150,931	1,086,374	1,010,186	2015	1,049,856	1,036,473	1,105,910
1992	957,936	930,447	889,406	2016	1,168,845	1,149,517	1,205,017
1993	822,942	822,215	796,546	2017	1,179,287	1,153,093	1,196,967
1994	915,094	897,191	799,205	2018	1,124,935	1,086,455	1,113,317
1995	915,240	904,501	862,195	2019	1,027,314	998,928	998,208
1996	965,520	952,160	914,873	2020	924,865	896,588	902,964
1997	968,361	957,733	880,534	2021	839,163	853,480	862,270
1998	848,942	837,148	823,651	2022	879,978	853,393	878,286
1999	751,421	746,404	738,181	2023		842,266	844,578
2000	791,004	779,774	756,765				
2001	858,992	820,066	786,536				

Table 2.27. Age 0 recruitment (1000x of fish) time series comparison (last year's ensemble and this year's ensembles).

		Thompson Ensemble		New Ensemble				Thompson Ensemble		New Ensemble	
Year	Last Year Est.	Est.	Stdev.	Est.	Stdev.	Year	Last Year Est.	Est.	Stdev.	Est.	Stdev.
1978	766,614	739,800	222,333	708,057	202,330	2002	364,961	370,861	72,664	370,545	62,046
1979	759,852	812,290	170,020	788,833	143,831	2003	335,736	318,168	58,994	310,860	49,978
1980	192,718	183,931	51,003	171,766	46,091	2004	238,668	233,180	42,193	228,155	34,845
1981	207,882	196,406	42,063	193,314	37,577	2005	285,658	301,897	51,435	313,446	44,599
1982	975,776	1,049,655	171,824	1,037,885	139,643	2006	814,597	847,684	120,003	814,900	87,582
1983	257,347	240,709	60,825	233,669	52,361	2007	324,302	322,339	51,724	340,349	42,521
1984	896,690	958,395	158,853	951,679	128,759	2008	1,179,169	1,250,607	178,845	1,173,941	133,938
1985	410,976	420,459	75,973	414,720	61,054	2009	167,007	188,396	40,026	193,918	35,557
1986	223,373	232,098	41,841	226,589	35,175	2010	744,020	756,808	109,727	744,748	86,412
1987	76,539	74,246	18,661	72,710	17,582	2011	957,563	1,048,211	160,422	1,004,635	119,649
1988	312,274	308,456	52,722	310,358	44,323	2012	450,942	465,052	83,532	503,449	74,329
1989	609,372	609,687	98,994	617,518	79,506	2013	1,205,273	1,252,542	196,255	1,170,319	145,080
1990	594,750	606,608	103,323	607,488	83,587	2014	222,115	220,133	41,397	210,153	35,169
1991	363,549	381,991	75,286	380,663	65,356	2015	306,665	325,722	49,875	307,735	40,531
1992	957,580	953,841	178,086	951,241	149,346	2016	217,134	221,693	44,130	209,288	35,990
1993	358,215	353,270	59,531	336,752	48,534	2017	136,750	155,833	36,435	182,075	38,592
1994	303,156	302,236	52,907	292,741	43,593	2018	749,239	838,971	134,624	807,998	109,270
1995	268,114	269,392	46,185	263,963	38,314	2019	225,354	169,273	42,663	160,438	38,284
1996	852,733	896,383	147,609	893,189	110,576	2020	409,968	358,465	68,097	354,043	59,431
1997	359,952	356,588	57,836	349,429	44,907	2021	506,865	513,555	77,998	505,249	60,451
1998	287,486	296,257	46,078	283,845	38,178	2022	506,865	513,555	77,660	505,249	60,521
1999	688,509	711,417	108,472	692,667	85,106						
2000	510,746	531,110	85,166	523,811	66,839						
2001	206,518	209,473	39,866	195,095	34,228						

Table 2.28. Instantaneous apical fishing mortality comparison (last year's ensemble and this year's ensembles).

		Thompson Ensemble		New Ensemble	
Year	Last Year Est.	Est.	Stdev.	Est.	Stdev.
1977	0.157	0.167	0.051	0.189	0.055
1978	0.192	0.217	0.063	0.238	0.067
1979	0.139	0.153	0.042	0.167	0.044
1980	0.145	0.108	0.024	0.115	0.025
1981	0.111	0.112	0.020	0.118	0.021
1982	0.086	0.085	0.012	0.093	0.014
1983	0.104	0.112	0.013	0.116	0.014
1984	0.143	0.140	0.015	0.139	0.016
1985	0.157	0.158	0.016	0.167	0.019
1986	0.150	0.152	0.016	0.162	0.019
1987	0.174	0.176	0.015	0.178	0.017
1988	0.206	0.229	0.019	0.238	0.021
1989	0.192	0.221	0.017	0.227	0.020
1990	0.215	0.240	0.018	0.252	0.020
1991	0.360	0.381	0.029	0.387	0.031
1992	0.391	0.380	0.032	0.392	0.037
1993	0.272	0.292	0.025	0.322	0.029
1994	0.368	0.383	0.029	0.400	0.033
1995	0.462	0.463	0.038	0.492	0.044
1996	0.433	0.439	0.046	0.468	0.052
1997	0.484	0.498	0.060	0.506	0.064
1998	0.387	0.389	0.052	0.393	0.055
1999	0.369	0.374	0.048	0.383	0.051
2000	0.353	0.368	0.042	0.377	0.047
2001	0.330	0.339	0.030	0.347	0.030
2002	0.350	0.354	0.027	0.364	0.029
2003	0.366	0.376	0.034	0.382	0.030
2004	0.376	0.378	0.034	0.388	0.030
2005	0.391	0.401	0.030	0.413	0.030
2006	0.402	0.420	0.037	0.423	0.041
2007	0.372	0.392	0.042	0.396	0.048
2008	0.439	0.457	0.056	0.457	0.064
2009	0.555	0.576	0.085	0.581	0.099
2010	0.535	0.515	0.068	0.500	0.076
2011	0.649	0.633	0.062	0.605	0.068
2012	0.569	0.567	0.043	0.547	0.046
2013	0.524	0.528	0.039	0.519	0.038
2014	0.572	0.553	0.056	0.541	0.048
2015	0.542	0.551	0.060	0.529	0.049
2016	0.486	0.505	0.051	0.485	0.044
2017	0.407	0.407	0.061	0.392	0.051
2018	0.293	0.297	0.032	0.289	0.027
2019	0.277	0.277	0.029	0.281	0.026
2020	0.274	0.272	0.024	0.269	0.023
2021	0.280	0.266	0.023	0.261	0.024
2022		0.336	0.030	0.325	0.030

Table 2.29. Standard harvest scenarios Thompson Series ensemble (M19.12, M19.12A, M21.3, and M21.2).

Female Spawning Biomass							
Yr	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**
2022	245,485	245,485	245,485	245,485	245,485	245,485	245,485
2023	245,934	245,934	245,934	245,934	245,934	245,934	245,934
2024	244,597	244,597	247,037	281,427	295,001	235,229	244,597
2025	238,854	238,854	242,453	308,226	338,802	224,632	238,854
2026	240,784	240,784	244,710	334,957	382,565	224,779	232,024
2027	250,237	250,237	254,243	364,627	428,304	233,499	236,682
2028	260,058	260,058	264,189	394,204	473,216	242,540	243,595
2029	266,505	266,505	271,305	420,581	514,213	248,102	248,278
2030	269,682	269,682	275,436	442,423	549,622	250,549	250,482
2031	270,892	270,892	277,550	459,688	579,048	251,301	251,224
2032	271,206	271,206	278,582	472,933	602,833	251,390	251,351
2033	271,204	271,204	279,091	482,879	621,653	251,305	251,295
2034	271,147	271,147	279,356	490,253	636,326	251,230	251,233
Full selection F							
2022	0.336	0.336	0.336	0.336	0.336	0.336	0.336
2023	0.291	0.291	0.274	0.072	0.000	0.353	0.291
2024	0.288	0.288	0.275	0.079	0.000	0.334	0.288
2025	0.279	0.279	0.270	0.079	0.000	0.317	0.339
2026	0.282	0.282	0.272	0.079	0.000	0.317	0.328
2027	0.293	0.293	0.284	0.079	0.000	0.330	0.335
2028	0.305	0.305	0.292	0.079	0.000	0.344	0.345
2029	0.313	0.313	0.298	0.079	0.000	0.352	0.352
2030	0.317	0.317	0.300	0.079	0.000	0.356	0.356
2031	0.319	0.319	0.301	0.079	0.000	0.357	0.357
2032	0.319	0.319	0.301	0.079	0.000	0.357	0.357
2033	0.319	0.319	0.302	0.079	0.000	0.357	0.357
2034	0.319	0.319	0.301	0.079	0.000	0.357	0.357
Catch (t)							
2022	152,146	152,146	152,146	152,146	152,146	152,146	152,146
2023	142,539	142,539	135,278	38,014	0	169,477	142,539
2024	138,417	138,417	134,590	46,533	0	152,727	138,417
2025	131,525	131,525	129,373	50,439	0	139,598	156,370
2026	135,712	135,712	133,800	54,471	0	142,706	150,712
2027	148,325	148,325	146,147	59,116	0	156,177	159,413
2028	160,368	160,368	156,566	63,481	0	168,741	169,537
2029	167,755	167,755	163,035	67,043	0	175,910	175,793
2030	171,085	171,085	166,277	69,749	0	178,756	178,478
2031	172,155	172,155	167,561	71,727	0	179,444	179,243
2032	172,294	172,294	167,966	73,138	0	179,386	179,281
2033	172,167	172,167	168,100	74,129	0	179,196	179,151
2034	172,030	172,030	168,144	74,814	0	179,060	179,043

Table 2.30. Standard harvest scenarios New Series ensemble (M22.1, M22.2, M22.3, and M22.4).

Yr	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
emale spawning biomass (t)							
2022	250,145	250,145	250,145	250,145	250,145	250,145	250,145
2023	245,594	245,594	245,594	245,594	245,594	245,594	245,594
2024	242,911	242,911	246,135	280,289	293,830	233,335	242,903
2025	235,969	235,969	241,088	306,147	336,498	221,475	235,952
2026	237,110	237,110	243,030	332,070	378,999	220,902	228,225
2027	246,217	246,217	252,486	361,034	423,493	229,394	232,560
2028	255,989	255,989	262,566	390,036	467,269	238,496	239,476
2029	262,503	262,503	269,463	415,936	507,251	244,199	244,279
2030	265,766	265,766	273,711	437,371	541,768	246,767	246,612
2031	267,027	267,027	276,114	454,265	570,399	247,586	247,442
2032	267,347	267,347	277,536	467,146	593,483	247,688	247,605
2033	267,338	267,338	278,367	476,734	611,698	247,593	247,557
2034	267,252	267,252	278,849	483,741	625,835	247,493	247,482
Full selection F							
2022	0.325	0.325	0.325	0.325	0.325	0.325	0.325
2023	0.293	0.293	0.273	0.072	0.000	0.356	0.293
2024	0.290	0.290	0.273	0.079	0.000	0.337	0.290
2025	0.281	0.281	0.267	0.079	0.000	0.319	0.341
2026	0.282	0.282	0.270	0.079	0.000	0.318	0.329
2027	0.294	0.294	0.281	0.079	0.000	0.331	0.336
2028	0.306	0.306	0.292	0.079	0.000	0.345	0.346
2029	0.314	0.314	0.296	0.079	0.000	0.353	0.354
2030	0.318	0.318	0.298	0.079	0.000	0.357	0.357
2031	0.320	0.320	0.298	0.079	0.000	0.359	0.358
2032	0.320	0.320	0.298	0.079	0.000	0.359	0.359
2033	0.320	0.320	0.298	0.079	0.000	0.359	0.359
2034	0.320	0.320	0.298	0.079	0.000	0.359	0.358
Catch (t)							
2022	152,146	152,146	152,146	152,146	152,146	152,146	152,146
2023	144,834	144,834	135,547	38,179	0	172,495	144,857
2024	140,159	140,159	134,534	46,559	0	154,870	140,185
2025	132,254	132,254	128,834	49,948	0	140,392	157,536
2026	135,719	135,719	132,845	53,890	0	142,646	150,907
2027	148,135	148,135	145,062	58,557	0	155,920	159,335
2028	160,233	160,233	156,828	62,974	0	168,591	169,487
2029	167,747	167,747	162,500	66,598	0	175,930	175,849
2030	171,222	171,222	165,339	69,396	0	178,930	178,657
2031	172,410	172,410	166,330	71,501	0	179,718	179,515
2032	172,585	172,585	166,868	73,058	0	179,702	179,597
2033	172,495	172,495	167,179	74,195	0	179,519	179,478
2034	172,393	172,393	167,359	75,014	0	179,374	179,364

FIGURES

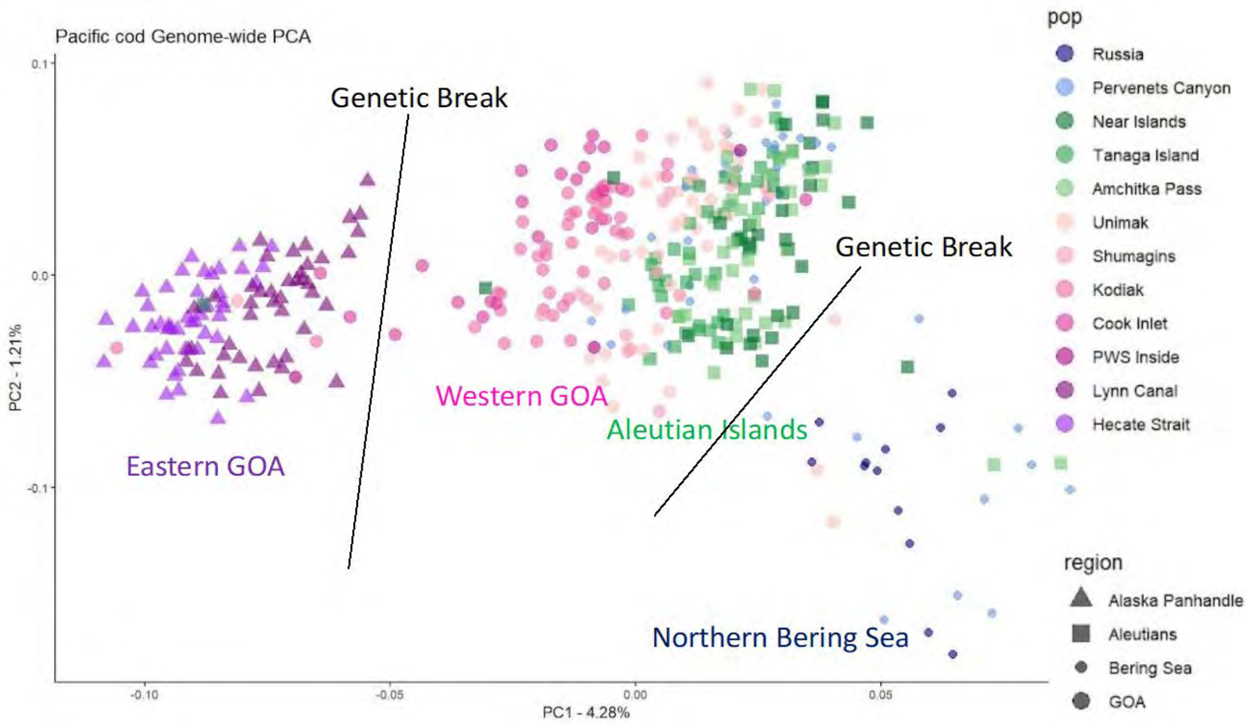


Figure 2.1. Principal components analysis of 1,922,927 polymorphic SNPs from the lcWGS dataset.

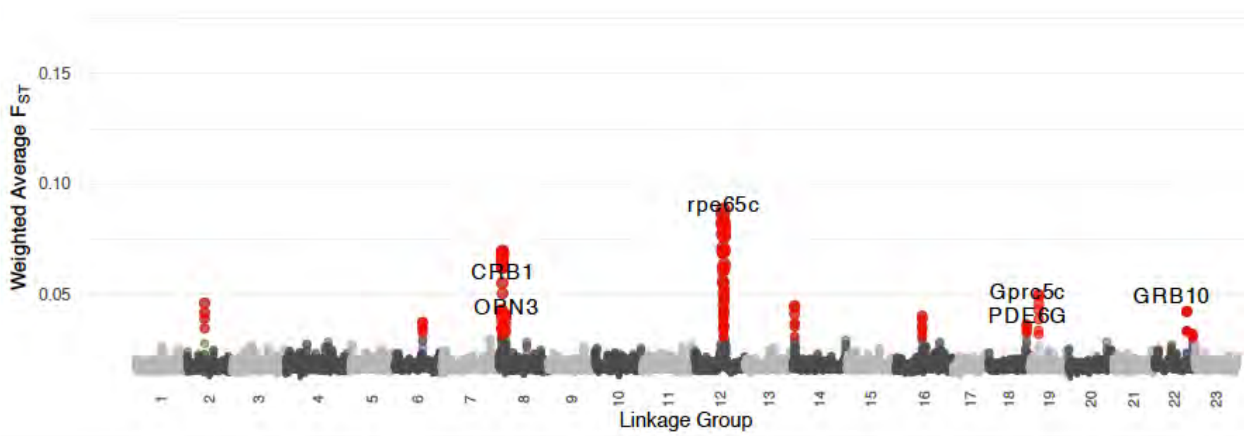


Figure 2.2. Regions of the genome that contain outlier loci, due to high F_{ST}, a measure of genetic differentiation. Figure based on Pool-Seq data (adapted from Spies et al. 2022).

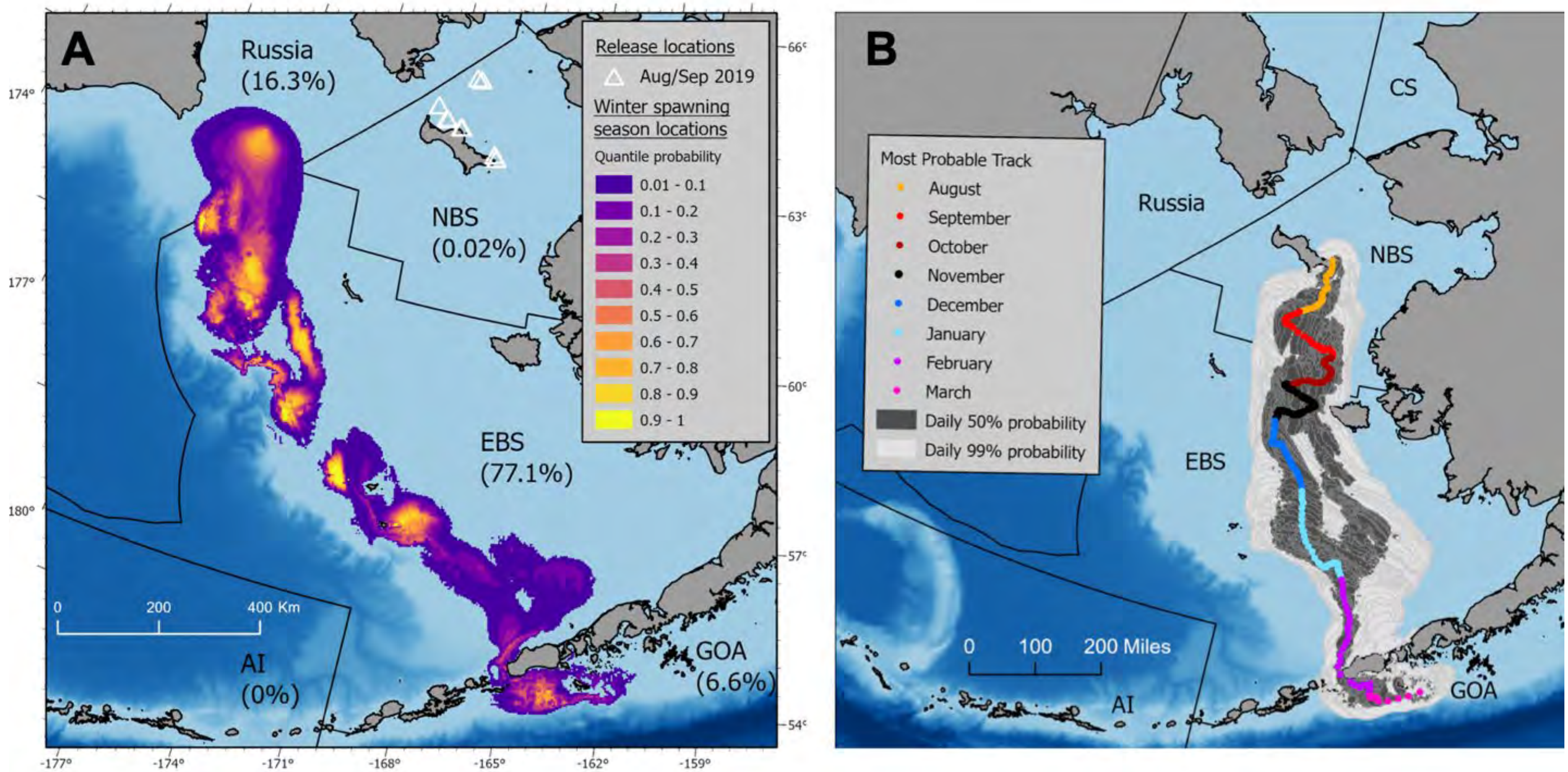


Figure 2.3. Seasonal movement of Pacific cod tagged in the NBS during the summer of 2019. A) Location probability for 12 satellite-tagged Pacific cod combined by management area during the peak spawning period of February 15 – March 31, 2020. B) Reconstructed spawning migration pathway for an individual fish that moved from St. Lawrence Island (NBS) in August 2019 to Sanak Island (GOA) during March 2020. Points indicate most probable daily location, color coded by month, while polygons indicate the highest 50% and 99% of the location probability on each day.

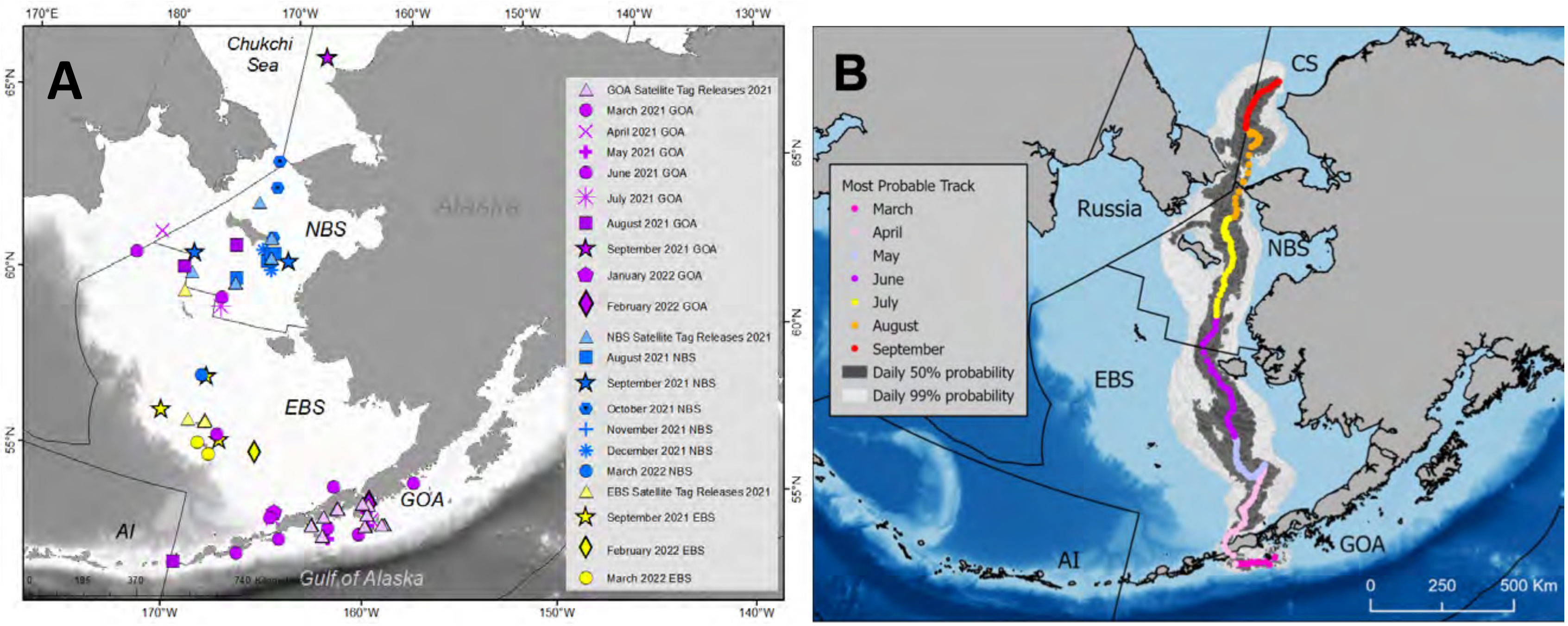


Figure 2.4. Seasonal movement of Pacific cod tagged in the GOA, NBS, and EBS during 2021. A) Monthly satellite tag recovery locations for Pacific cod tagged in the GOA during winter spawning (purple) and for Pacific cod tagged in the NBS (blue) and EBS (yellow) during summer foraging. B) Reconstructed migration pathway from winter spawning to summer foraging areas for a fish that moved from Sanak Island (GOA) in March 2021 to the Chukchi Sea (CS) in September 2021. Points indicate most probable daily location, color coded by month, while polygons indicate the highest 50% and 99% of the location probability on each day.

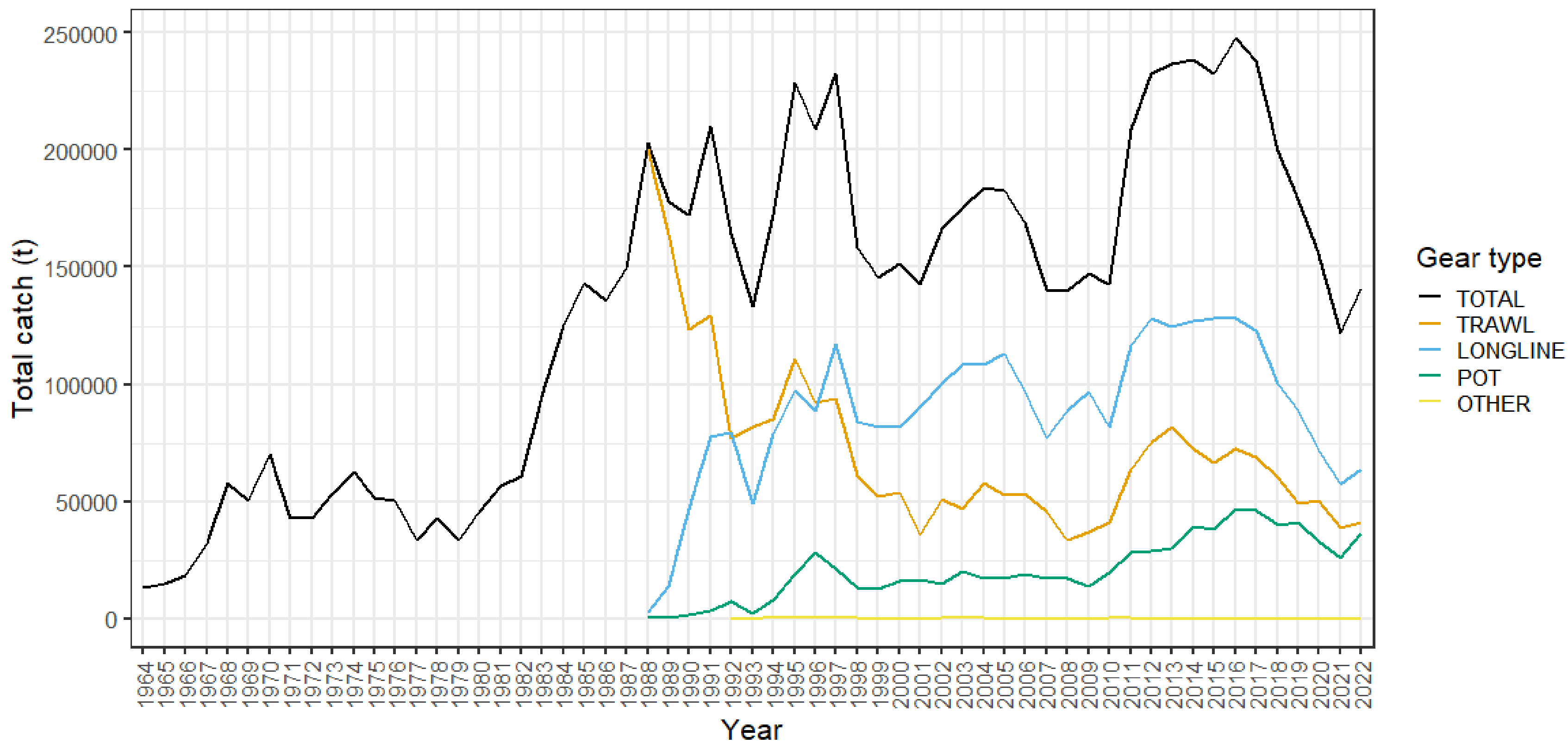


Figure 2.5. Total catch and catch by gear type.

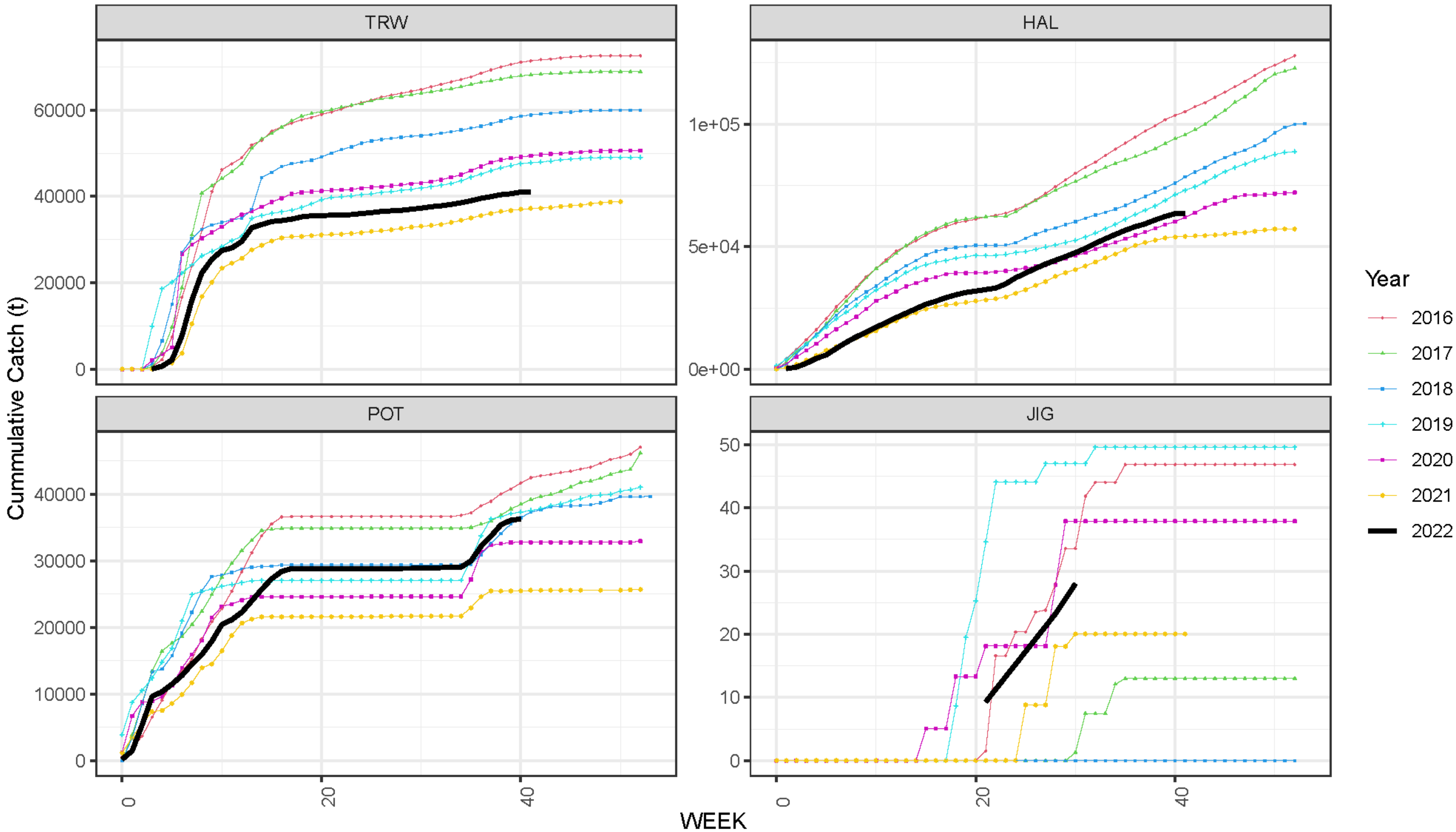


Figure 2.6. Cumulative Pacific cod catch by gear type for 2016-2022. Data for 2022 are current through October 9.

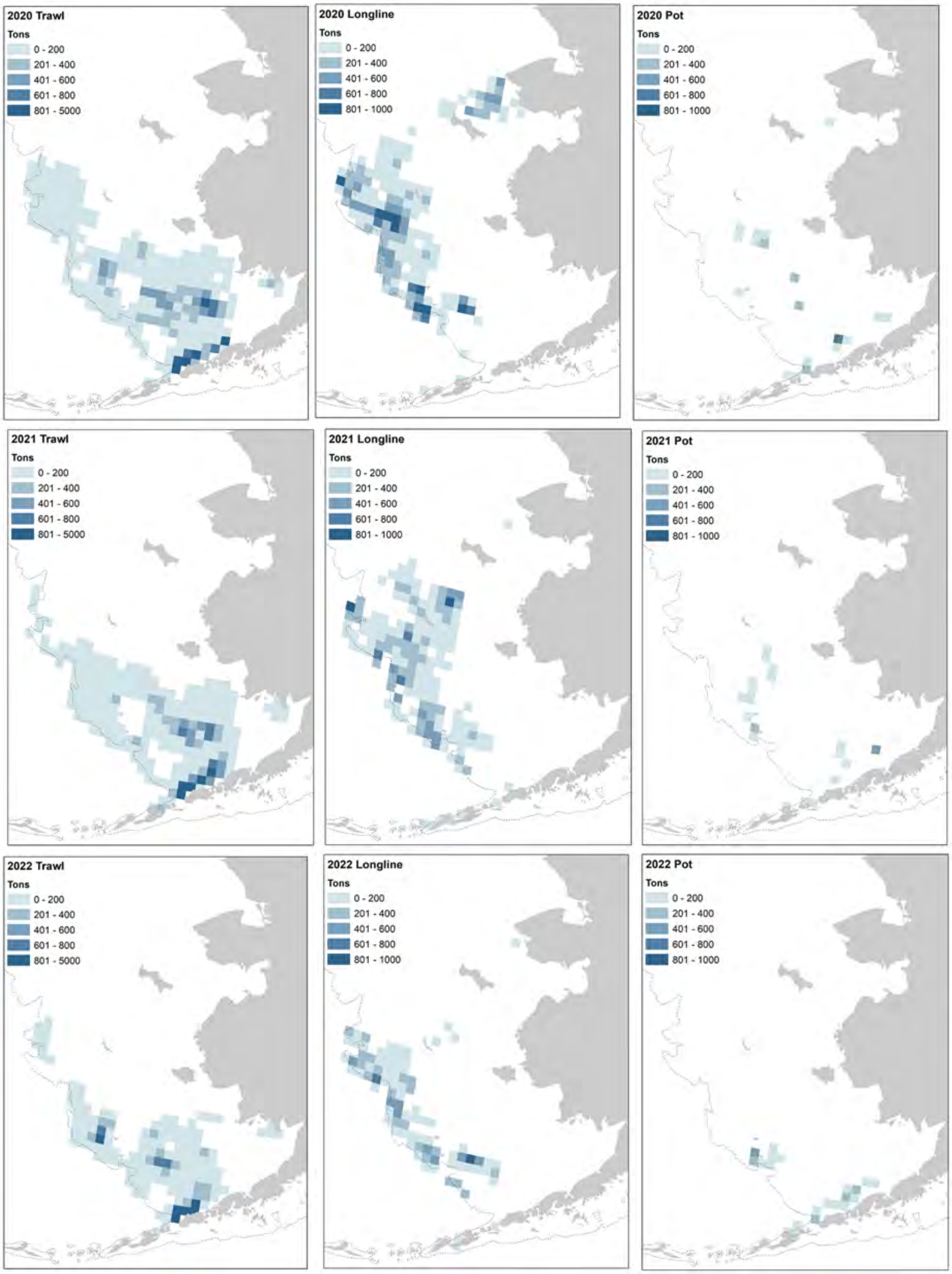


Figure 2.7. Observed catch by gear type for 2020-2022. Data are aggregated by bottom trawl survey grid cells (20nm^2) and all cells with fewer than 3 vessels fishing have been removed. Data for 2022 are through October 9. Bathymetry line (dotted gray) shown is at 200 m.

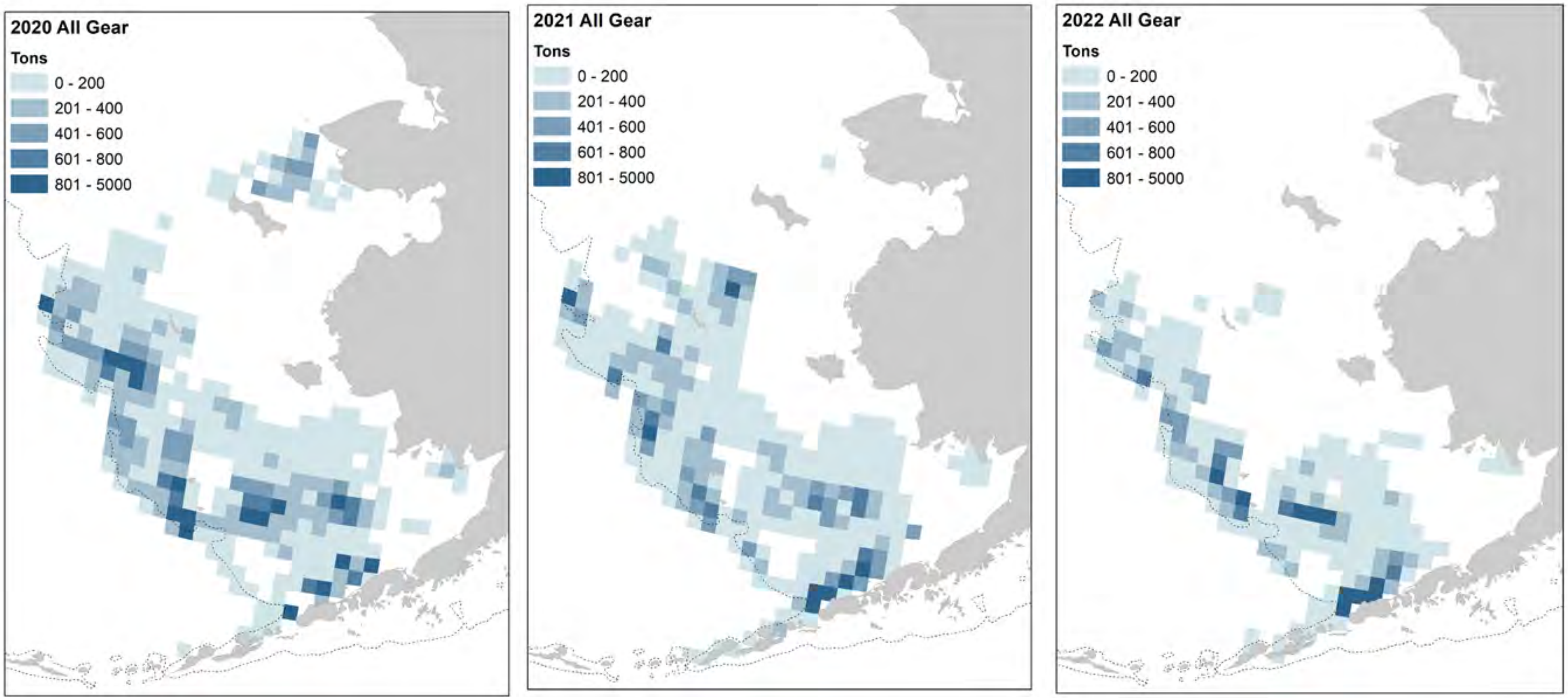


Figure 2.8. Total observed catch for 2020-2022. Data are aggregated by bottom trawl survey grid cells (20nm^2) and all cells with fewer than 3 vessels fishing have been removed. Data for 2022 are through October 9. Bathymetry line (dotted gray) shown is at 200 m.

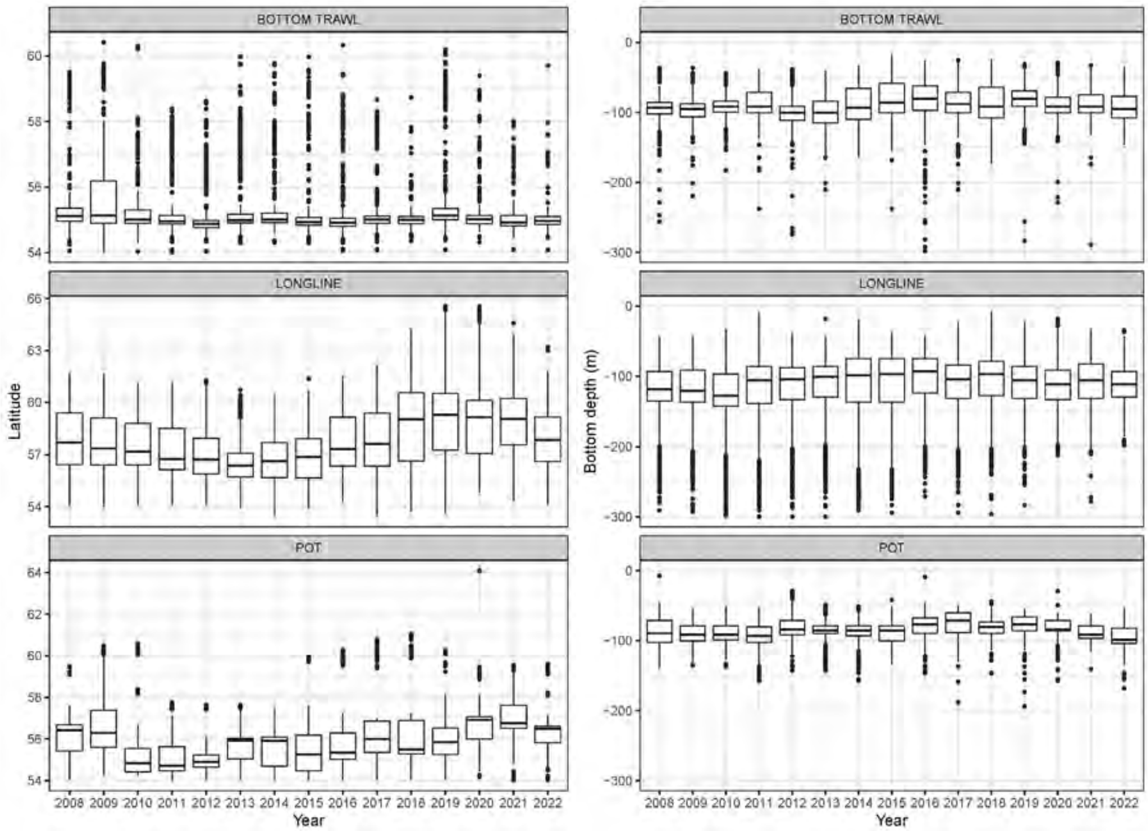


Figure 2.9. Distribution of Pacific cod hauls or sets by gear type for 2008-2022 by (left) Latitude and (right) bottom depth in meters. Data for 2022 are current through October 9.

