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

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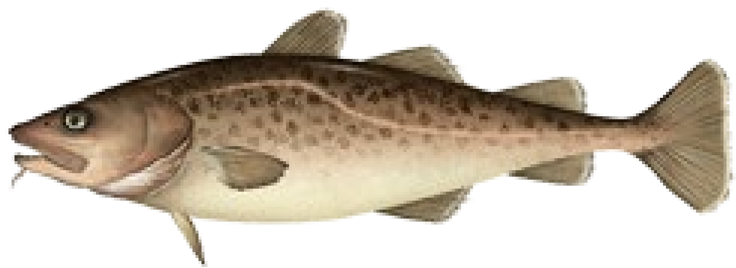
November 2022



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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, plots, and an excel spreadsheet), 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 2021 were updated and preliminary federal and state catch data for 2022 were included;
2. Commercial federal and state fishery size composition data for 2021 were updated, and preliminary commercial federal and state fishery size composition data for 2022 were included;
3. AFSC longline survey Pacific cod abundance index and length composition data for the GOA for 2022 were included;
4. AFSC bottom trawl survey conditional length-at-age data for 2021 were included;
5. Commercial federal conditional length-at-age data for 2021 were included;
6. Commercial state catch from 1997 – 2002 were added to the model's catch time series.

Changes in the methodology

The model used for 2022 (Model 19.1a) is last year's accepted model (Model 19.1) with the addition of new commercial state catch data described above. There were no other model changes made in this year's assessment.

Summary of Results

Model 19.1a indicates that the stock remains at low levels but that the stock remains above $B_{20\%}$; for 2023 the stock is estimated to be at $B_{25.5\%}$, less than $B_{40\%}$, placing it in sub-tier "b" of Tier 3. For the 2023 fishery, we recommend the maximum allowable ABC of 24,634 t. This ABC is a 25% decrease from the 2022 ABC of 32,811 t. This decrease is attributed to population declines as indicated by a 24% decline in the AFSC longline survey Relative Population Number index in 2022 compared to 2021, the only index of abundance that was updated in this year's assessment. The 2023 ABC is 14% smaller than the 2023 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: 2022	2023	As estimated or *specified this* year for: 2023	2024
M (natural mortality rate)	0.50	0.50	0.49*	0.49*
Tier	3b	3b	3b	3b
Projected total (age 0+) biomass (t)	178,961	199,841	163,477	193,510
Female spawning biomass (t)				
Projected	48,061	44,530	42,764	40,489
$B_{100\%}$	165,508	165,508	167,414	167,414
$B_{40\%}$	66,203	66,203	66,966	66,966
$B_{35\%}$	57,928	57,928	58,595	58,595
F_{OFL}	0.62	0.57	0.51	0.48
$maxF_{ABC}$	0.50	0.46	0.41	0.39
F_{ABC}	0.50	0.46	0.41	0.39
OFL (t)	39,555	34,673	**29,737**	27,507
maxABC (t)	32,811	28,708	24,634	22,683
ABC (t)	32,811	28,708	**24,634**	22,683
Status	As determined *last* year for: 2020	2021	As determined *this* year for: 2021	2022
Overfishing	No	n/a	No	n/a
Overfished	n/a	No	n/a	No
Approaching overfished	n/a	No	n/a	No

**Base natural mortality M varies between 0.49 and 0.84*
*** Assumed 2022 catch at the ABC, 32,811t . For 2024 projections the 2023 catch was assumed to be at the projected ABC.*

Area apportionment

Using the random effects model with the trawl survey biomass estimates through 2021, the area-apportioned ABCs are:

	Western	Central	Eastern	Total
Random effects area apportionment	30.3%	60.2%	9.5%	100%
2023 ABC	7,464	14,830	2,340	24,634
2024 ABC	6,873	13,655	2,155	22,683

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)

Apportionment in this assessment was not updated from last year's assessment because there was no new data to inform apportionments. However, in future assessments apportionment will be transitioned to the *rema* framework as well as investigations into including the AFSC longline survey as an additional index.

"*The Team recommends all GOA authors evaluate any bottom trawl survey information used in their assessment prior to 1990 including the 1984 and 1987 surveys and conduct sensitivity analyses to evaluate their usefulness to the assessment. This may apply for Aleutian Islands surveys but this was only raised during GOA assessment considerations."(GOA PT, Nov 2021).*

Model 19.1a does not use the 1984 or 1987 survey biomass estimates, age compositions, or length compositions but this information is reported in the SAFE document for informational purposes.

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 Dirichet-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 burnin, 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, Nov 2022)

As this is a transition year between senior authors, these comments are not addressed, but rather the accepted model from last year is used as this year's recommended model. To the extent possible and feasible given available data and whether the comments remain pertinent to future model alternatives explored, we will address these recommendations in future assessments.

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 March 2021 and 2022, 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. 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 March 2021, Pacific cod were tagged and released with 25 pop-up satellite tags and 957 conventional tags within 8 subareas of the western GOA near Shumagin and Sanak Islands in 2021 (Fig. 2.2). In April 2022, Pacific cod with 27 pop-up satellite tags were released along with 760 conventional tags in several of the same subareas as in 2021. 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. In 2021, pop-up locations of satellite tagged Pacific cod within 3 months of release were largely located within the vicinity of the release areas (March-May). However, more than half the fish with tags recovered between June through October (10 of 17 satellite-tagged fish with summer recovery locations) had moved substantial distances into the EBS, AI, northern Bering Sea (NBS), Russia, and the Chukchi Sea. These results contrasted with Pacific cod movement in 2022, where from June through October only 3 out of 23 satellite-tagged fish with summer recovery locations moved into the EBS (n=2) and NBS (n=1) and most fish stayed close to their original spawning areas. These movement patterns suggest seasonal connectivity between the western GOA and other management regions, such as the EBS, but with an unknown amount of interannual variability in these movement patterns. The research has also provided insights into resident vs. migratory fish. Some tagged fish are still at large with winter 2023 pop-up dates. Work is in progress to reconstruct movement paths of individual fish with a geolocation model which will provide valuable information on migration timing and pathways. Additional satellite and conventional tag releases are planned for March 2023.

Two genetics studies using Restriction-site Associated DNA sequencing have indicated significant genetic differentiation among spawning stocks of Pacific cod in the GOA and the EBS (Drinan *et al.* 2018; Spies *et al.* 2019). The most recent genomic analysis of Pacific cod includes a new publication that used pooled whole genome sequencing (Pool-Seq; Spies et al. 2022), as well as a new study conducted during 2021 and 2022 that used low coverage whole genome sequencing (lcWGS). Low-coverage whole-genome sequencing analysis of 429 samples of Pacific cod from known spawning regions during spawning season indicated population structure similar to what was previously known, but with finer resolution and greater power owing to the larger number of markers. Using 1,922,927 polymorphic SNPs (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 the zona pellucida gene region (Spies et al. 2021).

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 social processes (ESP) in the 2021 assessment (Barbeaux *et al.* 2021).

Fishery

Fishery history and management measures

During the two decades prior to passage of the Magnuson Fishery Conservation and Management Act (MFCMA) in 1976, the fishery for Pacific cod in the GOA was small, averaging around 3,000 t per year. Most of the catch during this period was taken by the foreign fleet, whose catches of Pacific cod were usually incidental to directed fisheries for other species. By 1976, catches had increased to 6,800 t. 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. Trawl gear took the largest share of the catch in every year but one from 1991-2002, although pot gear has taken the largest single-gear share of the catch in each year since 2003. 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. Changes in ABC over time are typically attributable to three factors: 1) changes in resource abundance, 2) changes in management strategy, and 3) changes in the stock assessment model. Assessments conducted prior to 1988 were based on survey biomass alone. From 1988-1993, the assessment was based on stock reduction analysis (Kimura *et al.* 1984). From 1994-2004, the assessment was conducted using the Stock Synthesis 1 modeling software (Methot 1986, 1990) with length-based data. The assessment was migrated to Stock Synthesis 2 (SS2) in 2005 (Methot 2005), at which time age-based data began to enter the assessment. Several changes have been made to the model within the SS2 framework (renamed “Stock Synthesis” or “SS3”, in 2008) each year since then.

For the first year of management under the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA, starting in 1977), the catch limit for GOA Pacific cod was established at slightly less than the 1976 total reported landings. During the period 1978-1981, catch limits varied between 34,800 and 70,000 t, settling at 60,000 t in 1982. Prior to 1981 these limits were assigned for “fishing years” rather than calendar years. In 1981 the catch limit was raised temporarily to 70,000 t and the fishing year was extended until December 31 to allow for a smooth transition to management based on calendar years, after which the catch limit returned to 60,000 t until 1986, when ABC began to be set on an annual basis. From 1986 (the first year in which an ABC was set) through 1996, TAC averaged about 83% of ABC and catch averaged about 81% of TAC. In 8 of those 11 years, TAC equaled ABC exactly. In 2 of those 11 years (1992 and 1996), catch exceeded TAC.

To understand the relationships between ABC, TAC, and catch for the period since 1997, it is important to understand that a substantial fishery for Pacific cod has been conducted during these years inside State of Alaska waters (Table 2.1), mostly in the Western and Central Regulatory Areas. To accommodate the State-managed fishery, the Federal TAC was set well below ABC (15-25% lower) in each of those years. Thus, although total (Federal plus State) catch has exceeded the Federal TAC in 16 of the 23 years since 1997, this is basically an artifact of the bi-jurisdictional nature of the fishery and is not evidence of overfishing as this would require exceeding OFL. At no time since the separate State waters fishery began in 1997 has total catch exceeded ABC, and total catch has never exceeded OFL.

Historically, the majority of the GOA catch has come from the Central regulatory area. To some extent the distribution of effort within the GOA is driven by regulation, as catch limits within this region have been apportioned by area throughout the history of management under the MFCMA. Changes in area-specific allocation between years have usually been traceable to changes in biomass distributions estimated by Alaska Fisheries Science Center (AFSC) trawl surveys or management responses to local concerns. Currently the area-specific ABC allocation is derived from the random effects model. 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.

In addition to area allocations, GOA Pacific cod is also allocated on the basis of processor component (inshore/offshore) and season. The inshore component is allocated 90% of the TAC and the remainder is allocated to the offshore component. Within the Central and Western Regulatory Areas, 60% of each component's portion of the TAC is allocated to the A season (January 1 through June 10) and the remainder is allocated to the B season (June 11 through December 31, although the B season directed fishery does not open until September 1).

NMFS has also published the following rule to implement Amendment 83 to the GOA Groundfish FMP:

> "Amendment 83 allocates the Pacific cod TAC in the Western and Central regulatory areas of the GOA among various gear and operational sectors, and eliminates inshore and offshore allocations in these two regulatory areas. These allocations apply to both annual and seasonal limits of Pacific cod for the applicable sectors. These apportionments are discussed in detail in a subsequent section of this rule. Amendment 83 is intended to reduce competition among sectors and to support stability in the Pacific cod fishery. The final rule implementing Amendment 83 limits access to the Federal Pacific cod TAC fisheries prosecuted in State of Alaska (State) waters adjacent to the Western and Central regulatory areas in the GOA, otherwise known as parallel fisheries. Amendment 83 does not change the existing annual Pacific cod TAC allocation between the inshore and offshore processing components in the Eastern regulatory area of the GOA.
>
> "In the Central GOA, NMFS must allocate the Pacific cod TAC between vessels using jig gear, catcher vessels (CVs) less than 50 feet (15.24 meters) length overall using hook-and-line gear, CVs equal to or greater than 50 feet (15.24 meters) length overall using hook-and-line gear, catcher/processors (C/Ps) using hook-and-line gear, CVs using trawl gear, C/Ps using trawl gear, and vessels using pot gear. In the Western GOA, NMFS must allocate the Pacific cod TAC between vessels using jig gear, CVs using hook-and-line gear, C/Ps using hook-and-line gear, CVs using trawl gear, and vessels using pot gear. Table 3 lists the proposed amounts of these seasonal allowances. For the Pacific cod sector splits and associated management measures to become effective in the GOA at the beginning of the 2012 fishing year, NMFS published a final

rule (76 FR 74670, December 1, 2011) and will revise the final 2012 harvest specifications (76 FR 11111, March 1, 2011)."

"NMFS proposes to calculate of the 2012 and 2013 Pacific cod TAC allocations in the following manner. First, the jig sector would receive 1.5 percent of the annual Pacific cod TAC in the Western GOA and 1.0 percent of the annual Pacific cod TAC in the Central GOA, as required by proposed § 679.20(c)(7). The jig sector annual allocation would further be apportioned between the A (60 percent) and B (40 percent) seasons as required by § 679.20(a)(12)(i). Should the jig sector harvest 90 percent or more of its allocation in a given area during the fishing year, then this allocation would increase by one percent in the subsequent fishing year, up to six percent of the annual TAC. NMFS proposes to allocate the remainder of the annual Pacific cod TAC based on gear type, operation type, and vessel length overall in the Western and Central GOA seasonally as required by proposed § 679.20(a)(12)(A) and (B)."

The longline and trawl fisheries are also associated with a Pacific halibut mortality limit which sometimes constrains the magnitude and timing of harvests taken by these two gear types.

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 historical distribution of catch from 1990-2015 for the three major gear types. Figure 2.6 shows the distribution of observed catch for the most recent year of catch data (2022) for the three major gear types, as well as the distinction between observed and electronic monitored catch. In the 1970's and early to mid-1980's the majority of Pacific cod catch in the Gulf of Alaska was taken by foreign vessels using longline. With the development of the domestic Gulf of Alaska trawl fleet in the late 1980's trawl vessels took an increasing share of Pacific cod and catch increased sharply to around 70,000 t throughout the 1990's. Although there had always been Pacific cod catch in crab pots, pots were first used to catch a measurable amount of Pacific cod in 1987. This sector initially comprised only a small portion of the catch, however by 1991 pots caught 14% of the total catch. Throughout the 1990s the share of the Pacific cod caught by pots steadily increased to more than a third of the catch by 2002 (Table 2.1 and Fig. 2.4). The portion of catch caught by the pot sector steeply increased in 2003 with incoming Steller sea lion regulations and halibut bycatch limiting trawl, and for 2003 through 2021 the pot sector caught on average 58% of the total catch of Pacific cod in the Gulf of Alaska annually.

In 2015 combined state and federal catch was 79,489t (23% below the ABC), while in 2016 combined catch was 64,087 t (35% below the ABC) and in 2017 catch was 48,734 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 15,247 t. For 2019 the ABC was set below the maximum ABC at 17,000 t and combined fishery caught 15,411 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 6,233 t was harvested (Table 2.1), the state having taken 2,318 t (91% of the GHL) and federal fisheries haven taken 3,916 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 2022 the federal TAC was set at 24,111 t and state GHL set at 8,700 t (Table 2.2). As of October 25, 2022 a total of 23,211 t (71% of the ABC) have been harvested (Table 2.1). State fisheries have harvested 6,998 t (80% of the GHL) and federal fisheries 16,219 t (67% of the TAC). In 2022 42% of the Pacific cod catch was by trawl, 29% by pot gear, and 28% by longline, while jig and other gear harvested less than 1% (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.

Longline

For 1990-2015 the longline fishery had been dispersed across the Central and Western GOA, and while the majority of longline catch was taken to the west of Kodiak, there was some longline fishing occurring in Barnabus trough and a small concentration of sets along the Seward Peninsula (Fig. 2.5). The 2017 longline fishery was 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 2018 and 2019, with the drastic cut in TAC, the fishery showed very little effort and the majority of catch was south of the Shumagin Islands straddling the Central and Western GOA management area edges. In 2020 there was no directed Pacific cod longline fishery in federal waters. In 2022 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 mean size of Pacific cod caught in the longline fishery is 64 cm (annual mean varies from 58cm to 70cm, 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 been more variable over 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 37 in 2021 and 31 in 2022. There were only 3 longline vessels fishing Pacific cod in the Western GOA in 2022, up from 1 in 2021 and none in 2020.

In both the Central and Western GOA catch in 2022 was similar to 2021 and was earlier than in 2018 or 2019, but like those years the A-season was completed by week 10 (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 in the last three years, 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 2022 the majority of catch from the pot fishery was centered around Kodiak (Fig. 2.6). The pot fishery in the Central GOA moved to deeper water in 2017 through 2019 compared to previous years, and this trend continues (Fig. 2.11). 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 in the last three years. 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.

The pot fishery generally catches fish greater than 40 cm (Fig. 2.12), 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 60cm on average caught during the 2016 fishery. The 2017 through 2021 fishery data show a sharp increase in mean length, and in 2022 the mean length was significantly larger than any other mean length in the pot fishery time series. This is potentially due to a combination of the fishery moving to deeper water (Fig. 2.11) and lower recruitment since 2014. However, it could also be driven by lack of length frequency sampling in the pot fishery, particularly in the Western GOA (Fig. 2.13).

In the Western GOA, approximately half the catch of the pot fishery was caught in a single week in March (Fig. 2.9). In the Central GOA the pot fishery increased in the spring at a higher rate than that since 2018 (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. In 2020 there was no observer coverage and since 2021 there has been little observer coverage of the pot fishery in the Western GOA (Fig. 2.12) despite substantial participation and catch. There was, however, biological data collected from the Western GOA region by the ADF&G port samplers which were incorporated into the stock assessment as a supplement to the observer data.

Trawl

The Gulf of Alaska Pacific cod trawl fishery rapidly developed starting in 1987, surpassing the catch from the foreign longline fishery (pursued in the 1970's to mid-1980s) in 1987. The trawl fishery dominated the catch into the early-2000s, but was then replaced by increases in pot fishing in the mid-2000's. This transition to pot fishing was partially due to Steller sea lion regulations, halibut bycatch caps, and development of an State of Alaska managed fishery. The distribution of catch from the trawl fishery for 1990-2015 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 2022, 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 2022 have exceeded catches since 2018 (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, particularly in the Central GOA (Fig. 2.13 and Fig. 2.14). 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 years 2005 and 2006 shows little observed fishing in the B-season when smaller fish are more often encountered with this gear type. The mean size shows a sharp increase in 2016 through 2022 (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. The change to deeper depth and variable sampling rates between the Central and Western GOA might partially explain this recent increase (Fig. 2.11 and Fig. 2.13) as well as lower recruitment in recent years leading to a larger overall population on average as older fish make up higher percentage of the population age structure.

The 2018-2019 directed A-season trawl fishery in the Central GOA started much later than previous years, and catch rates were lower and the fishery did not take the full TAC (Fig. 2.10). Since 2018, despite there being 14 to 26 vessels participating in the Western GOA trawl fishery, there was no observed effort from 2018 – 2020 and little observed effort compared to other fisheries (Fig. 2.11). There were no vessels participating in the directed Pacific cod fishery in the Central GOA for 2018-2020 and only 2 vessels in 2021 and 6 in 2022 (Fig. 2.8).

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). In 2017 there were 35 jig vessels participating in the GOA Pacific cod fishery, 27 in 2018, 61 vessels in 2019, 41 vessels in 2020, a sharp increase in 2021 to 65 vessels, and a decrease to 46 vessels in 2022 (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 2018, 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 considered to be relatively small at less than 400 t; data are available through 2021 (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

There is a long history of evaluating the health of a stock by its condition which examines changes in the weight to length relationship (Nash *et al.* 2006). Condition is measured in this document as the deviance from a log linear regression on weight by length for all Pacific cod A season (January-March) fishery data for 1999-2022. There is some variability in the length to weight relationships between Pacific cod captured in the Central and Western GOA fisheries and among gear types. However, there is a consistent trend in both areas for Pacific cod captured using longline and pot gear with lower condition during 2015-2016 (Fig. 2.15 and Fig. 2.16). In 2018 and 2019, where data are available the condition of fish in both the Central and Western GOA are mixed with differences in condition by gear and season. The Central GOA longline fishery shows improving condition in January through March in 2018 through 2021, but then a decrease in condition in 2022. The Central GOA pot fishery shows improvement in 2018 as well, but there were no data available since 2019. In the Western GOA, longline fishery cod condition in 2019 returned to average, increased in 2021, and was again average in 2022. The Western GOA pot fishery shows improved cod condition in 2017 and 2018 following the heatwave, drops to below average in 2019, and above average in 2022. There were no data for 2019-2021 to evaluate condition in the Western GOA pot fishery.

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. 2.17). 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. 2.18). For the walleye pollock fishery in areas 620 and 630 of the Central GOA, the 2022 value was low in 620, but increased in 630. The catch of Pacific cod in the shallow water flatfish fisheries was the lowest in 2017 with a generally increasing trend since. 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 – 2022 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 19.1a 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 2.19 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	AKFIN	metric tons	1977 – **2022**
Federal and state fishery catch-at-length, by gear type	AKFIN / FMA / ADF&G	number, by cm bin	1977 – **2022**
GOA NMFS bottom trawl survey biomass	AFSC	metric tons	1990 – 2021
AFSC Sablefish Longline survey Pacific cod Relative Population Numbers	AFSC	RPN	1990 – **2022**
GOA NMFS bottom trawl survey length composition	AFSC	number, by cm bin	1990 – 2021
GOA NMFS bottom trawl survey conditional age-at-length	AFSC	mean value and number	1990 – **2021**
AFSC Sablefish Longline survey Pacific Cod length composition	AFSC	number, by cm bin	1990 – **2022**
Federal fishery conditional age-at-length	AFSC	proportion age at length	2007 – **2021**
CFSR bottom temperature indices	National Center for Atmospheric Research	temperature anomaly at mean depth for P. cod size bins 10 cm and 40 cm.	1979 – **2022**

Fishery:

Catch Biomass

Catches for the period 1991-2022 are shown for the three main gear types in Table 2.1, with the catches for 2022 presented through October 25, 2022. 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 the first half of 2022. 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.

Addition of ADFG port sampling for pot, jig, and longline fishery length data

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 2021 survey was conducted with two chartered vessels that accomplished 529 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 2021 survey likely captured the trend and magnitude of the cod abundance in the GOA. The 2021 survey covered all strata; regions, and shelf, gully, and upper slope habitats to 700 m. The coefficient of variation of the biomass estimate was 8.7% and was lower than the historic average of 17.2%. The 2021 survey design was comparable to the 2013, 2017, and 2019 surveys that were also conducted with two vessels and achieved 547, 534, and 541 stations, respectively.

The spatial distribution of Pacific cod in the survey has been highly variable (Fig. 2.20) with inconsistent peaks in CPUE. In 2017 the survey had the lowest average density of the time series, but also no high density peaks in CPUE were observed in any survey station. There were some higher than average densities for the 2017 survey located along the Alaska Peninsula and south of Unimak island, but for the most part CPUE was universally low throughout the Gulf of Alaska. 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.

