Chapter 2: Assessment of the Pacific cod stock in the Gulf of Alaska

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Executive Summary

Pacific cod in the Gulf of Alaska are assessed on an annual stock assessment schedule to coincide with the availability of new survey data. We use a statistical age-structured model as the primary assessment tool for Gulf of Alaska Pacific cod which qualifies as a Tier 3 stock. This assessment consists of a population model, which uses survey and fishery data to generate a historical time series of population estimates, and a projection model, which uses results from the population model to predict future population estimates and recommended harvest levels. All data and results (including Stock Synthesis files and plots), as well as documents and presentations pertaining to this assessment can be found at this link.

Summary of Changes in Assessment Inputs

Relative to last year's assessment, the following changes have been made in the current assessment:

Changes in the input data

1. Federal and state catch data for 2022 were updated and preliminary federal and state catch data for 2023 were included;
2. Commercial federal and state fishery size composition data for 2022 were updated, and preliminary commercial federal and state fishery size composition data for 2023 were included;
3. AFSC longline survey Pacific cod abundance index and length composition data for the GOA for 2023 were included;
4. AFSC bottom trawl survey abundance index and length composition data for 2023 were included;
5. Commercial federal conditional age-at-length data for 2022 were included.

Changes in the methodology

The model used for 2023 (Model 19.1b) is last year's accepted model (Model 19.1a) with the adjustment of conditional age-at-length minimum sample size from 1 to 0.001(described in Appendix 2.2). There were no other model changes made in this year's assessment.

Summary of Results

Model 19.1b indicates that the stock remains at low levels but is above $B_{20\%}$; for 2024 the stock is estimated to be at $B_{29.7\%}$, less than $B_{40\%}$, placing it in sub-tier "b" of Tier 3. For the 2024 fishery, we recommend the maximum allowable ABC of 32,272 t. This ABC is a 31% increase from the 2023 ABC of 24,634 t. This increase is attributed to increases in both the AFSC bottom trawl survey population numbers (53% larger in 2023 compared to 2021) and the AFSC longline survey Relative Population Number index (32% larger in 2023 compared to 2022). The 2024 ABC is 42% larger than the 2024 ABC projected in last year's assessment. The corresponding reference values are summarized in the following table, with the recommended ABC and OFL values in bold. The stock is not being subject to overfishing, is not currently overfished, nor is it approaching a condition of being overfished.

Quantity	As estimated or *specified last* year for: 2023	2024	As estimated or *specified this* year for: 2024	2025
M (natural mortality rate)	0.49*	0.49*	0.46*	0.46*
Tier	3b	3b	3b	3b
Projected total (age 0+) biomass (t)	163,477	193,510	184,242	203,207
Female spawning biomass (t)				
Projected	42,764	40,489	51,959	47,931
$B_{100\%}$	167,414	167,414	175,187	175,187
$B_{40\%}$	66,966	66,966	70,075	70,075
$B_{35\%}$	58,595	58,595	61,315	61,315
F_{OFL}	0.51	0.48	0.52	0.48
$maxF_{ABC}$	0.41	0.39	0.42	0.38
F_{ABC}	0.41	0.39	0.42	0.38
OFL (t)	29,737	27,507	**38,712**	33,970
maxABC (t)	24,634	22,683	32,272	28,184
ABC (t)	24,634	22,683	**32,272**	28,184
Status	As determined *last* year for: 2021	2022	As determined *this* year for: 2022	2023
Overfishing	No	n/a	No	n/a
Overfished	n/a	No	n/a	No
Approaching overfished	n/a	No	n/a	No

**Base natural mortality M varies between 0.46 and 0.79*
*** Assumed 2023 catch to be the 2023 ABC. For 2025 projections the 2024 catch was assumed to be at the projected ABC.*

Area apportionment

Using the random effects model (as applied within the *rema* R-package, Sullivan et al. 2022) with the trawl survey biomass estimates through 2023, the area-apportioned ABCs are:

	Western	Central	Eastern	Total
Random effects area apportionment	27.1%	63.8%	9.1%	100%
2024 ABC	8,745	20,590	2,937	32,272
2025 ABC	7,638	17,981	2,565	28,184

Responses to SSC and Plan Team Comments on Assessments in General

"The SSC supports the JGPT's recommendation that stock assessment authors transition from the ADMB RE variants to the rema framework, which implements the same model variants in a single framework with several improvements."(SSC, Oct 2022)

In this year's assessment we have transitioned to using the *rema* R package.

"The SSC reiterates its previous recommendation that the number of levels should be collapsed from four to three to make the choices easier for the authors." (SSC, Dec 2022)

In this year's assessment we have collapsed the number of risk table levels from four to three.

"The SSC supports the JGPT recommendation to make reporting of fish condition routine and standardized across assessments." (SSC, Dec 2022)

Standardized fish condition is reported in the ESR (Appendix 2.1).

Responses to SSC and Plan Team Comments Specific to this Assessment

Specific additional recommendations include:

- *Provide a discussion of whether the period of elevated M estimated in recent models, and other environmentally-driven dynamics should be included in the calculation of reference points and/or stock status (see General Stock Assessment Comments)*
- *Provide an explanation as to whether all age-classes should be expected to be affected equally by marine heat waves, and over which time periods and by what mechanism they may be affected*
- *Please elaborate on how the Dirichlet-multinomial method verified that the current weights are "correct"*
- *Address implausibly large standardized residuals observed for smaller fish in the fit to NMFS bottom trawl length frequency data*
- *Provide more details about the spatial-temporal correlation that informs the historical beach-seine index where no historical data exist*
- *Include standard MCMC diagnostics for all model parameters and derived quantities if posterior distributions are to be evaluated as part of the model results. These should include tests for burn-in, auto-correlation and mixing of the MCMC chain(s).*
- *Explore the potential for hook-competition in the IPHC index if it is to be incorporated*

(SSC, Dec 2021)

We provide responses to each bullet above within the bullets below:

- It is the opinion of the senior author that recent stock dynamics that may substantially differ from historical dynamics should be considered and evaluated for inclusion in the calculation of reference points and/or stock status. However, it remains unclear as to how this should be done tactically in operational stock assessment models, and is an active area of research in fisheries stock assessment in general and at AFSC specifically. This area of research will continue to be monitored and methods applied as they are developed.
- It is unclear as to whether all age-classes should be expected to be affected equally by marine heat waves given the data available for this stock assessment. In theory, one would hypothesize that marine heat waves could have unequal impact on younger/smaller fish compared to

older/larger fish. However, the tension between parsimony and over-parameterization within stock assessment models and the interplay with what can be estimated with the data available makes age-specific mortality rates difficult to estimate, and doubtful as to whether any results should be considered even if estimates are obtained. Thus, in the current stock assessment model a simplifying assumption that has been made, however unsatisfying, is that mortality is constant across age. If at some point in the future there is research that can provide age-specific mortality rates as it relates to temperature pressures that can be used as priors, these priors will be investigated within the stock assessment model.

- Following the recent work at AFSC on investigating one step ahead residuals, we have refrained from evaluating the implausibly large residuals observed for smaller fish in the AFSC bottom trawl survey until we can apply this method, which may not indicate such large residuals. However, we note that the model continues to underestimate the peak in small lengths observed in the AFSC bottom trawl survey, particularly in 2009.
- The age-0 abundance index from western GOA beach-seines is generated from a Bayesian non-parametric regression model with a zero-inflated, negative binomial error structure, implemented in the R package *brms*. The model fits year (as a categorical covariate) and day of year of sampling (as a smooth) as population-level terms, and site identity nested within bay identity as group-level terms, and the posterior distribution is used to generate the point estimate and uncertainty for abundance in each year (https://github.com/mikelitzow/seine-data/blob/main/scripts/cohort_strength.R; Litzow et al. 2022).
- For this assessment we have used the R package *adnuts* (Monnahan and Kristensen 2018). In the *Uncertainty Results* subsection we have reported standard MCMC diagnostics as well as have included a figure with MCMC posterior histograms compared to MLE values for key parameters in the assessment.
- If the IPHC survey were ever to be investigated for use in this assessment, hook-competition would be considered.

"The authors noted that incomplete fishery length compositions are used for the current year in the assessment. It appears that a fairly substantial amount of catch occurs after October, at least in 2022. The SSC requests that the authors evaluate the benefit of including these data by showing the complete versus incomplete length compositions for the past few years and a retrospective of the assessment including and excluding these data." (SSC, Dec 2022)

In this assessment and the 2022 assessment we provide a figure that evaluates leaving out each additional source of data for the new assessment, which includes the current assessment year's fishery length composition (Fig. 2.31 in Hulson et al. 2022 and Fig. 2.28 in the current assessment). For both the 2022 assessment and the current assessment the removal of the current year's fishery length composition does not result in substantial changes to model estimates. Further, comparisons between the plots of mean length in Hulson et al. 2022 and the current assessment for each of the fishery gear types indicates little change in the length composition data when additional data is included post October (specifically for 2022). We have refrained from performing this requested retrospective analysis, but rather note to the SSC that equivalent evaluation to the requested analysis can be performed as each year's assessment is conducted going forward through comparison of the mean length and dataset removal plots between the current and previous assessments. We also point out that the benefit of including this partial data is to monitor the current trends in the fishery within the assessment.

"The SSC appreciates the preliminary evaluation of conditional age-at-length patterns and recommends further evaluation of growth-related issues, including updating the length-weight relationship with more recent data, evaluating if there have been significant growth changes, and examining empirical weight at age. The SSC encourages consistency with EBS and AI cod assessments in approaches to these and other issues, where possible." (SSC, Dec 2022)

"The Team recommended that the data for length-weight relationships be reevaluated and examined for sensitivity to the trends over time and areas." (Plan Team, Nov 2022)

"The Team recommended the authors look at the model-predicted mean weight-at-age (by gear type), and compare to the observed weight-at-age data to see if there are discernible spatial or temporal patterns that the model is missing." (Plan Team, Nov 2022)

"The Team recommended that an evaluation comparing how growth changes may affect the residuals be pursued. The Team also recommended the author investigate whether size-based selectivity affects the patterns observed." (Plan Team, Nov 2022)

We respond to these combined SSC and Plan Team comments as they relate to the same topic. In the current assessment we have updated the priors for the length-weight relationship to include data through the 2023 AFSC bottom trawl surveys. We have obtained funding to hire a post doc that is investigating environmental links within this stock assessment, with growth being one of the important model estimates that will be investigated. Part of this work will include evaluation of growth changes over time and space, and the consistency of the GOA cod assessment with the EBS and AI cod assessments. As a precursor to this work, preliminary results investigating environmental links with growth were presented at the September 2022 Plan Team meeting, with indications that growth estimation within the assessment can be greatly improved through such environmental linkages.

"Based on recent tagging and genetic studies, the SSC encourages further exploration of fish movement as a potential major cause of population changes. Movement should be considered in concert with high natural mortality events for future models, and specifically consideration should be given to an Alaska-wide stock or GOA/EBS model." (SSC, Dec 2022)

We have recently obtained funding to pursue investigations into movement and developing a stock assessment model that takes into account exchange between the Western GOA and EBS. We look forward to updating the SSC on this work in years to come.

Specific additional recommendations include:

- *The SSC reiterates their encouragement for the authors to consider whether information from the IPHC setline survey and NMFS longline survey, alongside the NMFS bottom trawl survey, may provide a superior basis for apportionment recommendations, perhaps through the use of an integrated spatiotemporal model or a multi-survey random effects model.*
- *Along with analyses addressing other previous recommendations, the SSC looks forward to an investigation of large residuals in the fit to pot fishery data and for smaller fish in the fit to bottom trawl survey data.*
- *The SSC suggests including information on changes in fishing practices that may explain the increase in the mean length of cod caught in pot fisheries (Figure 2.14).*
- *The SSC requests the authors provide the mean catchability used in the calculation of the temperature-adjusted and time-varying q*

(SSC, Dec 2022)

We provide responses to each bullet above within the bullets below:

- In future assessments we intend to investigate the inclusion of the AFSC longline survey as an additional index, although, a complicating factor is how to incorporate the environmental index used with the longline survey catchability parameter within the apportionment framework. Given the recent changes to the spatial distribution of the IPHC survey, this index may not be useful to monitor cod abundance outside of a dedicated spatial-temporal model applied to this data.
- Following the recent work at AFSC on investigating one step ahead residuals, we have refrained from performing this analysis until we can apply this method, which may not indicate such large residuals. However, in this year's assessment we note the disproportionate amount of length frequency sampling that is being observed within the pot fleet compared to the other fleets targeting cod.
- We note that the large mean length of cod caught in 2022 has reduced to historical values in 2023. It is likely that the large mean length observed in 2022 is the result of sampling variability rather than changes to the fishery.
- Mean catchability for the longline survey is reported in Table 2.13.

The Team recommended adding confidence intervals on the mean lengths by depth strata. Additionally, the Team recommended that the authors compare total fishing effort or catch (in addition to total sample size) to be sure that the observer coverage is capturing effort appropriately. (Plan Team, Nov 2022)

In this year's assessment we have removed the plot that the Plan Team was referring to (as it is redundant with the other mean length plots by fleet that are shown). Based on this recommendation we have included a plot that shows the relative proportion of catch by fleet in comparison to the proportion of length frequency sampling by fleet (Fig 2.12) in order to illustrate the magnitude of length frequency sampling in comparison to catch by fleet.

"The Team recommended examining the updated MCMC tools (e.g., adnuts) and diagnostics." (Plan Team, Nov 2022)

For this assessment we have used the R package *adnuts* (Monnahan and Kristensen 2018). In the *Uncertainty Results* subsection we have included figures with MCMC pairs plots (which include diagnostics) and posterior histograms compared to MLE values for key parameters in the assessment.

"Relative to the time-varying longline survey catchability being linked to an environmental covariate, the Team recommended that it be re-examined against a fixed value for comparison." (Plan Team, Nov 2022)

In the *Model Evaluation* subsection we have reported on the results of two additional tests that were performed in this year's assessment based on this recommendation. These two tests include comparing the author's recommended model (Model 19.1b) to (1) a model that does not include the environmental link to longline survey catchability, and (2) to 50 sets of 'white noise' indices generated with N(0,1). The results of this comparison show that the model with the environmental link continues to be preferred.

Introduction

Pacific cod (*Gadus macrocephalus*) is a transoceanic species, occurring at depths from shoreline to 500 m. The southern limit of the species' distribution is about 34° N latitude, with a northern limit of about 63° N latitude. Pacific cod is distributed widely over Gulf of Alaska (GOA), as well as the eastern Bering Sea (EBS) and the Aleutian Islands (AI) area. The Aleut word for Pacific cod, *atxidax*, literally translates to "the fish that stops" (Betts *et al.* 2011). Recoveries from archeological middens on Sanak Island in the Western GOA show a long history (at least 6,000 years) of exploitation. Over this period, the archeological record reveals fluctuations in Pacific cod size distribution, which Betts et al. (2011) tie to changes in abundance due to climate variability (Fig. 2.1). Over this long period colder climate conditions appear to have consistently led to higher abundance with more small/young cod in the population and warmer conditions to lower abundance with fewer small/young cod in the population. Recent comparisons of Pacific cod length distributions extrapolated from bones retrieved from middens and those from the modern domestic fishery show a cline in size from larger fish in the west to smaller fish in the southeastern GOA that has been consistent for over 6,000 years (West *et al.* 2020).

Tagging studies (e.g., Shimada and Kimura 1994) have demonstrated significant migration both within and between the eastern Bering Sea (EBS), Aleutian Islands (AI), and Gulf of Alaska (GOA) outside of their winter (January – April) spawning season. In 2021, a cooperative tagging study between the Alaska Fisheries Science Center (AFSC) and the Aleutian East Borough (AEB) was initiated to examine the seasonal movements of Pacific cod captured in the western GOA during the winter spawning season. Pop-up satellite tags will release and transmit data to satellites at predetermined lengths of time (e.g., 180 days), whereas conventional tags require a platform of recovery such as a fishery. Pathways between release and pop-up locations can be reconstructed from archival data provided by the satellite tags using a hidden Markov model. Satellite tags were deployed on Pacific cod in the western GOA in the vicinity of the Shumagin Islands and Sanak Island during March 2021 (n = 25, Fig. 2.2A) and April 2022 (n = 27, Fig. 2.2B). The goal of this study was to better understand the seasonal connectivity between winter spawning locations of Pacific cod in the western GOA and foraging locations in GOA and EBS during the summer months when both Alaska Fisheries Science Center's bottom-trawl surveys are conducted. In 2023, the study was expanded to the central GOA to understand seasonal migration patterns of both the western and central GOA populations. In March 2023, satellite tags were deployed on 54 Pacific cod at release locations ranging from Sanak Island to the entrance of Prince William Sound (Fig. 2.2C). Results to date indicate 1) substantial seasonal connectivity between the western GOA (Shumagin Islands and westward) and Bering Sea (including Russia and the Chukchi Sea), 2) limited seasonal connectivity between the GOA and AI management areas, 3) some tagged fish do not undertake large-scale migrations but instead remain in the release areas year-round, 4) the proportion of fish that undertake migrations and distance moved between winter spawning and summer foraging may vary by year (Fig. 2.2), and 5) preliminary results from 2023 indicate limited seasonal connectivity between western and central GOA. Additional satellite and conventional tag releases are planned for March 2024 in the GOA and summer 2024 in the Bering Sea.

Low-coverage whole-genome sequencing analysis of 429 samples of Pacific cod from known spawning aggregations indicated population structure similar to what was previously known, but with finer resolution due to a larger number of markers. Using 1,922,927 polymorphic SNPs (Fig. 2.3), 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 (Fig. 2.3), and was supported by previous research that highlighted distinct differences in the genes coding for the zona pellucida gene region ZP3 (Spies et al. 2021). Also notable is the lack of strong genetic differentiation among spawning cod from the eastern Gulf of Alaska and the western Gulf of Alaska.

Although there appears to be some genetic differentiation within the GOA management area and some cross migration between the Western GOA and Bering Sea that may vary seasonally, the Pacific cod stock in the GOA region is currently managed as a single stock. Further work is needed to understand the genetic stock structure of cod in the GOA and its relationship with the Bering Sea stock of cod during spawning and feeding periods.

A detailed account of Pacific cod life history, environmental drivers, economic and social indicators can be found in the GOA Pacific cod ecosystem and socioeconomic processes (ESP) in the 2021 assessment (Barbeaux *et al.* 2021).

Fishery

Fishery history and management measures

For a full description of the fishery history and management measures see Hulson et al. 2022, here we summarize this section and refer to the relevant Tables and Figures. Catches of Pacific cod since 1991 by gear type and jurisdiction are shown in Table 2.1; catches prior to that are listed in Thompson *et al.* (2011). Presently, the Pacific cod stock is exploited by a multiple-gear fishery, including trawl, longline, pot, and jig components; Figure 2.4 shows landings by gear since 1977. The history of acceptable biological catch (ABC) and total allowable catch (TAC) levels is summarized and compared with the time series of aggregate commercial catches in Table 2.2. The complete history of allocation (in percentage terms) by regulatory area within the GOA is shown in Table 2.3. Table 2.1 and Table 2.2 include discarded Pacific cod, estimated retained and discarded amounts are shown in Table 2.4.

Recent fishery performance

Data for managing the Gulf of Alaska groundfish fisheries are collected in multiple ways. The primary source of catch composition data in the federally managed fisheries for Pacific cod are collected by on-board observers (Faunce *et al.* 2017). The Alaska Department of Fish and Game (ADFG) sample individual deliveries for state managed fisheries (Nichols *et al.* 2015). Overall catch delivered is reported through a (historically) paper and electronic catch reporting system. Total catch is estimated through a blend of catch reporting, observer, and electronic monitoring data (Cahalan *et al.* 2014).

The distribution of directed cod fishing is distinct to gear type, Figure 2.5 shows the recent distribution of catch since 2015 for the three major gear types. Figure 2.6 shows the distribution of observed catch for the most recent year of catch data (2023) for the three major gear types, as well as the distinction between observed and electronic monitored catch.

In 2015 combined state and federal catch was 79,480 t (23% below the ABC), while in 2016 combined catch was 64,054 t (35% below the ABC) and in 2017 catch was 48,727 t (45% below the ABC) (Table

2.1). The ABC was substantially reduced for 2018 to 18,000 t from 88,342 t in 2017, an 81% reduction. This was a 65% reduction from the realized 2017 catch. In 2018 the total catch was 15,150 t. For 2019 the ABC was set below the maximum ABC at 17,000 t and combined fishery caught 15,715 t which was 91% of the ABC.

In 2020 the spawning stock biomass was projected to have dropped below 20% of the unfished spawning biomass ($B_{20\%}$) and the federal Pacific cod fishery in the GOA was closed by regulation to directed Pacific cod fishing. $B_{20\%}$ is a minimum spawning stock size threshold instituted to help ensure adequate forage for the endangered western stock of Steller sea lions. The State of Alaska directed Pacific cod fishery remained open and Pacific cod bycatch in other federally managed groundfish fisheries was allowed. The Pacific cod ABC for 2020 was set to 14,621 t, but the combined TAC and State of Alaska groundfish harvest level (GHL) was reduced to account for additional uncertainty. The State of Alaska managed fisheries are allocated 26.7% of the GOA Pacific cod ABC. The federal Pacific cod TAC was reduced by 40% from the maximum of 10,719 t as a further level of precaution to 6,431 t. ADF&G also reduced their maximum prescribed harvest limit of 3,902 t by 35% to 2,537 t. This resulted in a total combined federal TAC and State of Alaska GHL of 8,968 t or 61% of the maximum ABC. In 2020 a total combined catch of 6,840 t was harvested (Table 2.1), the state having taken 2,797 t (91% of the GHL) and federal fisheries haven taken 4,043 t (61% of the federal TAC). The catch in the federal fisheries were split primarily between the arrowtooth flounder (1,237 t), walleye pollock (1,040 t), and shallow water flatfish fisheries (938 t). In 2021 the stock was projected to be above $B_{20\%}$ and the federal fishery was once again allowed to open.

In 2023 the federal TAC was set at 18,103 t and state GHL set at 6,532 t (Table 2.2). As of October 16, 2023 a total of 18,231 t (74% of the ABC) have been harvested (Table 2.1). State fisheries have harvested 5,616 t (86% of the GHL) and federal fisheries 12,615 t (70% of the TAC). In 2023 40% of the Pacific cod catch was by trawl, 28% by pot gear, and 29% by longline, while jig and other gear harvested 3% (Table 2.1).

The largest component of incidental catch of other targeted groundfish species in the GOA Pacific cod fisheries by weight are skate species in combination followed by walleye pollock, arrowtooth flounder, and octopus (Table 2.5). Spiny dogfish, sablefish, and sculpin species also make up a major component of the bycatch in these fisheries. Incidental catch of non-target species in the GOA Pacific cod fishery are listed in Table 2.6.

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Longline

Since 2015 the longline fishery has been predominantly conducted on the border of the Central and Western GOA management areas, in deeper waters south of the Shumagin Islands, and South of Unimak Island to the western edge of the Western GOA management area shelf. In 2023 observers and electronic monitoring show a large portion of the longline catch coming from near the Shumagin Islands in the Western GOA, and the southern edge of Kodiak Island and the southern edge of the Seward Peninsula in the Central GOA (Fig. 2.6). The size of Pacific cod caught in the longline fishery ranges from 62 cm to 72 cm since 2020 (Fig. 2.7). There was a drop in the mean length of fish in the longline fishery between

1990 and 2010; however, this trend has increased in the last 10 years. In 2018 and 2019 fewer boats participated in the fishery (Fig. 2.8) and catch was substantially slower and lower than previous years (Fig. 2.9 and Fig. 2.10), this trend continued in 2020 when the federal fishery was closed. There was an increase in vessels participating in the Pacific cod longline fishery in the Central GOA from 3 in 2020 to greater than 30 since 2021. In both the Central and Western GOA catch in 2023 was similar to 2021 but lagged behind 2022 (Fig. 2.9 and Fig. 2.10).

CPUE figures were produced for the longline fisheries in the GOA in previous assessments (Barbeaux *et al.* 2021). However, the consistency of the data are in question because of electronic monitoring reducing the available data and changes in observer coverage due to COVID-19. It should be noted that CPUE is not available from the EM monitored vessels as number of hooks retrieved and soak time are not recorded. Thus, we do not present CPUE in this assessment but will continue to monitor developments in estimating CPUE.

Pot

The pot fishery is a relatively recent development (Table 2.1) and predominately pursued using smaller catcher vessels. In the State of Alaska managed fishery an average of 84% of the state catch comes from pot fishing vessels. In 2016, 60% of the overall GOA Pacific cod catch was removed using pots. Pot fishing occurs close to the major ports of Kodiak, Sand Point and on either side of the Seward Peninsula (Fig. 2.5). In 2017, the observer coverage rate of pot fishing vessels was greatly reduced from 14% to ~4%, which impacted our ability to adequately identify the spatial distribution of the pot fishery. From the data collected there appears to have been less fishing to the southwest of Kodiak in 2017, however this may be due to low observer coverage. In 2018 - 2020, there were few observed hauls throughout the GOA due to the lower TAC, low fishing levels, and the 2020 directed federal fishery closure. In 2023 the majority of catch from the pot fishery was centered around Kodiak and the Shumagin Islands (Fig. 2.6).

The pot fishery generally catches fish greater than 40 cm (Fig. 2.11), but like the longline fishery there was a declining trend in Pacific cod mean length in the fishery from 1998 through 2016 with the smallest fish at less than 60 cm on average caught during the 2016 fishery. The 2017 through 2021 fishery data show a sharp increase in mean length. In 2022 the mean length was significantly larger than any other year, while in 2023 the mean length decreased and was consistent with previous years. This variability in the mean length of the pot fishery could be driven by lack of length frequency sampling, particularly in comparison with the amount of catch taken by the pot fleet relative to the other fleets (Fig. 2.12).

In the Western and Central GOA, approximately half the catch of the pot fishery was caught in a single week in March (Fig. 2.9 and Fig. 2.10). In 2020 pot fishing was greatly reduced with 15 vessels in the Central GOA and 19 in the Western GOA compared to 27 and 33 the year previously (Fig. 2.8). In 2022 the number of participating vessels increased again to pre-closure levels with 31 vessels in the Central GOA and 41 in the Western GOA.

Like the longline fishery CPUE figures were produced for the pot fisheries in the GOA in previous assessments (Barbeaux *et al.* 2021), but similar consistency issues with the data exists. It should be noted that there were no data available for CPUE calculations in 2020 nor any CPUE data available for the Western GOA in 2021.

Trawl

The distribution of catch from the trawl fishery since 2015 shows it has been widely distributed across the Central and Western GOA (Fig. 2.5) with the highest concentration of catch coming from southeast of

Kodiak Island in the Central GOA and around the Shumigan Islands in the Western GOA. In 2016 trawl fishing in the Western GOA shifted away from the Shumigan Islands further to the west around Sanak Island and near the Alaska Peninsula, this shift continued through 2017. Trawl fishing in 2018 for the A-season had a similar pattern as 2017 with large catches from around Sanak Island, but some increased effort on Portlock Bank to the southeast of Kodiak. There was substantially less catch and observed effort in 2018 and 2019 than previous years. Although the 2020 directed federal Pacific cod fishery was closed, there were observations of Pacific cod catch in other fisheries; these observations primarily surrounded Kodiak from the pollock and shallow water flatfish fisheries. In 2023, there were observed catches in the Western GOA, but trawl catch of Pacific cod was primarily centered around Kodiak (Fig. 2.6). Trawl catch in the Western and Central GOA in 2023 are similar to catches in 2021 (Fig 2.9 and Fig. 2.10). Due to bycatch in other fisheries trawl catch of Pacific cod in 2020 remained above 3,000 t despite the closure of the federal directed fishery.

The trawl fishery generally catches smaller fish than the other two gear types with fish as small as 10 cm appearing in the observed length composition samples Fig. 2.13). The average size of Pacific cod caught by trawl in the 1980's was on average smaller and more variable than those caught later. The trawl fishery showed an increase in average size in the 1990s with the maturation of the domestic fishery. The decline in the mean length from the mid-1990s until 2015 mimics that observed in the longline and pot fisheries with some prominent outliers (2005-2006). The mean size shows an increase in 2016 through 2023 (with the exception of 2020, which was when the directed fishery was closed), which is similar to the mean length trend in the logline and pot fisheries.

Other gear types, non-directed, and non-commercial catch

There is a small jig fishery for Pacific cod in the GOA, which is a primarily state managed fishery and there is no observer data documenting distribution. This fishery has taken on average 2,400 t per year. In 2017 through 2020 the jig fishery remained low with catch at less than 500 t for all regions (Table 2.1; Fig. 2.9 and Fig. 2.10). Since 2017, the number of jig vessels participating in the GOA Pacific cod fishery ranged from 27 to 65 vessels (Fig. 2.8). Catch of jig vessels has increased since 2017, with the majority of catch coming from the Central GOA since 2020.

Pacific cod is also caught as bycatch in other commercial fisheries. Although historically the shallow water flatfish fishery caught the most Pacific cod, since 2019, the greatest sources of Pacific cod bycatch have been the bottom walleye pollock, arrowtooth flounder, halibut, and rockfish fisheries (Table 2.7).

Non-commercial catch of Pacific cod in the Gulf of Alaska is relatively small at less than 400 t; data are available through 2022 (Table 2.8). The largest component of this catch comes from the recreational fishery, generally taking approximately one-third to one-half of the accounted for non-commercial catch, and the IPHC Annual Longline survey also takes between one-third and one half of the accounted for non-commercial catch.

Other fishery related indices for stock health

Indices of fishery catch per unit effort (CPUE) can be informative to the health of a stock, however CPUE in directed fisheries can be hyper-stable with CPUE remaining high even at low abundance (Walters 2003). This phenomenon is believed to have contributed to the decline of the Northern Atlantic cod (*Gadus morhua*) on the eastern coast of Canada (Rose and Kulka 1999). Instead of showing directed CPUE, the non-targeted catch of Pacific cod in other directed fisheries is examined as an indicator of population trends. We examine two disparate fisheries to evaluate trends in incidental catch of Pacific cod, the pelagic walleye pollock fishery and the bottom trawl shallow water flatfish fishery. The occurrence of Pacific cod in the pelagic pollock fishery appears to be an index of abundance that is particularly sensitive to 2 year old Pacific cod, which are thought to be more pelagic. The shallow water flatfish fishery tracks a larger portion of the adult population of Pacific cod. For the pollock fishery we track incidence of occurrence as proportion of hauls with cod (Fig. 2.14). There were no haul data available from the pollock fishery in the Western GOA since 2020 due to electronic monitoring and COVID-19 restriction on observer deployment. In the shallow water flatfish fishery, catch rates in tons of Pacific cod per ton of all species caught were examined (Fig. 2.15). For the walleye pollock fishery in areas 620 and 630 of the Central GOA, the 2023 value was low in 620 and decreased in 630, while a recent increasing trend in 630 seems to persist. The catch of Pacific cod in the shallow water flatfish fisheries was the lowest in 2017 with a generally increasing trend since. The 2023 proportion of cod catch in the shallow water flatfish fishery was similar in magnitude to the proportions prior to 2015. It should be noted that none of these indices are controlled for gear, vessel, effort, or fishing practice changes.

The weight of catch of other commercial species caught in the Pacific cod targeted fisheries for 2018 through 2022 are shown in Table 2.5, and incidental catch of non-commercial species for 2018 – 2023 are shown in Table 2.6. Non-commercial catch of Pacific cod in other activities is provided in Table 2.8.

Data

This section describes data used in the current assessment. It does not attempt to summarize all available data pertaining to Pacific cod in the GOA. All data used for Model 19.1b are provided in Stock Synthesis data files as well as an excel spreadsheet found at the link provided in the *Executive Summary* section of this document.

The following table and Figure 2.16 presents the data included in this assessment (the years shown in bold font are those that are new to this assessment).

Data	Source	Type	Years
Federal and state fishery catch, by gear type (trawl, pot, and longline)	AKFIN	metric tons	1977 – **2023**
Federal and state fishery catch-at-length, by gear type	AKFIN / FMA / ADF&G	number, by 1 cm bin	1977 – **2023**
GOA NMFS bottom trawl survey abundance	AFSC	numbers	1990 – **2023**
AFSC Sablefish Longline survey Pacific cod Relative Population Numbers	AFSC	RPN	1990 – **2023**
GOA NMFS bottom trawl survey length composition	AFSC	number, by 1 cm bin	1990 – **2023**
GOA NMFS bottom trawl survey conditional age-at-length	AFSC	proportion, by age and 1 cm bin	1990 – 2021
AFSC Sablefish Longline survey Pacific Cod length composition	AFSC	number, by 1 cm bin	1990 – **2023**
Federal fishery conditional age-at-length	AFSC	proportion, by age and 1 cm bin	2007 – **2022**
CFSR bottom temperature indices	National Center for Atmospheric Research	temperature anomaly at mean depth for P. cod size bins	1979 – **2023**

Fishery:

Catch Biomass

Catches for the period 1991-2023 are shown for the three main gear types in Table 2.1, with the catches for 2023 presented through October 16, 2023. For the assessment model the Oct-Dec catch was assumed to reach the full TAC and state GHL. Three fishery fleets were modeled (by gear categories); trawl (all trawl types), longline (longline and jig) and pot.

Fishery Size Composition

Fishery size compositions are presently available by gear for at least one gear type in every year from 1977 through October of 2023. Size composition data are based on 1-cm bins ranging from 1 to 116 cm. As the maximum percent of fish larger than 110 cm over each year-gear type-season is less than 0.5%, the upper limit of the length bins was set at 116 cm, with the 116-cm bin accounting for all fish 116 cm and larger.

For length composition data prior to 1991, the fishery length composition data were estimated based on the extrapolated number of fish in each haul for all hauls in a gear type for each year based on the methods followed by the 2016 assessment models (called the '2016 Method'), as follows:

2016 Method: $p_{ygl} = \frac{\sum_h \frac{n_{yghl}}{\sum_l n_{yahl}} N_{ygh}}{\sum_h N_{yg}}$

where *p* is the proportion of fish at length *l* for gear type *g* in year *y*, *n* is the number of fish measured in haul *h* at length *l* from gear type *g*, and year *y* and *N* is the total extrapolated number of fish in haul *h* for gear type *g*, and year *y*.

The post-1991 length composition was estimated using the total Catch Accounting System (CAS) derived total catch weight for each gear type, NMFS management area, trimester, and year. Data prior to 1991 were unavailable at this resolution so those size composition estimates are unchanged.

Post-1991 method: $p_{ygl} = \sum_{t,a}\left(\left(\frac{\sum_h \frac{n_{ytaghl}}{\sum_l n_{ytaghl}} N_{ytagh}}{\sum_h N_{ytag}}\right)\left(\frac{W_{ytag}}{\sum_{tag} W_{ytag}}\right)\right)$

Where *p* is the proportion of fish at length *l* for gear type *g* in year *y*, *n* is the number of fish measured in haul *h* at length *l* from gear type *g*, NMFS area *a*, trimester *t*, and year *y* and *N* is the total extrapolated number of fish in haul *h* for gear type *g*, NMFS area *a*, trimester *t*, and year *y*. The *W* terms come from the CAS database and represent total (extrapolated) weight (in kg) for gear type *g*, NMFS area *a*, trimester *t,* and year *y*. In 2020 we have added the additional condition that there be more than 30 lengths measured for a gear type, trimester, and area or else the data for that gear type/trimester/area are not included. This has resulted in a loss of approximately 2% of the length data representing less than 1% of the overall catch.

<u>Addition of ADFG port sampling for pot, jig, and longline fishery length data</u>

The ADFG has routinely collected length data from Pacific cod landings since 1997. The ADFG port sampling and NMFS at-sea observer methods follow different sampling frames so combining those poses some challenges. We used ADFG data from the fishery for gear type/trimester/areas in which observer data were missing. The resolution of the ADFG data required the assumption that all of the samples collected in a gear type/trimester/area were representative of the overall catch for that gear type/trimester/area.

Method for ADFG data: $p_{ytagl} = \frac{n_{ygl}}{\sum_l n_{yal}}\left(\frac{W_{ytag}}{\sum_{tag} W_{ytag}}\right)$

Where *p* is the proportion of fish at length *l* for gear type *g* in NMFS area *a* in trimester *t* for year *y*, *n* is the number of fish measured at length *l* from gear type *g* in trimester *t* of year *y*. *W* is the catch accounting total weight for gear type *g*, NMFS area *a*, trimester *t,* and year *y*.

Age composition

Otoliths for fishery age composition have been collected since 1982. In 2017, the Age and Growth laboratory made a concerted effort to begin aging these data. These data have been processed in two ways, the first was to develop an age and gear specific age-length key which was then used in conjunction with the length composition data described above to create age composition distributions. The age data was also used to develop an annual conditional length-at-age matrix for each fishery.

Surveys:

Bottom trawl survey

The AFSC has been conducting standardized bottom trawl surveys for groundfish and crab in the Gulf of Alaska since 1984. From 1984-1997 surveys were conducted every third year, and every two years thereafter. Two or three commercial fishing vessels are contracted to conduct the surveys with fishermen working alongside AFSC scientists. Survey design is stratified random with the strata based on depth and distance along the shelf, with some concentrated strata in troughs and canyons (Raring *et al.* 2016). There are generally between 500 and 825 stations completed during each survey conducted between June and August starting in the western and ending in the southeastern Gulf of Alaska. Some changes in methods have occurred over the years with the addition of electronics to monitor how well the net is tending on-bottom, also to measure differences in net and trawl door dynamics and detect when general problems with the trawl gear occur. Surveys conducted prior to 1996 are considered to have more uncertainty given changes in gear mensuration. Also, the trawl duration was changed in 1996 to be 15 minutes instead of 30. Since 1996, methods have been consistent but in some years the extent of the survey has varied. In 2001 the Southeastern portion of the survey was omitted and in 2011, 2013, 2017, 2019, and 2021 deeper strata had fewer stations sampled than in other years due to budget and/or vessel constraints.

The 2023 survey was conducted with two chartered vessels that accomplished 526 stations following the protocols of Stauffer (2004) and von Szalay and Raring (2018). While the GOA Bottom Trawl Survey optimally employs three chartered vessels and targets 825 stations, the reduced 2023 survey likely captured the trend and magnitude of the cod abundance in the GOA. The 2023 survey covered all strata; regions, and shelf, gully, and upper slope habitats to 700 m. The coefficient of variation of the population numbers estimate was 12.1% and was lower than the historical average of 17%. The 2023 survey design was comparable to the 2013, 2017, 2019, and 2021 surveys that were also conducted with two vessels and achieved 547, 534, 541, and 539 stations, respectively.

The spatial distribution of Pacific cod in the survey has been highly variable (Fig. 2.17) with inconsistent peaks in catch. The 2019 survey showed an increase in cod in the area of the Central GOA east of Kodiak Island on Portlock Bank and South of Marmot Island, but fewer cod in the Eastern and Western GOA.

The distribution of cod in the 2021 survey is comparable to the 2019 survey except the peaks in CPUE east of Kodiak were not observed and more cod were encountered to the west of Kodiak Island and in the Western GOA near the Shumagin Islands. In the 2023 survey cod abundance increased in the Western and Central GOA, with sporadic catches in the Eastern GOA.

Biomass and abundance estimates

The Pacific cod biomass estimates from the bottom trawl survey are highly variable between survey years (Table 2.9). For example, the estimates dropped by 48% between the 1996 and 1999 estimates, but subsequent estimates were similar through 2005. The 2009 survey estimate spiked at 2 times the 2006 estimate, but was uncertain (CV = 18.5%). Subsequent surveys showed a decline through 2017 with a slight uptick in 2019, a drop in 2021, and another uptick in 2023. The 2017 estimates for abundance and biomass estimates were the lowest in the time series (a 71% drop in abundance and 58% drop in biomass compared to the 2015 estimate). Although the 2019 survey resulted in a 126% increase in abundance over 2017, the estimate remained historically low at 58% of the time series mean. The 2021 survey abundance estimate was the second lowest in the time series, next only to the 2017 estimate. The 2023 abundance estimate was 53% larger than the 2021 estimate and the 2023 biomass estimate was 33% larger than the 2021 estimate (Table 2.9 and Fig. 2.18).

Length Composition

The bottom trawl survey encounters fish as small as 5 cm and generally tracks large year-classes as they grow (e.g., the 1996, 2005-2008, and 2012 year-classes). The mean length in the trawl survey generally increased from 1990-2005 excepting the 1997 and 2001 surveys (Fig. 2.19). The decline in mean length in 2007 and 2009 were apparently due to the large incoming 2005-2008 year-classes. The mean length in the survey increased in the 2011-2017 survey then dropped again in 2019, increased again in 2021, but then dropped again in 2023. The average length of fish for 2007-2023 remains below the 1984-2005 overall average.