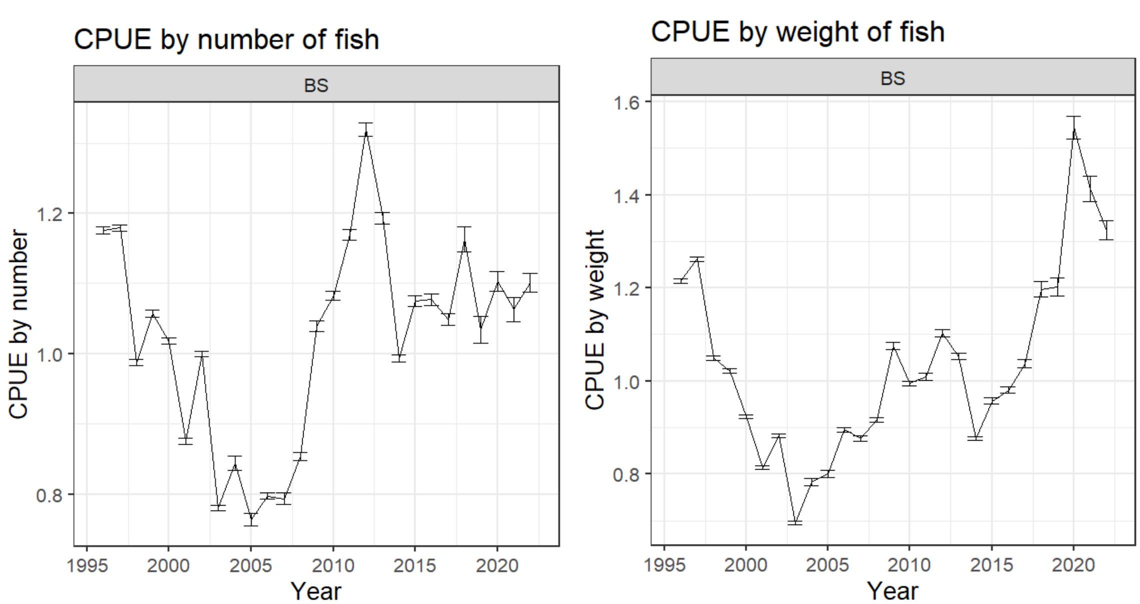


Figure 2.10. Thompson et al. (2021) combined fishery CPUE index estimates for 1996-2022 by (left) number and right weight of fish.

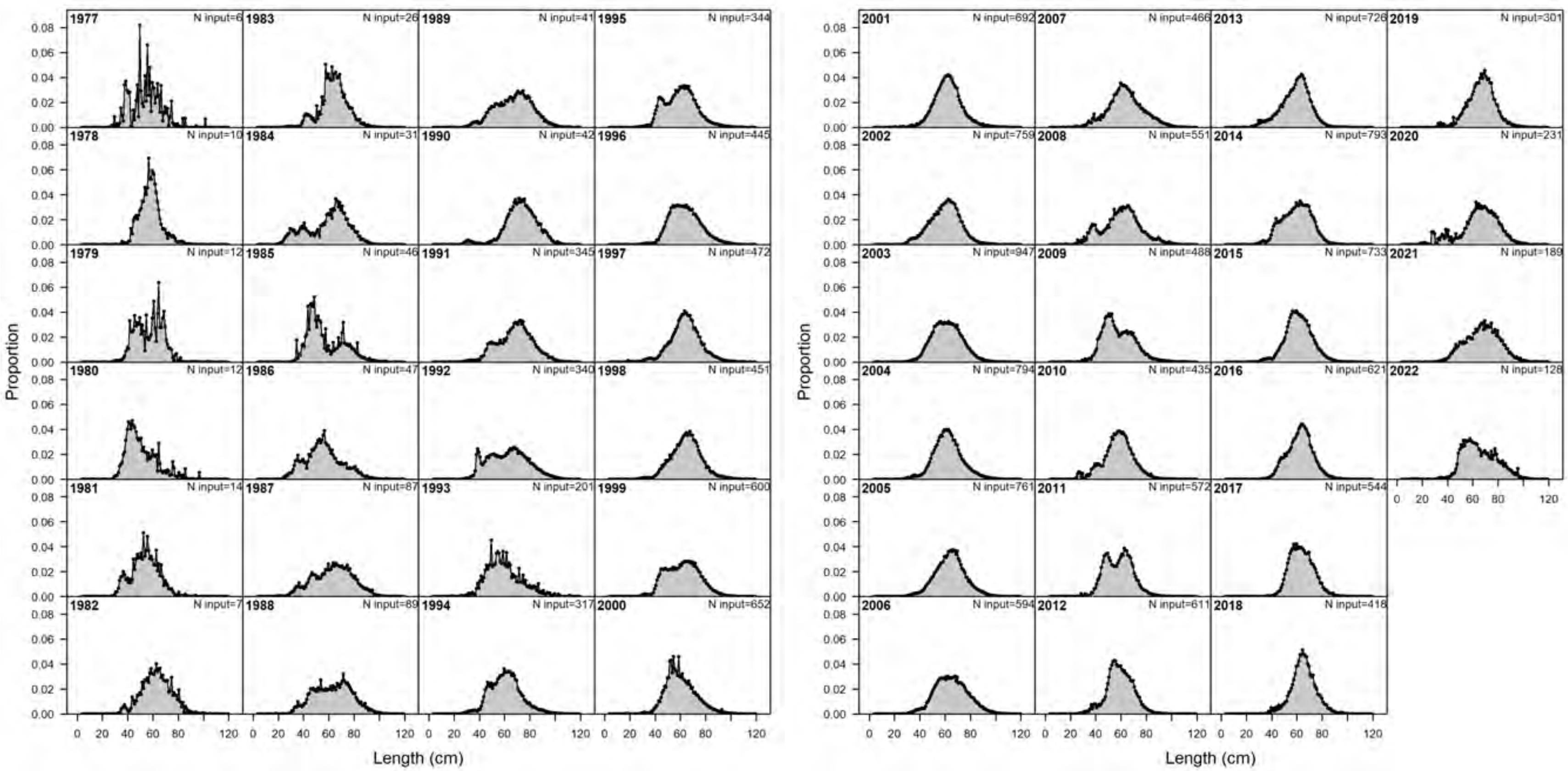


Figure 2.11. Combined fishery length composition distributions by year.

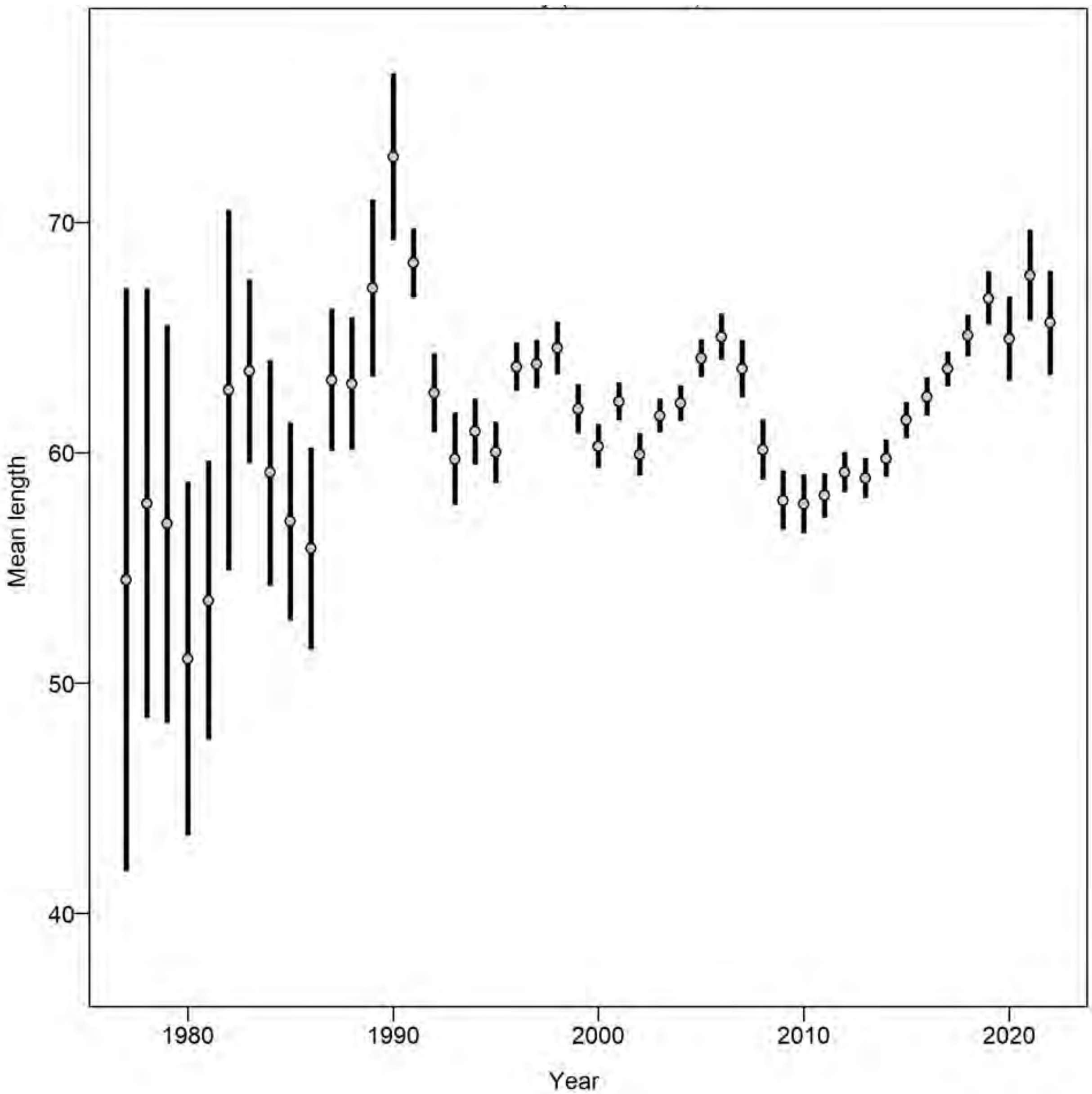


Figure 2.12. Combined fishery mean length (cm) by year.

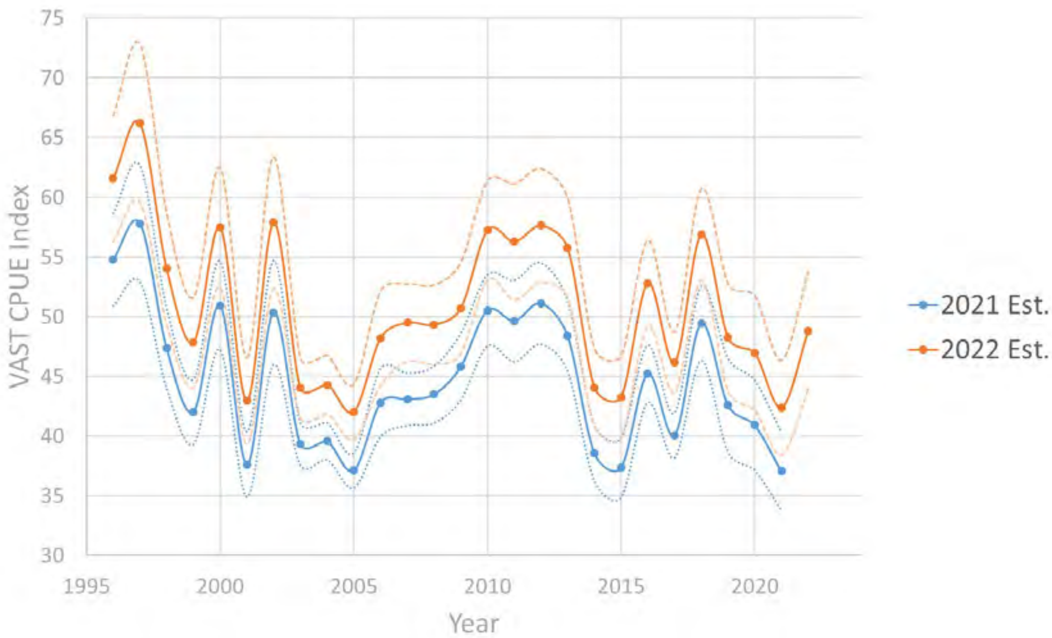


Figure 2.13. VAST derived winter (January-February) longline fishery CPUE index estimates from 2021 and 2022 for 1996-2022.

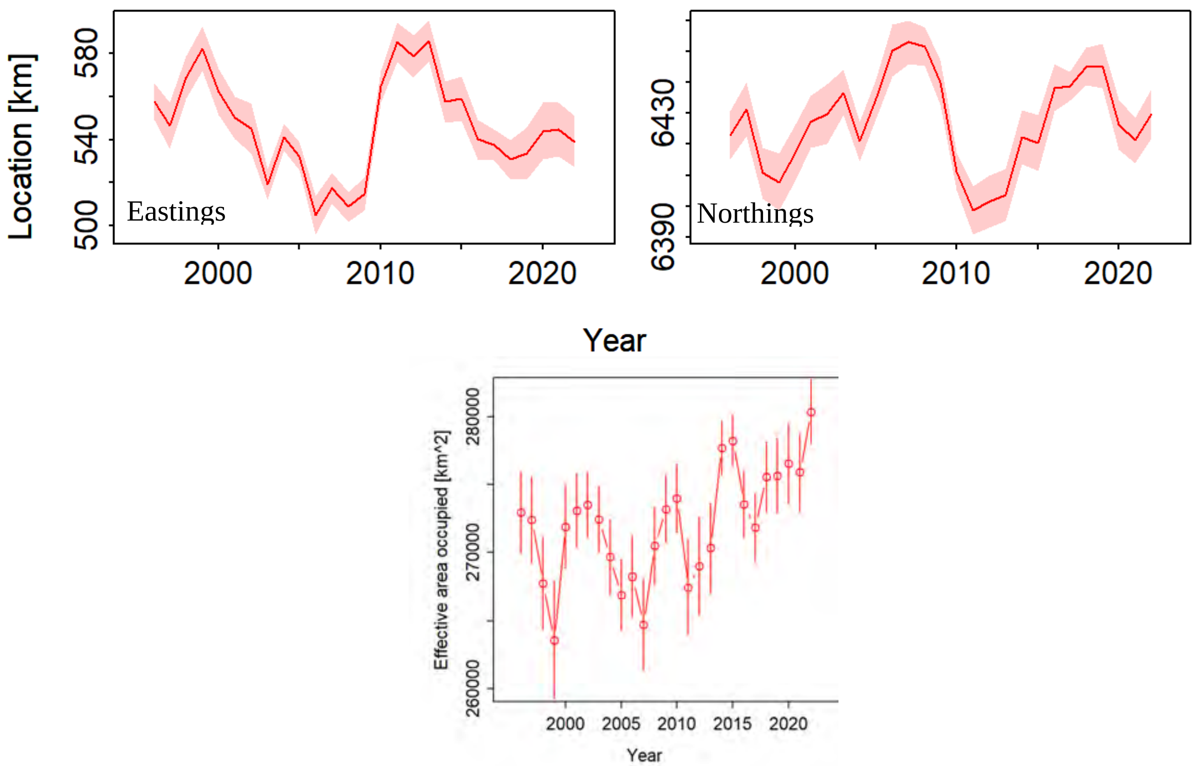


Figure 2.14. VAST winter (January- February) longline fishery CPUE index (top left) eastings where larger values indicate further east, (top right) northings where larger values indicate further north, and (bottom) effective area occupied.

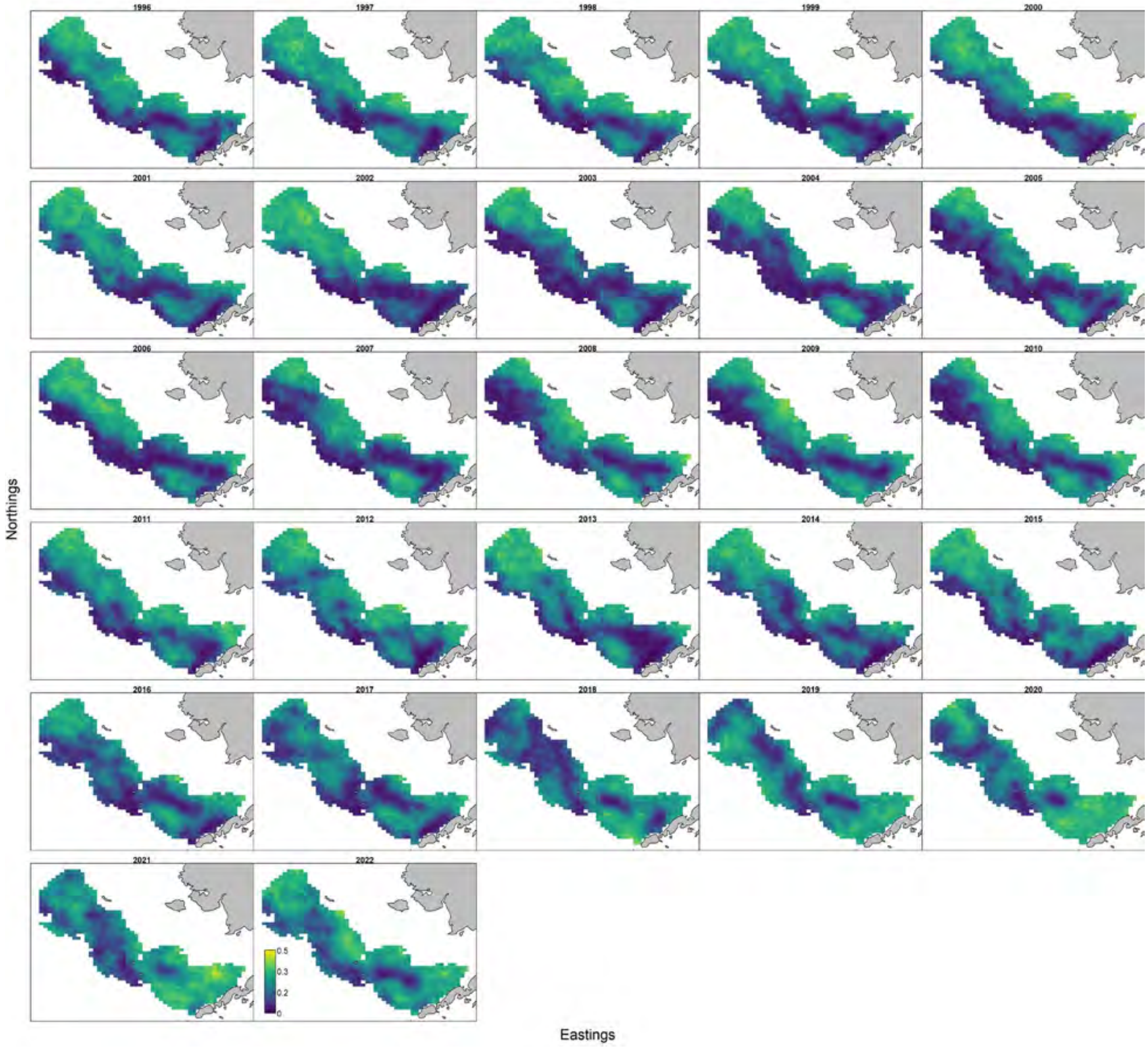


Figure 2.15. VAST winter longline fishery index CPUE log density maps by year.

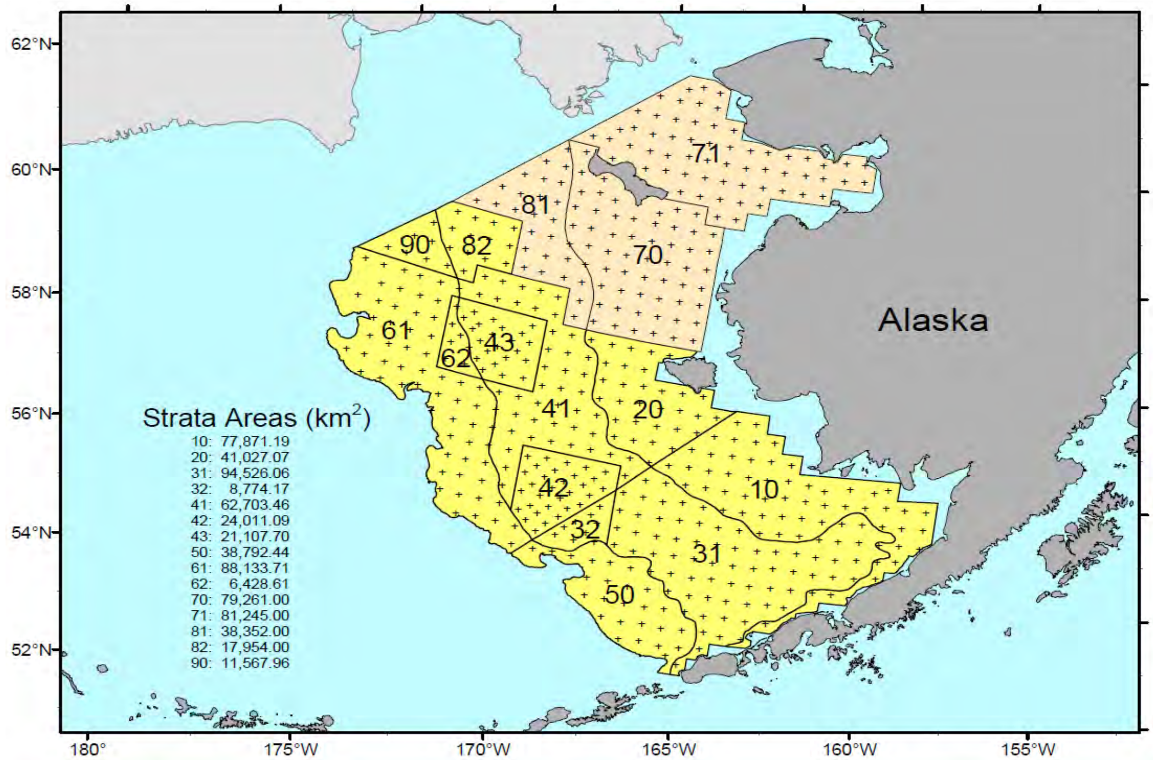


Figure 2.16. AFSC bottom trawl survey strata where crosses represent station locations.

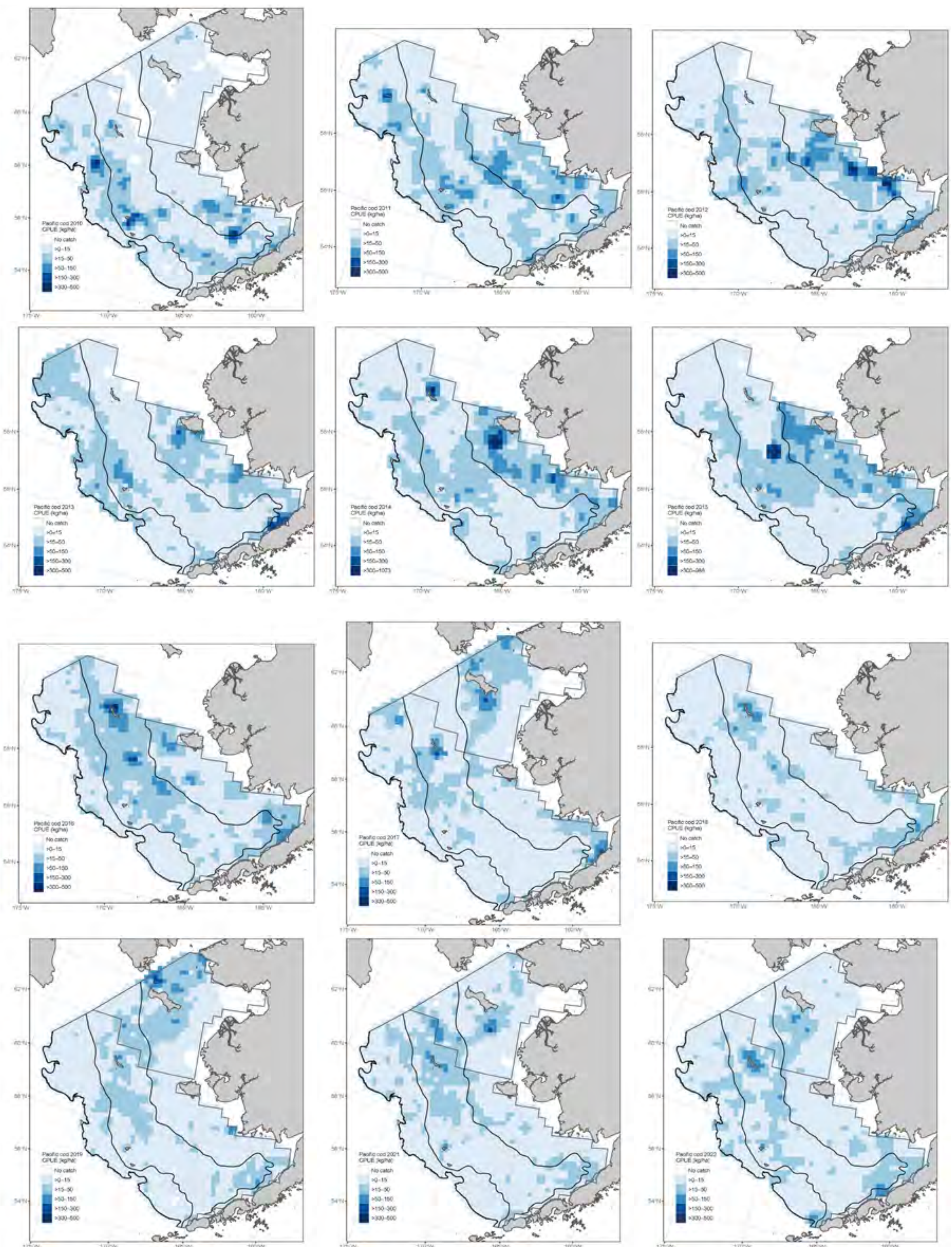


Figure 2.17. AFSC bottom trawl survey Pacific cod catch per unit effort for 2010-2022 (from top left to bottom right). Maps for 2010, 2017, 2019, and 2021-2022 include the northern Bering Sea. There was no survey in 2020. The 50m, 100m, and 200m bathymetry lines are shown.

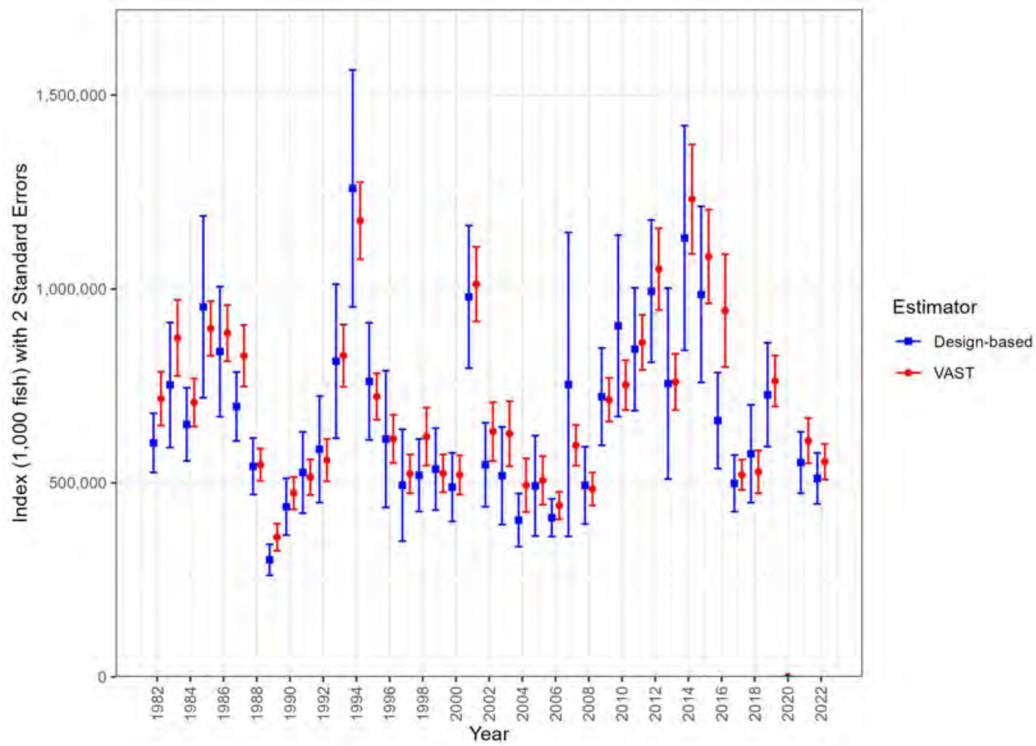


Figure 2.18. Pacific cod abundance estimates (1000s of fish) for design-based and VAST Bottom trawl survey time series.

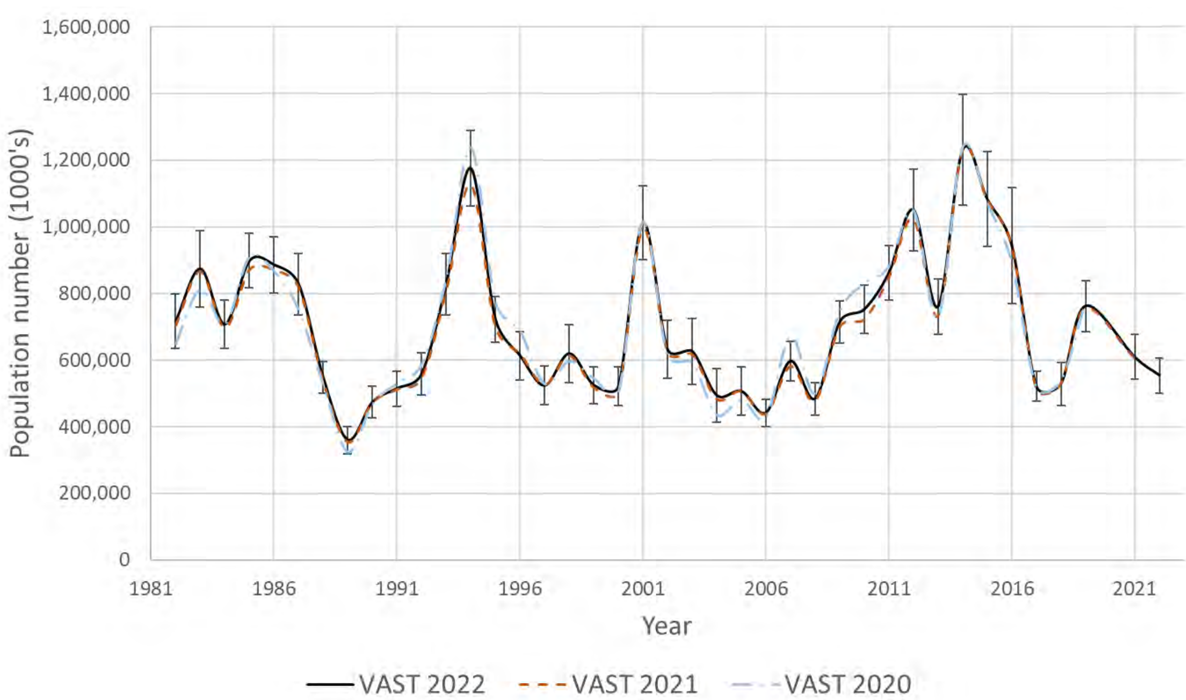


Figure 2.19. The 2020-2022 VAST Bottom trawl survey Pacific cod abundance (1000s of fish) estimates with 2022 confidence intervals (2 standard errors).

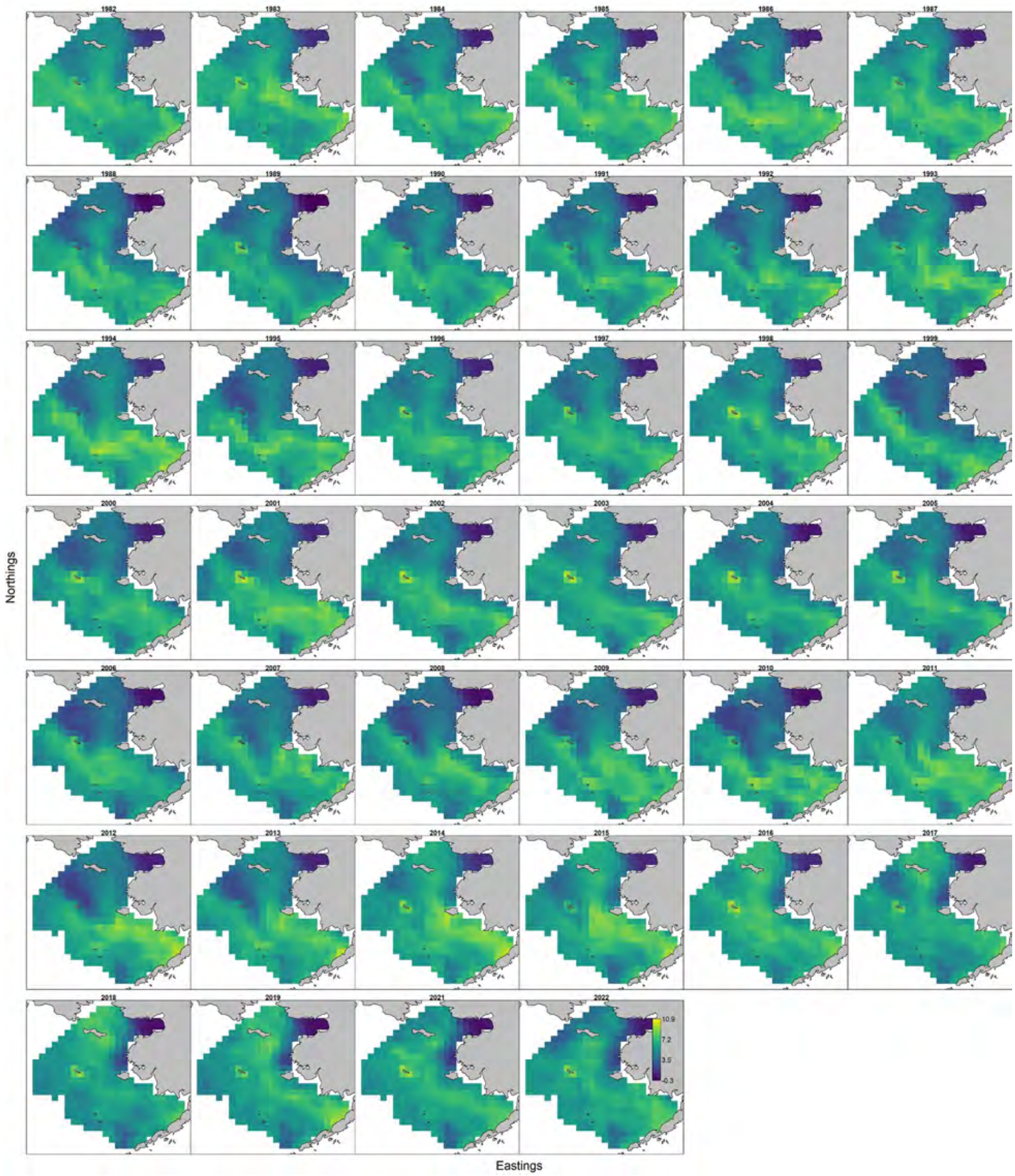


Figure 2.20. Survey abundance log density maps by year (VAST).

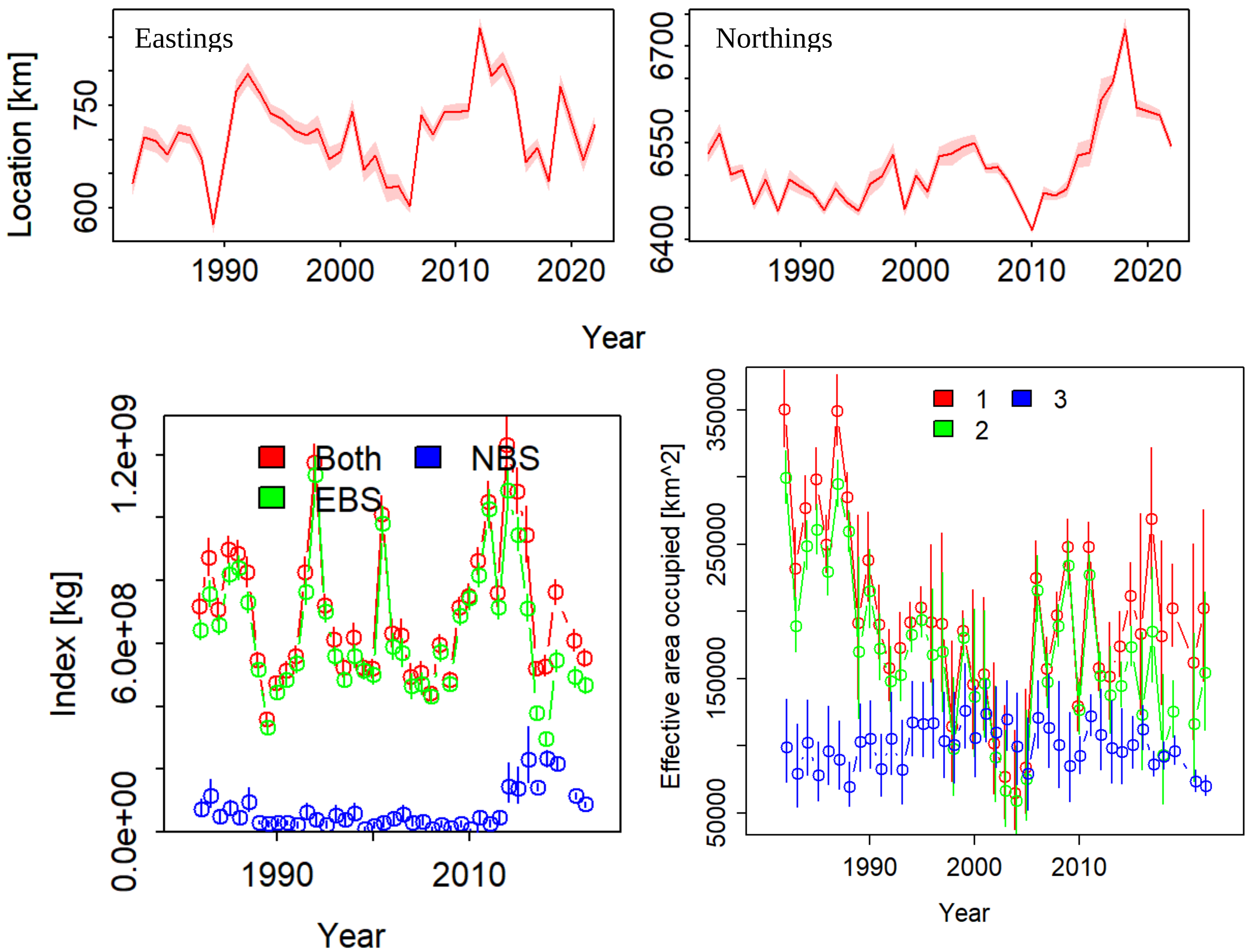


Figure 2.21. VAST bottom trawl survey index center of gravity (top left) eastings, (top right) northings, (bottom left) abundance index by area, and (bottom right) effective area occupied 1982-2022.

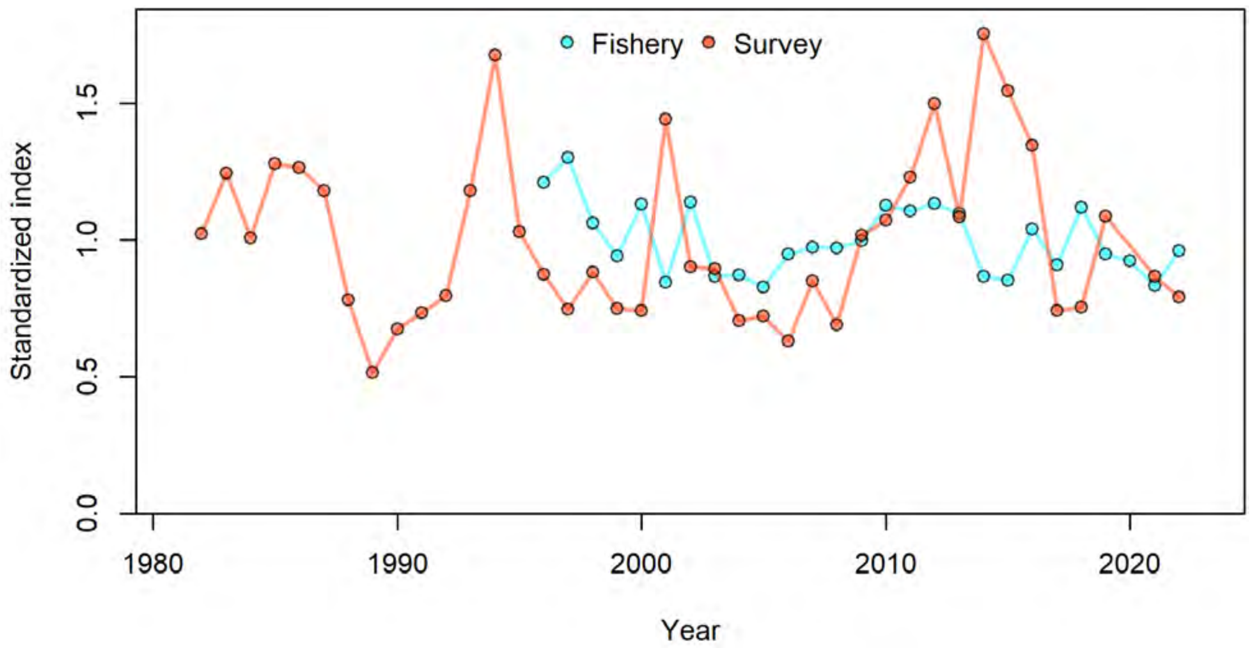


Figure 2.22. Standardized values of the VAST (Survey) bottom trawl survey index and (Fishery) winter longline fishery CPUE index.

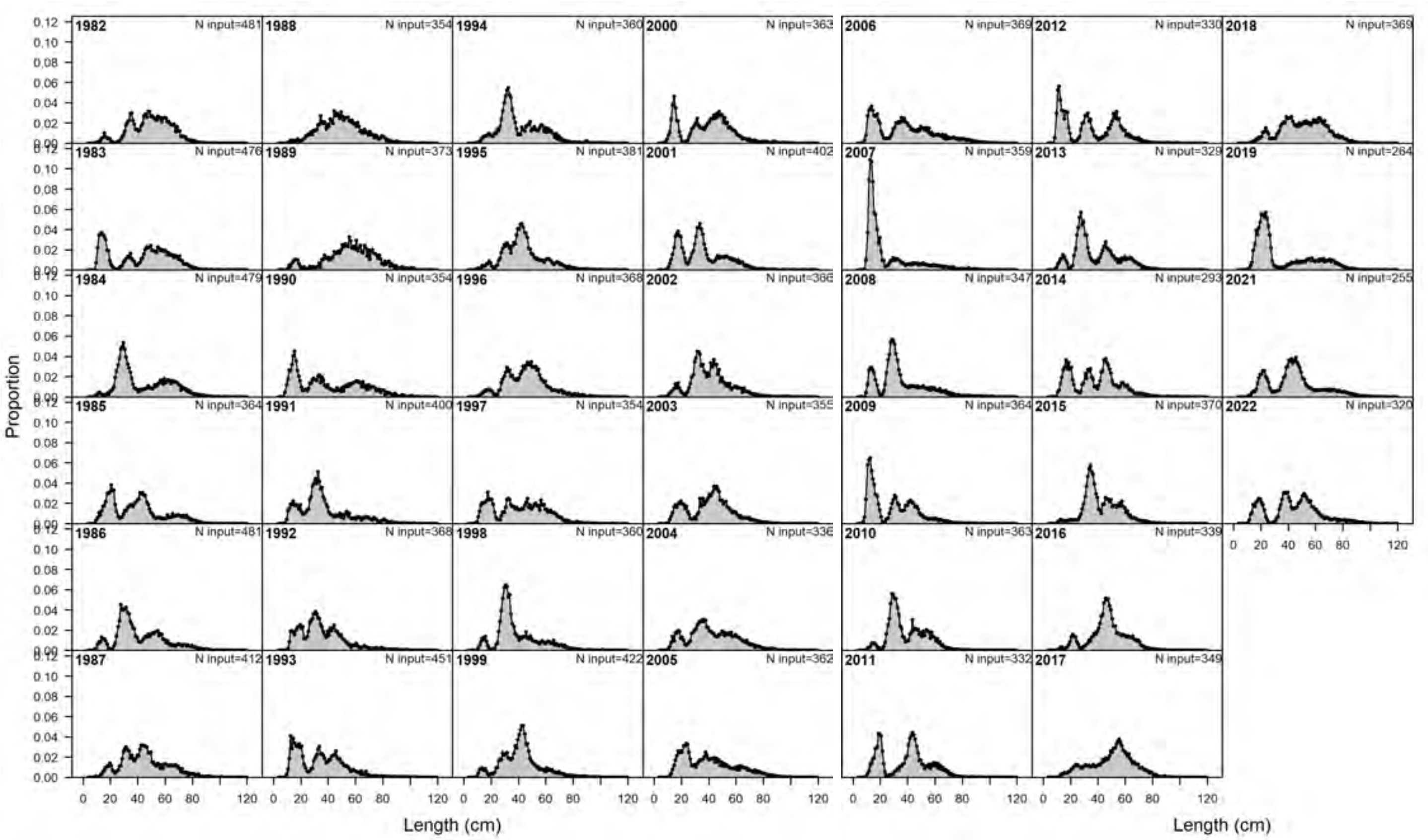


Figure 2.23. Bottom trawl survey length composition distributions by year.