Biomass and abundance estimates

The Pacific cod biomass estimates from the bottom trawl survey are highly variable between survey years (Table 2.9 and Fig. 2.21). 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 and drop in 2021. 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 (90,914,000) was the second lowest in the time series (41% of the time series mean), next only to the 2017 estimate. The 2021 abundance estimate was 73% lower than the 2013 estimate (337,992,000) and 28% lower than the 2019 estimate (127,118,000). The 2021 biomass estimate was only 4% lower than the 2019 biomass estimate and 62% higher than the 2017 biomass estimate. The 2021 biomass and abundance estimate were within the 95% confidence intervals of the 2019 survey estimates.

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 1984-2005 excepting the 1997 and 2001 surveys (Fig. 2.22). 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, but then increased again in 2021. The average length of fish for 2007-2021 remains below the 1984-2005 overall average.

Age Composition

Age compositions and conditional length at age from 1990-2021 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 paper Stark (2007) 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.

Abundance index

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 2.21). Details about these data and a description of the methods for the AFSC sablefish longline survey can be found in Hanselman *et al.* (2016) and Echave *et al.* (2012). 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%.

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. 2.23) and then a generally increasing mean size from 2015-2022. 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 2006-2021 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). 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 and 2021 with larger recruitment in 2017, 2018, 2020, and 2022 (Table 2.11 and Fig. 2.24).

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 (Table 2.12 and Fig. 2.25). 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 2022. 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 1988-2022. 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 (Table 2.13 and Fig. 2.25). 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. 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 survey.

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 10 cm and 40 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 1979-2020 (Table 2.14 and Fig. 2.26).

The mean depth of Pacific cod at 0-20 cm and 40-60 cm was found to be 47.9 m and 103.4 m in the Central GOA and 41.9 m and 64.07 m in the Western GOA. The temperatures of the 0-20 cm and 40-60 cm Pacific cod in the CFSR indices are highly correlated (R^2 = 0.89). The shallower index is more variable ($CV_{0\text{-}20\ cm}$ = 12% vs. $CV_{40\text{-}60cm}$= 8%). There are high peaks in water temperature in 1981, 1987, 1998, 2015, 2016 and 2019 with 2019 being the highest in both the 0-10 cm and 40-60 cm indices. 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 and in the 40-60 cm index in 2012. The trend is insignificant for both indices. In 2020 and 2021 the temperatures at both the 0-20 and 40-60 are below the time series mean with 2021 being within 1% of the 2020 temperatures. In 2022 for both 0-20 and 40-60 the temperatures were above the time series mean.

Sum of annual marine heatwave cumulative intensity index (MHWCI)

The daily sea surface temperatures for 1981 through October 2021 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 (Fig. 2.27). 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 2.14), 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. 2.27). 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 2022 remained cool or near average, with no heatwave says during the winter or spawning season.

Analytic Approach

General Model Structure

This year we present the accepted model from last year, Model 19.1, with updated data. We denote a new model number, Model 19.1a, to note the 1997 – 2002 State GHL harvest that were omitted from previous assessments but is now included in the current assessment (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 were run in Stock Synthesis version 3.30.18 (Methot and Wetzell 2013).

Model 19.1a 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 length at age 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 2015, giving the following values:

	Value
α:	5.631×10^{-6}
β:	3.1306
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 SS 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 2.15).

Natural Mortality

In the 1993 BSAI Pacific cod assessment (Thompson and Methot 1993), the natural mortality rate *M* was estimated to be 0.37. All subsequent assessments of the BSAI and GOA Pacific cod stocks (except the 1995 GOA assessment) have used this value for *M*, until the 2007 assessments, at which time the BSAI assessment adopted a value of 0.34 and the GOA assessment adopted a value of 0.38. Both of these were accepted by the respective Plan Teams and the SSC. The new values were based on Equation 7 of Jensen (1996) and ages at 50% maturity reported by Stark (2007; see “Maturity” subsection below). In response to a request from the SSC, the 2008 BSAI assessment included further discussion and justification for these values.

For the 2016 reference model (Model 16.08.25) *M* was estimated using a normal prior with a mean of 0.38 and CV of 0.1. In 2017 Dr. Thompson presented a new natural mortality prior based on a literature search (Table 2.16) for the Bering Sea stock assessment (Thompson 2017). For the Gulf of Alaska stock, we used the same methodology and literature search to devise a new prior for M. This resulted in a lognormal prior on M of -0.81 (μ=0.44) with a standard deviation of 0.41 for the Gulf of Alaska Pacific cod.

In 2017 it was hypothesized that due to the drop in all available survey indices between 2013 and 2017 it was suspected that there was an increase in natural mortality during the height of the 2014-2016 marine heatwave. The 2017 reference model, Model 17.09.35 used a block for 2015-2016 where M could be fit separately from all other years. In consideration of the marine heatwave analysis, models in 2018 expanded the natural mortality block to 2014-2016. For this $M_{standard}$ is fit separate from $M_{2014\text{-}2016}$ with a lognormal prior of log(μ) = -0.81 and σ of either 0.1 or 0.41. The σ of 0.41 was based on a reevaluation of the data presented by Dr. Thompson described above and in Table 2.16, but limited to not include data from the Gulf of Alaska used in the current model.

Natural mortality in the Model 19.1a were fit for two time blocks, 2014-2016 and all other years, as a single non-varying parameter for all ages for each block.

Growth

For Model 19.1a 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 19.1a 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-2021 assumed average recruitment for 1977-2021 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 19.1a:

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 19.1a 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 bias

For Model 19.1a aging 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 19.1a 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:

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

where $\bar{Q}$ was the mean catchability for the AFSC longline survey for 1977 through 2022,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. 2.26). 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 19.1a 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 19.1a 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 and Age Composition Data in Parameter Estimation

Previous explorations using the Dirichlet-multinomial configuration resulted in a recommendation of no change to the input weighting, therefore the model presented this year uses the same weighting as previous years. 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 last year, we set initial sample sizes for the fishery at the number of hauls sampled or 200 whichever is least, for the surveys both size and age composition sample sizes were set at 100.

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 2.17. Likelihoods by fleet are provided in Table 2.18. Retrospective results are presented in Figure 2.28 and 2.29. There is little to no retrospective pattern in spawning biomass (Mohn's rho of -0.032, Fig. 2.28), but a positive retrospective pattern resulted for recruitment (Mohn's rho of 1.4). A positive Mohn's rho indicates that as subsequent years of data are added to the model the estimates of recruitment decrease. This pattern is shown in Figure 2.29, which shows, in particular, that as the 2022 data was added to the model the estimates of recruitment decreased compared to 2021 for all recent year classes (since 2000), it also shows that this is generally the trend across assessment years. Model 19.1a performed reasonably well in a jitter analysis with a CV of 0.05 and 50 runs with a total of 45 of the 50 jitter runs converged with 78% of the converged models resulting in estimates at the lowest MLE from the accepted models. Leave-one-out (LOO) results are presented in Table 2.19 and Figures 2.30 and 2.31. 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 bias, i.e. was there a direction of change when data were removed from the complete models, and the variability of the variance estimates as data were removed. Model 19.1a resulted in relatively low bias across all examined parameters and derived quantities (Table 2.19). The highest bias was observed in the forecasted ABC, which remained below 3%. In Model 19.1a the removal of data after 2014 resulted in increased variability in model estimates, with the removal of the 2022 and 2018 data being most impactful on the forecasted spawning biomass and ABC (Fig. 2.30). In 2018 there was no trawl survey, but from 2017 to 2019 the two surveys fit exhibit opposite trends, with the longline survey decreasing and the trawl survey increasing. Removing the 2022 data (for which the only index data available is from the longline survey, which remained low) caused a sharp increase in spawning biomass and ABC for 2023. Without the 2022 data Model 19.1a was expecting a higher abundance in 2022 than observed in the 2022 indices and thus higher biomass estimates for 2023. Removing one data point (i.e., that was updated since last year's assessment) at a time showed that the longline survey index is the most influential on forecasted spawning biomass and ABC (Fig. 2.30).

Model 19.1a 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 19.1a presented this year is well within the bounds of models presented in previous years for the spawning stock biomass time series (Fig. 2.32). Model 19.1a 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 2.33 – 2.48. While Model 19.1a fits the bottom trawl survey abundance reasonably well it should be noted that positive residuals have resulted in the fit to the longline survey in 4 of the 5 years since 2018, that is, that the model's estimates of RPNs were larger than the observed values (Fig. 2.33). Overall, Model 19.1a yields reasonable results and we continue to use it to recommend the 2023 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 19.1a.

Biomass

Total biomass estimates show a long decline from their peak in 1988 (Table 2.20 and Fig. 2.34) 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 2022. Spawning biomass (Table 2.20 and Figure 2.32) 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 19.1a (Table 2.21, Fig. 2.49, and Fig. 2.53) 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 2.50. 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 2.22). 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. 2.51). 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. 2.52) 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 $B_{35\%}$ in 2017 and 2022, and projected to continue to be below through 2024. 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 1,000,000 iterations with 10,000 burn-in and thinned to every 2000th iteration leaving 490 iterations for constructing the posterior distributions. Geweke (1992) and Heidelberger and Welch (1983) MCMC convergence tests, as implemented in the *coda* R library (Plummer *et al.* 2006), concluded adequate convergence in the chain. Posterior distributions of key parameters appear well defined and bracket the MLE estimates (Fig. 2.53). Model 19.1a predicts a < 0.1% probability the stock was below $B_{20\%}$ or $B_{17.5\%}$ in 2022 and projects a < 0.5% probability of the stock being below $B_{20\%}$ or $B_{17.5\%}$ in 2023 (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 19.1a:

Reference point:	$B_{35\%}$	$B_{40\%}$	$B_{100\%}$
Spawning biomass:	58,595 t	66,966 t	167,414 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 (2017-2021). This apportionment of catch given the projected selectivity for each gear results in estimates of $F_{35\%}$ and $F_{40\%}$ of 0.82 and 0.66 in aggregate.

Specification of OFL and Maximum Permissible ABC

For Model 19.1a spawning biomass for 2023 is estimated by this year's model to be 42,764 t at spawning. This is below the $B_{40\%}$ value of 66,966 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 2023 and 2024 as follows (2024 values are predicated on the assumption of the full TAC and GHL being taken in 2022 and that the 2023 catch will be at maximum ABC in the projection):

Units	Year	Overfishing Level (OFL)	Maximum Permissible ABC
Harvest amount	2023	29,737	24,634
Harvest amount	2024	27,507	22,683
Fishing mortality rate	2023	0.51	0.41
Fishing mortality rate	2024	0.48	0.39

The age 0+ biomass projections for 2023 and 2024 from this year's model are 163,477 t and 193,510 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: Normal	Typical to moderately increased uncertainty/minor unresolved issues in assessment.	Stock trends are typical for the stock; recent recruitment is within normal range.	No apparent environmental/ecosystem concerns	No apparent fishery/resource-use performance and/or behavior concerns
Level 2: Substantially increased concerns	Substantially increased assessment uncertainty/ unresolved issues.	Stock trends are unusual; abundance increasing or decreasing faster than has been seen recently, or recruitment pattern is atypical.	Some indicators showing adverse signals relevant to the stock but the pattern is not consistent across all indicators.	Some indicators showing adverse signals but the pattern is not consistent across all indicators
Level 3: Major Concern	Major problems with the stock assessment; very poor fits to data; high level of uncertainty; strong retrospective bias.	Stock trends are highly unusual; very rapid changes in stock abundance, or highly atypical recruitment patterns.	Multiple indicators showing consistent adverse signals a) across the same trophic level as the stock, and/or b) up or down trophic levels (i.e., predators and prey of the stock)	Multiple indicators showing consistent adverse signals a) across different sectors, and/or b) different gear types
Level 4: Extreme concern	Severe problems with the stock assessment; severe retrospective bias. Assessment considered unreliable.	Stock trends are unprecedented; More rapid changes in stock abundance than have ever been seen previously, or a very long stretch of poor recruitment compared to previous patterns.	Extreme anomalies in multiple ecosystem indicators that are highly likely to impact the stock; Potential for cascading effects on other ecosystem components	Extreme anomalies in multiple performance indicators that are highly likely to impact the stock

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

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

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

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

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

Assessment considerations.

The GOA Pacific cod assessment does not show a strong retrospective bias in recent estimates of spawning biomass, either in the data retrospective (Fig. 2.28) or in the model retrospective across recent assessments (Fig. 2.32). However, a strong retrospective bias in recruitment estimates exist. As subsequent years of data were added to Model 19.1a in the data retrospective analysis, the estimates of recent year classes persistently decreased (Fig. 2.29). 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 2.21). While Model 19.1a fits the size composition data and bottom trawl survey abundance index reasonably well, in the last 4 of 5 years Model 19.1a has predicted larger RPNs than have been observed in the AFSC longline survey. 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 19.1a has estimated below average recruitment since 2014 for the last 8 years of the assessment. Thus, it is likely that the average recruitment value used for each year of the projections is larger than what the realized recruitment will be (and 122% larger than the average recent recruitment over the last 8 years). Therefore, given that the model is overestimating recent recruitment 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 rated the assessment considerations category as level 2, substantially increased concerns. If the recruitment retrospective pattern and the below average recruitment trend persists, the assessment related risk table score will likely be raised to a level 3 in future GOA Pacific cod SAFE documents .

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 from 1977 – 2021) 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 and 2019. 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, indicating that above average recent year classes are not being observed in the fishery or survey age and length composition data. Because of the persistent low levels of spawning biomass and below average recruitment, we rate the population dynamics considerations category at level 2, substantially increased concern. If the population remains at low levels without any indication of improved recent recruitment, this concern will rise to a level 3 in future GOA Pacific cod SAFE documents.

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 and Zador, 2022). The text below summarizes ecosystem information related to GOA Pacific cod provided from both the ESP and GOA ESR.

We scored this category as level 1 (normal concern) for Pacific cod given thermal conditions for adults and larvae within known thermal ranges, above average adult and juvenile cod prey base and condition indices, and potentially unchanged, low levels of predation and competition, with exception of competition from recent large year classes of sablefish. The GOA population persists at low levels since the 2014-2016 and 2019 marine heatwave periods. The 2020 year class was observed in high numbers as age-1s in 2021 surveys, and environmental conditions remain cautiously favorable for them to persist. The 2022 year class has mixed signals for success, with cooler ocean temperatures in the early spring but warm summer and fall temperatures during a period essential to overwinter survival, and an above average prey base.

Environmental Processes: Thermal conditions for 2022 and predicted 2023 are within known optimal ranges for Pacific cod life history stages: spawning (20m - 290m, 1°C - 7°C), egg (20m - 200m, 3°C - 6°C), larvae (0m - 45m, 5°C - 6°C). Spring temperatures at depth were cooler than average (Seward Line, Danielson 2022) and there were no heatwave events during the spawning period (Appendix 2.1: Spawning Heatwave GOA Model by S. Barbeaux), which are beneficial to spawning conditions. However, summer bottom temperatures were above average in the central GOA (47.9 m and 103.4 m) and western GOA (41.9 m and 64.07 m) (Appendix 2.1: Summer Temperature Bottom GOA Model by M. Wang), in alignment with above average bottom temperatures at the shelf edge (longline survey, Siwicke 2022), along the Seward Line (Seward Line survey, Danielson and Hopcroft 2022) and off Kodiak (ADF&G, Worton 2022). Warm summer temperatures at depth can potentially adversely influence adult growth and feeding conditions. However, the habitat suitability index developed at GAK 1 of the Seward line was above average suggesting suitable habitat for Pacific cod (Appendix 2.1: Winter Spring Pacific Cod Spawning Habitat Suitability GAK1 Model by L. Rogers). Fall surface temperatures continue to be above average (Satellite, Lemagie and Callahan 2022), at a time critical to overwinter survival of age-0 cod. Mesoscale eddy kinetic energy in the Kodiak region decreased to below average, implying slightly reduced retention in the area and reduced cross-shelf transport to suitable nearshore nursery environments (Appendix 2.1: Annual Eddy Kinetic Energy Kodiak Satellite by W. Cheng). Survival of the age-0 year class has moderate potential for success, with above average CPUE in western GOA beach seine (Appendix 2.1: Summer Pacific Cod CPUE YOY Nearshore Kodiak Survey by B. Laurel and M. Litzow), above average spring chl-a & zooplankton biomass and slightly later than average peak spring bloom (Appendix 2.1: Spring Chlorophyll a Peak WCGOA Satellite by M. Callahan), lower than average eddy kinetic energy, and summer/fall surface temperatures have been above average. 2023 surface temperatures are predicted to be average to cooler than average, in alignment with winter La Niña conditions and a negative Pacific Decadal Oscillation.

Prey: Foraging conditions for juveniles and adults were average (zooplankton) to above average (forage fish) in 2022. Limited information on biomass of calanoid copepod and euhausiids in 2022 indicate average availability (Seward Line, Danielson and Hopcroft 2022, zooplanktivorous seabird reproductive success, Drummond and Renner 2022 and Hatch et al. 2022, AFSC SECM survey Icy Strait, Fergusson 2022). Forage fish were above average across the GOA (planktivorous seabird reproductive success, Drummond and Renner 2022 and Hatch et al. 2022, herring, Hebert and Dressel 2022 and Pegau et al. 2022, Appendix 2.1: Annual Common Murre Reproductive Success Chowiet Survey by S. Zador). Tanner crab around Kodiak continue to increase (ADF&G trawl survey, Worton 2022) and shrimp have been increasing around Chirikof, Yakutat, and southeastern GOA regions, but declining around Kodiak from 2017-2021 (AFSC Bottom Trawl Survey, Palsson 2021). Biomass trends for other prey, including polychaetes and other invertebrates, are unknown. Pacific cod condition indices (Fig. 2.15 and Fig. 2.16) were above average (with the exception of CGOA longline data, a divergence potentially due to small sample size) indicating success at meeting energetic demands.

Predators and Competitors: There is no cause to suspect increased predation pressure on Pacific cod. In general predators of Pacific cod (including Pacific cod, halibut, salmon shark, northern fur seals, Steller sea lions, harbor porpoises, various whale species, and tufted puffin) 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. 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, although sablefish are increasing in abundance) (Whitehouse and Aydin 2021). Planktivorous juvenile cod may experience increased levels of competition from recent strong sablefish year classes, especially the potentially large (based on first estimates in the 2022 sablefish assessment) 2019 year class (D. Goethel, pers. comm.), although decreased competition from low, even year pink salmon returns.

<u>Fishery Performance</u>

Where data were available catch per unit effort measures in the GOA fisheries showed mixed signals. Condition of fish in the fisheries for 2022 were average with the exception of the Central GOA longline fishery. 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. We will continue to monitor the trend of increasing mean length, particularly in the pot fishery, as this could be an indication of poor recruitment coupled with the fisheries concentrating on larger and mature fish.

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.

<u>Summary and ABC recommendation</u>

These results are summarized in the table below:

Assessment-related considerations	Population dynamics considerations	Environmental/ecosystem considerations	Fishery Performance
Level 2: Substantially increased concern	Level 2: Substantially increased 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 – 2022 are provided in Table 2.23. While the largest score of the risk table is level 2, we do not recommend that ABC be set below the maximum permissible.

For 2023 the spawning stock biomass is projected to be above $B_{20\%}$, and despite a drop in spawning biomass in 2024 is projected to remain above $B_{20\%}$ in 2024. From Model 19.1a the maximum ABC for 2023 is 24,634 t and for 2024 is 22,683 t.

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 with the trawl survey biomass estimates through 2021 (Fig. 2.54), the area-apportioned ABCs for the two-year projections of Model 19.1a would be:

	Western	Central	Eastern	Total
Random effects area apportionment	30.3%	60.2%	9.5%	100%
2023 ABC	7,464	14,830	2,340	24,634
2024 ABC	6,873	13,655	2,155	22,683

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 2022 was estimated to be 32,811 t, equal to the 2022 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 2000-2020, recruitment was based on average recruitment from 1977-2022, and growth and mortality were as estimated in 2022.

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 2023, are as follow ("*max* F_{ABC}" refers to the maximum permissible value of F_{ABC} under Amendment 56):

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

Scenario 2: In all future years, F is set equal to the author's recommend level, max ABC.

Scenario 3: In all future years, F is set equal to the 2018-2022 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 2022 and above its B_{MSY} level in 2032 under this scenario, then the stock is not overfished.)

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

Scenarios 1 through 7 were projected 15 years from 2022 in Model 19.1a (Table 2.24). Scenarios 3, 4, and 5 (no fishing) project the stock to be below $B_{35\%}$ until 2025, scenarios 1, 2, 6, and 7 have the stock below $B_{35\%}$ until 2026. Fishing at the maximum permissible rate indicate that the spawning stock will be below $B_{35\%}$ in 2023 through 2025 due to poor recruitment and high mortality in 2015-2017 and 2019. Under an assumption of environmental conditions at the 1977-2021 mean, the stock recovers above $B_{35\%}$ by 2026.

Our projection model run under these conditions indicates that for Scenario 6, the GOA Pacific cod stock although below $B_{35\%}$ in 2022 at 51,734 t will be above its MSY value in 2032 at 75,315 t and therefore would not be classified as overfished.

Projections 7 with fishing at the OFL after 2023 results in an expected spawning biomass of 75,330 t by 2034 and would therefore not be approaching an overfished condition.

Under Scenarios 6 and 7 for Model 19.1a the Gulf of Alaska Pacific cod stock would not currently be considered overfished, nor would it be approaching an overfished status. The 2021 OFL given Model 19.1a would have produced a sum of apical F of 0.388 in 2021.

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.

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Tables

Table 2.1. Catch (t) for 1991 through 2022 by jurisdiction and gear type (as of 2022-10-25)

	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	6,885	4,606	4,725	3	16,219	354	5,670	974	6,998	23,217

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 2022 is current through 2022-10-25 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	23,217	24,111	32,811	39,555	8,700

Table 2.3. History of GOA Pacific cod allocations by regulatory area (in percent) for 1991-2023. 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

Table 2.4. Estimated retained and discarded GOA Pacific cod (2022 catch as of 2022-10-25)

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	1,575	21,643	23,218

Table 2.5. Weight of groundfish bycatch (t), discarded (D) and retained (R), for 2018 – 2022 for GOA Pacific cod as target species (AKFIN; as of 2022-10-25).