Age Composition

Age compositions and conditional length at age from 1990-2023 trawl surveys are available and included in this year's assessment model. Kastelle *et al.* (2017) state that one of the specific reasons for their study was to investigate the apparent mismatch between the mean length at age (from growth-zone based ages) and length-frequency modal sizes in the BSAI Pacific cod stock assessments and to evaluate whether age determination bias could account for the mismatch. Mean lengths at age (either from raw age-length pairs or age-length keys) were reported to be smaller than the modal size at presumed age from length distributions. In general, for the specimens in their study, there was an increased probability of a positive bias in fish at ages 3 and 4 (Kastelle *et al.* 2017); that is, they were over-aged. In effect, this over-ageing created a bias in mean length at age, resulting in smaller estimates of size at a given age. When correcting for ageing bias by reallocating age-length samples in all specimens aged 2–5 in proportion to that seen in the true age distribution, mean size at ages 2–4 did indeed increase (Kastelle *et al.* 2017). For example, there was an increase of 35 mm and 50 mm for Pacific cod aged 3 and 4, respectively. This correction brings the mean size at corrected age closer to modal sizes in the length compositions. While beyond the scope of their study, they postulate that the use of this correction to adjust the mean size at age data currently included in Pacific cod stock assessments should prove beneficial for rectifying discrepancies between mean length-at-age estimates and length-frequency modes.

To investigate aging bias the otoliths used in the seminal Stark (2007) paper were reread using the most recent methods and reading criteria. There appeared to be a substantial change in the results to younger fish at length for all collections used in the study. The length at age data were then plotted by year for each age and a pattern appears where post-2007 fish at ages 2 through 6 were substantially larger than those aged prior to 2007 (Barbeaux *et al.* 2020). Plotting all of the GOA AFSC bottom trawl survey age at length data for 1996-2017 as pre- and post-2007 shows the bias is most apparent from ages 3 onward with at least one year between length categories. Upon further investigation the apparent change in growth observed post-2007 with fish becoming larger at age may have been due to a change in reading criteria and predominant age readers. As in last year's model aging bias for the pre-2007 ages were included in this year's model configuration.

AFSC longline survey

Japan and the United States conducted a cooperative longline survey that was targeted for sablefish in the GOA annually from 1978 to 1994, adding the AI region in 1980 and the eastern BS in 1982 (Sasaki 1985; Sigler and Fujioka 1988). Since 1987, the AFSC has conducted annual longline surveys of the upper continental slope, referred to as domestic longline surveys, designed to continue the time series of the Japan-U.S. cooperative survey (Sigler and Zenger 1989). The domestic longline survey began annual sampling of the GOA in 1987, biennial sampling of the AI in 1996, and biennial sampling of the eastern BS in 1997 (Rutecki and Varosi 1997). The domestic survey also samples major gullies of the GOA in addition to sampling the upper continental slope. The order in which areas are surveyed was changed in 1998 to reduce interactions between survey sampling and short, intense fisheries. Before 1998, the order was AI and/or BS, Western Gulf, Central Gulf, Eastern Gulf. Starting in 1998, the Eastern Gulf area was surveyed before the Central Gulf area. International Pacific halibut longline survey.

The spatial distribution of Pacific cod in the longline survey is predominantly in the Western and Central GOA (Fig. 2.20) with inconsistent peaks in catch. The location of 2023 survey catches were similar to the 2022 survey, with consistent increases in catch in the Western GOA in 2023 compared to 2022.

<u>Abundance index</u>

A Relative Population Number (RPN) index of Pacific cod abundance and length compositions for 1990 through 2022 is available from this survey (Table 2.10 and Fig 2.18). Details about these data and a description of the methods for the AFSC sablefish longline survey can be found in Echave *et al.* (2012). This RPN index follows the trend observed in the bottom trawl survey for 1990 through 2018 with a decline in abundance from 1990 through 2008 and a sharp increase (154%) in 2009, and then continued increase through 2011 with the maturation of the large 2005-2008 year-classes. In 2012-2013 there appears a decline in the abundance index concurrent with a drop in overall shelf temperature potentially due to changes in availability of Pacific cod in these years as the population moved to shallower areas (Yang *et al.* 2019). In 2014-2016 the index increases but this may reflect increased availability with warmer conditions. The index showed a sharp drop (53%) in abundance from 2016 to 2017, again (40%) from 2017 to 2018, and yet again (37%) from 2018 to 2019. The 2019 estimate was 83% lower than the 2015 abundance estimate. The 2020 RPN showed a 30% increase from 2019, but the 2020 RPN remains the second lowest estimate of the time series. The increasing trend observed in 2020 continued in 2021 with a 58% increase, but then decreased again in 2022 by 24%. The 2023 RPN increased 32% compared to the 2022 RPN.

Length composition

Unlike the bottom trawl survey, the longline survey encounters few small fish. The size composition data show consistent and steep unimodal distributions with a stepped decreasing trend in mean size between 1990 and 2015 (Fig. 2.21) and then a generally increasing mean size from 2015-2023. This matches the trend observed in all three fisheries. Changes in mean size appear consistent with changing availability in the survey due to bottom temperatures and changes in the overall population with large year classes. A larger number of smaller fish are encountered during this survey in warm years vs. cold years. There is a sharp decline in mean size in 2009 when the large 2005 year-class would be becoming available to this survey. The even steeper decline in average length in 2015 was encountered in the second warmest year on record for the time series. In 2019 a more severe drop in average length was anticipated due to the increased temperatures on the shelf and an increase in abundance due to increased availability. That we observed neither of these anticipated outcomes portends that either very few small fish were available in the population, or a change in behavior.

Laurel and Litzow age-0 index

Beach seine sampling of age-0 cod was conducted at two Kodiak Island bays during 2006-2023 (n = 8 fixed stations per bay, 16 total stations, stations sampled 4 times per year) and an expanded survey was conducted since 2018 at 13 additional bays on Kodiak Island, the Alaska Peninsula, and the Shumagin Islands (n = 3 - 9 fixed stations per bay, 95 total stations, stations sampled 1 – 2 time per year). Sampling occurred during July and August (days of year 184-240), within two hours of a minus tide at the long-term Kodiak sites, and within three hours of a low tide at the expanded survey sites. At all sites, a 36 m long, negatively buoyant beach seine was deployed from a boat and pulled to shore by two people standing a fixed distance apart on shore. Wings on the seine (13 mm mesh) were 1 m deep at the ends and 2.25 m in the middle with a 5 mm delta mesh cod end bag. The seine wings were attached to 25 m ropes for deployment and retrieval from shore. The seine was set parallel to and ~ 25 m, making the effective sampling area ~ 900 m^2 of bottom habitat.

A model-based index of annual catch per unit effort (CPUE) for age-0 cod was used to resolve inter-annual differences in sampling across different bays and different days of the year. Specifically, a Bayesian zero-inflated negative binomial (ZINB) model was used invoking year as a categorical variable, day of year as a continuous variable, and site nested within bay as a group-level (random) effect. The day of year effect was modeled with thin plate regression splines to account for non-linear changes in abundance through the season and the number of basis functions was limited to 3 to avoid over-fitting data. This model was fit using Stan 2.21.0, R 4.0.2 and the *brms* package (Carpenter *et al.* 2017, Buerkner 2017, R Core Team 2022). The beach seine age-0 CPUE index showed the large 2012 year class and subsequent drop in CPUE for 2013-2016, and since 2016 there have been alternative small recruitment in 2019, 2021, and 2023 with larger recruitment in 2017, 2018, 2020, and 2022 (Fig. 2.22).

International Pacific halibut Commission (IPHC) longline survey

This survey differs from the AFSC longline survey in gear configuration and sampling design, but catches substantial numbers of Pacific cod. More information on this survey can be found in Soderlund *et al.* (2009). A major difference between the two longline surveys is that the IPHC survey samples the shelf consistently from ~ 10-500 meters, whereas the AFSC longline survey samples the slope and select gullies from 150-1000 meters. Because the majority of effort occurs on the shelf in shallower depths, the IPHC survey may catch smaller and younger Pacific cod than the AFSC longline survey. On the other hand, the IPHC uses larger hooks (16/0) than the AFSC longline survey (13/0) which may prevent very small Pacific cod from getting hooked. To compare these two surveys, IPHC relative population number’s

(RPN) were calculated using the same methods used to estimate the AFSC longline survey RPNs (but using different depth strata). Stratum areas (km^2) from the RACE trawl surveys were used for IPHC RPN calculations.

The IPHC survey estimates of Pacific cod tracks well with both the AFSC longline and AFSC bottom trawl surveys (Fig. 2.23). There was an apparent drop in abundance from 1997-1999 followed by a stable but low population through to 2006. The population increases sharply starting in 2007, likely with the incoming large 2005 year class and continues to increase through 2009 as the large 2005-2008 year classes matured. The population then remained relatively stable through to 2014. The RPN index shows a steep decline in 2015 and 2017 consistent with the two AFSC surveys. The 2017 RPN was the lowest on record for the 20-year time series. This index showed a slight increase of the population abundance in 2018 (28% from 2017) to values slightly higher than 2016, but remain the fourth lowest estimate on record after 2001, 2016, and 2017. The 2019 survey estimated a slight decrease (3.5%), however the uncertainty in the estimate is high, and then increased by 29% in 2021. The 2022 RPN decreased by 12% compared to 2021. The length composition data available from 2018 and 2019 show the IPHC survey encounters fish greater than 40 cm. The length data in 2018 have a mode at approximately 60 cm in the western GOA. The other management areas have modes slightly higher between 65 and 75 cm. 2019 shows a slight increase in these modes for all three areas.

Alaska Department of Fish and Game bottom trawl survey

The Alaska Department of Fish and Game (ADFG) has conducted bottom trawl surveys of nearshore areas of the Gulf of Alaska since 1987. Although these surveys are designed to monitor population trends of Tanner crab and red king crab, Pacific cod and other fish are also sampled. Standardized survey methods using a 400-mesh eastern trawl were employed from 1987 to the present. The survey is designed to sample at fixed stations from mostly nearshore areas from Kodiak Island to Unimak Pass, and does not cover the entire shelf area. The average number of tows completed during the survey is 360. On average, 89% of these tows contain Pacific cod. Details of the ADFG trawl gear and sampling procedures are in Spalinger (2006).

To develop an index from these data, a simple delta GLM model was applied covering 1988-2023. Data were filtered to exclude missing latitude and longitudes and missing depths. This model is separated into two components: one that tracks presence-absence observations and a second that models factors affecting positive observations. For both components, a fixed-effects model was selected and includes year, geographic area, and depth as factors. Strata were defined according to ADFG district (Kodiak, Chignik, South Peninsula) and depth (< 30 fathoms, 30-70 fathoms, > 70 fathoms). The error assumption of presence-absence observations was assumed to be binomial but alternative error assumptions were evaluated for the positive observations (lognormal versus gamma). The AIC statistic indicated the lognormal distribution was more appropriate than the gamma. Comparison of delta GLM indices with the area-swept estimates indicated similar trends. Variances were based on a bootstrap procedure, and CVs for the annual index values ranged from 0.06 to 0.14. These values underestimate uncertainty relative to population trends since the area covered by the survey is a small percentage of the GOA shelf area where Pacific cod have been observed.

The ADFG survey index follows the other three indices presented above with a drop in abundance between 1998 and 1999 (-45%) and relatively low abundance throughout the 2000s (Fig. 2.23). This survey differs from other indices as the estimates only increased in 2012 (an 89% increase from 2011), and then dropped off steadily afterwards to a record low in 2016. The 2017 survey index was 6% higher than the 2016 survey index. 2018 increased by 31% from 2017. The 2019 survey showed a slight decline

(15.8%) from 2018, but 2020 showed a sharp increase of 41% from 2019 and a 64% increase from the 2016 record low, but still below the time series average. 2021 showed a 19.8% decrease from 2020 with a biomass estimate 67% lower than the time series average. 2022 resulted in a slight increase of 4% compared to 2021 and 2024 increased by 29% compared to 2022. Length composition data from this survey show wide multi-modal length distributions are common with modes of age-0 fish at times available at near 10cm, however the 2019 through 2021 surveys have no fish smaller than 22 cm, while there were some fish smaller than 22 cm that occurred in the 2022 and 2023 surveys.

Environmental indices

CFSR bottom temperature indices

The Climate Forecast System Reanalysis (CFSR) is the latest version of the National Centers for Environmental Prediction (NCEP) climate reanalysis. The oceanic component of CFSR includes the Geophysical Fluid Dynamics Laboratory Modular Ocean Model version 4 (MOM4) with iterative sea-ice (Saha *et al.* 2010). It uses 40 levels in the vertical with a 10-meter resolution from surface down to about 262 meters. The zonal resolution is 0.5° and a meridional resolution of 0.25° between 10°S and 10°N, gradually increasing through the tropics until becoming fixed at 0.5° poleward of 30°S and 30°N.

To make the index, the CFSR reanalysis grid points were co-located with the AFSC bottom trawl survey stations. The co-located CFSR oceanic temperature profiles were then linearly interpolated to obtain the temperatures at the depths centers of gravity for 0-20 cm Pacific cod as determined from the AFSC bottom trawl survey. All co-located grid points were then averaged to get the time series of CFSR temperatures over the period of 1979-2023 (Table 2.11 and Fig. 2.24).

The mean depth of Pacific cod at 0-20 cm was found to be 47.9 m in the Central GOA and 41.9 m in the Western GOA. The temperatures of the 0-20 cm Pacific cod in the CFSR indices include high peaks in water temperature in 1981, 1987, 1998, 2015, 2016 and 2019 with 2019 being the highest in both the 0-20 cm index. There are low valleys in temperature in 1982, 1989, 1995, 2002, 2009, 2012, and 2013. The coldest temperature in the 0-20 cm index was in 2009. In 2020 and 2021 the temperatures for 0-20 cm are below the time series mean with 2021 being within 1% of the 2020 temperatures. In 2022 the temperatures were above the time series mean and in 2023 the temperature was again below the time series mean.

Sum of annual marine heatwave cumulative intensity index (MHWCI)

The daily sea surface temperatures for 1981 through October 2023 were retrieved from the NOAA High-resolution Blended Analysis Data database (NOAA 2017) and filtered to only include data from the central Gulf of Alaska between 145°W and 160°W longitude for waters less than 300m in depth. The overall daily mean sea surface temperature was then calculated for the entire region. These daily mean sea surface temperatures data were processed through the R package heatwaveR (Schlegel and Smit 2018) to obtain the marine heatwave cumulative intensity (MHCI; Hobday *et al.* 2016) value where we defined a heat wave as 5 days or more with daily mean sea surface temperatures greater than the 90th percentile of the 1 January 1982 through 31 December 2012 time series. The MHCI were then summed for each year to create an annual index ($MHCI_{AN}$), summed for each year for the months of January through March, November, and December to create an annual winter index ($MHCI_{W}$), and the months of February and March to create an annual spawning season index ($MHCI_{SP}$).

The marine heatwave analysis using the daily mean Central GOA sea surface temperatures indicated a prolonged period of increased temperatures in the Central GOA from 2 May 2014 to 13 January 2017 with heatwave conditions persisting for 815 of the 917 days in 14 events of greater than 5 days (Appendix 2.1) The longest stretch of uninterrupted heatwave conditions occurred between 14 December 2015 and 13 January 2017 (397 days). By the criteria developed by Hobday *et al.* (2018) for marine heatwave classification the event in the Central GOA reached a Category III (Severe) on 16 May 2016 with a peak intensity (I_{max}) of 3.02°C. The heatwave had a summed cumulative intensity (I_{cum}) for 2016 of 635.26°C days, more than 25% of the sum of the I_{cum} for the entire time series (1981-2018). The 14 events of this prolonged heatwave period summed to 1291.91°C days or 52% of the summed I_{cum} for the time series.

There have been three periods of increased winter heatwave activity in the Central GOA (Table 2.11), the first in 1983-1986, second in 2001-2006, and the third 2014-2021. Short winter marine heatwaves (Category I to II) occurred every winter between 1983 and 1986, however none of these exceeded 17 days and the total winter I_{cum} for this period was 84.23°C days over a total of 86 days. In the winter of 1997 there were two short (7 and 12 days) winter heatwave events with a total cumulative intensity of 17.19 °C days. In 1998 there was a strong heatwave from 3 March to the 14 June (102 days) with an I_{max} of 2.36°C and cumulative intensity of 146.01°C days. From 2001 through 2006 there were 6 winter heatwave events, most were minor and less than two weeks in length, however between 6 November 2002 and 4 March 2003 there were two that lasted in sum 141 days with a cumulative intensity of 165.94°C days and an I_{max} of 2.04°C. The 2014-2016 series of marine heatwave as described above was substantially longer lasting and more intense than anything experience previously in the region reaching a maximum SST anomaly of 3.12°C on 5 May 2016 and having a cumulative intensity of 1369.24 °C days across the three years. The most recent heatwave began 9 September 2018 to 23 December 2019. There are six distinct events making up the 2018-2019 heatwave with a maximum SST anomaly of 3.03 °C and a cumulative intensity of 625.23 °C days. For 2020 the sea surface temperatures dropped below the long-term mean in March but then increased in April (Fig. 2.25). After April the SST remained above the 1982-2012 mean oscillating into and out of heatwave conditions through October 2020 with four heatwave events occurring between 8 June and mid-October for a cumulative intensity of 131.24 °C days. The highest seasonal anomaly for 2020 was on 22 August at 2.68°C. The longest heatwave event in 2020 has lasted 48 days starting 13 September and continuing to 31 October. In 2021 there were three short heatwaves in January through March, two of 4 days and one of five days with a maximum temperature of 1.79 °C above the seasonal mean. For the most part, 2023 remained cool or near average, with no heatwave days during the winter or spawning season; this was the first year for this to occur since 2013.

Analytic Approach

General Model Structure

This year we present the accepted model from last year, Model 19.1a, with updated data. We denote a new model number, Model 19.1b, to note the decrease in the minimum sample size for conditional age-at-length data from 1 to 0.001 in order to include all this data in the model fitting (Appendix 2.2). To see the history of models used in this assessment refer to A'mar and Palsson (2015). The model for this year was run in Stock Synthesis version 3.30.21 (Methot and Wetzell 2013).

Model 19.1b is a single sex, age-based model with length-based selectivity. This model has data from three fisheries (longline, pot, and combined trawl fisheries) with a single season and two survey indices (post-1990 GOA bottom trawl survey and the AFSC Longline survey indices). Length composition data were available for all three fisheries and both survey indices. Conditional age-at-length data were available for the three fisheries and AFSC bottom trawl survey.

The Stock Synthesis control and forecast files for this year's model are found at the link provided in the *Executive Summary* section of this document.

Parameters Estimated Outside the Assessment Model

Variability in Estimated Age

Variability in estimated age in Stock Synthesis is based on the standard deviation of estimated age. Weighted least squares regression has been used in the past several assessments to estimate a linear relationship between standard deviation and age. The regression was recomputed in 2011, yielding an estimated intercept of 0.023 and an estimated slope of 0.072 (i.e, the standard deviation of estimated age was modeled as 0.023 + 0.072 × age), which gives a weighted R^2 of 0.88. This regression was retained in the present assessment.

Weight-at-Length

Parameters governing the weight-at-length were estimated outside the model using AFSC GOA bottom trawl survey data through 2023, giving the following values:

	Value
α:	6.038×10^{-3}
β:	3.1416
Samples:	7,366

Maturity

The length at 50% maturity was calculated using the *morp_mature* function in the sizeMat R package (Torrejon-Magallanes 2017) using all of the length-at-maturity data available from the Stark (2007) study for the Gulf of Alaska. This included some maturity data that was not available to Stark (2007) at the time of publication and some maturities from March and April not used in the calculation of $L_{50\%}$ published. This resulted in the following values: length at 50% maturity = 57.3 cm and slope of linearized logistic equation = -0.27365.

Aging Error

An aging error vector was included in the model. These were developed from age reader agreement testing results for otoliths read from the 2007-2017 bottom trawl surveys. The standard deviation at age 3 was 0.57 and at age 10 was 1.16, the model assumed a linear interpolation between these values and no error at ages 1 and 2.

Parameters Estimated Inside the Assessment Model

Parameters estimated conditionally (i.e., within individual Stock Synthesis runs, based on the data and the parameters estimated independently) in the model include the growth parameters, annual recruitment deviations, gear-specific fishery selectivity parameters, aging bias adjustment parameters, survey catchability, and survey and fishery selectivity parameters (Table 2.12).

Natural Mortality

For a description of the development of the priors used in this assessment for natural mortality rate *M* see Hulson et al. (2022). A lognormal prior on *M* of -0.81 (μ=0.44) with a standard deviation of 0.41 is used in this assessment. In Model 19.1b *M* was estimated for two time blocks, 2014-2016 and all other years, as a single non-varying parameter for all ages for each block. In 2017 it was hypothesized that due to the drop in all available survey indices between 2013 and 2017 that there was an increase in *M* during the height of the 2014-2016 marine heatwave.

Growth

For Model 19.1b length at age, L_a, were modeled as three parameter von Bertalanffy growth models with length in June, L_1, maximum asymptotic length, L_2, and growth rate, k, as:

$$L_a = L_2 - (L_2 - L_1)e^{-ak},$$

where a was age.

The initial growth parameters L_1, k, and L_2 initial values and 'priors' based on a nonlinear least squares regression of the 2007-2015 AFSC GOA bottom trawl survey length-at-age data. The *nls* function from the nlstools library (Baty *et al.* 2015) in R was used to fit the basic model. Variance of the parameters were determined through bootstrap of the model with 1,000 iterations. L_{inf} was estimated at μ=99.46 CV=0.015, K was μ = 0.1966 CV=0.03, L_0 was -0.11 CV=0.25. We recognized that these 'priors' are not true priors as they are drawn from the data used in the model, but were necessary in setting structure within the model while allowing some flexibility in the model fitting which we think is a compromise to fixing parameters. Previous modeling effort using uninformative priors on these three parameters has led to model convergence at unreasonable values or non-convergence.

Recruitment

In Model 19.1b recruitment by year, R_y, were modeled as:

$$R_y = \left(R_0 e^{\vartheta}\right) e^{-0.5 b_y \sigma_R^2 + \tilde{R}_y}\text{ , if } y \geq 1977 \rightarrow \vartheta = 0\text{, where } \tilde{R}_y = N\left(0;\ \sigma_R^2\right),$$

R_0 was the unfished equilibrium recruitment, $\tilde{R}_y$ was the lognormal recruitment deviation for year y, σ_R^2 was the standard deviation among recruitment deviations in log space and was fixed at 0.44, and b_y was a bias adjustment fraction applied during year, y (Methot and Taylor 2011). To account for an environmental regime change in 1977 (Anderson and Piatt 1999) the parameter ϑ was fit for recruitment allowing for a change in R_0 prior to the regime change in 1977. Projections in the base model post-2023 assumed average recruitment for 1977-2023 for R_y.

Survey and Fishery selectivity

The same functional form (pattern 24 for length-based selectivity) used in Stock Synthesis to define the fishery selectivity schedules in previous year's assessments was used this year for both the fishery and survey. This functional form, the double normal, is constructed from two underlying and rescaled normal distributions, with a horizontal line segment joining the two peaks. This form uses the following six parameters (selectivity parameters are referenced by these numbers in several of the tables in this assessment):

1. Beginning of peak region (where the curve first reaches a value of 1.0)
2. Width of peak region (where the curve first departs from a value of 1.0)
3. Ascending "width" (equal to twice the variance of the underlying normal distribution)
4. Descending width

5. Initial selectivity (at minimum length/age)
6. Final selectivity (at maximum length/age)

All but the “beginning of peak region” parameter are transformed: The widths are log-transformed and the other parameters are logit-transformed.

The following table provides the time varying selectivity components for Model 19.1b:

Component	**Temporal Blocks/Devs**
Longline Fishery	Annually variable 1978-1989
Trawl Fishery	Blocks – 1990-2004, 2005-2006, 2007-2016, 2017-2022
Pot Fishery	Blocks – 1977-2012 and 2013-2022
Bottom trawl survey	Blocks – 1990-1995, 1996-2006, 2007-2022

In this year’s model both fishery and survey selectivities were length-based. Uniform prior distributions were used for all selectivity parameters, except for *dev* vectors in models with annually varying selectivities which were constrained by input standard deviations (“sigma”) of 0.2.

For all parameters estimated within individual SS runs, the estimator used was the mode of the logarithm of the joint posterior distribution, which was in turn calculated as the sum of the logarithms of the parameter-specific prior distributions and the logarithm of the likelihood function.

Fishing mortality

In Model 19.1b the full set of year- and gear-specific fishing mortality rates were also estimated conditionally, but not in the same sense as the selectivity parameters. The fishing mortality rates are determined exactly rather than estimated statistically 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.

Ageing error and bias

Aging error was developed from age reader agreement testing results for otoliths read from the 2007-2017 bottom trawl surveys. The standard deviation at age 3 was 0.57 and at age 10 was 1.16, the model assumed a linear interpolation between these values and no error at ages 1 and 2. Ageing bias was estimated for ages 3+ with two parameters, bias at age 3 and bias at age 10, with a linear interpolation between the two, applied to all age data collected prior to 2007 (aged prior to 2008). Age data from post-2007 were assumed to be aged without bias.

Catchability

In Model 19.1b catchability for the AFSC bottom trawl survey was fit with a non-informative prior. An ecosystem-linked covariate on AFSC longline survey catchability has been in use since 2017 (Barbeaux *et al.* 2016) and will continue to be used in all of the models presented. Annual catchability, Q_y, was modeled using a multiplicative link as:

$$log(\mathrm{Q_y}) = \log(\overline{\mathrm{Q}})\mathrm{e}^{\tau \mathrm{f}_{Jy}},$$

where $\bar{Q}$ was the mean catchability for the AFSC longline survey for 1977 through 2023,τ was the ecosystem link parameter fit with an uninformative prior, and f_{Jy} was the June CFSR bottom temperature anomaly in the Central GOA in year *y* (Fig. 2.24). An analysis introducing this methodology was presented in 2017 (Barbeaux *et al.* 2017) and a method validating this methodology was presented at the 2018 September Plan team meeting and provided in Barbeaux *et al.* (2018) Appendix 2.1. Bottom trawl survey data show a centroid of distribution for cod greater than 34 cm shifts to deeper water in years with warmer shelf temperatures (Barbeaux *et al.* 2019). This relationship was verified in Yang *et al.* (2019) with a shift to deeper depths in all size classes examined during warm years and shift to shallower waters in cold years. This pattern would make cod more available to the AFSC longline survey in warm years, given that the survey station minimum depth is 150 m.

Likelihood Components

The model includes likelihood components for trawl survey relative abundance, fishery and survey size composition, fishery and survey mean size-at-age, recruitment, parameter deviations, and "softbounds" (equivalent to an extremely weak prior distribution used to keep parameters from hitting bounds), and initial (equilibrium) catch.

For Model 19.1b there were no parameters near bounds and the likelihoods appear well defined with the gradient of the objective function at less than $1e^{-5}$. Model 19.1b was examined by "jittering" starting parameters by a factor of 0.05 over 50 runs to evaluate if models had converged to local minima.

Use of Size Composition Data in Parameter Estimation

Size and age composition data were assumed to be drawn from a multinomial distribution specific to a particular year and gear within the year. In the parameter estimation process, SS weights of a given size composition observation (i.e., the size frequency distribution observed in a given year and gear) according to the emphasis associated with the respective likelihood component and the sample size specified for the multinomial distribution from which the data were assumed to have been drawn. As was done in previous assessments, we set input sample sizes for the fishery length composition at the number of hauls sampled or 200 whichever is least and for the surveys the length composition input sample sizes were set at 100. For fishery and survey conditional age-at-length the input sample sizes were set at the number of age samples per length bin multiplied by 0.14.

Results

Model Evaluation

Model evaluation criteria included log likelihood, model adherence to biological principles and assumptions, the relative sizes of the likelihood components, and how well the model fits to the survey indices, the survey and fishery length composition, and conditional age-at-length data, reasonable curves for fishery and survey selectivity, retrospective pattern, and model behavior during leave-one-out analysis.

Model likelihoods and key parameter estimates are provided in Table 2.13. Likelihoods by fleet are provided in Table 2.14. Retrospective results are presented in Figure 2.25 and 2.26. The retrospective pattern in spawning biomass decreased compared to the 2022 assessment (Mohn's rho of -0.1 in the current assessment compared to -0.032 in 2022). A negative retrospective pattern indicates that the model increases the estimates of spawning biomass in each subsequent year as data are added, and given the increase in the bottom trawl and longline survey indices in 2023 compared to the previous survey (2021 for the bottom trawl, 2022 for the longline) this pattern would be expected. A positive retrospective pattern persists for recruitment, indicating that as subsequent years of data are added to the model the estimates of recruitment decrease. This pattern is shown in Figure 2.26, which shows, in particular, that as the 2023 data was added to the model the estimates of recruitment decreased compared to 2022 for most of the recent larger year classes (since 2000), it also shows that this is generally the trend across assessment years.

To investigate model stability and sensitivity to data we performed jitter and leave-one-out (LOO) analyses. Model 19.1b performed reasonably well in the jitter analysis with a CV of 0.05 and 50 runs with a total of 49 of the 50 jitter runs converged with 80% of the converged models resulting in estimates at the lowest MLE from the accepted models. LOO results are presented in Table 2.15 and Figures 2.27 and 2.28. For the LOO analysis, data for a single year were pulled from the model sequentially and the model refit each time, or, the data added in this year's assessment were pulled one source at a time and the model was refit each time. We then examined the behavior of the model and the effects of removing the data on key parameter estimates (*M*, and *q*), and derived quantities ($F_{40\%}$, unfished spawning biomass, forecast spawning biomass, and ABC). Stability of the model estimates and estimates of variance while removing data provided insights on model performance and sensitivity to noise within the data. For this analysis we focused on the difference between the full model and the model with data left out, i.e. was there a direction of change when data were removed from the complete model, and the variability of the variance estimates as data were removed. Model 19.1b resulted in relatively low differences across all examined parameters and derived quantities (Table 2.15). The highest difference was observed in the forecasted ABC and bottom trawl log catchability, but both remained below a difference of 4%. In Model 19.1b the removal of data after 2013 resulted in increased variability in model estimates, with the removal of the 2022 and 2023 data being most impactful on the forecasted spawning biomass and ABC (Fig. 2.27). Removing the 2022 data (for which the only index data available is from the longline survey, which remained low) caused an increase in spawning biomass and ABC, whereas removing the 2023 data (for which both the bottom trawl and longline survey indices were available) resulted in a decrease in spawning biomass and ABC. Removing one data point (i.e., that was updated since last year's assessment) at a time showed that the bottom trawl survey index is the most influential on forecasted spawning biomass and ABC (Fig. 2.28), followed by the bottom trawl and longline survey length compositions, all of which indicate a decrease in spawning biomass and ABC when removed.

In order to evaluate the environmental link with the longline survey catchability parameter we performed two tests. First, we removed the environmental link and ran the model using only the mean longline survey catchability parameter. Second, we generated 50 iterations of 'white noise' (with N(0,1)) and used this in place of the CFSR index and fit the model. We compared Model 19.1b with these two tests using Akaike Information Criterion (AIC, Burnham and Anderson 2002). The AIC value from the model that did not include the CFSR index was 11.4 larger than the AIC value from Model 19.1b. On average, the AIC value from the 50 model runs with white noise in place of the CFSR index was 6.9 larger than the AIC of Model 19.1b (where 45 of the 50 runs resulted in an AIC value for Model 19.1b that was smaller than a model using white noise). Given the results of these two tests, Model 19.1b using the CFSR index for the longline survey catchability parameter is preferred and continues to be recommended.

Model 19.1b with data updated through 2023 results in reasonable fits to the data, estimates biologically plausible parameters, and produces consistent patterns in abundance compared to previous assessments. It should be noted that the results from the GOA Pacific cod stock assessment have been particularly volatile with a wide-array of models presented over the past 18 years (A'mar and Palsson 2015). Model 19.1b presented this year is well within the bounds of models presented in previous years for the spawning stock biomass time series (Fig. 2.29). Model 19.1b fit to the bottom trawl and longline survey indices, survey and gear specific fishery conditional age-at-length, and survey and gear specific fishery length composition, as well as estimated survey and fishery selectivity, are shown in Figures 2.30 – 2.45. While Model 19.1b fits the bottom trawl survey abundance reasonably well it should be noted that positive residuals have resulted in the fit to the longline survey between 2018 and 2022, where a negative residual resulted for 2023 (Fig. 2.30). Overall, Model 19.1b yields reasonable results and we continue to use it to recommend the 2024 ABC and OFL.

Additional results and figures can be found at the link provided in the *Executive Summary* section of this document.

Time Series Results

Definitions

The biomass estimates presented here will be defined in two ways: 1) total biomass was defined as age 0+ biomass, consisting of the biomass of all fish aged 0 years or greater in a given year; and 2) spawning biomass was defined as the biomass of all spawning females in a given year. The recruitment estimates presented here were defined as numbers of age-0 fish in a given year; actual recruitment to fishery and survey depends on selectivity curves as estimated (noting that there are no indices involving age-0 Pacific cod). All results presented are from Model 19.1b.

Biomass

Total biomass estimates show a long decline from their peak in 1988 (Table 2.16 and Fig. 2.31) to a low in 2006 and then an increase to another peak in 2014, after which there was a sharp decline through 2018 followed by a slight increase through 2023. Spawning biomass (Table 2.16 and Figure 2.29) shows a similar trend of decline since the late 1980s with a peak in 1989 to a low in 2008. There was then a short increase in spawning biomass coincident with the maturation of the 2005-2008 year classes through 2014, after which the decline continued to lowest level in 2019 and 2020. The spawning biomass then slightly increased in 2021 and 2022 and is projected to slightly decrease in 2023.

Recruitment and Numbers-at-Age

The recruitment predictions in Model 19.1b (Table 2.17, Fig. 2.46, and Fig. 2.50) show above average recruitment for most of the 1980s, below average recruitment from the mid-1990s to mid-2000s, above average recruitment from the mid-2000s to 2013, and below average recruitment since. Numbers-at-age and length, with the mean age and length, are shown in Figure 2.47. Overall, in the population estimates the average age and length have both decreased since 2019.

Fishing Mortality

Fishing mortality appears to have increased steadily with the decline in abundance from 1990 through a peak in 2008 with continued high fishing mortality through 2017 in all models examined (Table 2.18). 2017 had the highest total exploitation rate of the time series. The period between 1990 and 2008 saw both a decline in recruitment paired with increases in catch. The period of increasing fishing mortality was mainly attributed to the rise in the pot fishery, which also shows the largest increase in continuous F (Fig. 2.48). In 2018 through 2020 there was a sharp decrease in fishing mortality coincident with the drastic cuts in ABC and closure of the federal directed fishery in 2020. In 2021 with the reopening of the federal fishery mortality once again increased, but remained lower than observed in the previous decade prior to 2017. In retrospect the phase plane plots (Fig. 2.49) show that F was estimated to have been above the ABC control rule advised levels for 2008 and 2015 to 2017 and biomass was below $B_{35\%}$ since 2017, and projected to continue to be below through 2025. It should be noted that this plot shows what the current model predicts, not what the past assessments had estimated.

Uncertainty Results

MCMC were conducted with the R package *adnuts* (Monnahan and Kristensen 2018, Monnahan et al. 2020). 2,500,000 MCMC iterations were thinned to every 2000th iteration and the first half of the iterations were removed to account for the burn-in period. The pairs plot for key parameters are shown in Figure 2.50, and the histograms of these parameters are shown in Figure 2.51. These parameters appear well defined and bracket the MLE estimates (Fig. 2.51). Model 19.1a predicts a < 0.1% probability the stock was below $B_{20\%}$ or $B_{17.5\%}$ in 2023 or 2024 (Fig 2.52).

Harvest Recommendations

Amendment 56 Reference Points

Amendment 56 to the GOA 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 GOA 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: $B/B_{40\%} \leq 0.05$

$F_{OFL} = 0$

$F_{ABC} = 0$

Other useful biomass reference points which can be calculated using this assumption are $B_{100\%}$ and $B_{35\%}$, defined analogously to $B_{40\%}$. These reference points are estimated as follows, based on this year's model, Model 19.1b:

Reference point:	$B_{35\%}$	$B_{40\%}$	$B_{100\%}$
Spawning biomass:	61,315 t	70,075 t	175,187 t

For a stock exploited by multiple gear types, estimation of $F_{35\%}$ and $F_{40\%}$ requires an assumption regarding the apportionment of fishing mortality among those gear types. For this assessment, the apportionment was based on this year's model's estimates of fishing mortality by gear for the five most recent complete years of data (2018-2022).

Specification of OFL and Maximum Permissible ABC

For Model 19.1b spawning biomass for 2024 is estimated by this year's model to be 51,959 t at spawning. This is below the $B_{40\%}$ value of 70,075 t, thereby placing Pacific cod in sub-tier "b" of Tier 3. Given this, the model estimates OFL, maximum permissible ABC, and the associated fishing mortality rates for 2024 and 2025 as follows (2025 values are predicated on the assumption of the full TAC and GHL being taken in 2023 and that the 2024 catch will be at maximum ABC in the projection):

Units	Year	Overfishing Level (OFL)	Maximum Permissible ABC
Harvest amount	2024	38,712	32,272
Harvest amount	2025	33,970	28,184
Fishing mortality rate	2024	0.52	0.42
Fishing mortality rate	2025	0.48	0.38

The age 0+ biomass projections for 2024 and 2025 from this year's model are 184,242 t and 203,207 t, respectively.

Risk Table and ABC Recommendation

Overview

The following template is used to complete the risk table:

	Assessment-related considerations	*Population dynamics considerations*	*Environmental/ecosystem considerations*	*Fishery Performance*
Level 1: No Concern	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: 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 3: 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.”

Assessment considerations.

The GOA Pacific cod assessment does not show an exceptionally strong retrospective bias in recent estimates of spawning biomass, either in the data retrospective (Fig. 2.25) or in the model retrospective across recent assessments (Fig. 2.29). However, a strong retrospective bias in recruitment estimates persists (Fig. 2.26). As subsequent years of data were added to Model 19.1b in the data retrospective analysis, the estimates of stronger recent year classes (2012 and 2013) consistently decreased. This has also been shown to be the case in the assessment retrospective, as estimates of recent year classes decrease with each new assessment (e.g., Table 2.17). An additional assessment concern, as it relates to projecting biomass and management quantities, is that the projection model uses mean recruitment from 1977 – 2021 to project biomass into future years. However, Model 19.1b has estimated below average recruitment since 2014. Therefore, given that the model decreases recent recruitment estimates as data are added and the projections are likely assuming unrealistically large cohorts, there is a substantial probability that the forecasted spawning biomass is overly optimistic. For these reasons, we continue to rate the assessment considerations category as level 2, major concern.

Population dynamics considerations

Female spawning biomass is currently estimated to decrease over the next 2 years, then increase in the medium-term once the projected year classes (i.e., based on mean recruitment since 1977) begin contributing to the SSB. To reiterate, mean recruitment levels have not been estimated in the model since 2014 (i.e., the last 8 year classes have been well below average). The current assessment couples these estimates of poor recruitment since 2014 with increased natural mortality during the recent marine heatwaves 2014-2016. Information from spring ichthyoplankton and beach seine of age-0 fish surveys suggest a very weak 2019 year class, a strong 2020 year class, and above average 2017, 2018, and 2022 year classes. How these indices relate to overall recruitment into the fishery and population is currently unknown, but they have yet to materialize in the estimates of recruitment in the assessment. Because of the persistent low levels of spawning biomass and below average recruitment, we continue to rate the population dynamics considerations category at level 2, major concern.

Environmental/Ecosystem considerations

Appendix 2.1 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 Gulf of Alaska Ecosystem Status Report (GOA ESR; Ferriss, 2023). The text below summarizes ecosystem information related to GOA Pacific cod provided from both the ESP and GOA ESR.

The most recent data available suggest an ecosystem risk Level 1 – Normal: “No apparent environmental/ecosystem concerns.” This score is informed by optimal thermal conditions, below average to average prey base but adequate for adult energetic needs (average adult condition), and moderate predation and competition pressures. There is potential for low survival of the 2023 age-0 year class. Predicted warm surface temperatures in 2024 pose an elevated risk for larval survival of the 2024 year class but present a low risk for adult cod survival and spawning habitat at depth.

Environmental Processes: Thermal conditions for 2023 are within known optimal ranges for Pacific cod life history stages: spawning (Feb-Apr: 20m - 290m, 1°C - 7°C), egg (Mar-Apr: 20m - 200m, 3°C - 6°C), larvae (Apr-May: 0m - 45m, 5°C - 6°C). Spawning conditions were considered average to good, based on the lack of heatwave events during the spawning period (Appendix 2.1: S. Barbeaux) and slightly below average habitat suitability index (based on temperatures at GAK 1 of the Seward line (Appendix 2.1: L. Rogers). Fall surface temperatures continue to be above average (Satellite, Lemagie 2023), at a time critical to overwinter survival of age-0 cod. Mesoscale eddy kinetic energy in the Kodiak region continued to be below average, implying slightly reduced retention in the area and reduced cross-shelf transport to suitable nearshore nursery environments (Appendix 2.1: by W. Cheng). Surface temperatures are predicted to warm in late winter/early spring of 2024, in alignment with El Niño conditions (Bond 2023), potentially leading to early hatch times of cod eggs (up to 19 days earlier), and early spring phytoplankton bloom. There is potential for the surface temperatures to exceed the optimal temperatures for larvae survival and feeding, negatively impacting the 2024 year class. As it takes time for warm surface waters to extend to depth, shelf bottom temperatures are not expected to warm in the spring and cod spawning habitat is not expected to be impacted.