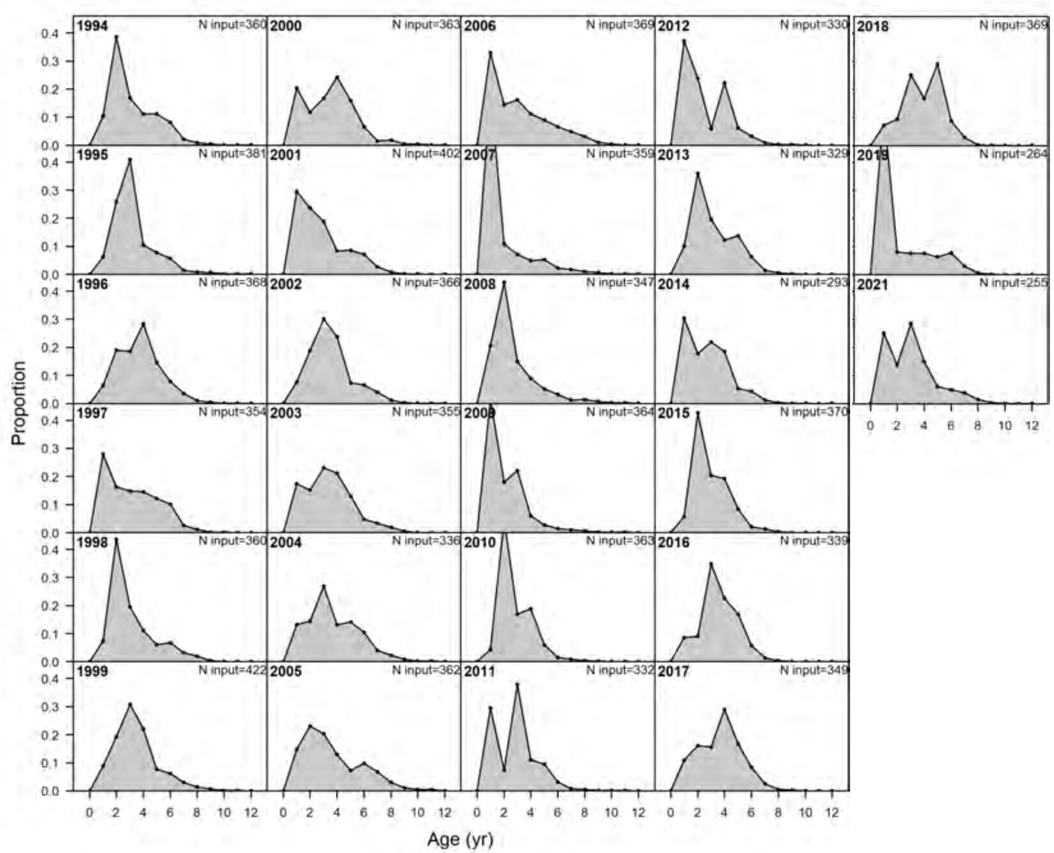
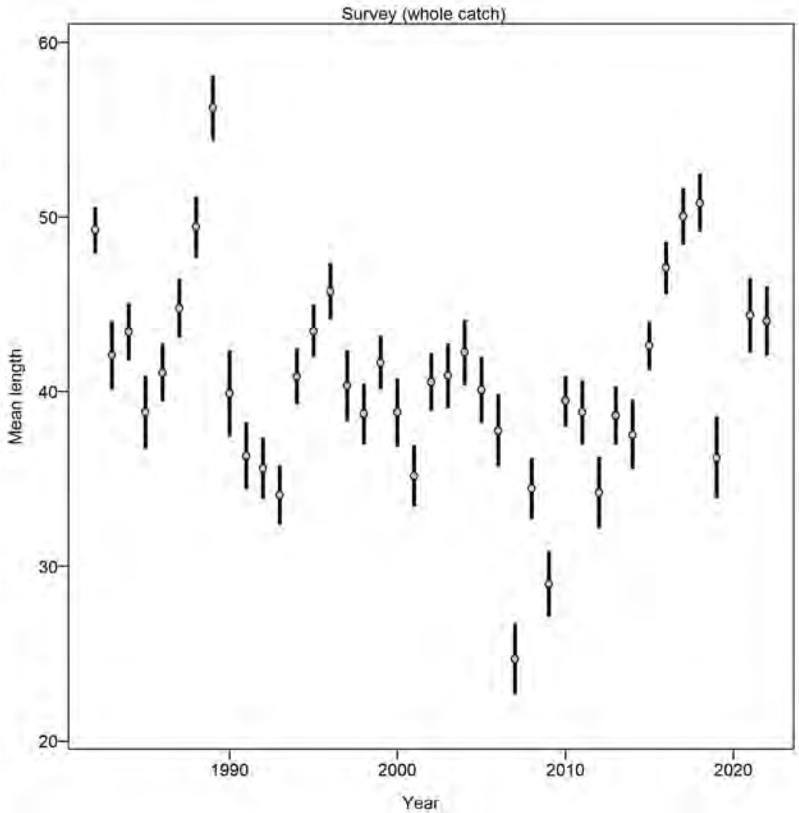


Figure 2.24. Bottom trawl survey age composition distributions by year.



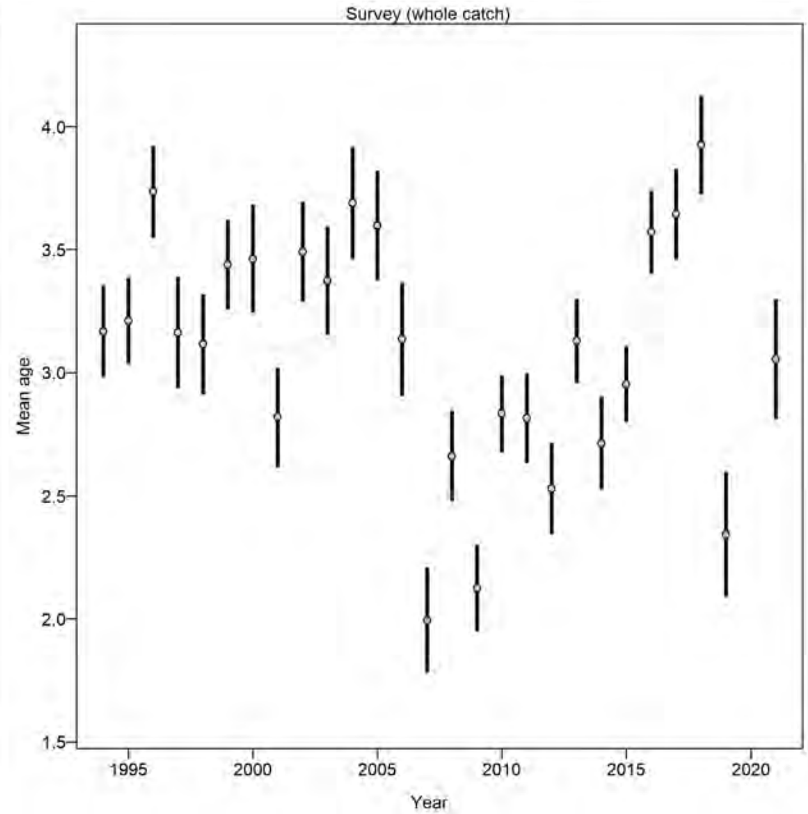


Figure 2.25. AFSC bottom trawl survey (left) mean length (cm) and (right) mean age by year.

Figure 2.26. Locations of AFSC longline survey stations in the EBS region.

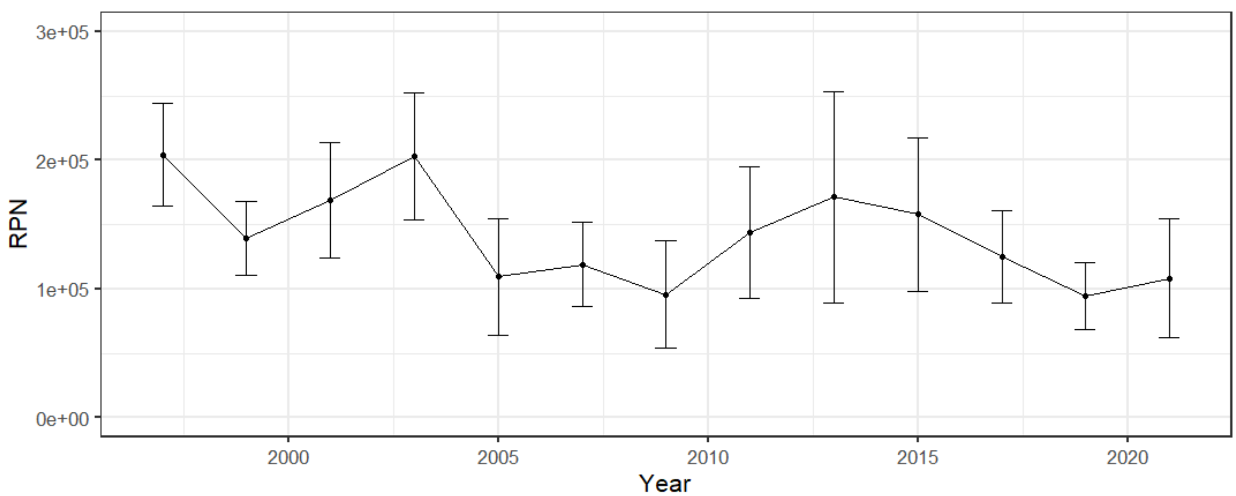


Figure 2.27. AFSC longline survey relative population numbers (RPN) for EBS region.

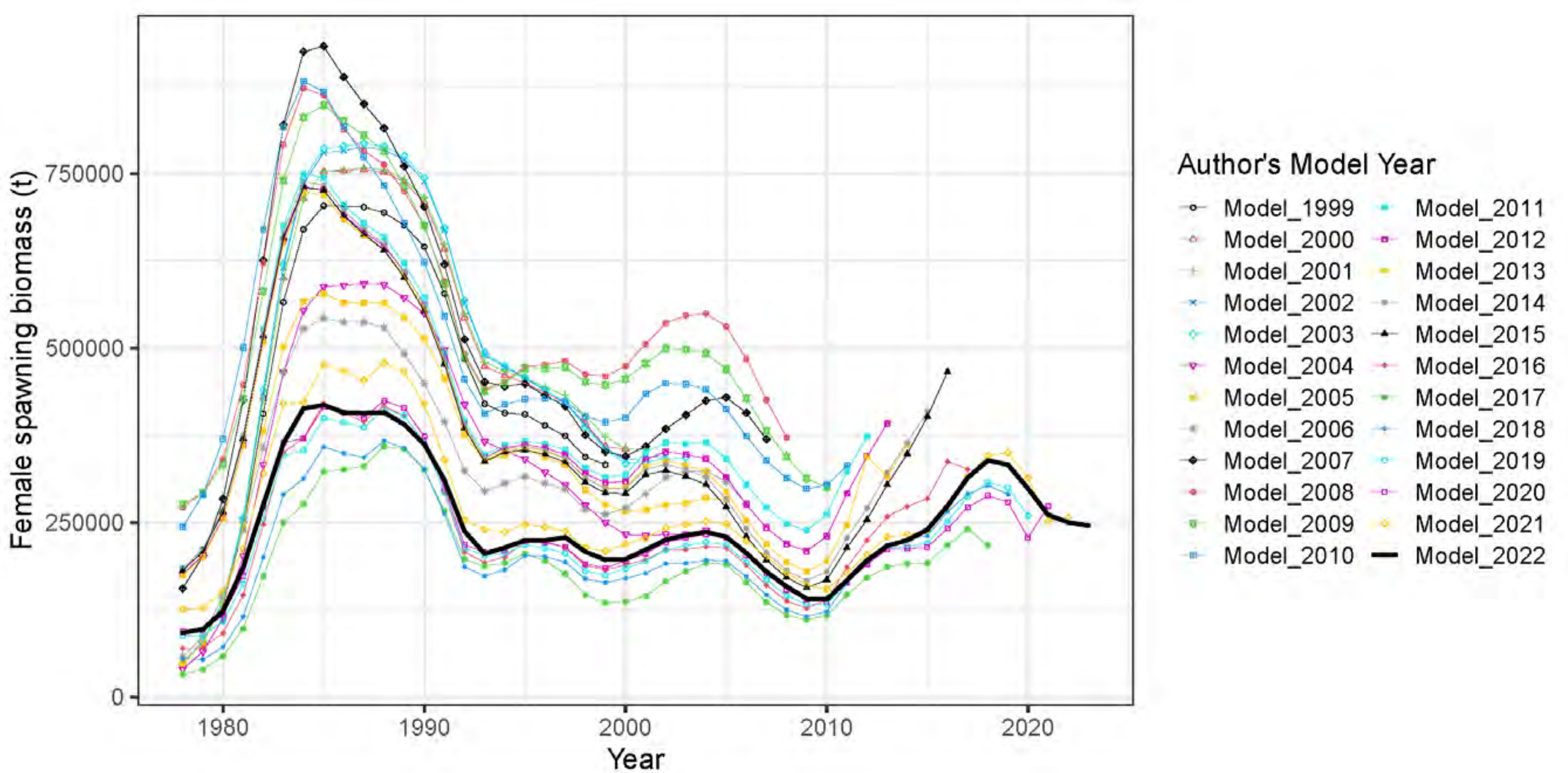


Figure 2.28. History of model estimated female spawning biomass from 1999-2021 accepted models and the 2022 New Series ensemble.

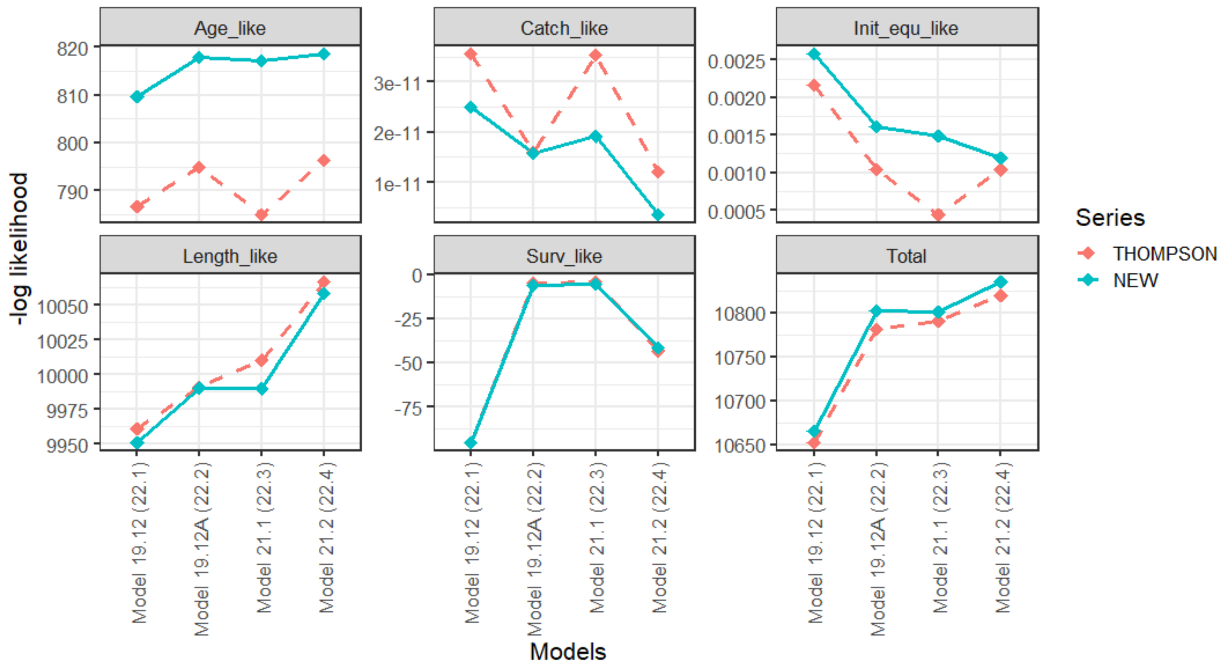


Figure 2.29. Objective function by likelihood component and total for all models comparing Thompson Series and New Series of models.

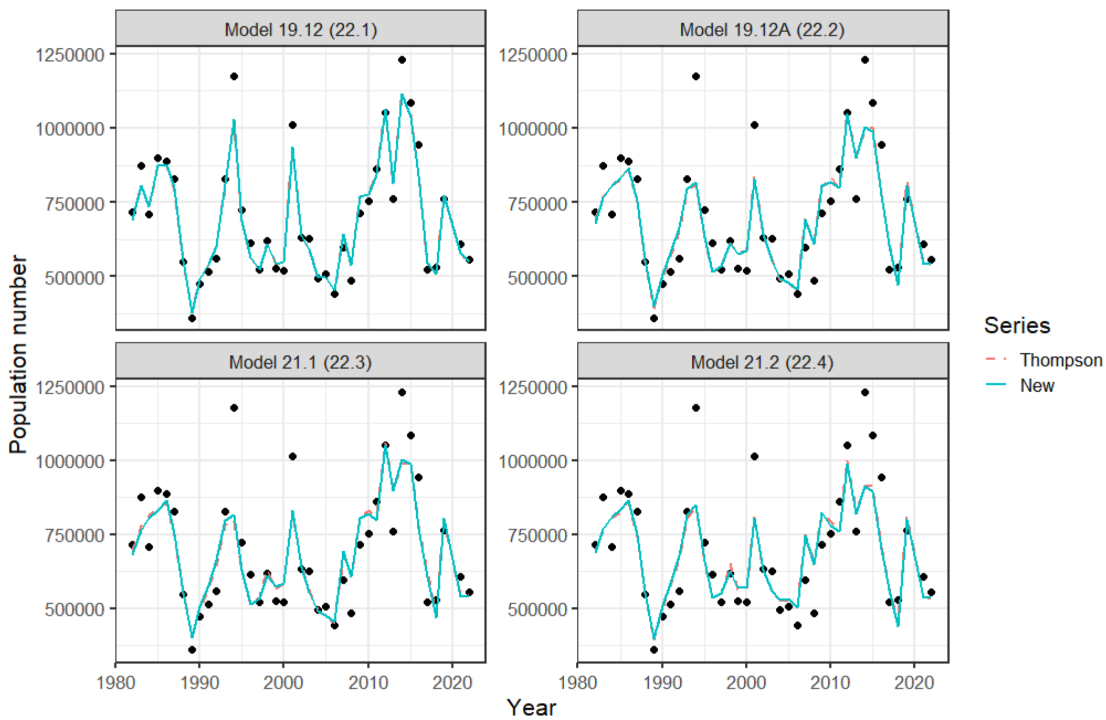


Figure 2.30. Fits to the bottom trawl survey data (population numbers for both the Thompson (red dotted) and New Series (blue solid) of models. Black dots are the observed values.

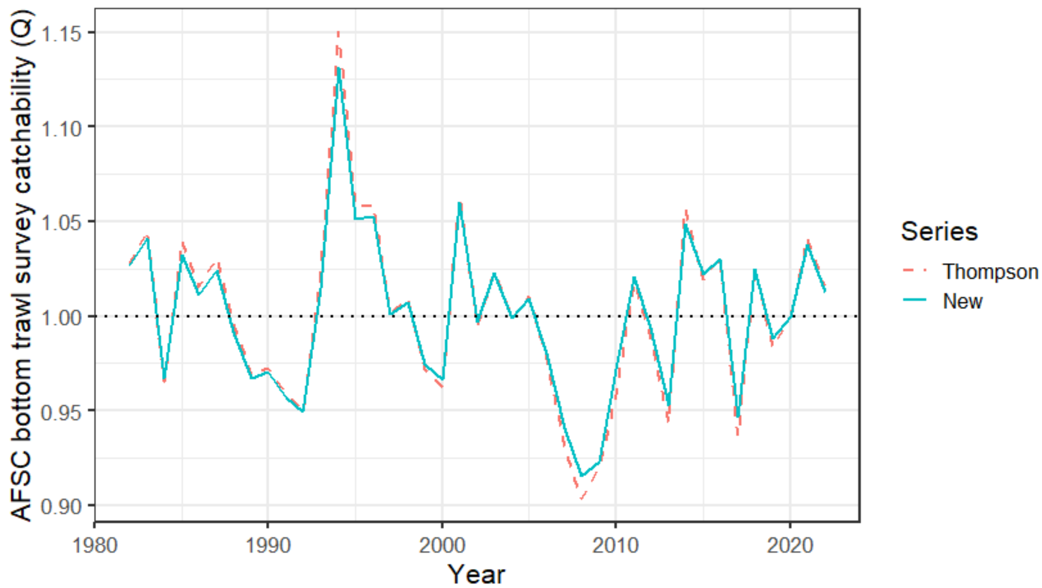


Figure 2.31. Bottom trawl survey catchability (Q) for both the Thompson (Model 19.12; red dotted) and New Series (Model 22.1; blue solid) of models.

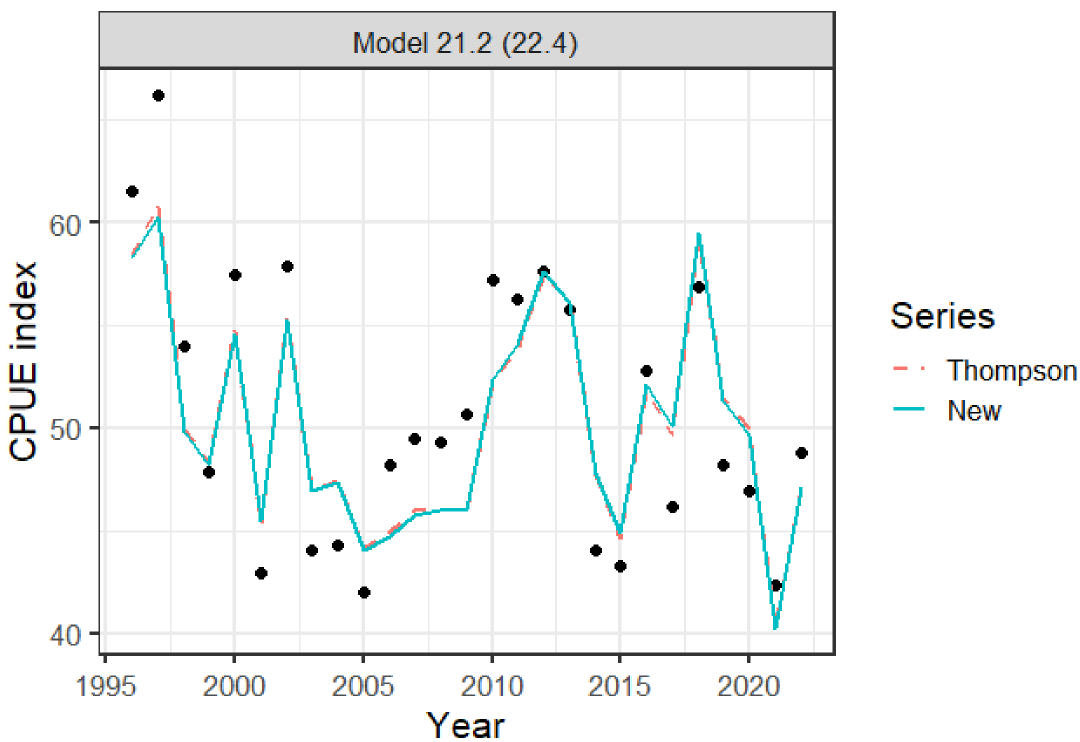


Figure 2.32. Fit to the winter longline fishery CPUE index data for both the Thompson (Model 21.2; red dotted) and New Series (Model 22.4; blue solid) of models. Black dots are the observed values.

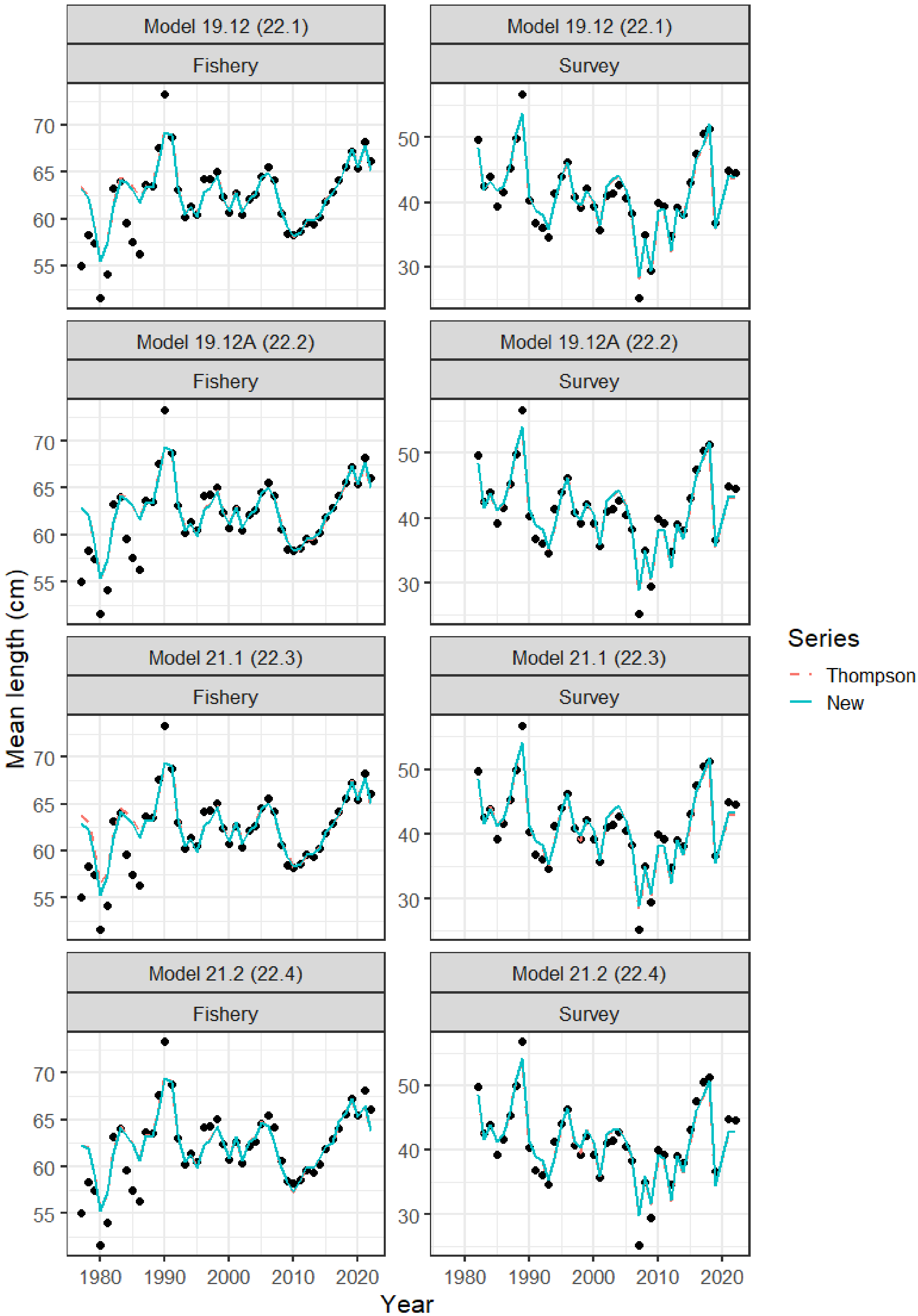


Figure 2.33. Mean length and fits to mean length by model for both the Thompson (red dotted) and New Series (blue solid) of models. Black dots are the observed values.

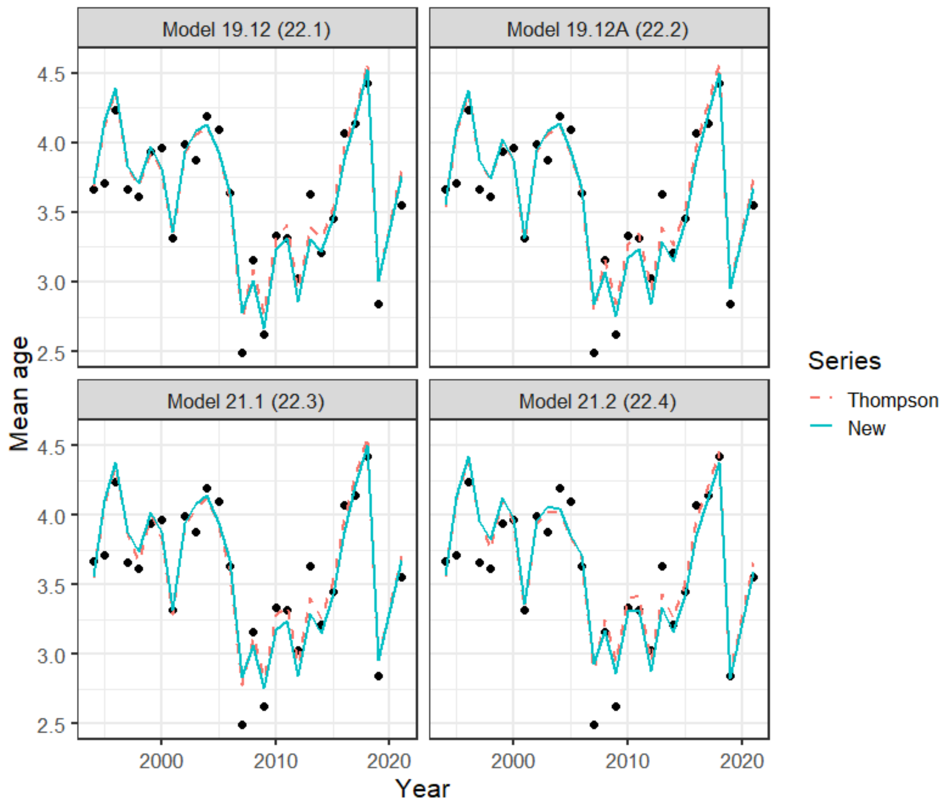


Figure 2.34. Mean age and fits to mean age by model for both the Thompson (red dotted) and New Series (blue solid) of models. Black dots are the observed values.

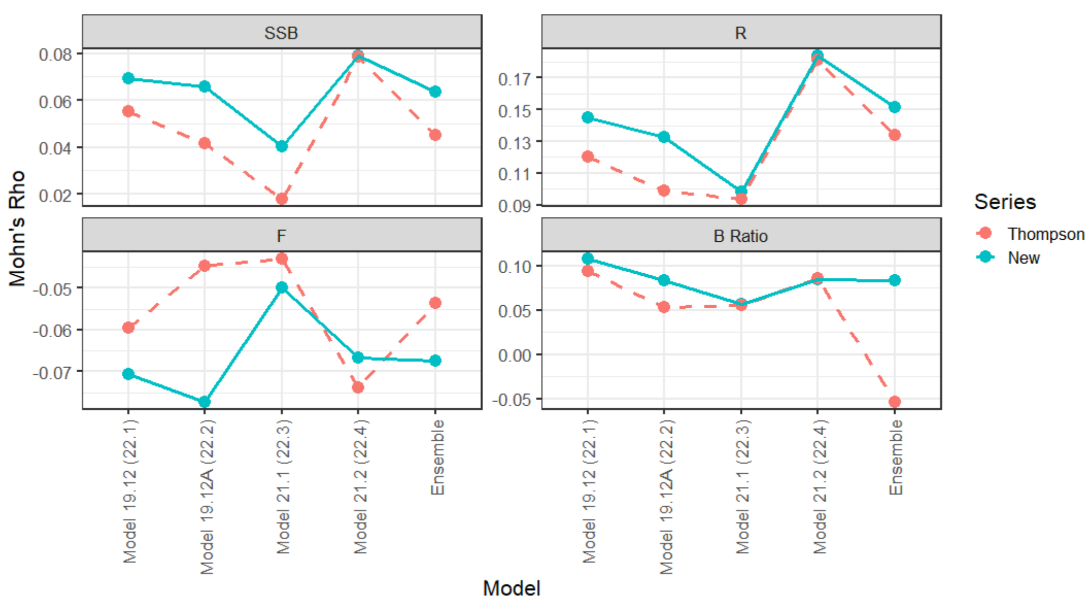


Figure 2.35. Mohn's Rho values for all models for spawning stock biomass (SSB), full selection fishing mortatlity (F), age-0 recruitment (R), and Spawning biomass to unfished biomass ratio (B Ratio) by ensemble series.

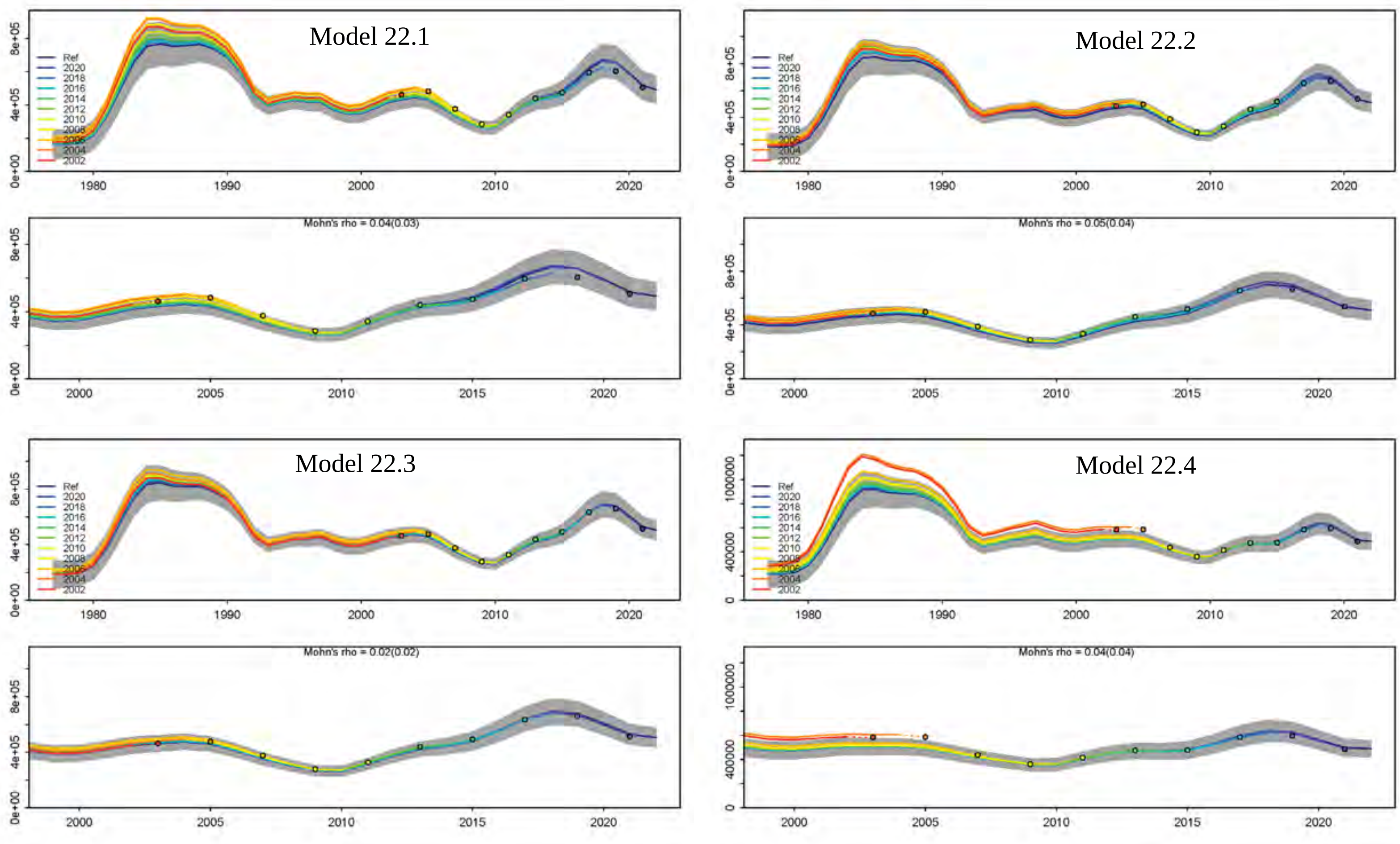


Figure 2.36. Retrospective plots of spawning stock biomass for the New Series of models. Upper figure in each quadrant is the full time series, bottom is the most recent 10 years and includes the Mohn's rho and in parenthesis the Predictive rho values for each model. Plots from the ss3diags R library (Winker et al. 2022) and described in Carvalho et al. (2021).

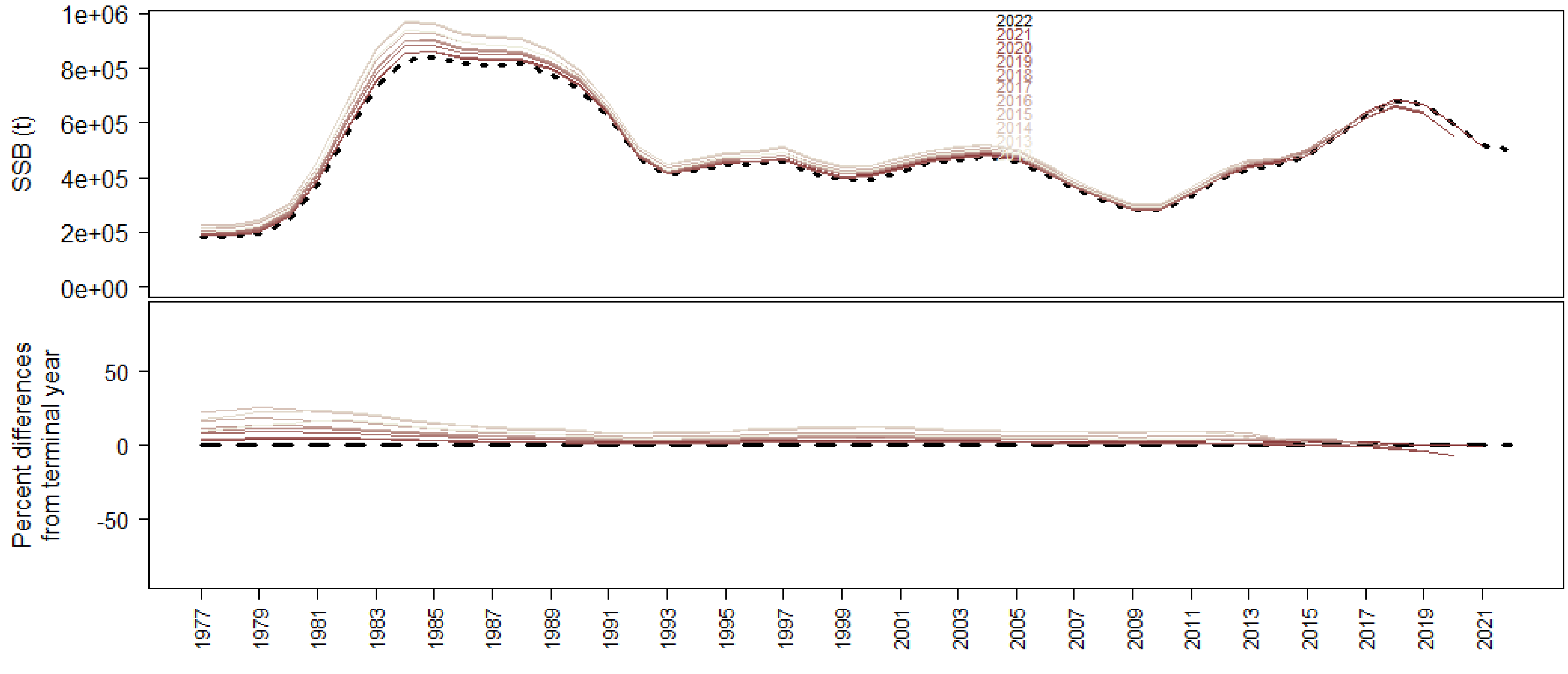


Figure 2.37. Retrospective analysis of the total spawning biomass (t) for the seven North Pacific projection scenarios from the ensemble of the New Series of models.

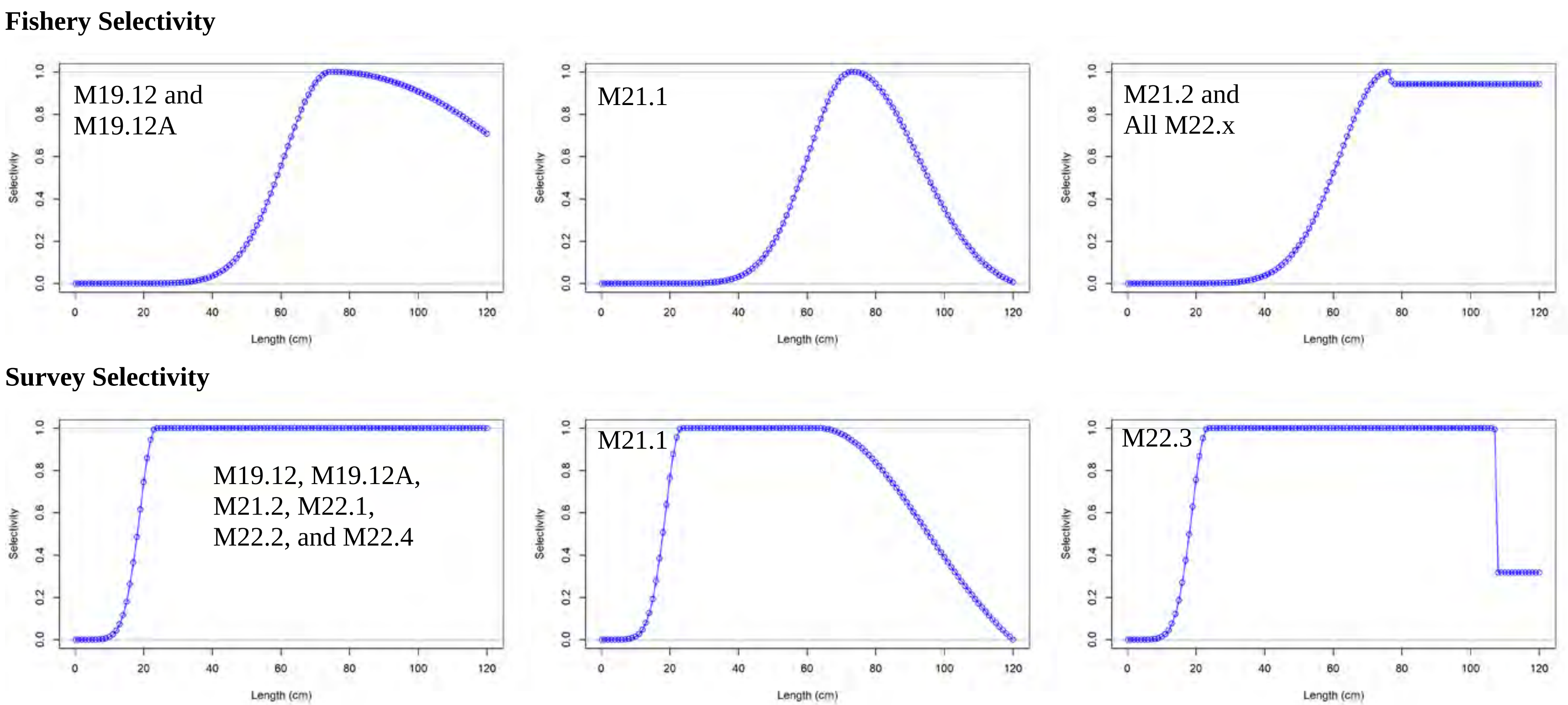


Figure 2.38. Basic shapes for fishery and survey selectivities for all models. Note that for all models the selectivities are time varying, however the basic shape remains the same over time. This figure demonstrates the basic shape fit for each.