	2018		**2019**		**2020**		**2021**		**2022**	
	D	**R**	**D**	**R**	**D**	**R**	**D**	**R**	**D**	**R**
skate, other	168.41	12.86	202.31	32.58	3.80	0.09	269.30	18.01	116.10	0.16
big skate	53.02	20.65	133.53	29.95	3.51	1.10	158.63	46.93	177.26	62.52
walleye pollock	24.58	71.59	71.49	31.05	11.37	4.38	271.94	21.82	129.54	29.73
arrowtooth flounder	103.77	6.67	224.42	18.48	50.44	0.26	147.54	2.02	58.56	0.33
North Pacific octopus	10.26	142.35	39.69	192.28	0.03	12.01	14.43	23.28	10.25	40.87
spiny dogfish	104.11	0.00	104.10	0.00	14.29		161.03		12.39	0.03
longnose skate	26.95	39.74	50.27	35.96	4.79	3.05	80.44	41.24	70.60	36.25
sablefish	57.43	2.88	36.43	53.04	5.50	24.37	64.08	64.52	5.64	12.56
sculpin	83.39	0.32	100.95	0.24	0.61	0.20				
shallow water flatfish	31.35	0.37	43.93	37.98	3.37	0.04	24.19	0.61	32.03	8.59
flathead sole	22.12	0.68	92.54	8.53	0.11	0.00	18.14	2.77	6.52	1.12
other rockfish	6.29	18.31	5.53	16.61	0.47	0.69	16.85	12.66	25.52	8.61
rex sole	4.51	0.01	27.68	2.00	0.15		1.63	0.02	8.53	0.16
Atka mackerel	3.01	0.24	32.79	0.24			2.91	0.01	0.05	
Pacific ocean perch	0.07	0.01	0.16	19.37	0.01	7.76	0.20	1.52	0.04	0.03
dusky rockfish	3.49	3.97	2.34	5.54	0.00	0.81	2.51	2.28	2.90	0.80
Pacific sleeper shark	2.71		9.90		0.21		0.62		3.63	
northern rockfish	3.59	1.40	3.33	0.25		0.00	3.43	1.01	0.35	0.01
Aleutian skate		2.11		1.13				0.39		7.89
shortraker rockfish	0.11	0.31	1.15	0.18	0.10	0.03	4.56	0.38	2.27	0.50
rougheye rockfish	0.74	1.80	0.72	1.29	0.09	0.22	2.42	0.82	0.23	0.31
thornyhead rockfish	0.53	2.01	0.61	1.16	0.04		0.36	0.60	0.98	1.32
deep water flatfish	0.09	0.01	0.64	0.01	0.16	0.00	1.17		2.42	
shark, other			0.61	0.45			0.57	0.01	0.45	
salmon shark	0.45					0.28				
Alaskan skate		0.07		0.08				0.01		0.03
whitebloched skate		0.01								
Total	711	328	1,185	488	99	55	1,247	241	666	212

Table 2.6. Incidental catch (t or birds by number) of non-target species groups by GOA Pacific cod fisheries, 2018-2022 (as of 2022-10-25). 0.00 indicates ≤0.005 tons, a blank indicates no catch.

Species Group	2022	2021	2020	2019	2018
Benthic urochordata				0.23	0.01
Birds - Gull	37	8		23	180
Birds - Northern Fulmar	205	21			13
Birds - Shearwaters					7
Birds - Unidentified		9			138
Bivalves	0.64	0.00		0.23	2.74
Brittle star unidentified	0.02				0.00
Corals Bryozoans - Corals Bryozoans Unidentified	0.06	0.08	0.17	1.55	1.46
Eelpouts	0.02			0.19	
Giant Grenadier	49.06	79.55		0.12	0.12
Greenlings	0.09	0.45		0.77	0.77
Grenadier - Rattail Grenadier Unidentified	0.07	0.12		0.15	0.59
Hermit crab unidentified	0.06	0.01		0.92	0.09
Invertebrate unidentified	0.77	0.01	0.11	0.08	0.08
Misc crabs	0.05	0.14		0.14	0.43
Misc crustaceans	0.00			0.00	
Misc fish	23.88	33.33	7.71	15.35	31.40
Sculpin	141.73	119.50			
Scypho jellies	0.03	0.19	0.02	2.65	
Sea anemone unidentified	0.76	1.09	0.00	1.31	2.63
Sea pens whips	1.47	0.04		0.46	0.34
Sea star	23.58	18.39	1.59	37.47	37.69
Snails	1.92	0.27	0.06	4.74	6.78
Sponge unidentified	0.34	0.05		5.36	2.09
State-managed Rockfish	0.43	2.24		3.45	2.80
urchins dollars cucumbers	0.28	0.03		0.31	0.39

Table 2.7. Pacific cod catch (t) by trip target in Gulf of Alaska groundfish fisheries. Data for 2022 is as of 2022-10-25.

Trip Target	2018	2019	2020	2021	2022	Average
Pacific Cod	12,010	11,978	2,330	14,110	17,228	11,531
Pollock - bottom	782	711	899	2,843	3,272	1,701
Arrowtooth Flounder	880	1,439	1,237	379	408	869
Halibut	286	301	555	474	889	501
Rockfish	401	322	170	660	626	436
Shallow Water Flatfish - GOA	251	405	938	254	222	414
Pollock - midwater	65	100	141	74	113	99
Sablefish	39	50	43	56	23	42
Rex Sole - GOA	76	83	14	0	22	39
Flathead Sole	2	18	0	3	0	5
Atka Mackerel	2	0	0	0	0	0
Grand Total	14,793	15,405	6,327	18,852	22,804	16,505
Non-Pacific cod trip target total	2,782	3,427	3,997	4,742	5,576	4,974

Table 2.8. Noncommercial fishery catch (in kg); total source amounts less than 1 kg were omitted (AFSC for GOA bottom trawl survey values; AKFIN for other values, as of 2022-10-25)

Source	2017	2018	2019	2020	2021
AFSC Annual Longline Survey	15,597	10,242	5,530	10,200	13,050
GOA Shelf and Slope Walleye Pollock Acoustic-Trawl Survey	53				
Gulf of Alaska Bottom Trawl Survey	5,197		7,796		7,853
IPHC Annual Longline Survey	38,927	89,231	104,968	30,032	75,279
IPHC Research		34			
Kachemak Bay Large Mesh Trawl Survey	1,254				
Kenai/Prince William Sound Walleye Pollock Acoustic-Trawl Survey	15				
Kodiak Scallop Dredge	1				
Large-Mesh Trawl Survey	6,597	6,361	7,317	7,921	5,032
Prince William Sound Large Mesh Trawl Survey	164				
Shumagin Islands Walleye Pollock Acoustic-Trawl Survey	11	23			
Small-Mesh Trawl Survey	161	151	341	664	67
Sport Fishery	56,994	42,446	78,575	70,054	182,359
Spot Shrimp Survey		1	4	3	3
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	
Total	124,971	148,489	204,601	118,879	283,644

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

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			

Table 2.11. Age-0 Pacific cod beach seine index (number/haul) and CVs.

Year	Number/haul	CV
2006	118.30	0.30
2007	8.10	0.37
2008	29.52	0.34
2009	30.69	0.50
2010	11.71	0.47
2011	33.55	0.37
2012	187.89	0.33
2013	8.32	0.38
2014	8.82	0.48
2015	1.37	0.91
2016	1.95	0.47
2017	76.75	0.31
2018	110.89	0.22
2019	2.27	0.55
2020	194.27	0.28
2021	22.07	0.26
2022	124.91	0.26

Table 2.12. IPHC Longline Relative Population Numbers (RPNs) and CVs for Pacific cod. A full survey was not conducted in 2020 due to COVID-19.

Year	RPN	CV	Year	RPN	CV
1997	29,431	0.24	2010	27,815	0.16
1998	16,368	0.21	2011	31,747	0.17
1999	12,373	0.22	2012	23,509	0.18
2000	14,642	0.22	2013	26,432	0.19
2001	12,169	0.24	2014	27,751	0.16
2002	16,495	0.22	2015	16,722	0.20
2003	15,404	0.24	2016	11,918	0.22
2004	16,047	0.20	2017	10,356	0.24
2005	16,301	0.23	2018	13,910	0.22
2006	15,805	0.21	2019	13,412	0.20
2007	18,206	0.20	2020	-	-
2008	22,218	0.18	2021	17,236	0.20
2009	30,160	0.16			

Table 2.13. ADFG trawl survey deltaGLM biomass index and CVs for Pacific cod.

Year	Index	CV	Year	Index	CV
1988	2.74	0.093	2006	0.89	0.088
1989	3.63	0.086	2007	1.06	0.080
1990	2.72	0.080	2008	1.23	0.066
1991	1.85	0.137	2009	1.24	0.070
1992	2.81	0.084	2010	1.05	0.072
1993	2.28	0.085	2011	1.35	0.070
1994	2.04	0.082	2012	2.55	0.090
1995	2.26	0.109	2013	1.92	0.098
1996	2.29	0.085	2014	1.32	0.097
1997	2.47	0.079	2015	1.19	0.096
1998	2.22	0.085	2016	0.82	0.112
1999	1.23	0.071	2017	0.87	0.106
2000	0.96	0.077	2018	1.13	0.097
2001	0.84	0.075	2019	0.95	0.092
2002	1.07	0.069	2020	1.35	0.090
2003	0.86	0.079	2021	1.08	0.091
2004	1.31	0.073	2022	1.12	0.096
2005	1.03	0.092			

Table 2.14. CFSR bottom temperature index for 0-10 cm and 40-60 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 1979-2021. Note that the MHCI for 2022 are only through September 13.

Year	0-10 cm	40-60 cm	Ann. MHCI	Winter MHC1	Spawn MHCI	Year	0-20 cm	40-60 cm	Ann. MHCI	Winter MHCI	Spawn MHCI
1979	4.91	5.08	0	0	0	2001	4.98	5.02	46.91	23.35	11.33
1980	5.03	4.92	0	0	0	2002	4.20	4.36	51.27	51.27	0
1981	5.71	5.36	0	0	0	2003	5.30	5.39	207.85	151.48	108.12
1982	4.00	4.52	0	0	0	2004	4.60	4.98	117.64	0	0
1983	5.11	5.25	31.88	15.20	4.73	2005	4.91	5.27	284.60	3.78	0
1984	4.73	5.23	88.21	43.10	0.00	2006	4.63	4.97	35.14	5.81	0
1985	4.57	5.17	24.61	24.61	19.68	2007	4.13	4.29	0	0	0
1986	4.73	5.00	16.35	16.35	0	2008	4.33	4.56	0	0	0
1987	5.30	5.31	5.58	0	0	2009	3.66	4.31	0	0	0
1988	4.70	4.95	0	0	0	2010	5.21	5.08	6.52	0	0
1989	4.05	4.40	0	0	0	2011	4.55	4.66	0	0	0
1990	4.12	4.53	8.72	0	0	2012	4.00	4.08	0	0	0
1991	4.38	4.62	0	0	0	2013	4.18	4.64	0	0	0
1992	4.89	4.89	0	0	0	2014	4.73	4.96	283.02	105.44	0.00
1993	4.52	4.70	19.10	0	0	2015	5.88	5.59	402.32	202.38	133.28
1994	4.47	4.82	0	0	0	2016	5.71	5.10	630.87	314.57	155.56
1995	4.04	4.62	0	0	0	2017	4.75	4.58	53.03	38.78	0
1996	4.50	4.77	0	0	0	2018	5.10	5.02	128.50	99.89	0
1997	4.56	4.85	142.05	23.24	0	2019	5.94	5.63	496.74	199.48	100.45
1998	5.73	5.52	150.85	87.05	80.81	2020	4.30	4.70	146.45	31.38	0
1999	4.43	4.86	0	0	0	2021	4.26	4.70	15.38	15.38	10.71
2000	4.51	4.79	0	0	0	2022	5.09	5.00	71.59	0	0

Table 2.15. Number of parameters by category for Model 19.1a.

	Model 19.1a
Recruitment	
Early Init Ages	10
Early Rec. Devs (1977)	1
Main Rec. Devs (1978-2019)	42
Late Rec. Devs (2020-2022)	3
Future Rec. Devs. (2023-2037)	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	211

Table 2.16. Studies of Pacific cod natural mortality and statistics on the combined values. "Used?" Column indicates whether the value was used in developing this year's assessment model prior on natural mortality.

Area	Author	Year	Value	ln(value)	Used?	Statistics	
EBS	Low	1974	0.375	-0.981	Y	mu:	-0.815
EBS	Wespestad et al.	1982	0.7	-0.357	Y	sigma:	0.423
EBS	Bakkala and Wespestad	1985	0.45	-0.799	Y	Arithmetic:	0.484
EBS	Thompson and Shimada	1990	0.29	-1.238	Y	Geometric:	0.443
EBS	Thompson and Methot	1993	0.37	-0.994	Y	Harmonic:	0.405
EBS	Shimada and Kimura	1994	0.96	-0.041	Y	Mode:	0.370
EBS	Shi et al.	2007	0.45	-0.799	Y	L95%:	0.193
EBS	Thompson	2007	0.34	-1.079	Y	U95%:	1.015
EBS	Thompson	2016	0.36	-1.022	Y		
GOA	Thompson and Zenger	1993	0.27	-1.309	Y		
GOA	Thompson and Zenger	1995	0.5	-0.693	Y		
GOA	Thompson	2007	0.38	-0.968	Y		
GOA	Barbeaux et al.	2016	0.47	-0.755	N		
BC	Ketchen	1964	0.595	-0.519	Y		
BC	Fournier	1983	0.65	-0.431	Y		

Table 2.17. Likelihood components and derived quantities for Model 19.1a.

Likelihood components	
TOTAL_like	3841.47
Survey_like	-15.42
Length_comp_like	1715.64
Age_comp_like	2124.90
Recruitment	3.93
InitEQ_Regime	2.35
Forecast_Recruitment	2.26
Parm_priors_like	1.28
Derived quantitites	
Recr_Virgin_millions	455.77
SR_LN(R0)	13.03
NatM (min)	0.49
NatM (max)	0.85
L_at_Amin	6.33
L_at_Amax	99.46
VonBert K	0.19
Q bottom trawl index	1.09
SSB unfished 1000's t	198.92
SSB unfished CV	0.08
F_{MSY} (sum apical F)	0.66
2023 F_{ABC} (sum apical F)	0.41
SSBratio 2022	0.31
SSBratio 2023	0.26

Table 2.18. Likelihood components by source for Model 19.1a.

Label	ALL	FshTrawl	FshLL	FshPot	TWLSrv	LLSrv
Age_like	2124.90	456.59	486.68	419.75	761.88	
Catch_like	1.12E-12	3.36E-13	3.76E-13	4.04E-13		
Length_like	1715.64	545.81	322.65	420.85	182.75	243.58
Surv_like	-15.42				-10.36	-5.06

Table 2.19. Leave-one-out bias analysis results. MLE are the maximum likelihood estimated values. Mean difference is the average difference from the MLE. Note that the SSB is female spawning biomass.

	MLE			Leave-one-out	
Label	**Value**	**σ**	**CV**	**Mean difference**	**Mean difference/MLE Value**
ABC_{2023}	24,634	4,904	0.20	658.25	0.027
$F_{40\%}$	0.664	0.049	0.07	0.005	0.007
M_{base}	0.486	0.018	0.04	0.002	0.004
$Q_{Bottom\ trawl}$	0.089	0.077	NA	-0.002	-0.023
$SSB_{Unfished}$	167,414	12,317	0.07	1804.73	0.011
SSB_{2023}	42,764	4,127	0.10	1047.08	0.024

Table 2.20. Estimated female spawning biomass (t) and total biomass (t, age 0+) from the last year's assessment and the author's recommended Model 19.1a.

	Last Year's Model (19.1)			Model 19.1a		
	Sp.Bio	St.dev	Tot. Bio. 0+	Sp.Bio	St.dev	Tot. Bio. 0+
1977	105,723	22,311	342,781	92,967	18,993	297,981
1978	117,226	23,593	360,209	104,326	20,349	313,729
1979	114,370	22,260	415,846	102,381	19,523	360,747
1980	112,318	20,687	483,380	100,290	18,279	423,438
1981	134,208	23,981	517,038	119,196	21,385	457,450
1982	160,243	28,116	541,779	143,623	25,633	481,650
1983	168,784	28,884	585,680	153,763	27,183	523,406
1984	170,866	28,419	632,697	156,226	27,388	570,766
1985	189,897	28,881	683,824	174,891	28,132	629,649
1986	218,353	29,286	732,867	204,308	28,501	688,282
1987	237,217	28,197	782,490	227,282	27,352	737,809
1988	241,051	25,465	798,727	236,673	24,971	758,800
1989	253,103	23,483	794,743	246,814	22,704	761,416
1990	254,500	21,177	772,193	248,159	20,308	746,639
1991	233,360	18,559	731,935	230,388	17,957	713,259
1992	213,108	16,508	702,773	213,001	16,105	691,923
1993	198,338	15,180	666,905	200,365	14,878	666,335
1994	201,236	14,421	636,597	205,996	14,194	646,758
1995	202,277	13,243	594,030	210,227	13,092	612,981
1996	180,906	11,347	521,432	192,335	11,290	548,208
1997	153,341	9,400	462,156	166,602	9,324	493,721
1998	127,133	7,878	411,385	138,253	7,749	438,935
1999	113,050	7,081	371,229	122,007	6,863	392,705
2000	99,436	6,515	329,155	104,988	6,219	340,710
2001	89,635	5,917	310,120	92,439	5,587	311,860
2002	84,463	5,364	314,352	84,866	5,030	307,981
2003	83,097	5,078	315,306	79,759	4,767	300,900
2004	84,097	5,129	296,214	81,895	4,857	285,813
2005	80,924	4,989	268,601	79,790	4,776	260,949
2006	73,244	4,467	255,663	73,029	4,316	248,789
2007	64,086	3,987	265,118	64,425	3,873	256,856
2008	59,220	3,900	300,799	59,572	3,786	290,058
2009	64,159	4,419	346,125	64,239	4,269	333,418
2010	84,726	5,605	400,730	84,634	5,391	386,732
2011	97,196	6,737	422,163	96,909	6,472	407,856
2012	105,131	7,951	430,148	104,695	7,646	414,540
2013	110,731	9,086	461,599	110,162	8,772	441,572
2014	116,051	10,450	544,567	114,924	10,124	518,159
2015	82,679	6,459	413,710	82,365	6,276	400,775
2016	65,816	4,700	274,478	66,547	4,599	272,627
2017	47,801	3,545	162,220	49,557	3,561	166,160
2018	39,721	3,559	136,739	42,245	3,609	143,409
2019	38,692	3,401	144,511	42,175	3,472	152,663
2020	39,414	3,482	155,524	43,896	3,538	158,779
2021	46,190	3,836	171,976	51,289	3,810	165,795
2022	48,061	4,476	178,961	51,734	4,039	163,954
2023				42,764	4,127	163,477

Table 2.21. Age-0 recruitment and standard deviation of age-0 recruits by year for last year's model and Model 19.1a. Highlighted are the 1977 and 2012 year classes.

Year	Model 19.1 - 2021 Age-0 x 10^9	Model 19.1 - 2021 Stdev	Model 19.1a Age-0 x 10^9	Model 19.1a Stdev
1977	1.25	0.32	0.99	0.25
1978	0.54	0.17	0.50	0.15
1979	0.45	0.14	0.40	0.12
1980	0.63	0.17	0.49	0.14
1981	0.90	0.22	0.77	0.19
1982	0.88	0.22	0.76	0.20
1983	0.73	0.20	0.70	0.21
1984	0.64	0.18	0.62	0.19
1985	1.21	0.24	0.89	0.20
1986	0.54	0.14	0.61	0.14
1987	0.72	0.14	0.61	0.12
1988	0.67	0.13	0.64	0.12
1989	0.74	0.14	0.65	0.12
1990	0.87	0.16	0.83	0.14
1991	0.56	0.11	0.55	0.10
1992	0.50	0.09	0.48	0.09
1993	0.34	0.07	0.35	0.07
1994	0.38	0.07	0.37	0.07
1995	0.52	0.08	0.52	0.08
1996	0.34	0.06	0.34	0.06
1997	0.36	0.06	0.35	0.06
1998	0.29	0.05	0.27	0.04
1999	0.41	0.07	0.37	0.06
2000	0.49	0.08	0.45	0.07
2001	0.33	0.05	0.31	0.05
2002	0.23	0.04	0.21	0.03
2003	0.27	0.04	0.25	0.04
2004	0.33	0.05	0.29	0.04
2005	0.49	0.07	0.44	0.06
2006	0.75	0.11	0.68	0.09
2007	0.54	0.08	0.50	0.07
2008	0.75	0.11	0.66	0.10
2009	0.51	0.09	0.47	0.08
2010	0.59	0.10	0.51	0.08
2011	0.72	0.13	0.63	0.11
2012	1.42	0.27	1.25	0.23
2013	0.90	0.20	0.84	0.18
2014	0.32	0.08	0.30	0.07
2015	0.28	0.06	0.27	0.06
2016	0.30	0.06	0.28	0.05
2017	0.20	0.04	0.21	0.04
2018	0.27	0.05	0.17	0.03
2019	0.14	0.04	0.08	0.02
2020	0.25	0.07	0.22	0.05
2021	0.52	0.24	0.26	0.10
2022			0.46	0.21
Mean 1977-2019	0.57		0.50	
Stdev(Ln(x))		0.51		0.54

Table 2.22. Estimated fishing mortality in terms of apical F and total exploitation for Model 19.1a.