Prey: Foraging conditions for juveniles and adults were below average to average in 2023. For larval and juvenile cod, total zooplankton biomass decreased across all reported GOA surveys in 2023, where euphausiids were above average across the GOA in the spring and summer, and large and small calanoid copepods varied in abundance spatially and temporally (Shelikof St., Kimmel 2023 and Appendix 2.1: Rogers; Seward Line, Hopcroft 2023; Icy St., Fergusson and Strasburger 2023). Planktivorous seabird reproductive success, an indicator of zooplankton availability and nutritional quality, was approximately average across the GOA (from west to east: Chowiet Isl., E. Amatuli Isl, Middleton Isl., and St. Lazaria Isl., Drummond et al. 2023, Whelan et al. 2023,). Survival of the age-0 cod year class has below average potential for success, with below average CPUE in western GOA beach seine (Appendix 2.1: B. Laurel and M. Litzow), potentially tied to below average spring chl-a biomass, a late peak spring bloom in the WGOA (Appendix 2.1: M. Callahan), and lower total spring zooplankton biomass (but above average euphausiid biomass). The adult cod prey base was approximately average with signs of reduced abundance. Herring biomass remains elevated but is decreasing in southeast Alaska (Hebert and Dressel 2023) and capelin populations are rebounding but perhaps only in their core areas (e.g., around Kodiak; Whelan 2023). Age-0 pollock had very low abundance (Shelikof St., Rogers and Porter 2023). The reproductive success of piscivorous, diving seabirds (e.g., common murres and tufted puffins with an overlapping prey base) decreased to below average/average across the GOA (Drummond et al. 2023, Whelan 2023, Appendix 2.1: Zador). There were also signs of decreased abundance in invertebrate prey (Tanner crab, shrimp, motile epifauna, Worton, 2023, Whitehouse, 2023). Juvenile Pacific cod condition remained below average and adult Pacific cod condition indices declined to approximately average in 2023 (Appendix 2.1: Rohan). These forage conditions appear sufficient for adult cod to meet energetic demands but are trends to watch for 2024.

Predators and Competitors: There is no cause to suspect increased predation pressure on Pacific cod. Predators of Pacific cod appear to be stable or at relatively low population levels. The most recent data available suggest that Steller sea lion trends have stabilized (eastern GOA) or continued to be at low levels (western GOA) in the Gulf of Alaska (Appendix 2.1: Sweeney). Pacific halibut, large Pacific cod (representing cannibalistic predation) are estimated at low biomass. In general, apex fish predators in the GOA are at relatively low abundances (including cod and arrowtooth flounder, Appendix 2.1: Shotwell; although sablefish are increasing in abundance, Goethel et al. 2023, Whitehouse 2023). The population status of other potential predators is not well known (salmon shark, northern fur seals, harbor porpoises, various whale species, and tufted puffin). Potential competitors of planktivorous juveniles include large returns of pink salmon (Whitehouse 2023, Vulstek and Russell 2023), a relatively large population of Pacific Ocean perch, large year classes of juvenile sablefish, and an increasing population of walleye pollock.

Fishery Performance

Where data were available catch per unit effort measures in the GOA fisheries showed mixed signals. Condition of fish in the fisheries for 2023 were average. It should be noted that catch levels and fishery participation have been low over the past 4 years in comparison with previous years. Bycatch in other fisheries still remain low compared to prior to the 2014-2016 marine heatwave, with the exception of the shallow water flatfish fishery, within which Pacific cod catch has increased.

We consider the concern level to be 1 – mixed signals in the fishery showing no consistent trend for adverse conditions on this stock more than normal.

Summary and ABC recommendation

These results are summarized in the table below:

Assessment-related considerations	Population dynamics considerations	Environmental/ecosystem considerations	Fishery Performance
Level 2: Major concern	Level 2: Major concern	Level 1: Normal	Level 1: Normal

From 2008-2017 the GOA Plan Team and SSC recommended setting the ABC at the maximum permissible level under Tier 3. For 2018 through 2019 an ABC was recommended below the maximum ABC in an attempt to ensure the 2019 and 2020 SSB would remain above $B_{20\%}$. For 2020 although the ABC was set at the maximum the stock was below $B_{20\%}$ and because of the rules in place to protect forage for Steller sea lions the directed federal fishery was be required to remain closed. However for added precaution both the federal TAC and state GHL were reduced. Biological reference points from GOA Pacific cod SAFE documents for years 2002 – 2024 are provided in Table 2.19. While the largest score of the risk table is level 2, we do not recommend that ABC be set below the maximum permissible.

For 2024 the spawning stock biomass is projected to be above $B_{20\%}$, and despite a drop in spawning biomass in 2025 is projected to remain above $B_{20\%}$ in 2025.

Area Allocation of Harvests

In 2012, the ABC for GOA Pacific cod was apportioned among regulatory areas using a Kalman filter approach based on trawl survey biomass estimates. In the 2013 assessment, the random effects model (which is similar to the Kalman filter approach, and was recommended in the Survey Average working group report which was presented to the Plan Team in September 2013) was used; this method was used for the ABC apportionment for 2014. The SSC concurred with this method in December 2013. Using this method (as applied in the 'rema' R package) with the trawl survey biomass estimates through 2023 (Fig. 2.53), the area-apportioned ABCs for the two-year projections of Model 19.1b would be:

	Western	Central	Eastern	Total
Random effects area apportionment	27.1%	63.8%	9.1%	100%
2024 ABC	8,745	20,590	2,937	32,272
2025 ABC	7,638	17,981	2,565	28,184

Status Determination

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). The standard harvest scenarios have been made within Stock Synthesis. Year-end catch for 2023 was estimated to be 24,634 t, equal to the 2023 ABC. 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.

Selectivity used in the projections was the mean selectivity over 2000-2021, recruitment was based on average recruitment from 1977-2023 and growth and mortality were as estimated in 2023.

Five of the seven standard scenarios will be 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 TAC for 2024, 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 the author's recommend level, max ABC.

Scenario 3: In all future years, F is set equal to the 2019-2023 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, F is set equal to the $F_{75\%}$. (Rationale: This scenario was developed by the NMFS Regional Office based on public feedback on alternatives.

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 follows (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 expected to be above half of its B_{MSY} level in 2023 and above its B_{MSY} level in 2033 under this scenario, then the stock is not overfished.)

Scenario 7: In 2024 and 2025, 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 2025 or 2) above 1/2 of its MSY level in 2025 and expected to be above its MSY level in 2035 under this scenario, then the stock is not approaching an overfished condition.)

Scenarios 1 through 7 were projected 15 years from 2023 in Model 19.1b (Table 2.20). Scenarios 3, 4, and 5 (no fishing) project the stock to be below $B_{35\%}$ until 2026, scenarios 1, 2, 6, and 7 have the stock below $B_{35\%}$ until 2027. Fishing at the maximum permissible rate indicate that the spawning stock will be below $B_{35\%}$ in 2024 through 2026 due to poor recruitment and high mortality in 2015-2017. Under an assumption of environmental conditions at the 1977-2022 mean, the stock recovers above $B_{35\%}$ by 2027.

Our projection model run under these conditions indicates that for Scenario 6, the GOA Pacific cod stock although below $B_{35\%}$ in 2023 at 55,170 t will be above its MSY value in 2033 at 75,355 t and therefore would not be classified as overfished.

Projections 7 with fishing at the OFL after 2024 results in an expected spawning biomass of 75,354 t by 2035 and would therefore not be approaching an overfished condition.

Under Scenarios 6 and 7 for Model 19.1b the Gulf of Alaska Pacific cod stock would not currently be considered overfished, nor would it be approaching an overfished status. The 2022 OFL given Model 19.1b would have produced a sum of apical F of 0.44 in 2022.

Ecosystem Considerations

An Ecosystem and Socioeconomic Profile has been provided in Appendix 2.1.

Data Gaps and Research Priorities

Research is needed around three linked themes:

1) **Better understanding effects of warming temperatures on Pacific cod ecology and population dynamics**, with a focus on indices and parameters to improve the stock assessment (e.g. mortality, growth, maturity),

2) **Expanded early life history work** (spawning, larval, age-0) to focus on spatial-temporal variation in stock reproductive output, survival processes, and how these vary with changes in climate, and

3) **Resolving stock spatial structure, migration patterns, and connectivity** based on tagging and new genetics/genomics approaches. Research that covers a wide range of methods, including understanding early life history, satellite tagging, modelling, genetics, surveys, and maturity are needed.

Specific project to support these research themes:

Growth and survival of young cod

Continuation of age-0 juvenile surveys across the Western GOA and Central GOA will generate better estimates of growth and survival for juvenile cod in the stock assessment model. Expanding the temporal scale of Kodiak surveys would help identify the timing of settlement to nearshore habitat, validate a spatial-temporal spawning model and understand overwintering ecology/survival. Larger projects (3-5 years) would include linking observations of spawning - larvae - juvenile surveys to identify climate-driven reproductive output.

Tagging to determine cod movement

Pop-up satellite tags in GOA recording temperature and depth (modeled location) combined with bioenergetics models could be used to ascertain movement, growth, and spawn timing. Tagging is also useful for improving age estimation for cod, which is critical for successful stock assessment models. In addition it is apparent from the most recent satellite tagging efforts that at least the Western GOA Pacific cod population is highly connected with the Bering Sea and Chukchi Sea.

Improved stock assessment modeling

In connection with the pop-up tag study, there is a need to develop a multi-area assessment model for the BSAI and GOA. The further development of the ecosystem-linked GOA models is also needed to evaluate impacts of climate change and appropriate management strategies in a warming planet.

Survey

Research on seasonal migration of Pacific cod and impacts of annual variability in migration on the standard survey estimates would improve our understanding of how climate variability and survey timing impact survey estimates. One way to accomplish this would be to increase bottom trawl survey effort outside of the standard summer survey. To understand seasonal migration and interannual variability in Pacific cod migration would require several, 5 or more, years of survey effort in the spring, but could include a much smaller spatial area limited to the Central and Eastern GOA in waters < 200 m. Besides increasing funding for surveys, there would need to be additional survey staff needed to conduct this work as there is currently a shortage of trained personnel for current survey efforts.

Genetics

Genetics studies are needed to improve understanding of stock structure, which will improve our ability to realistically model stock size. Genetics studies will also allow us to identify the spawning stock origin of different components of the population, to track movement of cod from winter to summer, and to inform selectivity and stock size relative to summer surveys. All of these insights are critical to inform better understanding of stock structure, which will improve management.

Maturity

The stock assessment critically needs better estimates of size- and age-at-maturity and how these parameters are affected by temperature. Since 2006, there has been an ~200% increase in average individual mass of age-0 juveniles observed in August (Laurel et al. 2023). These changes in body size adhere to the 'temperature size rule' for fish, which are predicted to lead to initially larger body size for early stages, but ultimately result in earlier maturity, smaller body sizes and lower productivity as adults (Atkinson 1994). Such changes in maturity schedules, size-at-age and spawning response to temperature (e.g., skip spawning) need to be further studied for Pacific cod in the Gulf of Alaska.

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Tables

Table 2.1. Catch (t) for 1991 through 2023 by jurisdiction and gear type (as of 2023-10-16)

	Federal					State				
Year	Trawl	Long-line	Pot	Other	Subtotal	Long-line	Pot	Other	Subtotal	Total
1991	58,092	7,630	10,464	115	76,301	0	0	0	0	76,301
1992	54,593	15,675	10,154	325	80,747	0	0	0	0	80,747
1993	37,806	8,963	9,708	11	56,488	0	0	0	0	56,488
1994	31,447	6,778	9,161	100	47,486	0	0	0	0	47,486
1995	41,875	10,978	16,055	77	68,985	0	0	0	0	68,985
1996	45,990	10,196	12,040	53	68,279	0	0	0	0	68,279
1997	48,406	10,978	9,065	26	68,475	0	7,368	1,327	8,695	77,170
1998	41,570	10,012	10,510	29	62,121	0	9,183	1,320	10,503	72,624
1999	37,167	12,363	19,015	70	68,615	0	12,410	1,518	13,928	82,543
2000	25,443	11,660	17,351	54	54,508	0	10,399	1,644	12,043	66,551
2001	24,383	9,910	7,171	155	41,619	0	7,829	2,083	9,912	51,531
2002	19,810	14,666	7,694	176	42,346	0	10,578	1,714	12,292	54,638
2003	18,884	9,525	12,765	161	41,335	62	7,943	3,242	11,247	52,582
2004	17,513	10,326	14,966	400	43,205	51	10,602	2,765	13,418	56,623
2005	14,549	5,732	14,749	203	35,233	26	9,653	2,673	12,352	47,585
2006	13,132	10,244	14,540	118	38,034	55	9,146	662	9,863	47,897
2007	14,775	11,539	13,573	44	39,931	270	11,378	682	12,330	52,261
2008	20,293	12,106	11,229	63	43,691	317	13,438	1,568	15,323	59,014
2009	13,976	13,968	11,951	206	40,101	676	9,919	2,500	13,095	53,196
2010	22,035	16,538	20,116	429	59,118	826	14,604	4,045	19,475	78,593
2011	16,456	16,622	29,233	722	63,033	1,033	16,675	4,627	22,335	85,368
2012	20,084	14,467	21,238	722	56,511	866	15,940	4,613	21,419	77,930
2013	21,706	12,836	17,011	476	52,029	1,088	14,156	1,303	16,547	68,576
2014	26,917	14,735	19,957	1,046	62,655	1,007	18,445	2,838	22,290	84,945
2015	22,268	13,047	20,653	408	56,376	577	19,719	2,808	23,104	79,480
2016	15,217	8,123	19,248	346	42,934	803	18,609	1,708	21,120	64,054
2017	13,041	8,965	13,426	67	35,499	155	13,011	62	13,228	48,727
2018	3,818	3,033	4,013	121	10,985	310	3,660	195	4,165	15,150
2019	4,535	2,763	3,732	178	11,208	358	3,820	329	4,507	15,715
2020	3,427	586	30	0	4,043	527	1,779	491	2,797	6,840
2021	5,989	3,834	3,427	52	13,302	558	4,230	1,085	5,873	19,175
2022	8,210	5,777	4,912	3	18,902	371	5,658	994	7,023	25,925
2023	5,034	3,665	3,538	378	12,615	567	3,637	1,412	5,616	18,231

Table 2.2. History of Pacific cod catch (t, includes catch from State waters), Federal TAC (does not include State guideline harvest level), ABC, OFL and State of Alaska GHL (1997-Present). Catch for 2023 is current through 2023-10-16 and includes catch from State of Alaska waters fisheries and inside waters. The values in the column labeled “TAC” correspond to “optimum yield” for the years 1980-1986, “target quota” for the year 1987, and true TAC for the years 1988-present. Source: NPFMC staff.

Year	Catch	TAC	ABC	OFL	GHL
1980	35,345	60,000	-	-	-
1981	36,131	70,000	-	-	-
1982	29,465	60,000	-	-	-
1983	36,540	60,000	-	-	-
1984	23,898	60,000	-	-	-
1985	14,428	60,000	-	-	-
1986	25,012	75,000	136,000	-	-
1987	32,939	50,000	125,000	-	-
1988	33,802	80,000	99,000	-	-
1989	43,293	71,200	71,200	-	-
1990	72,517	90,000	90,000	-	-
1991	76,301	77,900	77,900	-	-
1992	80,747	63,500	63,500	87,600	-
1993	56,488	56,700	56,700	78,100	-
1994	47,486	50,400	50,400	71,100	-
1995	68,985	69,200	69,200	126,000	-
1996	68,279	65,000	65,000	88,000	-
1997	77,170	69,115	81,500	180,000	12,385
1998	72,624	66,060	77,900	141,000	11,840
1999	82,543	67,835	84,400	134,000	16,565
2000	66,551	59,800	76,400	102,000	17,685
2001	51,531	52,110	67,800	91,200	15,690
2002	54,638	44,230	57,600	77,100	13,370
2003	52,582	40,540	52,800	70,100	12,260
2004	56,623	48,033	62,810	102,000	14,777
2005	47,585	44,433	58,100	86,200	13,667
2006	47,897	52,264	68,859	95,500	16,595
2007	52,261	52,264	68,859	97,600	16,595
2008	59,014	50,269	64,493	88,660	16,224
2009	53,196	41,807	55,300	66,000	13,493
2010	78,593	59,563	79,100	94,100	19,537
2011	85,368	65,100	86,800	102,600	21,700
2012	77,930	65,700	87,600	104,000	21,900
2013	68,576	60,600	80,800	97,200	20,200
2014	84,945	64,738	88,500	107,300	23,762
2015	79,480	75,202	102,850	140,300	27,648
2016	64,054	71,925	98,600	116,700	26,675
2017	48,727	64,442	88,342	105,378	23,900
2018	15,150	13,096	18,000	23,565	4,904
2019	15,715	12,368	17,000	23,669	4,632
2020	6,840	6,431	14,621	17,794	2,537
2021	19,175	17,321	23,627	28,977	6,306
2022	25,925	24,111	32,811	39,555	8,700
2023	18,231	18,103	24,634	29,737	6,532

Table 2.3. History of GOA Pacific cod allocations by regulatory area (in percent) for 1991-2024. See Barbeaux et al. (2018) for 1977-1990.

Year(s)	Western	Central	Eastern
1991	33	62	5
1992	37	61	2
1993-1994	33	62	5
1995-1996	29	66	5
1997-1999	35	63	2
2000-2001	36	57	7
2002	39	55	6
2002	38	56	6
2003	39	55	6
2003	38	56	6
2004	36	57	7
2004	35.3	56.5	8.2
2005	36	57	7
2005	35.3	56.5	8.2
2006	39	55	6
2006	38.54	54.35	7.11
2007	39	55	6
2007	38.54	54.35	7.11
2008	39	57	4
2008	38.69	56.55	4.76
2009	39	57	4
2009	38.69	56.55	4.76
2010	35	62	3
2010	34.86	61.75	3.39
2011	35	62	3
2011	35	62	3
2012	35	62	3
2012	32	65	3
2013	38	60	3
2014	37	60	3
2015	38	60	3
2016	41	50	9
2017	41	50	9
2018	44.9	45.1	10
2019	44.9	45.1	10
2020	33.8	57.8	8.4
2021	33.8	57.8	8.4
2022	30.3	60.2	9.5
2023	30.3	60.2	9.5
2024	27.1	63.8	9.1

Table 2.4. Estimated retained and discarded GOA Pacific cod (as of 2023-10-16)

Year	Discarded	Retained	Grand Total
1991	1,427	74,873	76,301
1992	3,920	76,827	80,747
1993	5,886	50,602	56,488
1994	3,122	44,363	47,485
1995	3,546	65,439	68,985
1996	7,555	60,725	68,280
1997	4,828	72,342	77,170
1998	1,732	70,893	72,625
1999	1,645	80,898	82,543
2000	1,378	65,174	66,551
2001	1,904	49,627	51,530
2002	3,715	50,923	54,637
2003	2,485	50,097	52,582
2004	1,268	55,355	56,624
2005	1,043	46,541	47,584
2006	1,852	46,045	47,897
2007	1,448	50,813	52,261
2008	3,307	55,707	59,014
2009	3,944	49,252	53,196
2010	3,097	75,496	78,593
2011	2,178	83,189	85,367
2012	949	76,981	77,930
2013	4,560	64,016	68,576
2014	5,302	79,643	84,945
2015	1,723	77,758	79,481
2016	868	63,187	64,055
2017	711	48,016	48,727
2018	604	14,546	15,150
2019	1,194	14,522	15,716
2020	1,748	5,093	6,841
2021	1,407	17,769	19,176
2022	1,680	24,245	25,925
2023	1,595	16,636	18,231

Table 2.5. Weight of groundfish bycatch (t), discarded (D) and retained (R), for 2019 – 2023 for GOA Pacific cod as target species (as of 2023-10-20).

	2019		**2020**		**2021**		**2022**		**2023**	
	D	**R**	**D**	**R**	**D**	**R**	**D**	**R**	**D**	**R**
skate, other	202.31	32.58	3.80	0.09	269.30	18.01	294.16	3.12	83.08	3.96
big skate	133.53	29.95	3.51	1.10	158.63	46.93	270.67	72.29	122.2	47.04
walleye pollock	71.49	31.05	11.37	4.38	271.94	21.82	132.08	50.4	63.86	16.99
arrowtooth flounder	224.42	18.48	50.44	0.26	147.54	2.02	82.75	14.28	65.19	0.54
North Pacific octopus	39.69	192.28	0.03	12.01	14.43	23.28	49.49	60.17	36.59	30.25
spiny dogfish	104.10	0.00	14.29		161.03		64.79	0.09	47.17	0.00
longnose skate	50.27	35.96	4.79	3.05	80.44	41.24	127.71	49.23	131.43	34.72
sablefish	36.43	53.04	5.50	24.37	64.08	64.52	104.54	17.03	4.87	34.1
sculpin	100.95	0.24	0.61	0.20						
shallow water flatfish	43.93	37.98	3.37	0.04	24.19	0.61	31.68	95.15	18.92	1.38
flathead sole	92.54	8.53	0.11	0.00	18.14	2.77	7.5	1.28	5.08	2.24
other rockfish	5.53	16.61	0.47	0.69	16.85	12.66	45.22	0.98	1.83	0.2
rex sole	27.68	2.00	0.15		1.63	0.02	8.55	0.2	7.61	
Atka mackerel	32.79	0.24			2.91	0.01	0.46			
Pacific ocean perch	0.16	19.37	0.01	7.76	0.20	1.52	0.85	6.21	0.1	
dusky rockfish	2.34	5.54	0.00	0.81	2.51	2.28	2.4	1.9	0.12	1.23
Pacific sleeper shark	9.90		0.21		0.62		3.25		2.79	
northern rockfish	3.33	0.25		0.00	3.43	1.01	0.41	0.83	0.6	0.24
Aleutian skate		1.13				0.39		93.17		13.22
shortraker rockfish	1.15	0.18	0.10	0.03	4.56	0.38	1.28	0.64	1.05	0.09
rougheye rockfish	0.72	1.29	0.09	0.22	2.42	0.82	0.35	0.31	0.18	0.12
thornyhead rockfish	0.61	1.16	0.04		0.36	0.60	1.61	2.69	0.36	0.45
deep water flatfish	0.64	0.01	0.16	0.00	1.17		2.39	0.00	7.09	
shark, other	0.61	0.45			0.57	0.01	0.13		0.01	
salmon shark				0.28			0.00	0.1		
Alaskan skate		0.08				0.01		0.03		0.01
Total	1,185	488	99	55	1,247	241	1,232	470	600	187

Table 2.6. Incidental catch (t or birds by number) of non-target species groups by GOA Pacific cod fisheries (as of 2023-10-20). 0.00 indicates ≤0.005 tons, a blank indicates no catch or confidential data.

Species Group	2023	2022	2021	2020	2019
Benthic urochordata		0.00			0.23
Birds - Gull		36	8		23
Birds - Northern Fulmar	21	225	21		
Birds - Unidentified	10		9		
Birds - Unidentified Albatross		11			
Bivalves	0.01	0.64	0.00		0.23
Brittle star unidentified	0.01	0.02			
Corals Bryozoans - Corals Bryozoans Unidentified	0.54	0.08	0.08	0.18	1.55
Eelpouts		0.02			0.19
Giant Grenadier		48.09	79.55		0.12
Greenlings	0.27	0.29	0.45		0.77
Grenadier - Rattail Grenadier Unidentified		0.07	0.12		0.15
Hermit crab unidentified	0.04	0.08	0.01		0.92
Invertebrate unidentified	2.15	0.75	0.01	0.11	0.08
Misc crabs	2.92	0.05	0.14		0.14
Misc crustaceans		0.00			0.00
Misc fish	16.13	34.79	33.35		14.78
Sculpin	92.41	175.88	119.66		
Scypho jellies	0.03	0.03	0.19	0.02	2.65
Sea anemone unidentified	0.74	1.11	1.09		1.31
Sea pens whips	0.12	1.44	0.04		0.46
Sea star	11.44	22.44	18.44	1.66	37.47
Snails	2.30	2.19	0.27	0.06	4.74
Sponge unidentified	0.01	1.11	0.05		5.36
State-managed Rockfish	0.35	2.28	2.24		3.45
urchins dollars cucumbers	0.11	0.64	0.03		0.30

Table 2.7. Pacific cod catch (t) by trip target in Gulf of Alaska groundfish fisheries (as of 2023-10-20).

Trip Target	2019	2020	2021	2022	2023	Average
Pacific Cod	11,978	2,330	14,110	19,658	13,073	12,230
Pollock - bottom	711	899	2,843	3,358	2,705	2,103
Arrowtooth Flounder	1,439	1,237	379	415	467	788
Halibut	301	555	474	966	1,012	662
Rockfish	322	170	660	670	336	432
Shallow Water Flatfish - GOA	405	938	254	222	81	380
Pollock - midwater	100	141	74	121	48	97
Sablefish	50	43	56	30	29	41
Rex Sole - GOA	83	14	-	22	-	40
Flathead Sole	18	-	3	-	-	10
Grand Total	15,407	6,327	18,853	25,462	17,751	16,783
Non-Pacific cod trip target total	3,429	3,997	4,743	5,804	4,678	4,553

Table 2.8. Noncommercial fishery catch (in kg); total source amounts less than 1 kg were omitted (as of 2023-10-20)

Source	2018	2019	2020	2021	2022
AFSC Annual Longline Survey	10,242	5,530	10,200	13,050	14,712
GOA Shelf and Slope Walleye Pollock Acoustic-Trawl Survey	-	-	-	96	-
Gulf of Alaska Bottom Trawl Survey	-	7,796	-	7,853	-
IPHC Annual Longline Survey	89,231	104,968	30,032	75,279	34,799
IPHC Research	34	-	-	-	-
Large-Mesh Trawl Survey	6,361	7,317	7,921	5,032	6,198
Shumagin Islands Walleye Pollock Acoustic-Trawl Survey	23	-	-	-	-
Small-Mesh Trawl Survey	151	341	664	67	136
Sport Fishery	42,446	78,575	70,054	182,359	223,803
Spot Shrimp Survey	1	4	3	3	1
Summer Acoustic-Trawl Survey of Walleye Pollock in the Gulf of Alaska	-	70	-	-	-
Winter Acoustic-Trawl Survey of Walleye Pollock in Shelikof Strait and Vicinity	-	-	5	4	6
Total	148,489	204,601	118,879	283,743	279,655

Table 2.9. Pacific cod abundance measured in biomass (t) and numbers of fish (1000s), as assessed by the GOA bottom trawl survey. Point estimates are shown along with coefficients of variation.

Year	Biomass(t)	CV	Abundance	CV
1984	550,971	0.096	320,525	0.102
1987	394,987	0.085	247,020	0.121
1990	416,788	0.100	212,132	0.135
1993	409,848	0.117	231,963	0.124
1996	538,154	0.131	319,068	0.140
1999	306,413	0.083	166,584	0.074
2001	257,614	0.133	158,424	0.118
2003	297,402	0.098	159,749	0.085
2005	308,175	0.170	139,895	0.135
2007	232,035	0.091	192,306	0.114
2009	752,651	0.195	573,469	0.185
2011	500,975	0.089	348,060	0.116
2013	506,362	0.097	337,992	0.099
2015	253,694	0.069	196,334	0.079
2017	107,342	0.128	56,199	0.117
2019	181,581	0.218	127,188	0.243
2021	174,414	0.088	90,914	0.087
2023	231,184	0.126	138,683	0.121

Table 2.10. AFSC Longline survey Relative Population Numbers (RPNs) and CVs for Pacific cod.

Year	RPN	CV	Year	RPN	CV
1990	116,398	0.139	2007	34,992	0.140
1991	110,036	0.141	2008	26,881	0.228
1992	136,311	0.087	2009	68,391	0.138
1993	153,894	0.114	2010	86,722	0.138
1994	96,532	0.094	2011	93,732	0.141
1995	120,700	0.100	2012	63,749	0.148
1996	84,530	0.141	2013	48,534	0.162
1997	104,610	0.169	2014	69,653	0.143
1998	125,846	0.115	2015	88,410	0.160
1999	91,407	0.113	2016	83,887	0.172
2000	54,310	0.145	2017	39,523	0.101
2001	33,841	0.181	2018	23,853	0.121
2002	51,900	0.170	2019	14,933	0.185
2003	59,952	0.150	2020	19,459	0.218
2004	53,108	0.118	2021	30,830	0.162
2005	29,864	0.214	2022	23,393	0.159
2006	34,316	0.197	2023	30,802	0.209

Table 2.11. CFSR bottom temperature index for 0-20 cm Pacific cod in June and marine heatwave cumulative intensity index (MHCI) in °C days for full year, winter (Jan-Mar & Oct-Dec), and spawning (Feb-Mar) for 1979-2023. Note that the MHCI for 2023 are only through September 25.

Year	0-20 cm	Ann. MHCI	Winter MHC1	Spawn MHCI	Year	0-20 cm	Ann. MHCI	Winter MHCI	Spawn MHCI
1979	4.91	0	0	0	2002	4.20	51.27	51.27	0
1980	5.03	0	0	0	2003	5.30	207.85	151.48	108.12
1981	5.71	0	0	0	2004	4.60	117.64	0	0
1982	4.00	0	0	0	2005	4.91	284.60	3.78	0
1983	5.11	31.88	15.20	4.73	2006	4.63	35.14	5.81	0
1984	4.73	88.21	43.10	0.00	2007	4.13	0	0	0
1985	4.57	24.61	24.61	19.68	2008	4.33	0	0	0
1986	4.73	16.35	16.35	0	2009	3.66	0	0	0
1987	5.30	5.58	0	0	2010	5.21	6.52	0	0
1988	4.70	0	0	0	2011	4.55	0	0	0
1989	4.05	0	0	0	2012	4.00	0	0	0
1990	4.12	8.72	0	0	2013	4.18	0	0	0
1991	4.38	0	0	0	2014	4.73	283.02	105.44	0.00
1992	4.89	0	0	0	2015	5.88	402.32	202.38	133.28
1993	4.52	19.10	0	0	2016	5.71	630.87	314.57	155.56
1994	4.47	0	0	0	2017	4.75	53.03	38.78	0
1995	4.04	0	0	0	2018	5.10	128.50	99.89	0
1996	4.50	0	0	0	2019	5.94	496.74	199.48	100.45
1997	4.56	142.05	23.24	0	2020	4.30	146.45	31.38	0
1998	5.73	150.85	87.05	80.81	2021	4.26	15.38	15.38	10.71
1999	4.43	0	0	0	2022	5.09	71.59	0	0
2000	4.51	0	0	0	2023	4.44	0	0	0
2001	4.98	46.91	23.35	11.33					

Table 2.12. Number of parameters by category for the author's recommended model.

	Model 19.1b
Recruitment	
Early Init Ages	10
Early Rec. Devs (1977)	1
Main Rec. Devs (1978-2020)	43
Late Rec. Devs (2021-2023)	3
Future Rec. Devs. (2024-2038)	15
R_0	1
1976 R reg.	1
Natural mortality	2
Growth	5
Aging Bias	2
Survey Catchability	
Q_{trawl}	1
$Q_{longline}$	2
Selectivity	
Trawl Survey	16
Longline survey	5
Trawl Fishery	58(39 dev)
Longline Fishery	39(24 dev)
Pot Fishery	8
Total	212

Table 2.13. Likelihood components and derived quantities for the author's recommended model.

Likelihood components	
TOTAL_like	2930.97
Survey_like	-3.32
Length_comp_like	1817.93
Age_comp_like	1101.99
Recruitment	-0.55
InitEQ_Regime	3.09
Forecast_Recruitment	4.32
Parm_priors_like	1.00
Derived quantitites	
Recr_Virgin_millions	383.70
SR_LN(R0)	12.86
NatM (min)	0.46
NatM (max)	0.79
L_at_Amin	6.10
L_at_Amax	99.46
VonBert K	0.19
Q bottom trawl index	1.08
Q longline index	1.06
SSB unfished 1000's t	205.60
SSB unfished CV	0.07
F_{MSY} (sum apical F)	0.58
2024 F_{ABC} (sum apical F)	0.42
SSBratio 2023	0.31
SSBratio 2024	0.35

Table 2.14. Likelihood components by source for the author's recommended model.

Label	ALL	FshTrawl	FshLL	FshPot	TWLSrv	LLSrv
Age_like	1101.99	156.73	246.39	192.50	506.37	
Catch_like	1.09E-12	3.27E-13	3.65E-13	3.97E-13		
Length_like	1817.93	578.07	330.22	453.49	189.42	266.73
Surv_like	-3.32				-5.58	2.26

Table 2.15. Leave-one-out analysis results. MLE are the maximum likelihood estimated values. Mean difference is the average difference from the MLE.

	MLE			Leave-one-out	
Label	**Value**	**σ**	**CV**	**Mean difference**	**Mean difference/MLE Value**
ABC_{2024}	31,527	5,263	0.17	798.67	0.025
$F_{40\%}$	0.579	0.035	0.06	0.007	0.011
M_{base}	0.457	0.015	0.03	0.003	0.007
$\ln Q_{Bottom\ trawl}$	0.081	0.069	NA	-0.003	-0.033
$SSB_{Unfished}$	174,558	12,395	0.07	1568.55	0.009
SSB_{2024}	51,959	4,225	0.08	1013.39	0.020

Table 2.16. Estimated female spawning biomass (t) and total biomass (t, age 0+) from the last year's assessment and the author's recommended model.

	Last Year's Model (19.1a)			Model 19.1b		
	Sp.Bio	St.dev	Tot. Bio. 0+	Sp.Bio	St.dev	Tot. Bio. 0+
1977	92,967	18,993	297,981	86,689	15,935	272,441
1978	104,326	20,349	313,729	98,380	17,214	289,235
1979	102,381	19,523	360,747	97,764	16,847	330,096
1980	100,290	18,279	423,438	96,007	15,934	386,068
1981	119,196	21,385	457,450	111,789	18,228	418,191
1982	143,623	25,633	481,650	134,330	21,932	443,790
1983	153,763	27,183	523,406	145,538	23,773	485,373
1984	156,226	27,388	570,766	149,802	24,401	530,505
1985	174,891	28,132	629,649	168,636	25,105	587,423
1986	204,308	28,501	688,282	197,793	25,243	647,087
1987	227,282	27,352	737,809	220,914	24,054	698,761
1988	236,673	24,971	758,800	231,755	21,809	724,226
1989	246,814	22,704	761,416	243,439	19,800	733,137
1990	248,159	20,308	746,639	246,919	17,781	724,593
1991	230,388	17,957	713,259	230,939	15,820	694,233
1992	213,001	16,105	691,923	214,700	14,233	673,111
1993	200,365	14,878	666,335	201,964	13,093	647,461
1994	205,996	14,194	646,758	207,132	12,396	630,312
1995	210,227	13,092	612,981	211,697	11,446	601,250
1996	192,335	11,290	548,208	194,439	9,959	541,257
1997	166,602	9,324	493,721	169,657	8,367	489,569
1998	138,253	7,749	438,935	142,072	7,078	436,698
1999	122,007	6,863	392,705	125,721	6,289	391,753
2000	104,988	6,219	340,710	108,573	5,720	340,653
2001	92,439	5,587	311,860	95,796	5,163	311,814
2002	84,866	5,030	307,981	88,198	4,683	307,313
2003	79,759	4,767	300,900	82,955	4,429	300,217
2004	81,895	4,857	285,813	84,857	4,465	286,487
2005	79,790	4,776	260,949	82,850	4,406	263,066
2006	73,029	4,316	248,789	76,512	4,062	251,563
2007	64,425	3,873	256,856	68,076	3,711	258,308
2008	59,572	3,786	290,058	63,092	3,638	288,235
2009	64,239	4,269	333,418	67,153	3,999	329,541
2010	84,634	5,391	386,732	86,782	4,889	382,329
2011	96,909	6,472	407,856	99,472	5,860	404,507
2012	104,695	7,646	414,540	107,731	6,958	411,061
2013	110,162	8,772	441,572	114,121	8,126	433,983
2014	114,924	10,124	518,159	118,695	9,489	500,671
2015	82,365	6,276	400,775	86,062	5,895	394,061
2016	66,547	4,599	272,627	70,066	4,279	277,065
2017	49,557	3,561	166,160	53,898	3,435	177,128
2018	42,245	3,609	143,409	47,454	3,547	156,630
2019	42,175	3,472	152,663	48,468	3,492	168,218
2020	43,896	3,538	158,779	51,108	3,576	176,942
2021	51,289	3,810	165,795	59,590	3,794	186,120
2022	51,734	4,039	163,954	61,228	3,989	180,883
2023	42,764	4,127	163,477	55,170	4,034	173,300
2024				51,959	4,225	184,242

Table 2.17. Age-0 recruitment and standard deviation of age-0 recruits by year for last year's model and the author's recommended model. Highlighted are the 1977 and 2012 year classes.

	Last Year's Model (19.1a)		Model 19.1b	
Year	Age-0 x 10^9	Stdev	**Age-0 x 10^9**	**Stdev**
1977	0.99	0.25	0.79	0.18
1978	0.50	0.15	0.40	0.11
1979	0.40	0.12	0.34	0.09
1980	0.49	0.14	0.42	0.11
1981	0.77	0.19	0.62	0.14
1982	0.76	0.20	0.63	0.15
1983	0.70	0.21	0.56	0.16
1984	0.62	0.19	0.54	0.15
1985	0.89	0.20	0.73	0.15
1986	0.61	0.14	0.52	0.11
1987	0.61	0.12	0.51	0.09
1988	0.64	0.12	0.55	0.09
1989	0.65	0.12	0.54	0.09
1990	0.83	0.14	0.70	0.11
1991	0.55	0.10	0.45	0.08
1992	0.48	0.09	0.41	0.07
1993	0.35	0.07	0.29	0.05
1994	0.37	0.07	0.33	0.05
1995	0.52	0.08	0.44	0.06
1996	0.34	0.06	0.29	0.04
1997	0.35	0.06	0.30	0.04
1998	0.27	0.04	0.24	0.03
1999	0.37	0.06	0.33	0.04
2000	0.45	0.07	0.38	0.05
2001	0.31	0.05	0.27	0.04
2002	0.21	0.03	0.18	0.03
2003	0.25	0.04	0.22	0.03
2004	0.29	0.04	0.26	0.03
2005	0.44	0.06	0.39	0.05
2006	0.68	0.09	0.58	0.07
2007	0.50	0.07	0.45	0.06
2008	0.66	0.10	0.57	0.07
2009	0.47	0.08	0.43	0.06
2010	0.51	0.08	0.42	0.06
2011	0.63	0.11	0.54	0.09
2012	1.25	0.23	1.05	0.17
2013	0.84	0.18	0.69	0.13
2014	0.30	0.07	0.27	0.06
2015	0.27	0.06	0.26	0.05
2016	0.28	0.05	0.26	0.04
2017	0.21	0.04	0.20	0.03
2018	0.17	0.03	0.16	0.02
2019	0.08	0.02	0.09	0.02
2020	0.22	0.05	0.15	0.03
2021	0.26	0.10	0.18	0.04
2022	0.46	0.21	0.24	0.06
2023			0.38	0.18
Mean 1977 - (final year – 2)	0.50		0.42	

Table 2.18. Estimated fishing mortality in terms of apical F and total exploitation for the author's recommended model.

	Sum Apical F		Total		Sum Apical F		Total
Year	F	σ	Exploitation	Year	F	σ	Exploitation
1977	0.011	0.003	0.008	2001	0.356	0.021	0.165
1978	0.055	0.010	0.042	2002	0.414	0.024	0.178
1979	0.071	0.014	0.045	2003	0.422	0.024	0.175
1980	0.167	0.033	0.092	2004	0.450	0.026	0.198
1981	0.113	0.019	0.086	2005	0.501	0.062	0.181
1982	0.087	0.014	0.066	2006	0.530	0.060	0.190
1983	0.108	0.018	0.075	2007	0.522	0.034	0.202
1984	0.069	0.012	0.045	2008	0.618	0.043	0.205
1985	0.060	0.013	0.025	2009	0.485	0.033	0.161
1986	0.085	0.017	0.039	2010	0.573	0.038	0.206
1987	0.064	0.012	0.047	2011	0.556	0.038	0.211
1988	0.063	0.006	0.047	2012	0.459	0.034	0.190
1989	0.078	0.010	0.059	2013	0.377	0.030	0.158
1990	0.183	0.014	0.100	2014	0.539	0.043	0.170
1991	0.209	0.016	0.110	2015	0.707	0.049	0.202
1992	0.237	0.017	0.120	2016	0.706	0.046	0.231
1993	0.173	0.012	0.087	2017	0.653	0.065	0.275
1994	0.142	0.009	0.075	2018	0.200	0.019	0.097
1995	0.209	0.012	0.115	2019	0.199	0.017	0.093
1996	0.225	0.013	0.126	2020	0.076	0.006	0.039
1997	0.302	0.017	0.158	2021	0.199	0.015	0.103
1998	0.344	0.019	0.166	2022	0.271	0.020	0.143
1999	0.463	0.026	0.211	2023	0.204	0.016	0.105
2000	0.424	0.025	0.195				

Table 2.19. Biological reference points from GOA Pacific cod SAFE documents for years 2002 – 2023, and recommended for 2024 from the author's recommended model (in italics).