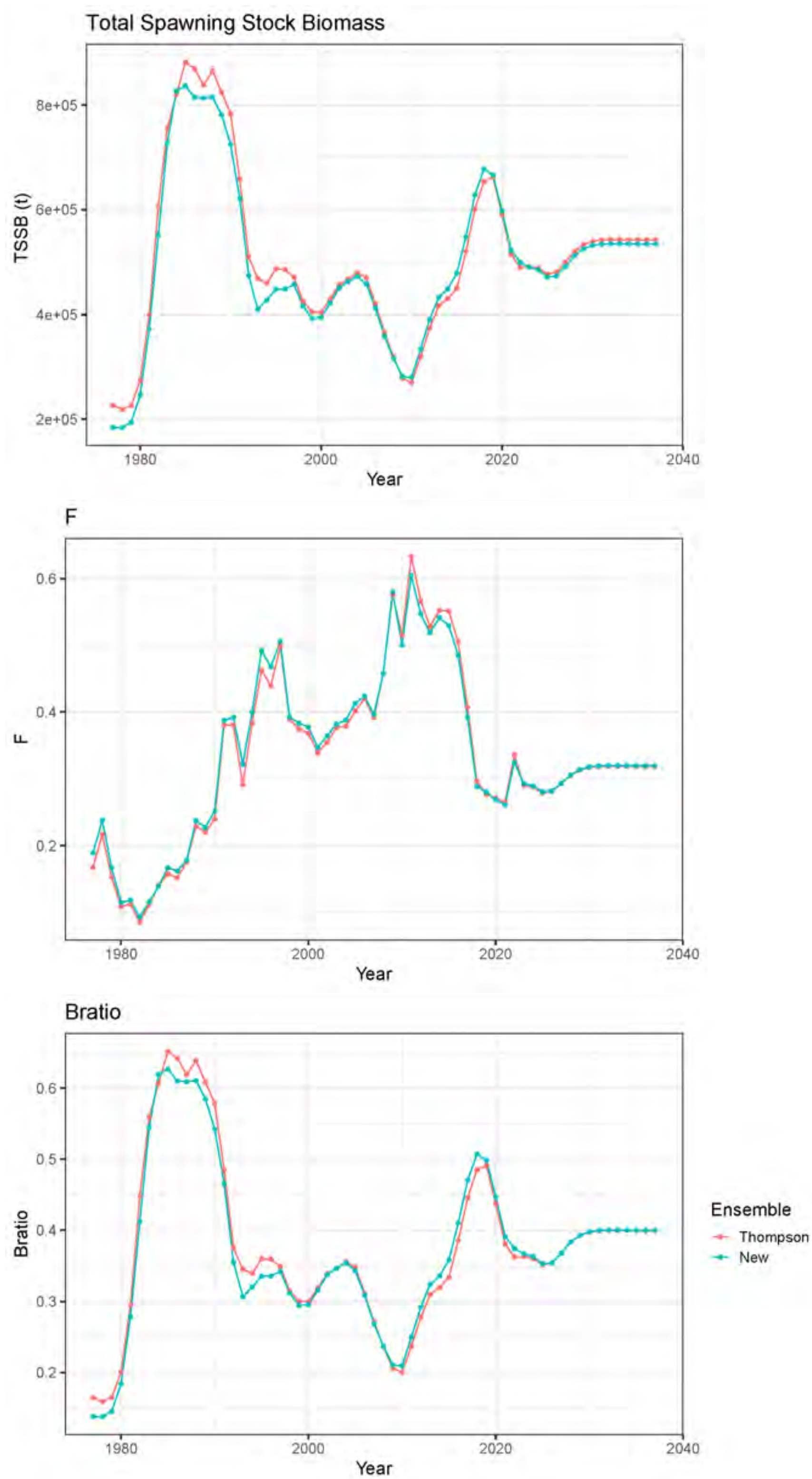


Figure 2.39. (Top) Total spawning biomass (t), (middle) F (sum of the apical fishing mortality), and (bottom) Bratio (spawning biomass/virgin biomass) for Thompson (red dotted) and New Series (blue solid) ensembles.

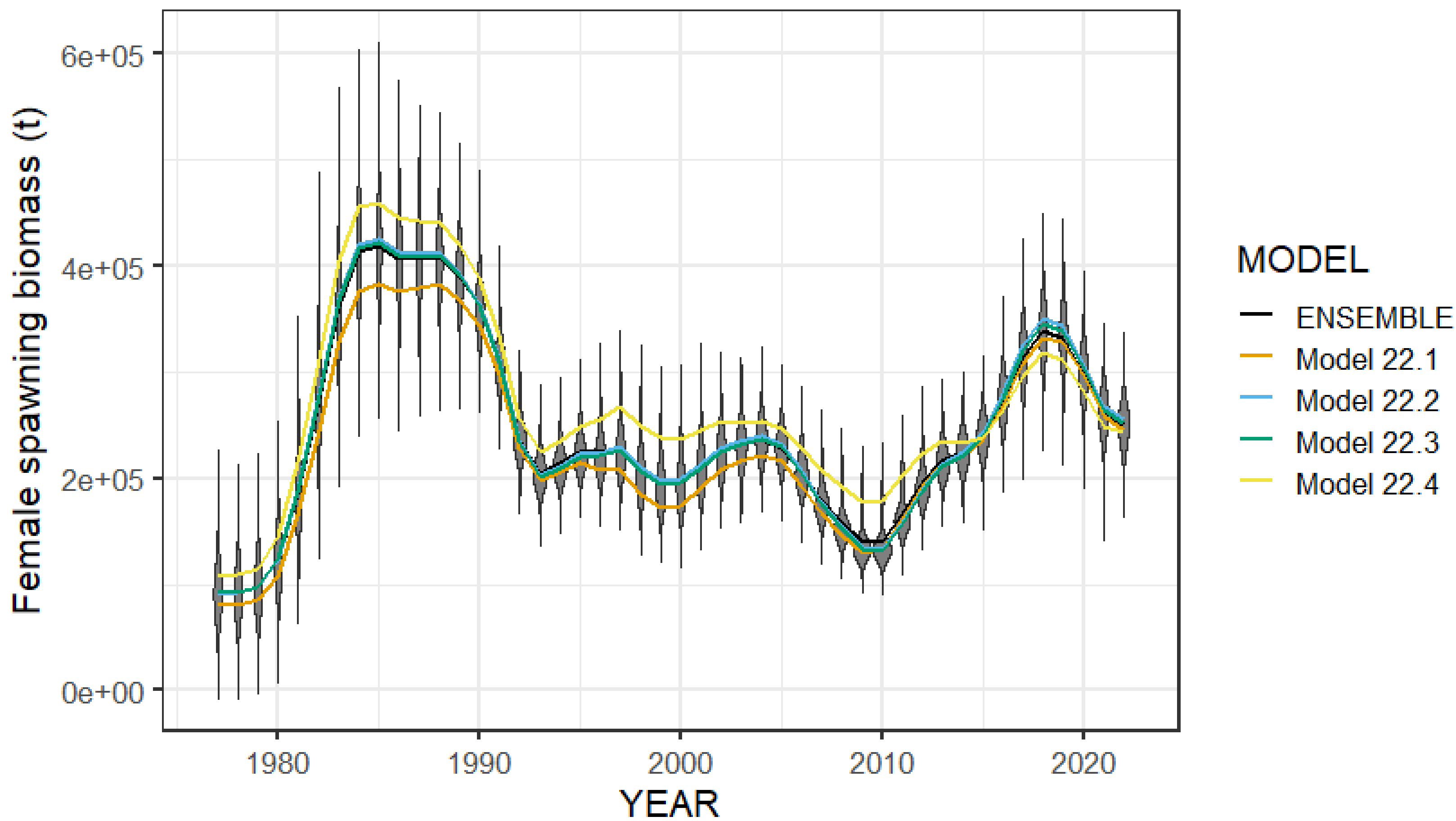


Figure 2.40. Female spawning biomass (t) for (lines) all models in the New Series and (violin plot) New Series ensemble distribution.

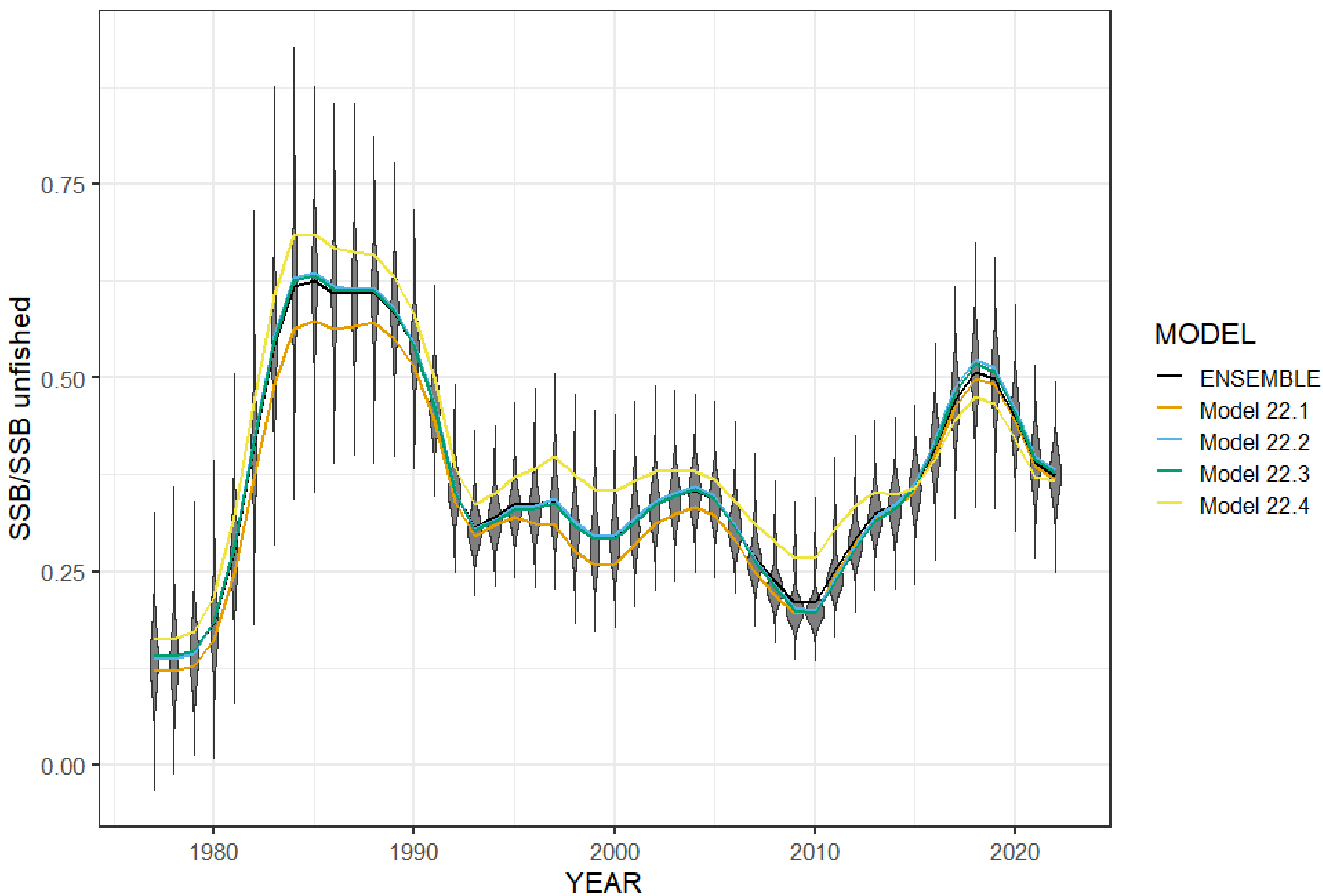


Figure 2.41. Ratio of spawning stock biomass to unfished spawning biomass for (lines) all models in the New Series and (violin plot) New Series ensemble distribution.

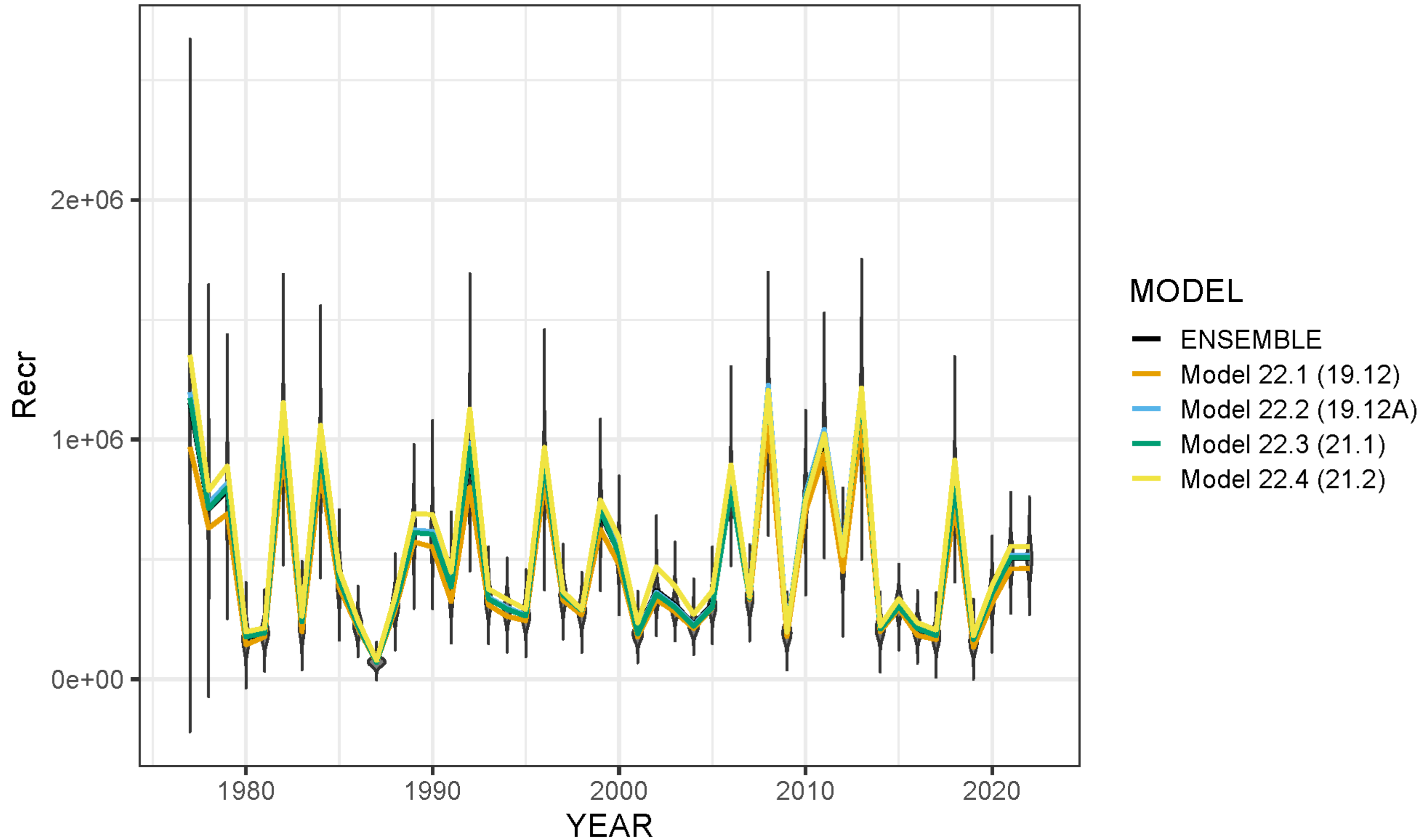


Figure 2.42. Recruitment (1,000s at age-0) for (lines) all models in the New Series and (violin plot) New Series ensemble distribution.

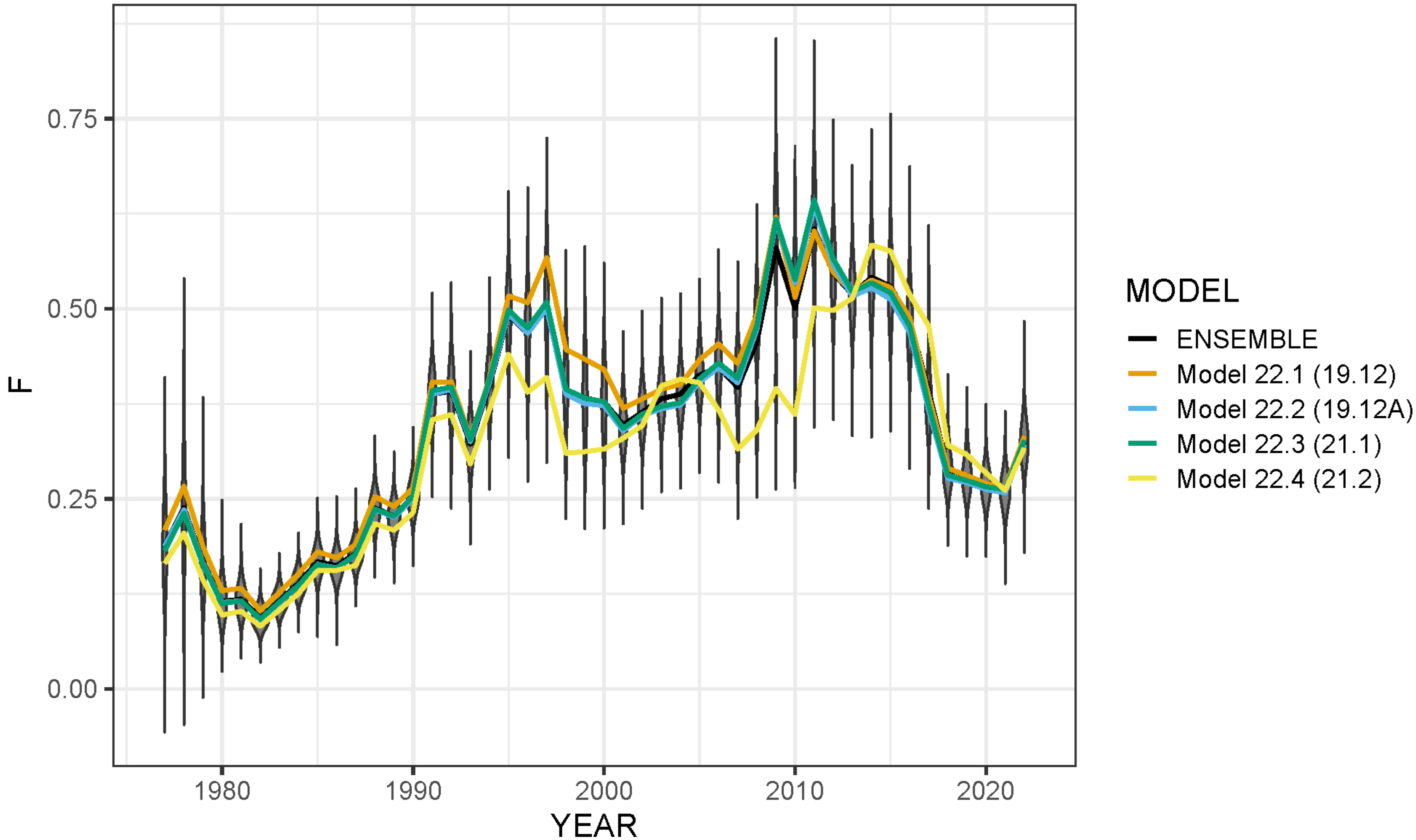


Figure 2.43. Instantaneous apical fishing mortality (F) for (lines) all models in the New Series and (violin plot) New Series ensemble distribution.

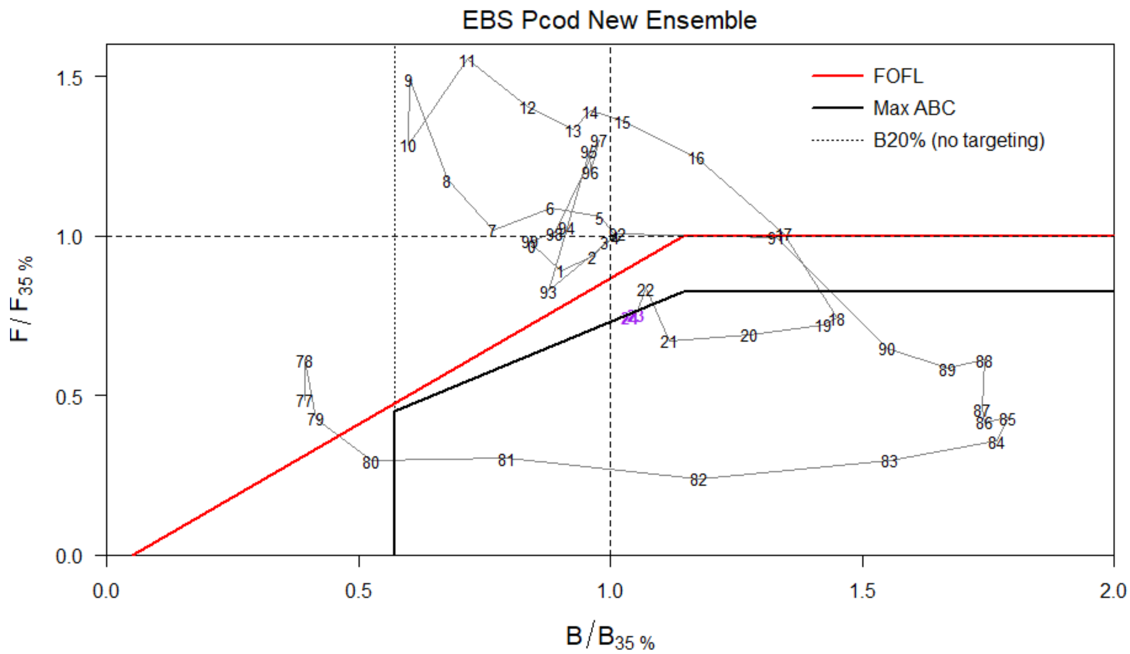


Figure 2.44. Phase plane plot for the New Series ensemble.

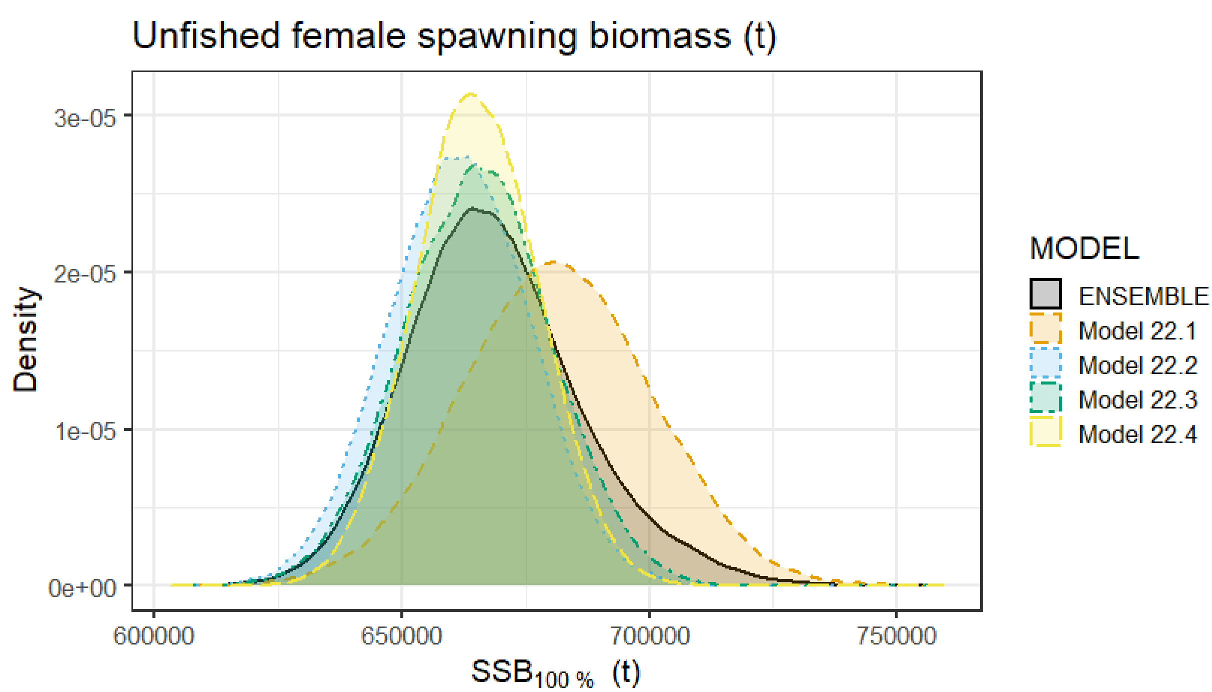


Figure 2.45. Distribution of female unfished spawning biomass ($SSB_{100\%}$) for New Series models and ensemble.

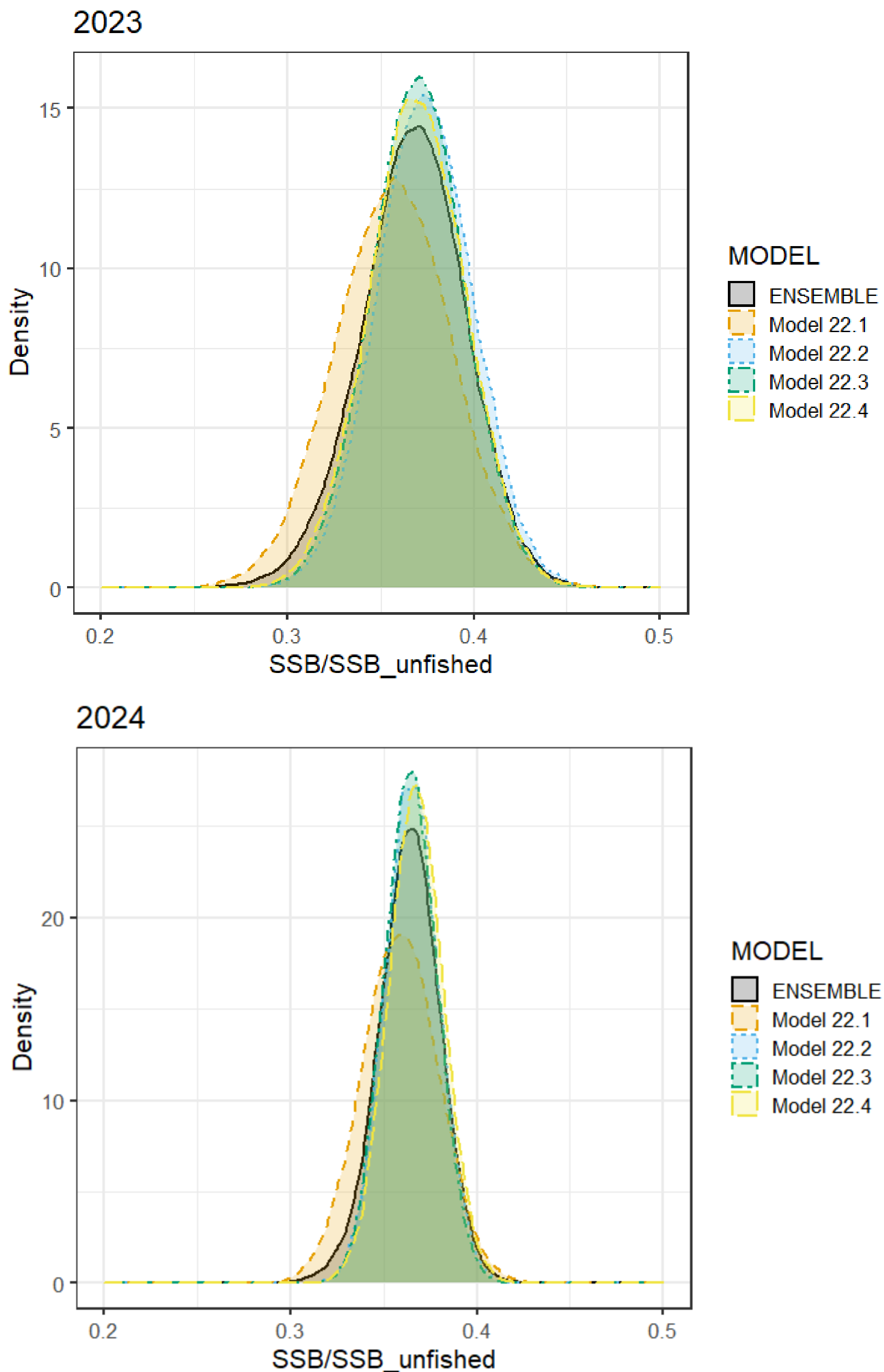


Figure 2.46. Ratio of spawning stock biomass to unfished spawning biomass for (top) 2023 and (bottom) 2024 for New Series models and ensemble distributions.

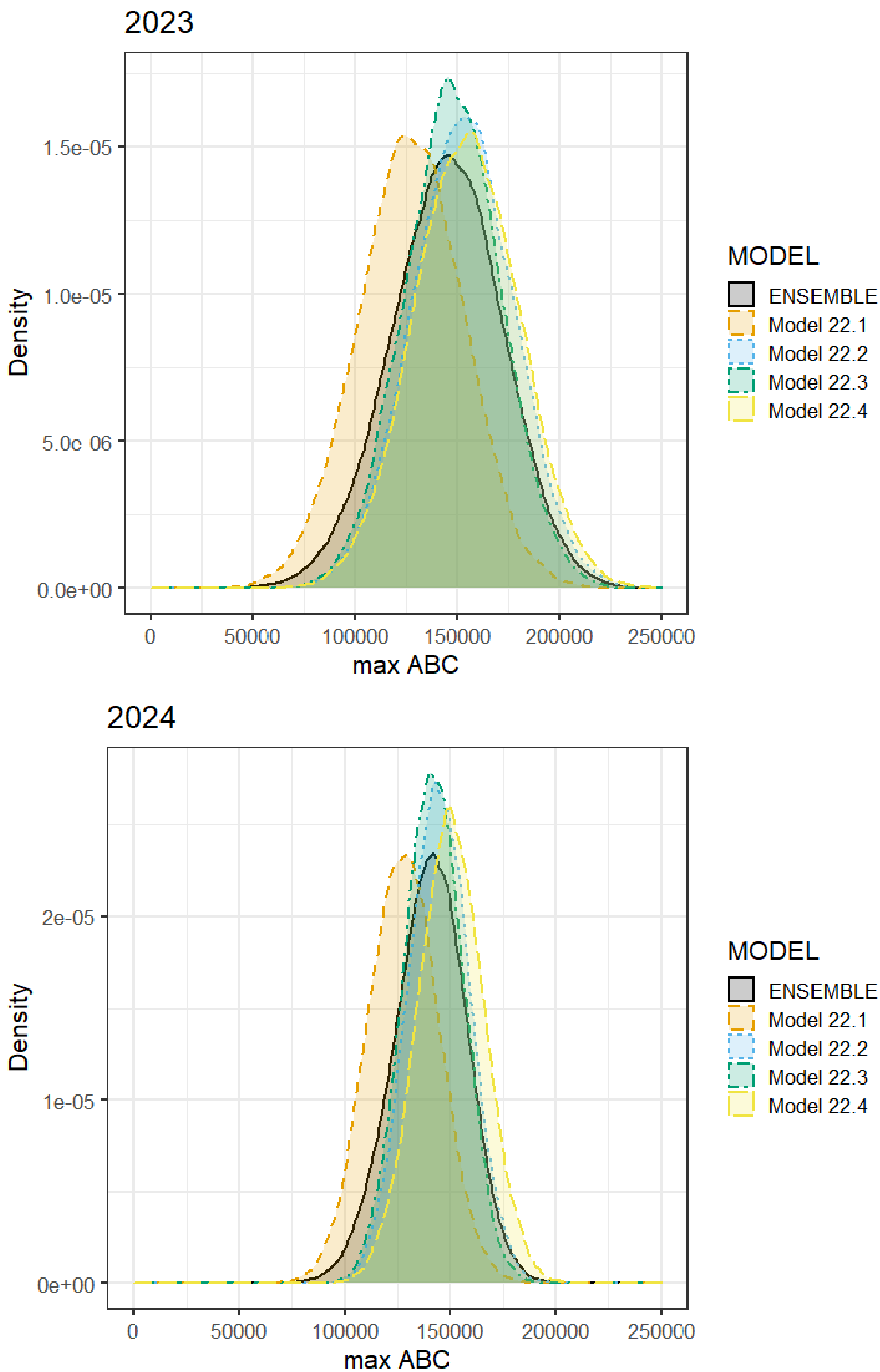


Figure 2.47. Forecasted maximum ABC for (top) 2023 and (bottom) 2024 for all New Series models and ensemble distributions.

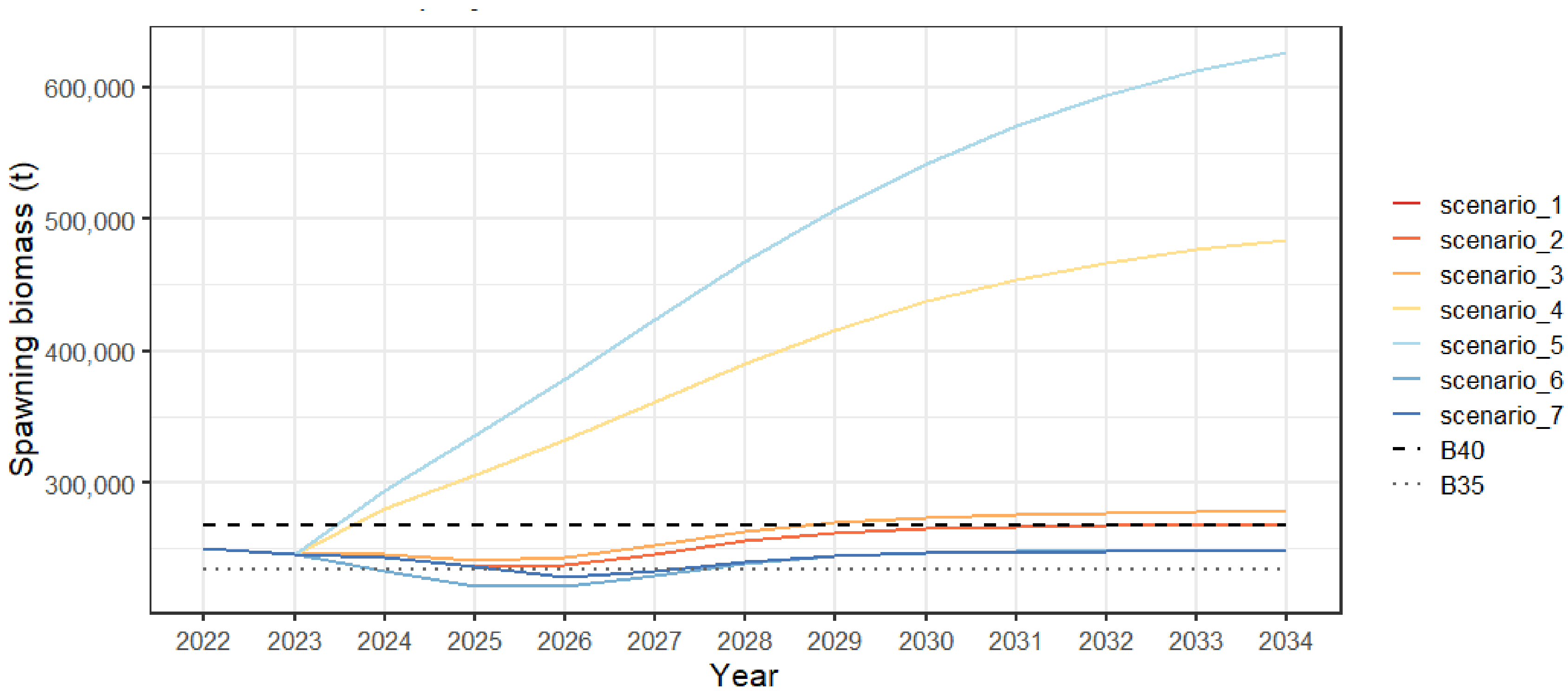


Figure 2.48. Female spawning biomass (t) for the seven North Pacific projection scenarios from the New Series ensemble.

Appendix 2.1 2022 Bering Sea Pacific Cod September Report

Steven Barbeaux

September 2022

Introduction

For 2022 the Eastern Bering Sea (EBS) Pacific cod stock assessment lead authorship has changed for the first time in ~35 years. Grant Thompson had lead authorship for this stock from the mid 1980's through 2021. The new author, Steve Barbeaux, worked with Grant on the assessment in 2020 and 2021 and worked with Grant through the latest CIE review in 2021. The SSC recommended the new author make minimal changes to the assessment in the 2022 transition year. For the most part the models presented here for 2022 match those accepted for the ensemble for 2021 (Thompson et al. 2021; Table 1), however there are some minor changes explored that were thought to potentially improve the assessment model, or were necessary given software constraints.

Explored changes to the ensemble models:

1) Developing a new script for the seasonally corrected annual weight at length relationship fit outside the model.
2) New algorithm used for constructing the fishery length composition data using a developed R script.
3) Removing the seasonally corrected annual weight at length relationship from the model (NOWL).
4) Alternative aging bias assuming bias in those otoliths aged prior to 2007 and no bias in those aged after 2007 instead of bias assumed in 1994-2007 and 2008+ blocks. (AGE)
5) Alternative input sample size used for the fishery length composition and additional tuning to ensure the Dirichlet multinomial log theta parameter is not fit at or near a bound. (WT)
6) Fitting an additional standard error term on the VAST bottom trawl survey index. (SE)

Data Changes

Seasonally corrected annual weight at length relationship

Since 2015 the EBS Pacific cod stock assessment has used a seasonally corrected annually varying weight at length (WL) relationship derived from a nonlinear regression model developed by (now retired) Grant Thompson in an older (now unsupported) version of Mathcad. As this could not be replicated, the new lead author has developed a generalized additive modeling approach that achieves a similar product.

We started with the same base linear formula across all data for all years 1977-2021

$$log(W) = log(\alpha_1) + \beta_1 log(L)$$

Where W = weight in kg, L is length in cm. A generalized additive model was then fit to take into account annual and week effects:

$$log(W) = Y * log(L) + s(t): \log(L) + s(t)$$

Where *Y* is the factor year and *t* is week of the year. The *s* are cyclic cubic regression splines with basis dimension of K=7 for log length by week and then week (Fig. 1). The basis dimension of 7 was chosen as it best replicated the original model developed by Grant Thompson.

The GAM was then used to predict weight across all years for all 52 weeks and for size bins from 10 to 120 cm at 10 cm increments with the standard bias correction of

$$W = e^{log(\widehat{W})+\sigma^2/2}$$

Where σ is the error term from the GAM.

A linear regression was fit across all predictions for all weeks combined for each year.

$$log(\dot{W}_Y) = log(\alpha_{2Y}) + B_{2Y}log(\dot{L_Y})$$

and the annual deviation in α and β used as annual indices on weight at length (Fig. 2) were calculated as alpha dev = exp(α_1) – exp(α_{2Y}) and Beta dev = exp(β_1)- exp(β_{2Y}). The results show up as annual variability in weight at length in the model (Fig. 3).

Annual length distribution data

The annual fishery length distribution data have been processed differently resulting in a new distribution used in the models (Fig. 4). The change was necessary as the previous author had manually processed the data in Excel, replicating this effort would not be possible, but more tedious than necessary. In developing the script to process the data, the author generalized the code to match that used in the Gulf of Alaska Pacific cod assessment. In prior assessments, for 1977-1990 the raw length measurements were used as the length distributions and for 1991-present fishery length compositions were weighted by catch weight by NMFS area (area), month, and gear and processed in EXCEL. Only areas with registered catch and greater than 30 lengths measured were used in the length composition data. For the current assessment and for all years the annual fishery length distributions were weighted by catch number per haul, vessel, area, month, and gear and processed through a function developed as an R script. For the 2022 models the total number of fish caught were calculated using average weights by area, gear, month, and year strata from the observer data where there were more than 30 fish weighed for each strata. Where there were fewer than 30 fish within a stratum the aggregation level was expanded by the following stratification levels until 30 or more weighed fish were encountered: 1) year, gear, month, 2) year, gear, quarter, 3) year, area, month, and 4) gear and year. An analysis of average weights revealed gear and time of year had a greater impact on average weights than area of capture. Length measurements from year, area, gear, month strata with less than 30 measurements were not included in the distributions. These measurements made up less than 1% of the total length measurements collected.

The overall difference in the distributions when using the new method was small with a slight shift to smaller fish overall (Fig.4) with the greatest impact in the 1977-1989 composition data.

There was a minor change in the survey length distribution produced by RACE for 2021 from those shown in the previous assessment with fewer small fish (< 30 cm) from the distribution, but otherwise remained largely the same (Fig. 5).

Change in assessment results due to data changes

We ran Model 19.12A with both the old and new data sets to examine changes in model results due to changes in the data. In general, the fits remain approximately the same (Table 2), however there was a small increase in estimated recruitment and spawning biomass post-1990 (Fig.6). Natural mortality changed from 0.361 to 0.369, survey catchability changed from 0.92 to 0.87, unfished spawning biomass from 1.30 to 1.31 million tons, the 2022 projected spawning biomass went from 518 kt to 528 kt and $F_{40\%}$ from 0.44 to 0.42 with the 2022 max ABC changing from 175 kt to 179 kt (Table 2 and Fig. 6). The largest change in Age-0 recruitment in 2020 and 2021 was due to a change in the 2021 survey and 2020 and 2021 fishery size composition data.

In review of the 2021 models, we discovered that the addition of the WL relationship resulted in nearly the same or even poorer fit to the length and age composition data (Table 2) in both the new and old configuration. Comparing the 2021 model using the 2021 data with and without the WL relationship shows that not using WL relationship improves the fit (-0.7 log likelihood). In addition, the redevelopment of the WL relationship described above similarly did not improve the model fit (Table 1). The removal of the WL relationship results in an improved retrospective pattern with a Mohn’s Rho value closer to 0 across all four models (Table 3). For Model 19.12A for both old and new composition data the removal of the WL relationship results in lower M, a higher survey Q, lower recruitment on average, and lower spawning biomass over the time series (Fig. 7). This results in a lower $F_{40\%}$ and lower recommended ABC for 2022 (Table 2). Model results for all models with and without the WL relationship are provided in Table 4 and Table 5. Only Model 21.2 showed a small improvement (-1.3 LL) with the inclusion of the WL relationship.

Because of the lack of improvement to fit by including it and difficulty in projecting this relationship, I recommend that the seasonally corrected annual weight at length relationship used in the base model be discarded for 2022 and that we explore other options for modeling seasonality and annual changes in growth in 2023.

Model Changes

Alternate aging bias

The 2021 base models fit two periods for aging bias 1994-2007 and 2008-present. The models fit a positive bias (aged older than reality) in the 1994-2007 survey ages and some negative bias (aged younger than reality) in the 2008-present ages (Table 5 and Fig.8). Through isotope analysis Kastelle et al. (2016) validated that the previous aging method was positively biased. This bias is believed to have been corrected in the most recent, 2008-present, aging. The opinion of the Age and Growth Laboratory is that that current methods should no longer be biased (D. Anderl, personal communication). To be in alignment with this opinion we propose fitting models with no assumed bias for 2008-present and only fit aging bias for 1994-2007 data.

Removing the two parameters used to fit the 2008-present aging bias results in an overall degradation in model fit (Table 5). There was a small increase in negative log likelihood in all components, but as would be expected, the largest difference was in the fit to the survey age composition data. Although there is a reduction in model goodness of fit, given the advice of the age and growth laboratory, the authors think the reduced model is a better representation of the actual bias in the age data. If aging in the most recent time period is unbiased, the change in fit may be due to changes in growth in recent years and should be more explicitly explored in future models. Explorations of impacts on fit to the survey and CPUE data can be found in Table 5 and Table 6. Graphs of changes in fits and differences in parameters over the models explored can be found in Figure 9 and Figure 10. Changes in fits to the survey are provided in Figure 11 and for Model 21.2 to the winter longline CPUE index in Figure 12. Figures 13 through 17 show change in spawning stock biomass and recruitment at age-0 for all of the models and proposed changes. The overall impact of changing the aging bias assumptions on model results varied among models, but in all cases was relatively minor.

In regards to advice from the Age and Growth Laboratory and despite the degradation in model fit I recommend that fitting aging bias for the most recent time period be removed for the 2022 models and that I explore more options for capturing variability in growth in 2023.

Alternate input sample size for fishery and survey length composition
The length composition input sample sizes used the 2021 Pacific cod models were calculated from the number of hauls. For the survey age and length composition the raw number of hauls conducted during the annual survey were used as the input sample size. For the fishery length composition, the input sample sizes were scaled from the number of hauls sampled such that average input sample size for the fishery length composition data equaled the average number of hauls in the bottom trawl survey time series. This reduced the input sample size from 5,625 hauls per year on average to 358. The method of scaling the fishery input sample size to the number of survey hauls was a holdover from the multinomial approach. The 2021 model employed the Dirichlet multinomial and for the length composition data, both survey and fishery, the log theta parameter was fixed at the high bound, as fitting the log theta resulted in high values greater and hampered model conversion (Table 8). A model with high log theta values near the bound may indicate that the input sample sizes are too low or the variance of the other data components such as the indices are too low. In effect the value of using the Dirichlet multinomial as parameterized in Stock Synthesis is that the theta parameter rescales the weighting of the composition data where input sample sizes are too high, however it does not rescale composition data where input samples sizes are too low. Note that the input sample size used in the model is in effect weighting the data within the model in relation to other data and model assumptions. Inappropriately low input sample sizes can down-weight the data in the model.

There are a number of methods currently employed at the AFSC for determining input sample sizes for composition data using multinomial and Dirichlet multinomial distributions. Raw haul numbers are commonly used, as are fixed 'rule of thumb' values, an effective sample size is calculated when VAST is used to estimate age composition data which has been suggested for use (Thorson; personal communication). In addition, a bootstrap approach for calculating effective sample size for the survey size and age composition data has been developed and could be used as input sample size (Hulson et al 2012). A similar bootstrap approach is in development for the fishery size and age composition data.

For 2022 I examined: 1) changing the fishery length composition sample size to the raw number of hauls per year, 2) continue to use the raw number of survey hauls for the age composition data, and 3) scale the survey length composition such that the log theta parameter of the Dirichlet multinomial is not near a bound using an input variance adjustment factor in the Stock Synthesis control file. For the survey length composition this resulted in input sample sizes being increase by a multiple of 5. The Dirichlet multinomial sample size multiplier fit for each model and version are provided in Table 8 and resulting average corrected input sample size for each data type are provided in Table 9. Note that while the theta 'corrected' new sample sizes for the length composition data are increased substantially, the theta 'corrected' input sample size for the age composition data drops. The new method for calculating sample sizes results in a substantially higher weight for the length composition data in the objective function going from a ~9,600 LL to ~22,000 LL in all models.

When the length composition input sample sizes were increased the fits to both the survey and age composition data are degraded in all models (Table 5). A reduction in fit to the survey although not wholly unexpected is troubling as it was greater than anticipated and should be further explored when the VAST bottom trawl survey index is updated for this year.