	Sum Apical F		Total		Sum Apical F		Total
Year	F	σ	**Exploitation**	**Year**	F	σ	**Exploitation**
1977	0.011	0.003	0.008	2001	0.381	0.026	0.165
1978	0.052	0.010	0.039	2002	0.444	0.029	0.177
1979	0.068	0.014	0.041	2003	0.453	0.029	0.175
1980	0.164	0.035	0.083	2004	0.482	0.031	0.198
1981	0.106	0.019	0.079	2005	0.576	0.085	0.182
1982	0.081	0.015	0.061	2006	0.609	0.082	0.193
1983	0.103	0.019	0.070	2007	0.572	0.041	0.203
1984	0.067	0.012	0.042	2008	0.682	0.053	0.203
1985	0.059	0.014	0.023	2009	0.528	0.041	0.160
1986	0.086	0.018	0.036	2010	0.616	0.047	0.203
1987	0.062	0.013	0.045	2011	0.595	0.046	0.209
1988	0.062	0.007	0.045	2012	0.494	0.041	0.188
1989	0.078	0.010	0.057	2013	0.407	0.036	0.155
1990	0.189	0.017	0.097	2014	0.585	0.052	0.164
1991	0.217	0.018	0.107	2015	0.776	0.062	0.198
1992	0.248	0.021	0.117	2016	0.785	0.059	0.235
1993	0.181	0.014	0.085	2017	0.893	0.169	0.293
1994	0.148	0.011	0.073	2018	0.269	0.046	0.106
1995	0.217	0.015	0.113	2019	0.264	0.038	0.103
1996	0.236	0.015	0.125	2020	0.096	0.010	0.043
1997	0.317	0.020	0.156	2021	0.263	0.031	0.116
1998	0.363	0.023	0.165	2022	0.479	0.058	0.200
1999	0.490	0.031	0.210				
2000	0.450	0.030	0.195				

Table 2.23. Biological reference points from GOA Pacific cod SAFE documents for years 2002 – 2022, and recommended for 2023 from Model 19.1a (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*

Table 2.24. Results for the projection scenarios from Model 19.1a. 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
2022	32,811	32,811	32,811	32,811	32,811	32,811	32,811
2023	24,634	24,634	14,055	6,067	0	29,737	24,634
2024	22,683	22,683	15,385	7,551	0	25,174	22,683
2025	32,047	32,047	22,590	11,738	0	35,396	38,806
2026	53,579	53,579	36,992	17,841	0	59,138	60,301
2027	68,568	68,568	45,462	22,721	0	78,067	78,034
2028	73,739	73,739	51,472	26,651	0	81,715	81,652
2029	75,802	75,802	54,830	29,244	0	82,716	82,682
2030	76,603	76,603	56,628	30,902	0	82,980	82,967
2031	76,907	76,907	57,539	31,898	0	83,054	83,049
2032	77,051	77,051	58,052	32,547	0	83,092	83,090
2033	77,100	77,100	58,289	32,902	0	83,101	83,100
2034	77,118	77,118	58,400	33,097	0	83,104	83,103
2035	77,124	77,124	58,451	33,204	0	83,104	83,104
F							
2022	0.48	0.48	0.48	0.48	0.48	0.48	0.48
2023	0.41	0.41	0.22	0.09	0.00	0.51	0.41
2024	0.39	0.39	0.23	0.10	0.00	0.46	0.39
2025	0.46	0.46	0.28	0.13	0.00	0.54	0.57
2026	0.61	0.61	0.36	0.15	0.00	0.72	0.73
2027	0.66	0.66	0.36	0.15	0.00	0.82	0.82
2028	0.66	0.66	0.36	0.15	0.00	0.82	0.82
2029	0.66	0.66	0.36	0.15	0.00	0.82	0.82
2030	0.66	0.66	0.36	0.15	0.00	0.82	0.82
2031	0.66	0.66	0.36	0.15	0.00	0.82	0.82
2032	0.66	0.66	0.36	0.15	0.00	0.82	0.82
2033	0.66	0.66	0.36	0.15	0.00	0.82	0.82
2034	0.66	0.66	0.36	0.15	0.00	0.82	0.82
2035	0.66	0.66	0.36	0.15	0.00	0.82	0.82
SSB							
2022	51,734	51,734	51,734	51,734	51,734	51,734	51,734
2023	42,764	42,764	42,764	42,764	42,764	42,764	42,764
2024	40,489	40,489	44,449	47,482	49,811	38,608	40,489
2025	47,514	47,514	53,299	58,617	63,325	45,144	47,514
2026	61,794	61,794	69,645	77,771	85,859	58,804	59,503
2027	74,150	74,150	86,131	99,503	112,587	69,909	69,933
2028	80,342	80,342	98,227	117,371	136,372	73,654	73,608
2029	83,004	83,004	105,371	129,764	154,755	74,805	74,774
2030	84,126	84,126	109,473	138,271	169,035	75,156	75,142
2031	84,571	84,571	111,640	143,604	179,092	75,259	75,253
2032	84,792	84,792	112,926	147,259	186,721	75,315	75,312
2033	84,867	84,867	113,519	149,259	191,415	75,327	75,326
2034	84,893	84,893	113,794	150,355	194,302	75,330	75,330
2035	84,903	84,903	113,923	150,956	196,078	75,331	75,331

Figures

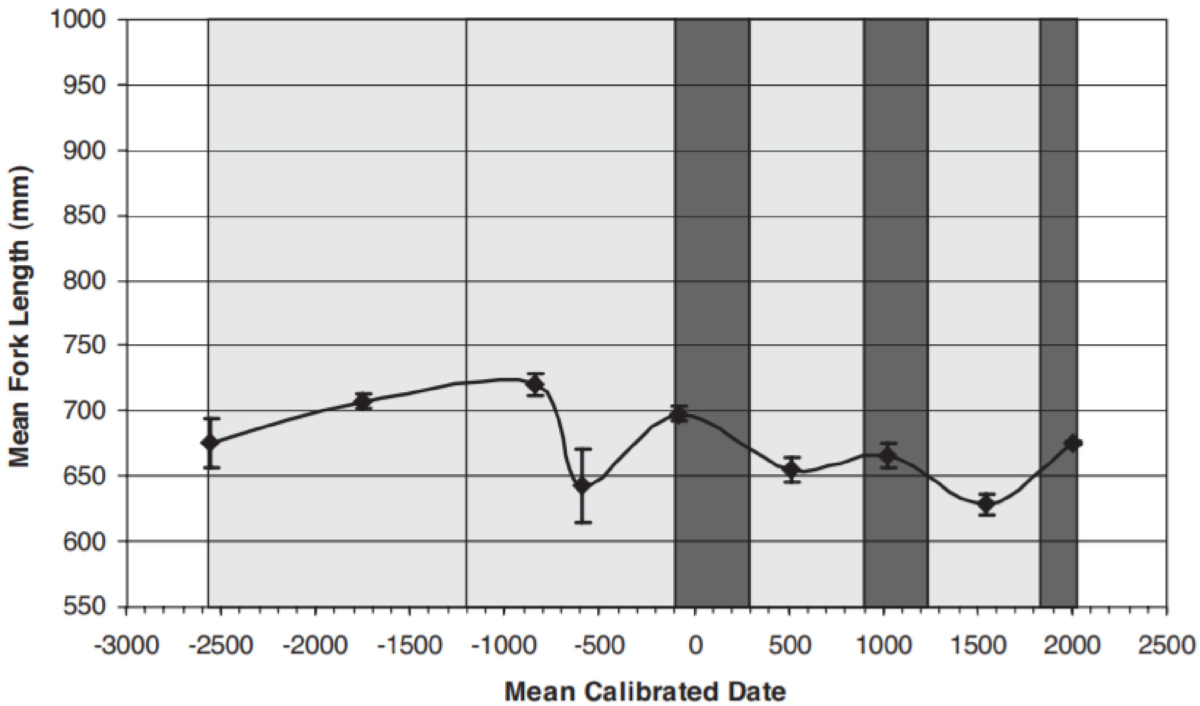

Figure 2.1. Gulf of Alaska mean lengths with climate reconstruction. The shaded boxes represent periods of significant changes in air temperature, sea surface temperature, storminess, and ocean circulation that drive ocean productivity. The lightly shaded boxes represent periods of cooler and stormier 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).

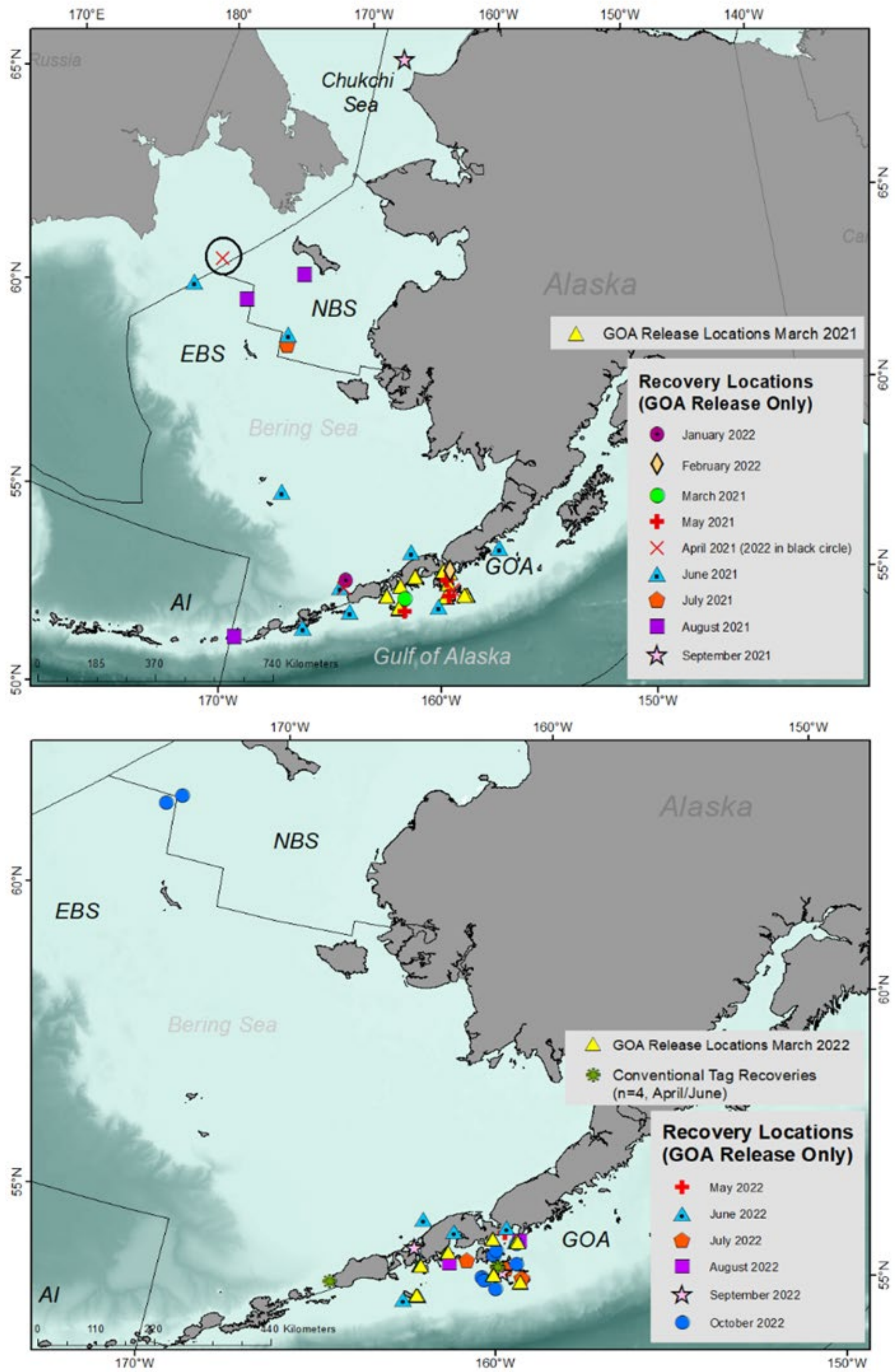

Figure 2.2. Popup satellite tag releases for March 2021/2022 (yellow triangles) and monthly tag recovery locations for 2021 (top) and 2022 (bottom) by region (NBS = Northern Bering Sea, EBS = Eastern Bering Sea, AI = Aleutian Islands, and GOA = Gulf of Alaska).

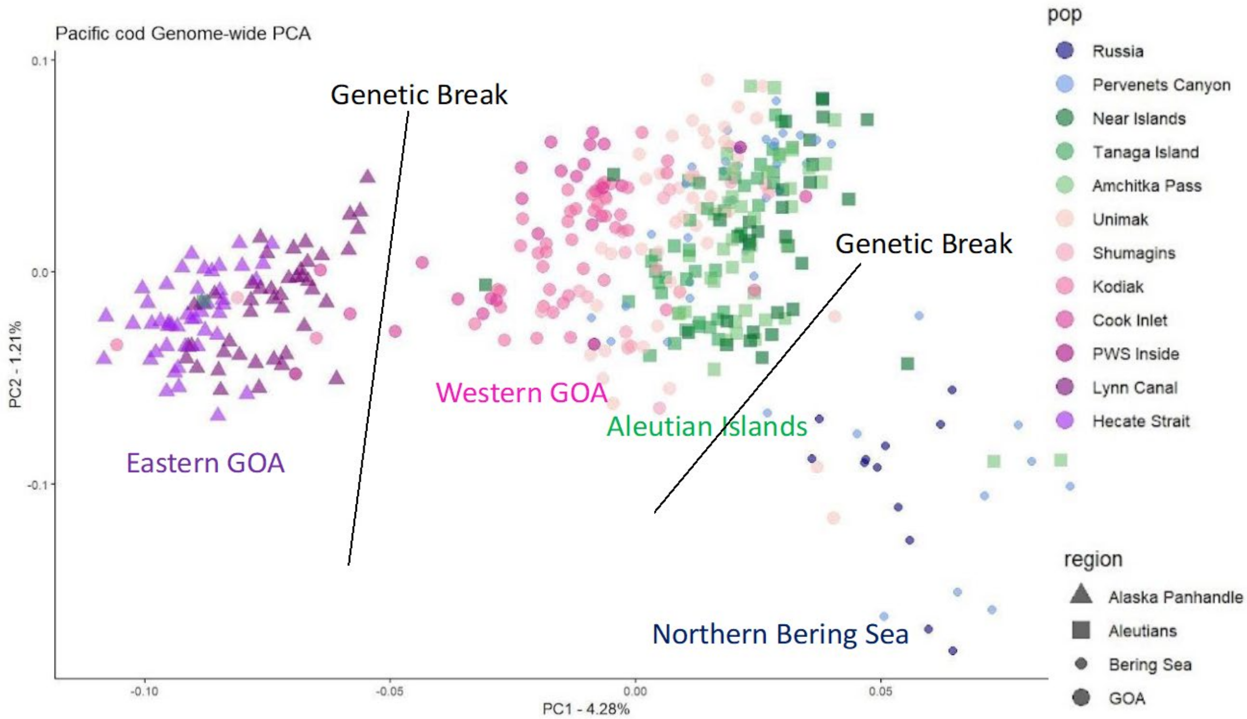

Figure 2.3. Principal components analysis of 1,922,927 polymorphic SNPs from the lcWGS dataset.

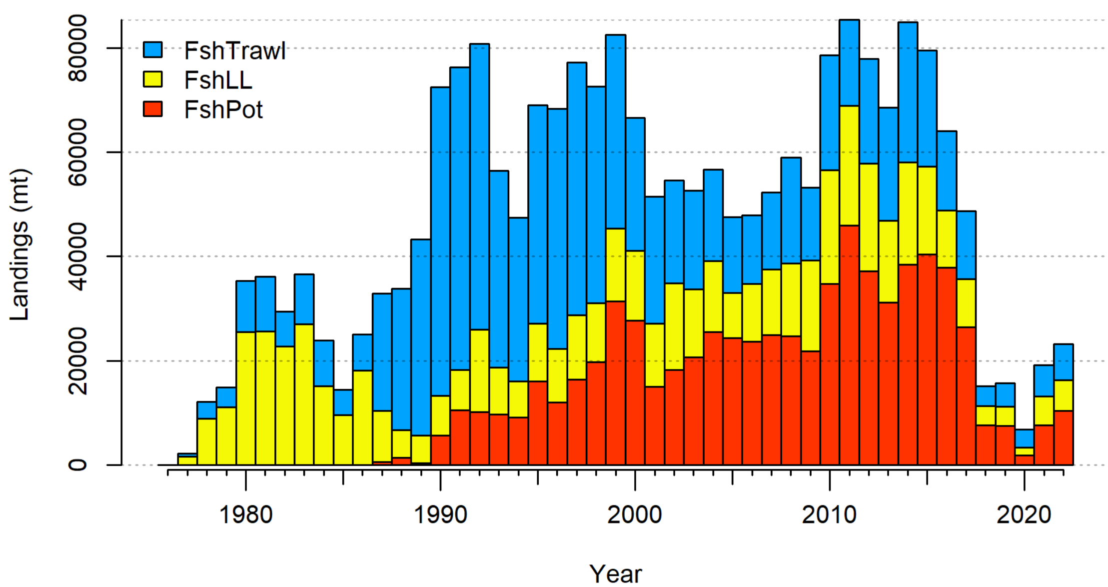

Figure 2.4. Gulf of Alaska Pacific cod catch from 1977-2022. Note that 2022 catch was through October 25.

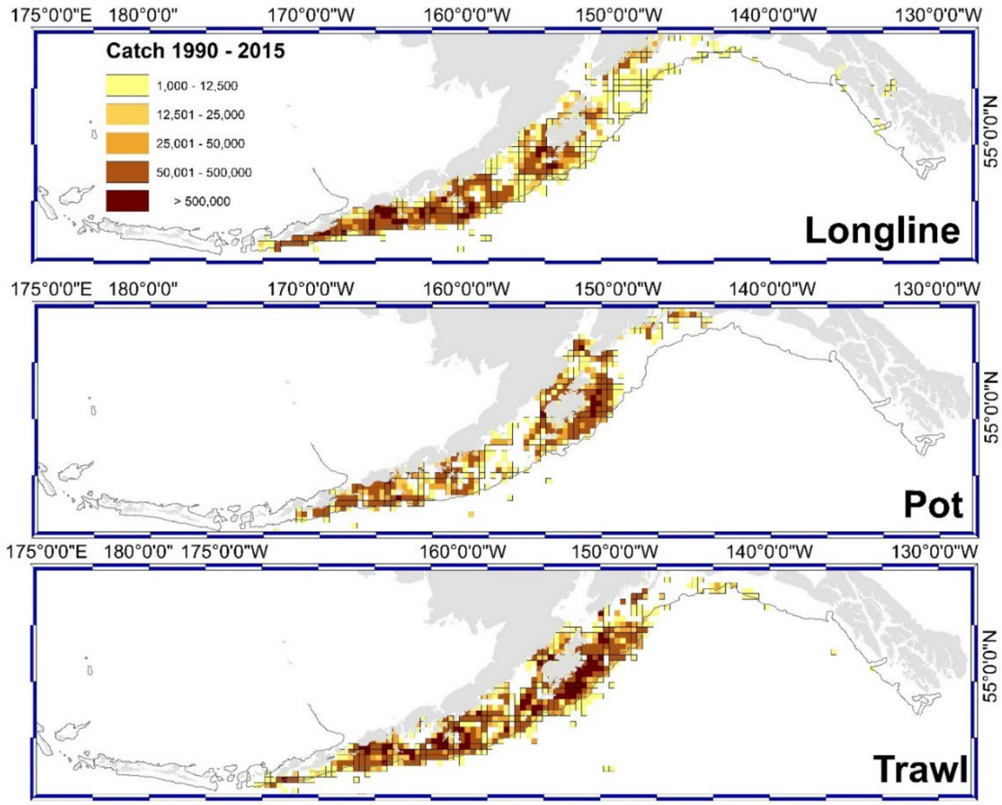

Figure 2.5. Commercial catch of Pacific cod in the Gulf of Alaska by 20km^2 grid for 1990-2015.

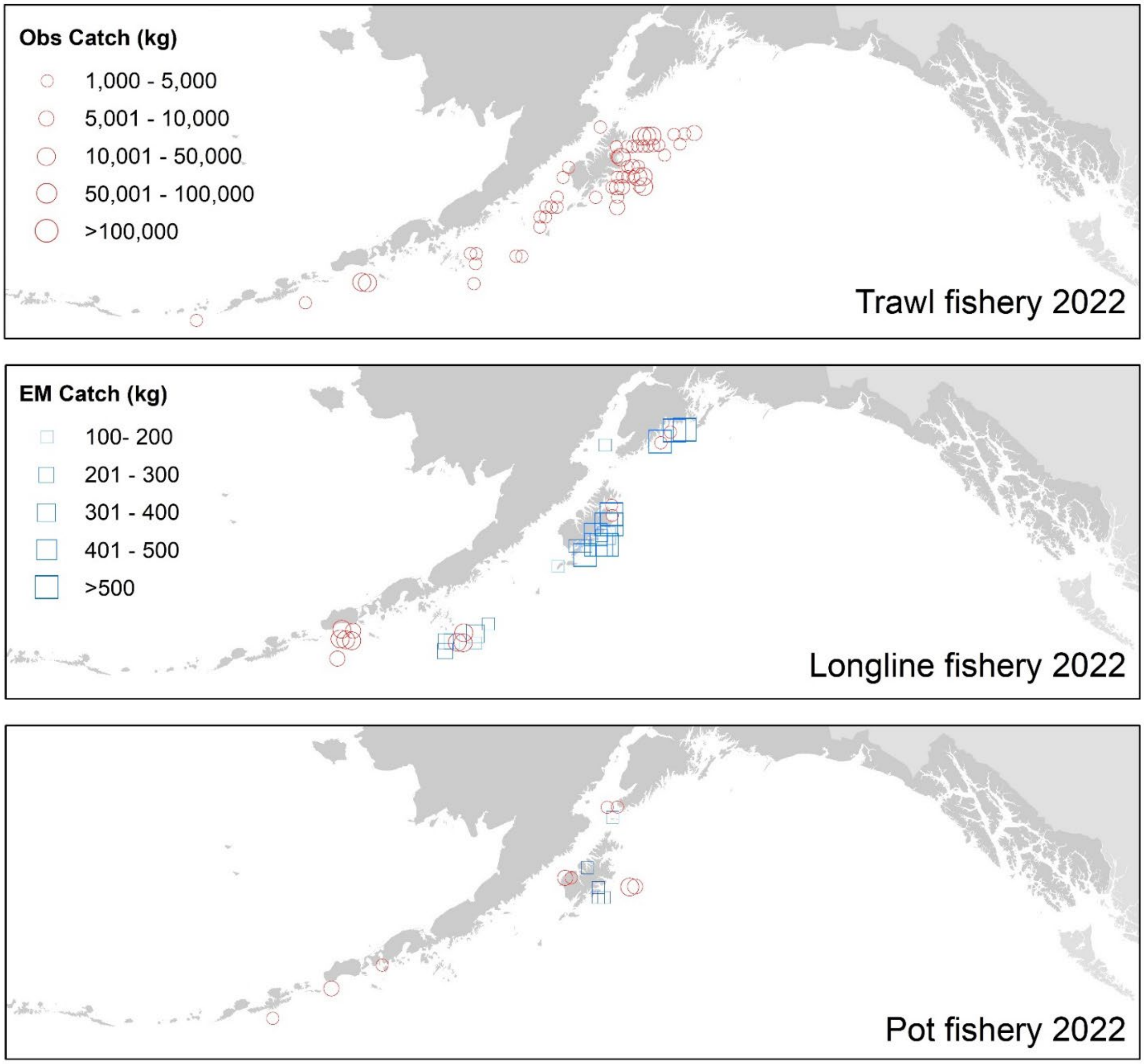

Figure 2.6. Observed (Obs) and electronic monitored (EM) commercial catch of Pacific cod in the Gulf of Alaska by 20km^2 grid for 2022These data include bycatch Pacific cod, but do not include trawl EM data as locations are not yet available.