Year	**$SB_{100\%}$**	**$SB_{40\%}$**	**$F_{40\%}$**	**OFL_{y+1}**	**$maxABC_{y+1}$**
2002	212,000	85,000	0.41	82,000	57,600
2003	226,000	90,300	0.35	88,300	52,800
2004	222,000	88,900	0.34	103,000	62,810
2005	211,000	84,400	0.31	91,700	58,100
2006	329,000	132,000	0.56	165,000	68,859
2007	259,000	103,000	0.46	136,000	68,859
2008	302,000	121,000	0.49	108,000	66,493
2009	255,500	102,200	0.52	88,000	55,300
2010	291,500	116,600	0.49	117,600	79,100
2011	256,300	102,500	0.42	124,100	86,800
2012	261,000	104,000	0.44	121,000	87,600
2013	234,800	93,900	0.49	111,000	80,800
2014	227,800	91,100	0.54	120,100	88,500
2015	316,500	126,600	0.50	155,400	102,850
2016	325,200	130,000	0.41	116,700	98,600
2017	196,776	78,711	0.53	105,378	88,342
2018	168,583	67,433	0.34	23,565	19,401
2019	172,240	68,896	0.29	23,669	19,665
2020	187,780	75,112	0.22	17,794	14,621
2021	180,111	72,045	0.33	28,977	23,627
2022	165,508	66,203	0.50	39,555	32,811
2023	167,414	66,966	0.41	29,737	24,634
2024	*175,187*	*70,075*	*0.42*	*38,712*	*32,272*

Table 2.20. Results for the projection scenarios from the author's recommended model. Catch in tons, fishing mortality (F), and Female spawning stock biomass (SSB) in tons for the 7 standard projection scenarios.

Catch	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
2023	18,232	18,232	18,232	18,232	18,232	18,232	18,232
2024	32,272	31,527	11,485	8,200	0	38,712	32,272
2025	28,184	27,761	13,368	9,982	0	30,865	28,184
2026	34,918	34,538	18,291	14,017	0	37,880	42,073
2027	52,048	51,720	24,753	18,419	0	56,689	58,124
2028	65,760	65,015	30,119	22,617	0	74,593	74,588
2029	70,174	69,599	34,415	26,089	0	77,564	77,496
2030	72,125	71,617	37,309	28,539	0	78,466	78,425
2031	72,918	72,446	39,093	30,124	0	78,700	78,681
2032	73,252	72,805	40,177	31,132	0	78,772	78,764
2033	73,420	72,987	40,876	31,809	0	78,814	78,811
2034	73,481	73,057	41,254	32,194	0	78,824	78,822
2035	73,504	73,086	41,459	32,411	0	78,826	78,825
2036	73,513	73,097	41,570	32,535	0	78,827	78,826
F							
2023	0.20	0.20	0.20	0.20	0.20	0.20	0.20
2024	0.42	0.42	0.14	0.10	0.00	0.52	0.42
2025	0.38	0.39	0.15	0.11	0.00	0.45	0.38
2026	0.42	0.43	0.17	0.13	0.00	0.49	0.52
2027	0.53	0.53	0.19	0.13	0.00	0.61	0.62
2028	0.58	0.58	0.19	0.13	0.00	0.72	0.72
2029	0.58	0.58	0.19	0.13	0.00	0.72	0.72
2030	0.58	0.58	0.19	0.13	0.00	0.72	0.72
2031	0.58	0.58	0.19	0.13	0.00	0.72	0.72
2032	0.58	0.58	0.19	0.13	0.00	0.72	0.72
2033	0.58	0.58	0.19	0.13	0.00	0.72	0.72
2034	0.58	0.58	0.19	0.13	0.00	0.72	0.72
2035	0.58	0.58	0.19	0.13	0.00	0.72	0.72
2036	0.58	0.58	0.19	0.13	0.00	0.72	0.72
SSB							
2023	55,170	55,170	55,170	55,170	55,170	55,170	55,170
2024	51,959	51,959	51,959	51,959	51,959	51,959	51,959
2025	47,699	47,931	55,700	56,984	60,210	45,269	47,699
2026	52,244	52,578	64,446	66,814	73,377	49,259	52,244
2027	63,935	64,346	79,936	83,479	94,212	60,482	61,401
2028	74,921	75,412	97,849	103,109	118,876	70,498	70,565
2029	80,518	81,247	112,557	119,692	141,125	73,728	73,679
2030	83,196	84,089	123,052	132,066	159,547	74,836	74,796
2031	84,358	85,359	129,873	140,494	173,536	75,164	75,143
2032	84,870	85,940	134,196	146,089	183,872	75,273	75,263
2033	85,140	86,254	137,111	150,014	191,839	75,338	75,333
2034	85,237	86,373	138,687	152,240	196,886	75,351	75,350
2035	85,273	86,421	139,541	153,502	200,082	75,355	75,354
2036	85,287	86,440	140,004	154,219	202,107	75,355	75,355

Figures

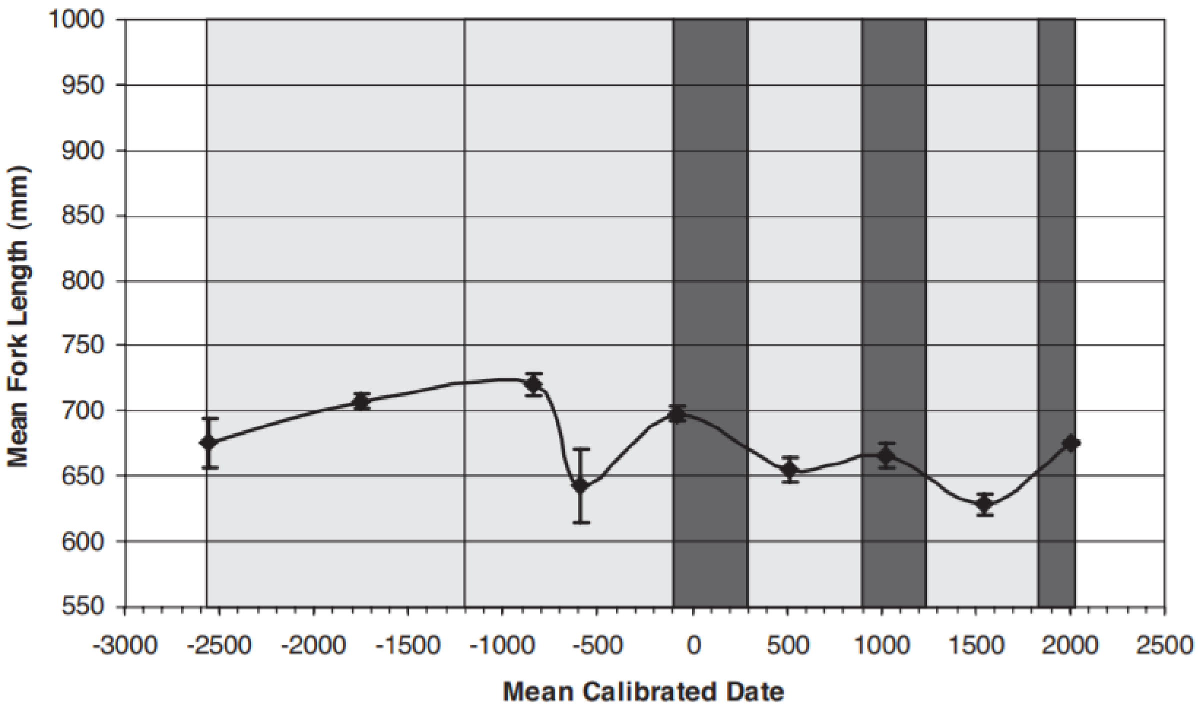

Figure 2.1. Gulf of Alaska mean lengths with climate reconstruction. The shaded boxes represent periods of significant changes in air temperature, sea surface temperature, storminess, and ocean circulation that drive ocean productivity. The lightly shaded boxes represent periods of cooler and stormier environments, which are generally more productive, while the darkly shaded boxes represent warmer and generally less productive environments. Dates are presented as calibrated means; (From Betts *et al.* 2011; Figure 11.4).

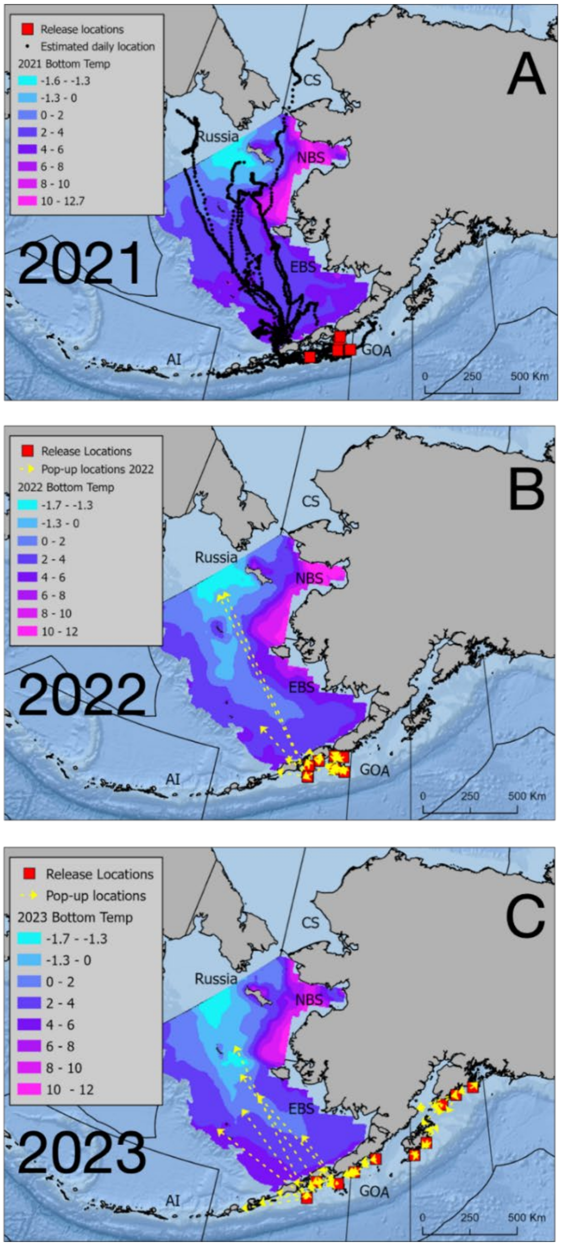

Figure 2.2. Movement of satellite-tagged Pacific cod from winter spawning areas in the Gulf of Alaska (GOA) to summer foraging locations. A) daily location estimates output by a geolocation model for cod tagged in 2021 in the western GOA, B) pop-up locations for cod tagged in 2022 in the western GOA, and C) pop-up locations for cod tagged in 2023 in western and central GOA. Bering Sea bottom temperatures for each year provided by Sean Rohan (RACE). Temperatures colder than -1.3 C (the minimum temperature observed for satellite-tagged fish) indicate potential physiological barriers to movement.

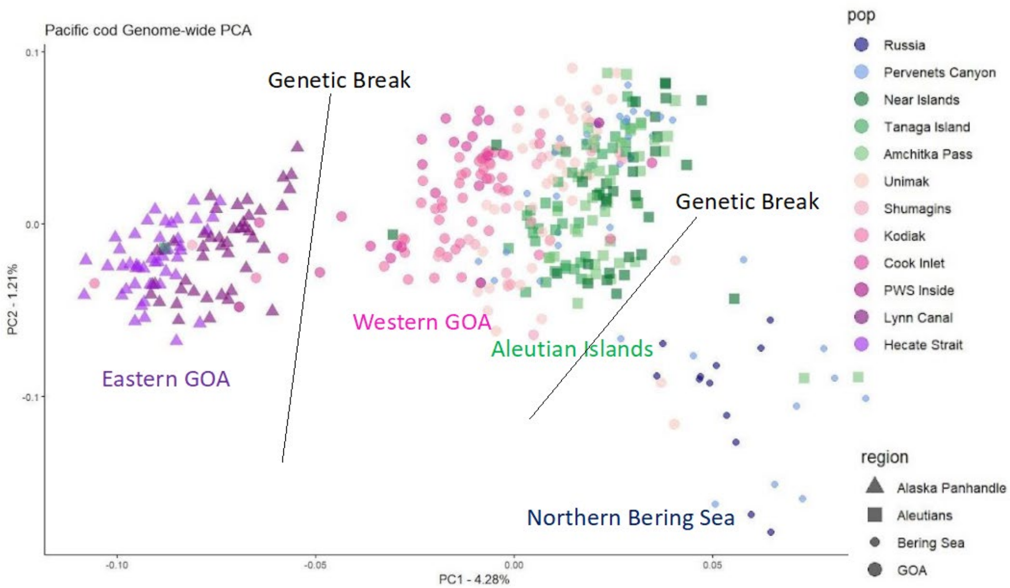

Figure 2.3. Principal components analysis of 1,922,927 polymorphic SNPs from the lcWGS dataset.

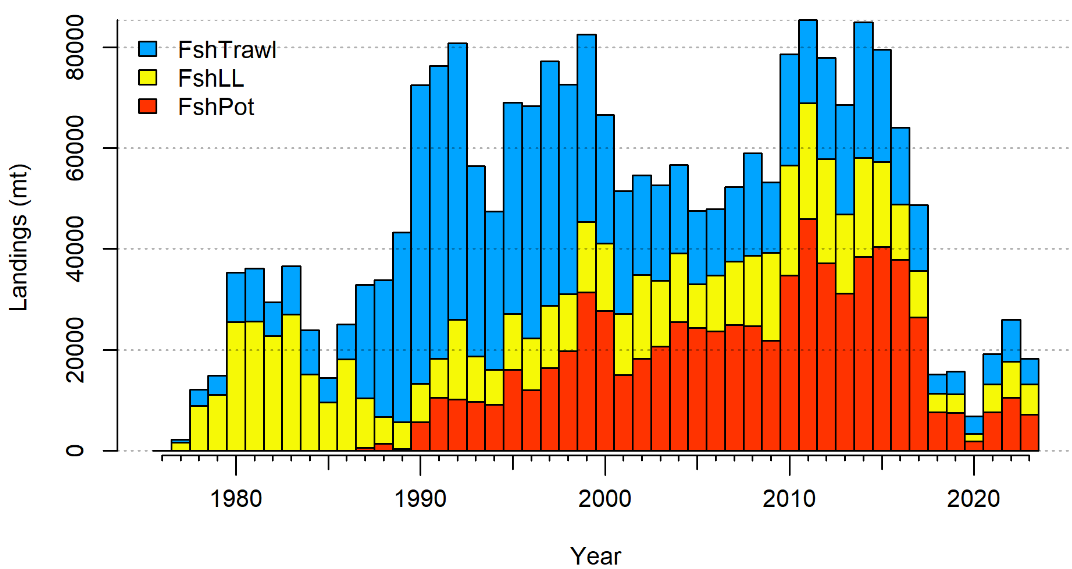

Figure 2.4. Gulf of Alaska Pacific cod catch from 1977-2023. Note that 2023 catch was through October 16.

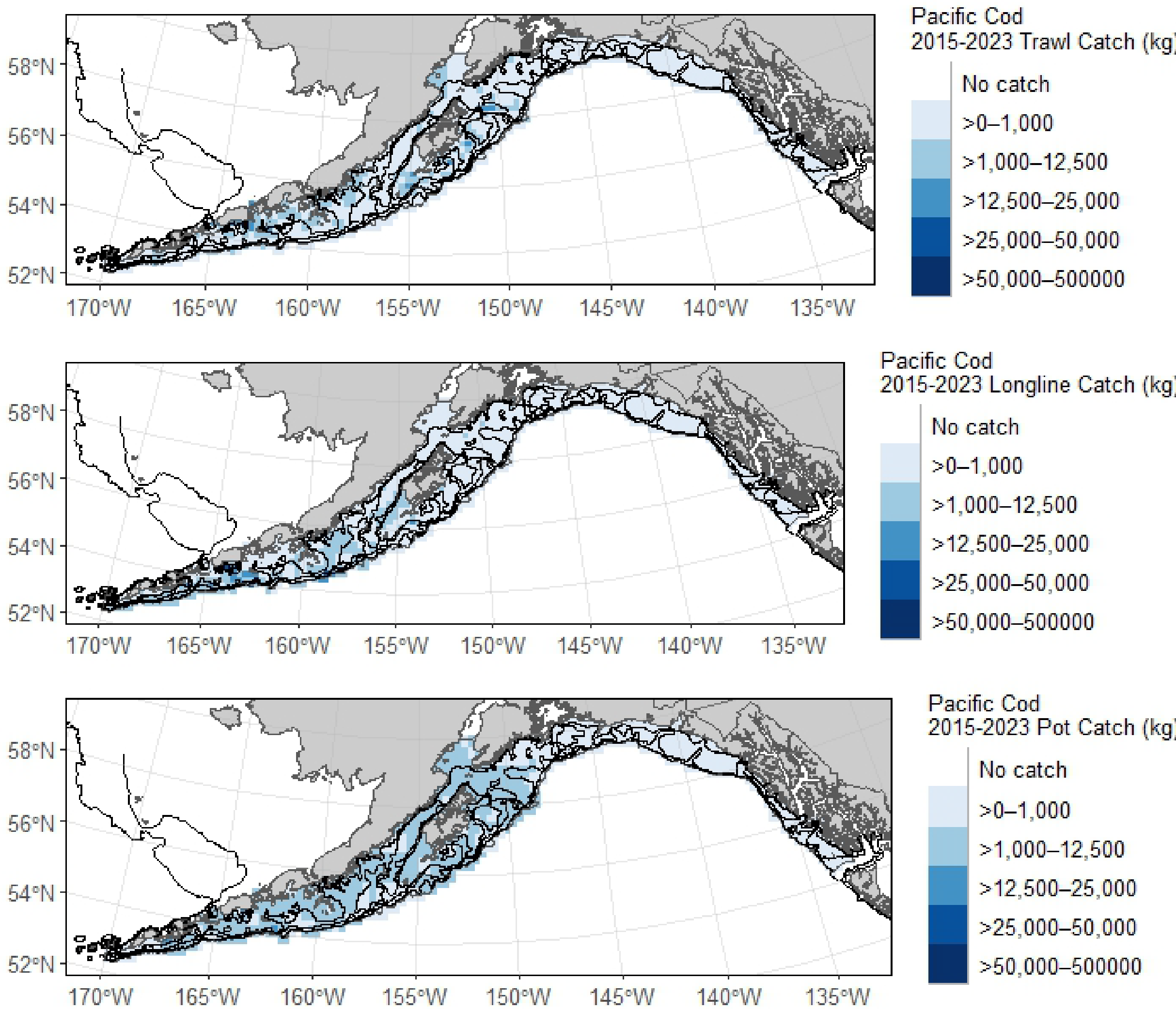

Figure 2.5. Commercial catch of Pacific cod in the Gulf of Alaska by $20km^2$ grid for 1990-2015.

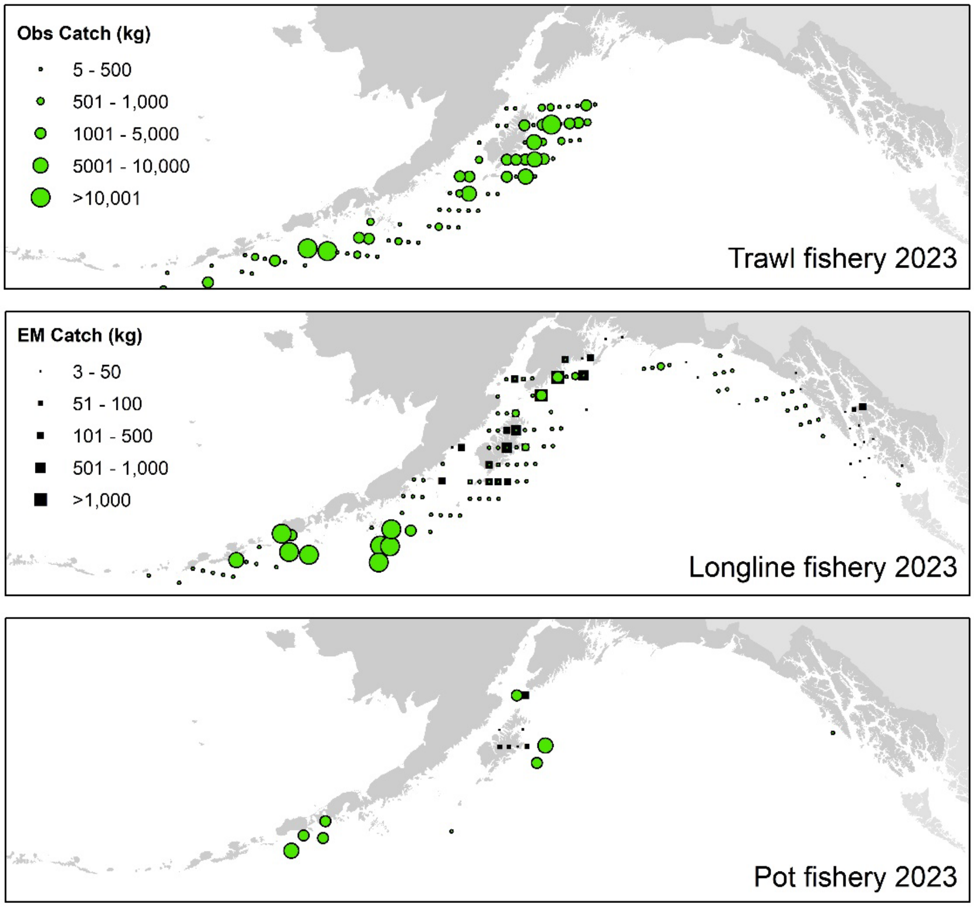

Figure 2.6. Observed (Obs) and electronic monitored (EM) commercial catch of Pacific cod in the Gulf of Alaska by 20km^2 grid for 2023. These data include bycatch Pacific cod, but do not include trawl EM data as locations are not yet available.

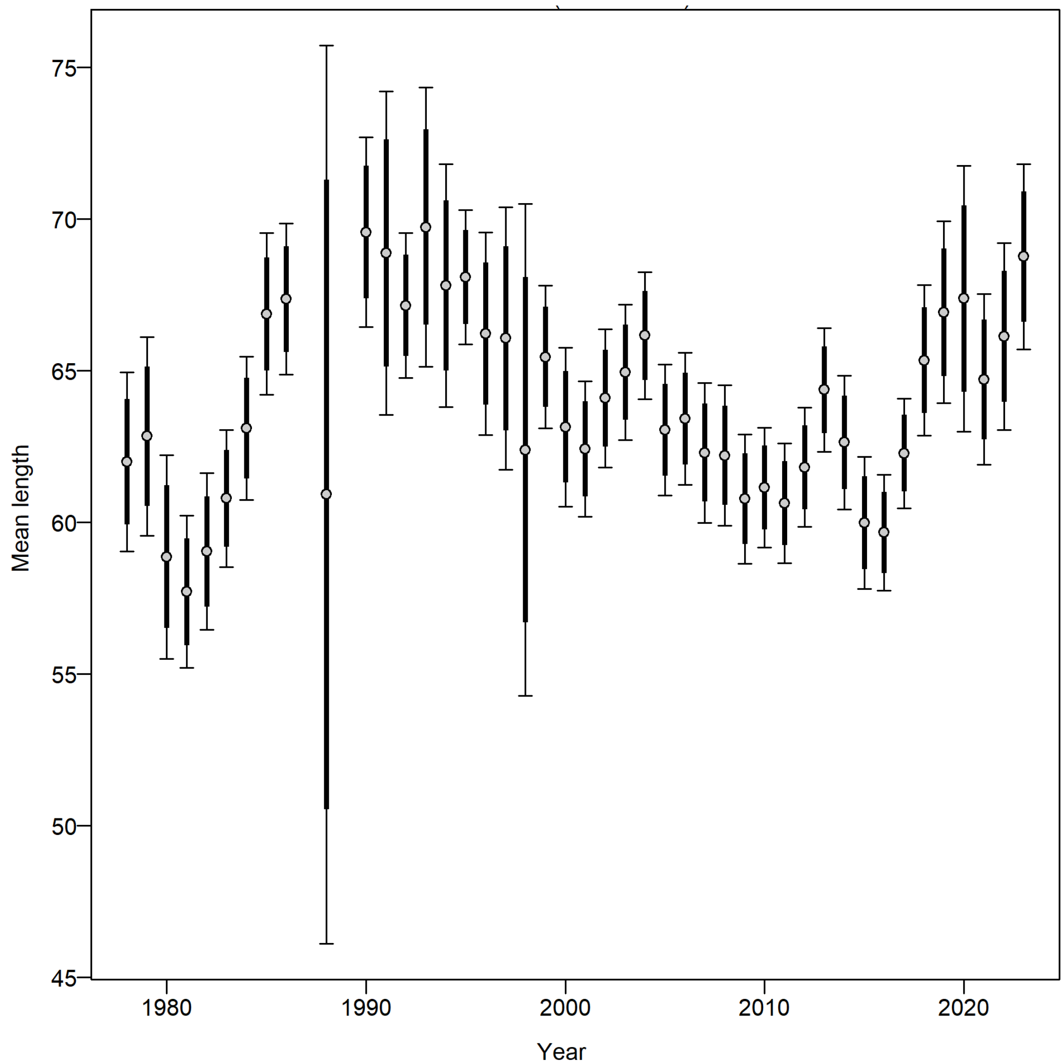

Figure 2.7. Mean length (cm) of Pacific cod from the Gulf of Alaska longline fishery.

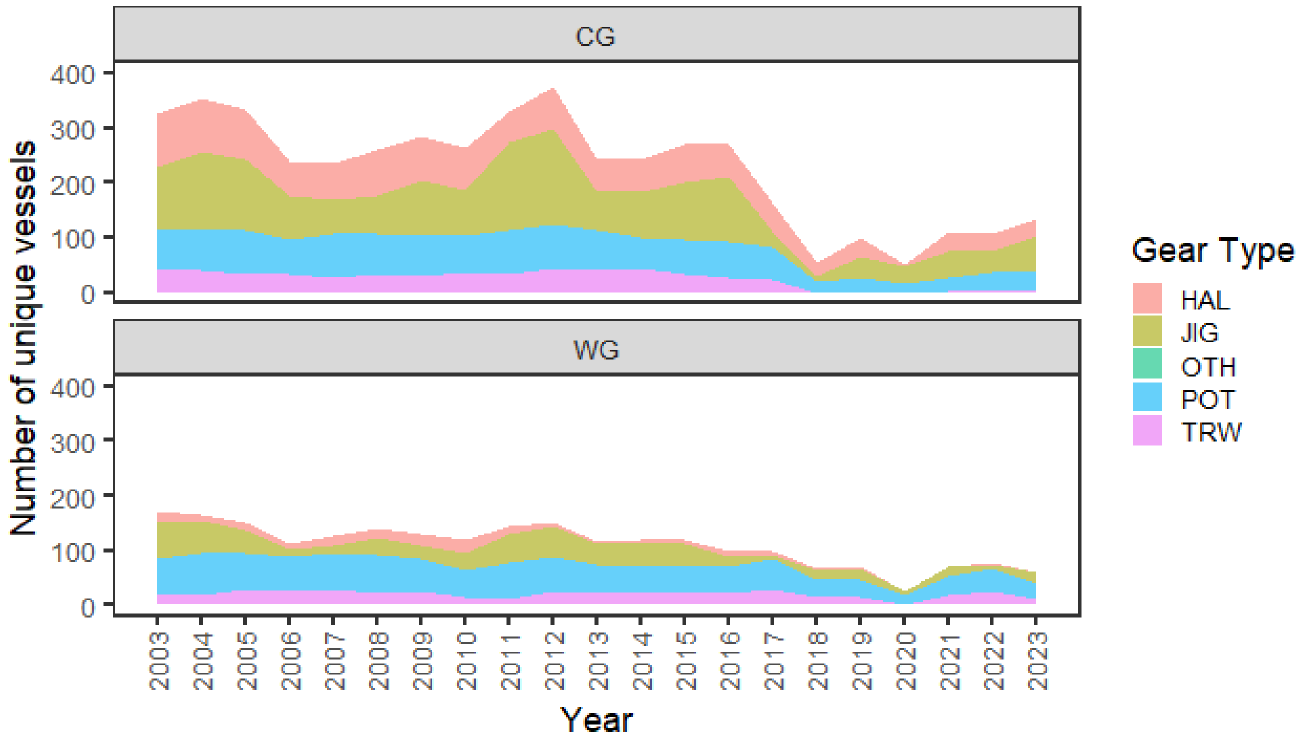

Figure 2.8. Vessel participation in the directed cod fishery by year.

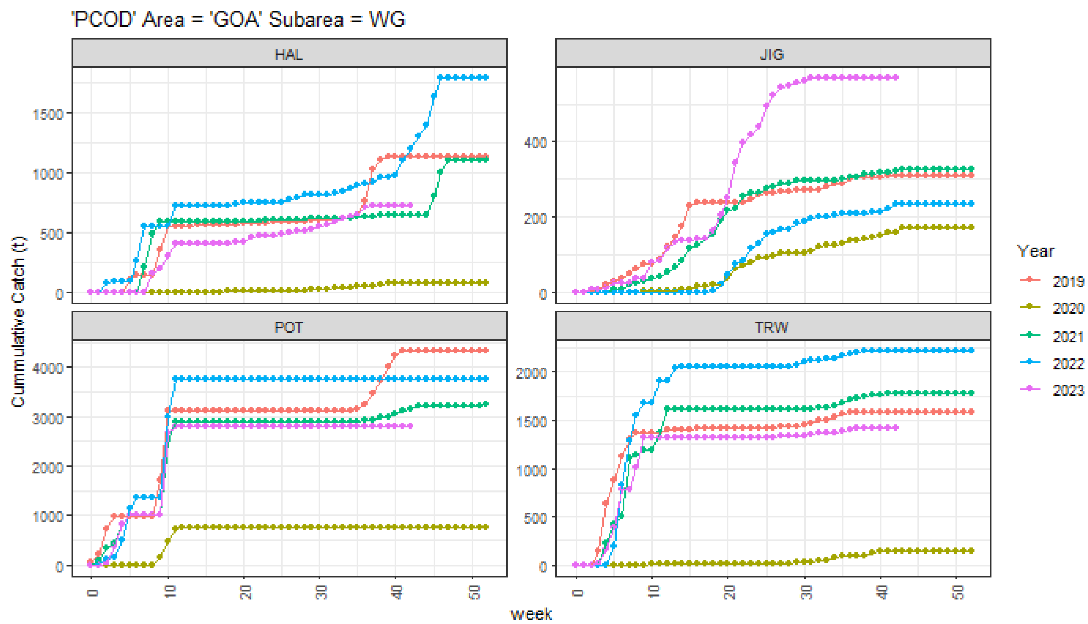

Figure 2.9. Cumulative catch week of the year for 2019-2023 by fleet for the Western Gulf of Alaska (2023 catch through week 42).

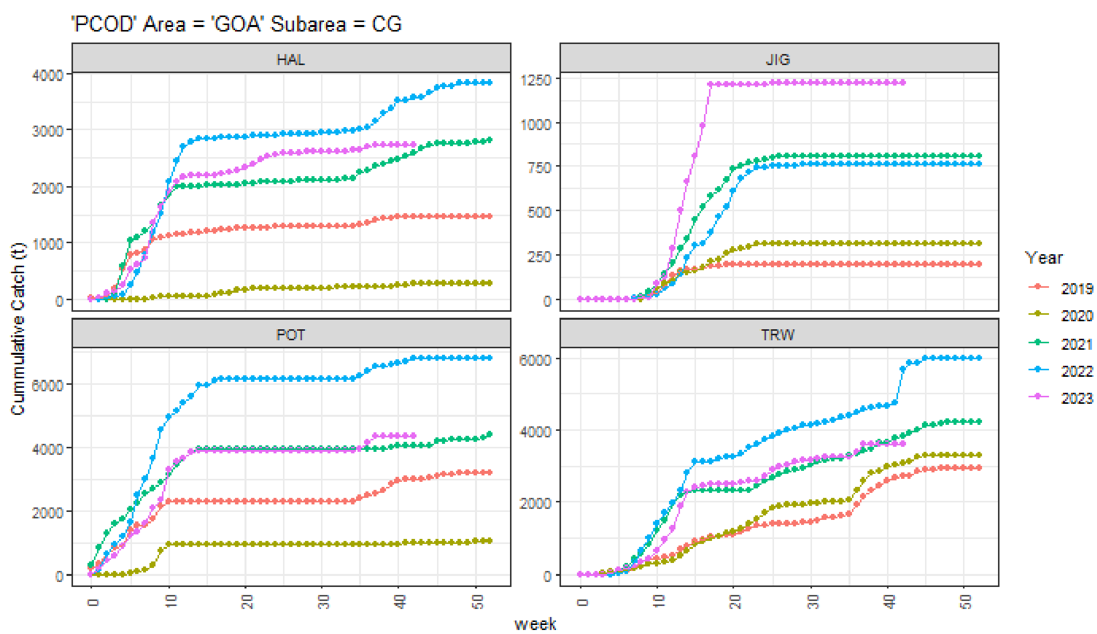

Figure 2.10. Cumulative catch week of the year for 2019-2023 by fleet for the Central Gulf of Alaska (2023 catch through week 42).

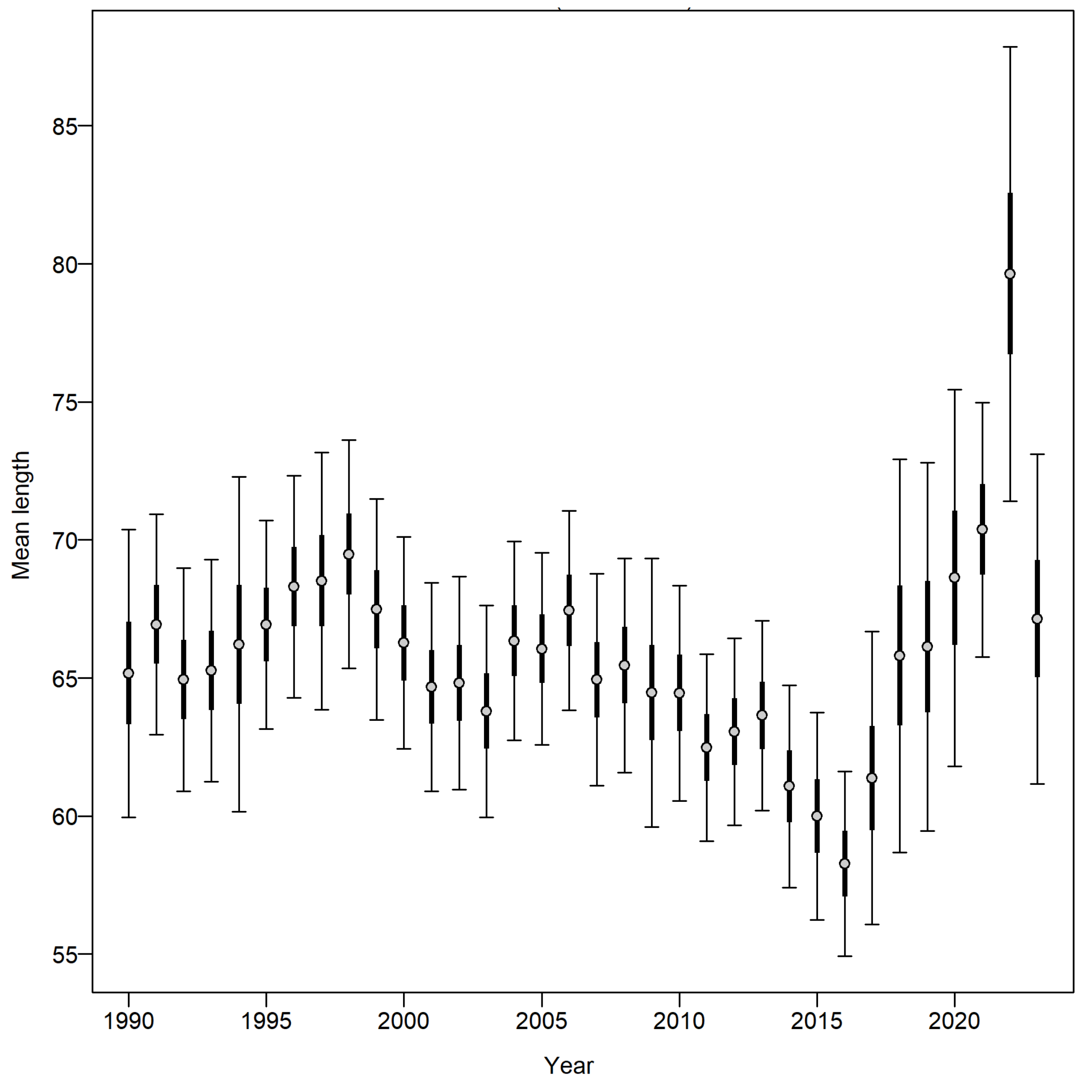

Figure 2.11. Mean length (cm) of Pacific cod from the Gulf of Alaska pot fishery.

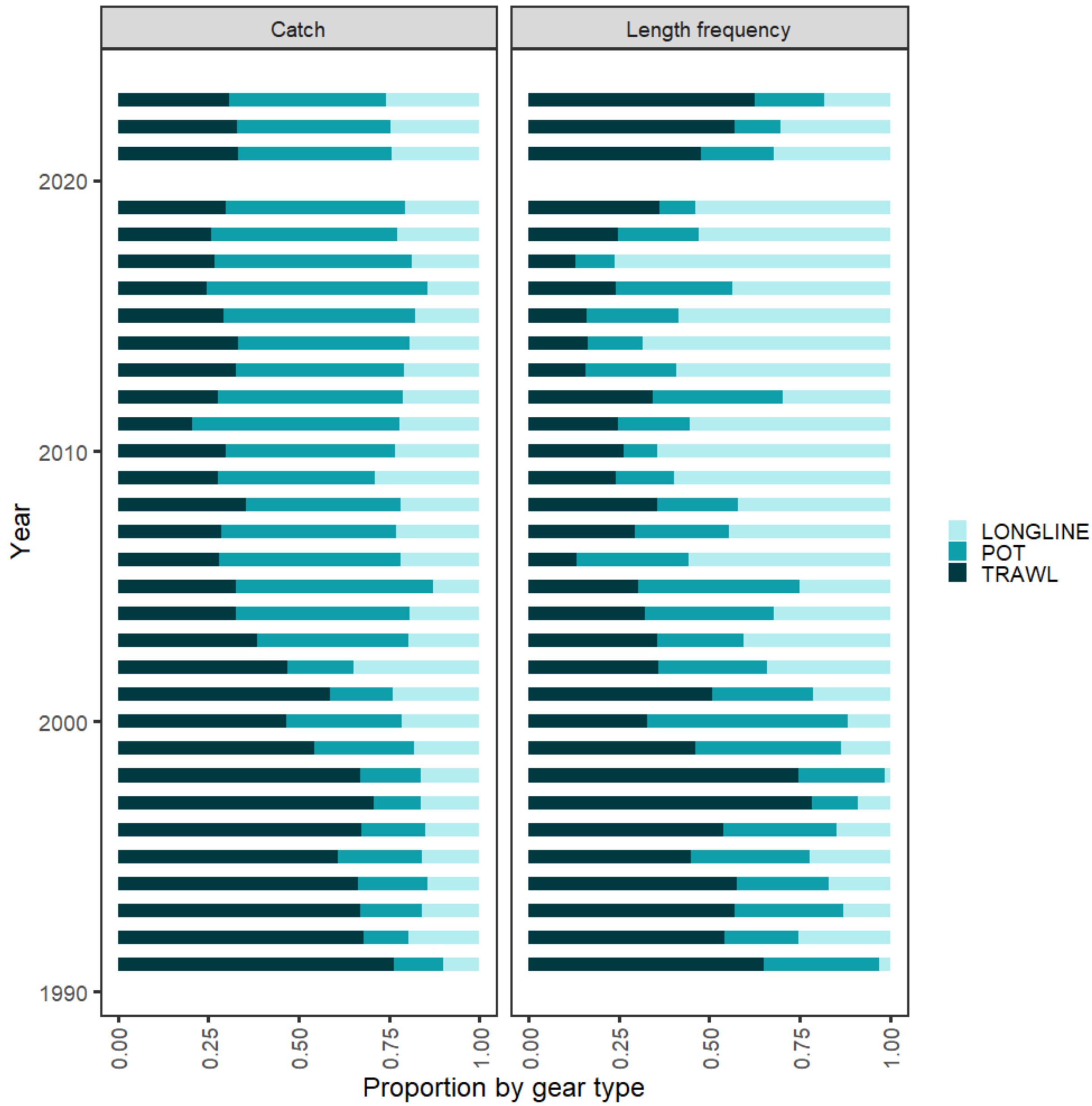

Figure 2.12. Proportion of total catch (left panel) and length frequency samples (right panel) by gear type.