The change in weighting of the length composition data also resulted in an increase in the sigma values for the annually varying selectivity parameters (Table 7). Having increased value of the objective function specifically attributable to the size composition places more emphasis on fitting the length composition data better, the models do so by having the selectivity curves vary more from year to year through increasing these sigmas. With the change in input sample size and increased variability allowed in selectivity, the retrospective pattern across three of the four models is degraded with a substantial increase in the spawning stock biomass Mohn's Rho values (Table 3).

Parameter estimates also vary more among the models than they had previously. In fitting catchability, the models had ranged between 0.87 and 1.04 for all previous models and versions (Table 6). For the new input sample size method survey catchability fit among the four models ranged between 0.69 and 1.14. Similarly, the range of natural mortality was increased from between 0.33-0.38 in all previous models and versions to 0.31-0.4 in the models with the new input samples sizes. These differences result in larger differences in key model results including reference points and current status among the four ensemble models (Table 7, and Fig. 9 - Fig 17).

The 2021 model's method of down-weighting the fishery survey sample size to the average number of hauls in the survey has been consistently used in this model for several years, however it is unique to this stock and has little support in the literature. In theory, the parameterization of the Dirichlet multinomial in Stock Synthesis has the ability, through the fitting of the Theta parameter to reduce the input sample size to one consistent with other data in the model and therefore reduction in the initial input sample size would not be required. This is of course assuming that the number of hauls is an adequate proxy for input sample sizes. This method of setting input sample size is commonly used , however it too has mixed quantitative support for use and shown could be an overestimate of sample size in some cases (Pennington and Vølstad 1994).

I recommend that the new weighting of the length composition data be considered for 2022, however acceptance of the new weighting be examined more thoroughly once the new 2022 survey and fishery data are added to the model with further examination of model stability and sensitivity to this change. **In addition, I recommend alternative means for calculating the length and age composition input sample sizes should be explored in 2023 including bootstrap and VAST derived effective sample sizes.**

Fitting additional variance on the VAST survey index

The variance of the VAST survey index is small compared to the previous design based estimates with the design based average survey CV at 0.10 and average VAST based CV at 0.05 (Fig. 18). In addition the VAST estimates have changed as new years have been added to the index. This type of variability is not captured in the variance estimates provided. As is, the low variance estimates for the VAST survey results in the survey index having substantially more influence on results in the current model than the design based survey had in previous models. Fitting an additional variance parameter for survey estimates to account for unknown sources of variability is a common practice (Johnson et al. 2021) and implemented in the latest version of stock synthesis.

The addition of a standard error parameter in all models results in the uncertainty (log SE) of the bottom trawl survey being increased by between 0.15 to 0.19 (Table 6). Although the likelihood for these models is substantially reduced as a function of increased variance around the surveys, the apparent (visually assessed) fit to the survey and CPUE index is substantially worse. Across all ensemble models fitting a higher variance for the survey caters to an improved overall fit to the length composition data as the weighting among model components shifts. With the additional flexibility in the models with the increase in variance for both indices, The retrospective analysis shows a substantial increase in absolute bias in all four ensemble models (Table 3) with the Mohn's Rho across models going from a range of -0.01 to -0.05 to a range of -0.08 to -0.38. Figure 19 includes a graph of the retrospective pattern for Model 19.12A 2021 version spawning stock biomass and Figure 20 includes a graph of the same for Model 19.12A version with the increased index standard errors.

I recommend that fitting additional standard error to the indices not be adopted for this year's set of ensemble models. Additional exploration of proper variance attribution of VAST indices within the assessment model should continue to be explored in 2023.

Additional observations on current ensemble
There is a set of new tools useful for examining stock synthesis model performance described by Carvalho et al. (2021) and provided in the R library ss3diags. All of the ensemble models and versions were analyzed using these tools.

Joint-index residual plots were produced for each data type for all models and versions using the SSplotJABBAres function from the ss3diags R library. This function also produced joint RMSE values for each data type (Table 10). The change in input sample sizes, retuning of the models, and the fitting of additional standard error on the abundance indices resulted in substantial inflation of the RMSE of the abundance indices.

Residual runs tests were performed to examine the distribution of the residuals and whether the residuals were randomly distributed (Table 11). Every model and version, except Model 19.12A Version with no WL (NOWL), 1977-2007 aging bias only (+AGE), new input sample size (+WT), and fitted with additional standard error for the indices (+SE)(Fig. 20), failed in at least one data component. All of the models passed for the mean age residuals, but there were mixed results for all of the other data components. All of the versions with the 2021 length composition input sample sizes failed the runs test for the fishery mean length residuals. Except for all versions of Model 19.12 with annually varying survey catchability and Model 19.12A version NOWL+AGE+WT+SE, the remaining models and versions failed the survey mean length residual runs tests. By version the NOWL+AGE+WT+SE performed the best with 4 failures total across all models and data components, NOWL+AGE+WT next with only 5 failures, the remaining versions had 8 failures each, but in different Models and data components.

The Mean absolute scaled error (MASE) values examine the prediction skill of the models and versions, values greater than 1.0 indicated performance worse than a random walk. Results of the MASE tests are provided in Table 12. For the bottom trawl survey index all models and versions, except Version NOWL+AGE+WT+SE performed better than the random walk. Only the 2021 version of Model 21.2 performed better than a random walk for predicting the fishery mean length with the NOWL+AGE+WT+SE version performing particularly badly. None of the models or versions predicted survey mean length particularly well with all of the new input sample size versions performing particularly badly. Survey mean age predictions were better than a random walk for all of the 2021 input sample size versions, but worse for all of the models and versions with the new input sample size.

These examinations lead to the conclusion that none of these model or versions are particularly exceptional. Fitting of the fishery length composition data is particularly problematic. Pacific cod grow rather quickly and I believe there are substantial seasonal and spatial influences that are not captured in any of these models.

I recommend that the authors in 2023 re-explore a seasonal model for Bering Sea Pacific cod and in light of the most recent genetic and tagging data (McDermott personal comm.) explore an expanded spatial model that incorporates the western Gulf of Alaska in the model. The genetics and tagging data will be more fully addressed in the complete assessment for November.

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Appendix 2.1 Tables

Table 2.1.1. Model features for the ensemble from 2021.

Feature	M19.12a	M19.12	M20.1	M20.2
Feature 1: Allow catchability to vary?	No	Yes	No	No
Feature 2: Allow domed survey selectivity?	No	No	Yes	No
Feature 3: Use fishery CPUE?	No	No	No	Yes

Table 2.1.2. Comparison of key elements from Model 19.12A for old data and new data with and without (NOWL) the seasonally adjusted annual weight at length relationship.

Label	Old Data	Old Data /NOWL	New Data	New Data /NOWL
# Parameters	301	301	301	301
Total Likelihood	10448.3	10447.6	10473.5	10468.0
Survey Likelihood	-7.6	-7.7	-3.7	-4.4
Length comp Likelihood	9602.9	9602.4	9618.7	9616.3
Age comp Likelihood	780.391	780.2	787.0	784.3
Recr. Virgin ($n \times 10^9$)	560.393	534.9	616.9	551.3
M	0.361	0.355	0.369	0.357
BTS Q	0.92	0.94	0.87	0.94
L at Amax	112.1	112.7	110.6	113.3
VonBert K	0.119	0.118	0.122	0.115
Unfished spawning biomass ($T \times 10^6$)	1.300	1.303	1.310	1.321
Bratio_2021	0.39	0.41	0.424	0.41
SPRratio_2020	0.52	0.53	0.52	0.55
$F_{40\%}$	0.36	0.35	0.35	0.33
2022 ABC (t)	174,678	167,833	183,826	161,352

Table 2.1.3. Retrospective Mohn's rho from 10-year peal for all models and versions. Version is 2021 = 2021 base models, NOWL=No seasonally corrected weight at length relationship, +AGE = New Aging bias, +WT = new length composition data input sample sizes, +SE = Fit extra standard error for bottom trawl survey.

Mohn's rho	Model 19.12	Model 19.12A	Model 21.1	Model 21.2
2021	-0.05	-0.08	-0.07	0.09
NOWL	-0.08	-0.03	-0.03	0.09
NOWL+AGE	-0.08	-0.02	-0.02	0.07
NOWL+AGE+WT	-0.01	-0.05	-0.02	-0.03
NOWL+AGE+WT+SE	-0.20	-0.26	-0.08	-0.38

Table 2.1.4. Aging bias parameter fit for models and versions. Version is 2021 = 2021 base models, NOWL=No seasonally corrected weight at length relationship, +AGE = New Aging bias, +WT = new length composition data input sample sizes, +SE = Fit extra standard error for bottom trawl survey.

Label	Model 19.12	Model 19.12A	Model 21.1	Model 21.2	Version
Age 1 delta 1977	0.342	0.350	0.348	0.349	2021
Age 1 delta 1977	0.343	0.347	0.346	0.349	NOWL
Age 1 delta 1977	0.343	0.347	0.347	0.351	NOWL+AGE
Age 1 delta 1977	0.343	0.344	0.340	0.350	NOWL+AGE+WT
Age 1 delta 1977	0.343	0.344	0.343	0.346	NOWL+AGE+WT+SE
Age 10 delta 1977	1.114	1.005	1.019	0.985	2021
Age 10 delta 1977	1.103	1.040	1.046	0.969	NOWL
Age 10 delta 1977	1.046	0.989	0.990	0.903	NOWL+AGE
Age 10 delta 1977	1.135	1.010	1.253	0.997	NOWL+AGE+WT
Age 10 delta 1977	1.176	1.074	1.298	1.166	NOWL+AGE+WT+SE
Age 1 delta 2008	0.015	0.006	0.006	0.010	2021
Age 1 delta 2008	0.016	0.009	0.009	0.011	NOWL
Age 1 delta 2008					NOWL+AGE
Age 1 delta 2008					NOWL+AGE+WT
Age 1 delta 2008					NOWL+AGE+WT+SE
Age 10 delta 2008	-1.726	-1.488	-1.482	-1.553	2021
Age 10 delta 2008	-1.770	-1.557	-1.552	-1.619	NOWL
Age 10 delta 2008					NOWL+AGE
Age 10 delta 2008					NOWL+AGE+WT
Age 10 delta 2008					NOWL+AGE+WT+SE

Table 2.1.5. Comparison of likelihood elements from models with new data. Version is is 2021 = 2021 base models, NOWL=No seasonally corrected weight at length relationship, +AGE = New Aging bias, +WT = new length composition data input sample sizes, +SE = Fit extra standard error for bottom trawl survey. Parameters include the annual dev pseudo-parameters.

Label	Model 19.12	Model 19.12A	Model 21.1	Model 21.2	VERSION
Parameters	342	301	305	302	2021
Parameters	342	301	305	302	NOWL
Parameters	340	299	303	300	NOWL+AGE
Parameters	342	301	305	302	NOWL+AGE+WT
Parameters	343	302	306	304	NOWL+AGE+WT+SE
AIC	21,447	21,549	21,553	21,625	2021
AIC	21,431	21,538	21,546	21,628	NOWL
AIC	21,472	21,584	21,588	21,663	NOWL+AGE
AIC	45,948	46,383	46,202	46,535	NOWL+AGE+WT
AIC	45,914	46,043	45,766	45,777	NOWL+AGE+WT+SE
Total Likelihood	10381.3	10473.5	10471.4	10510.7	2021
Total Likelihood	10373.3	10468.0	10468.2	10512.0	NOWL
Total Likelihood	10395.8	10493.2	10491.2	10531.7	NOWL+AGE
Total Likelihood	22632.1	22890.6	22796.1	22965.7	NOWL+AGE+WT
Total Likelihood	22613.8	22719.4	22577.0	22584.6	NOWL+AGE+WT+SE
Survey Likelihood	-91.3	-3.7	-2.7	-39.6	2021
Survey Likelihood	-92.5	-4.4	-3.5	-40.0	NOWL
Survey Likelihood	-91.7	-3.9	-3.7	-39.6	NOWL+AGE
Survey Likelihood	-83.5	81.2	84.9	177.5	NOWL+AGE+WT
Survey Likelihood	-42.4	-35.8	-40.8	-64.86	NOWL+AGE+WT+SE
Length comp Likelihood	9587.7	9618.7	9617.3	9685.2	2021
Length comp Likelihood	9579.1	9616.3	9616.7	9692.1	NOWL
Length comp Likelihood	9580.6	9618.6	9617.1	9690.1	NOWL+AGE
Length comp Likelihood	21716.1	21854.4	21755.6	21849.7	NOWL+AGE+WT
Length comp Likelihood	21700.7	21801.0	21657.1	21702.6	NOWL+AGE+WT+SE
Age comp Likelihood	775.9	787.1	785.6	786.9	2021
Age comp Likelihood	776.3	784.3	783.5	784.0	NOWL
Age comp Likelihood	796.5	806.9	806.3	805.1	NOWL+AGE
Age comp Likelihood	849.3	844.1	848.3	844.1	NOWL+AGE+WT
Age comp Likelihood	850.3	844.4	857.8	848.4	NOWL+AGE+WT+SE

Table 2.1.6. Comparison of key model results from models with new data. Version is 2021 = 2021 base models, NOWL=No seasonally corrected weight at length relationship, +AGE = New Aging bias, +WT = new length composition data input sample sizes, +SE = Fit extra standard error for bottom trawl survey.

Label	Model 19.12	Model 19.12A	Model 21.1	Model 21.2	VERSION
M	0.337	0.369	0.364	0.363	2021
M	0.342	0.357	0.354	0.353	NOWL
M	0.328	0.348	0.345	0.350	NOWL+AGE
M	0.381	0.339	0.312	0.396	NOWL+AGE+WT
M	0.401	0.364	0.288	0.411	NOWL+AGE+WT+SE
BTS Q	1.04	0.87	0.90	0.867	2021
BTS Q	1.01	0.94	0.95	0.908	NOWL
BTS Q	1.04	0.94	0.95	0.877	NOWL+AGE
BTS Q	0.79	1.00	1.14	0.685	NOWL+AGE+WT
BTS Q	0.72	0.94	1.23	0.678	NOWL+AGE+WT+SE
BTS SE+	0.15	0.19	0.16	0.18	NOWL+AGE+WT+SE
CPUE Q				0.0003	2021
CPUE Q				0.0003	NOWL
CPUE Q				0.0003	NOWL+AGE
CPUE Q				0.0004	NOWL+AGE+WT
CPUE Q				0.0003	NOWL+AGE+WT+SE
CPUE SE+				0.17	
L at Amax	118.686	110.612	112.958	115.160	2021
L at Amax	115.876	113.26	114.202	116.899	NOWL
L at Amax	115.999	112.928	113.566	114.013	NOWL+AGE
L at Amax	111.537	115.060	105.588	111.207	NOWL+AGE+WT
L at Amax	111.285	115.211	103.655	111.903	NOWL+AGE+WT+SE
VonBert K	0.101	0.122	0.115	0.104	2021
VonBert K	0.109	0.115	0.112	0.099	NOWL
VonBert K	0.107	0.113	0.111	0.105	NOWL+AGE
VonBert K	0.126	0.112	0.152	0.125	NOWL+AGE+WT
VonBert K	0.126	0.110	0.154	0.124	NOWL+AGE+WT+SE
Unfished spawning biomass (T x 10^6)	1.339	1.312	1.313	1.310	2021
Unfished spawning biomass (T x 10^6)	1.350	1.321	1.330	1.325	NOWL
Unfished spawning biomass (T x 10^6)	1.391	1.353	1.361	1.357	NOWL+AGE
Unfished spawning biomass (T x 10^6)	1.427	1.393	1.698	1.488	NOWL+AGE+WT
Unfished spawning biomass (T x 10^6)	1.411	1.301	1.737	1.431	NOWL+AGE+WT+SE
Recr. Virgin (n x 10^9)	460.768	616.934	587.841	594.063	2021
Recr. Virgin (n x 10^9)	487.184	551.436	538.143	547.416	NOWL
Recr. Virgin (n x 10^9)	448.448	530.263	520.981	560.104	NOWL+AGE
Recr. Virgin (n x 10^9)	719.073	483.368	451.887	849.215	NOWL+AGE+WT
Recr. Virgin (n x 10^9)	850.824	571.669	373.608	928.794	NOWL+AGE+WT+SE
2022 ABC (t)	114,901	183,826	172,691	151,208	2021
2022 ABC (t)	132,621	161,532	154,662	134,968	NOWL
2022 ABC (t)	114,434	155,920	150,405	145,152	NOWL+AGE
2022 ABC (t)	204,251	137,028	142,616	233,444	NOWL+AGE+WT
2022 ABC (t)	167,343	62,215	138,340	195,555	NOWL+AGE+WT+SE
F40%	0.29	0.35	0.35	0.36	2021
F40%	0.31	0.33	0.33	0.34	NOWL
F40%	0.30	0.32	0.32	0.33	NOWL+AGE
F40%	0.34	0.30	0.27	0.35	NOWL+AGE+WT
F40%	0.36	0.33	0.25	0.37	NOWL+AGE+WT+SE
Bratio_2021	0.352	0.424	0.408	0.367	2021
Bratio_2021	0.382	0.407	0.398	0.357	NOWL
Bratio_2021	0.360	0.400	0.393	0.367	NOWL+AGE
Bratio_2021	0.479	0.377	0.380	0.473	NOWL+AGE+WT
Bratio_2021	0.424	0.284	0.405	0.447	NOWL+AGE+WT+SE
SPRratio_2020	0.60	0.52	0.54	0.56	2021
SPRratio_2020	0.58	0.55	0.56	0.58	NOWL
SPRratio_2020	0.60	0.55	0.56	0.57	NOWL+AGE
SPRratio_2020	0.48	0.58	0.56	0.45	NOWL+AGE+WT
SPRratio_2020	0.49	0.63	0.58	0.46	NOWL+AGE+WT+SE

Table 2.1.7. Tuned sigma values for annually varying parameters. Version is 2021 = 2021 base models, NOWL=No seasonally corrected weight at length relationship, +AGE = New Aging bias, +WT = new length composition data input sample sizes, +SE = Fit extra standard error for bottom trawl survey. Note that the NOWL and NOWL+AGE versions were not retuned from the 2021 values.

Model	Model 19.12	Model 19.12A	Model 21.1	Model 21.2	Version
ln sigma R	0.6637	0.6651	0.6663	0.6453	2021,NOWL,NOWL+AGE
ln sigma R	0.6719	0.6604	0.7170	0.6132	NOWL+AGE+WT
ln sigma R	0.7037	0.7235	0.6280	0.6623	NOWL+AGE+WT+SE
L min	0.1752	0.1757	0.1730	0.1749	2021,NOWL,NOWL+AGE
L min	0.2965	0.2077	0.1518	0.2012	NOWL+AGE+WT
L min	0.2067	0.2021	0.1978	0.1978	NOWL+AGE+WT+SE
Ascend_se (fishery)	0.1595	0.1634	0.1819	0.1903	2021,NOWL,NOWL+AGE
Ascend_se (fishery)	0.2525	0.2481	0.2710	0.2657	NOWL+AGE+WT
Ascend_se (fishery)	0.2509	0.2442	0.2795	0.2521	NOWL+AGE+WT+SE
End_logit (fishery)	0.7610	0.8870	0.6760	1.3919	2021,NOWL,NOWL+AGE
End_logit (fishery)	1.4967	1.2715	1.3599	1.8832	NOWL+AGE+WT
End_logit (fishery)	1.5607	1.3512	1.3937	1.5919	NOWL+AGE+WT+SE
Ascend_se (survey)	0.8394	0.8342	0.7610	0.7428	2021,NOWL,NOWL+AGE
Ascend_se (survey)	1.3657	1.2910	1.4924	1.4711	NOWL+AGE+WT
Ascend_se (survey)	1.3777	1.3255	1.4270	1.5538	NOWL+AGE+WT+SE
Peak (survey)	0.2255	0.2194	0.2071	0.2033	2021,NOWL,NOWL+AGE
Peak (survey)	0.3462	0.3199	0.3758	0.3697	NOWL+AGE+WT
Peak (survey)	0.3508	0.3328	0.3445	0.3909	NOWL+AGE+WT+SE

Table 2.1.8. Dirichlet multinomial sample size multiplier. Grey values were fixed near the upper bound.

Label	Model 19.12	Model 19.12A	Model 21.1	Model 21.2	Version
Fishery Length	1	1	1	1	2021
Fishery Length	1	1	1	1	NOWL
Fishery Length	1	1	1	1	NOWL+AGE
Fishery Length	0.643	0.607	0.658	0.633	NOWL+AGE+WT
Fishery Length	0.644	0.609	0.675	0.647	NOWL+AGE+WT+SE
Survey Length	1	1	1	1	2021
Survey Length	1	1	1	1	NOWL
Survey Length	1	1	1	1	NOWL+AGE
Survey Length	0.589	0.622	0.578	0.547	NOWL+AGE+WT
Survey Length	0.595	0.640	0.602	0.587	NOWL+AGE+WT+SE
Survey Age	0.496	0.419	0.434	0.384	2021
Survey Age	0.470	0.441	0.448	0.393	NOWL
Survey Age	0.394	0.366	0.371	0.324	NOWL+AGE
Survey Age	0.249	0.290	0.250	0.235	NOWL+AGE+WT
Survey Age	0.245	0.284	0.228	0.247	NOWL+AGE+WT+SE

Table 2.1.9. Resulting average input sample size after Dirichlet multinomial sample size multiplier applied.

Label	Model 19.12	Model 19.12A	Model 21.1	Model 21.2	Version
Fishery Length	358	358	358	358	2021
Fishery Length	358	358	358	358	NOWL
Fishery Length	358	358	358	358	NOWL+AGE
Fishery Length	3616	3416	3701	3560	NOWL+AGE+WT
Fishery Length	3625	3424	3795	3640	NOWL+AGE+WT+SE
Survey Length	358	358	358	358	2021
Survey Length	358	358	358	358	NOWL
Survey Length	358	358	358	358	NOWL+AGE
Survey Length	1054	1111	1033	979	NOWL+AGE+WT
Survey Length	1063	1144	1076	1050	NOWL+AGE+WT+SE
Survey Age	177	150	155	137	2021
Survey Age	168	158	160	140	NOWL
Survey Age	141	131	133	116	NOWL+AGE
Survey Age	89	104	89	84	NOWL+AGE+WT
Survey Age	87	102	82	88	NOWL+AGE+WT+SE

Table 2.1.10. Joint RMSE values (Carvalho et al. 2021) for all models and versions. Version is 2021 = 2021 base models, NOWL=No seasonally corrected weight at length relationship, +AGE = New Aging bias, +WT = new length composition data input sample sizes, +SE = Fit extra standard error for bottom trawl survey.

Label	Model 19.12	Model 19.12A	Model 21.1	Model 21.2	Version
Indices	5.9	13	13.1	11.7	2021
Indices	5.8	13	13.1	11.8	NOWL
Indices	5.9	13	13	11.8	NOWL+AGE
Indices	7.3	17.2	17.2	16.7	NOWL+AGE+WT
Indices	25.8	25.7	28.9	24.1	NOWL+AGE+WT+SE
Length Comp	3.8	3.9	3.9	4	2021
Length Comp	3.7	3.9	3.9	4	NOWL
Length Comp	3.8	4	3.9	4.1	NOWL+AGE
Length Comp	3	3.4	2.6	3.3	NOWL+AGE+WT
Length Comp	2.7	3.4	3	3.1	NOWL+AGE+WT+SE
Age Comp	4.9	5.5	5.5	6.4	2021
Age Comp	5	5.4	5.4	6.3	NOWL
Age Comp	5.5	6.1	6.1	6.7	NOWL+AGE
Age Comp	6.6	6.2	6.8	6.4	NOWL+AGE+WT
Age Comp	6.7	6.9	7.2	7.2	NOWL+AGE+WT+SE

Table 2.1.11. Residual runs test (Carvalho et al. 2021) p-Values for fit to survey and fishery CPUE indices for all models and versions. The p-value is a test of whether the observed residual distribution is further than three standard deviations away from the expected residual process average of 0. Red values are significantly different at α = 0.05. Version is 2021 = 2021 base models, NOWL=No seasonally corrected weight at length relationship, +AGE = New Aging bias, +WT = new length composition data input sample sizes, +SE = Fit extra standard error for bottom trawl survey.

Version	***Model 19.12***	***Model 19.12A***	***Model 21.1***	***Model 21.2***	***Label***
2021	0.315	0.315	0.566	0.008	BT Survey index
NOWL	0.315	0.147	0.147	0.008	BT Survey index
NOWL+AGE	0.315	0.315	0.315	0.008	BT Survey index
NOWL+AGE+WT	0.135	0.013	0.135	0.147	BT Survey index
NOWL+AGE+WT+SE	0.021	0.58	0.008	0.129	BT Survey index
2021				0.120	Fishery Index
NOWL				0.120	Fishery Index
NOWL+AGE				0.120	Fishery Index
NOWL+AGE+WT				0.024	Fishery Index
NOWL+AGE+WT+SE				0.000	Fishery Index
2021	0.019	0.002	0.012	0.000	Fishery Length
NOWL	0.002	0.012	0.002	0.000	Fishery Length
NOWL+AGE	0.002	0.003	0.002	0.000	Fishery Length
NOWL+AGE+WT	0.049	0.099	0.087	0.024	Fishery Length
NOWL+AGE+WT+SE	0.000	0.209	0.155	0.091	Fishery Length
2021	0.129	0.001	0.001	0.000	Survey Length
NOWL	0.129	0.001	0.001	0.000	Survey Length
NOWL+AGE	0.326	0.001	0.001	0.000	Survey Length
NOWL+AGE+WT	0.039	0.348	0.533	0.111	Survey Length
NOWL+AGE+WT+SE	0.081	0.326	0.081	0.199	Survey Length
2021	0.512	0.512	0.512	0.08	Survey Age
NOWL	0.512	0.512	0.512	0.08	Survey Age
NOWL+AGE	0.704	0.057	0.057	0.219	Survey Age
NOWL+AGE+WT	0.355	0.355	0.448	0.541	Survey Age
NOWL+AGE+WT+SE	0.704	0.355	0.355	0.355	Survey Age

Table 2.1.12. Mean absolute scaled error (MASE) values for model data components for all models and versions. Version is 2021 = 2021 base models, NOWL=No seasonally corrected weight at length relationship, +AGE = New Aging bias, +WT = new length composition data input sample sizes, +SE = Fit extra standard error for bottom trawl survey. Red values indicate predictions skills worse than a random walk (Carvalho et al. 2021).

Version	Model 19.12	Model 19.12A	Model 21.1	Model 21.2	Label
2021	0.19	0.36	0.36	0.51	BT Survey Index
NOWL	0.17	0.35	0.35	0.50	BT Survey Index
NOWL+AGE	0.18	0.35	0.34	0.50	BT Survey Index
NOWL+AGE+WT	0.26	0.48	0.47	0.68	BT Survey Index
NOWL+AGE+WT+SE	1.03	1.14	1.10	0.99	BT Survey Index
2021				0.55	CPUE Index
NOWL				0.53	CPUE Index
NOWL+AGE				0.47	CPUE Index
NOWL+AGE+WT				1.04	CPUE Index
NOWL+AGE+WT+SE				2.46	CPUE Index
2021	0.33	0.31	0.33	0.38	Fishery Mean Length
NOWL	0.29	0.31	0.31	0.38	Fishery Mean Length
NOWL+AGE	0.28	0.30	0.31	0.37	Fishery Mean Length
NOWL+AGE+WT	0.42	0.29	0.37	0.43	Fishery Mean Length
NOWL+AGE+WT+SE	0.61	0.45	0.50	0.50	Fishery Mean Length
2021	1.00	0.93	0.92	1.00	Survey Mean Length
NOWL	0.93	0.92	0.91	0.99	Survey Mean Length
NOWL+AGE	0.96	0.92	0.91	1.00	Survey Mean Length
NOWL+AGE+WT	1.43	1.28	1.30	1.37	Survey Mean Length
NOWL+AGE+WT+SE	1.51	1.80	1.77	1.75	Survey Mean Length
2021	0.83	0.76	0.77	0.78	Survey Mean Age
NOWL	0.77	0.74	0.74	0.79	Survey Mean Age
NOWL+AGE	0.87	0.89	0.87	0.89	Survey Mean Age
NOWL+AGE+WT	1.35	1.09	1.10	1.21	Survey Mean Age
NOWL+AGE+WT+SE	1.34	1.58	1.58	1.59	Survey Mean Age

Appendix 2.1 Figures

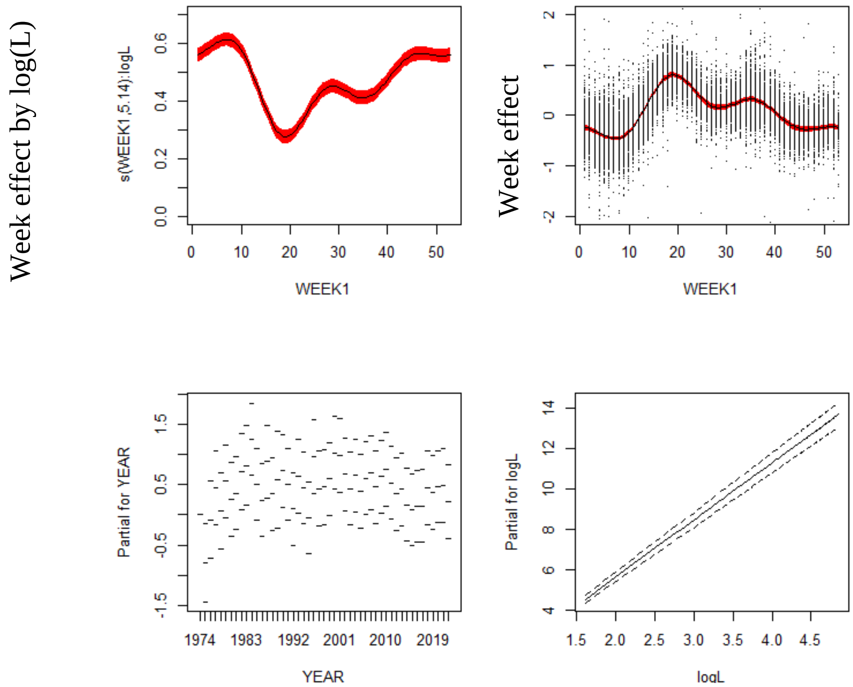


Figure 2.1.1. GAM model of weekly and annual effects on weight at length.

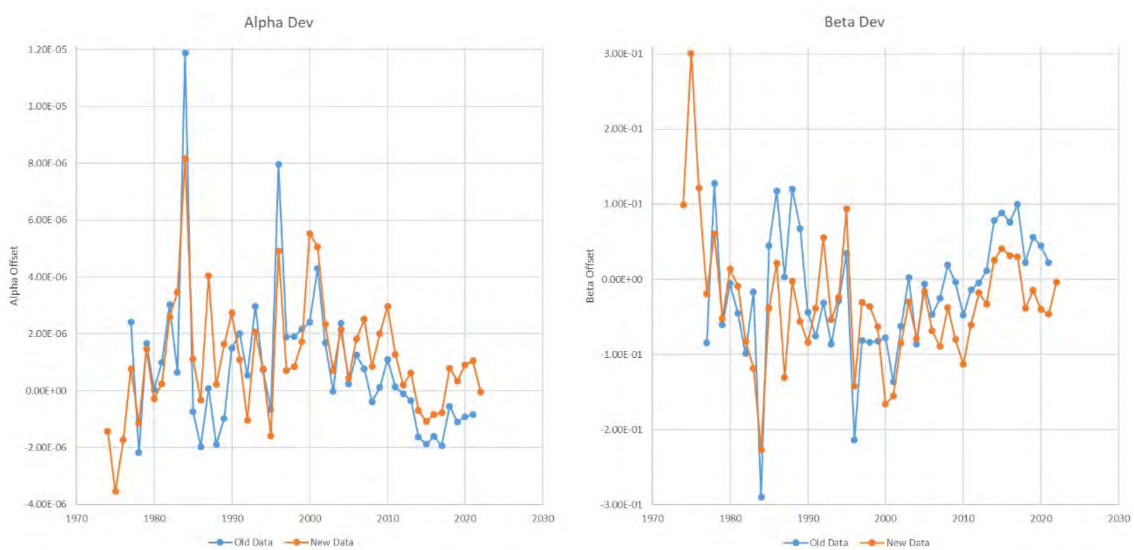


Figure 2.1.2. Annual deviation indices for Alpha and Beta for the weight at length relationship used in the assessment models for 1974-2022 for old and new method.

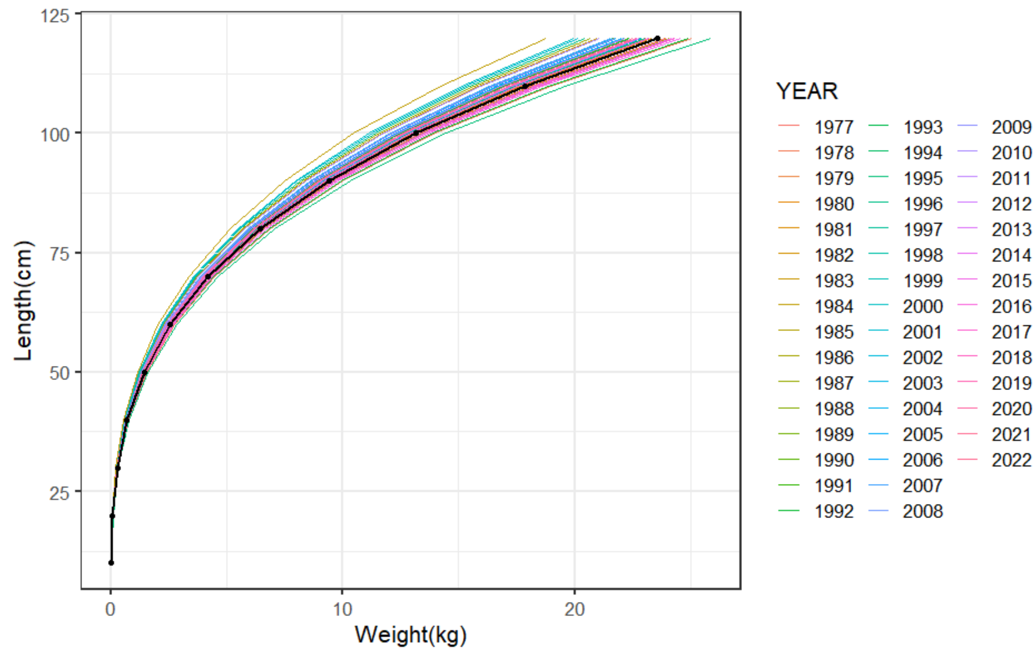


Figure 2.1.3. Variability in weight at length for BS Pacific cod 1977-2022 for new method. The black line is the overall weight at length relationship for all data.

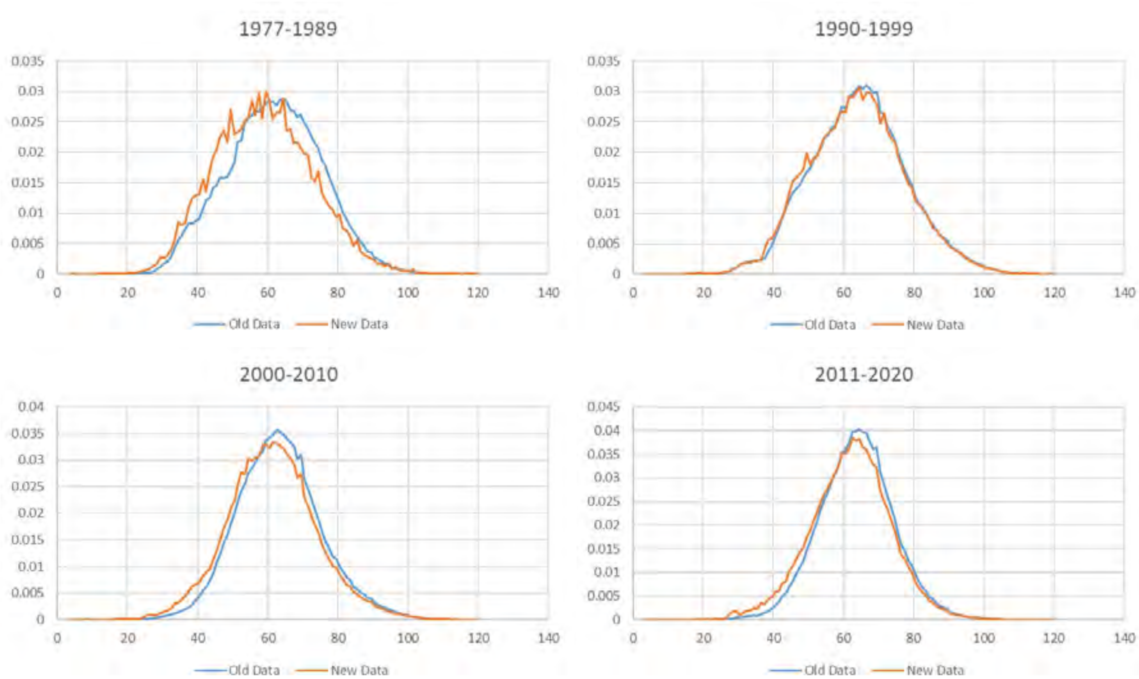


Figure 2.1.4. Overall fishery length distributions summed by each decade from the method used by the previous lead author (Old Data) and the new lead author (New Data).

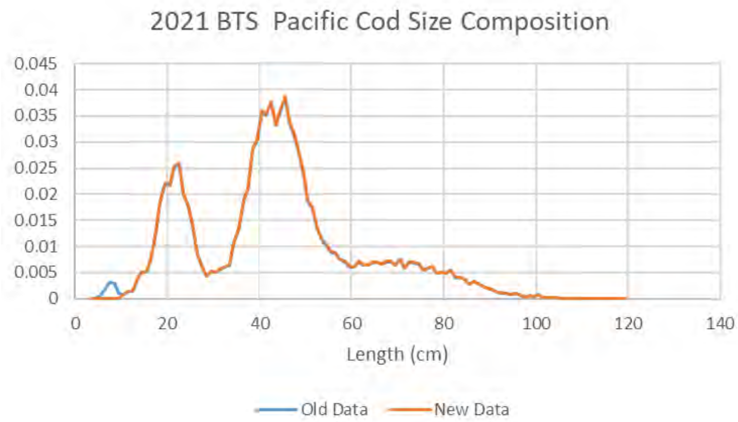


Figure 2.1.5. 2021 Bottom trawl survey Pacific cod size composition data for old data and new data.

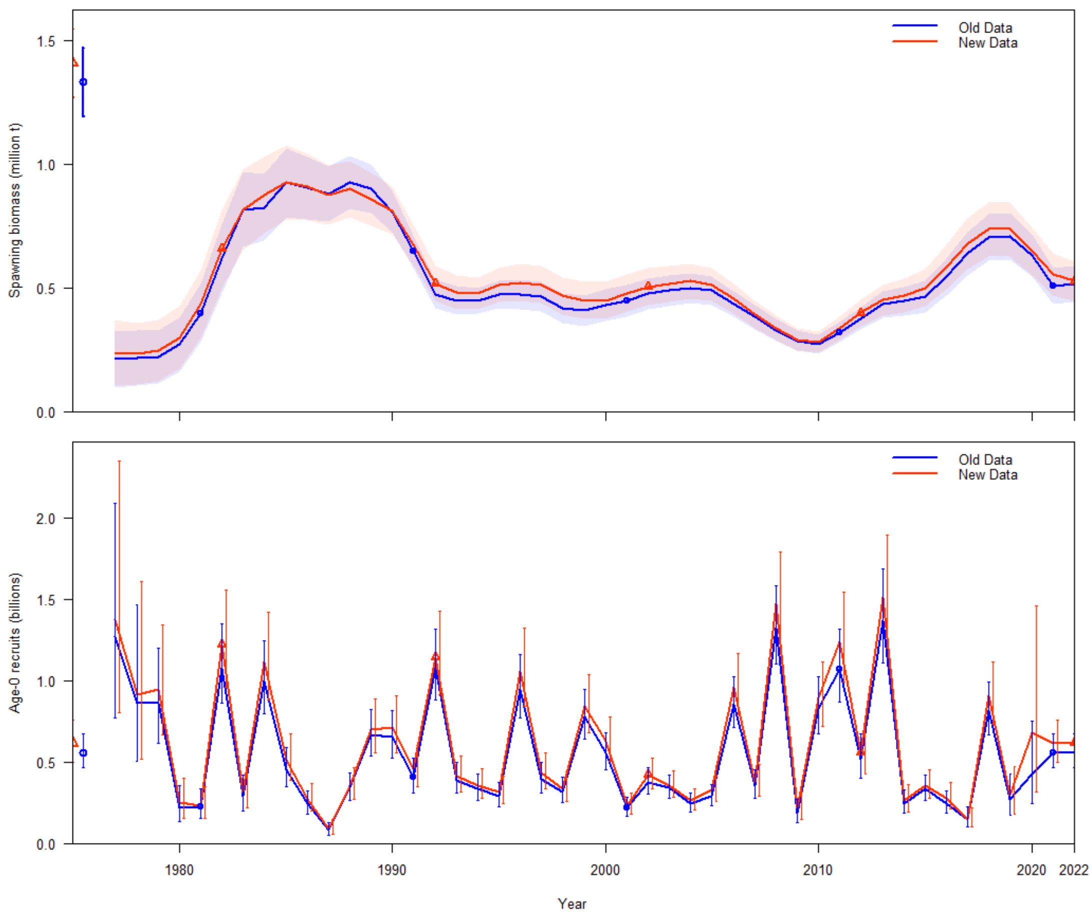


Figure 2.1.6. (Top) spawning biomass estimates (t x 10^9) and (bottom) age-o recruits (n x 10^{12}) from Model 19.12A with old and new length composition data and annual seasonally corrected weight at length relationship.

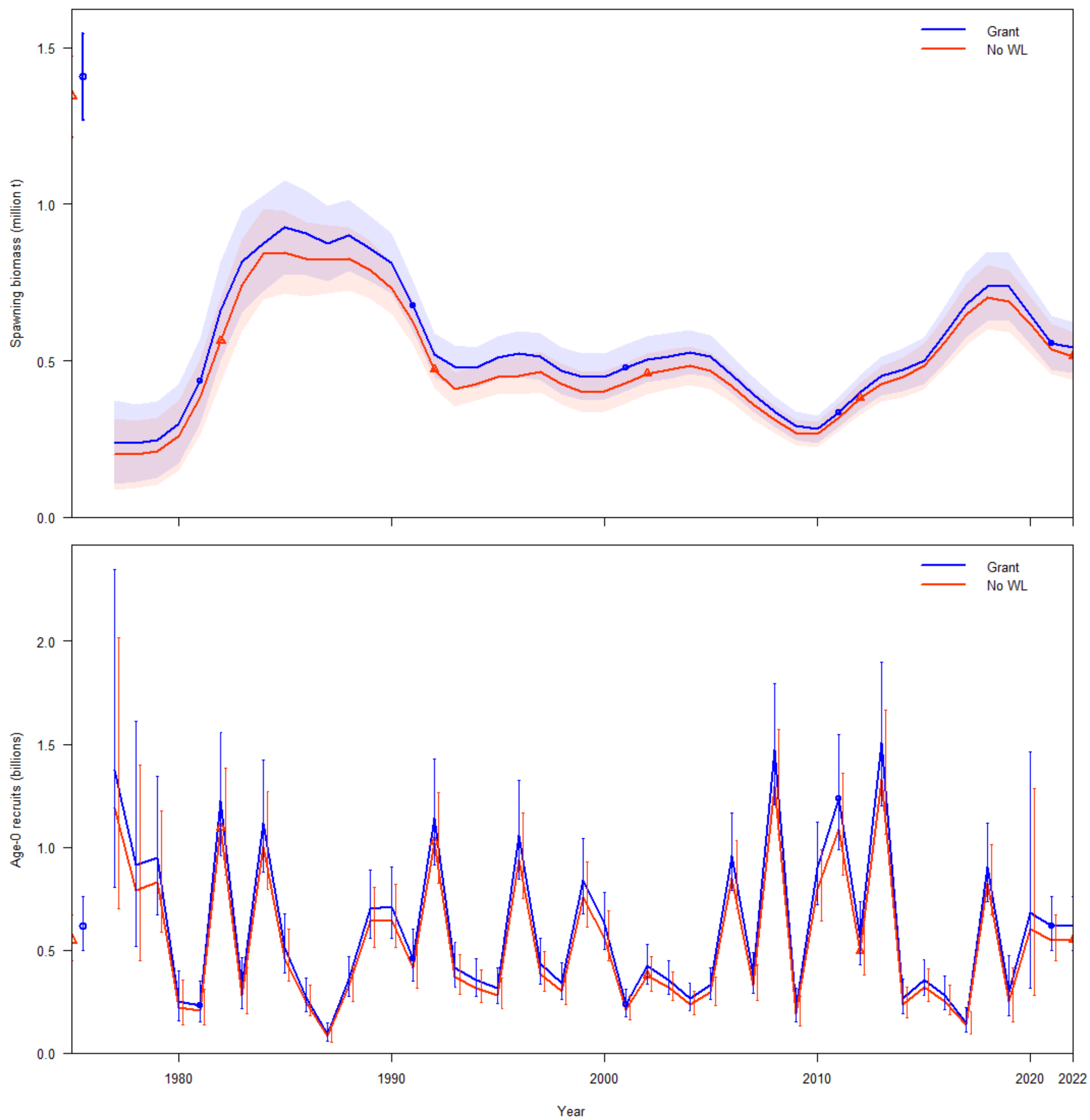


Figure 2.1.7. (Top) spawning biomass estimates (t x 109) and (bottom) age-0 recruits (n x 1012) from Model 19.12A with new length composition data and with (GRANT) and without (No WL) annual seasonally corrected weight at length relationship.