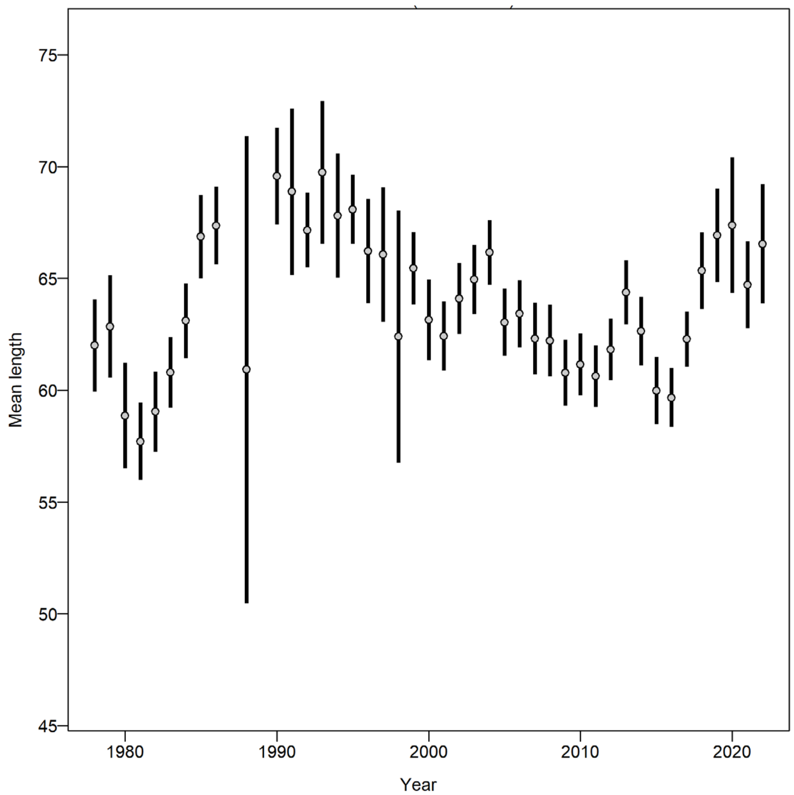

Figure 2.7. Mean length (cm) of Pacific cod from the Gulf of Alaska longline fishery.

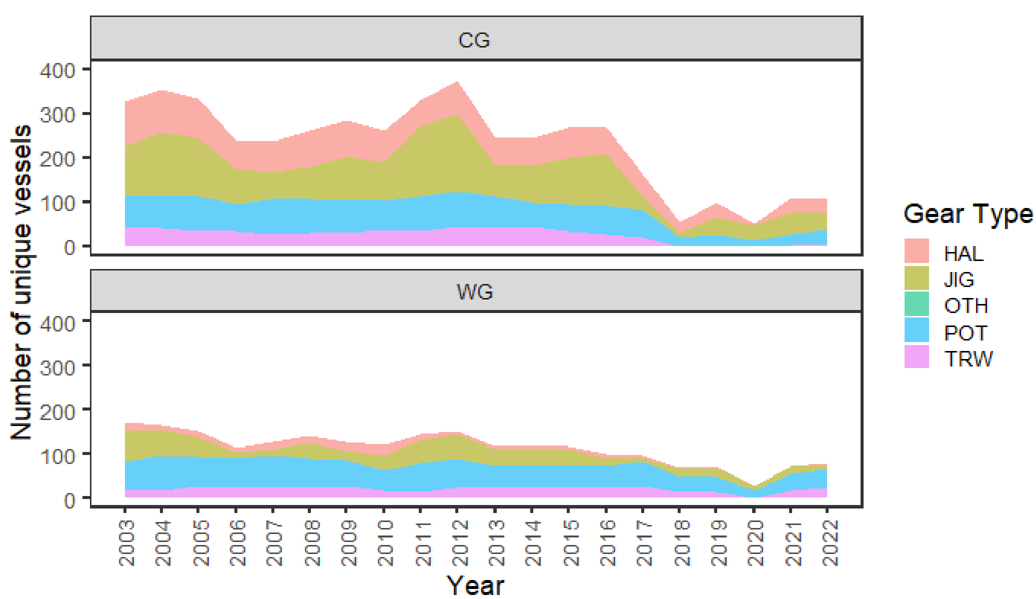

Figure 2.8. Vessel participation in the directed cod fishery by year.

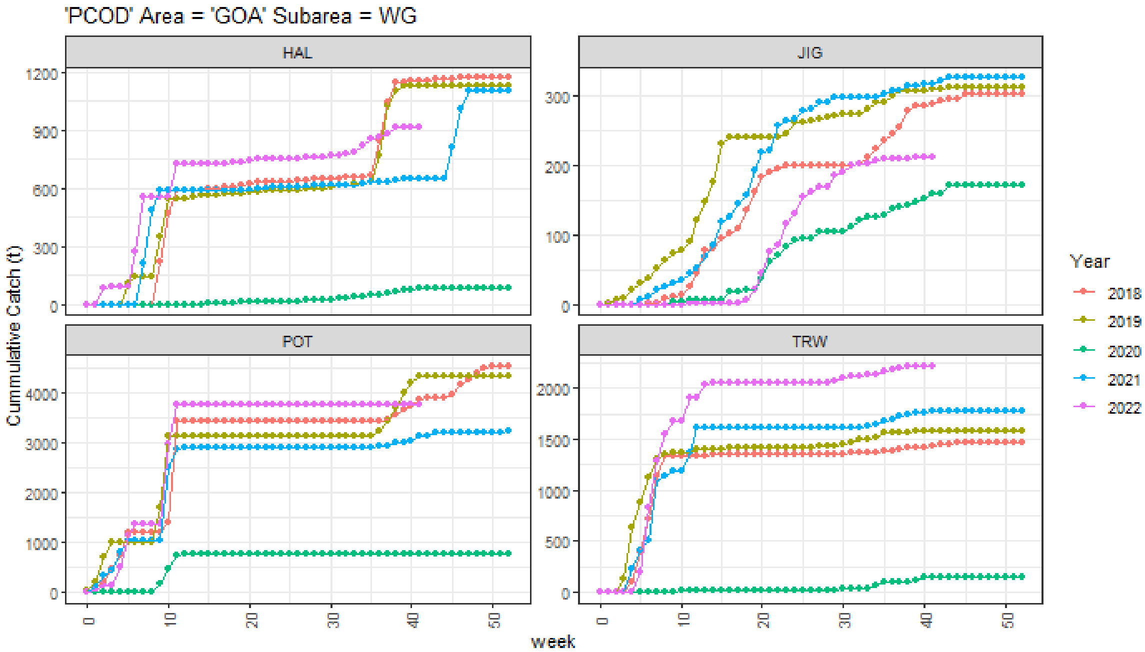

Figure 2.9. Cumulative catch week of the year for 2018-2022 by fleet for the Western Gulf of Alaska (2022 catch through week 41).

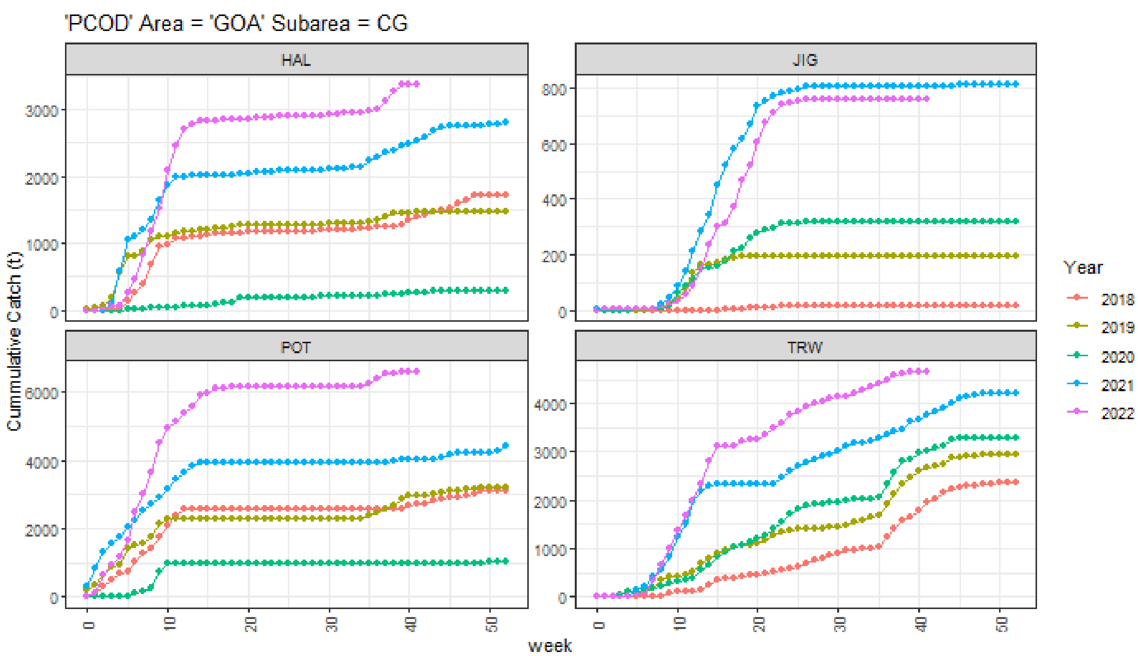

Figure 2.10. Cumulative catch week of the year for 2016-2021 by fleet for the Central Gulf of Alaska (2022 catch through week 41).

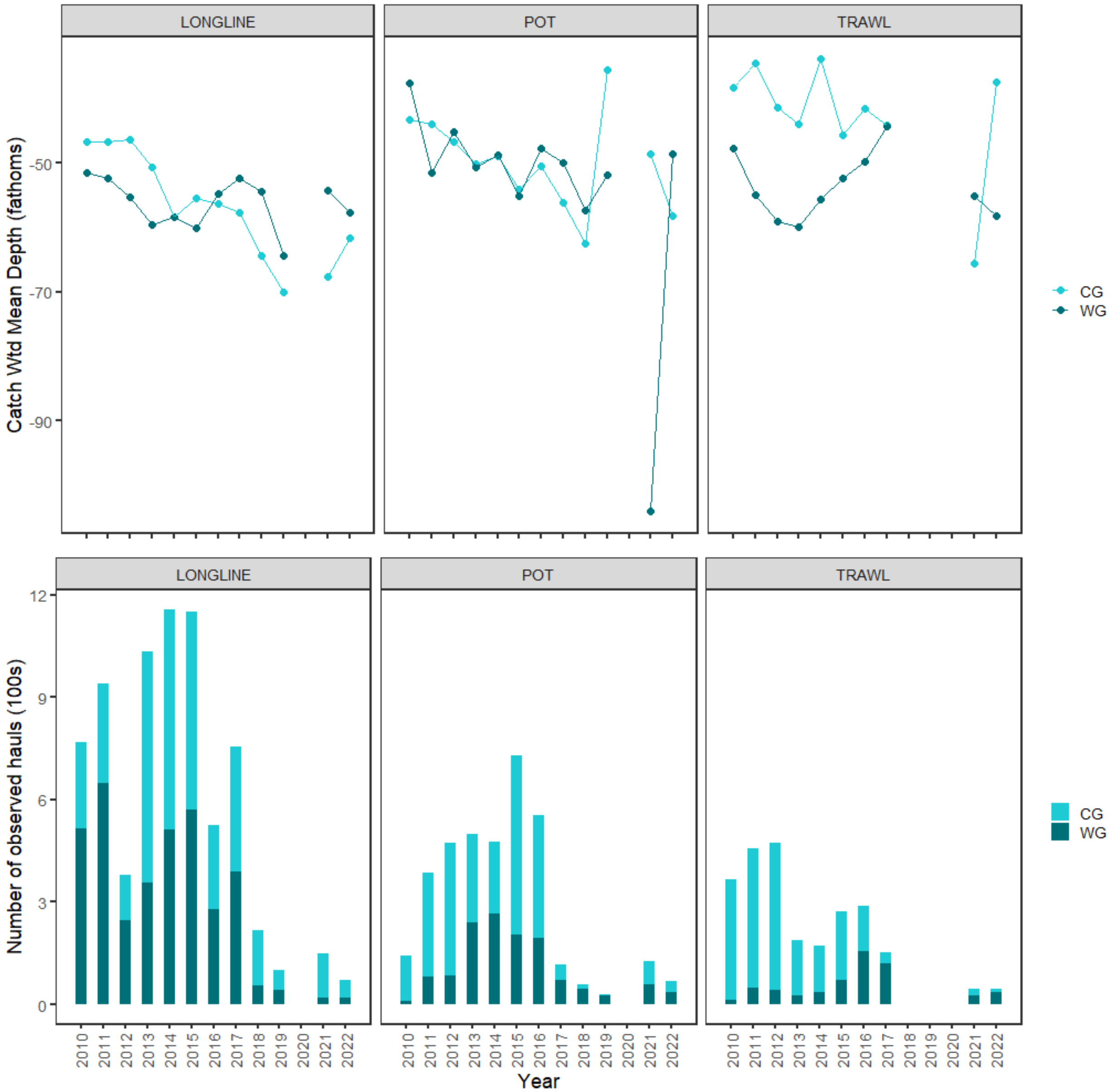

Figure 2.11. Catch weighted mean depth of directed fishing for Pacific cod (top) and the number of observed hauls by fishery and region (bottom).

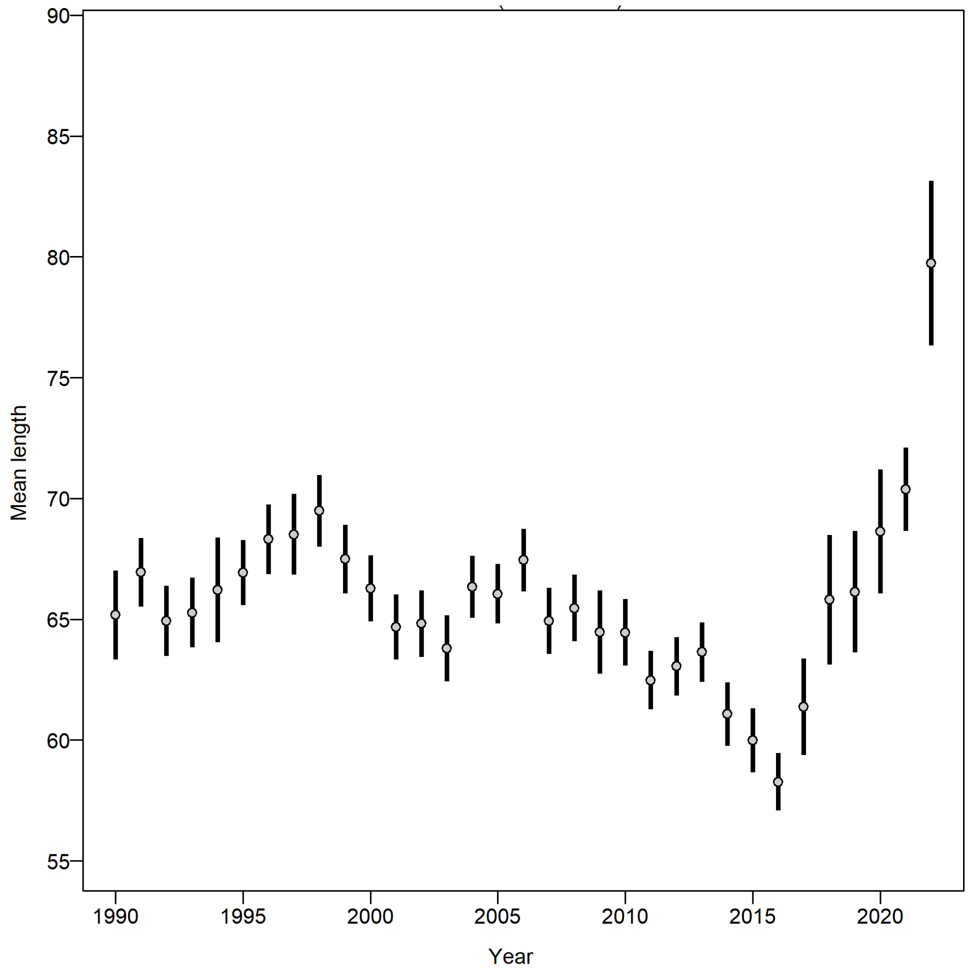

Figure 2.12. Mean length (cm) of Pacific cod from the Gulf of Alaska pot fishery.

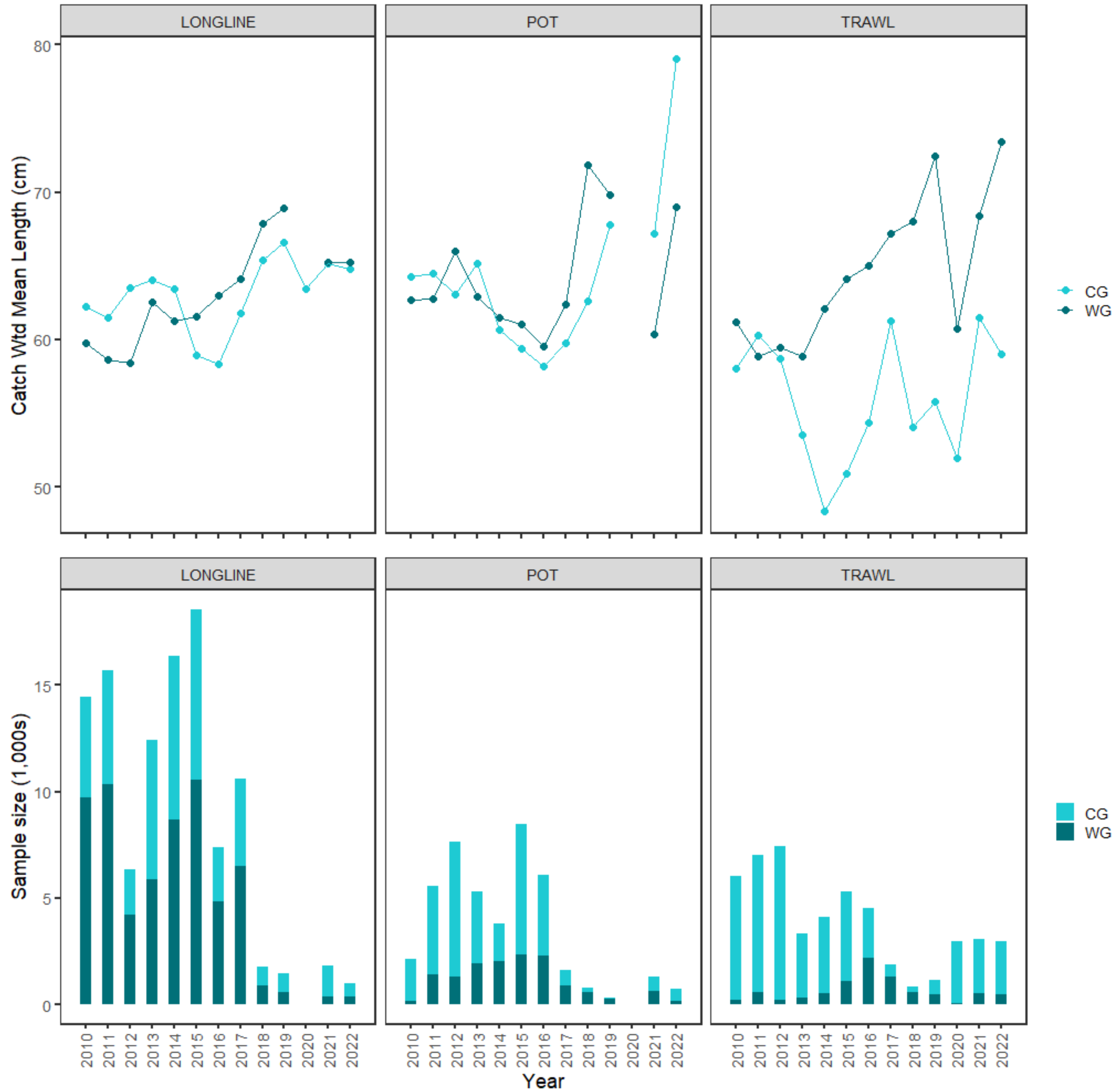

Figure 2.13. Catch weighted mean length by fishery and region (top) and the number of lengths sampled by fishery and region (bottom). These data include both directed and incidental catch.

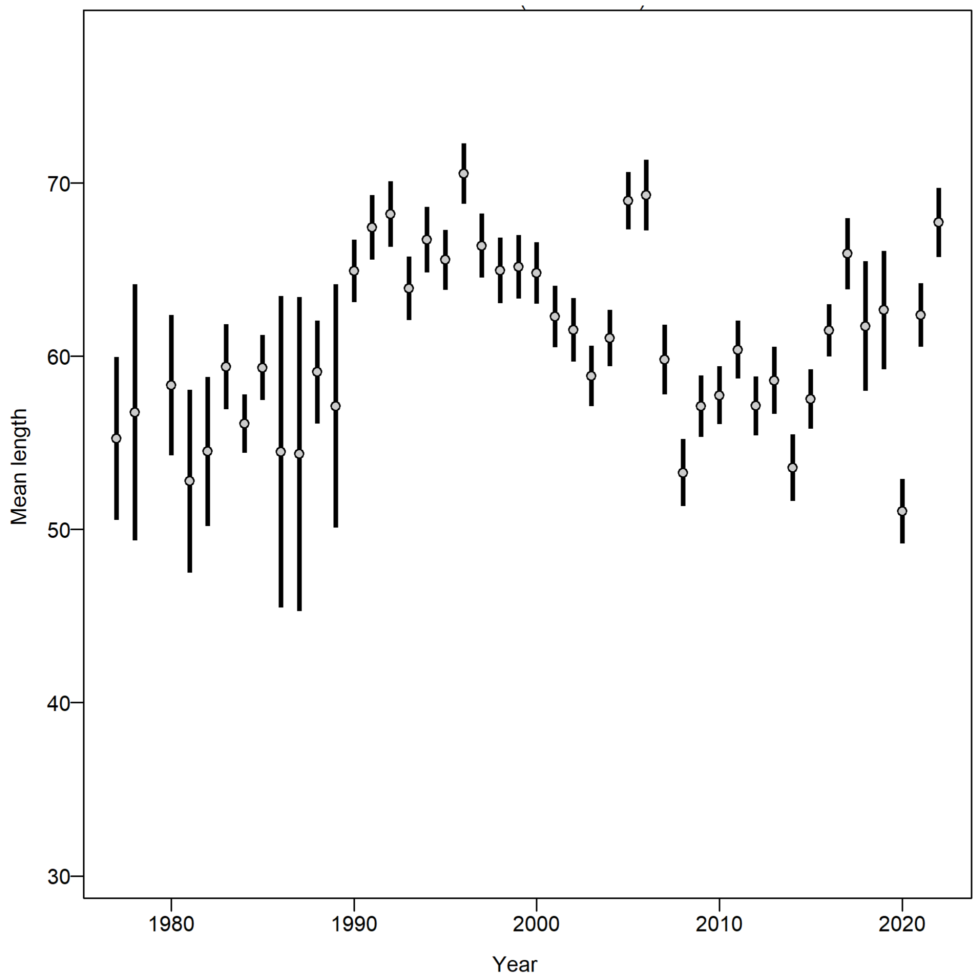

Figure 2.14. Mean length (cm) of Pacific cod from the Gulf of Alaska trawl fishery.