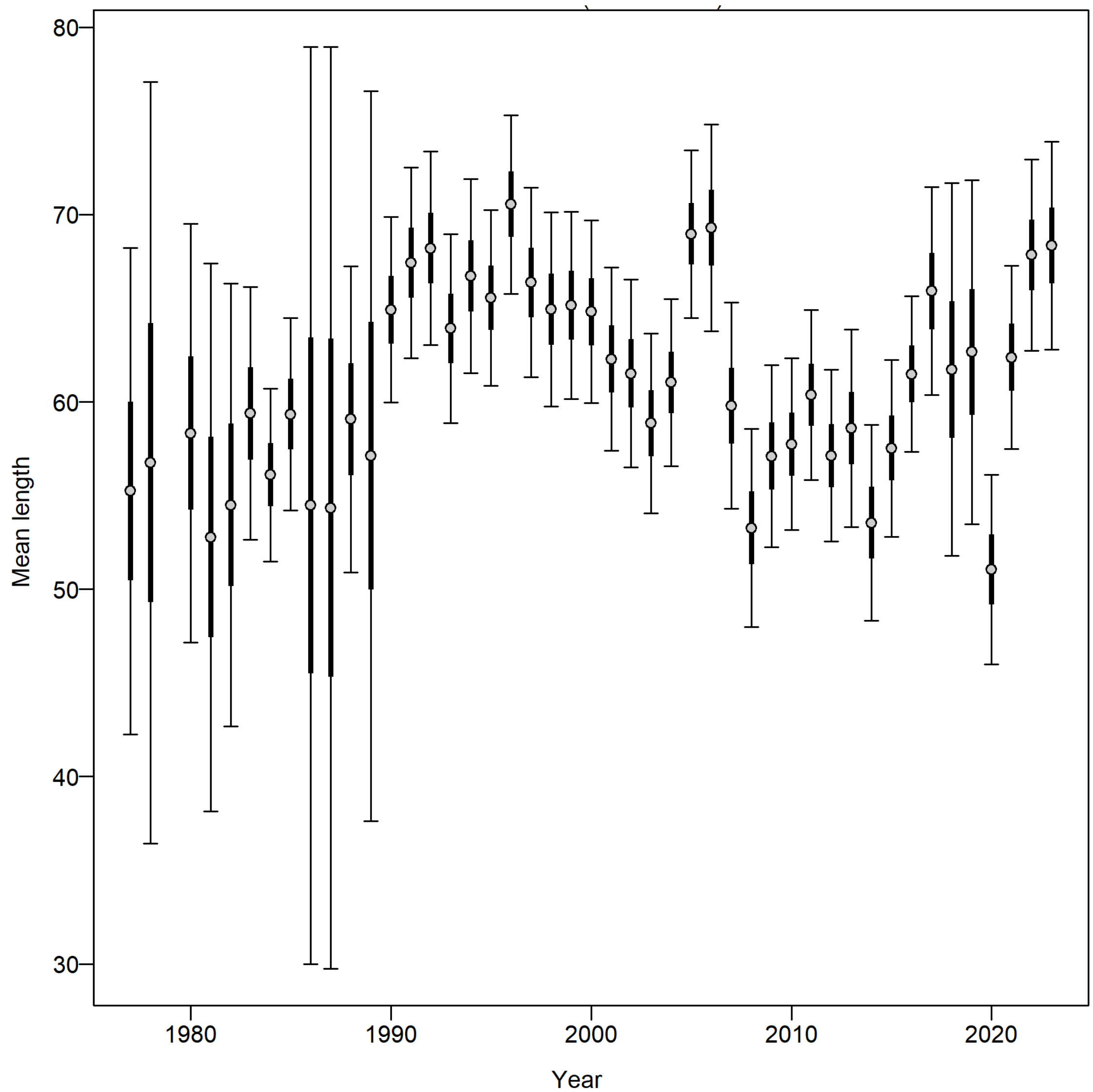

Figure 2.13. Mean length (cm) of Pacific cod from the Gulf of Alaska trawl fishery.

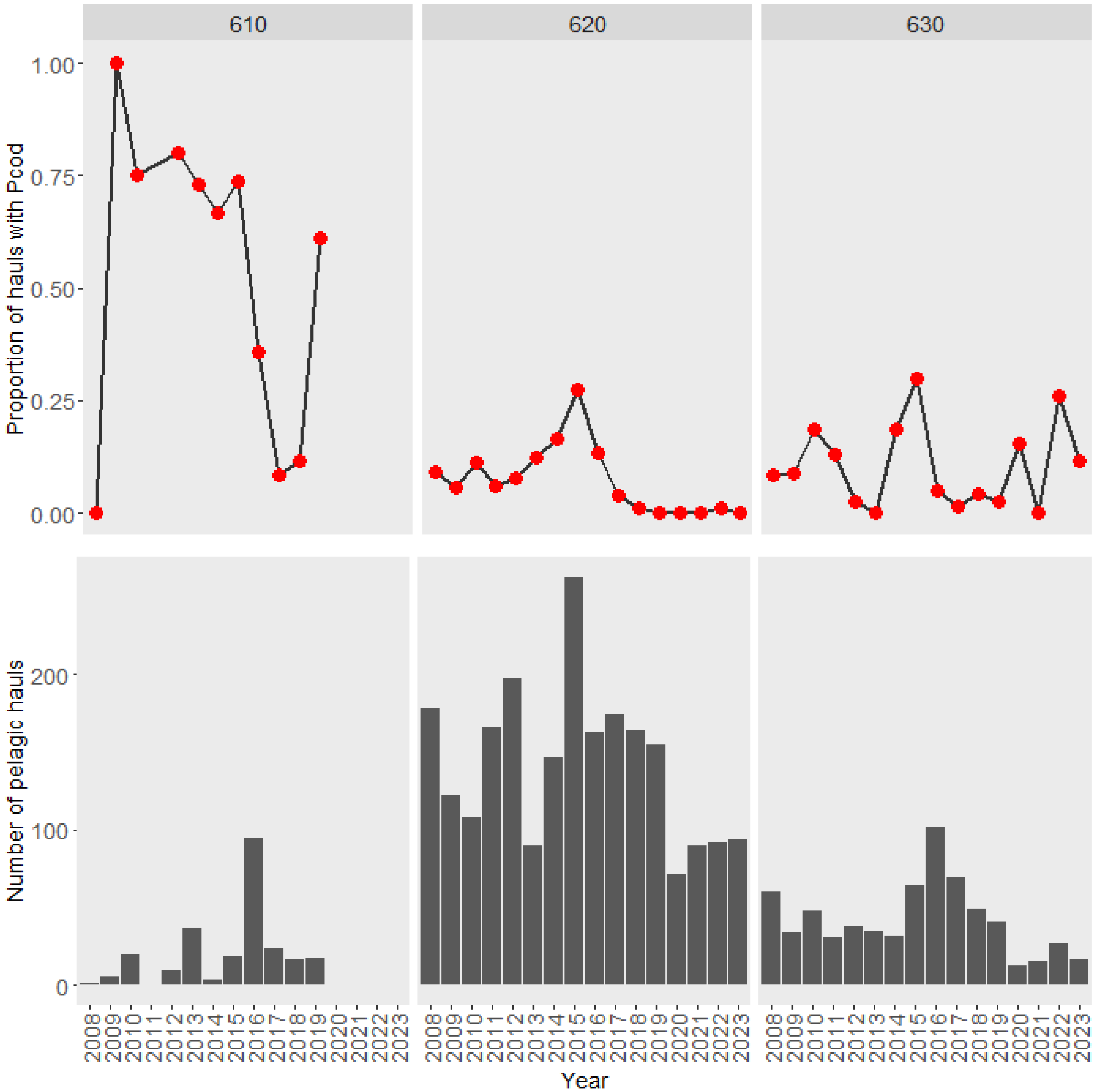

Figure 2.14. Proportion of pelagic trawls in the A Season (January-April) walleye pollock fishery with Pacific cod present by region (top) and number of hauls (bottom).

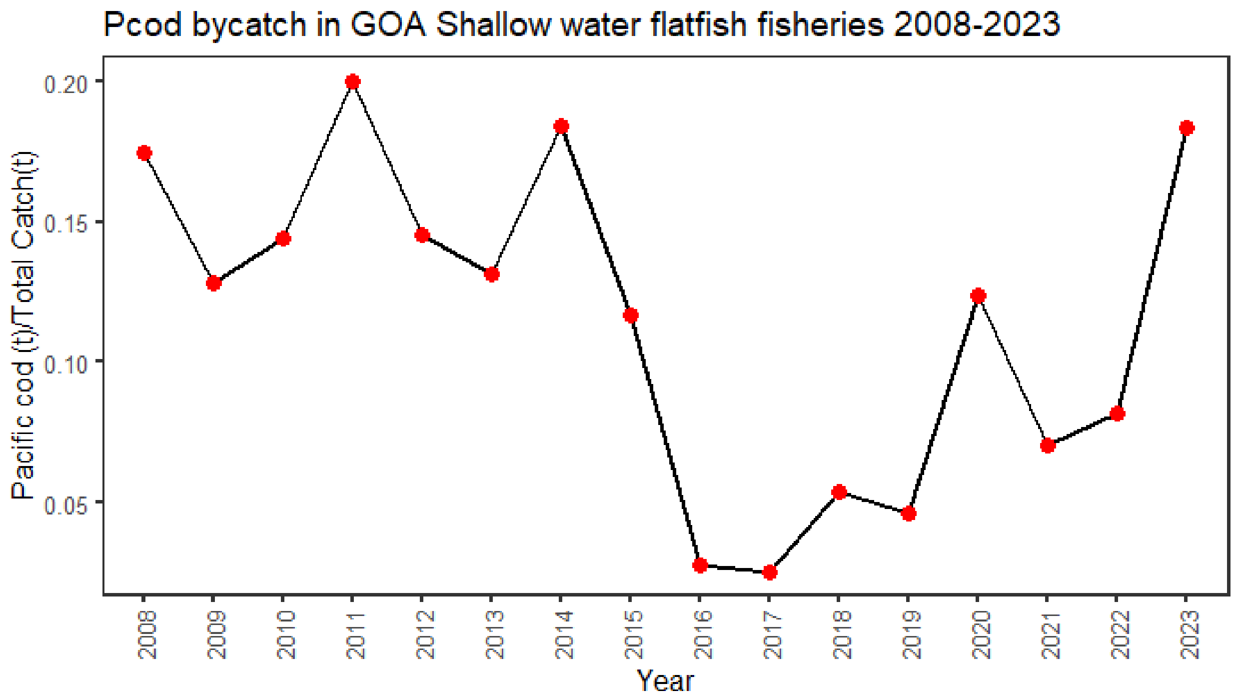

Figure 2.15. Pacific cod bycatch in the Gulf of Alaska shallow water flatfish fishery as tons of Pacific cod per tons of total catch in the fishery by year.

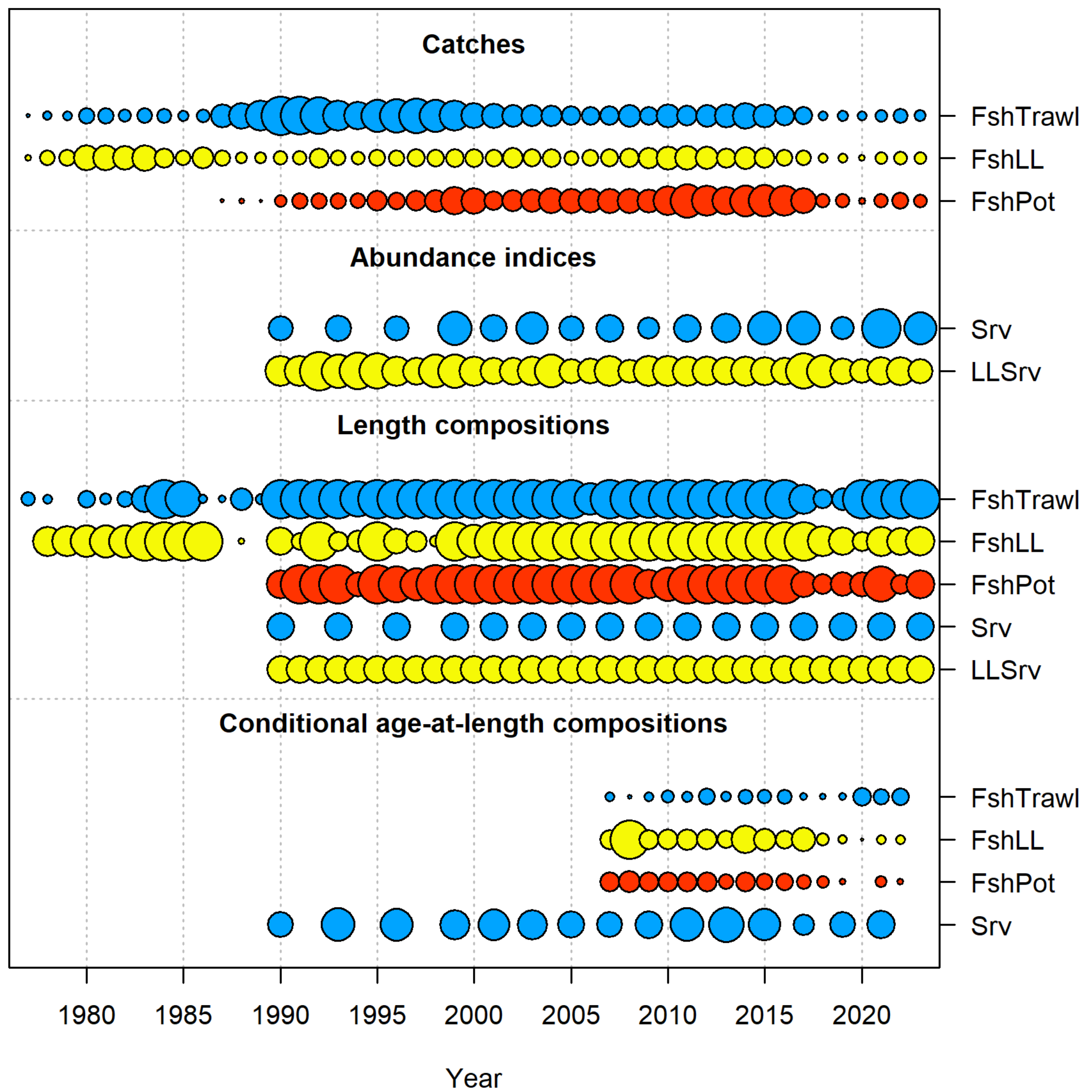

Figure 2.16. Data fit in the author's recommended model. Circles are proportional to total catch for catches; to precision for indices and to total sample size for compositions and length-at-age observations. Note that since the circles are scaled relative to maximum within each type, the plots of scaling across dataset types should not be compared.

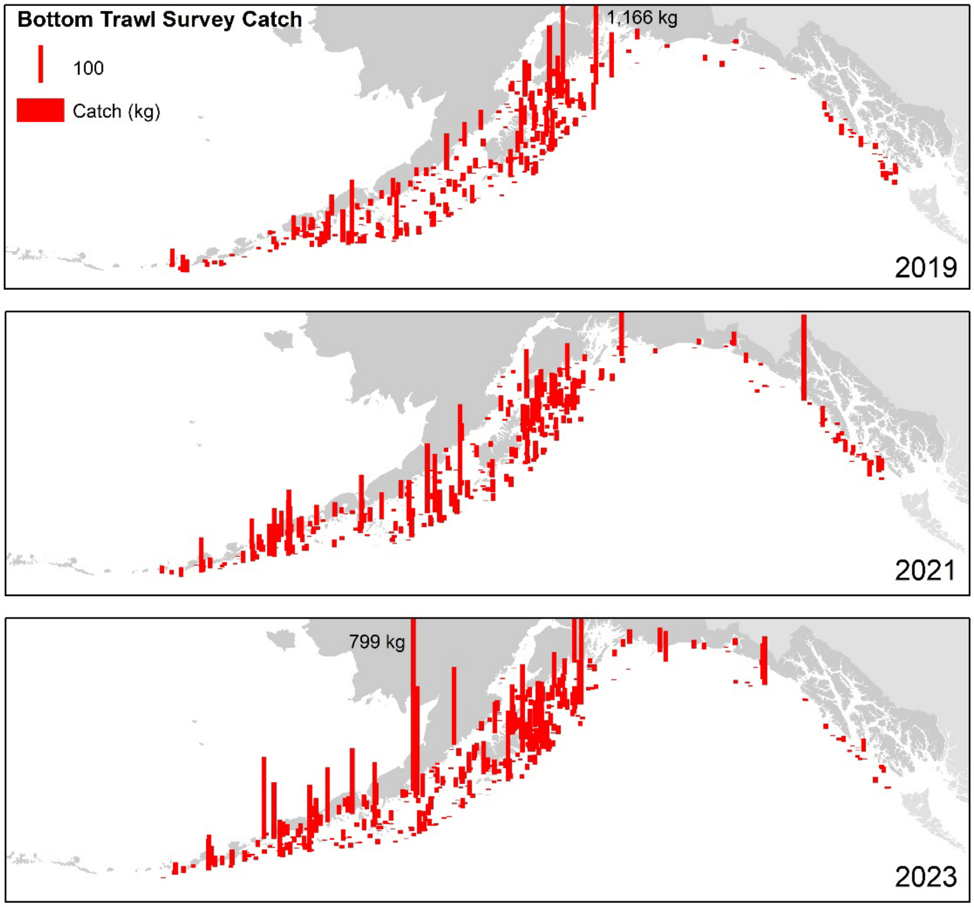

Figure 2.117. Distribution of AFSC bottom trawl survey catch of Pacific cod for 2019-2023.

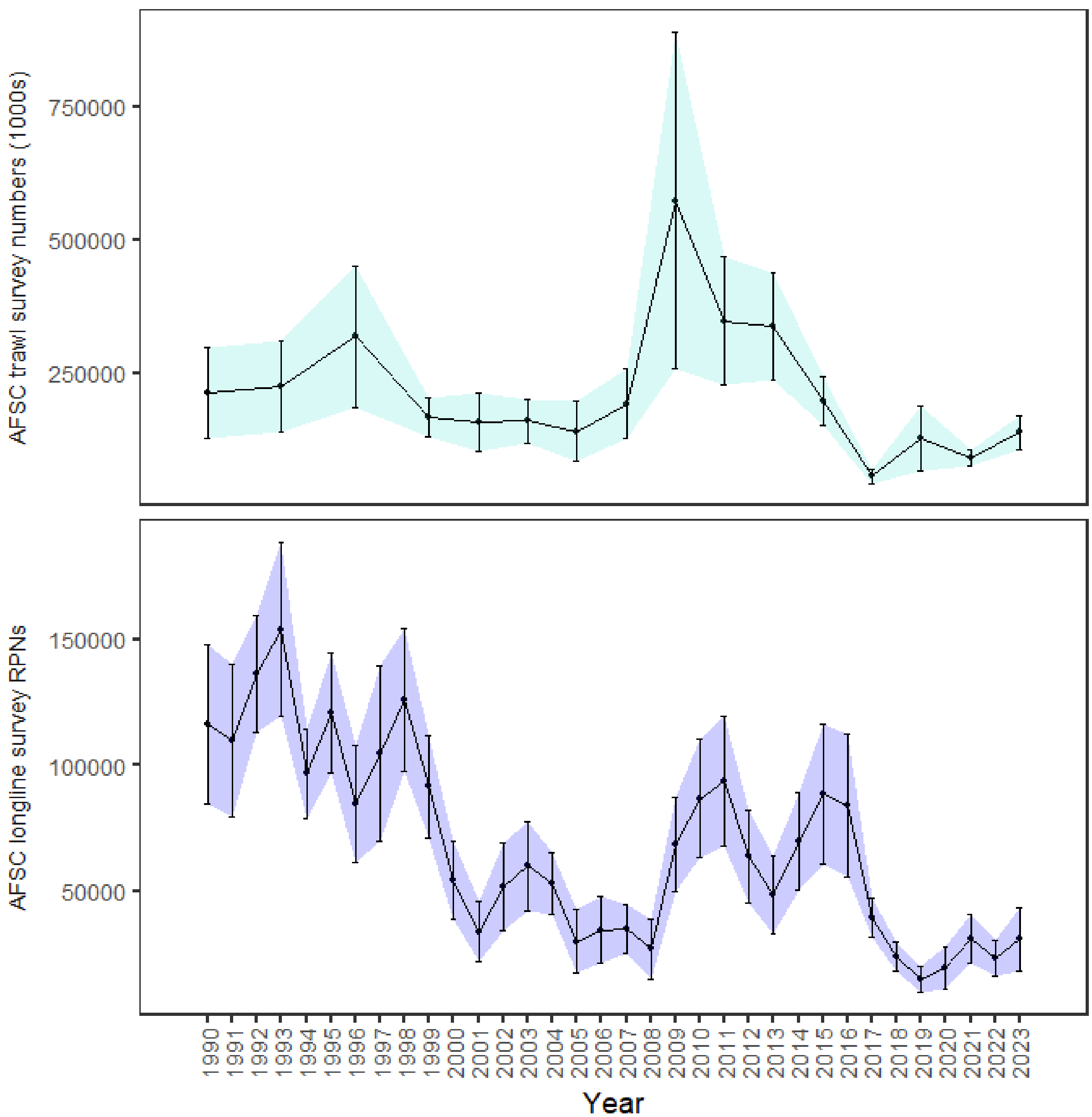

Figure 2.18. Population indices fit by the assessment model, including AFSC bottom trawl survey abundance (numbers – top panel) and AFSC longline survey relative population numbers (RPN – bottom panel). Bars and shading indicate the 95th percentile confidence intervals.

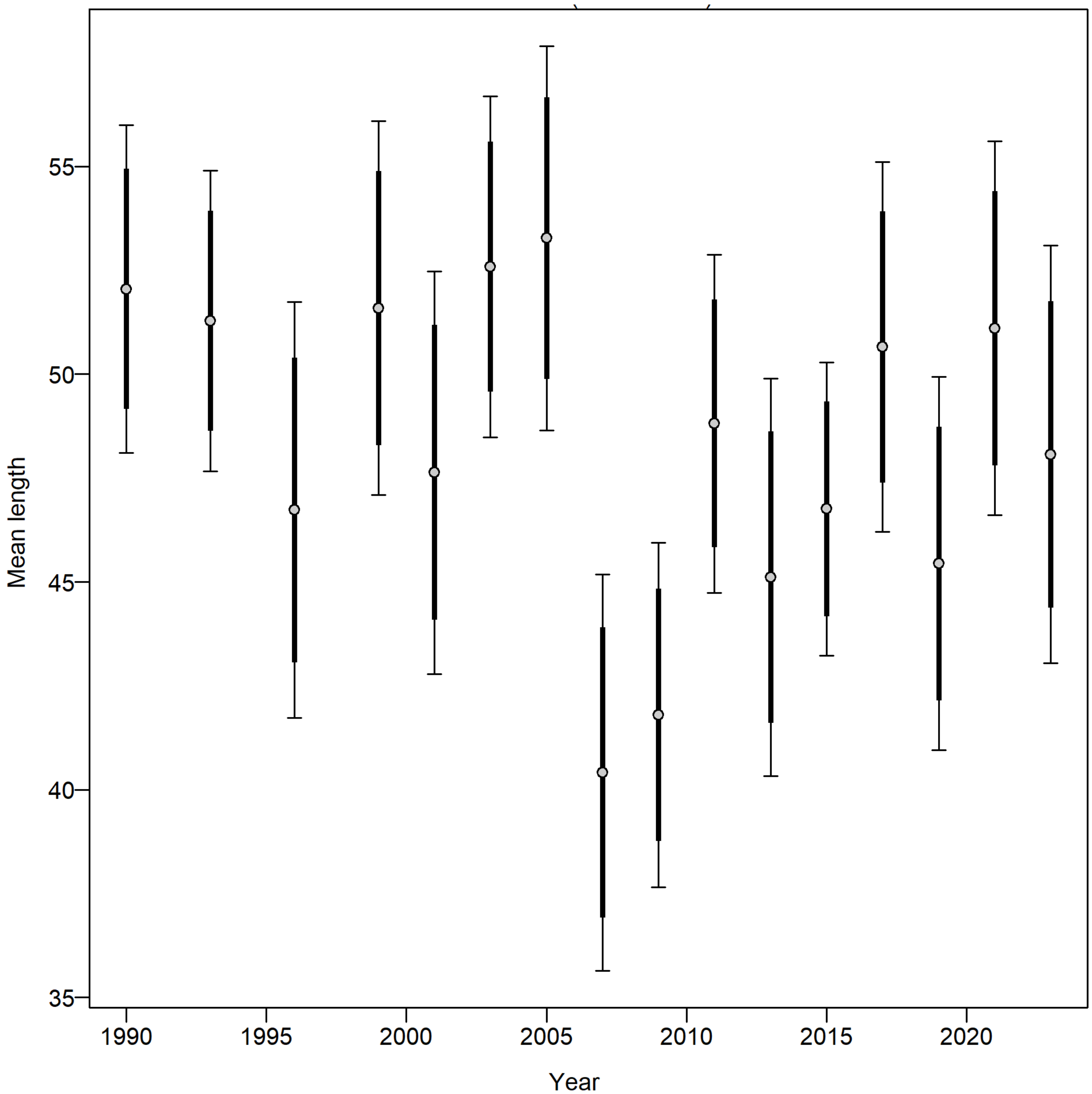

Figure 2.19. Mean length (cm) of Pacific cod in the AFSC GOA bottom trawl survey.

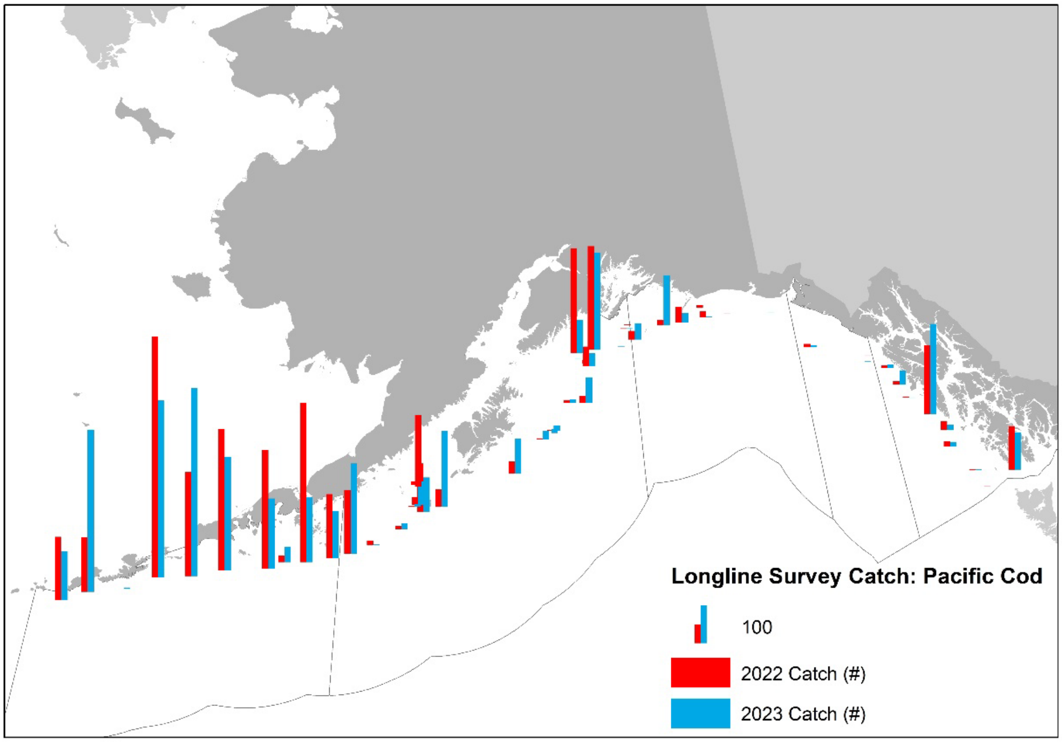

Figure 2.20. Distribution of AFSC longline survey catch of Pacific cod in 2022 and 2023.

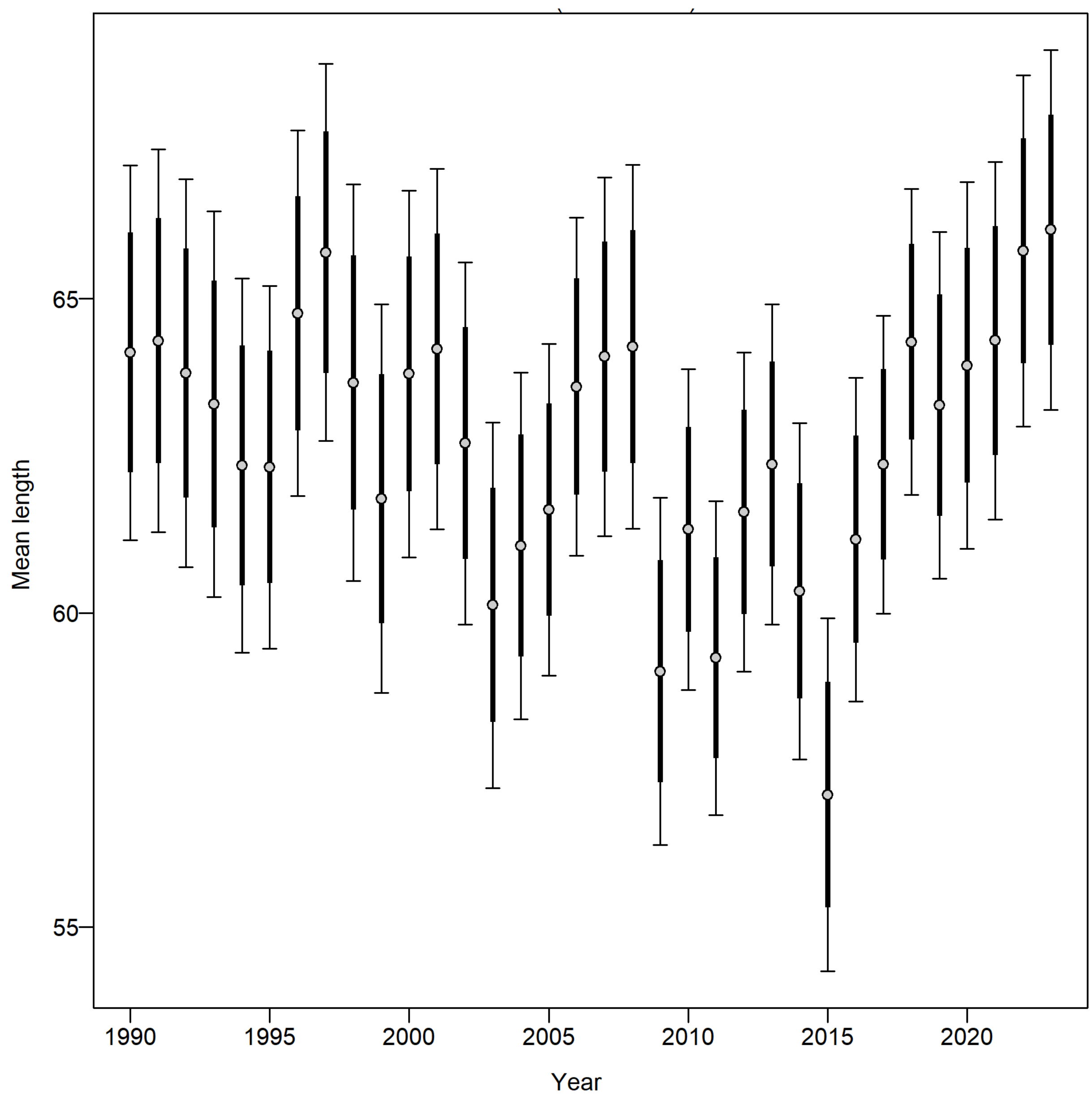

Figure 2.21. Mean length (cm) of Pacific cod from the AFSC longline survey.

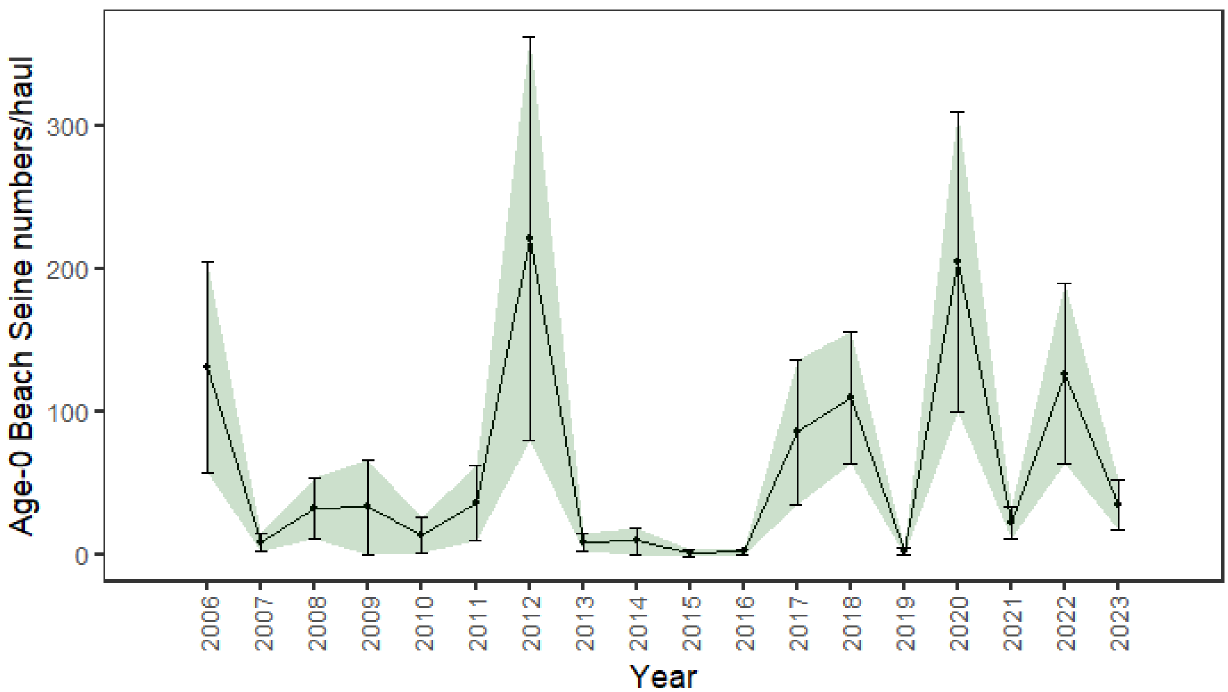

Figure 2.22. Age-0 beach seine survey numbers per haul, bars and shading indicate the 95th percentile confidence intervals.

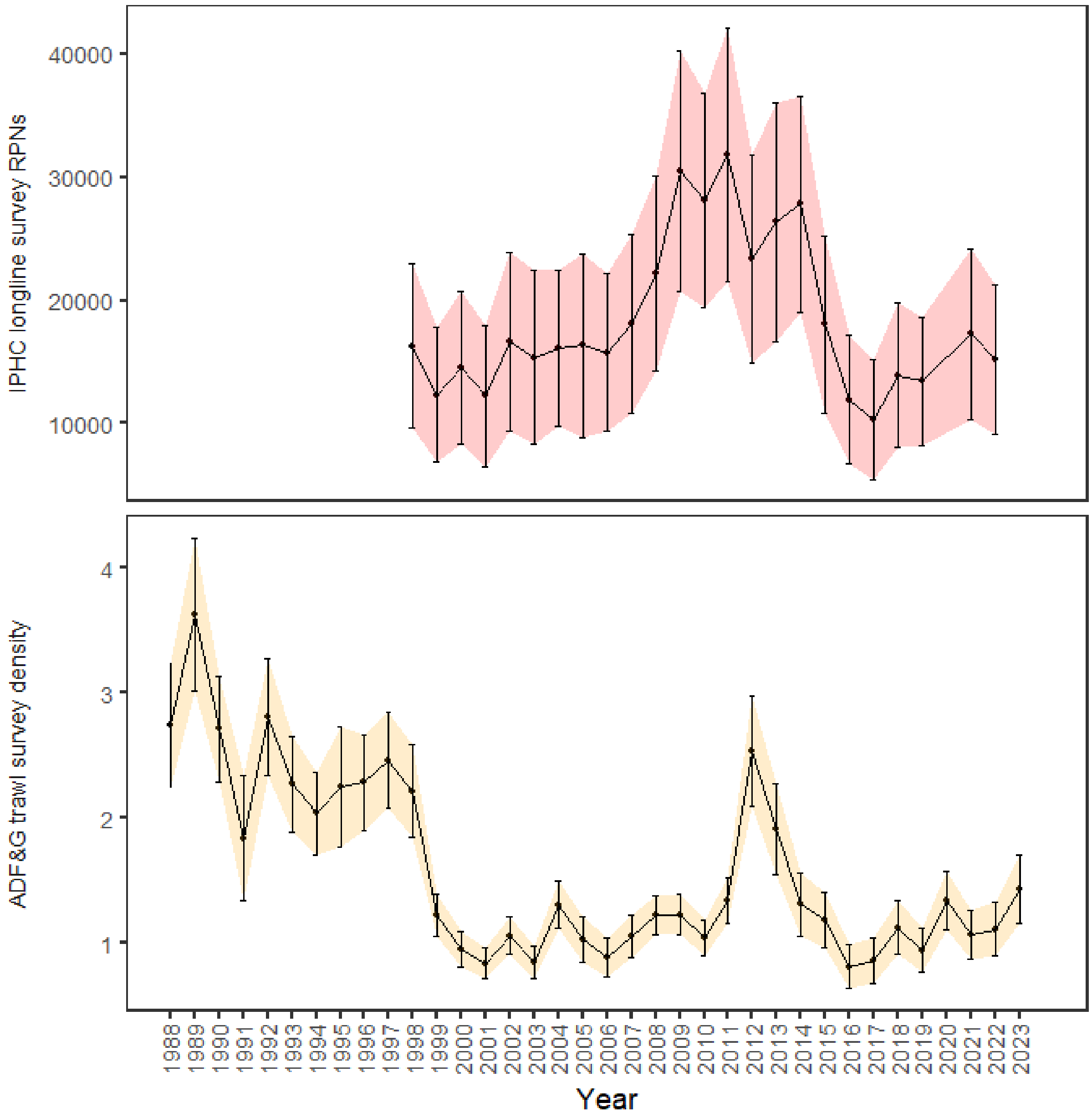

Figure 2.23. Population indices included for consideration but not fit in the assessment, including the IPHC longline survey relative population numbers (RPN – top panel) and ADF&G bottom trawl survey delta-glm density (bottom panel). Bars and shading indicate the 95th percentile confidence intervals.

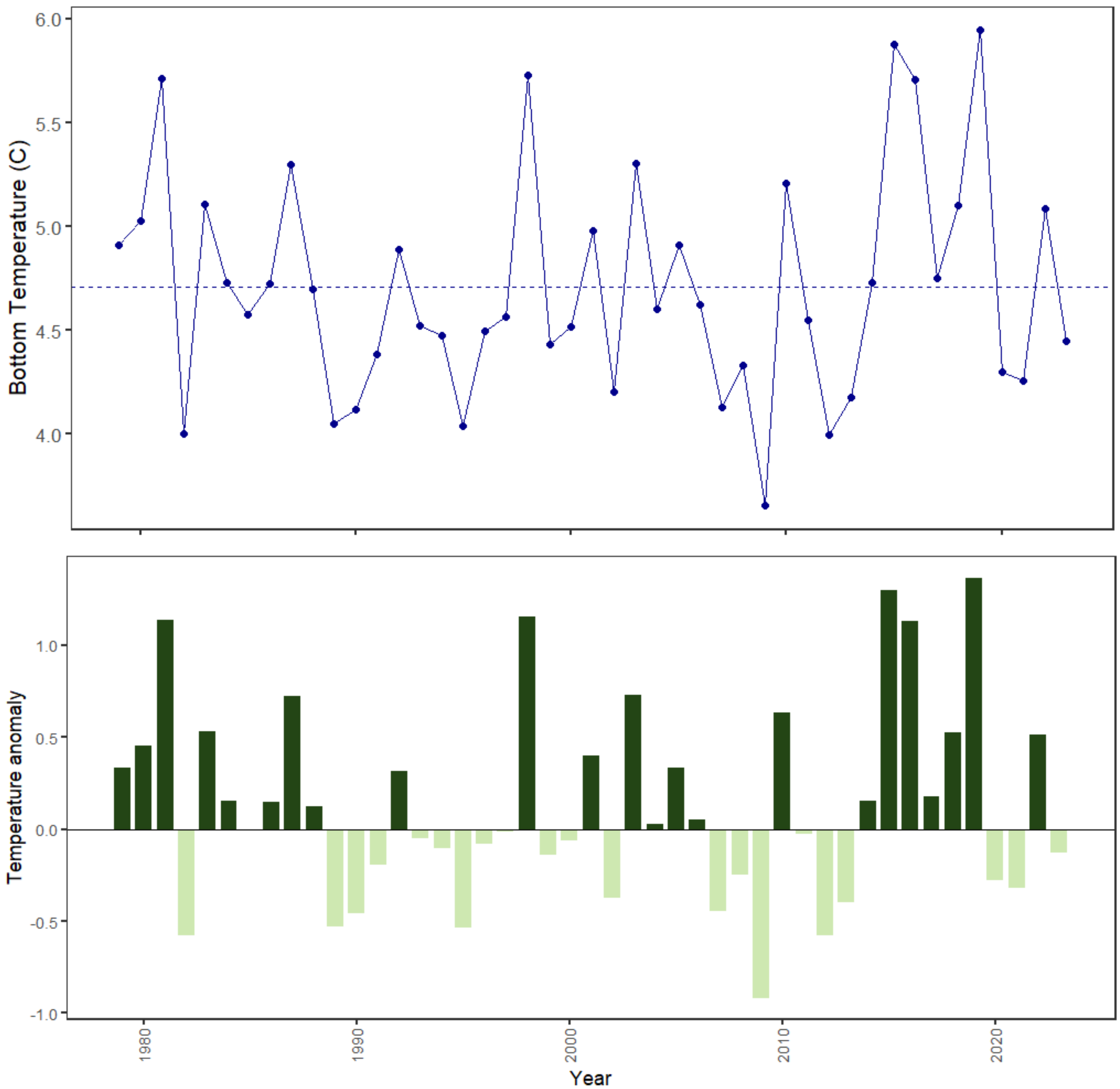

Figure 2.24. Climate Forcast System Reanalysis (CFSR) Central Gulf of Alaska bottom temperatures at the AFSC bottom trawl survey mean depths for 0-20 cm Pacific cod in June (top) and temperature anomailies used as a covariate to the AFSC longline survey catchability (bottom).