Figure 2.1.8. Aging bias fit in all models and versions. X-axis is age in years, y-axis is average bias in years.

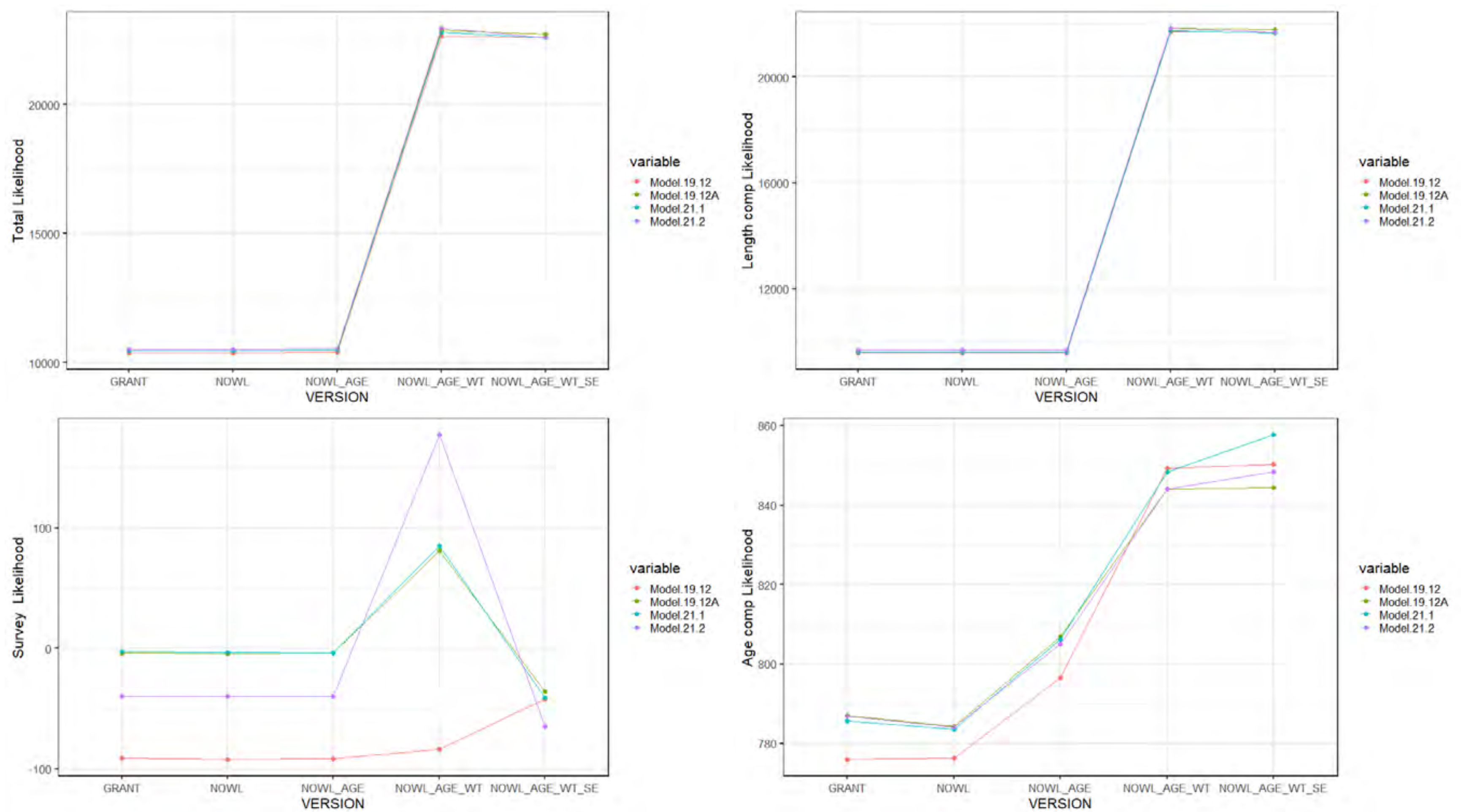


Figure 2.1.9. Comparison of likelihood elements from models with new data. Version is GRANT=2021 base models with new data, NOWL=No seasonally corrected weight at length relationship, +AGE = New Aging bias, +WT = new length composition data input sample sizes, +SE = Fit extra standard error for bottom trawl survey.

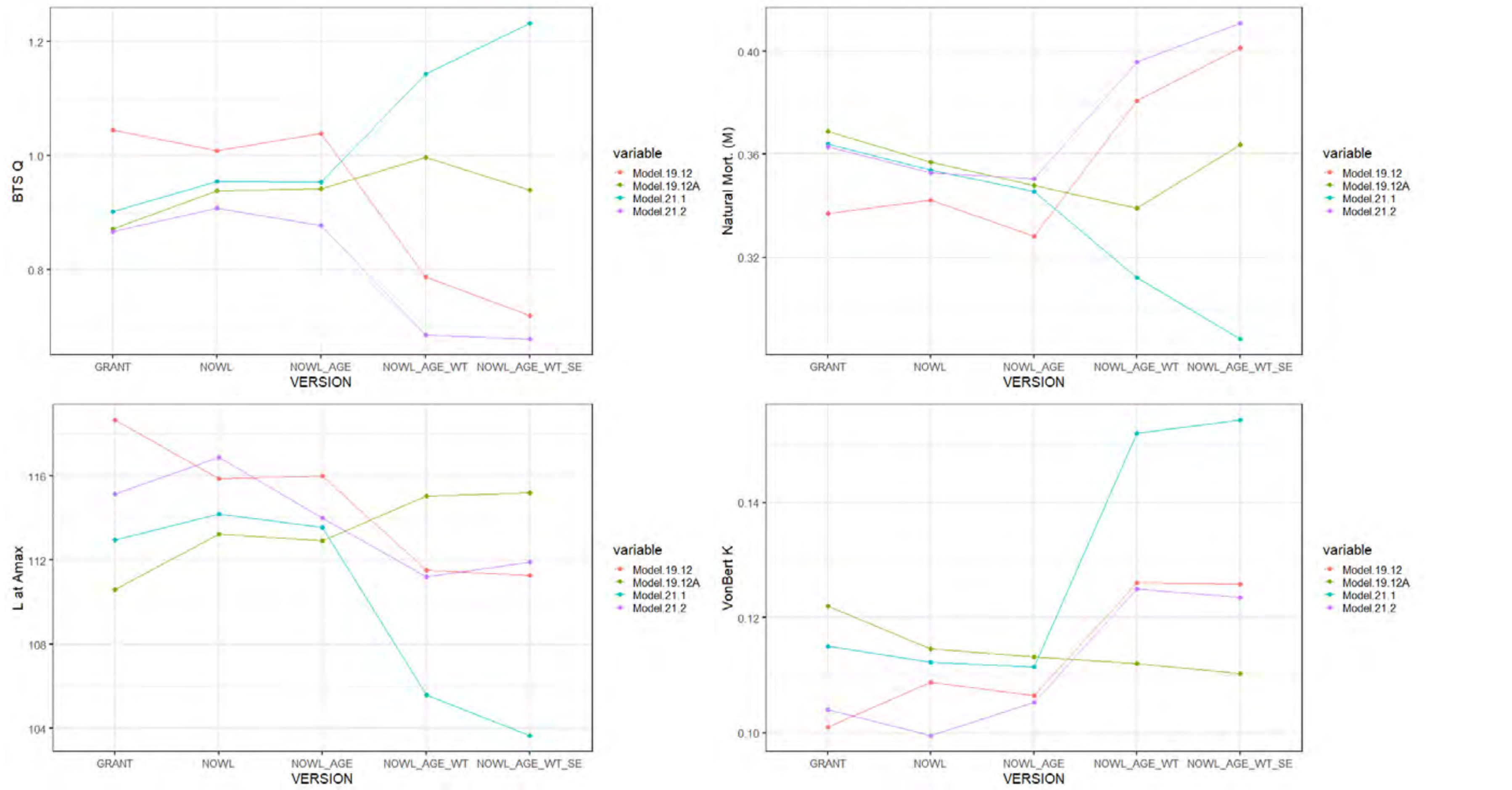


Figure 2.1.10. Comparison of key model results from models with new data. Version is GRANT=2021 base models with new data, NOWL=No seasonally corrected weight at length relationship, +AGE = New Aging bias, +WT = new length composition data input sample sizes, +SE = Fit extra standard error for bottom trawl survey.

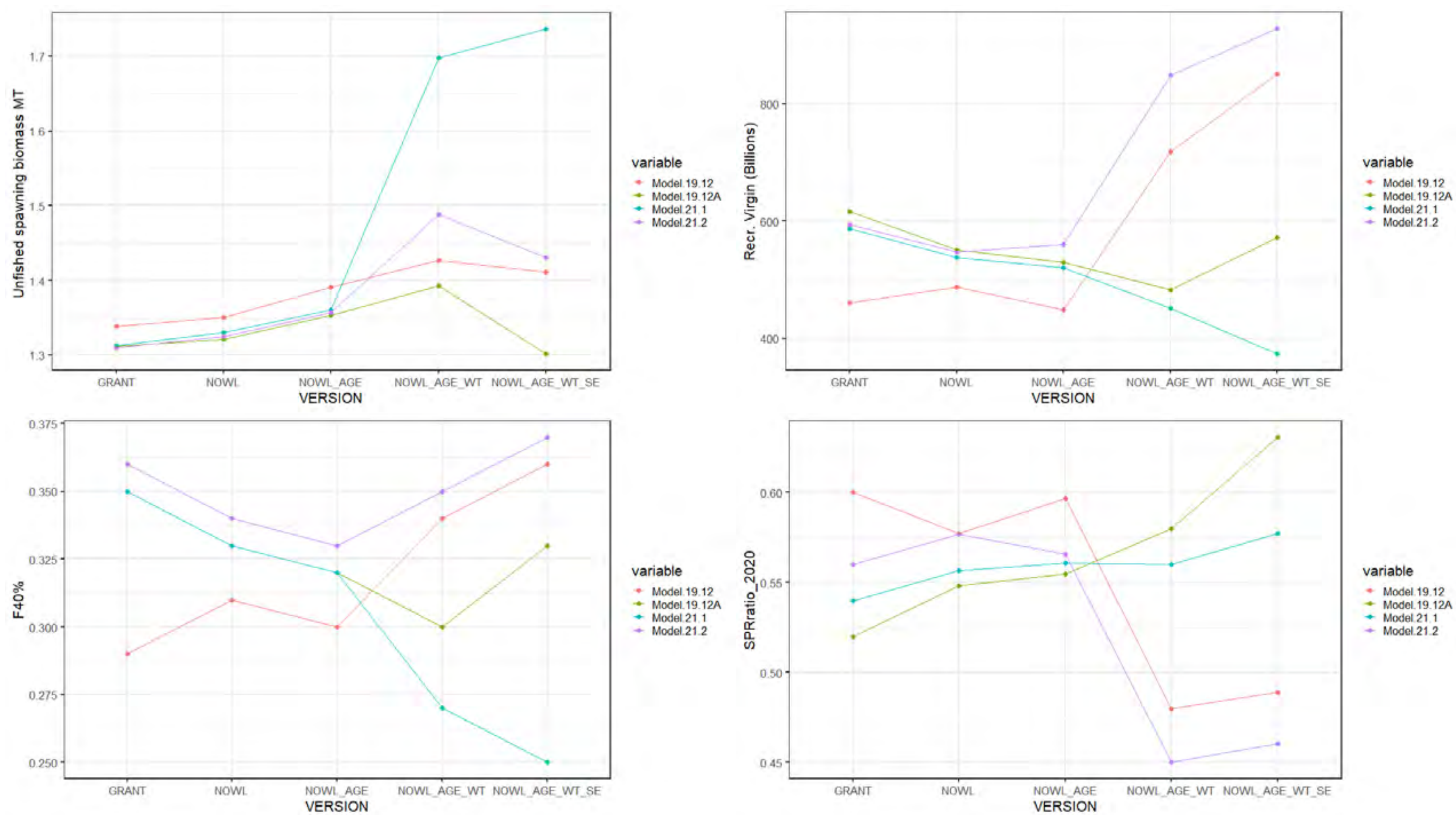
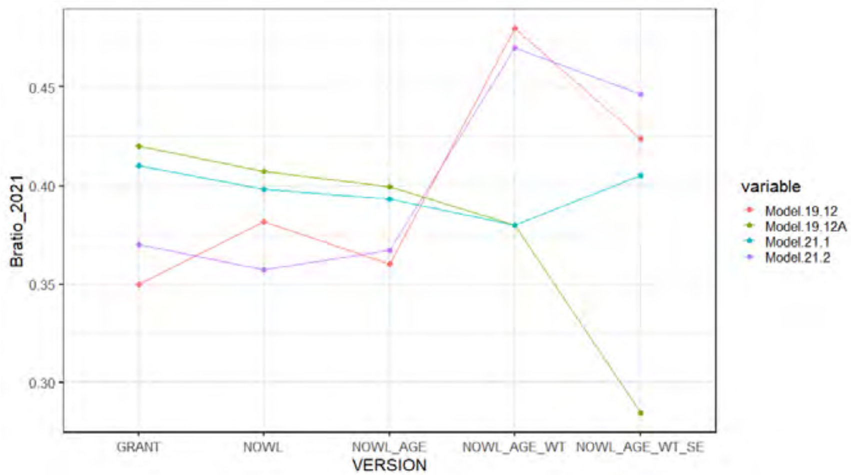


Figure 2.1.10 Cont. Comparison of key model results from models with new data. Version is GRANT=2021 base models with new data, NOWL=No seasonally corrected weight at length relationship, +AGE = New Aging bias, +WT = new length composition data input sample sizes, +SE = Fit extra standard error for bottom trawl survey.



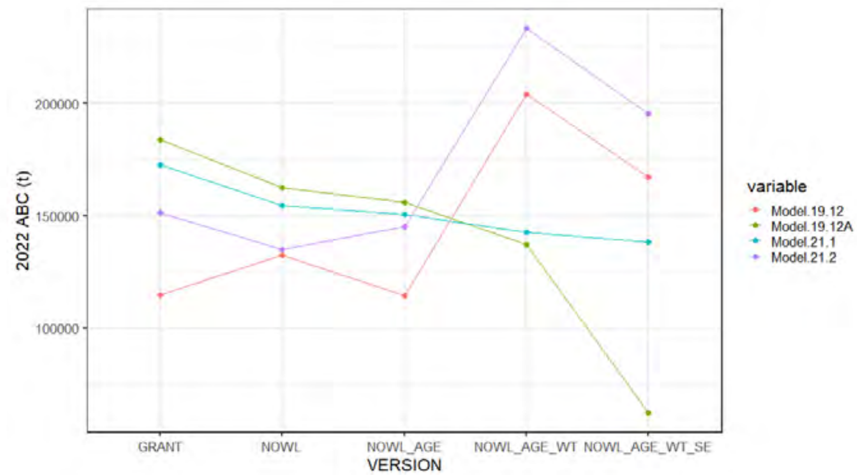


Figure 2.1.10 Cont. Comparison of key model results from models with new data. Version is GRANT=2021 base models with new data, NOWL=No seasonally corrected weight at length relationship, +AGE = New Aging bias, +WT = new length composition data input sample sizes, +SE = Fit extra standard error for bottom trawl survey.

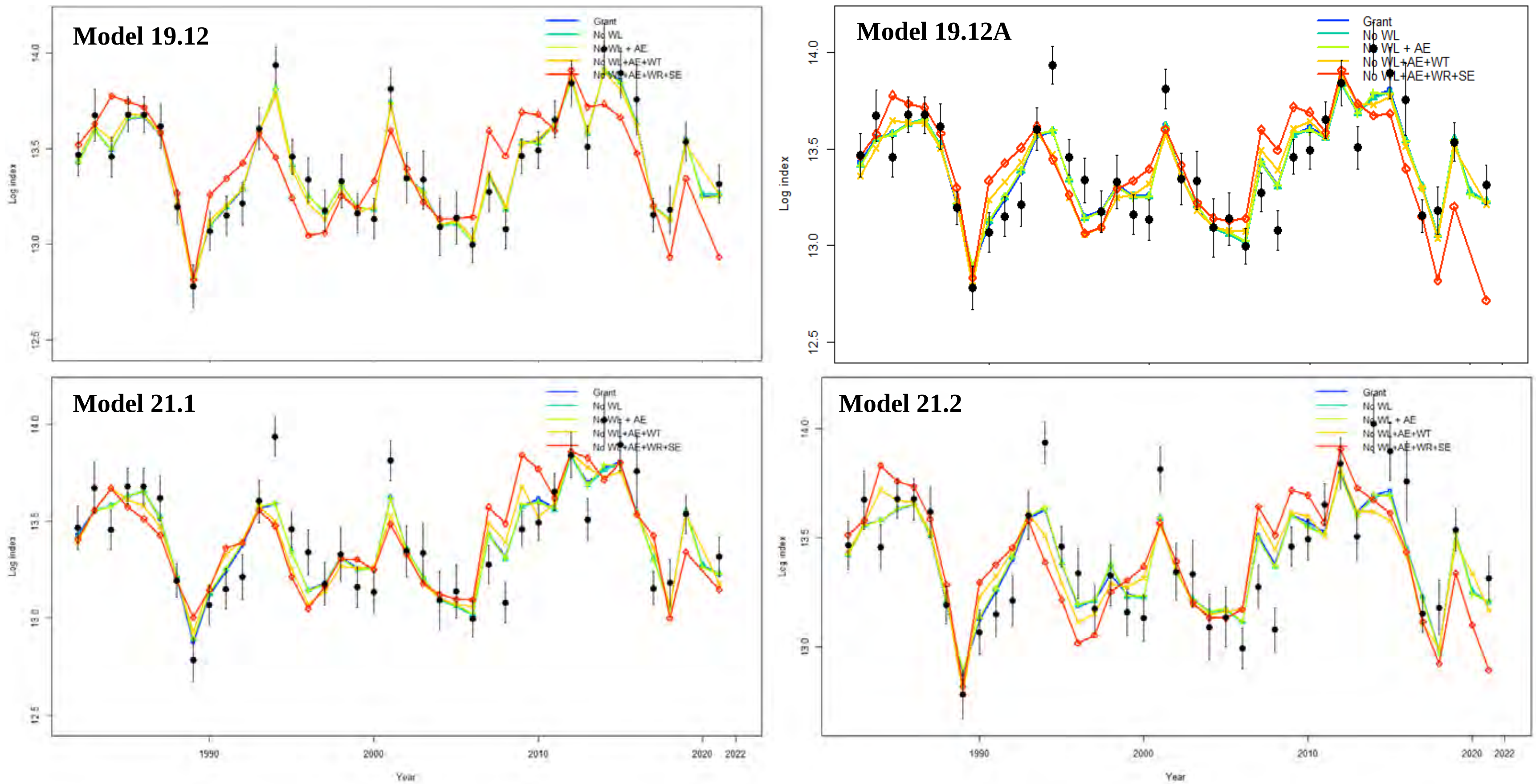


Figure 2.1.11. Fit to the VAST combined Bering Sea bottom trawl survey index (log numbers) for alternative models with new data with versions GRANT = 2021 base model, No WL=No seasonally corrected weight at length relationship, +AGE = New Aging bias, +WT = new length composition data input sample sizes, +SE = Fit extra standard error for bottom trawl survey.

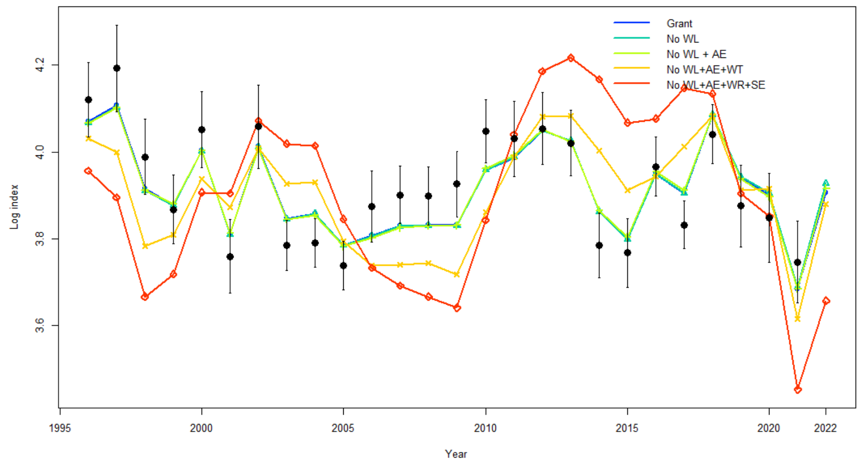


Figure 2.1.12. Model 21.2 fit to the winter longline fishery VAST CPUE index (log numbers) for alternative models with new data with versions GRANT = 2021 base model, No WL=No seasonally corrected weight at length relationship, +AGE = New Aging bias, +WT = new length composition data input sample sizes, +SE = Fit extra standard error for bottom trawl survey and CPUE Index.

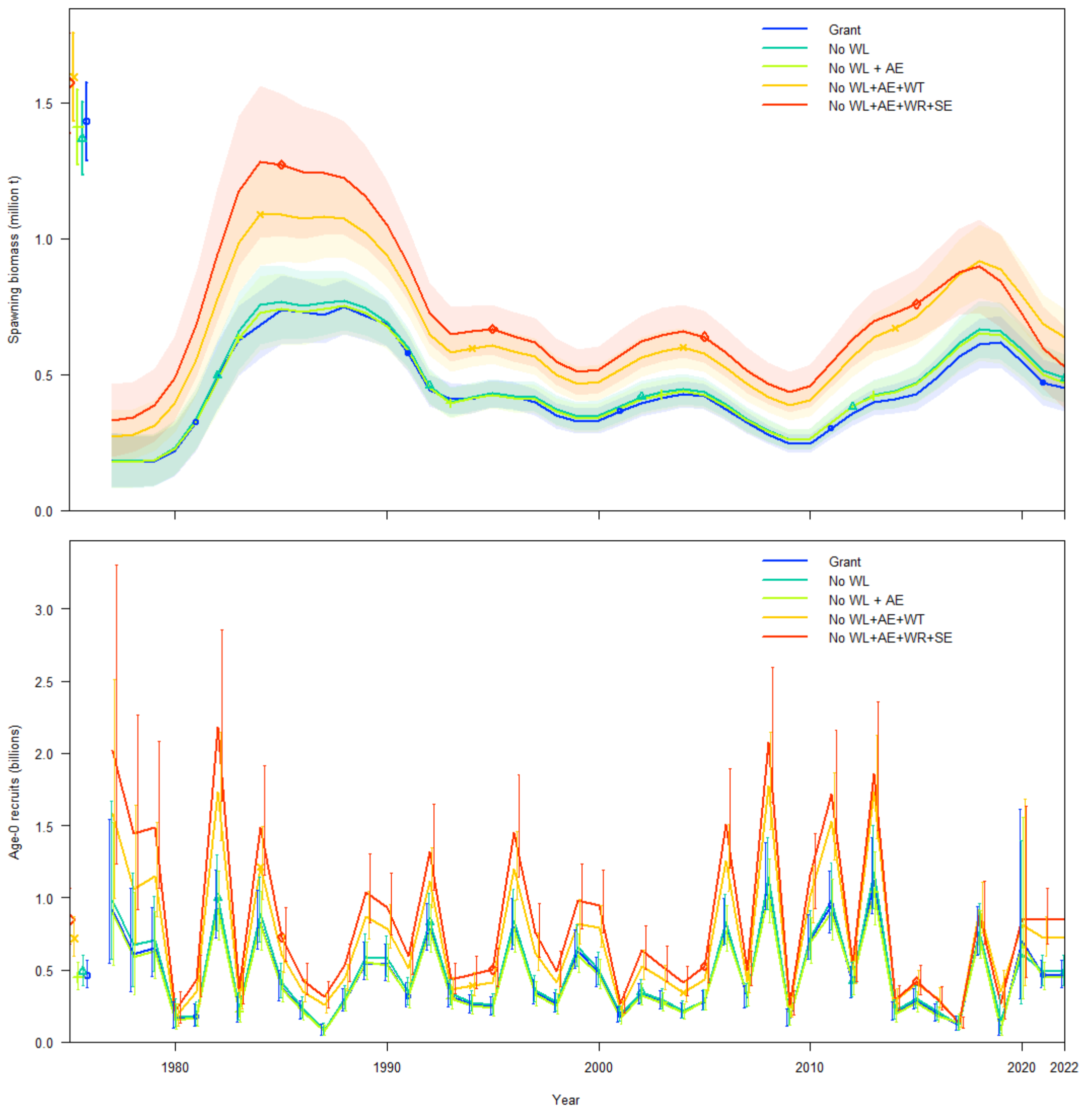


Figure 2.1.13. (Top) spawning biomass estimates (t x 10^9) and (bottom) age-o recruits (n x 10^{12}) from Model 19.12 with new data with versions GRANT = 2021 base model, No WL=No seasonally corrected weight at length relationship, +AGE = New Aging bias, +WT = new length composition data input sample sizes, +SE = Fit extra standard error for bottom trawl survey.

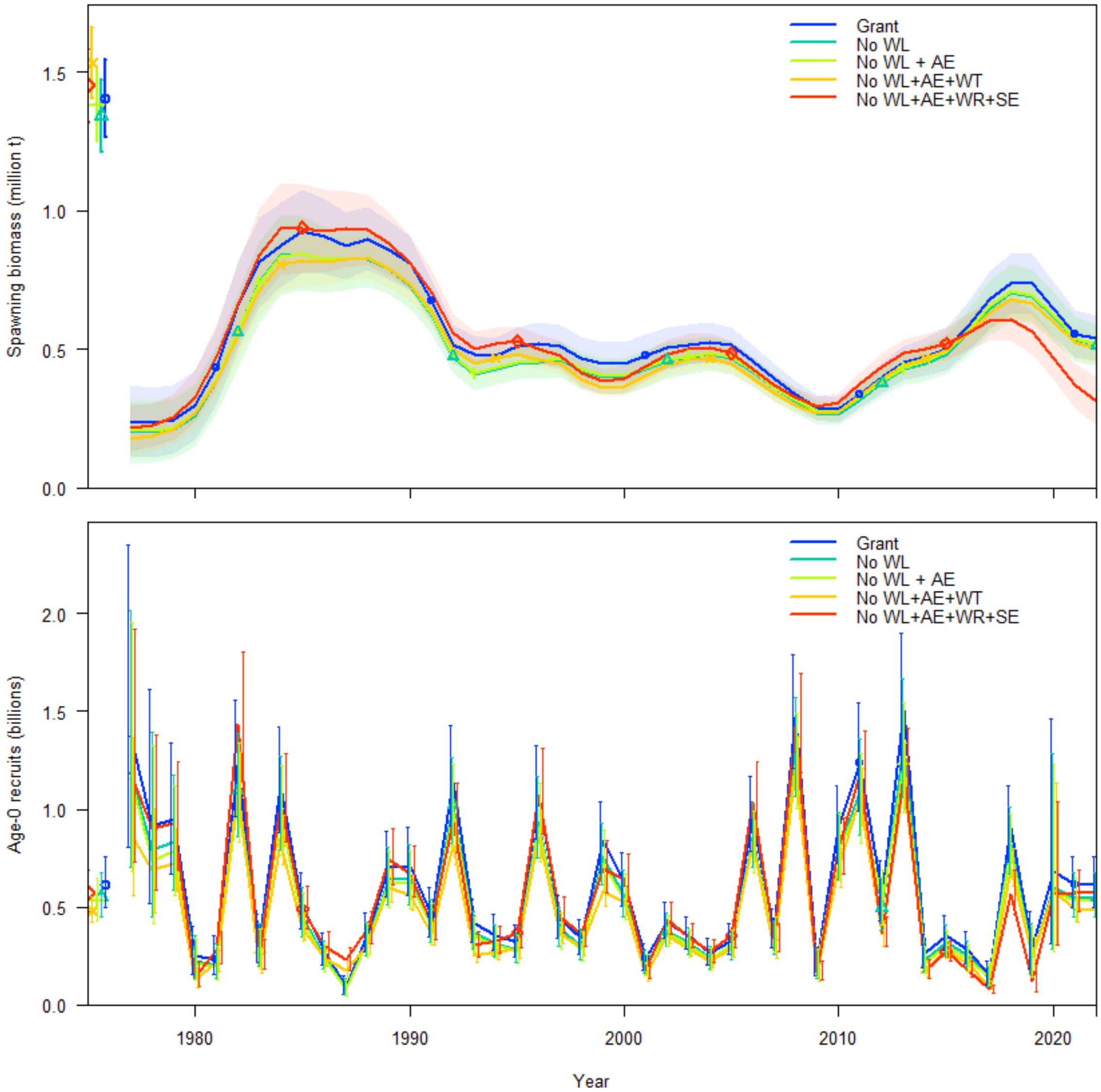


Figure 2.1.14. (Top) spawning biomass estimates (t x 10^9) and (bottom) age-o recruits (n x 10^{12}) from Model 19.12A with new data with versions GRANT = 2021 base model, No WL=No seasonally corrected weight at length relationship, +AGE = New Aging bias, +WT = new length composition data input sample sizes, +SE = Fit extra standard error for bottom trawl survey.

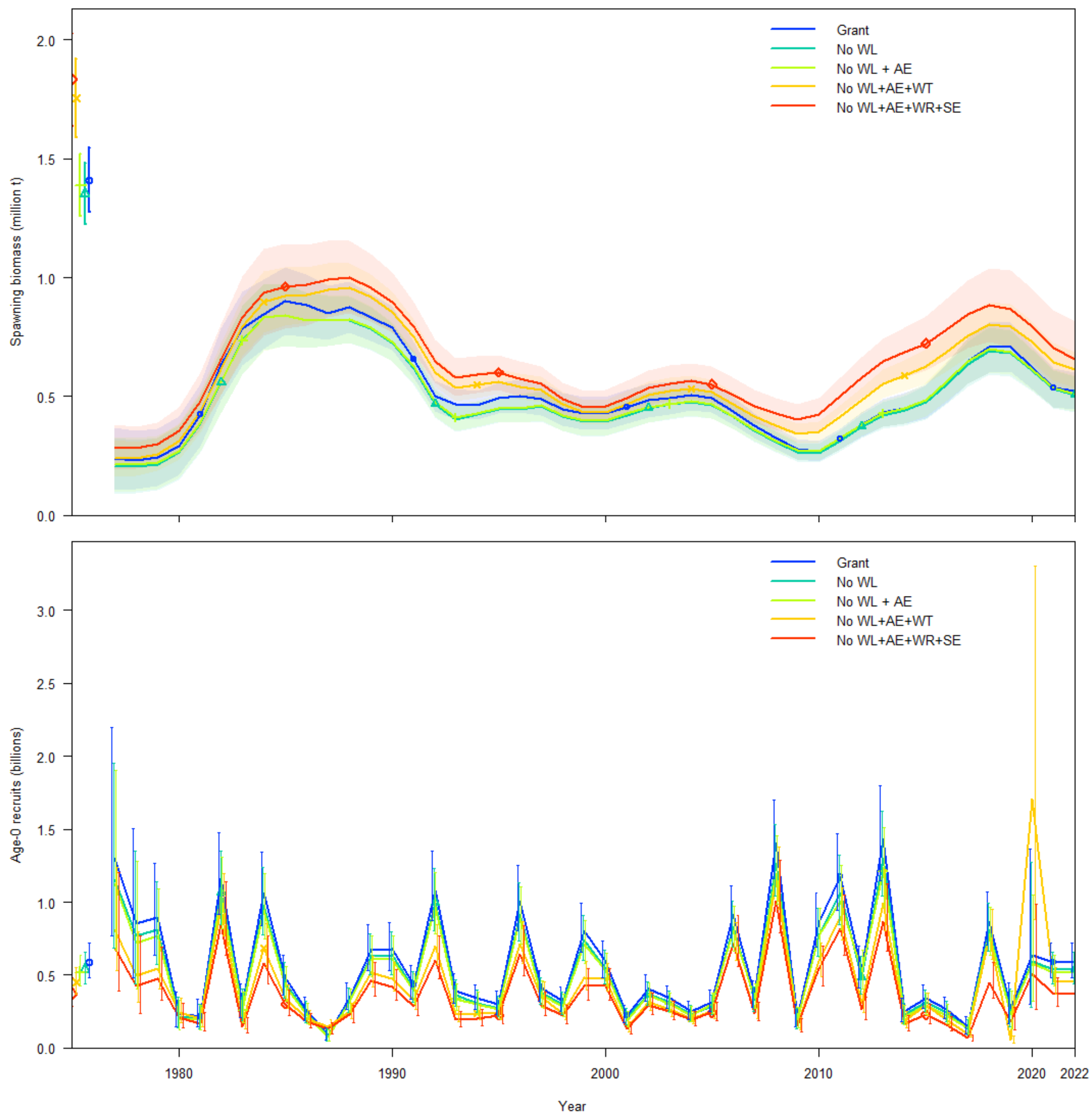


Figure 2.1.15. (Top) spawning biomass estimates (t x 10^9) and (bottom) age-o recruits (n x 10^{12}) from Model 21.1 with new data with versions GRANT = 2021 base model, No WL=No seasonally corrected weight at length relationship, +AGE = New Aging bias, +WT = new length composition data input sample sizes, +SE = Fit extra standard error for bottom trawl survey.

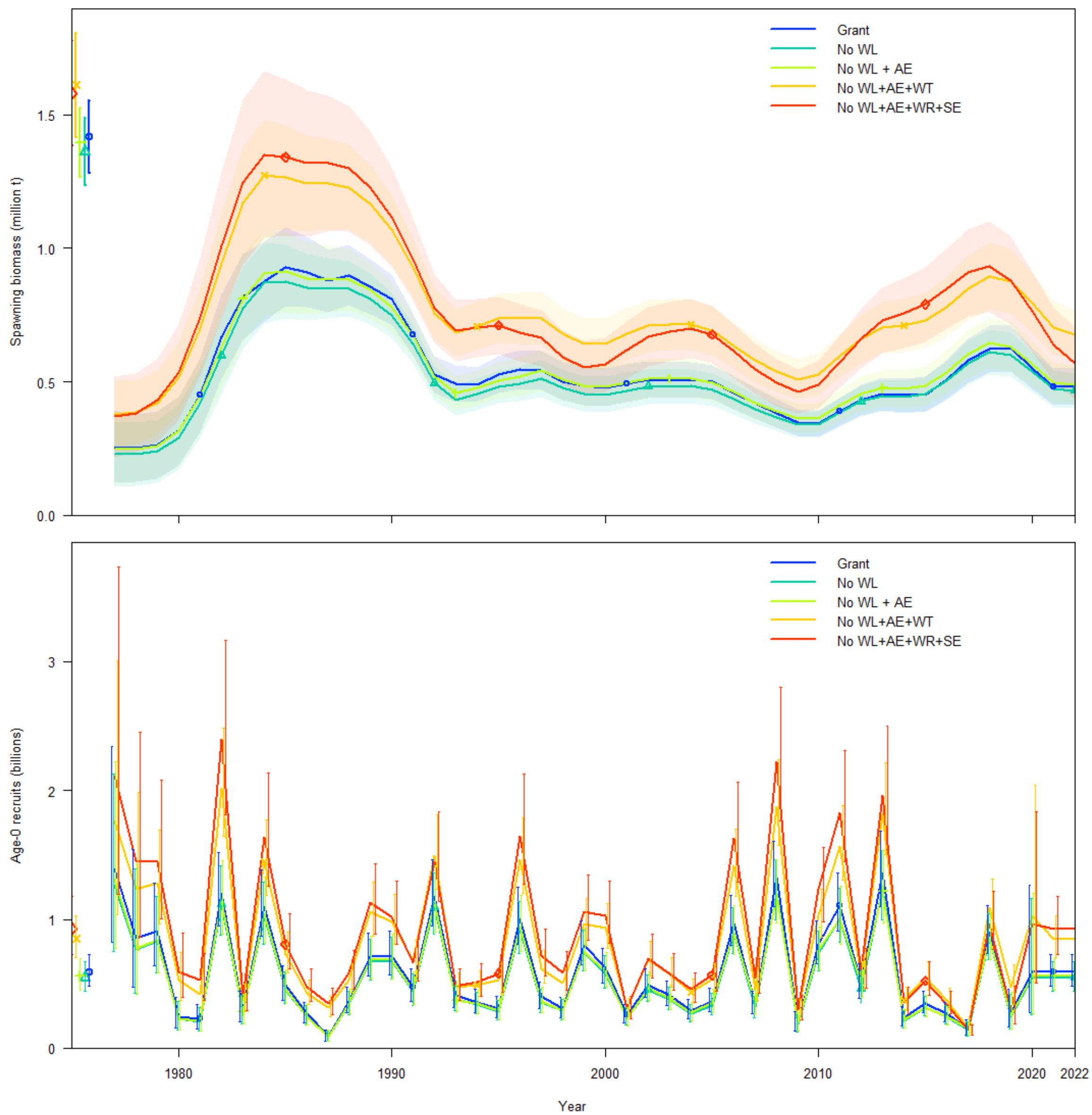


Figure 2.1.16. (Top) spawning biomass estimates (t x 10^9) and (bottom) age-o recruits (n x 10^{12}) from Model 21.2 with new data with versions GRANT = 2021 base model, No WL=No seasonally corrected weight at length relationship, +AGE = New Aging bias, +WT = new length composition data input sample sizes, +SE = Fit extra standard error for bottom trawl survey.

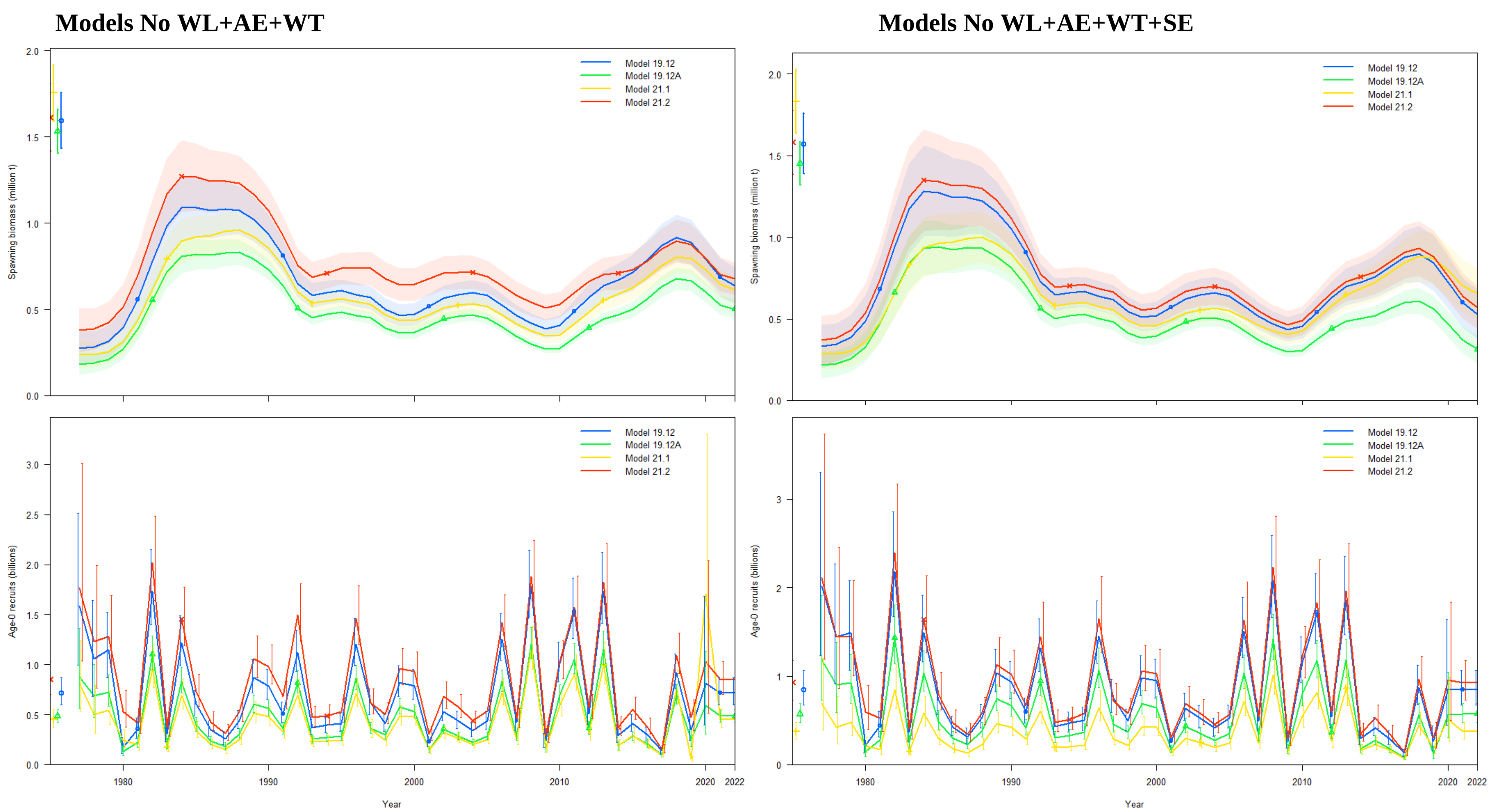
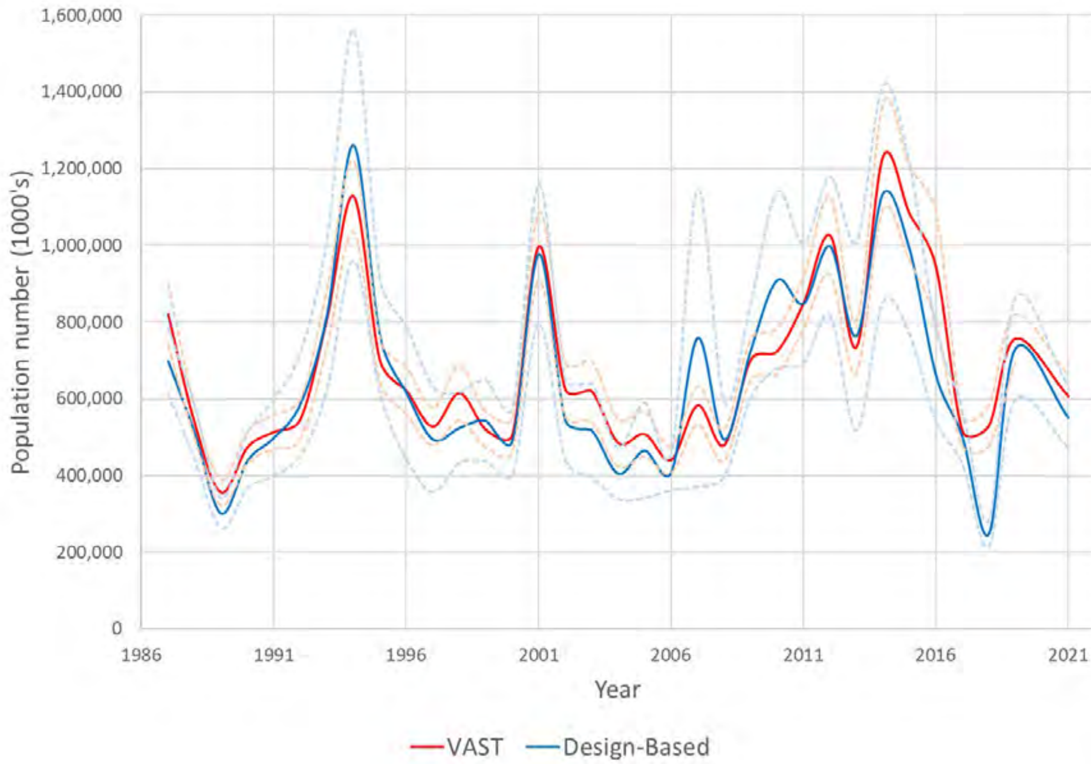


Figure 2.1.17. (Top) spawning biomass estimates (t x 10^9) and (bottom) age-o recruits (n x 10^{12}) from alternative models with new data for (left) no seasonally corrected weight at length relationship, new aging bias and new length composition data input sample sizes and (right) for no seasonally corrected weight at length relationship, new aging bias, new length composition data input sample sizes and fit with extra standard error for bottom trawl survey



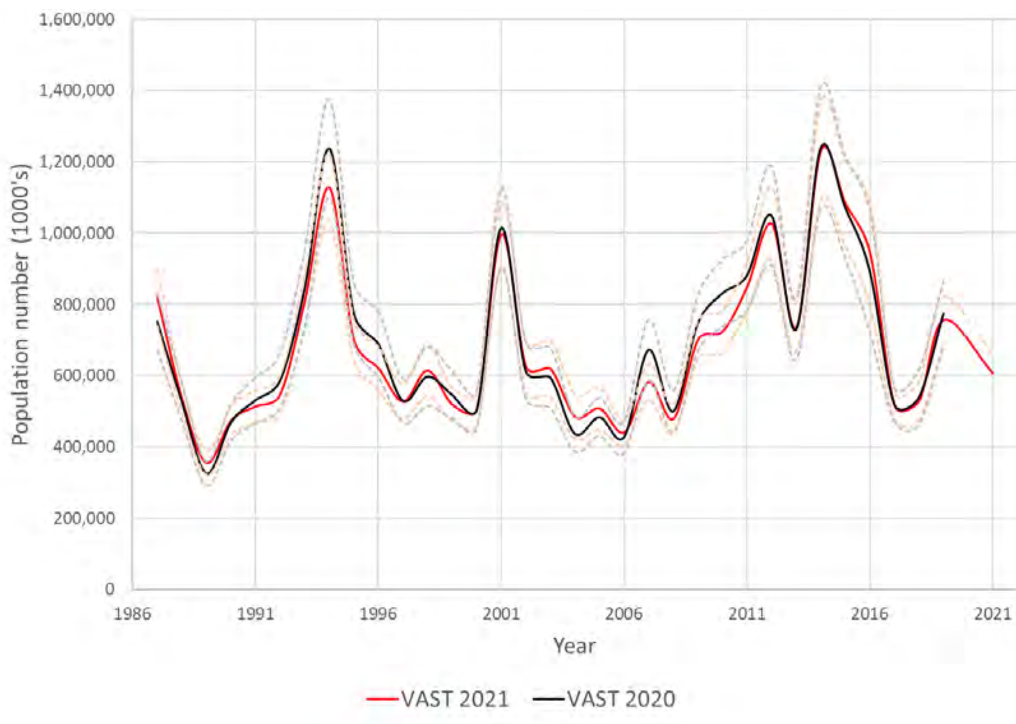


Figure 2.1.18. Eastern Bering Sea plus Northern Bering Sea survey indices for (top) the design-based in blue and 2021 VAST derived estimates in red and (bottom) the 2021 VAST derived estimates in red and 2020 VAST derived estimates in black.