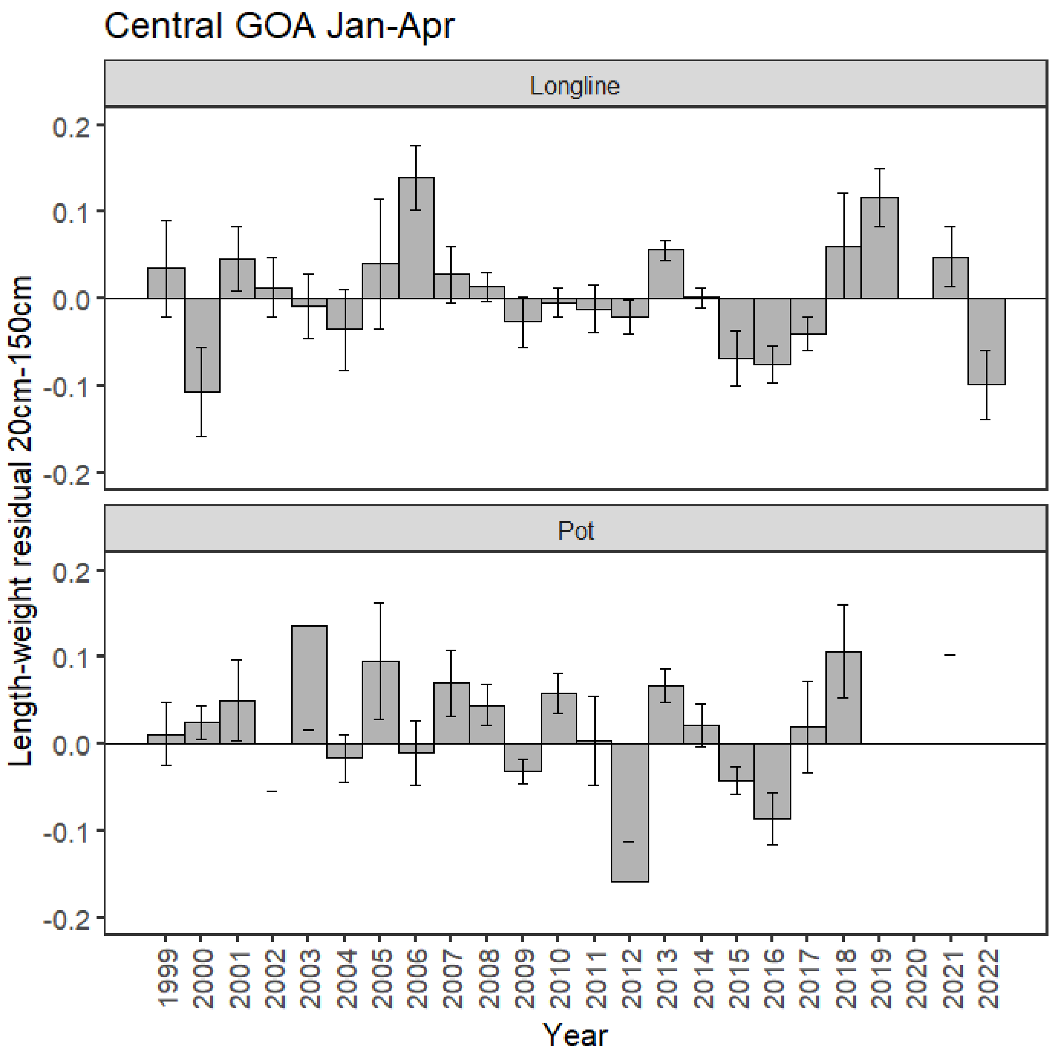

Figure 2.15. Condition of Pacific cod by year in the Central GOA in January-April. Years with zero residuals without error bars are without data.

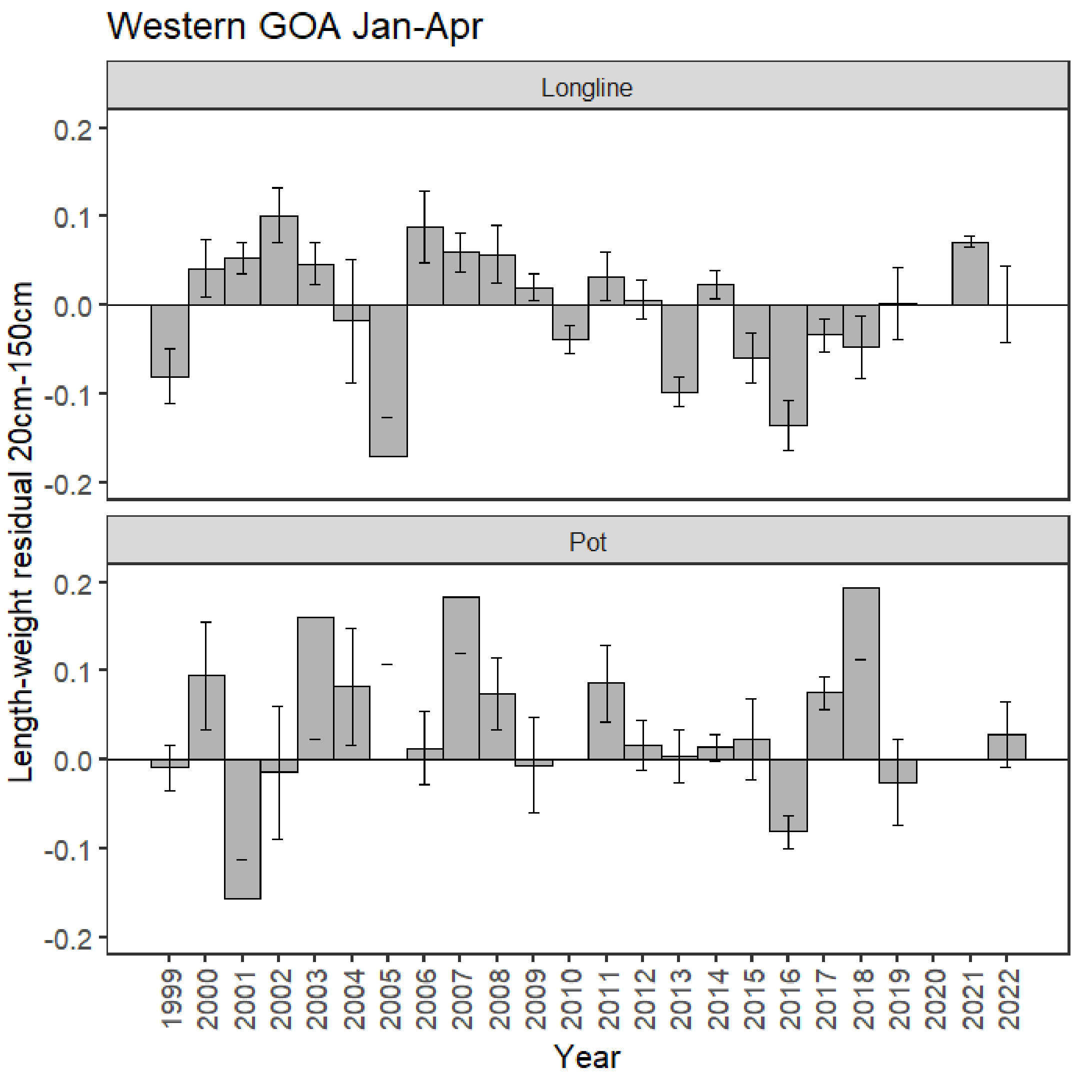

Figure 2.16. Condition of Pacific cod by year in the Western GOA in January-April. Years with zero residuals without error bars are years without data.

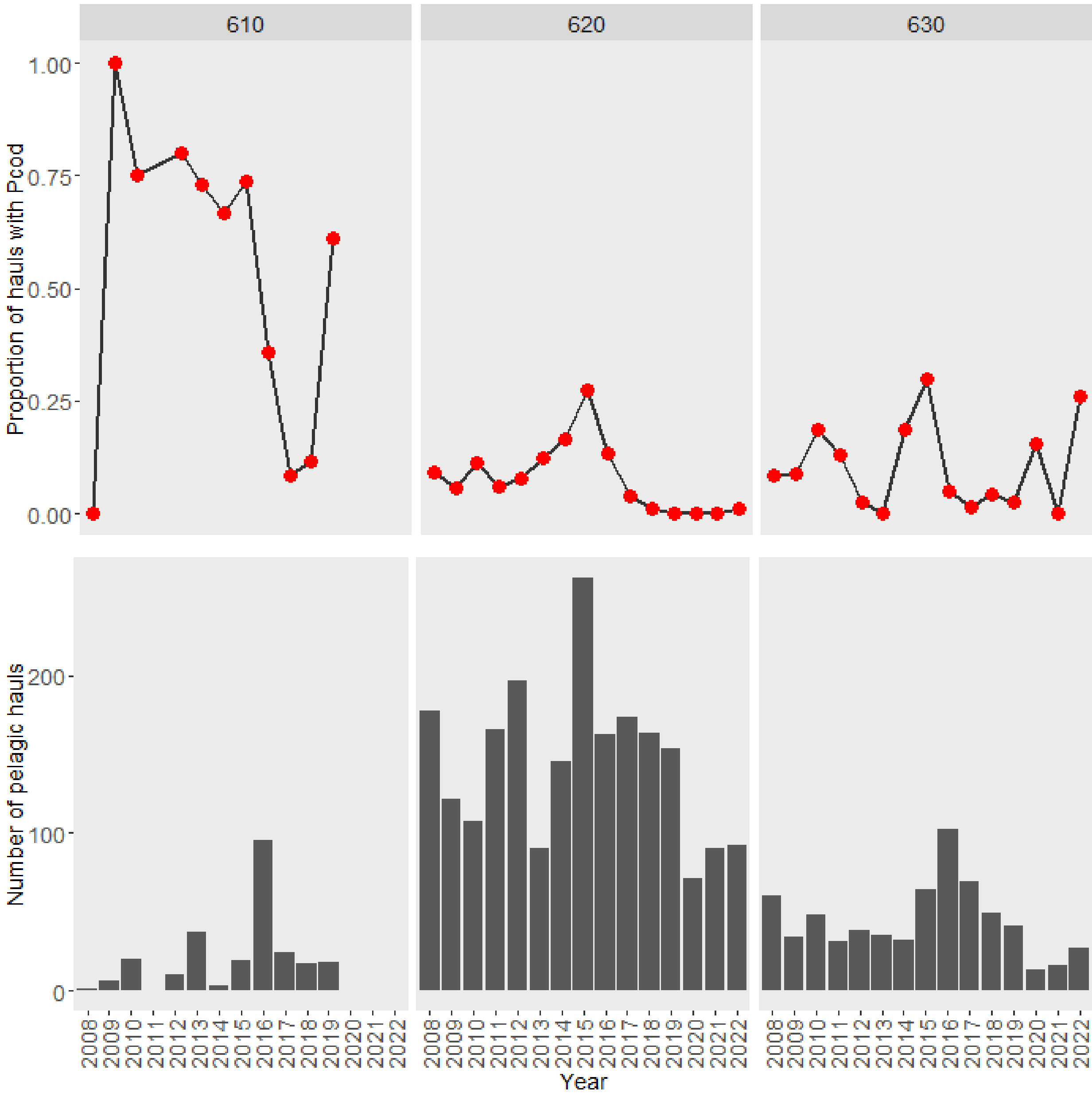

Figure 2.17. Proportion of pelagic trawls in the A Season (January-April) walleye pollock fishery with Pacific cod present by region (top) and number of hauls (bottom).

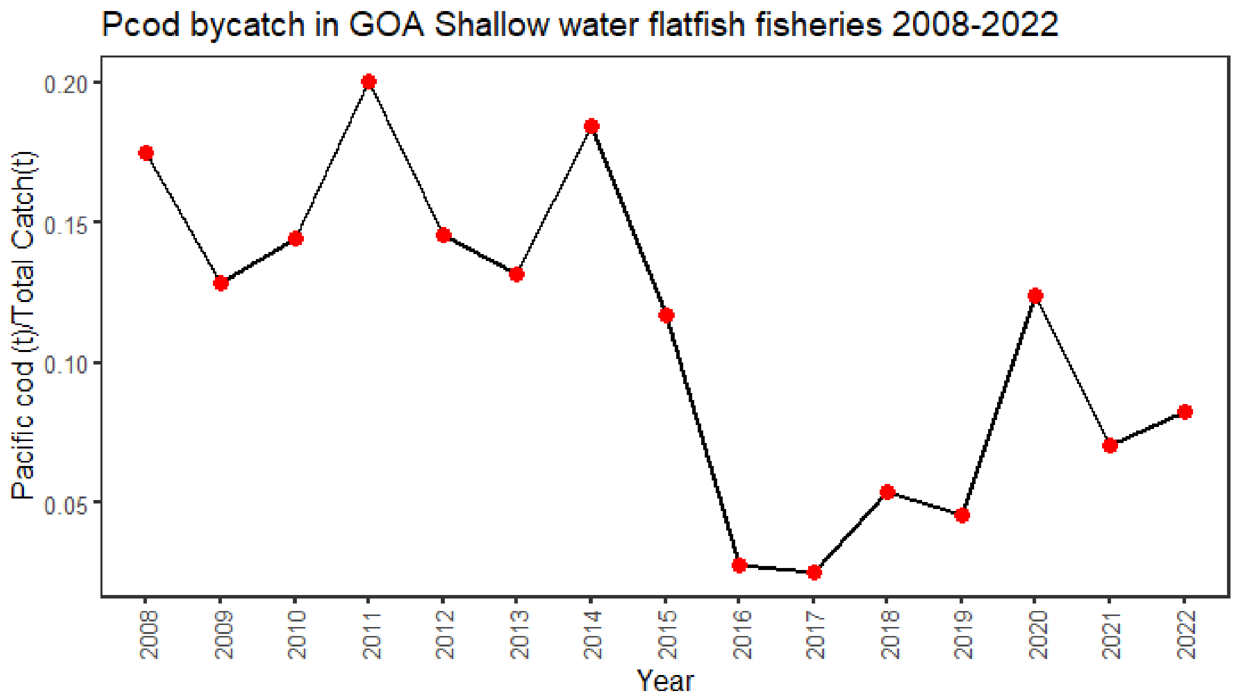

Figure 2.18. Pacific cod bycatch in the Gulf of Alaska shallow water flatfish fishery as tons of Pacific cod per tons of total catch in the fishery by year.

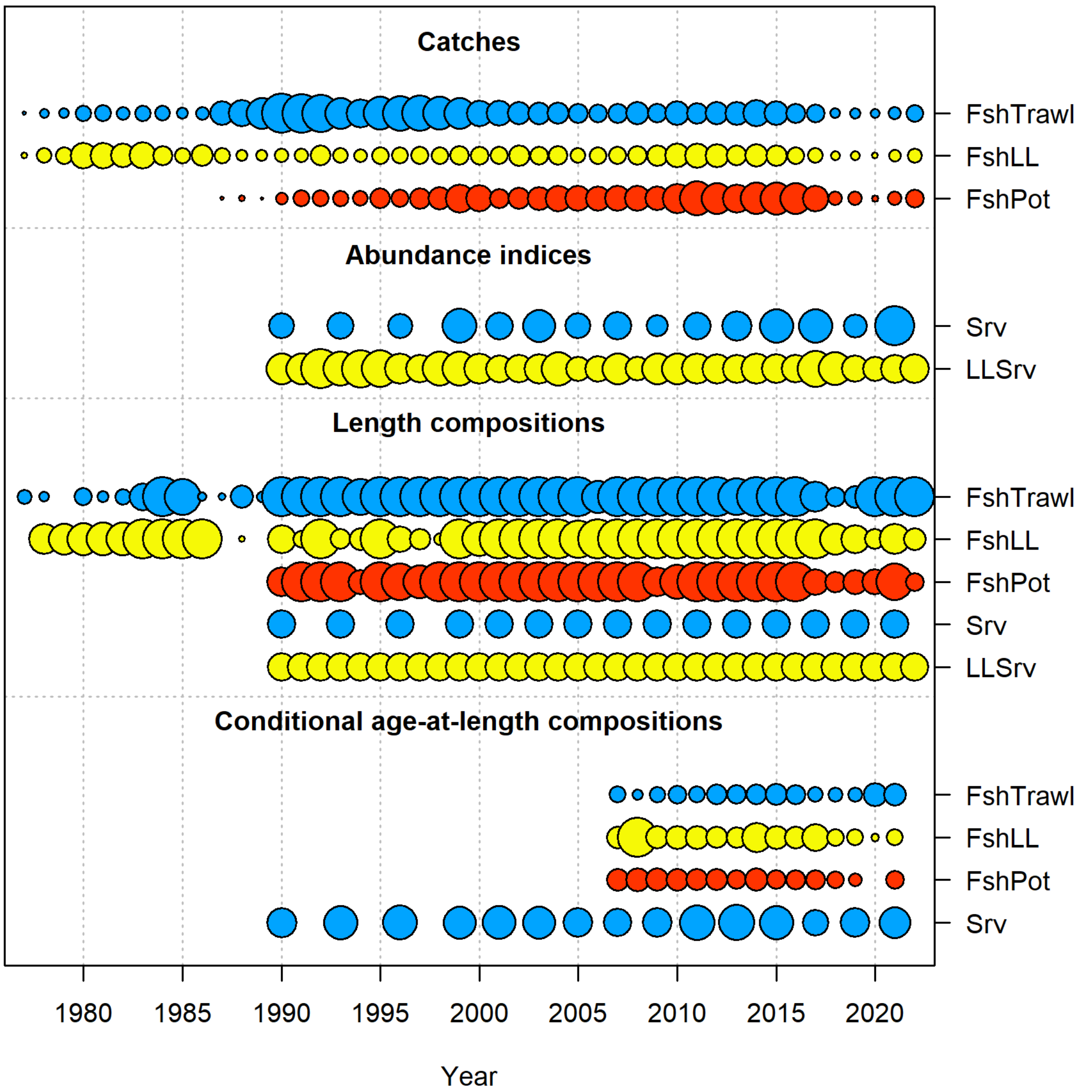

Figure 2.19. Data fit in Model 19.1a. Circles are proportional to total catch for catches; to precision for indices and to total sample size for compositions and length-at-age observations. Note that since the circles are scaled relative to maximum within each type, the plots of scaling across dataset types should not be compared.

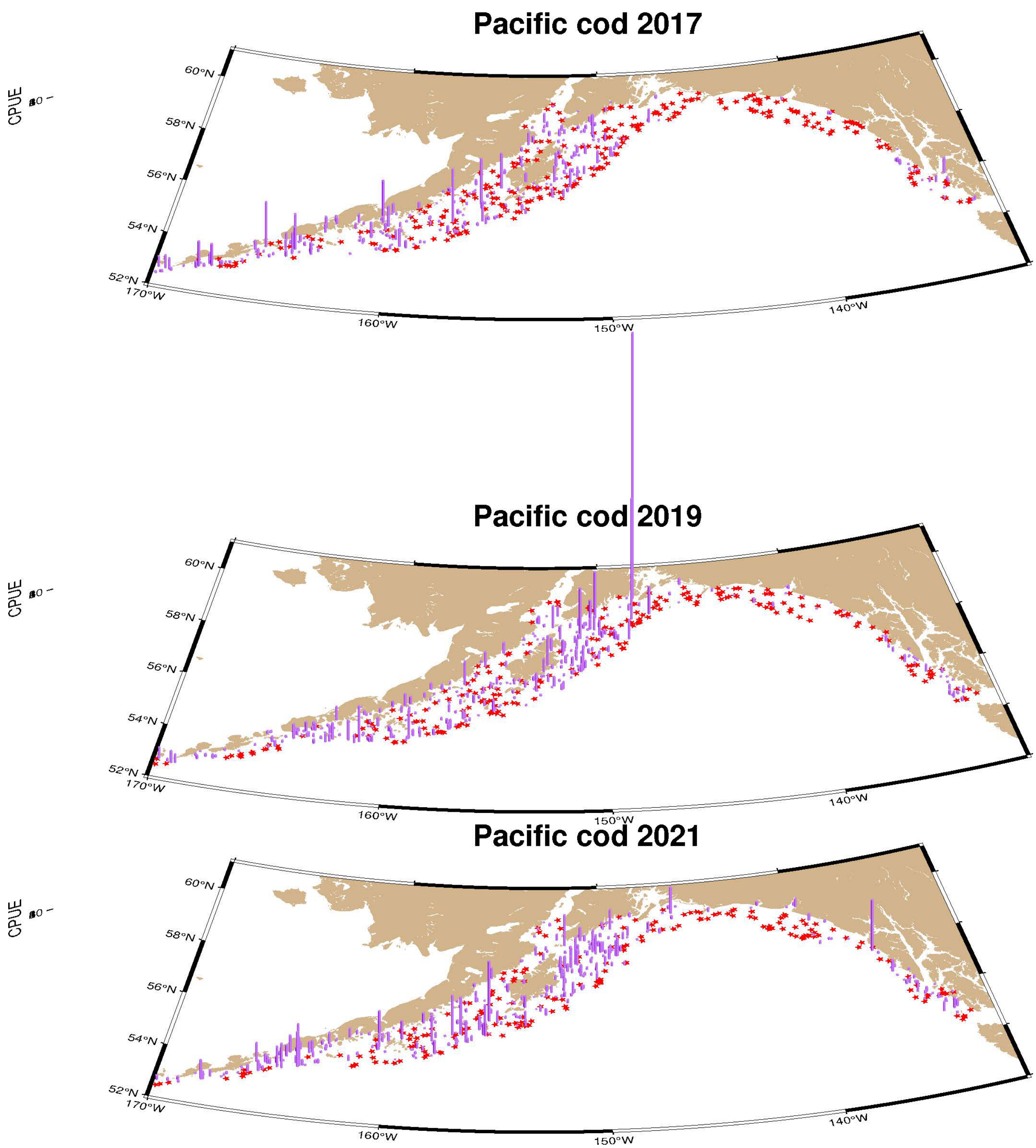

Figure 2.120. Distribution of AFSC bottom trawl survey CPUE of Pacific cod for 2017-2021.