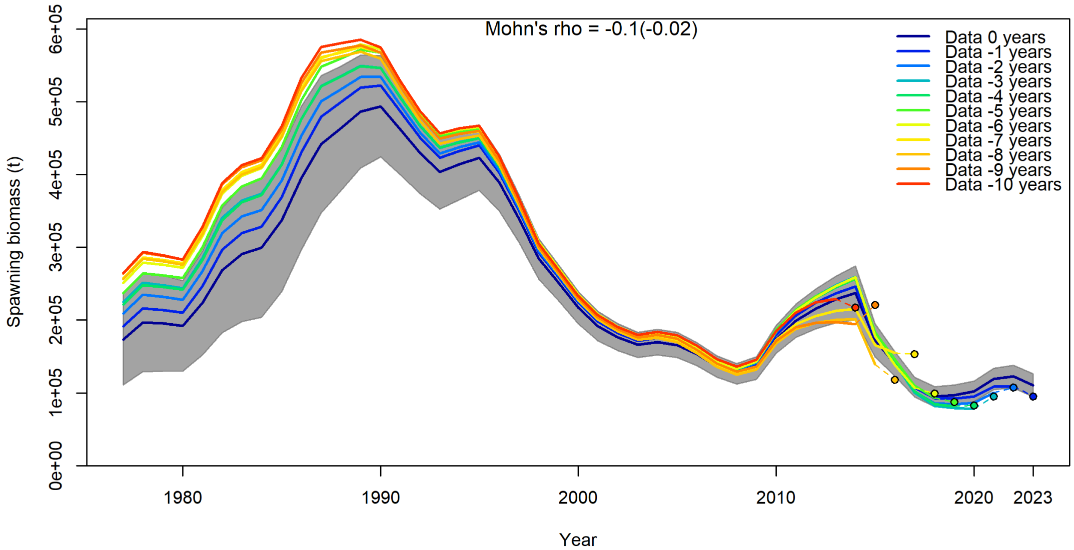

Figure 2.25. Retrospective analysis of spawning biomass for the author's recommended model (overall Mohn's rho shown, with Mohn's rho for forecasted biomass shown in parentheses).

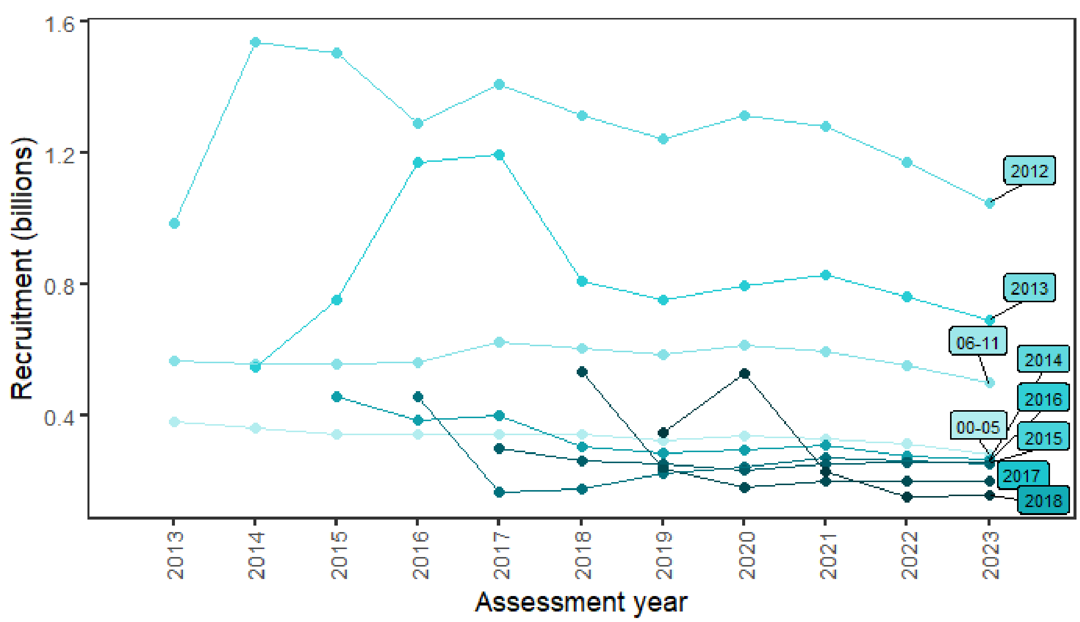

Figure 2.26. Retrospective analysis of recruitment by recent year classes compared to the average of year classes from 2000 – 2005 and 2006 – 2011 from the author's recommended model.

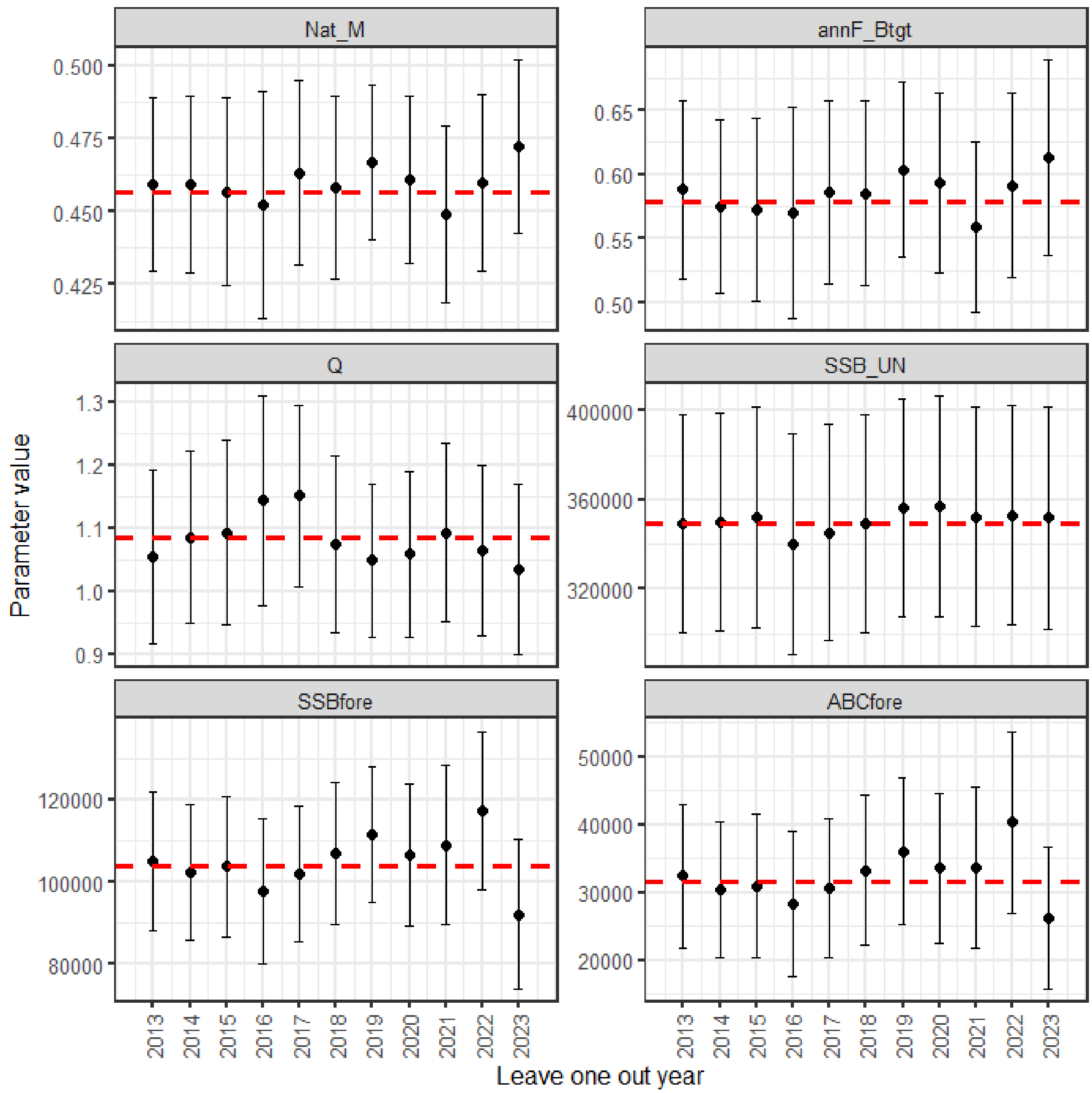

Figure 2.27. Leave-one-out analysis showing parameters and derived quantities as one year of data were removed from the model fit of the author's recommended model. Nat_M is the base natural mortality, annF_Btgt is the $F_{40\%}$, Q is the AFSC bottom trawl catchability, SSB_UN is the unfished spawning biomass, SSBfore is the one-year forecasted total spawning biomass and ABCfore is the one-year forecasted ABC.

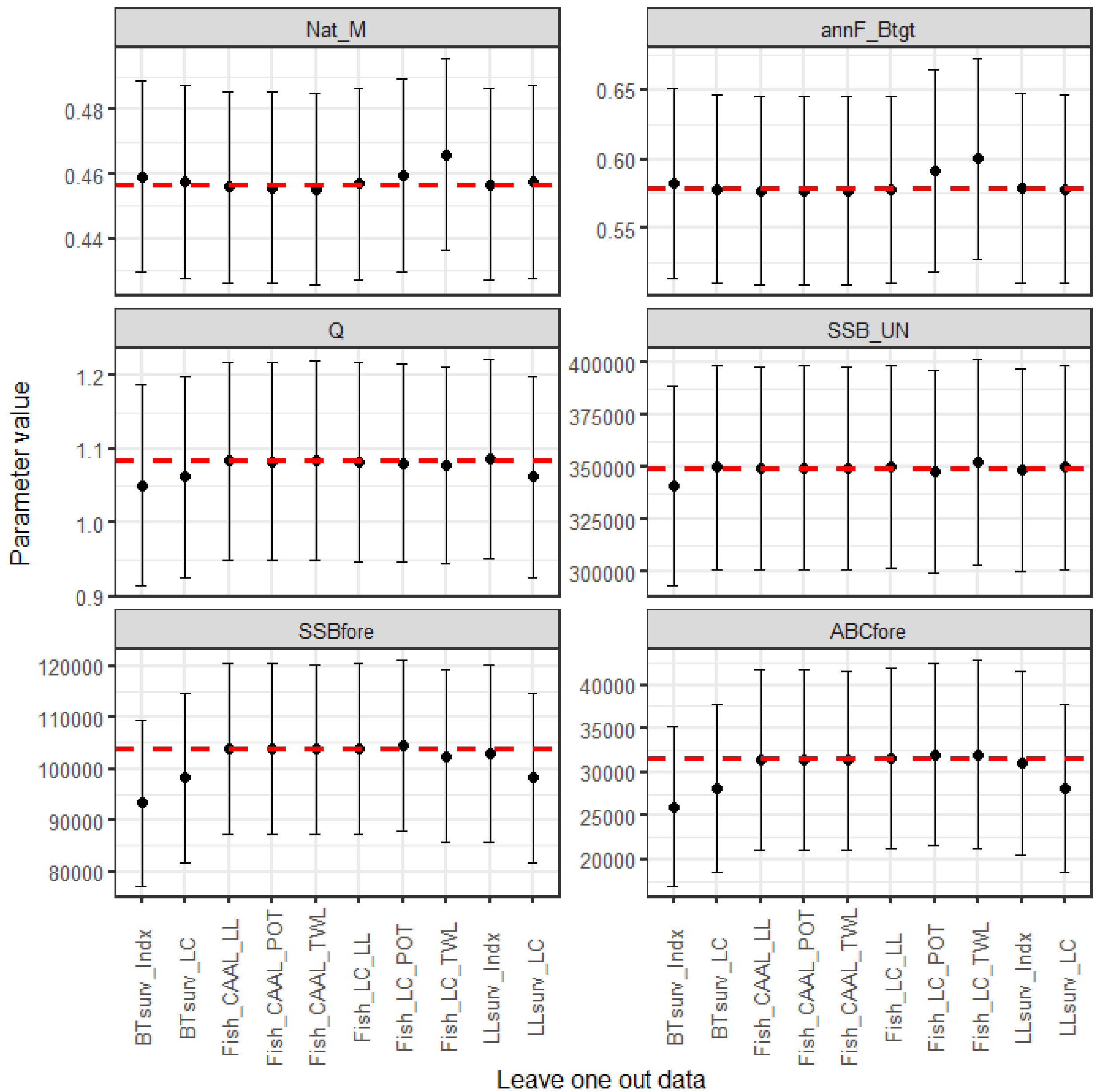

Figure 2.28. Leave-one-out analysis showing parameters and derived quantities as one data source added to this years assessment were removed from the model fit for the author's recommended model. CAAL denotes conditional age-at-length data, LC denotes length comp data, and Indx denotes index data from the bottom trawl survey (BTsurv), longline survey (LLsurv) and fisheries (denoted with gear type). The parameters and quantities are as in Fig. 2.30.

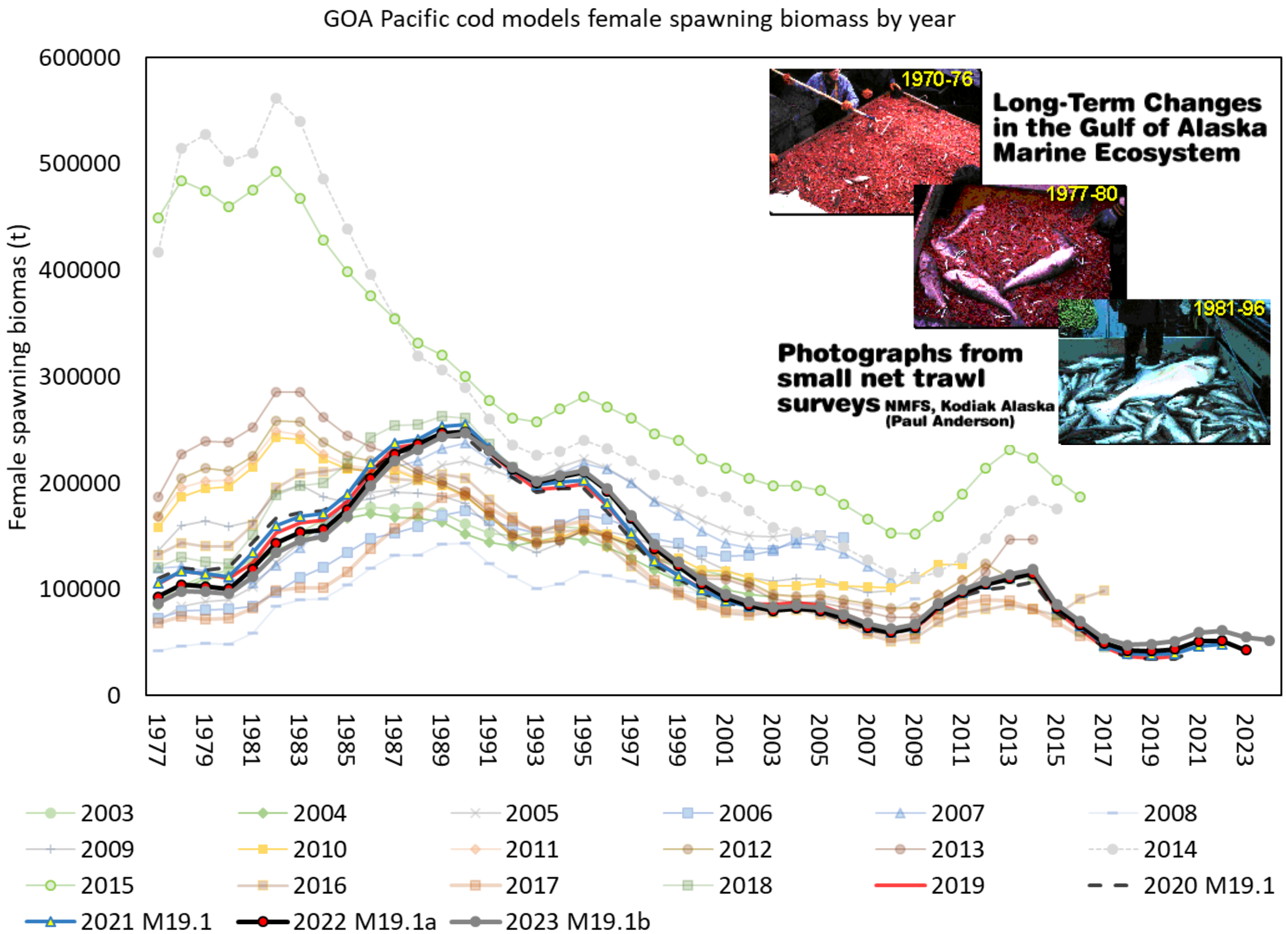

Figure 2.29. Gulf of Alaska Pacific cod estimated female spawning biomass from the 2003 through 2023 stock assessments and (inset) images from the NMFS small net surveys off Kodiak Alaska showing change in species composition over time from: https://www.thenakedscientists.com/articles/science-features/ecosystem-shifts-and-sharks-alaska

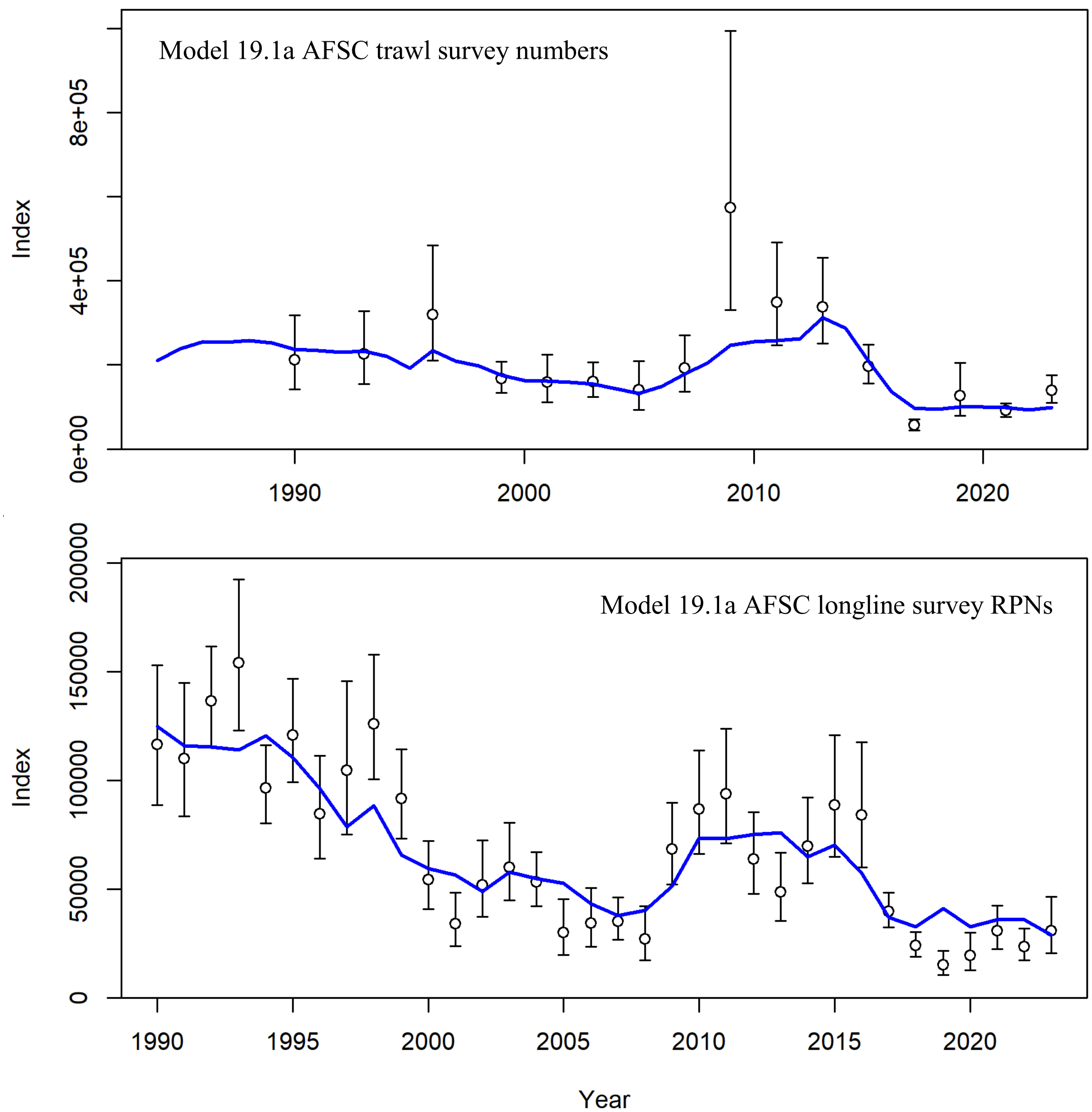

Figure 2.30. Model fits to AFSC bottom trawl survey numbers (top) and AFSC longline survey relative population numbers (RPNs, bottom).

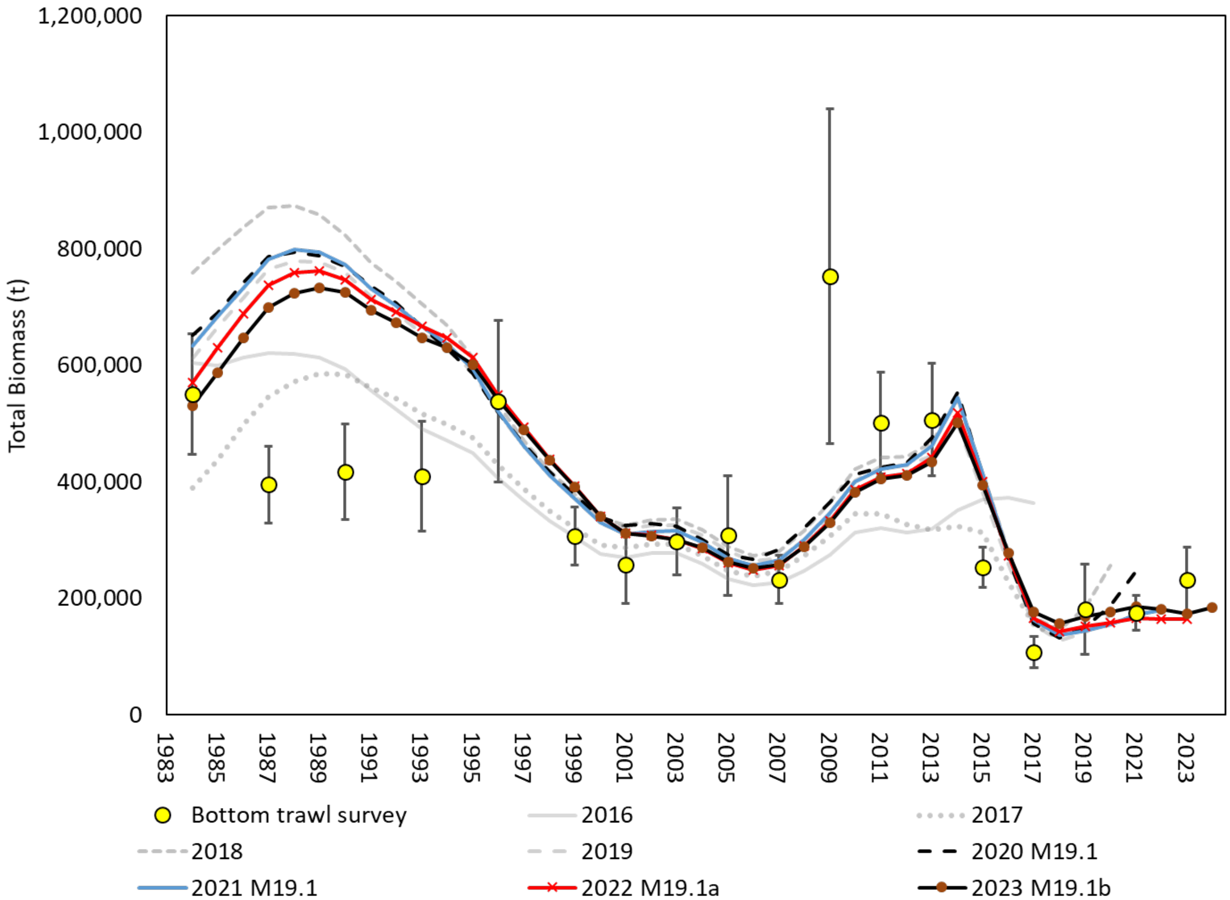

Figure 2.31. Total biomass estimates from 2016 through 2023 stock assessments and NMFS bottom trawl survey biomass estimates with 95% confidence bounds.

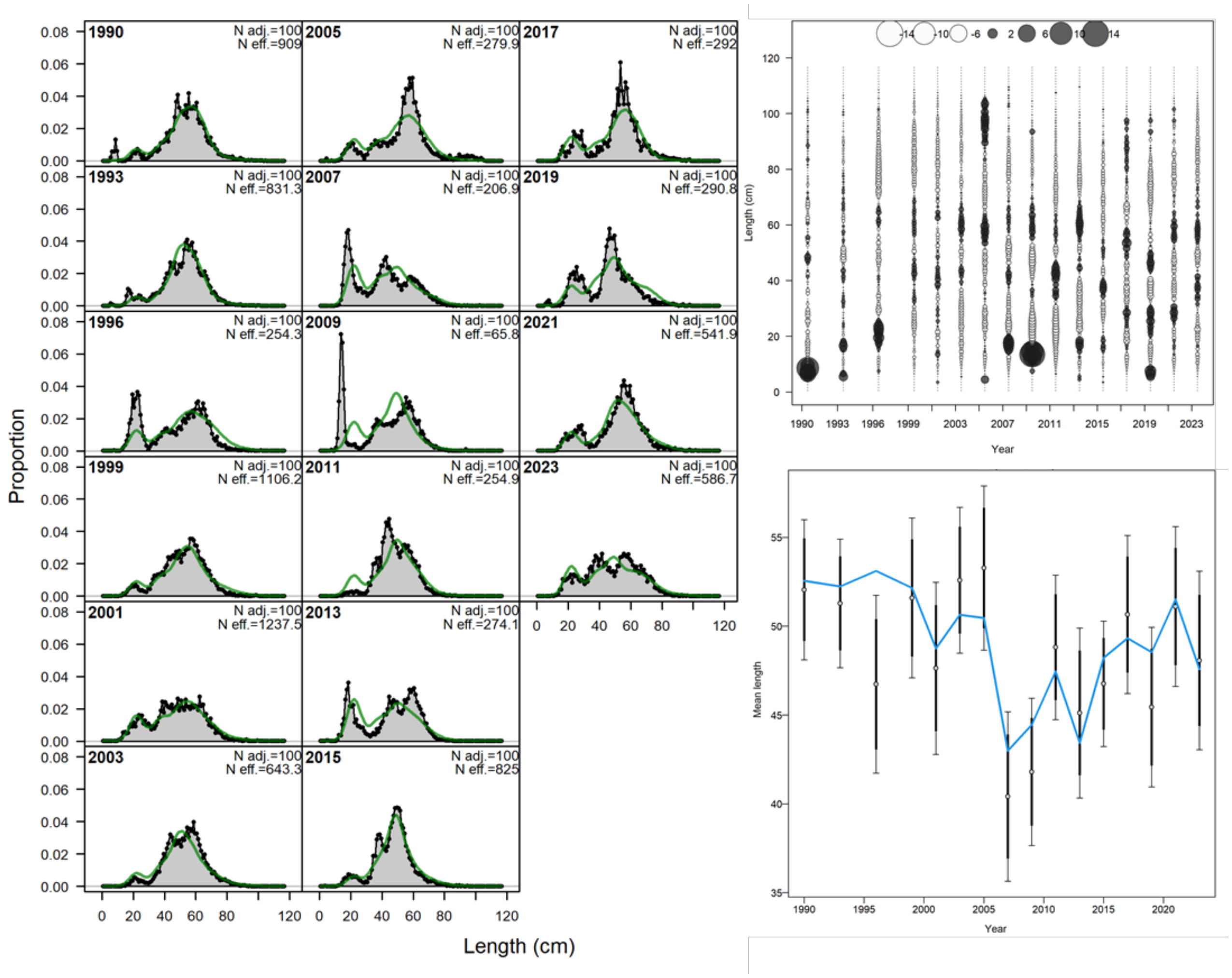

Figure 2.32. NMFS bottom trawl survey length composition and the author's recommended model fit (left), Pearson residuals (top right), and mean length (cm; bottom right).

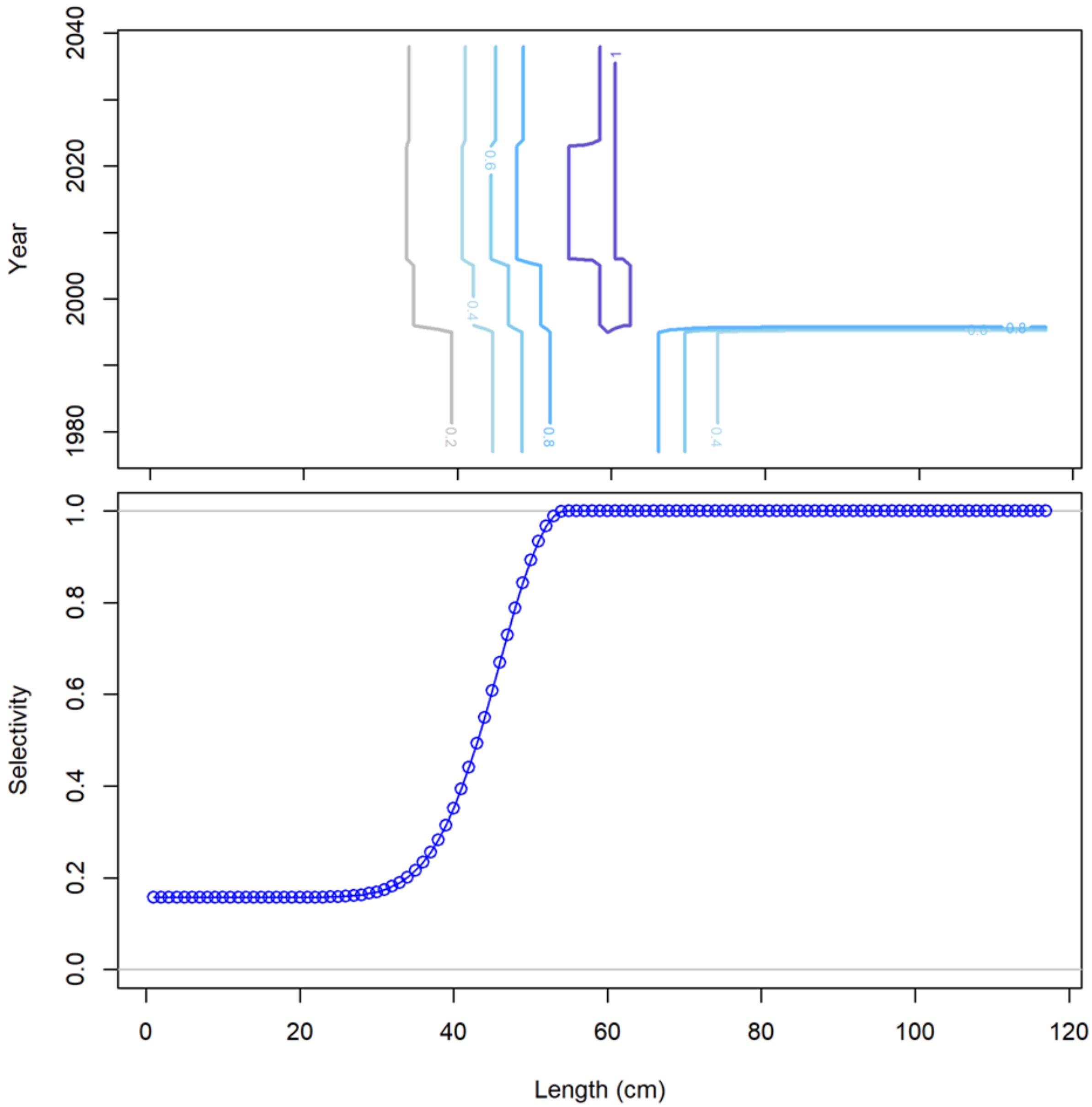

Figure 2.33. NMFS bottom trawl survey selectivity at length from the author's recommended model across time (top), and in final year of model (bottom).

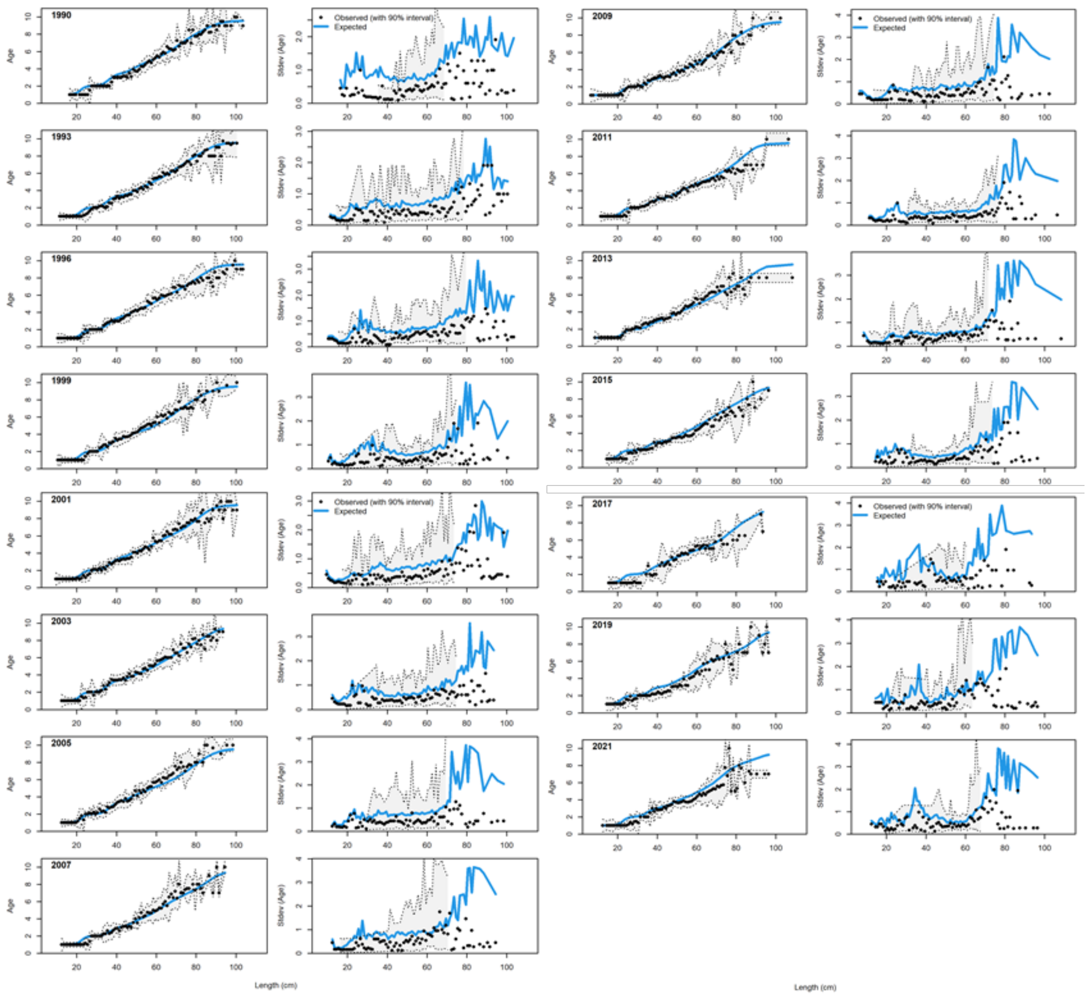

Figure 2.34. NMFS bottom trawl survey conditional age at length data and standard deviation with the author's recommended model fit (blue line).

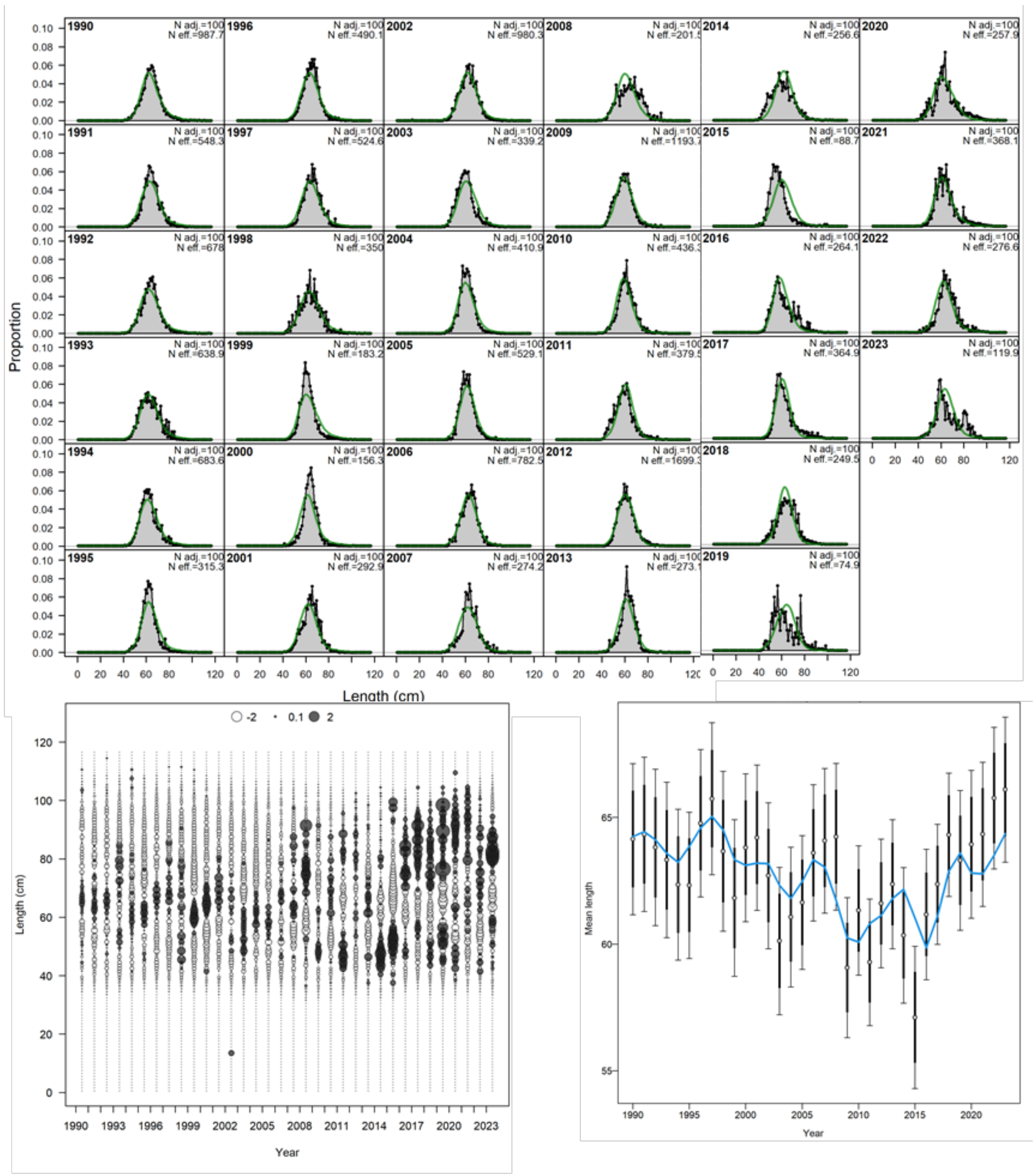

Figure 2.35. AFSC Longline survey length composition and the author's recommended model fit (top), Pearson residuals (left bottom), and mean length (cm; right bottom).