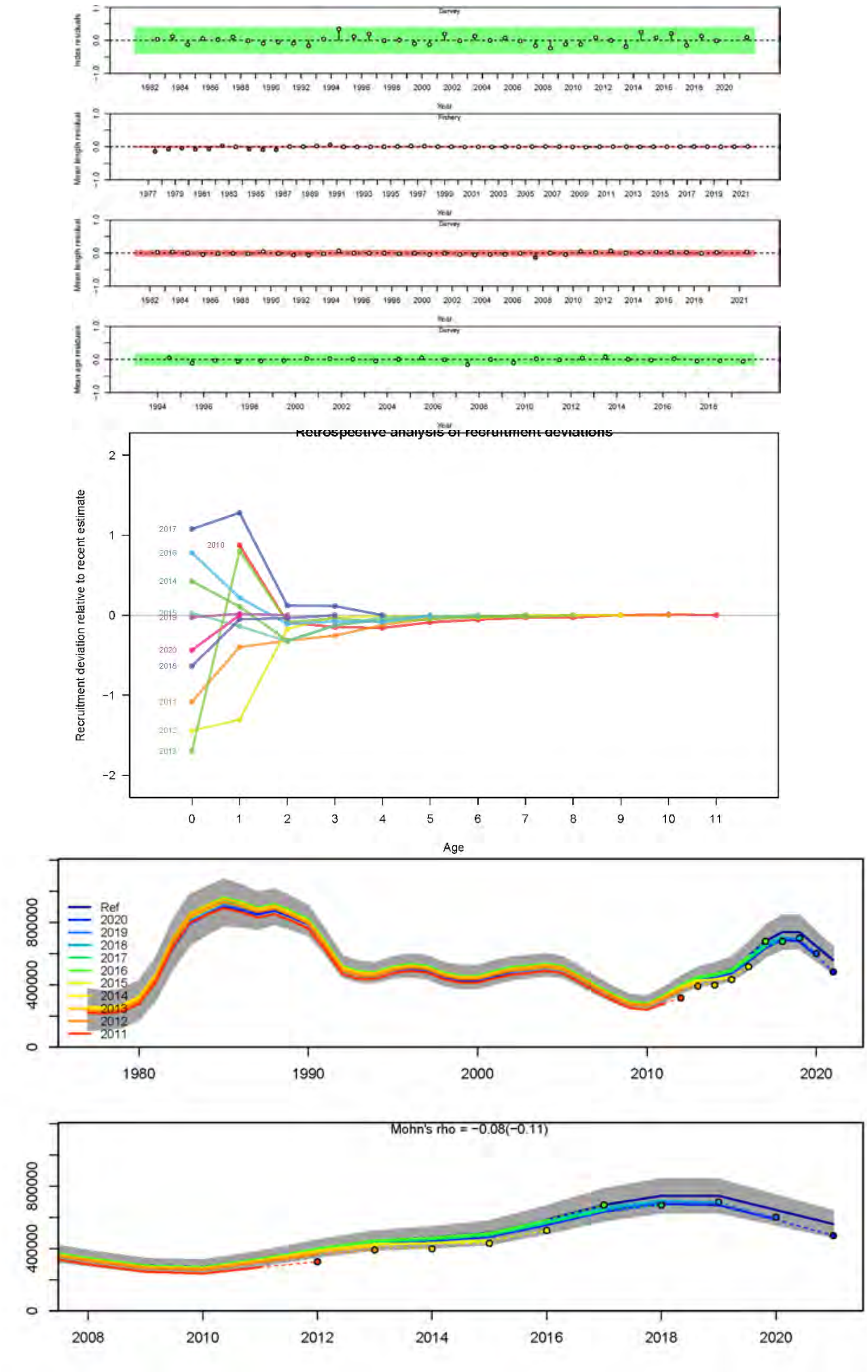


Figure 2.1.19. Model19.12A version 2021 result graphs from from Carvalho et al. (2021) (top left) residual run tests for correlated residuals, (top right) retrospective examination of year classes 2011-2020, (bottom) retrospective test showing spawning stock biomass (t).

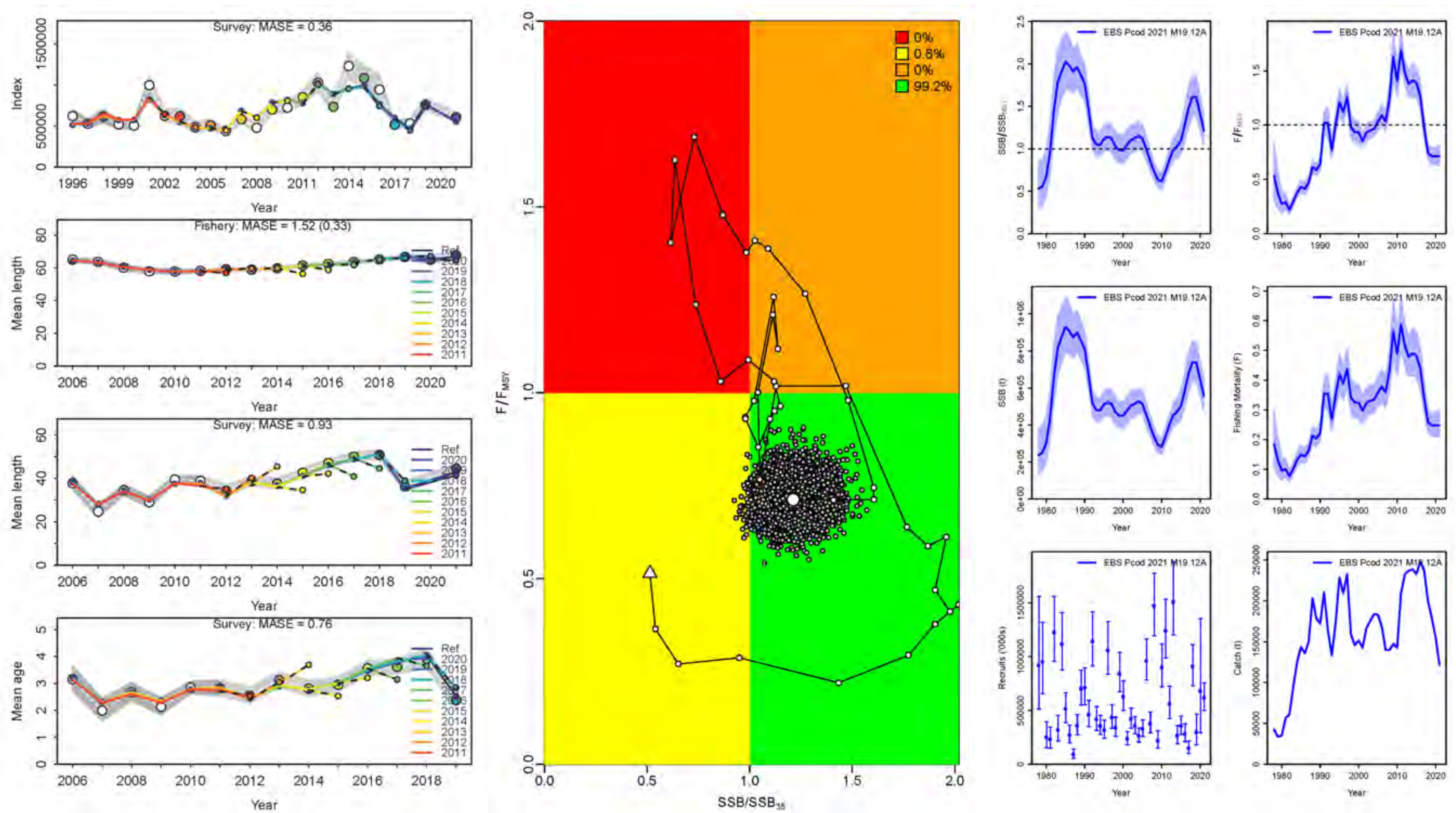


Figure 2.1.19 cont. Model19.12A version 2021 analysis results from Carvalho et al. (2021) (left) MASE analysis, (center) Kobe phase plot showing delta-Multivariate lognormal approximation Kobe probability distributions, (right) plots of various model results.

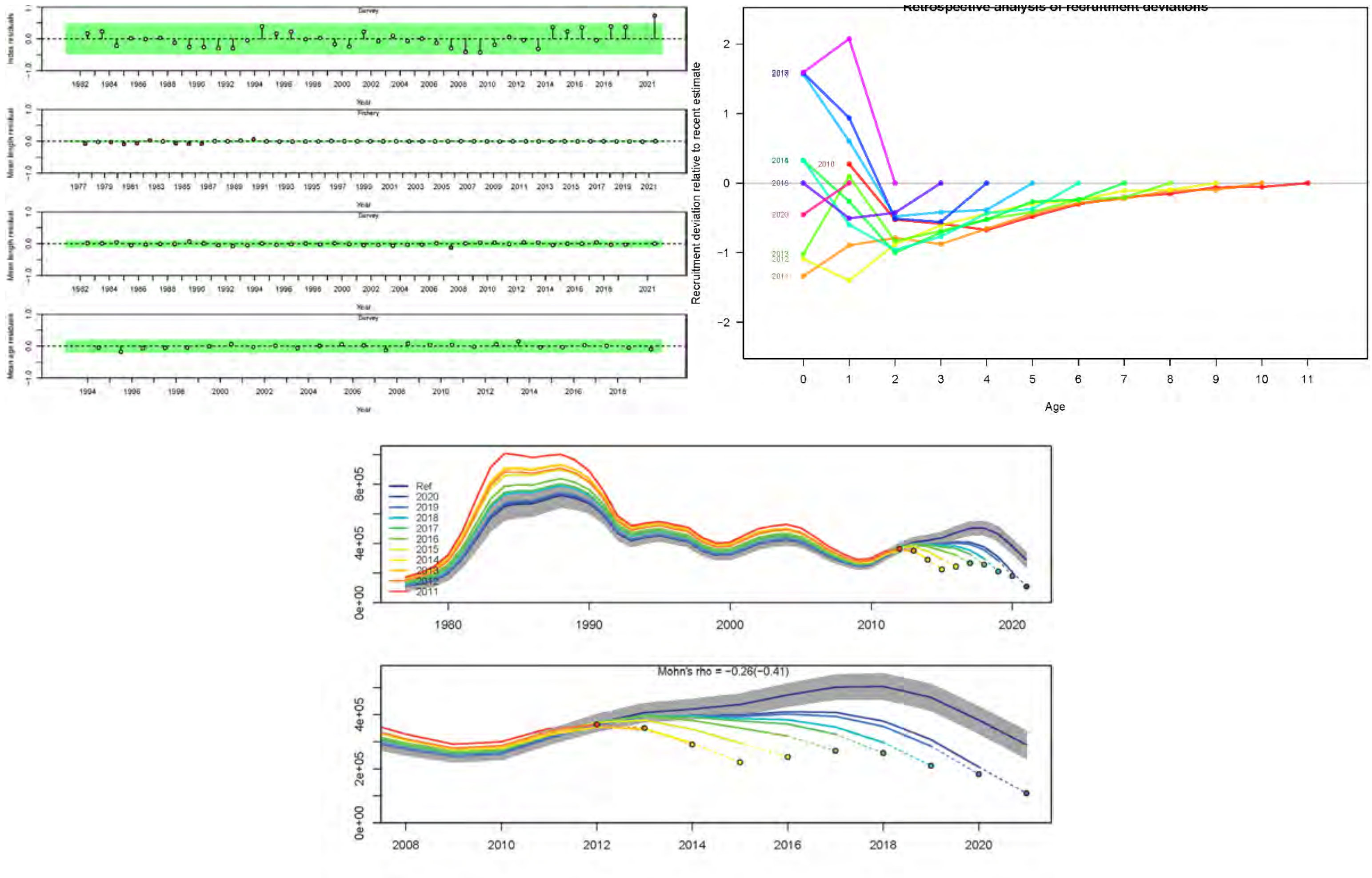


Figure 2.1.20. Model19.12A version NOWL+AGE+WT+SE result graphs from from Carvalho et al. (2021) (top left) residual run tests for correlated residuals, (top right) retrospective examination of year classes 2011-2020, (bottom) retrospective test showing spawning stock biomass (t).

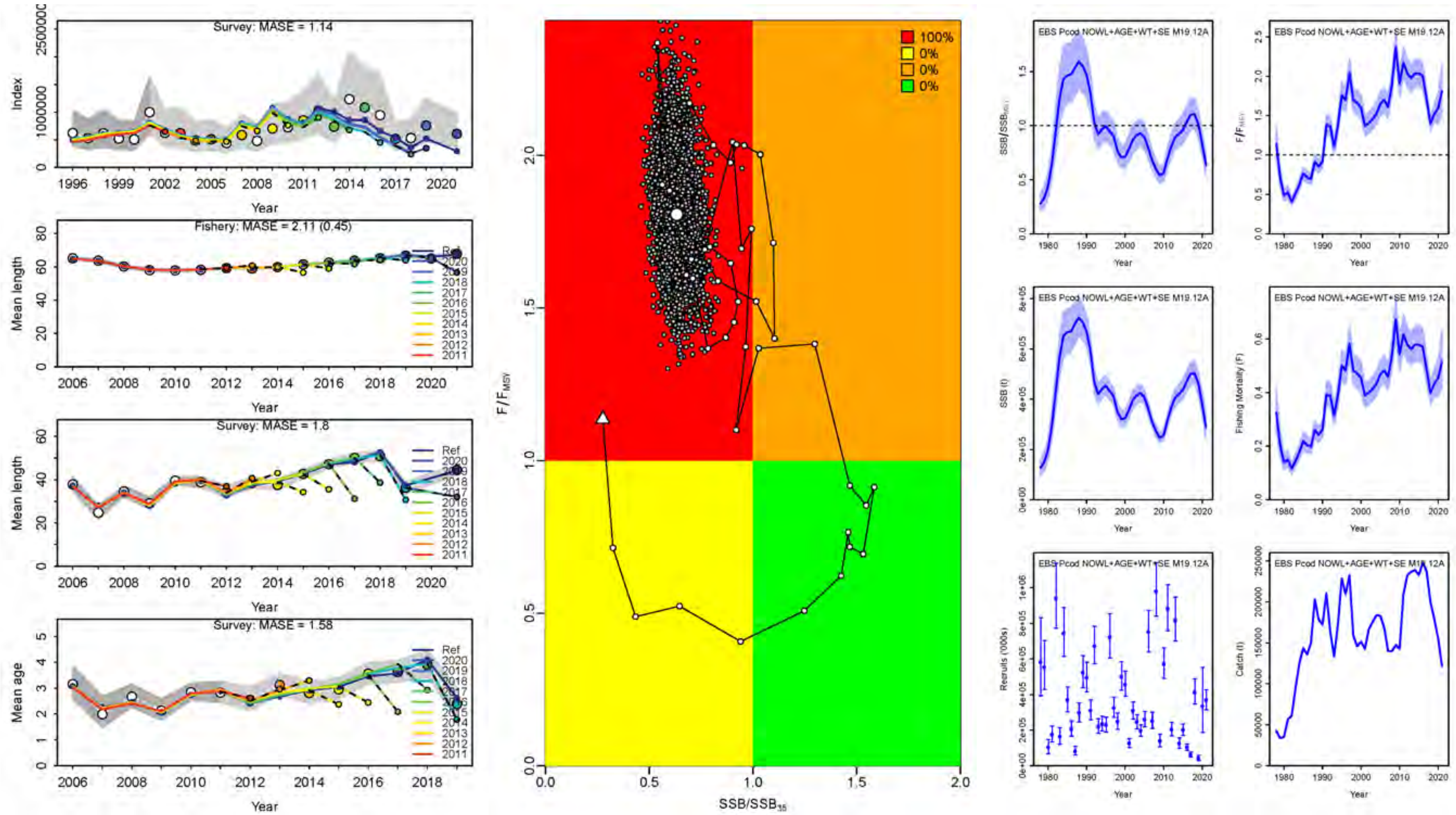


Figure 2.1.20 cont. Model19.12A version NOWL+AGE+WT+SE analysis results from Carvalho et al. (2021) (left) MASE analysis, (center) Kobe phase plot showing delta-Multivariate lognormal approximation Kobe probability distributions, (right) plots of various model results.

Appendix 2.2 Ecosystem and Socioeconomic Profile of the Pacific cod stock in the Eastern Bering Sea - Report Card

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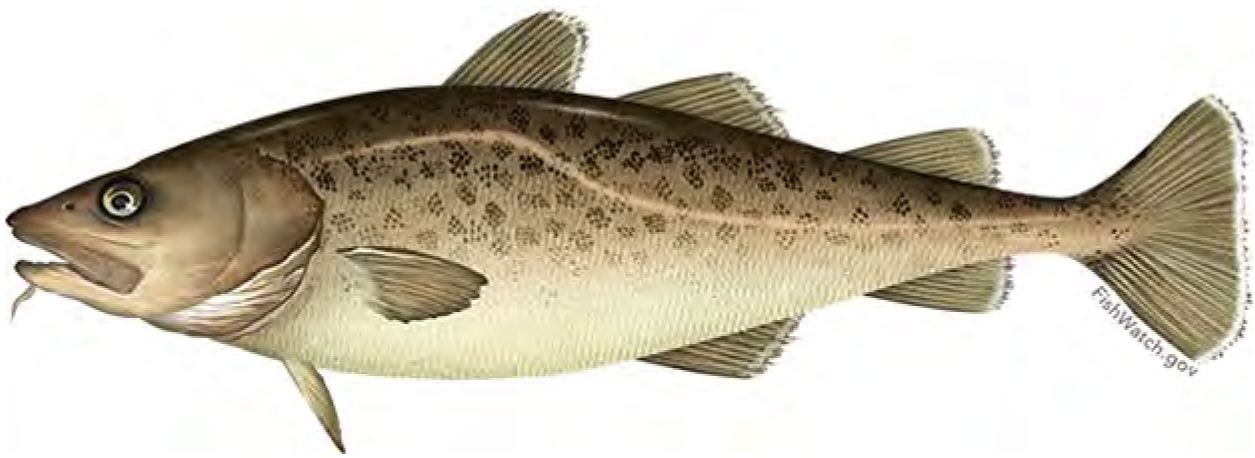

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Current Year Update

The ecosystem and socioeconomic profile or ESP is a standardized framework for compiling and evaluating relevant stock-specific ecosystem and socioeconomic indicators and communicating linkages and potential drivers of the stock within the stock assessment process (Shotwell et al., *In Review*). The ESP process creates a traceable pathway from the initial development of indicators to management advice and serves as an on-ramp for developing ecosystem-linked stock assessments.

Please refer to the last full ESP for further information regarding the ecosystem and socioeconomic linkages for this stock (Shotwell et al., 2021, available online within the Eastern Bering Sea (EBS) Pacific cod stock assessment and fishery evaluation report of Thompson et al., 2021, Appendix 2.2, pp. 347-411).

Management Considerations

The following are the summary considerations from current year updates to the ecosystem and socioeconomic indicators evaluated for EBS Pacific cod:

- North Pacific Index remains high signifying a weak Aleutian Low, high sea level pressure, warming sea surface temperatures, higher precipitation, increased downwelling, and generally calmer conditions
- Winter sea-ice extent during the advance season increased to above the time series mean from a period of below average extent since 2014, while ice extent during the retreat season is just below average increasing steadily since 2020
- Spring and summer surface temperature decreased but remains above average while bottom temperature decreased to below the time series mean
- Spring bloom peak timing was earlier than the time series mean, but bloom timing varies spatially and match would be dependent on spawning and movement of the Pacific cod population
- Condition for juvenile and adult Pacific cod were both above average, which is an increase from 2021, suggesting prey resources are sufficient
- Center of gravity estimates suggest the Pacific cod population has moved slightly more east and south in 2022, with a slightly above average area occupied, similar to the 2019 survey
- Arrowtooth flounder biomass has steadily increased over the time series but has stabilized since 2009, with a 14% increase in the 2022 bottom trawl survey
- Ex-vessel value decrease to below one standard deviation of the time series mean, and price and revenue-per-unit-effort also decreased from above average to below average in 2021
- Overall, ecosystem indicators were average in 2022 with socioeconomic indicators below average in 2021

Modeling Considerations

The following are the summary results from the intermediate and advanced stage monitoring analyses for EBS Pacific cod:

- Highest ranked predictor variable of EBS Pacific cod recruitment based on the importance methods in the intermediate stage indicator analysis was the spring and summer sea surface temperature on the southern EBS shelf (inclusion probability > 0.5)

Assessment

Ecosystem and Socioeconomic Processes

Figure 2.2.1 provides a life history conceptual model for EBS Pacific cod that summarizes ecological information and key ecosystem processes affecting survival by life stage. Pacific cod release all their eggs near the bottom in a single event during the late winter/ early spring period in the Bering Sea (Stark, 2007). Unlike most cod species, Pacific cod eggs are negatively buoyant and are semi-adhesive to the ocean bottom substrate during development (Alderdice and Forrester, 1971). Known areas of EBS Pacific cod spawning occur north of Unimak Island, near the Pribilof Islands, and on the shelf break in the vicinity of Zhemchug Canyon with spawning occurring in late-March and early April (Shimada and Kimura, 1994; Neidetcher et al., 2014). It is unknown whether recent warming events have allowed a northward expansion of the spawning distribution or a shift in the timing of spawning. Preliminary results from a recent tagging study in the northern Bering Sea (NBS) suggest that EBS Pacific cod tagged in the NBS in late summer and fall left the NBS and moved southward into deeper waters in the EBS and EBS slope as sea ice advanced in January to March. Tagged fish also traveled as far south as the Gulf of Alaska or west to Russian waters (S. McDermott, *pers. commun*.). Hatch timing/success is highly temperature-dependent (Laurel et al., 2008), with optimal hatch occurring in waters ranging between 4-6°C (Bian et al., 2016; Laurel and Rogers, 2020) over a broad range of salinities (Alderdice and Forrester, 1971). Eggs hatch into 4 mm larvae in ~2 weeks at 5°C (Laurel et al., 2008) and become surface oriented and available to pelagic ichthyoplankton nets during the spring (Doyle and Mier, 2016). During this period, Pacific cod larvae are feeding principally on eggs, nauplii and early copepodite stages of copepod prey <300 um (Strasburger et al., 2014). Warm surface waters can accelerate larval growth when prey are abundant (Hurst et al., 2010). Laboratory studies suggest warm temperatures can also indirectly impact Pacific cod larvae by way of two mechanisms: 1) increased susceptibility to starvation when the timing and biomass of prey is 'mis-matched' under warm spring conditions (Laurel et al., 2011), and 2) reduced growth by way of changes in the lipid/fatty acid composition of the zooplankton assemblage (Copeman and Laurel, 2010). Recent work has shown a stage-dependent sensitivity of cod larvae to elevated CO2 associated with ongoing ocean acidification (Hurst et al., 2019). Pacific cod larvae are known to occur in the southeastern Bering Sea along the Alaska Peninsula, but the full distribution of larvae is not well known due to spatial and temporal limitations of historical ichthyoplankton sampling. Newly hatched larvae are surface oriented and make extended diel vertical migrations with increased size and development (Hurst et al., 2009). Larvae reach a developmental milestone ('flexion') between 10-15 mm and gradually become more competent swimmers with increasing size (Voesenek et al., 2018). The dominant current regimes suggest a dispersal from south to north over the shelf and to the east along the Alaska Peninsula, and there is evidence of coherent patterns of dispersal which may link juvenile distributions to specific spawning areas (Miller et al., 2016). Age-0 Pacific cod are found in coastal areas along the Alaska Peninsula and in surface and sub-surface waters over the middle shelf (Hurst et al., 2012, 2015; Parker-Stetter et al., 2013). Meso-scale distributions have been linked to conditions with higher abundances at sites with higher local temperatures and growth potential (Hurst et al., 2012, 2018), suggesting a behavioral mechanism contributing to shifting juvenile distributions.

Juvenile cod feed predominantly on copepods and euphausiids, with additional contributions of pteropods, shrimp, crab zoea, and fishes (Strasburger et al., 2014; Farley et al., 2016). Growth conditions in summer-fall are related to temperature and foraging conditions with warm years resulting in larger body sizes but lower energy content (i.e., lower lipid content) (Farley et al., 2016). Bioenergetic model estimates of growth potential suggest that temperatures above the thermal optimal for growth combined with lower energetic content of the diet may lead to reduced late-summer growth during warm years in the southeastern Bering Sea (Hurst et al., 2018). Adult Pacific cod are opportunistic predators, eating a variety of zooplankton (including euphausiids), crab, and fish species (Aydin and Mueter, 2007) and are able to switch between benthic and demersal foraging based on prey availability (Aydin, 2020). In the eastern Bering Sea, Pacific cod feed on zooplankton until reaching approximately 20cm fork length, then feed primarily on benthic epifauna between 20-60cm fork length, and at larger sizes (60cm+) switch to feeding on fish, crustaceans, and other large invertebrates, in particular walleye pollock (Gadus chalcogrammus) and Chionoecetes spp. of crab (snow crab and tanner crab). There have been limited surveys in the NBS but of the years surveyed, for most years Chionoecetes spp. (primarily identified as snow crab) were the largest portion of cod diet, except for 2010 in which both flatfish and forage fish were the main prey items. These diet trends may be related to the extent of the cold pool in some year. Competitors for prey resources may also provide indirect evidence of conditions experienced by Pacific cod. While historical recruitment trends between Pacific cod and walleye pollock have mirrored each other, suggesting that the species respond similarly to environmental conditions, the time series appear to decouple after approximately 2010 and may indicate broad-scale transitions in the southeastern Bering Sea ecosystem (Siddon et al., 2019). Other competitors of EBS Pacific cod may include gray whales (feeding on benthic amphipods, zooplankton) and seabirds (e.g., short-tailed shearwaters are planktivorous birds and feed on euphausiids). Pacific cod are cannibalistic and rates of cannibalism might be expected to increase as the abundance of older, larger fish increases concurrent with increases in juvenile abundance. However, a spatial mismatch may mediate that stressor; based on bottom trawl survey results, large increases of small fish occurred over the EBS while larger fish occurred over the NBS (L. Britt, pers commun.). Other predators of Pacific cod include northern fur seals, Steller sea lions, various whale species, and tufted puffin.

Catches of Pacific cod are the second largest in the Bering Sea and Aleutian Islands region. Pacific cod accounted for 10% of the BSAI's FMP groundfish harvest and 93% of the total Pacific cod harvest in Alaska (Fissel et al., 2021). The Pacific cod total allowable catch (TAC) is allocated to multiple sectors (fleets). CDQ entities receive 10% of the total BSAI quota. The largest sectoral allocation goes to the freezer longline catcher/processors (CPs), which receive roughly 44% of the total BSAI cod quota (48.7% non-CDQ quota). While not an official catch share program, the freezer longline CPs have formed a voluntary cooperative that allows them to form private contracts among members to distribute the sectoral allocation. The remaining large sectors are the trawl CPs, trawl catcher vessels (CVs), pot gear CVs, and some smaller sideboard limits to cover the catch of Pacific cod while targeting other species.

Tables 2.2.1a-c provide a stock specific summary for EBS Pacific cod of the economic information presented in the current Economic SAFE (A. Ableman, *per. commun.*). The CVs (collectively referred to as the inshore sector) make deliveries to shore-based processors, and catcher/processors process catch at-sea before going directly to the wholesale markets. Among the at-sea CPs, catch is distributed approximately three-quarters to hook-and-line and one quarter to trawl. U.S. exports of cod are roughly proportional to U.S. cod production. More than 90% of the exports are H&G, much of which goes to China for secondary processing and re-export. The cod industry has largely avoided U.S. tariffs that would have a significant negative impact on them in the U.S.-China trade war. However, Chinese tariffs on U.S. products could inhibit future growth in that market. Japan and Europe (mostly Germany and the Netherlands) are also important export destinations. Japan and Europe accounted for 12% and 22% of the export volume respectively. Approximately 35% of Alaska's cod production is estimated to remain in the U.S. Because U.S. cod production is approximately 15% of global production and the BSAI is over 90% of U.S. production, BSAI Pacific cod is a significant component of the broader global cod market. A portion of the Russian catch of Pacific cod became MSC certified in Oct. 2019, which could put further downward pressure on prices going forward.

An analysis of commercial processing and harvesting data may be conducted to examine sustained participation for those communities substantially engaged in a commercial fishery. The Annual Community Engagement and Participation Overview (ACEPO) is a new report that evaluates engagement at the community level and focuses on providing an overview of harvesting and processing sectors of identified highly engaged communities for groundfish and crab fisheries in Alaska (Wise et al., 2021). In 2019, 73% of retained catch occurred At Sea. Several other communities accounted for smaller, but notable percentages of landed volume, including Akutan, Adak, and Unalaska/Dutch Harbor. The number of processors landing BSAI Pacific cod has decreased since 2000; however the number of communities engaging in processing has increased to include False Pass, St. Paul, and Nome (Wise et al., 2021).

Indicator Suite
The following list of indicators for EBS Pacific cod is organized by categories, three for ecosystem indicators (physical, lower trophic, and upper trophic) and three for socioeconomic indicators (fishery performance, economic, and community). A short description and contact name for the indicator contributor are provided. For ecosystem indicators, we also include the anticipated sign of the proposed relationship between the indicator and the stock population dynamics where relevant. Please refer to the full ESP document for detailed information regarding the ecosystem and socioeconomic indicator descriptions and proposed mechanistic linkages for this stock (Shotwell et al., 2021). Time series of the ecosystem and socioeconomic indicators are provided in Figure 2.2.2a and Figure 2.2.2b, respectively.

This year, the morphometric condition indicator was estimated using VAST (Grüss et al., 2020; Thorson, 2019) instead of the stratum biomass weighted length-weight residual method from previous years. The VAST relative condition indicator is the ratio of weight-at-length relative to the time series mean based on annual allometric intercepts. In other words, we use VAST to estimate annual allometric intercepts, a, in the length-weight equation, W=aL^b, and divide the annual intercepts by the mean allometric intercept, condition = a_year/mean(a) (S. Rohan, *pers. commun.*). Trends in the historical and new indicator are similar based on the strong correlation between the historical and new indicator (r = 0.91 for juveniles, r = 0.87 for adults), although there are notable differences in some years. Specifically, for juveniles, 2017 was a negative year using the old indicator (~1 standard deviation below the mean) but a neutral year with the new indicator, negative years in 2009 and 2012 are still negative but the anomaly is larger, and the anomaly in 1999 decreased from 3.2 standard deviations below the mean to 1.8 standard deviations below the mean (a 'cold' year with an early survey start). Specifically, for adults, the year with the lowest condition for the old indicator was 1999 (a 'cold' year with an early survey start), with an anomaly greater than two standard deviations from the mean. Based on the new VAST relative condition indicator, 1999 was a neutral year and the year with the lowest condition was 2012. Despite these differences, new indicator trends generally match the trend from the old indicator (S. Rohan, *pers. commun.*).

<u>Ecosystem Indicators:</u>

Physical Indicators (Figure 2.2.2a.a-e)

a.) North Pacific Index (NPI) calculated as the area-weighted sea level pressure (SLP) from November to March over the region 30°N-65°N, 160°E-140°W (contact: M. Wang). Proposed sign of relationship is positive and the time series is not lagged for the intermediate stage indicator analysis.
b.) Anomalies of average daily sea-ice extent relative to 1978-2010 mean computed over ice-advance season of December through February (contact: M. Wang). Proposed sign of relationship is positive and the time series is not lagged for the intermediate stage indicator analysis.
c.) Anomalies of average daily sea-ice extent relative to 1978-2010 mean computed over ice-retreat season of March through May (contact: M. Wang). Proposed sign of relationship is positive.
d.) Spring to summer (April-June) daily sea surface temperatures (SST) for the EBS shelf from the NOAA Coral Reef Watch Program (contact: M. Callahan). Proposed sign of

relationship is negative and the time series is not lagged for the intermediate stage indicator analysis.

e.) Summer (July-September) bottom temperatures over the EBS shelf from the Bering 10K ROMS-NPZ model (contact K. Kearney). Proposed sign of relationship is negative and the time series is not lagged for the intermediate stage indicator analysis.

Lower Trophic Indicators (Figure 2.2.2a.f-g)

f.) Peak timing of the spring bloom averaged across individual ADF&G statistical areas in the EBS from the MODIS satellite (contact: J. Nielsen). Proposed sign of relationship is positive.

g.) Summer euphausiid abundance for the EBS shelf from the AFSC acoustic survey (contact: P. Ressler). Proposed sign of relationship is positive.

Upper Trophic Indicators (Figure 2.2.2a.h-m)

h.) Summer condition for juvenile (<460 mm) Pacific cod from the AFSC EBS shelf bottom trawl survey (contact: S. Rohan). Proposed sign of relationship is positive.

i.) Summer condition for adult (>=460 mm) Pacific cod from the AFSC EBS shelf bottom trawl survey (contact: S. Rohan). Proposed sign of relationship is positive.

j.) Summer Pacific cod center of gravity eastings estimated by a spatio-temporal model using the package VAST on AFSC EBS bottom trawl survey data (contact: L. DeFilippo and J. Conner). Proposed sign of relationship is positive and the time series is not lagged for the intermediate stage indicator analysis.

k.) Summer Pacific cod center of gravity northings estimated by a spatio-temporal model using the package VAST on AFSC EBS bottom trawl survey data (contact: L. DeFilippo and J. Conner). Proposed sign of relationship is negative and the time series is not lagged for the intermediate stage indicator analysis.

l.) Summer Pacific cod area occupied estimated by a spatio-temporal model using the package VAST on AFSC EBS bottom trawl survey data (contact: L. DeFilippo and J. Conner). Proposed sign of relationship is positive and the time series is not lagged for the intermediate stage indicator analysis.

m.) Arrowtooth flounder total biomass from the most recent stock assessment model in the EBS (contact: K. Shotwell). Proposed sign of relationship is negative and the time series is lagged two years for the intermediate stage indicator analysis.

Socioeconomic Indicators:

Economic Indicators (Figure 2.2.2b.a-c)

a.) Annual estimated real ex-vessel value of EBS Pacific cod (contact: J. Lee)

b.) Annual real ex-vessel price per pound of EBS Pacific cod from fish ticket information (contact: J. Lee).

c.) Annual estimated real revenue per unit effort measured in weeks fished of EBS Pacific cod (contact: J. Lee)

Community Indicators (Figure 2.2.2b.d-e)

d.) Regional quotient of Pacific cod for harvesting revenue of the highly engaged community of Unalaska Dutch Harbor (contact: S. Wise)

e.) Regional quotient of Pacific cod for processing revenue of the highly engaged community of Unalaska Dutch Harbor (contact: S. Wise)

Indicator Monitoring Analysis

There are up to three stages (beginning, intermediate, and advanced) of statistical analyses for monitoring the indicator suite listed in the previous section. The beginning stage is a relatively simple evaluation by traffic light scoring. This evaluates the current year trends relative to the mean of the whole time series, and provides a historical perspective on the utility of the whole indicator suite. The intermediate stage uses importance methods related to a stock assessment variable of interest (e.g., recruitment, biomass, catchability). These regression techniques provide a simple predictive performance for the variable of interest and are run separate from the stock assessment model. They provide the direction, magnitude, uncertainty of the effect, and an estimate of inclusion probability. The advanced stage is used for testing a research ecosystem linked model and output can be compared with the current operational model to understand information on retrospective patterns, prediction performance, and comparisons of other model output such as terminal spawning stock biomass or mean recruitment. This stage provides an on-ramp for introducing an alternative ecosystem linked stock assessment model to the current operational stock assessment model and can be used to understand the potential reduction in uncertainty by including the ecosystem information.

Beginning Stage: Traffic Light Test

We use a simple scoring calculation for this beginning stage traffic light evaluation. Indicator status is evaluated based on being greater than (“high”), less than (“low”), or within (“neutral”) one standard deviation of the long-term mean. A sign based on the anticipated relationship between the indicator and the stock (generally shown in Figure 2.2.1 and specifically by indicator in the Indicator Suite, Ecosystem Indicators section) is also assigned to the indicator where possible. If a high value of an indicator generates good conditions for the stock and is also greater than one standard deviation above the mean, then that value receives a "+1" score. If a high value generates poor conditions for the stock and is greater than one standard deviation above the mean, then that value receives a "-1" score. All values less than or equal to one standard deviation from the long-term mean are average and receive a "0" score. The scores are summed by the three organizational categories within the ecosystem (physical, lower trophic, and upper trophic) or socioeconomic (fishery performance, economic, and community) indicators and divided by the total number of indicators available in that category for a given year. The scores over time allow for comparison of the indicator performance and the history of stock productivity (Figure 2.2.3). We also provide five year indicator status tables with a color (ecosystem indicators only) for the relationship with the stock (Tables 2.2.2a,b) and evaluate the current year status in the historical indicator time series graphic (Figures 2.2.2a,b) for each ecosystem and socioeconomic indicator.

We evaluate the status and trends of the ecosystem and socioeconomic indicators to understand the pressures on the EBS Pacific cod stock regarding recruitment, movement, stock productivity, and stock health. We start with the physical indicators and proceed through the increasing trophic levels, then evaluate the economic and community indicators as listed above. Here we concentrate on updates since the last ESP (Shotwell et al., 2021). Overall, the physical, lower trophic, and upper trophic level indicators scored average for 2022 (Figure 2.2.3). Compared to last year’s results, this is the same value for both physical and lower trophic indicators, and an improvement from below average for the upper trophic indicators. We also note caution when comparing scores between odd to even years as there is one lower trophic indicator missing in even years due to an off-cycle year survey. Also, there were survey cancellations due to COVID-19 or survey delays in 2020 through 2022 that have limited production of several indicators. Economic and community indicators are all lagged by at least one year due to timing of the availability of the current year information and the production of this report. Economic indicators scored below average for 2021 (data received in 2022), which is a decrease from average in 2020. There have been no updates for community indicators since 2019.

For physical indicators (Table 2.2.2a, Figure 2.2.2a.a-e), the winter to spring North Pacific Index (NPI) decreased slightly but remains high in 2022 (Figure 2.2.2a.a). The NPI effectively represents the state of the Aleutian Low with higher values signifying high sea level pressure, warming sea surface temperatures, higher precipitation, and increased downwelling (Weingartner, 2005). The extent of the sea ice during the ice advance season (Dec-Feb) decreased dramatically in 2014 and continued to decline to a time-series low in 2018, but increased somewhat in 2019-2021 but jumped to above average in 2022

(Figure 2.2.2a.b). Similarly, the extent of sea ice during the ice retreat season (Mar-May) steadily decreased from a time-series high in 2012 to the time-series low in 2018, remained low in 2019, but increased in 2020 and has been steadily increasing to just below the time-series average in 2022 (Figure 2.2.2a.c). Spring to summer surface temperatures decreased from last year but remain above average in the warm stanza that has dominated since 2014 (Figure 2.2.2a.d). The simulated 2022 conditions were very near the historical (1971-2022) average (Figure 2.2.2a.e). The mean SEBS bottom temperature in July was 2.53°C, just below the mean of 2.78°C. The 2°C cold pool index was 0.39, likewise just to the cool side of the mean of 0.35. For the first time since 2017, below-0°C water remained in the northern part of the SEBS region in the summer, resulting in a 0°C cold pool index of 0.09 (historical mean 0.11). 2022 resembles other average-to-cool years, with a spatial pattern characterized by summer <2°C water across much of the southeast middle shelf, patches of <1°C water in both the northern and southern parts of the southeast middle shelf and some <0°C water in the northern southeast middle shelf. When compared to previous years, conditions most closely resemble 2017.

For lower trophic indicators (Table 2.2.2a, Figure 2.2.2a.f-g), the timing of the spring bloom was earlier than average (Figure 2.2.2a.f). The bloom timing varies spatially, with blooms occurring earlier in the inner domain to later in the outer domain (Nielsen et al., 2021). A match or mismatch with larvae of the EBS Pacific cod stock would likely depend on where the primary spawning was occurring from year to year and thus seems dependent on movement. The euphausiid abundance index (Figure 2.2.2a.g) steadily dropped from a high in 2009 to a low in 2016, with only a moderate increase in 2018 and again in 2022 (still low for the time-series), similar to the Gulf of Alaska euphausiid index (Ressler, 2018, 2019; Kimmel et al., 2020). The 2022 year class may have encountered higher abundances of euphausiids in spring and late summer.

For upper trophic indicators (Table 2.2.2a, Figure 2.2.2a.h-m), condition of juvenile Pacific cod in the EBS in 2022 was slightly above average but within one standard deviation of the time series mean, which continues the trend of neutral morphometric condition since 2017. Historically condition of juveniles increased from 1999 to 2004, decreased from 2005 to 2009, then fluctuates around neutral from 2010 to 2022, aside from a negative year in 2012 and positive year in 2016 (Figure 2.2.2a.h). The condition of adult Pacific cod in the EBS in 2022 was above average but within one standard deviation of the time series mean, which also continues the trend of neutral morphometric condition since 2018. The neutral condition in recent years (2018–2022) represents an increase from the three prior years with below average condition from 2015–2017. Historically condition of adults increased from 1999 to 2003, decreased from 2003 to 2006, then fluctuating around neutral from 2007 to 2022, aside from negative years in 2009, 2012, 2015, and 2017 (Figure 2.2.2a.h-i). The current condition of juveniles and adults suggests that prey resources were sufficient. Many factors may contribute to the variation in morphometric condition such as temperature-dependent metabolic rates, survey timing, stomach fullness of individual fish, migration patterns, and distribution of samples within survey strata (Rohan and Prohaska, 2022). Center of gravity estimates for EBS Pacific cod have shifted from 2021, with the population center moving more east (slightly east of average) and south (still north of average) (Figure 2.2.2a.j-k). Area occupied has increased to slightly above average (Figure 2.2.2a.l). Arrowtooth flounder biomass remains well above average from the most recent stock assessment model (Shotwell et al., 2020) and 2022 survey estimates are 14% higher than in 2021 from the bottom trawl survey (shelf habitat).

For economic indicators (Table 2.2.2b, Figure 2.2.2b.a-c), ex-vessel value decreased below one standard deviation of the time series mean and similar to the previous low value of 2009 (Figure 2.2.2b.a). Price per pound and revenue per unit effort also decreased from above average to below average (but still within one standard deviation of the time series mean) (Figure 2.2.2b.b-c). Since 2016 reductions in global supply have put upward pressure on prices, resulting in significant year over year price increases in

2017 and 2018. In 2019 prices leveled off, decreasing slightly, as markets have adjusted. In 2020 COVID-19 closures resulted in increased demand for retail products and frozen products, and decreased foodservice and fresh products. Retail and foodservice are both significant components of the market for cod products. As such, the impact of COVID-19 on prices appears muted, with only marginal changes in first-wholesale and export prices. Cost pressure from COVID-19 mitigation efforts likely had impacts on net revenues as well as upstream impacts on ex-vessel prices, which decreased significantly.