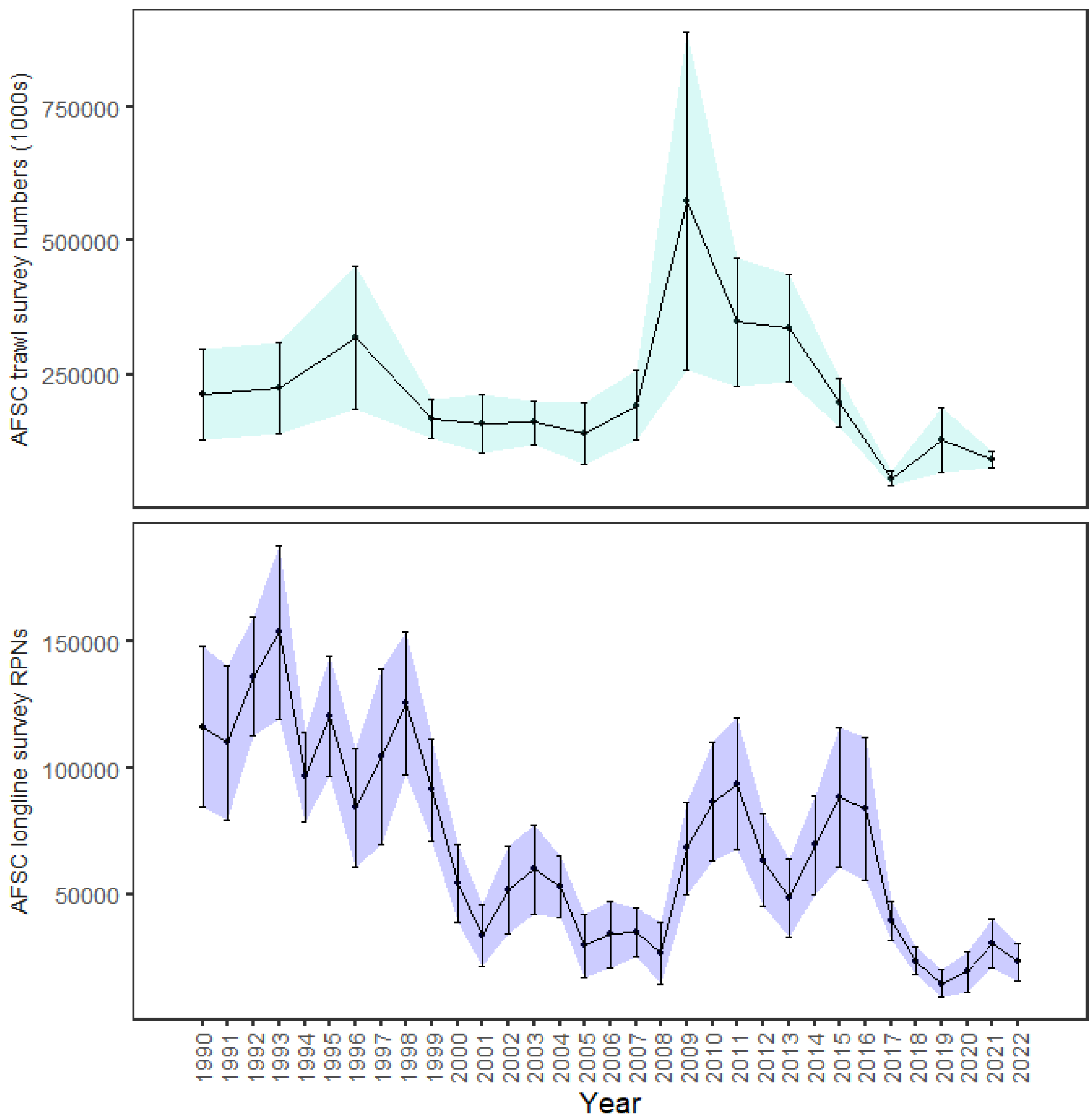

Figure 2.21. Population indices fit by the assessment model, including AFSC bottom trawl survey abundance (numbers – top panel) and AFSC longline survey relative population numbers (RPN – bottom panel). Bars and shading indicate the 95th percentile confidence intervals.

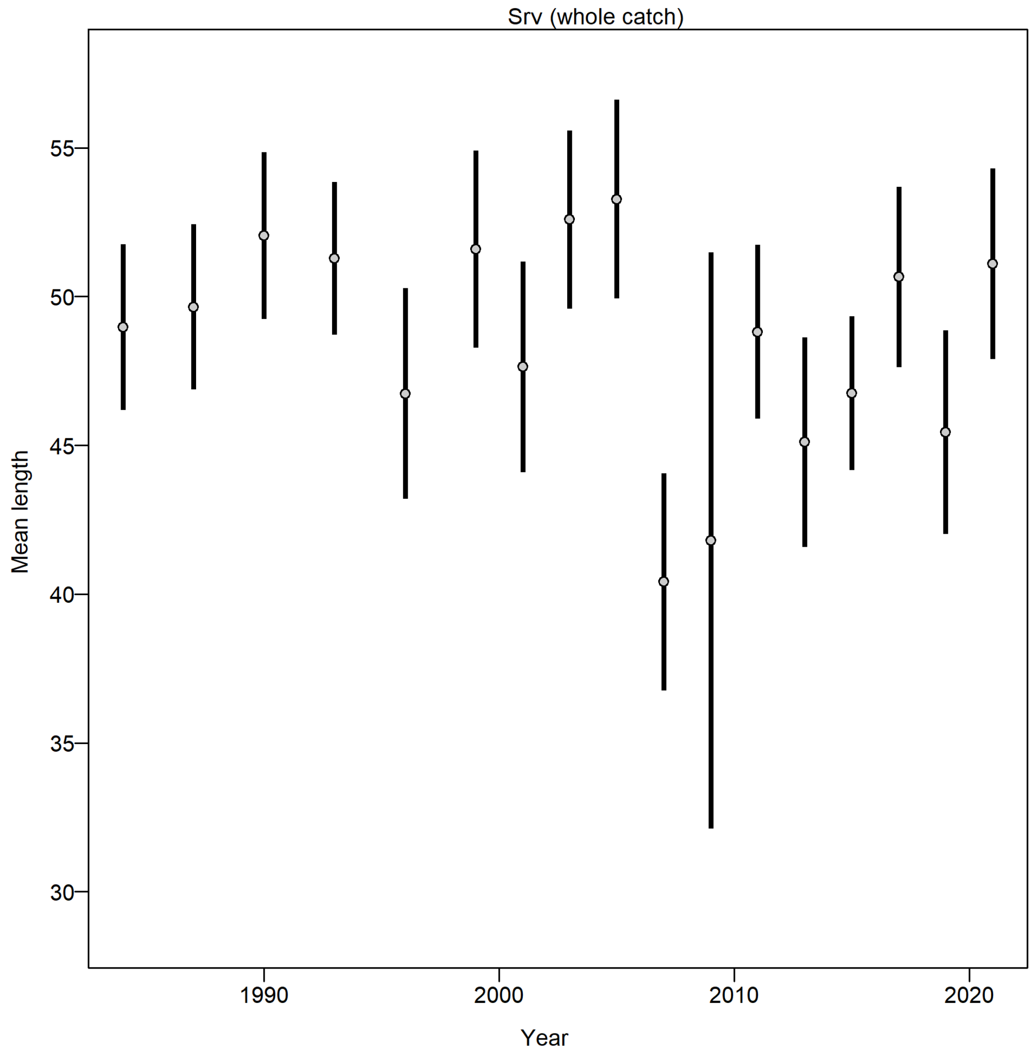

Figure 2.22. Mean length (cm) of Pacific cod in the AFSC GOA bottom trawl survey.

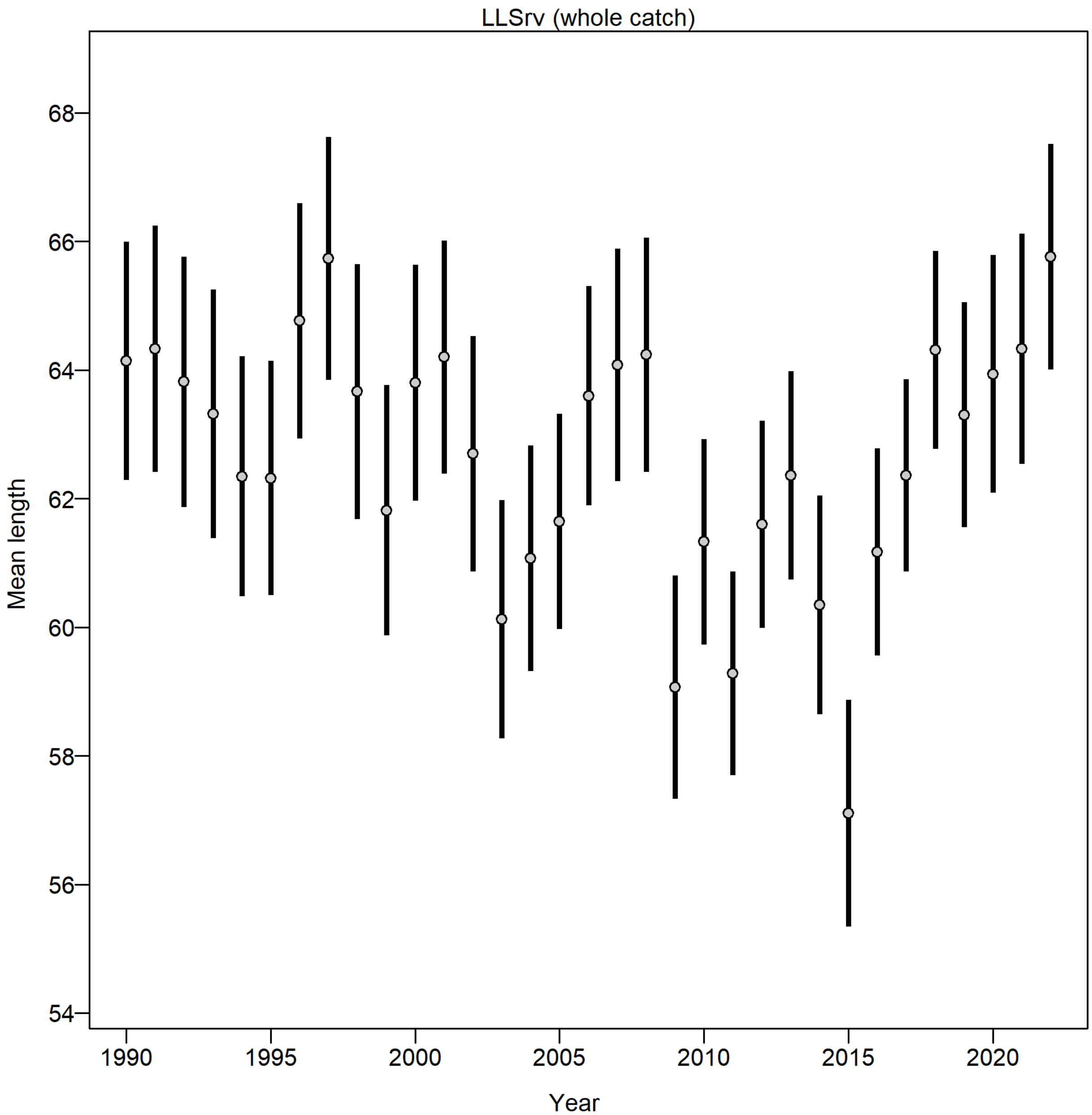

Figure 2.23. Mean length (cm) of Pacific cod from the AFSC longline survey.

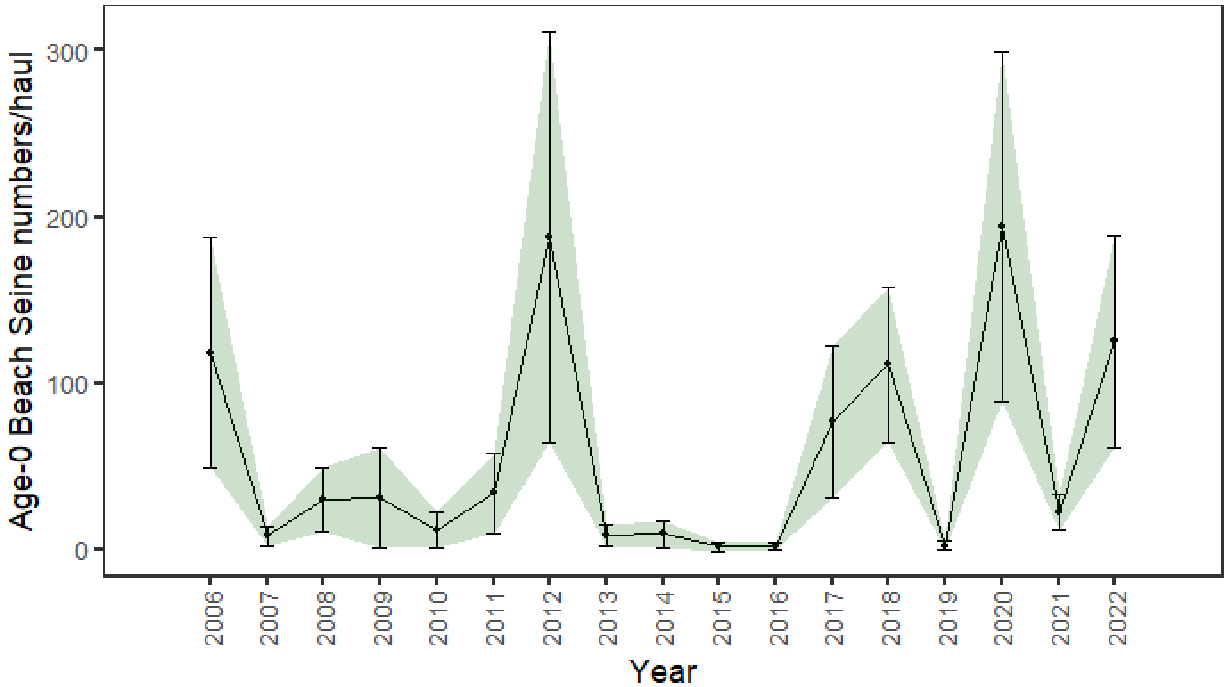

Figure 2.24. Age-0 beach seine survey numbers per haul, bars and shading indicate the 95th percentile confidence intervals.

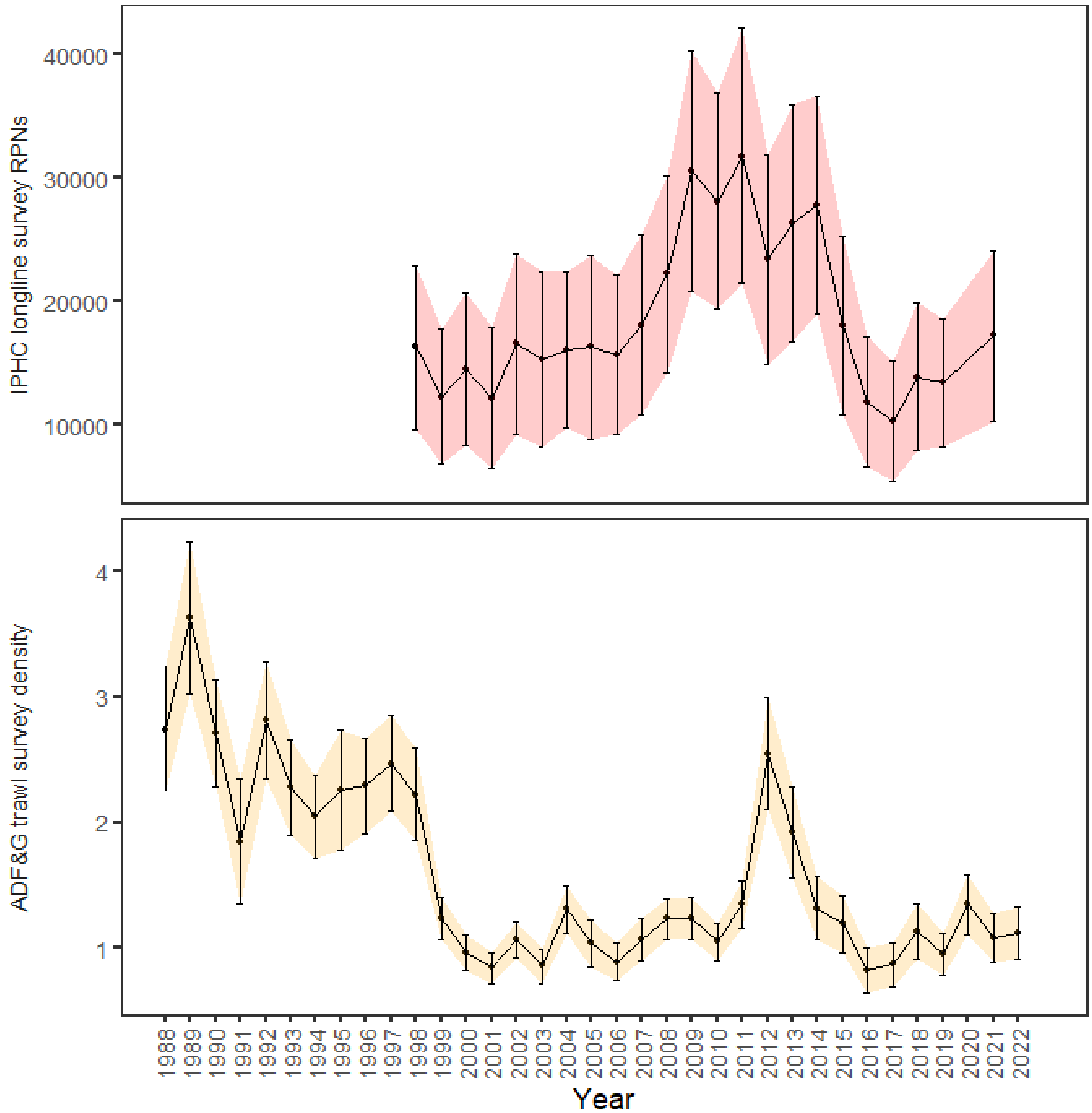

Figure 2.25. Population indices included for consideration but not fit in the assessment, including the IPHC longline survey relative population numbers (RPN – top panel) and ADF&G bottom trawl survey delta-glm density (bottom panel). Bars and shading indicate the 95th percentile confidence intervals.

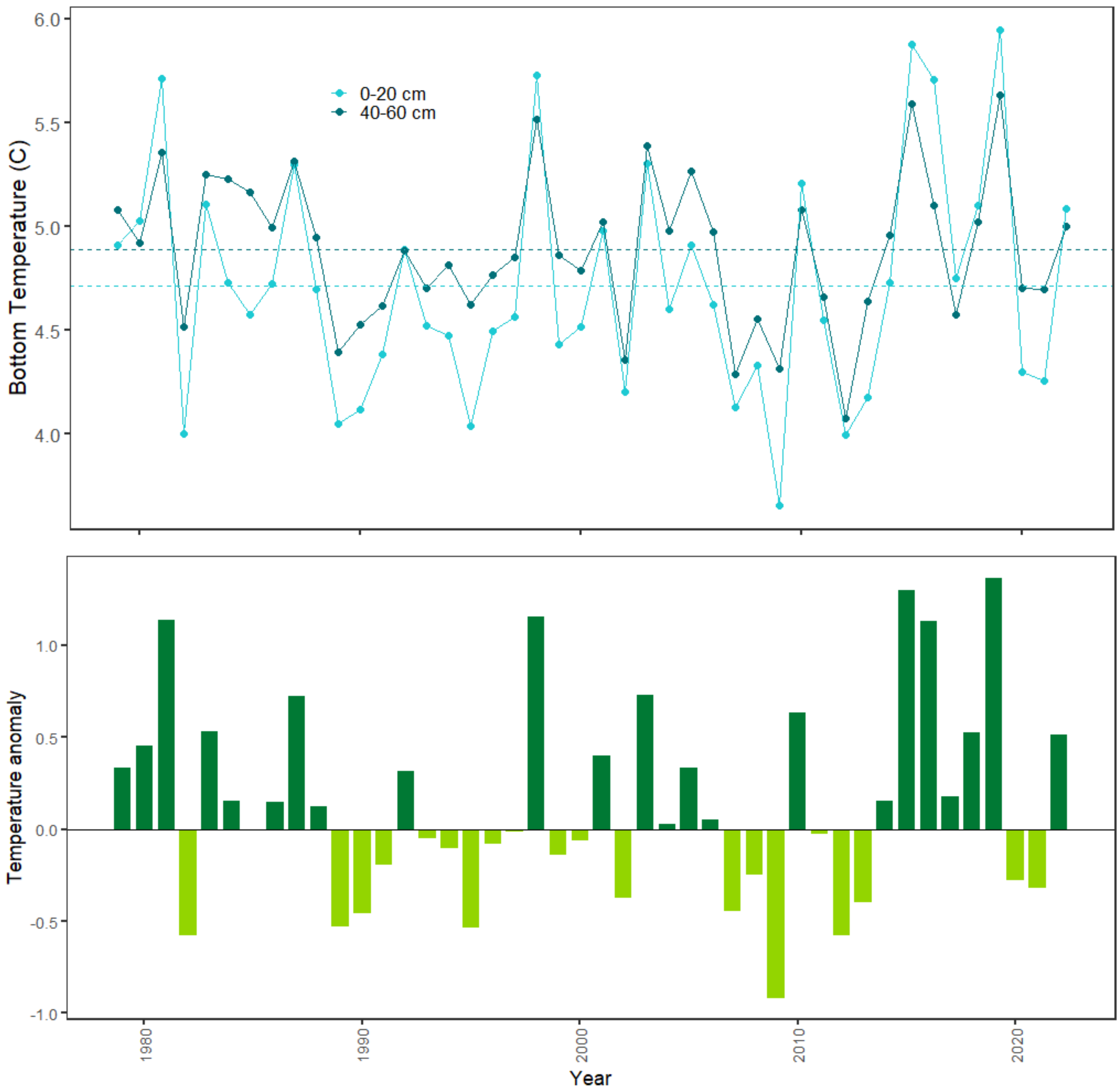

Figure 2.26. Climate Forcast System Reanalysis (CFSR) Central Gulf of Alaska bottom temperatures at the AFSC bottom trawl survey mean depths for 0-20 cm and 40-60 cm Pacific cod in June (top) and temperature anomailies used as a covariate to the AFSC longline survey catchability (bottom).