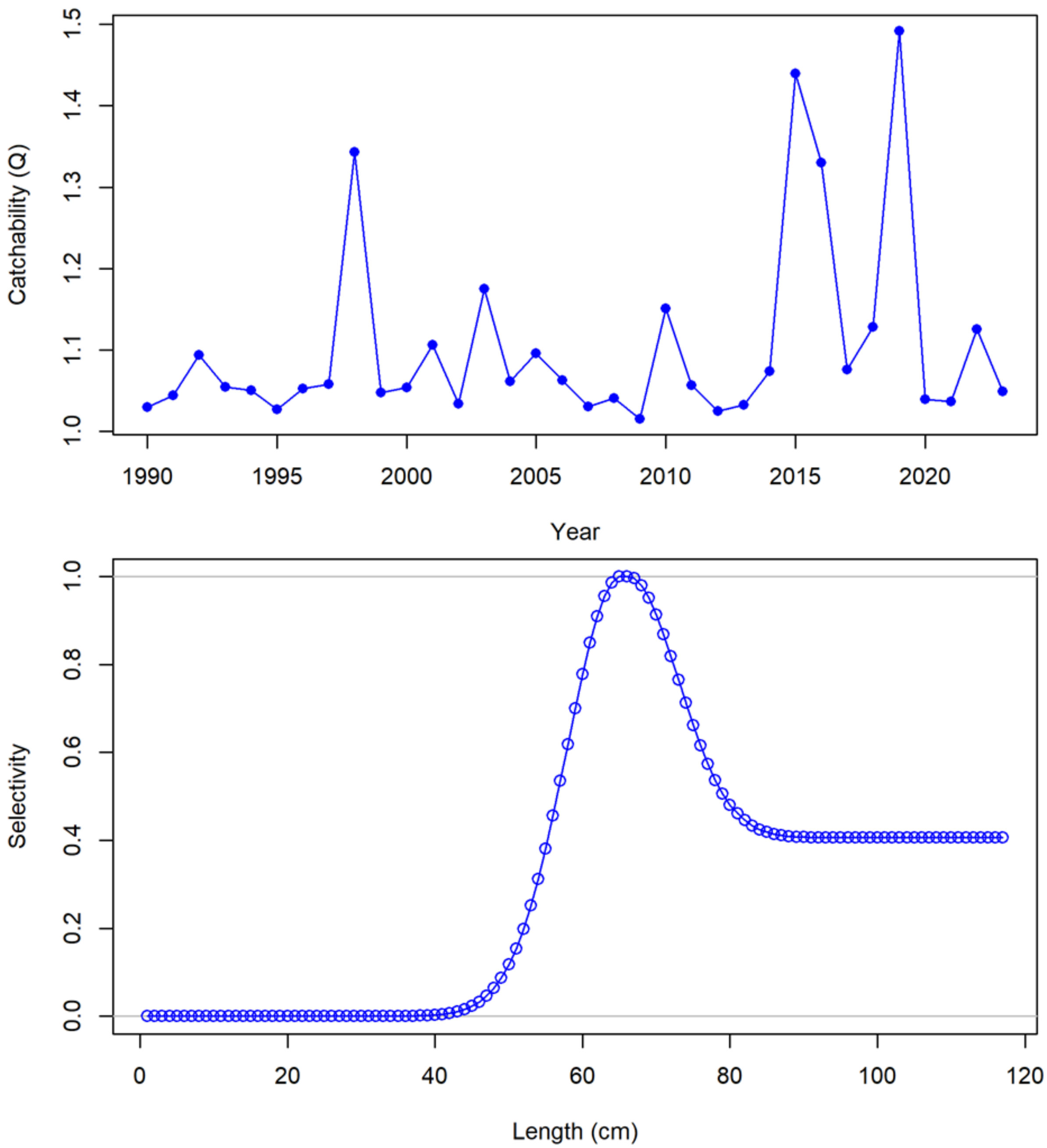

Figure 2.36. AFSC Longline survey time-dependent catchability (top; as estimated with CFSR anomaly covariate) and selectivity at length (bottom) from the author's recommended model.

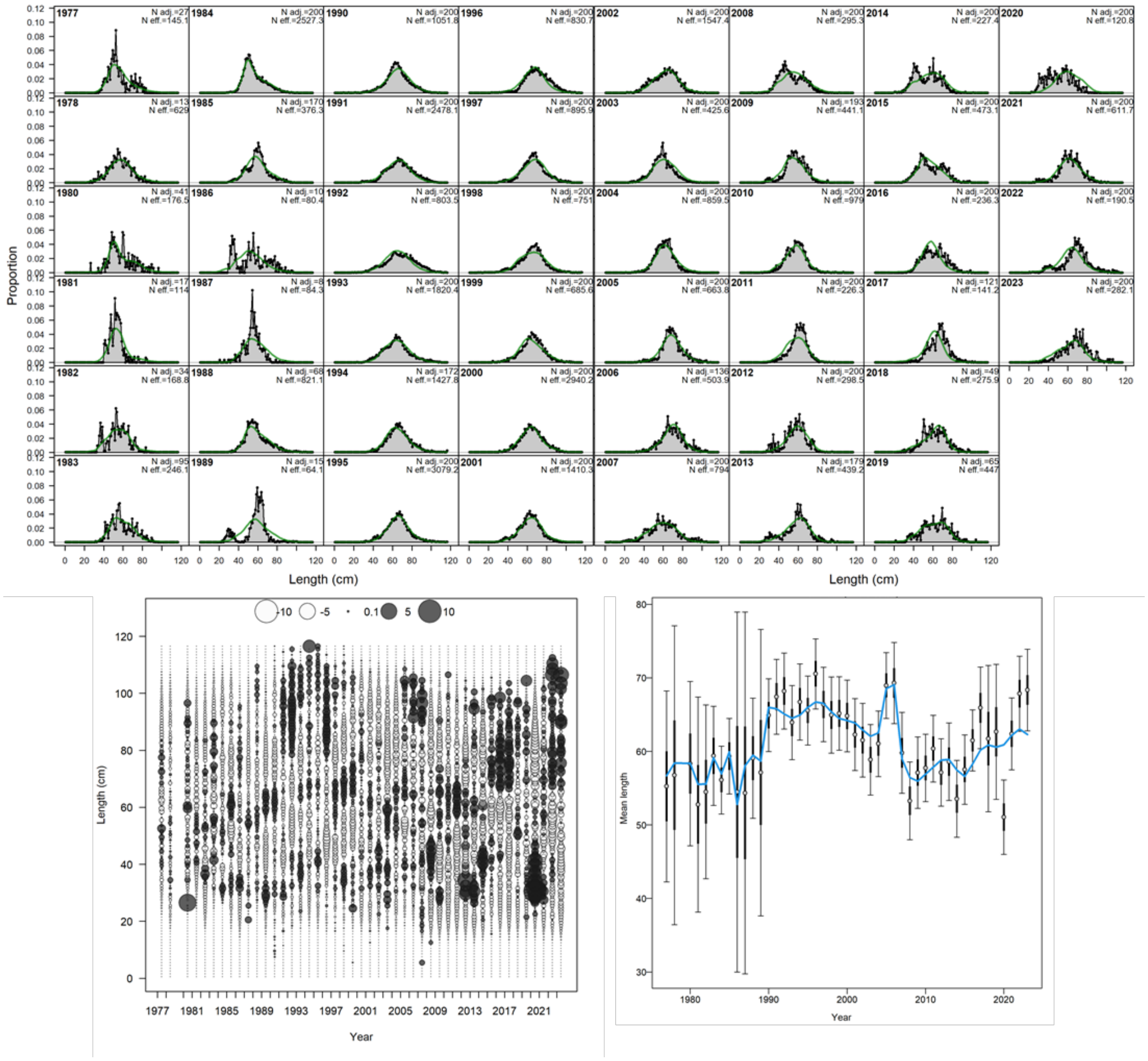

Figure 2.37. Trawl fishery length composition and the author’s recommended model fit (top), Pearson residuals (left bottom), and mean length (cm; right bottom).

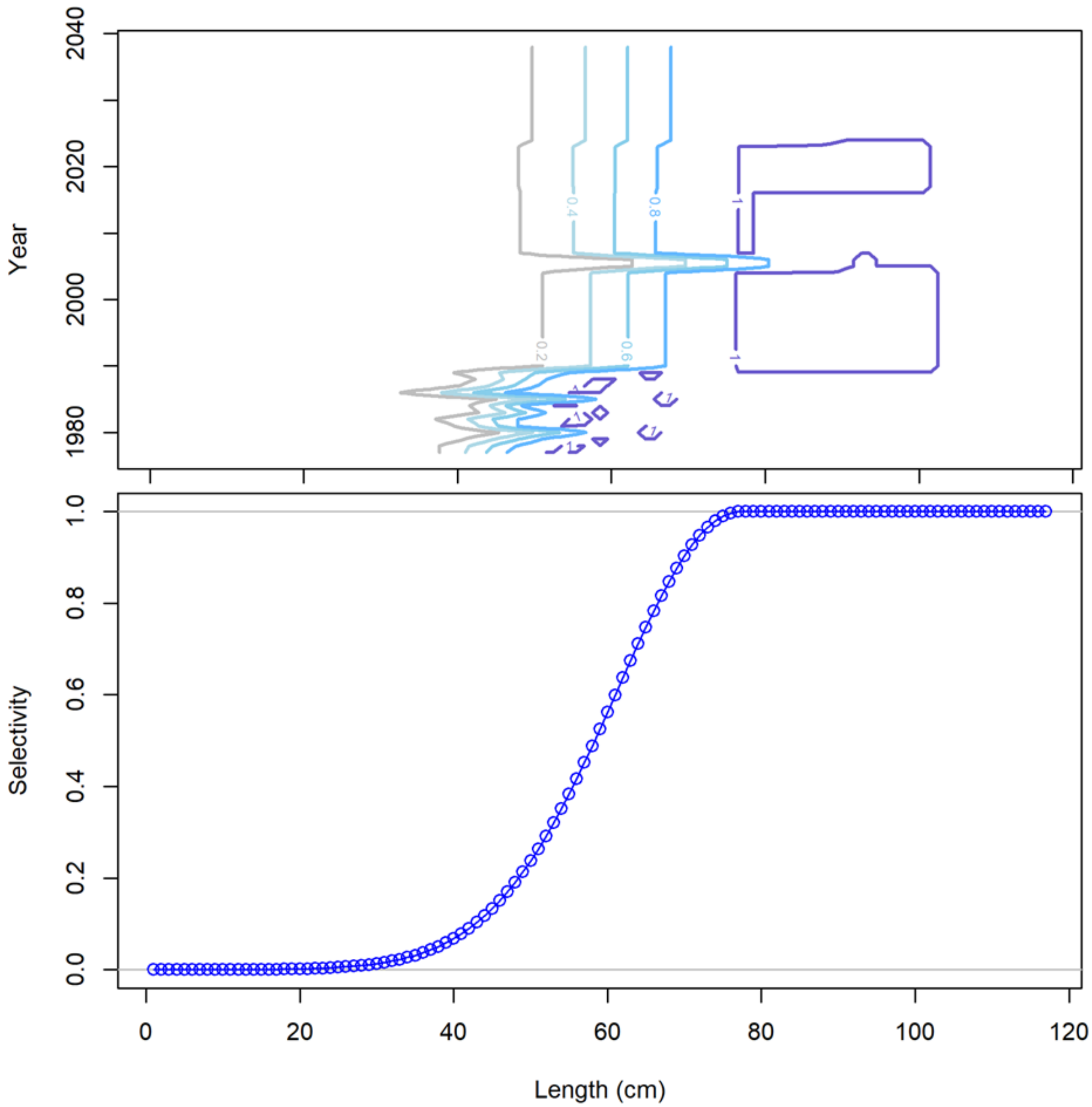

Figure 2.38. Trawl fishery selectivity at length from the author's recommended model across time (top), and in final year of model (bottom).

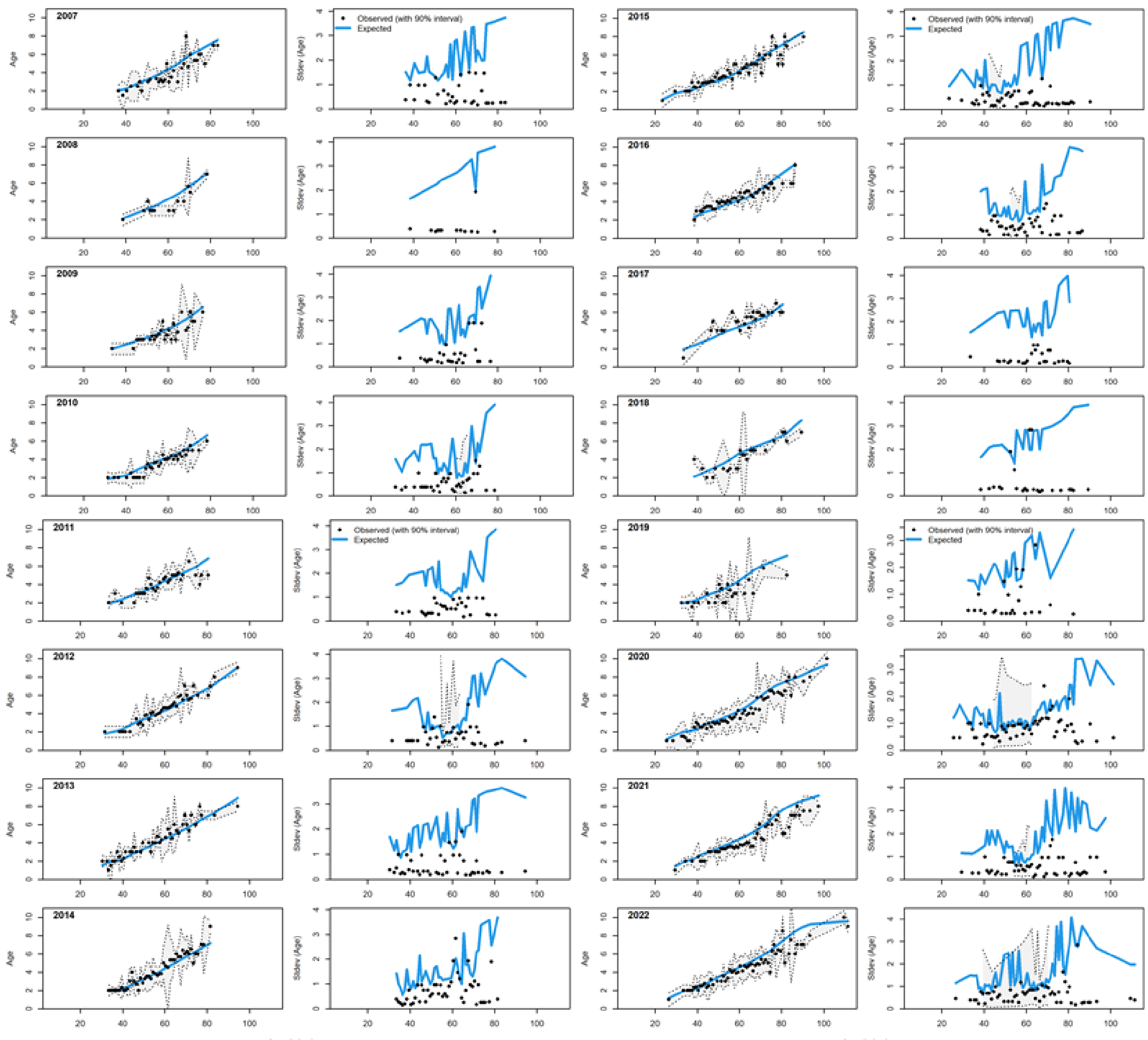

Figure 2.39. Trawl fishery conditional age at length data and standard deviation with the author's recommended model fit (blue line).

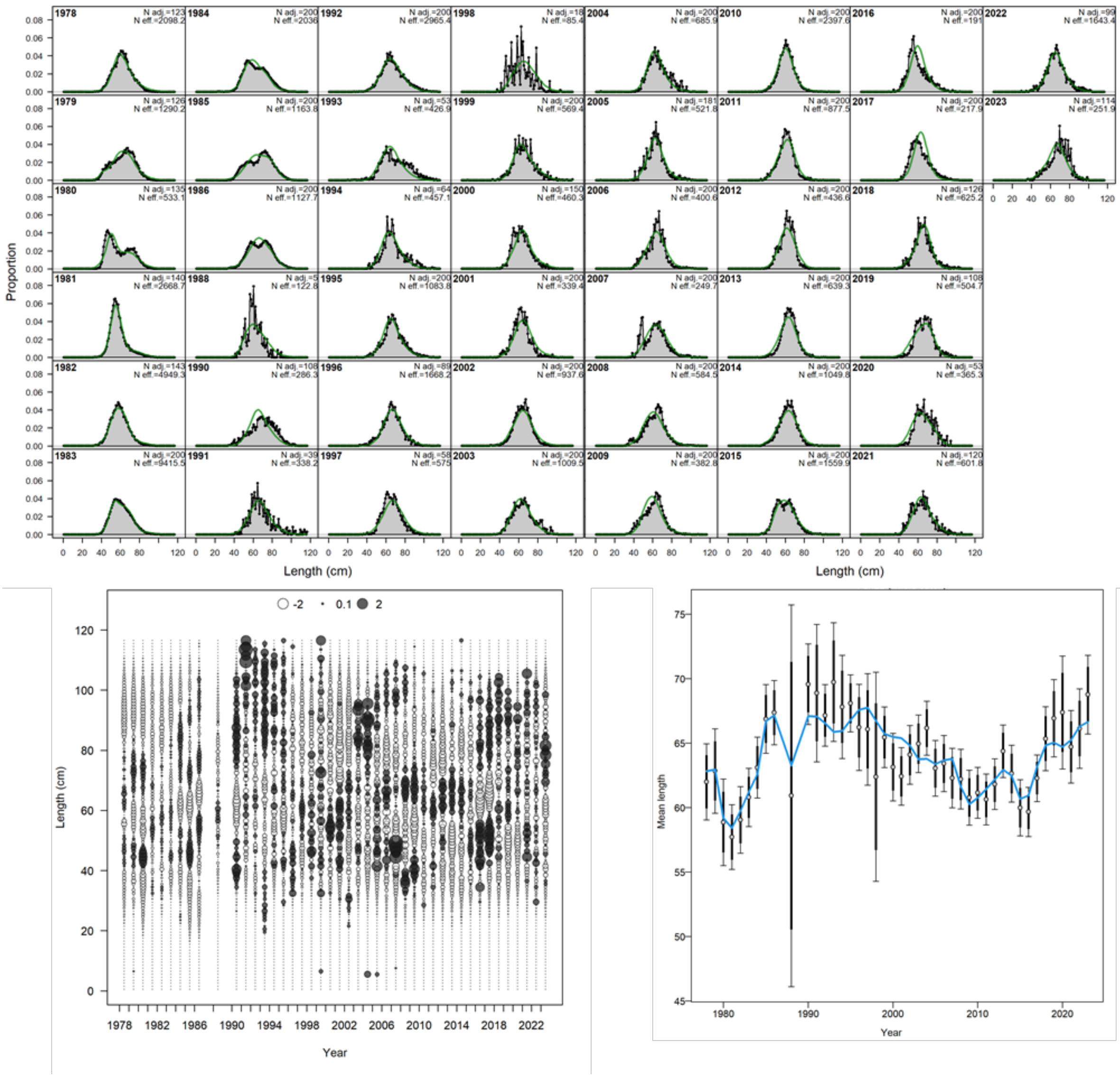

Figure 2.40. Longline fishery length composition and the author's recommended model fit (top), Pearson residuals (left bottom), and mean length (cm; right bottom).

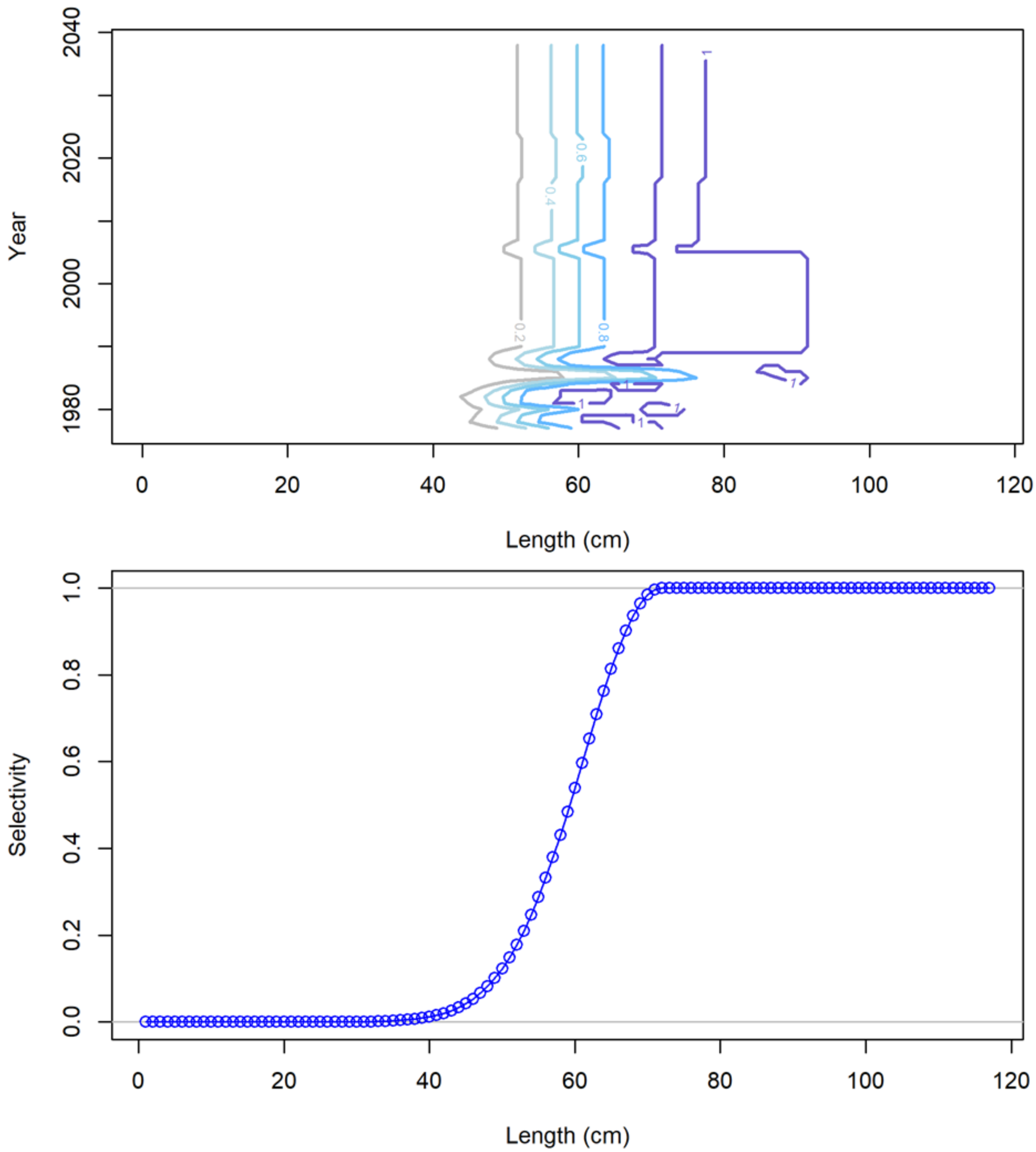

Figure 2.41. Longline fishery selectivity at length from the author's recommended model across time (top), and in final year of model (bottom).

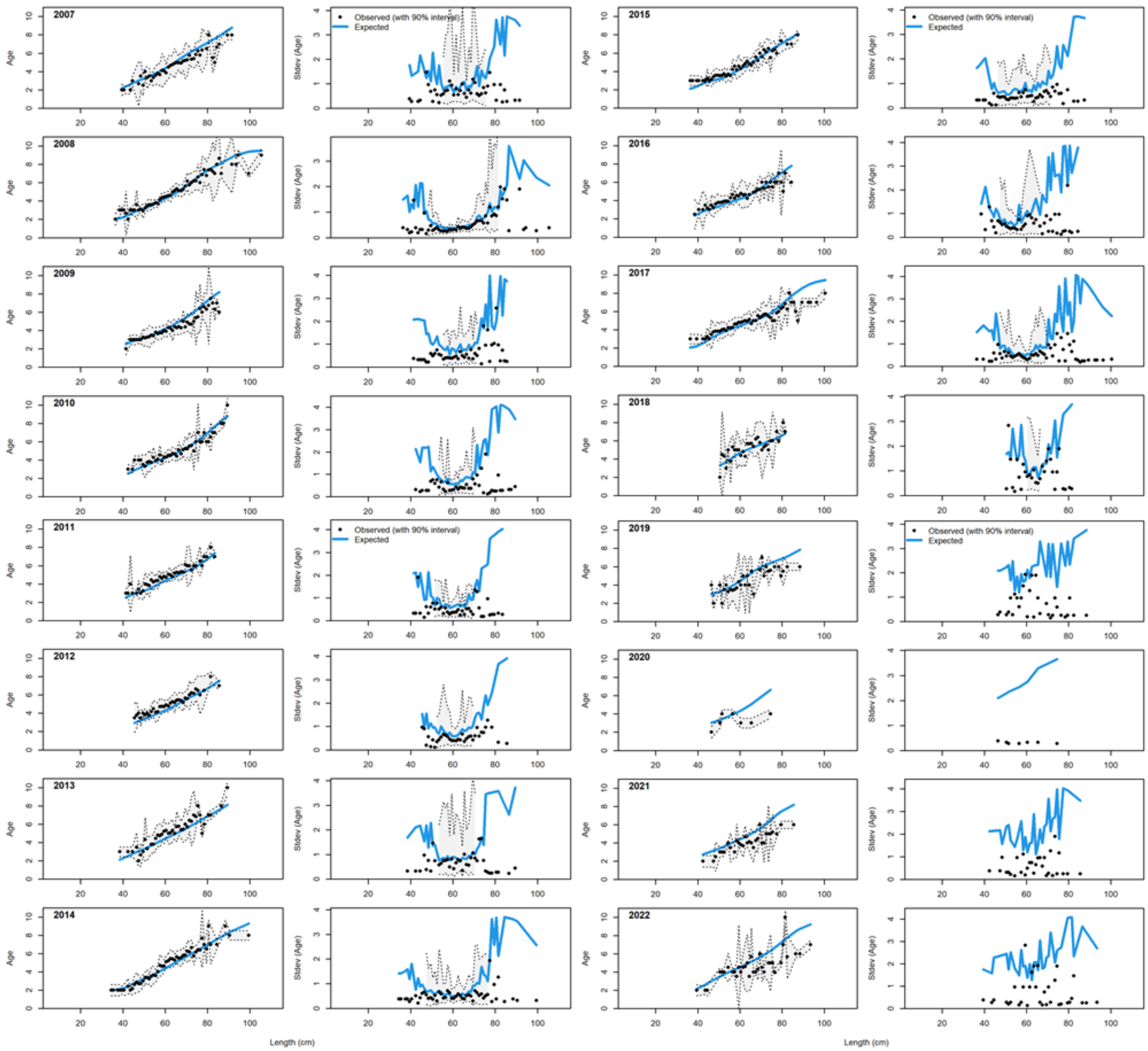

Figure 2.42. Longline fishery conditional age at length data and standard deviation with the author's recommended model fit (blue line).

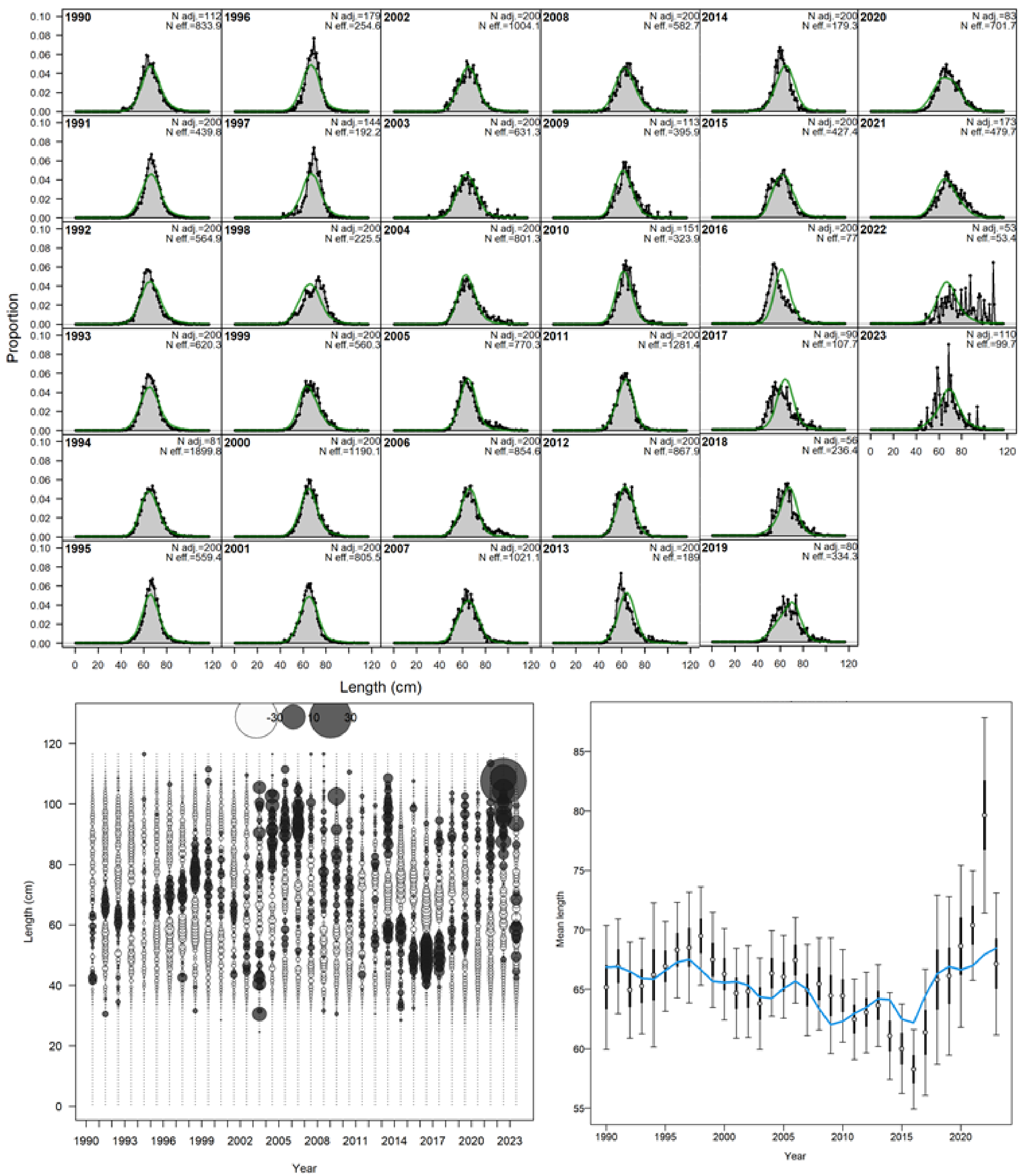

Figure 2.43. Pot fishery length composition and the author's recommended model fit (top), Pearson residuals (left bottom), and mean length (cm; right bottom).

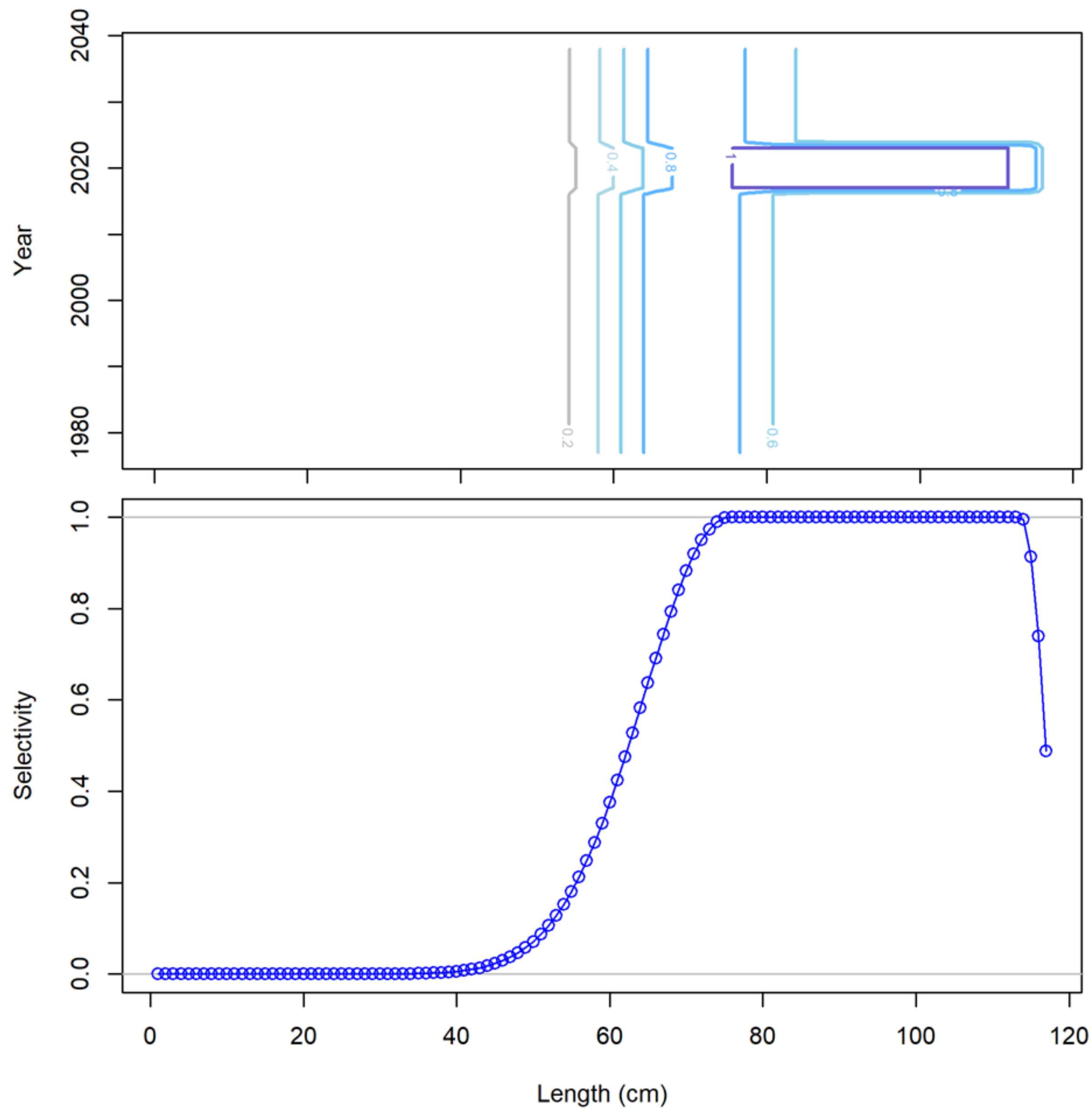

Figure 2.44. Pot fishery selectivity at length from the author's recommended model across time (top), and in final year of model (bottom).

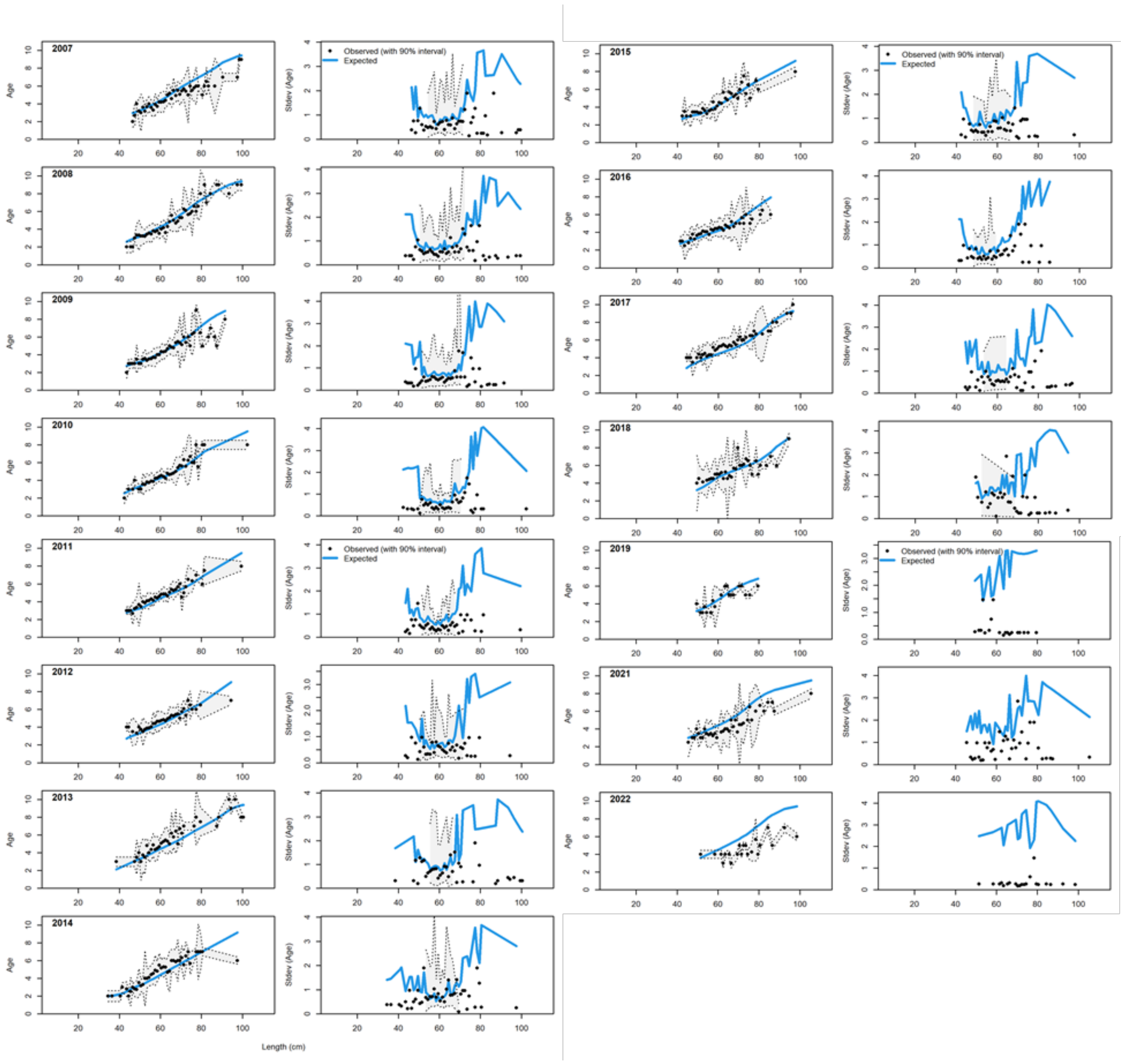

Figure 2.45. Pot fishery conditional age at length data and standard deviation with the author's recommended model fit (blue line).

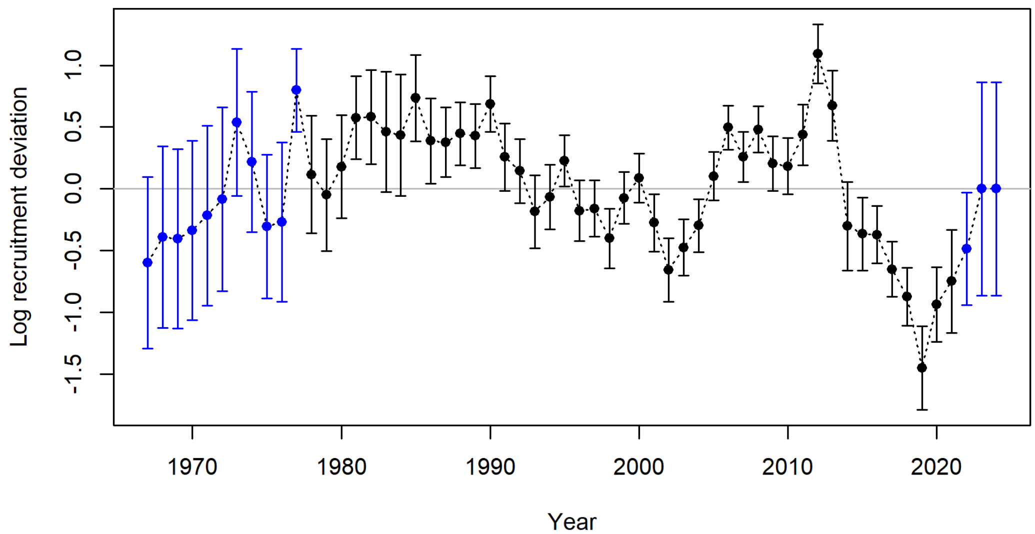

Figure 2.46. Log recruitment deviations with 95% asymtotic error intervals from the author's recommended model.