The community indicators evaluated in the ESP are similar to those presented in the ACEPO report, but on the stock level rather than the community level (Table 2.2.2b, Figure 2.2.2b.d-e). The indicators are separated into two categories of fisheries involvement: commercial processing and commercial harvesting (Wise et al., 2021). By separating commercial processing from commercial harvesting, the engagement indices highlight the importance of fisheries in communities that may not have a large amount of landings or processing in their community, but have a large number of fishers and/or vessel owners that participate in commercial fisheries who are based in the community. At this time there are no updates to the community indicators. In the future we plan to evaluate how to reference the products available in the ACEPO report for use in the ESPs to inform on stock health.

<u>Intermediate Stage: Importance Test</u>

Bayesian adaptive sampling (BAS) was used for the intermediate stage statistical test to quantify the association between hypothesized predictors and EBS Pacific cod recruitment and to assess the strength of support for each hypothesis. In this stage, the full set of indicators is first winnowed to the predictors that could directly relate to recruitment and highly correlated covariates are removed. We further restrict potential covariates to those that can provide the longest model run and through the most recent estimate of recruitment that is well estimated in the current operational stock assessment model (Figure 2.2.4a). This results in a model run from 1985 through the 2019 year-class. We then provide the mean relationship between each predictor variable and log EBS Pacific cod recruitment over time (Figure 2.2.4b, left side), with error bars describing the uncertainty (95% confidence intervals) in each estimated effect and the marginal inclusion probabilities for each predictor variable (Figure 2.2.4b, right side). A higher probability indicates that the variable is a better candidate predictor of EBS Pacific cod recruitment. The highest ranked predictor variable (inclusion probability > 0.5) based on this process is the spring summer sea surface temperature index on the shelf (same as last year) (Figure 2.2.4).

<u>Advanced Stage: Research Model Test</u>

In the future, highly ranked predictor variables could be evaluated in the advanced stage statistical test, which is a modeling application that analyzes predictor performance and estimates risk within the operational stock assessment model. A multi-species statistical catch-at-age assessment model (known as CEATTLE; Climate- Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics; Holsman et al., 2016) has been developed for understanding trends in age-1 total mortality for walleye pollock, Pacific cod, and arrowtooth flounder from the EBS (Holsman et al., 2021). Total mortality rates are based on residual mortality inputs (M1), model estimates of annual predation mortality (M2), and fishing mortality (F). CEATTLE for the southeastern Bering Sea has recently been implemented in Template Model Builder (Kristensen et al., 2015) to allow for the fitting of multiple sources of data, time-varying selectivity, time-varying catchability, and random effects. The model is based, in part, on the parameterization and data used for the most recent stock assessment model of each species (Ianelli et al., 2021, Thompson et al., 2021, and Shotwell et al., 2020). The model is fit to data from five fisheries and seven surveys, including both age and length composition (assumed to come from a multinomial distribution). Model estimates of M2 are empirically driven by bioenergetics-based consumption information and diet data from the EBS to inform predator-prey suitability. The most recent model was fit to data from 1979 to 2021 and showed evidence of continued decline in predation mortality on age-1 EBS Pacific cod, pollock, and arrowtooth flounder. The warm temperatures in this system continue to lead to high metabolic (and energetic) demand of predators; however, declines in total predator biomass may be contributing to an overall decline in total consumption and therefore reduced predation rates and mortality.

The EBS CEATTLE model can provide gap-free estimates of predation mortality that could be tested in the operational stock assessment model. Additionally, the time series of bioenergetics-based consumption input to the CEATTLE model could be compared to condition indicators from the surveys for context on recent condition trends. The spring and summer sea surface temperature index could be used directly to help explain the variability in recruitment deviations and predict pending recruitment events for EBS Pacific cod. Also, the sea ice extent during the ice retreat period, or simply the center of gravity northings from the VAST model, could be used as covariates if future spatial models were developed for this stock.

Data Gaps and Future Research Priorities

While the metric and indicator assessments provide a relevant set of proxy indicators for evaluation at this time, there are certainly areas for improvement. Gaps in indicator time series cause issues with updating the ESP and can lead to difficulty in identifying impending shifts in the ecosystem that may impact the EBS Pacific cod population. Development of high-resolution remote sensing (e.g., regional surface temperature, transport estimates, primary production estimates) or climate model indicators (e.g., bottom temperature, nutrient-phytoplankton-zooplankton variables) would assist with the current multi-year data gap for several indicators if they sufficiently capture the main trends of the survey data and are consistently and reliably available.

Refinements or updates to current indicators may also be helpful. More specific phytoplankton indicators tuned to the spatial and temporal distribution of EBS Pacific cod larvae as well as phytoplankton community structure information (e.g., hyperspectral information for size fractionation) could be more useful for understanding Pacific cod larval fluctuations. Current estimates of zooplankton biomass are only available at smaller spatial scales and regional to gulf-wide estimates of zooplankton biomass as well as offshore to nearshore monitoring of Pacific cod larvae and zooplankton are needed to elucidate prey trends at the spatial scales relevant to fisheries management. The AFSC continues investigating environmental regulation of first year of life processes in Pacific cod to better understand the interrelationship between processes occurring during pre-settlement (spawning/larvae), settlement (summer growth) and post-settlement (first overwintering) phases. Work is underway to develop a spawning habitat index for Pacific cod, analogous to that for the Gulf of Alaska, based on refined bottom temperature measurements and ROMS model output. This research will characterize spatial and temporal changes in spawning habitat in the EBS and its importance for larval phenology, advection, and survival. Transport processes and connectivity between larval and juvenile nursery areas will continue to be an important area of research as the Regional Oceanographic Model (ROMS) for the Bering Sea is updated.

We currently lack an indicator of predation on YOY Pacific cod during their first autumn and winter, during a period when predation mortality is thought to be significant. Sampling of predator diets in fall and winter would help to fill this gap. The EBS CEATTLE model might also allow for a gap-free index of age-1 predation mortality and bioenergetics indices for EBS Pacific cod (e.g., annual ration, consumption). Additionally, evaluating condition and energy density of juvenile and adult Pacific cod samples at the outer edge of the population may be useful for understanding the impacts of shifting spatial statistics such as center of gravity and area occupied. Information is available from the northern Bering Sea bottom trawl survey and the AFSC longline survey that could be used for evaluating the northern and western edge of the EBS Pacific cod population. The North Pacific Research Board has funded an integrated ecosystem research program in the Arctic that may also be helpful for evaluating the northern edge of the EBS Pacific cod population.

We plan to evaluate the information provided in the Economic SAFE and ACEPO report to determine what socioeconomic indicators could be provided in the ESP that are not redundant with those reports and related directly to stock health. This may result in a transition of indicators currently reported in this ESP to a different series of socioeconomic indicators in future ESPs and may include a shift in focus from engagement to dependency. Additional considerations should be given regarding the timing of the economic and community reports that are delayed by 1-2 years depending on the data source from the annual stock assessment cycle. The Scientific and Statistical Committee (SSC) recently recommended that local knowledge, traditional knowledge, and subsistence information may be helpful for understanding recent fluctuations in stock health, shifts in stock distributions, or changes in size or condition of species in the fishery. We could include this information as supportive evidence and perspective on many indicators monitored within the ESP.

As indicators are improved or updated, they may replace those in the current set of indicators to allow for refinement of the BAS model and potential evaluation of performance and risk within the operational stock assessment model. Incorporating additional importance methods in the intermediate stage indicator analysis may also be useful for evaluating the full suite of indicators and may allow for identifying robust indicators for potential use in the operational stock assessment model. The annual request for indicators (RFI) for the EBS Pacific cod ESP will include these data gaps and research priorities along with a list of potential new indicators that could be developed for the next full ESP assessment.

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Appendix 2.2 Tables

Table 2.2.1a. Bering Sea & Aleutian Islands Pacific cod catch and ex-vessel data. Total and retained catch (thousand metric tons), number of vessel, catcher/processor (CP) hook-and-line (H&L) share of catch, CP trawl share of catch, Shoreside retained catch (thousand metric tons), shoreside number of vessel, shoreside pot gear share of catch, shoreside trawl share of catch, shoreside ex-vessel value and price (million US$), and fixed gear to trawl price premium (US$ per pound); 2012-2016 average and 2017-2021.

	2012-2016 Average	2017	2018	2019	2020	2021
Total catch K mt	250.66	253	220.3	198	169.9	135.7
Retained catch K mt	246.28	250.07	218.01	195.93	167.39	132.04
Vessels #	164	173	193	196	189	146
CP H&L share of BSAI catch	51.02%	49.7%	46.27%	45.21%	43.95%	44.64%
CP trawl share of BSAI catch	15.22%	12.77%	13.91%	13.04%	13.18%	13.73%
Shoreside retained catch K mt	76.04	87.97	82.48	77.53	68.34	52.64
Shoreside catcher vessels #	113.6	128	144	149	151	115
CV pot gear share of BSAI catch	12.78%	17.26%	19.38%	21.98%	21.4%	23.12%
CV trawl share of BSAI catch	17.7%	17.88%	18.03%	16.98%	18.86%	16.61%
Shoreside ex-vessel value M $	$41.96	$53.98	$65	$62.26	$53.43	$39.32
Shoreside ex-vessel price lb $	$0.27	$0.32	$0.4	$0.42	$0.39	$0.37
Shoreside fixed gear ex-vessel price premium	$0.02	$0.05	$0.07	$0.11	$0.1	$0.04

Source: NMFS Alaska Region Blend and Catch-accounting System estimates; NMFS Alaska Region At-sea Production Reports; and ADF&G Commercial Operators Annual Reports (COAR). Data compiled and provided by the Alaska Fisheries Information Network (AKFIN).

Table 2.2.1b. Bering Sea & Aleutian Islands Pacific cod first-wholesale market data. First-wholesale production (thousand metric tons), value (million US$), price (US$ per pound); fillet and head and gut volume (thousand metric tons), value share, and price (US$ per pound); At-sea share of value and at-sea shoreside price difference (US$ per pound); 2012-2016 average and 2017-2021.

	2012-2016 Average	2017	2018	2019	2020	2021
All Products volume K mt	122.95	119.54	107.41	94.97	77.62	62.86
All Products value M $	$358.12	$434.67	$458.84	$346.52	$265.77	$236.67
All Products price lb $	$1.32	$1.65	$1.94	$1.66	$1.55	$1.71
Fillets volume K mt	8.06	10.01	10.36	8.02	7.51	5.61
Fillets value share	14.65%	18.8%	20.53%	19.98%	23.25%	22.43%
Fillets price lb $	$2.95	$3.7	$4.12	$3.91	$3.73	$4.29
Head & Gut volume K mt	100.41	92.38	79.04	70.25	55.04	45.96
Head & Gut value share	78.3%	73.71%	70.73%	71.53%	65.97%	68.53%
Head & Gut price lb $	$1.27	$1.57	$1.86	$1.6	$1.44	$1.6
At-sea value share	70.91%	69.72%	63.54%	66.96%	63.82%	65.49%
At-sea price premium ($/lb)	-$0.134	-$0.33	-$0.51	-$0.36	-$0.48	-$0.34

Source: NMFS Alaska Region Blend and Catch-accounting System estimates; NMFS Alaska Region At-sea Production Reports; and ADF&G Commercial Operators Annual Reports (COAR). Data compiled and provided by the Alaska Fisheries Information Network (AKFIN).

Table 2.2.1c. Cod U.S. trade and global market data. Global production (thousand metric tons), U.S. share of global production, and Europe's share of global production; U.S. export volume (thousand metric tons), value (million US$), and price (US$ per pound); U.S. cod consumption (estimated), and share of domestic production remaining in the U.S. (estimated); and the share of U.S. export volume and value for head and gut (H&G), fillets, China, Japan, and Europe; 2012-2016 average and 2017-2021.

	2012-2016 Average	2017	2018	2019	2020	2021
Global cod catch K mt	1763.16	1760.31	1636.16	1565.77	1483.09	-
U.S. P. cod share of global catch	21.3%	21.2%	18.2%	17.2%	15.2%	-
Europe Share of global catch	75.1%	75.9%	78.3%	78.5%	80.3%	-
Pacific cod share of U.S. catch	99.6%	99.8%	99.9%	99.8%	99.7%	-
U.S. cod consumption K mt (est.)	107.83	118.56	113.62	106.28	103.36	107.08
Share of U.S. cod not exported	29.4%	32.5%	35.5%	36.8%	45%	53.1%
Export volume K mt	107.74	92.79	73.14	65.1	44.48	32.52
Export value M US$	$326.55	$295.5	$253.37	$217.88	$139.4	$101.68
Export price lb US$	$1.37	$1.44	$1.57	$1.52	$1.42	$1.42
Frozen (H&G) volume share	89.49%	93.6%	90.95%	92.31%	92.32%	89.44%
Frozen (H&G) value share	88.19%	92.15%	90.42%	90.71%	89.83%	84.21%
Fillets volume share	4.34%	4.12%	4.97%	4.68%	5.86%	8.73%
Fillets value share	5.78%	5.33%	5.69%	5.84%	7.38%	12.93%
China volume share	51.63%	52.4%	47.55%	41.52%	39.52%	31.36%
China value share	49.01%	49.67%	46.46%	40.21%	37.35%	28.38%
Japan volume share	14.57%	16.09%	15.06%	11.86%	13.04%	10.99%
Japan value share	15.1%	18.36%	16.67%	12.97%	13.89%	11.78%
Europe* volume share	21.05%	17.35%	15.95%	21.6%	20.13%	11.53%
Europe* value share	22.65%	17.73%	17.67%	23.12%	20.69%	10.95%

Notes: Pacific cod in this table is for all U.S. unless noted, `cod' in this table refers to Atlantic and Pacific cod. Russia, Norway, and Iceland account for the majority of Europe's cod catch which is largely focused in the Barents Sea.
*Europe refers to: Austria, Belgium, Denmark, France, Germany, Greece, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and United Kingdom
Source: FAO Fisheries & Aquaculture Dept. Statistics http://www.fao.org/fishery/statistics/en. NOAA Fisheries, Fisheries Statistics Division, Foreign Trade Division of the U.S. Census Bureau, http://www.st.nmfs.noaa.gov/commercial-fisheries/foreign-trade/index. U.S. Department of Agriculture http://www.ers.usda.gov/data-products/agricultural-exchange-rate-data-set.aspx.

Table 2.2.2a. Beginning stage ecosystem indicator analysis for EBS Pacific cod, including indicator title and the indicator status of the last five available years. The indicator status is designated with text, (greater than = “high”, less than = “low”, or within 1 standard deviation = “neutral” of the time series mean). Fill color of the cell is based on the sign of the anticipated relationship between the indicator and the stock (blue or italicized text = good conditions for the stock, red or bold text = poor conditions, white = average conditions). A gray fill and text = “NA” will appear if there were no data for that year.

Indicator category	Indicator	2018 Status	2019 Status	2020 Status	2021 Status	2022 Status
Physical	Winter Spring North Pacific Index Model	*high*	neutral	*high*	neutral	neutral
	Winter Sea Ice Advance BS Satellite	**low**	**low**	neutral	neutral	neutral
	Spring Sea Ice Retreat BS Satellite	**low**	**low**	neutral	neutral	neutral
	Spring Summer Temperature Surface SEBS Satellite	**high**	**high**	**high**	neutral	neutral
	Summer Temperature Bottom SEBS Model	**high**	**high**	neutral	neutral	neutral
Lower Trophic	Spring Chlorophyll a Peak SEBS Satellite	*high*	**low**	neutral	neutral	neutral
	Summer Euphausiid Abundance EBS Survey	neutral	NA	NA	NA	neutral
Upper Trophic	Summer Pacific Cod Condition Juvenile EBS Survey	neutral	neutral	NA	neutral	neutral
	Summer Pacific Cod Condition Adult EBS Survey	neutral	neutral	NA	neutral	neutral
	Summer Pacific Cod Center Gravity East EBS Model	**low**	*high*	NA	neutral	neutral
	Summer Pacific Cod Center Gravity North EBS Model	**high**	**high**	NA	**high**	neutral
	Summer Pacific Cod Area Occupied EBS Model	neutral	neutral	NA	neutral	neutral
	Annual Arrowtooth Biomass EBS Model	neutral	**high**	**high**	**high**	NA

Table 2.2.2b. Beginning stage socioeconomic indicator analysis for EBS Pacific cod, including indicator title and the indicator status of the last five available years. The indicator status is designated with text, (greater than = “high”, less than = “low”, or within 1 standard deviation = “neutral” of time series mean). A gray fill and text = “NA” will appear if there were no data for that year.

Indicator category	Indicator	2018 Status	2019 Status	2020 Status	2021 Status	2022 Status
Economic	Annual Pacific Cod Real Exvessel Value EBS Fishery	high	neutral	neutral	low	NA
	Annual Pacific Cod Real Exvessel Price EBS Fishery	neutral	neutral	neutral	neutral	NA
	Annual Pacific Cod Real Revenue Per Unit Effort EBS Fishery	high	high	neutral	neutral	NA
Community	Annual Pacific Cod RQ Harvesting Revenue Dutch Harbor Fishery	neutral	neutral	NA	NA	NA
	Annual Pacific Cod RQ Processing Revenue Dutch Harbor Fishery	neutral	low	NA	NA	NA

Appendix 2.2 Figures

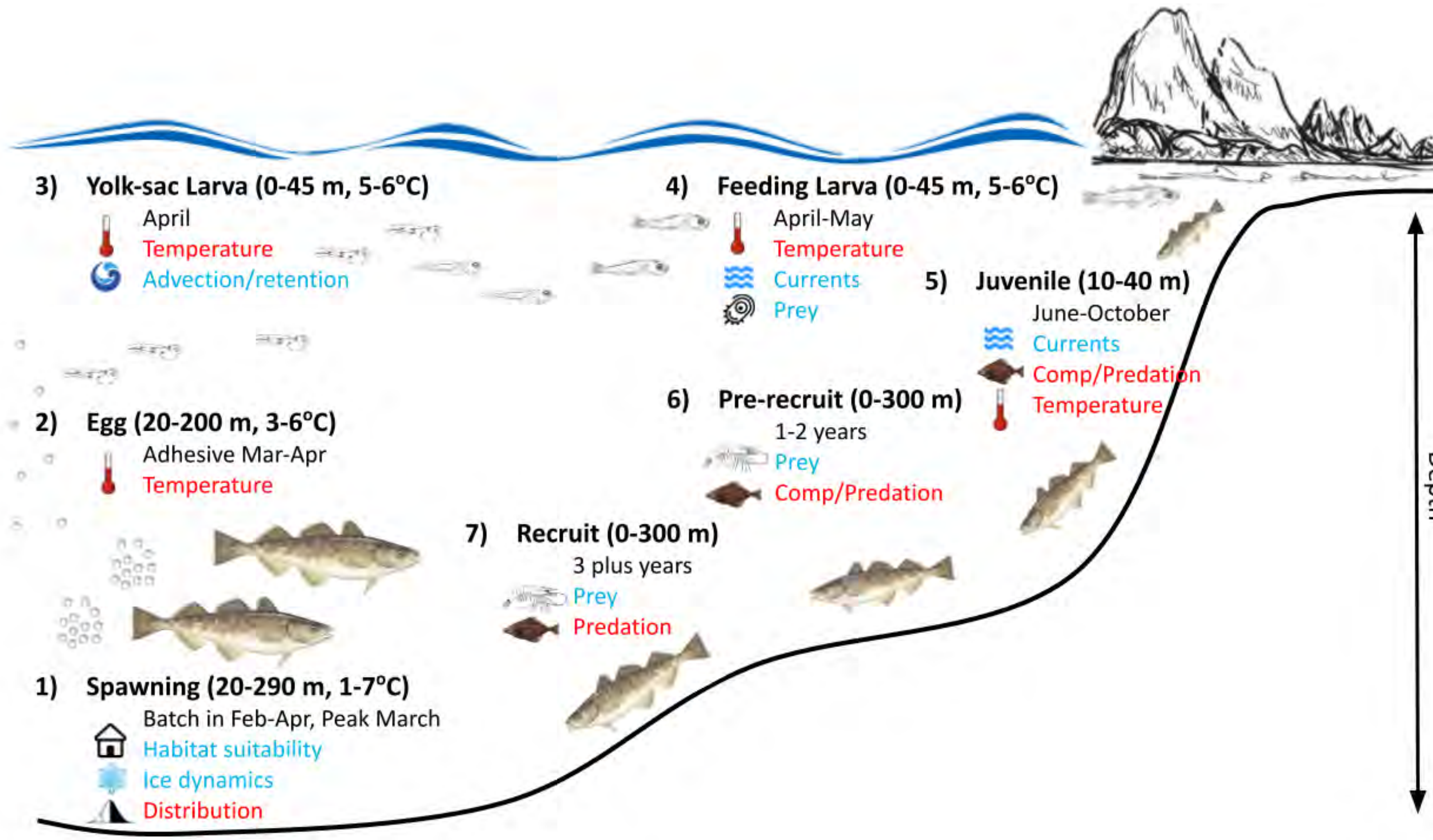

Figure 2.2.1: Life history conceptual model for EBS Pacific cod summarizing ecological information and key ecosystem processes affecting survival by life history stage. Red text means increases in the process negatively affect survival, while blue text means increases in the process positively affect survival.

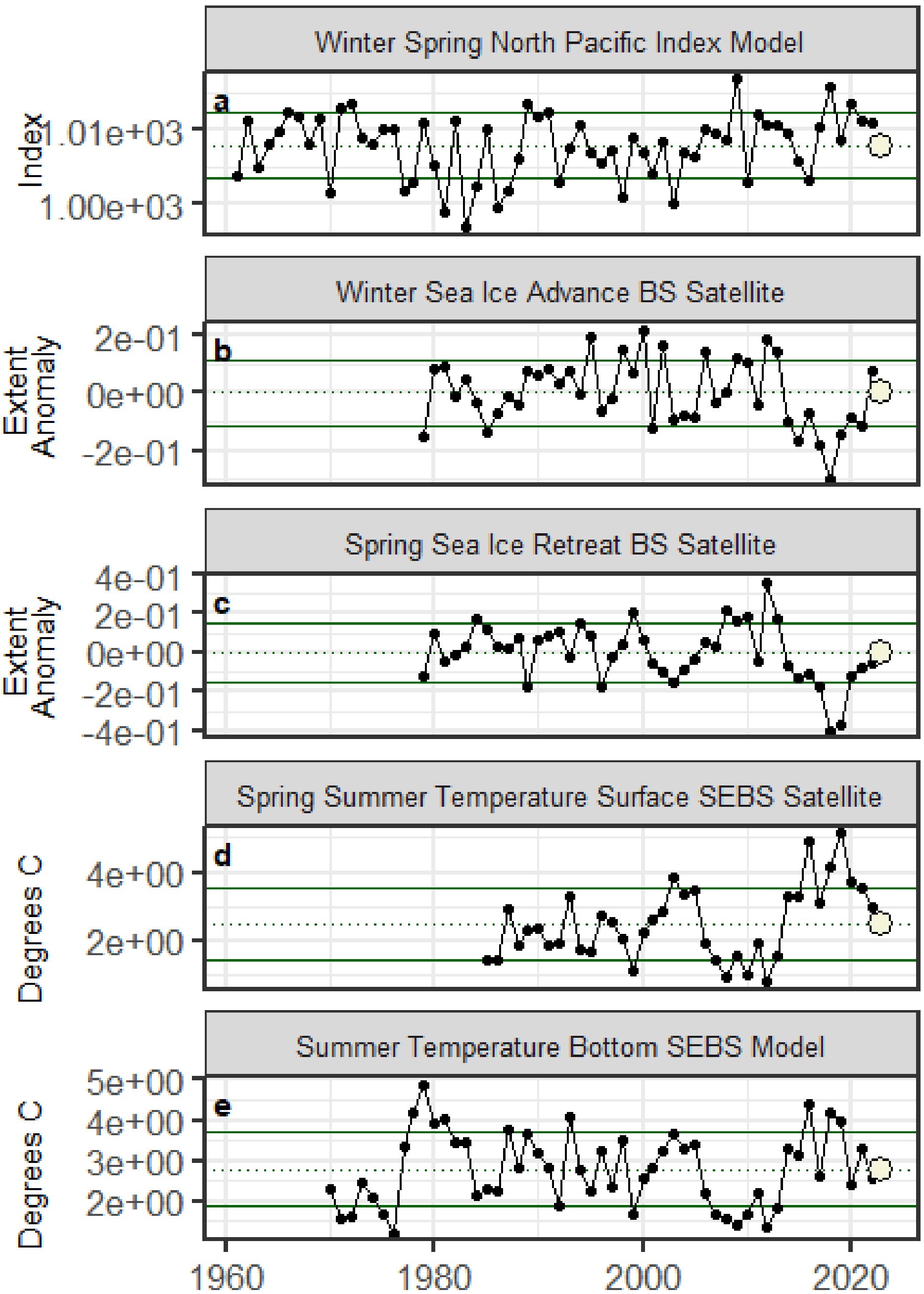

Figure 2.2.2a. Selected ecosystem indicators for EBS Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. A symbol appears when current year data are available and follows the traffic light status table designations (triangle direction represents if above or below 1 standard deviation of the time series mean, color represents proposed relationship for stock with blue for good conditions, red for poor conditions, and a white circle is neutral).

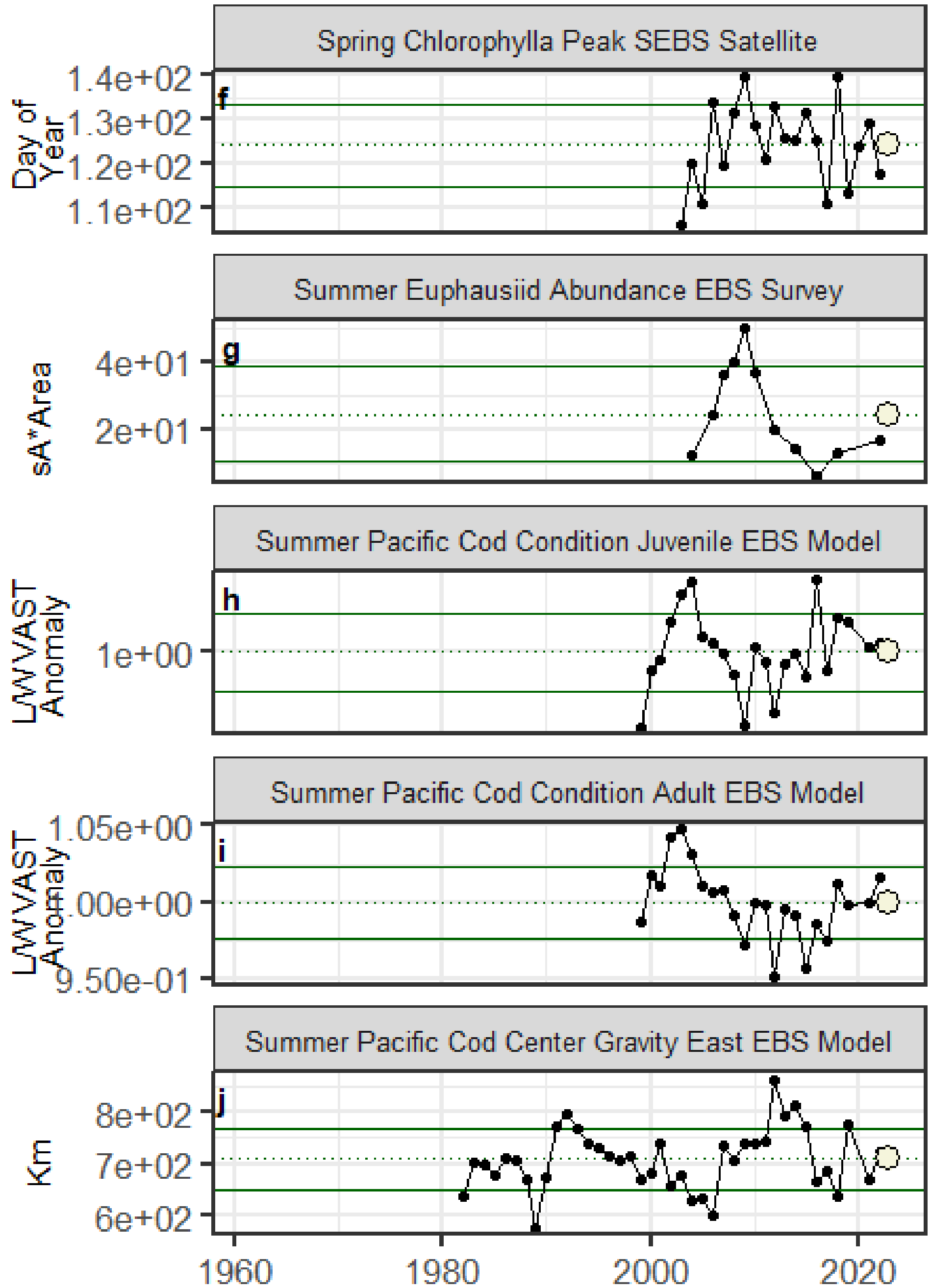

Figure 2.2.2a (cont.). Selected ecosystem indicators for EBS Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. A symbol appears when current year data are available and follows the traffic light status table designations (triangle direction represents if above or below 1 standard deviation of the time series mean, color represents proposed relationship for stock with blue for good conditions, red for poor conditions, and a white circle is neutral).

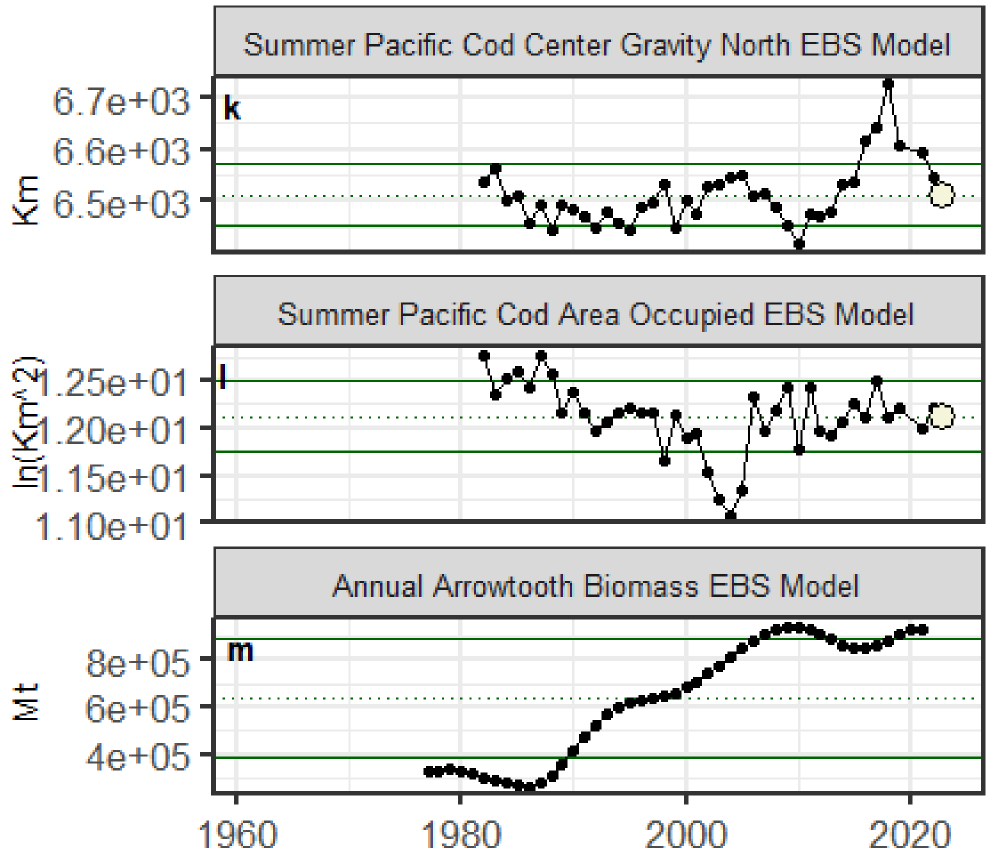

Figure 2.2.2a (cont.). Selected ecosystem indicators for EBS Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. A symbol appears when current year data are available and follows the traffic light status table designations (triangle direction represents if above or below 1 standard deviation of the time series mean, color represents proposed relationship for stock with blue for good conditions, red for poor conditions, and a white circle is neutral).

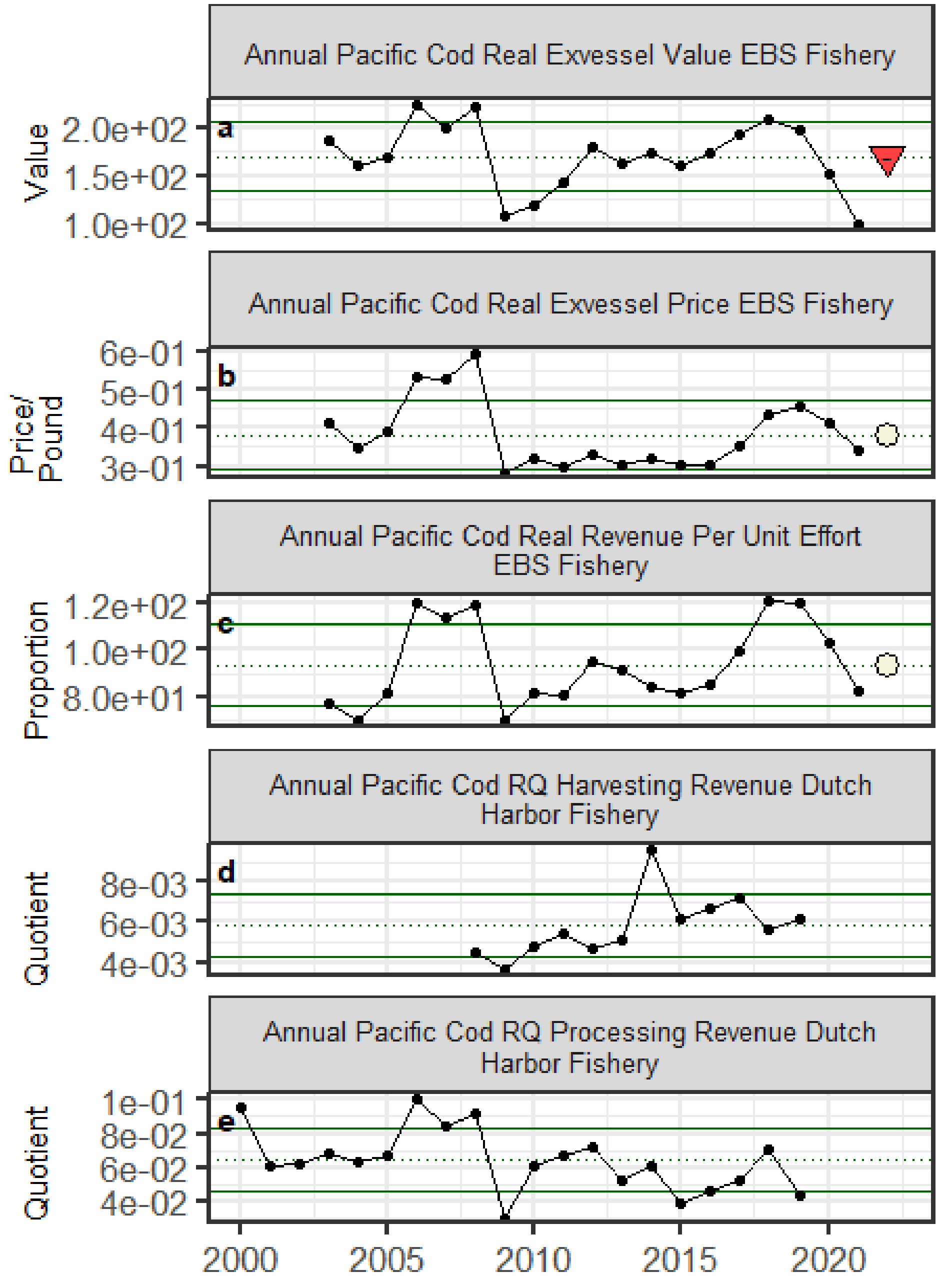

Figure 2.2.2b. Selected socioeconomic indicators for EBS Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. A symbol appears when current year data are available and follows the traffic light status table designations (triangle direction represents if above or below 1 standard deviation of the time series mean, color only designates above (blue) or below (red) one standard deviation of the time series mean, no implied relationship with the stock).

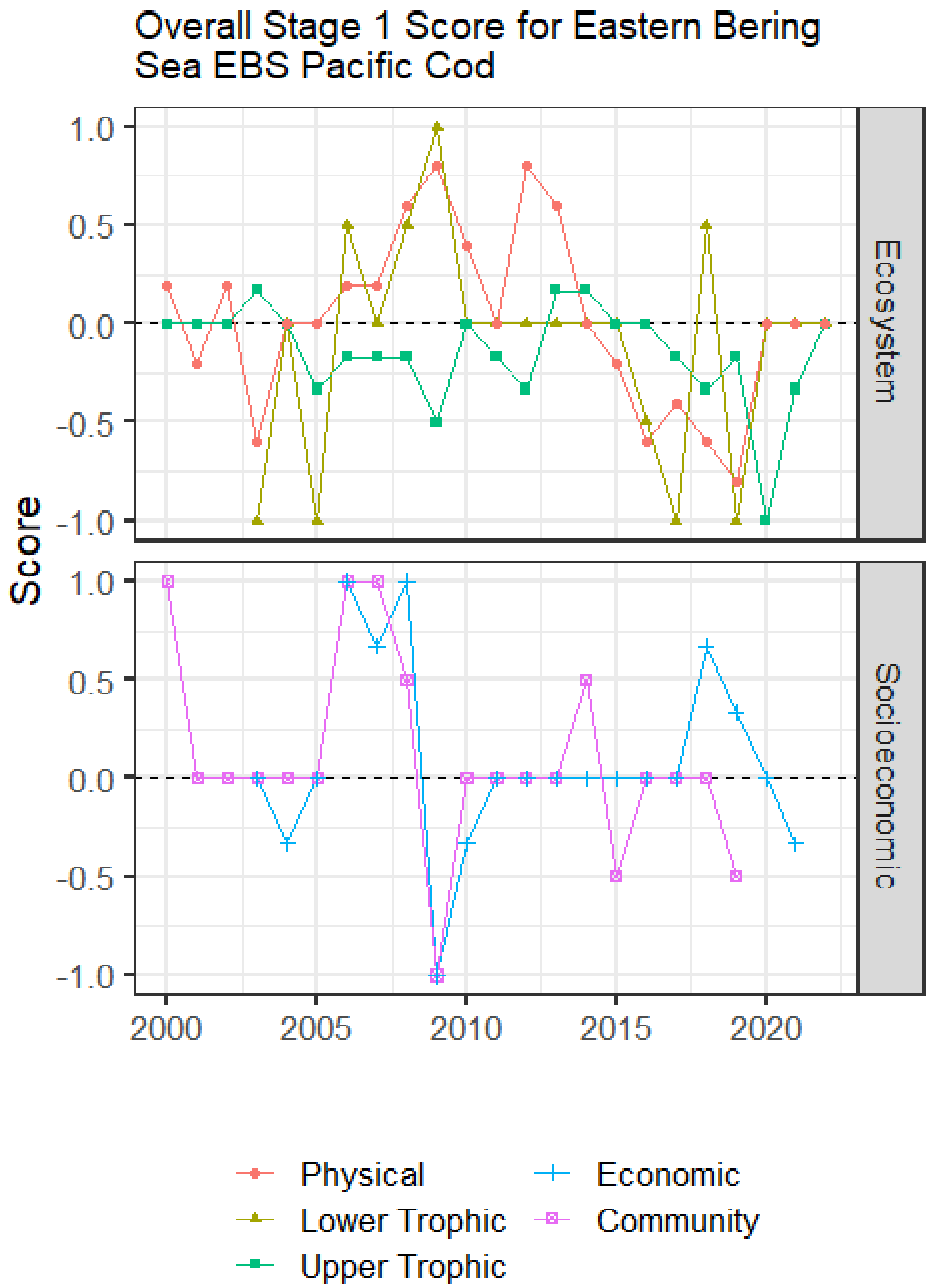

Figure 2.2.3: Simple summary traffic light score by category for ecosystem and socioeconomic indicators from 2000 to present.

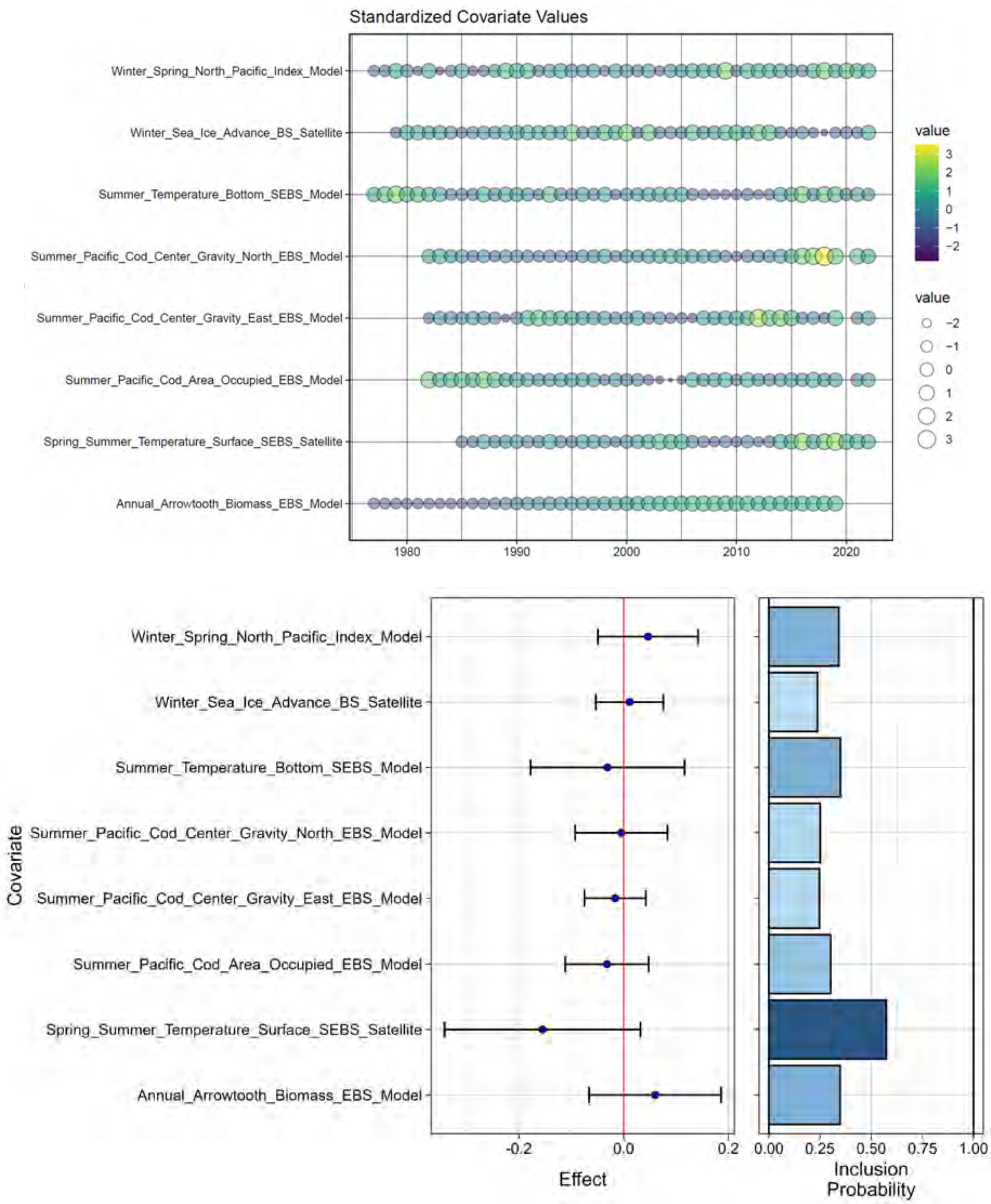

Figure 2.2.4: Bayesian adaptive sampling output showing (top graph) standardized covariates and (bottom graph) the mean relationship and uncertainty (95% confidence intervals) with log EBS Pacific cod recruitment, in each estimated effect (left bottom graph), and marginal inclusion probabilities (right bottom graph) for each predictor variable of the subsetted covariate set.

Appendix 2.3

Appendix 2.3: Thompson Series Models SS Files (.zip)

Appendix 2.4

Appendix 2.4: New Series Models SS Files (.zip)

Appendix 2.5

Appendix 2.5: All Model Data and Results tables Excel file (.xlsx)