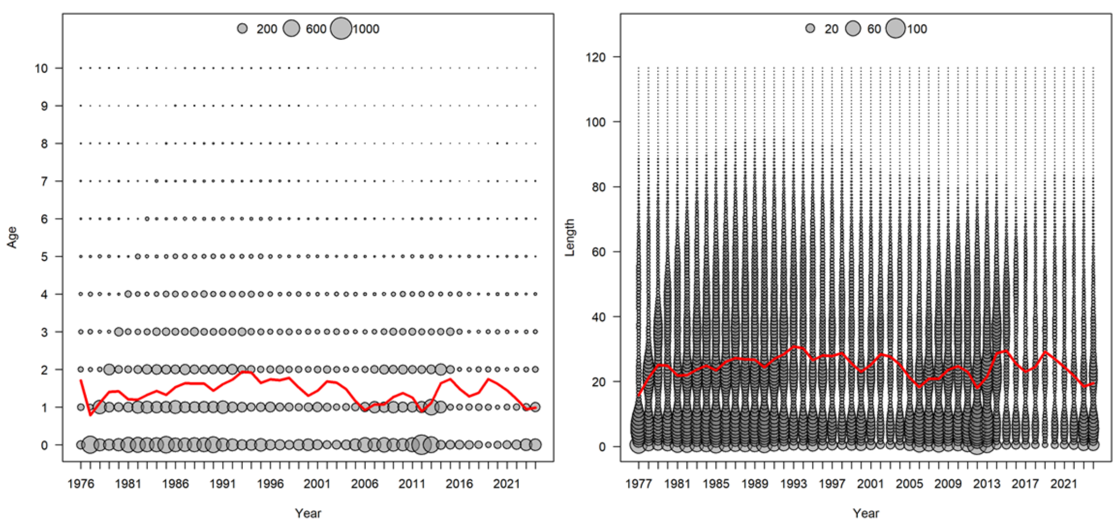

Figure 2.47. Predictions of middle of the year number at age (left) with mean age (red line) and number-at-length (right)with mean length (red line) from the author's recommended model.

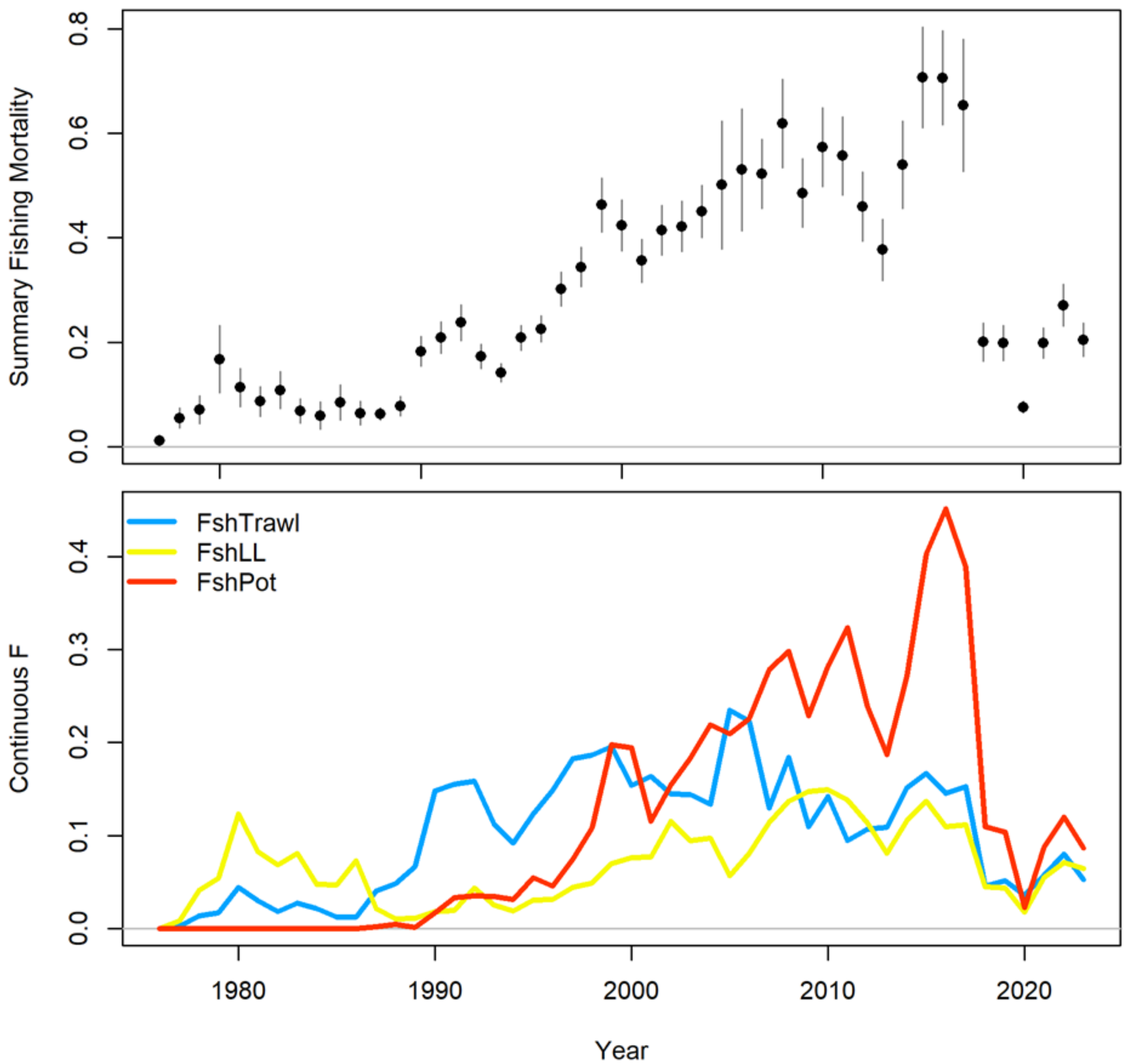

Figure 2.48. Sum of apical fishing mortality (top) and continuos fishing mortality by trawl (FshTrawl), longline (FshLL) and pot (FshPot) fisheries (bottom) from the author's recommended model.

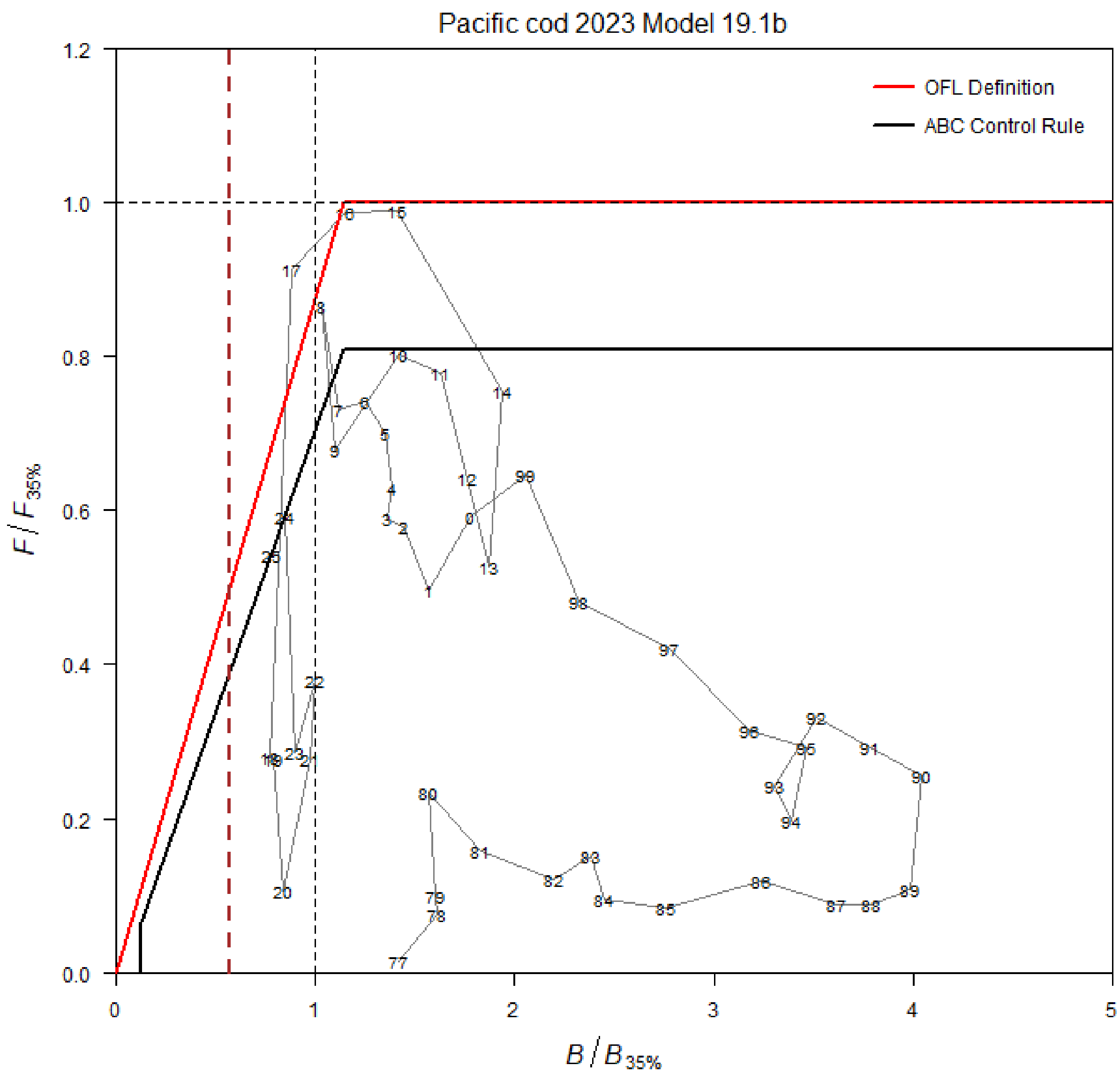

Figure 2.49. Ratio of historical $F/F_{35\%}$ versus female spawning biomass relative to $B_{35\%}$ for GOA pacific cod, 1977-2025 from the author's recommended model. The Fs presented are the sum of the full Fs across fleets. Dashed red line is at $B_{20\%}$, Steller sea lion closure rule for GOA Pacific cod.

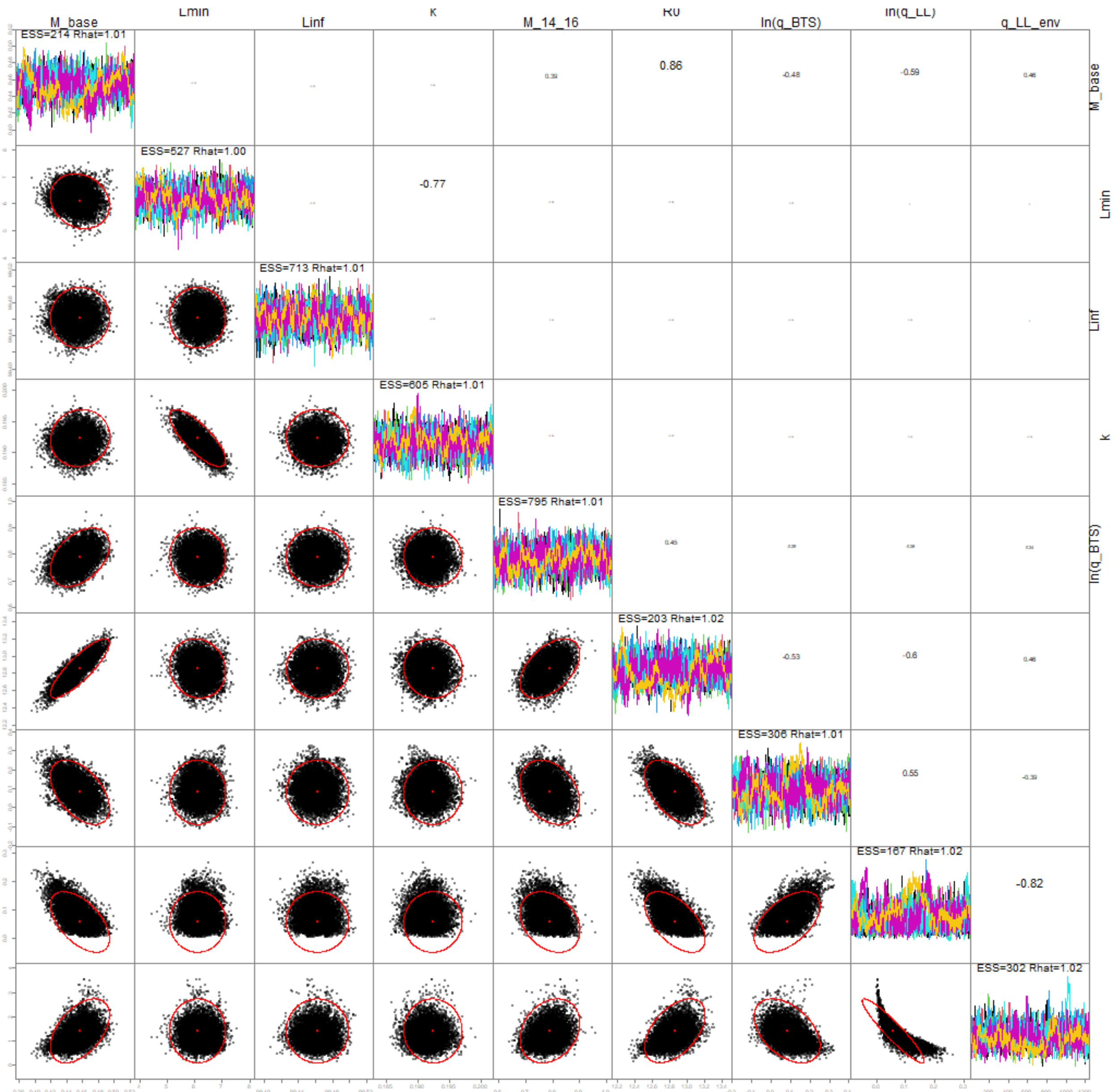

Figure 2.50. MCMC pairs plot of key model parameters, with diagnostics shown in the diagonal and parameter correlations shown in the top right.

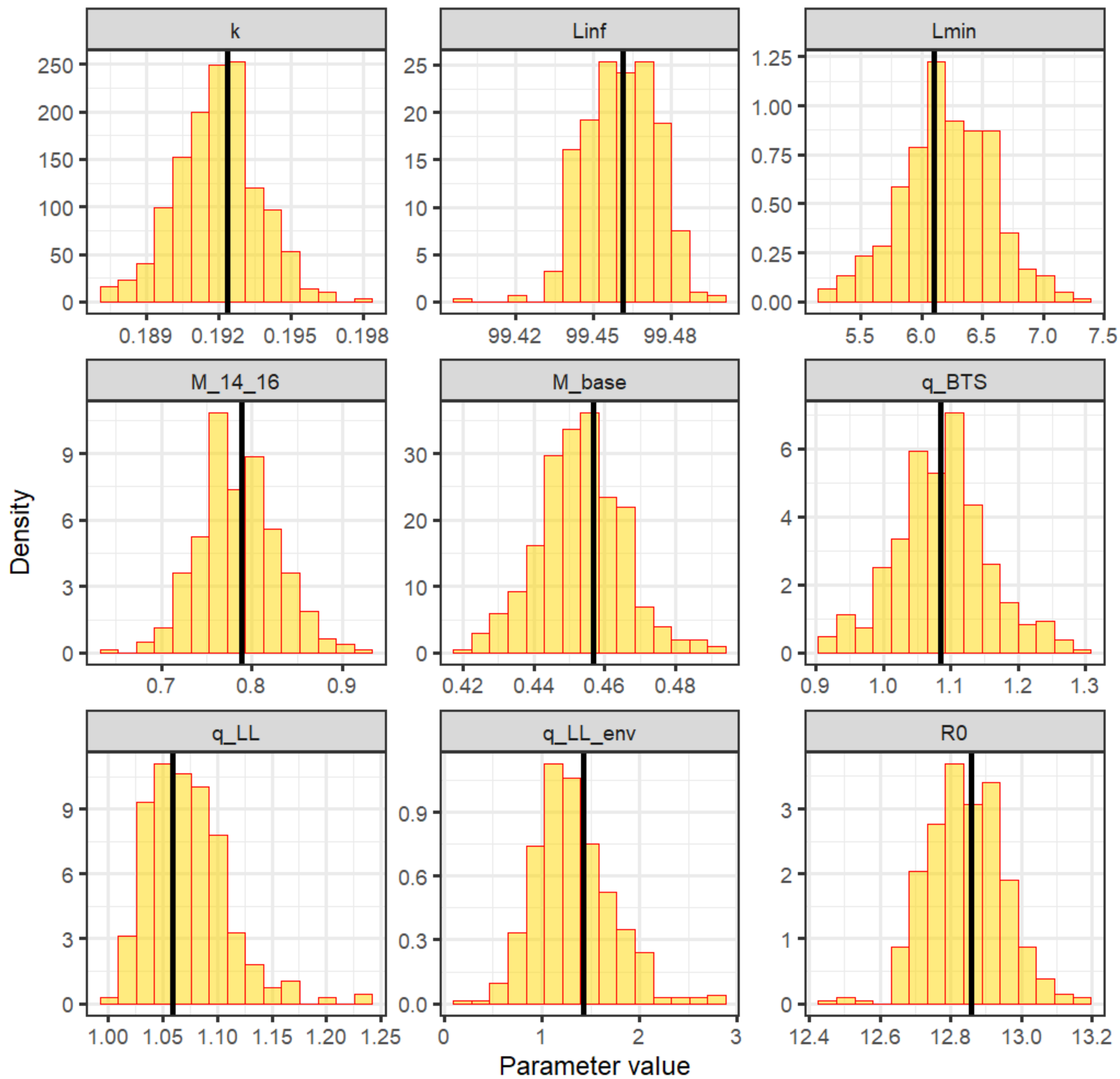

Figure 2.51. Histograms of MCMC draws for key parameters from the author's recommended model compared to MLE estimate (verticle black line).

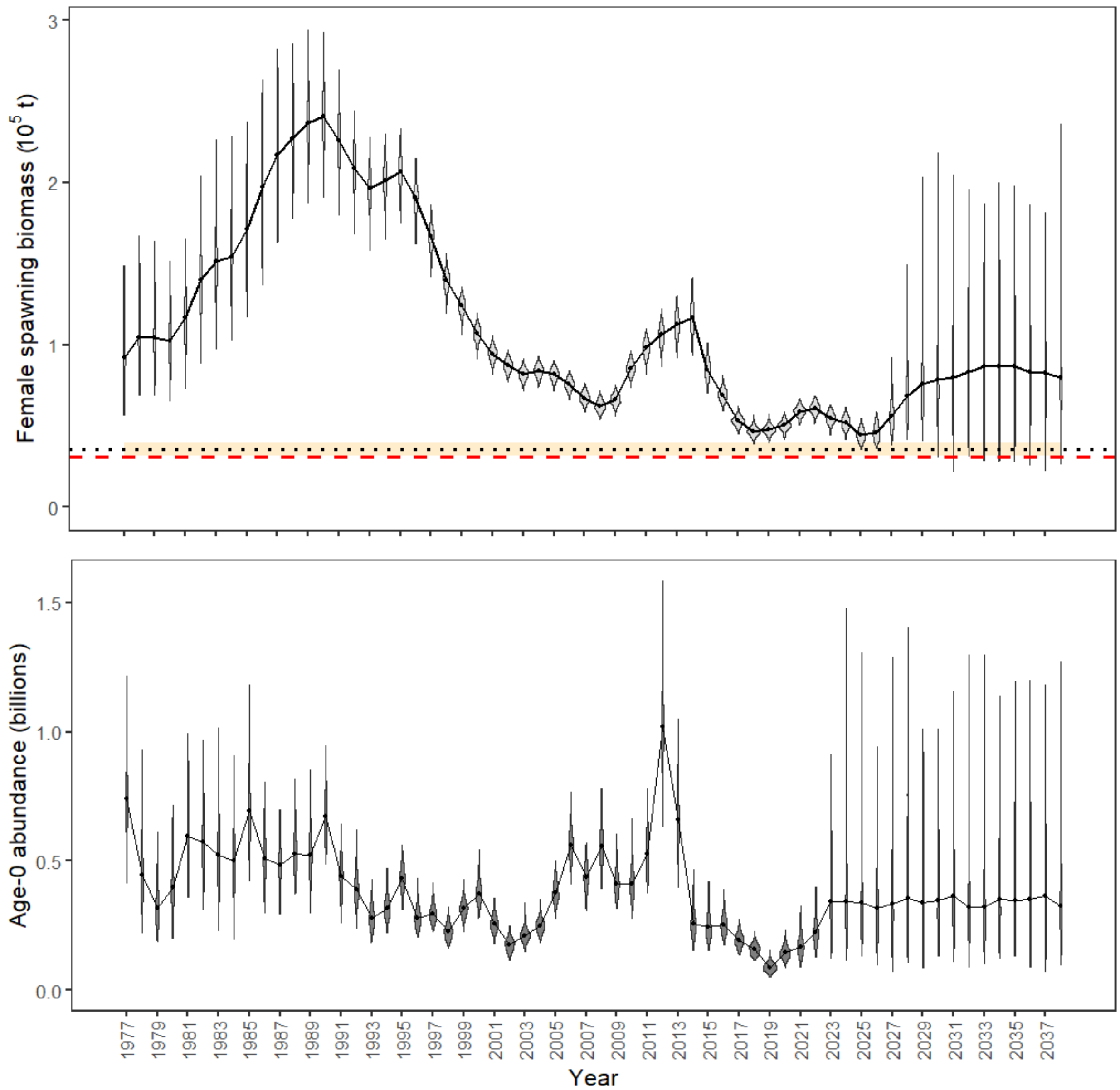

Figure 2.52. MCMC posterior distribitions of beginning of the year female spawning biomass (top) and age-0 abundance (bottom) from the author's recommended model. Dotted line is the projected $SSB_{20\%}$ with 95% confidence interval in orange and the red dashed line is $SSB_{17.5\%}$.

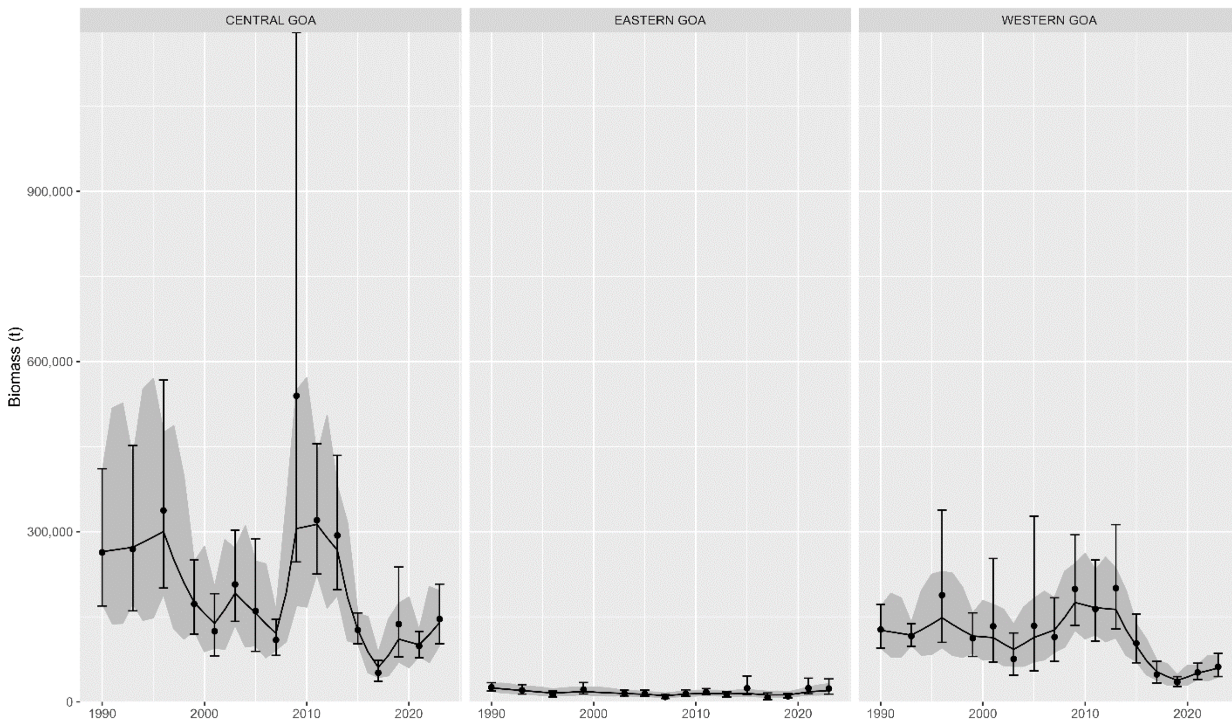

Figure 2.53. Random effects model results for the AFSC bottom trawl survey area used for area allocation.

Appendix 2.1 Ecosystem and Socioeconomic Profile of the Pacific cod stock in the Gulf of Alaska - Report Card

Appendix 2.2 Adjustment of conditional age-at-length minimum sample size

Introduction

In the process of compiling data for the 2023 assessment it was discovered that the minimum sample size for conditional age-at-length was set to 1 in the Stock Synthesis data file. This was because in version 3.24 of Stock Synthesis the minimum sample size for compositional data had a default value of 1 and this was never adjusted in subsequent versions of the data file for this assessment. In Stock Synthesis, the minimum sample size is the floor value of the input sample size applied in the multinomial likelihood for compositional data, including conditional age-at-length. In practice, if an input sample size for a particular set of compositional data were to be less than the minimum sample size, the input sample size is adjusted to be the minimum sample size in the data fitting step within Stock Synthesis. In this assessment the input sample size for conditional age-at-length data is set at the nominal sample size (the number of ages per length bin) multiplied by 0.14. This results in input sample sizes that are less than 1 for those length bins that have less than 8 age observations (which represents greater than 60% of the available conditional age-at-length data). Thus, in these cases these data have been weighted proportionally larger than was intended in model 19.1a and previous assessments. In this year's assessment we set the minimum sample size for conditional age-at-length to be 0.001, which then reduces the input sample size for conditional age-at-length data. To denote this change the recommended model this year will be denoted as Model 19.1b. We include this appendix to document this change, both in the model numbering but also in the model results.

Results

With the reduction in conditional age-at-length minimum sample size from 1 to 0.001 the total likelihood decreases, which is driven by a decrease in the conditional age-at-length likelihood component (Table 2.2.1). This decrease in the conditional age-at-length likelihood component is explained by the decrease in the input sample size for data that have an input sample size less than 1. There is an increase in the likelihood component for the survey indices fit, although, the difference is minor and nearly imperceptible visually (Fig. 2.2.1 and 2.2.2).Overall, recruitment (Fig. 2.2.3) and spawning biomass (Fig. 2.2.4) increase in Model 19.1b compared to 19.1a, with an average increase of around 5% in spawning biomass. In order to proportionally weight the conditional age-at-length in the manner it was intended, we recommend that the minimum sample size be set at 0.001 rather than 1. We note, that in future assessments the input sample size for composition data will be further evaluated.

Tables

Table 2.1.1. Likelihood components and derived quantities for Model 19.1a and 19.1b.

Likelihood component	Model 19.1a	Model 19.1b
TOTAL_like	4084.3	2931.0
Survey_like	-7.9	-3.3
Length_comp_like	1821.9	1817.9
Age_comp_like	2256.2	1102.0
Recruitment	-0.5	-0.5
InitEQ_Regime	3.1	3.1
Forecast_Recruitment	3.9	4.3
Parm_priors_like	1.2	1.0

Figures

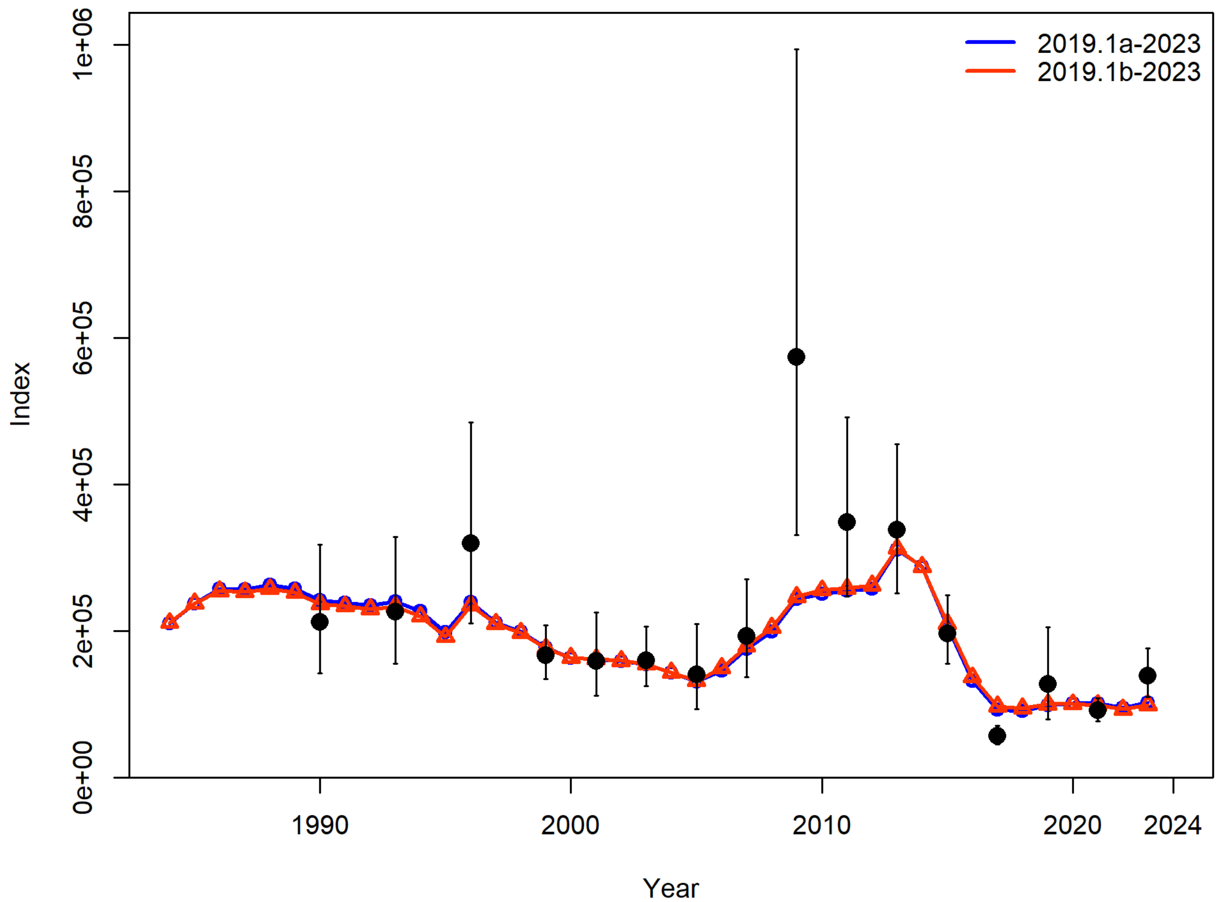

Figure 2.2.1. Model fits to bottom trawl survey numbers from Model 19.1a compared to Model 19.1b.

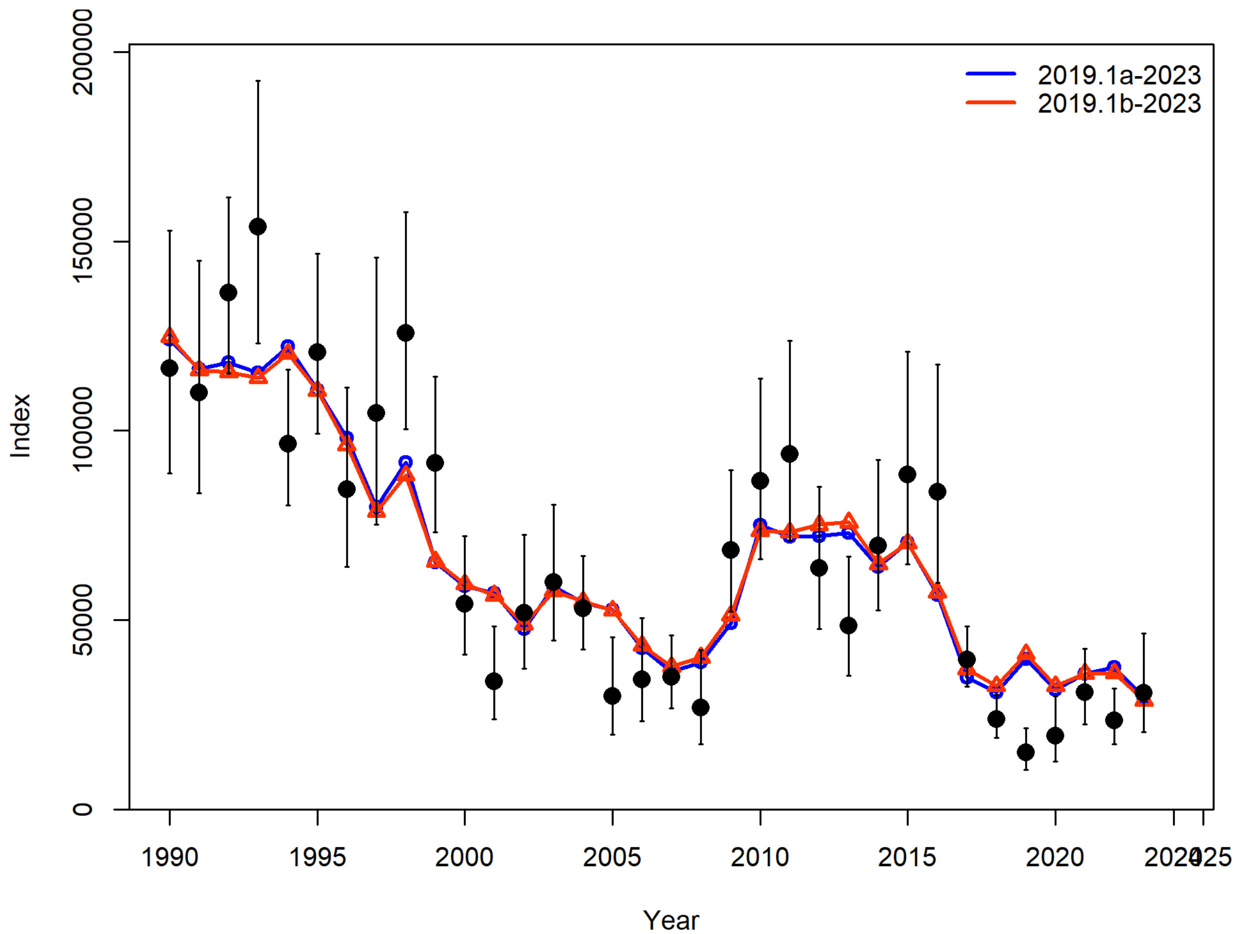

Figure 2.2.2. Model fits to longline survey RPNs from Model 19.1a compared to Model 19.1b.

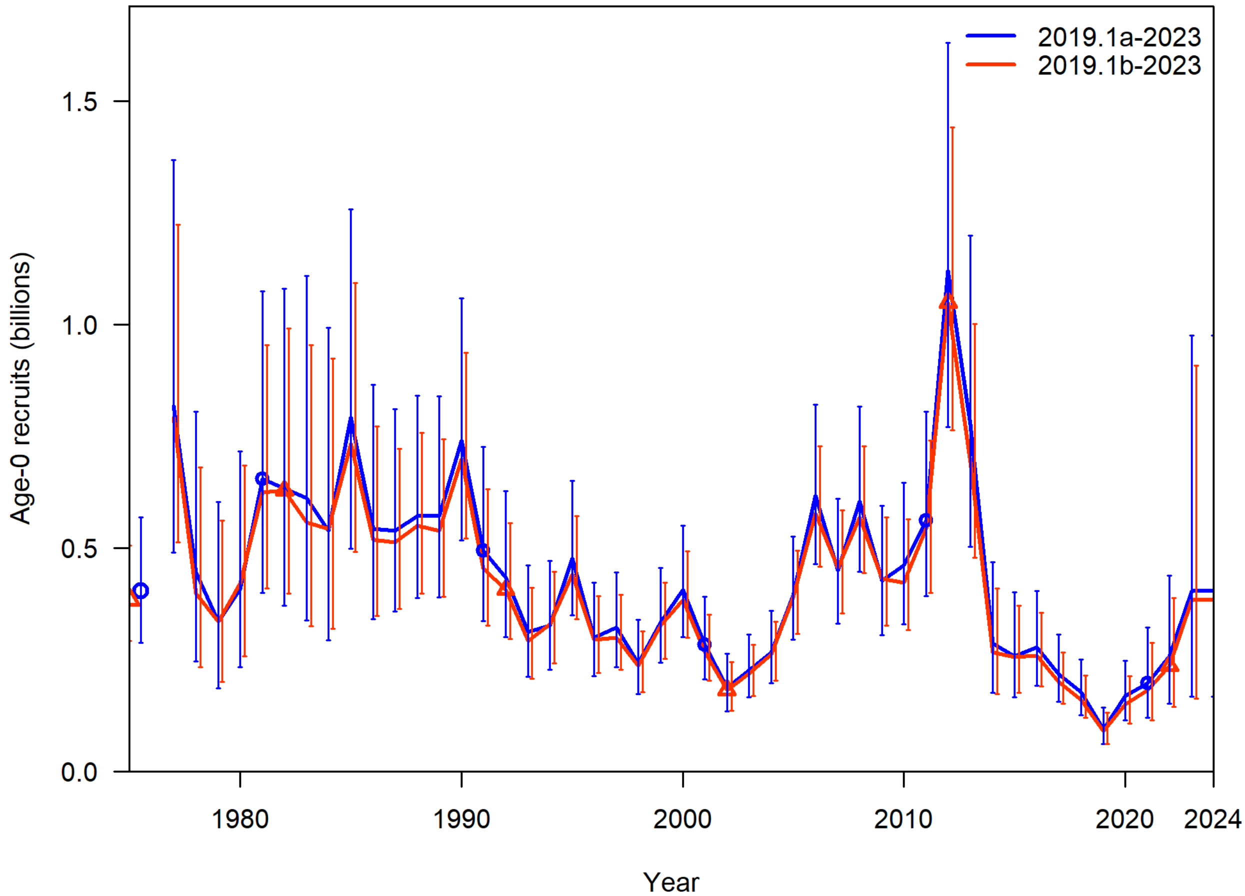

Figure 2.2.3. Estimated recruitment with 95% confidence intervals from Model 19.1a compared to Model 19.1b.

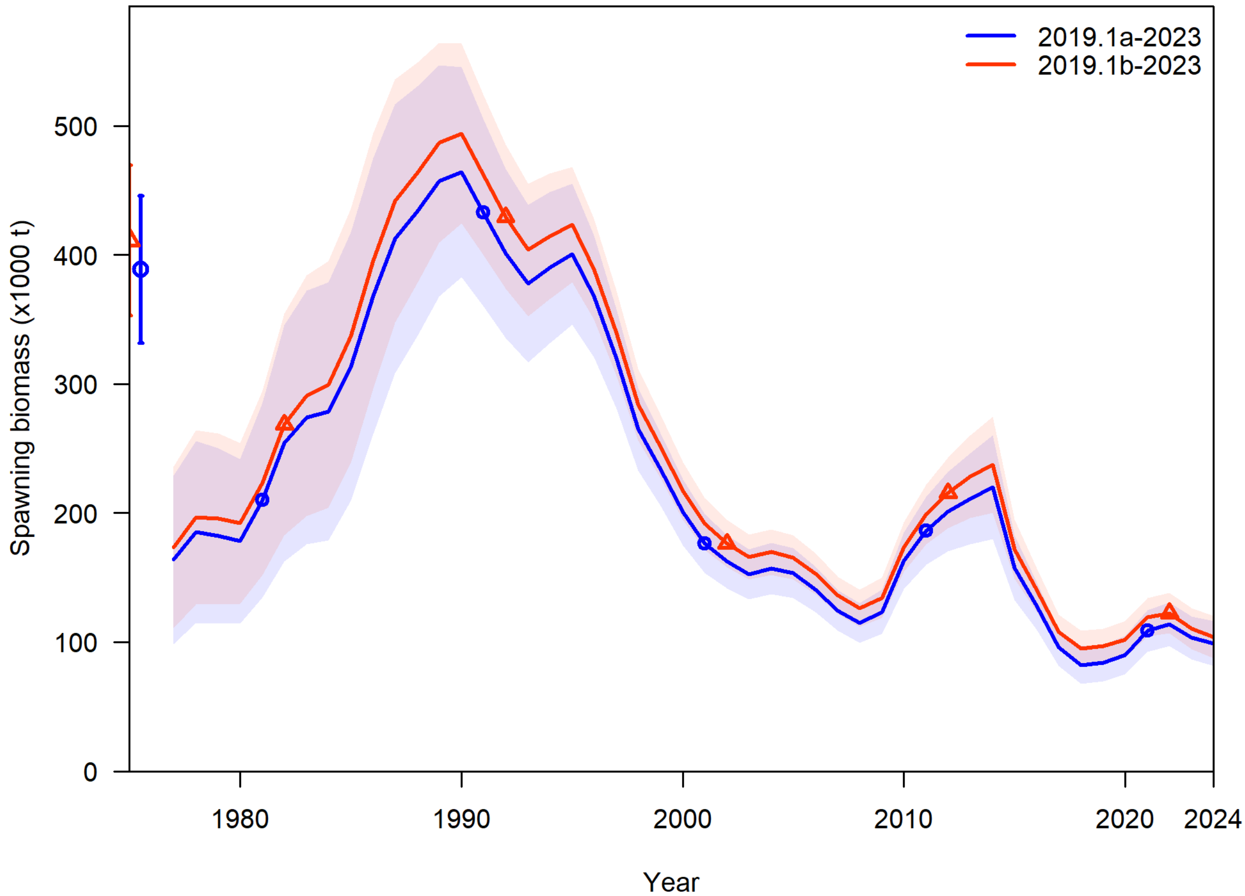

Figure 2.2.3. Estimated spawning biomass with 95% confidence bands (shaded regions) from Model 19.1a compared to Model 19.1b.