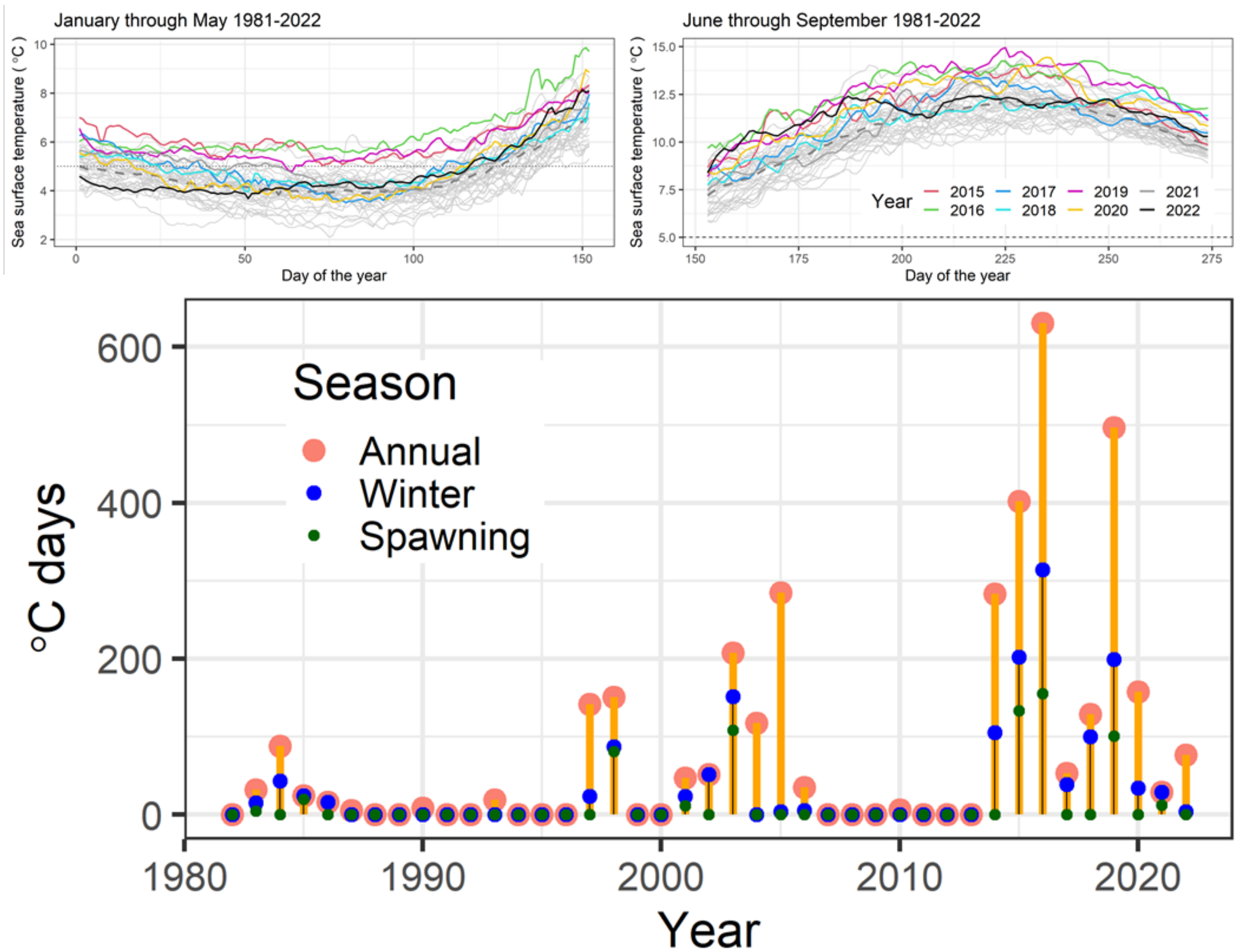

Figure 2.27. Sea surface temperatures February to March (top left), June through September (top right), and index of the sum of the annual marine heatwave cumulative intensity (°C days) for 1981-2021 (larger yellow points) and index of the sum of the annual winter marine heatwave cumulative intensity for 1981-2021 (smaller blue points) from the daily mean sea surface temperatures NOAA high resolution blended analysis data for the Central Gulf of Alaska (bottom). The 2022 index value is the sum through 13 September 2022.

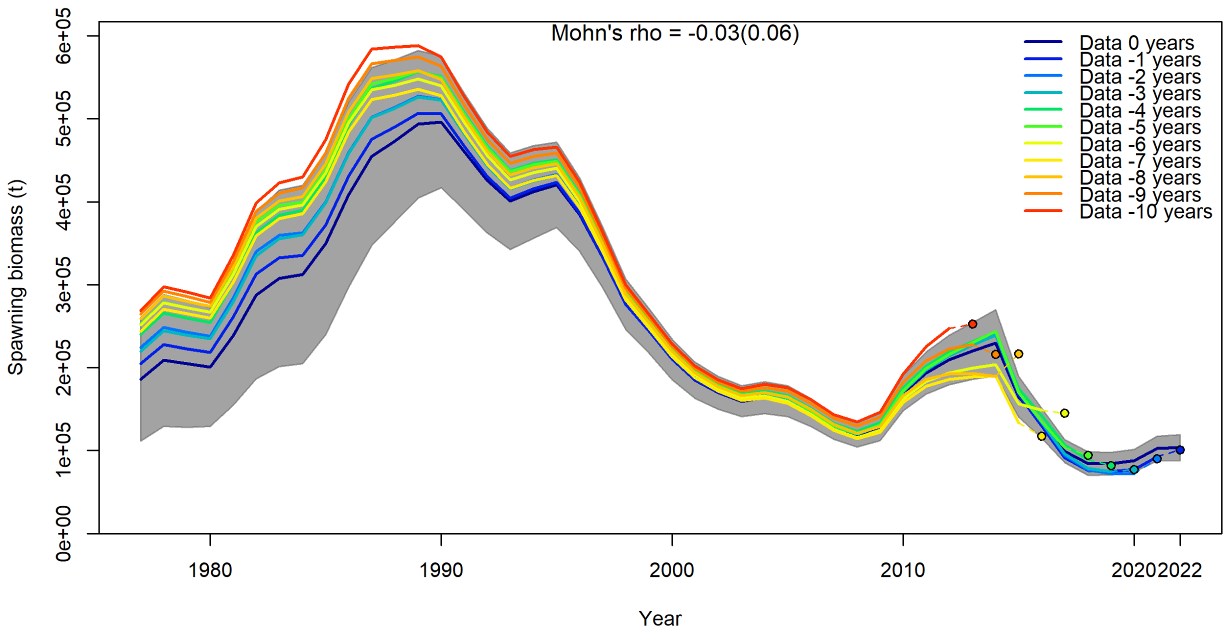

Figure 2.28. Retrospective analysis of spawning biomass for Model 19.1a (overall Mohn's rho shown, with Mohn's rho for forecasted biomass shown in parentheses).

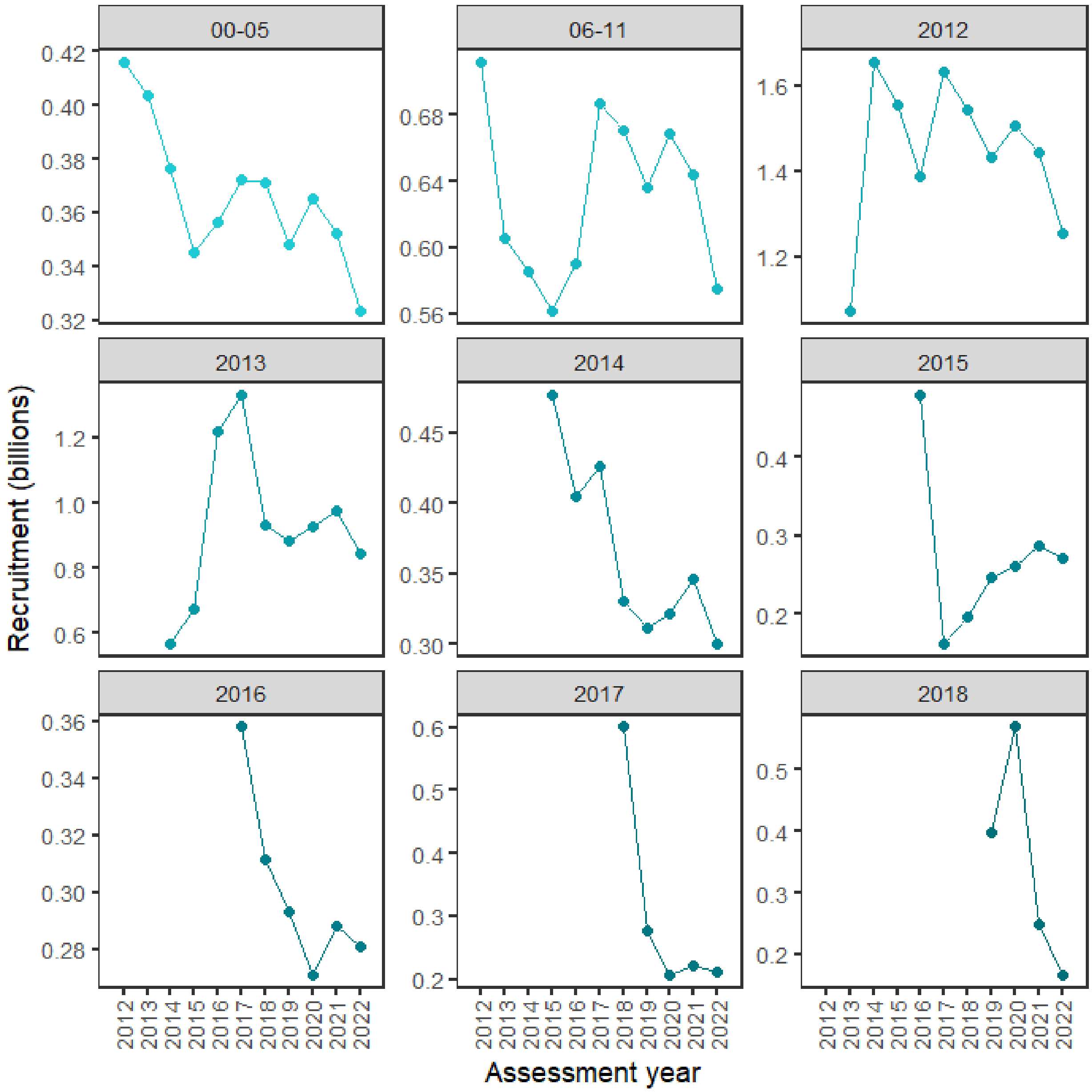

Figure 2.29. Retrospective analysis of recruitment by recent year classes (denoted at the top of each panel) for Model 19.1a.

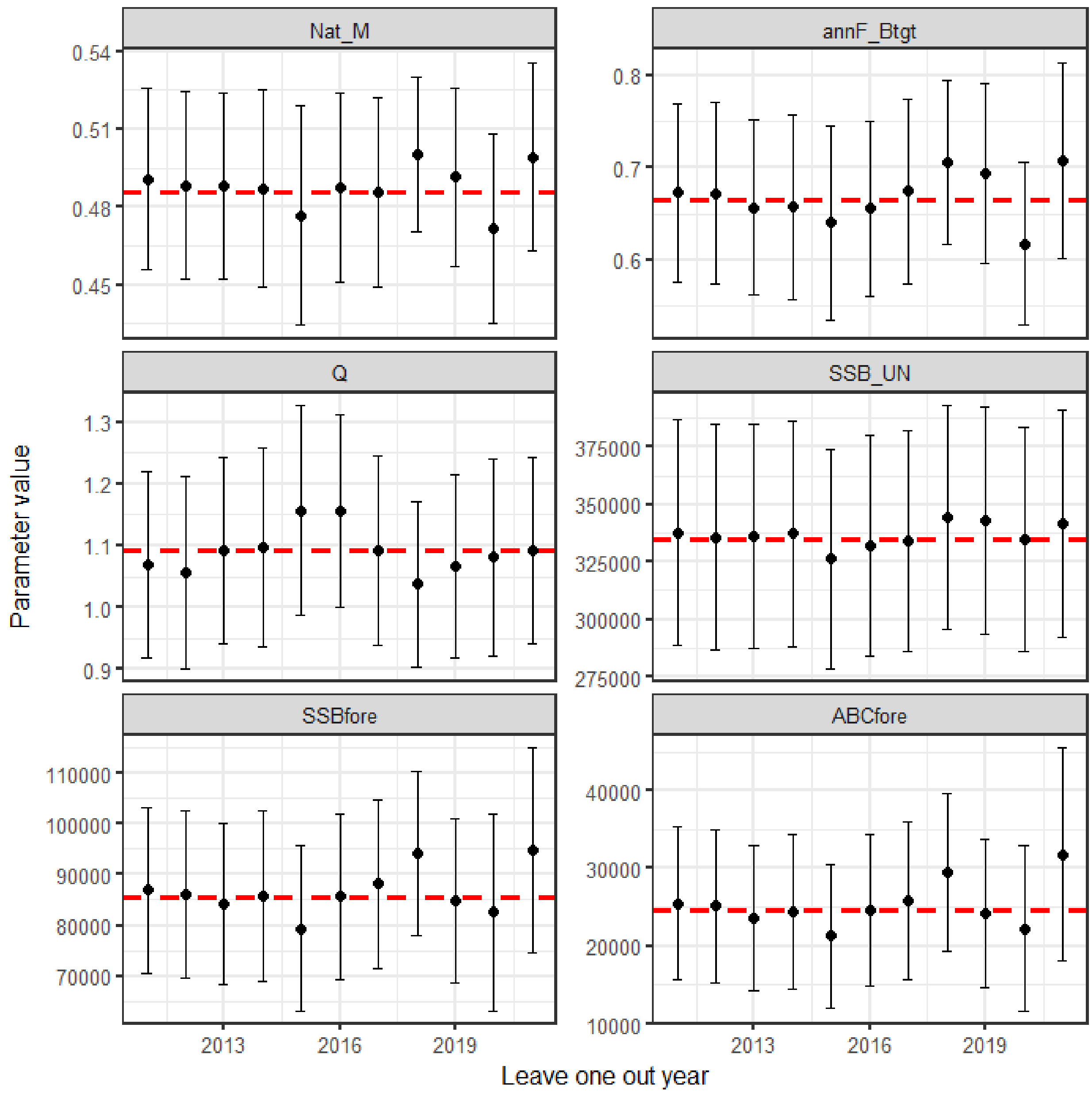

Figure 2.30. Model 19.1a leave-one-out analysis showing parameters and derived quantities as one year of data were removed from the model fit. Nat_M is the base natural mortality, annF_Btgt is the $F_{40\%}$, Q is the AFSC bottom trawl catchability, SSB_UN is the unfished spawning biomass, SSBfore is the total spawning biomass for 2023 and ABCfore is the estimated ABC for 2023.

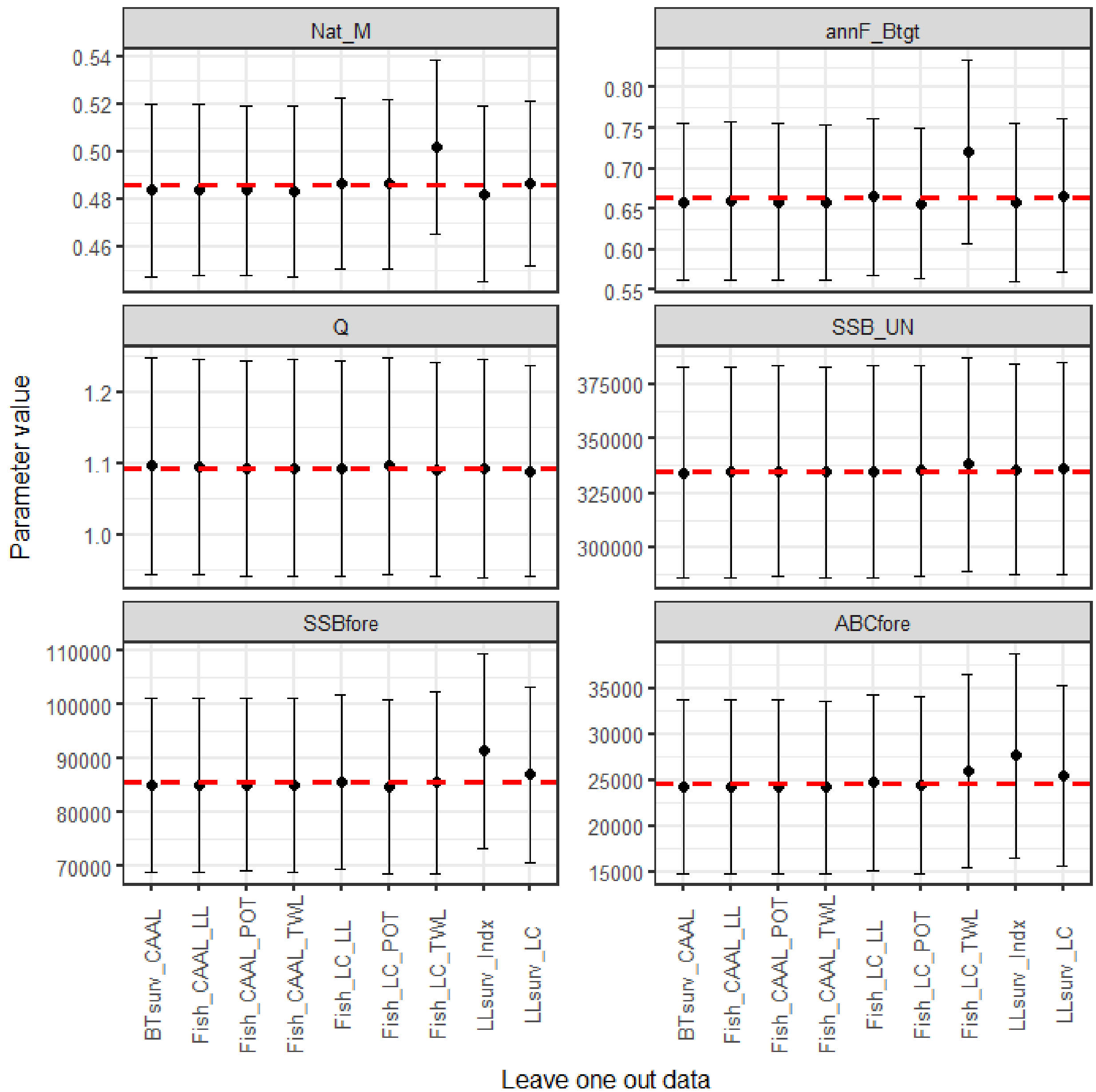

Figure 2.31. Model 19.1a leave-one-out analysis showing parameters and derived quantities as one data source added to this years assessment were removed from the model fit. CAAL denotes conditional age-at-length data, LC denotes length comp data, and Indx denotes index data from the bottom trawl survey (BTsurv), longline survey (LLsurv) and fisheries (denoted with gear type). The parameters and quantities are as in Fig. 2.29.

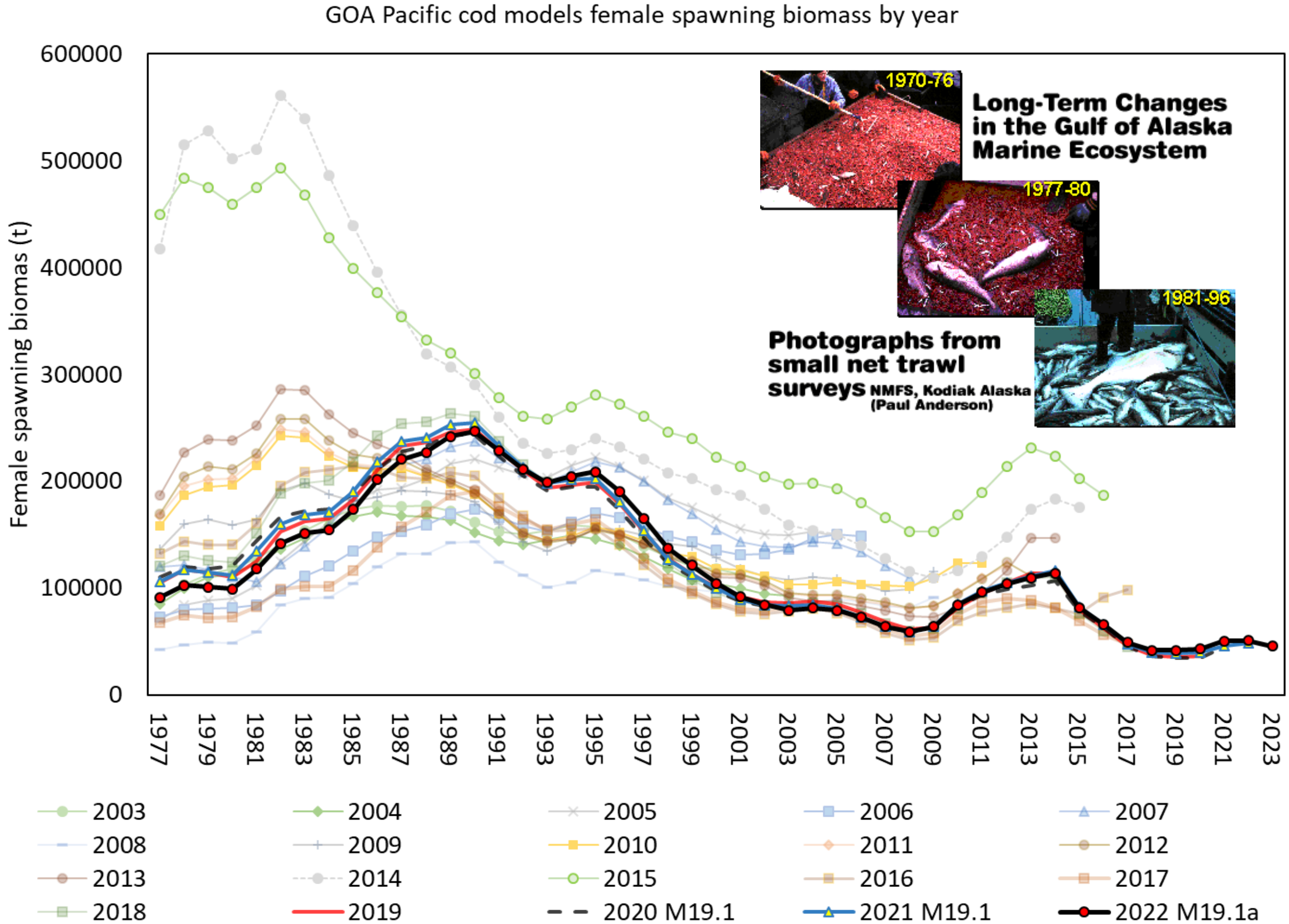

Figure 2.32. Gulf of Alaska Pacific cod estimated female spawning biomass from the 2003 through 2022 stock assessments and (inset) images from the NMFS small net surveys off Kodiak Alaska showing change in species composition over time from: https://www.thenakedscientists.com/articles/science-features/ecosystem-shifts-and-sharks-alaska

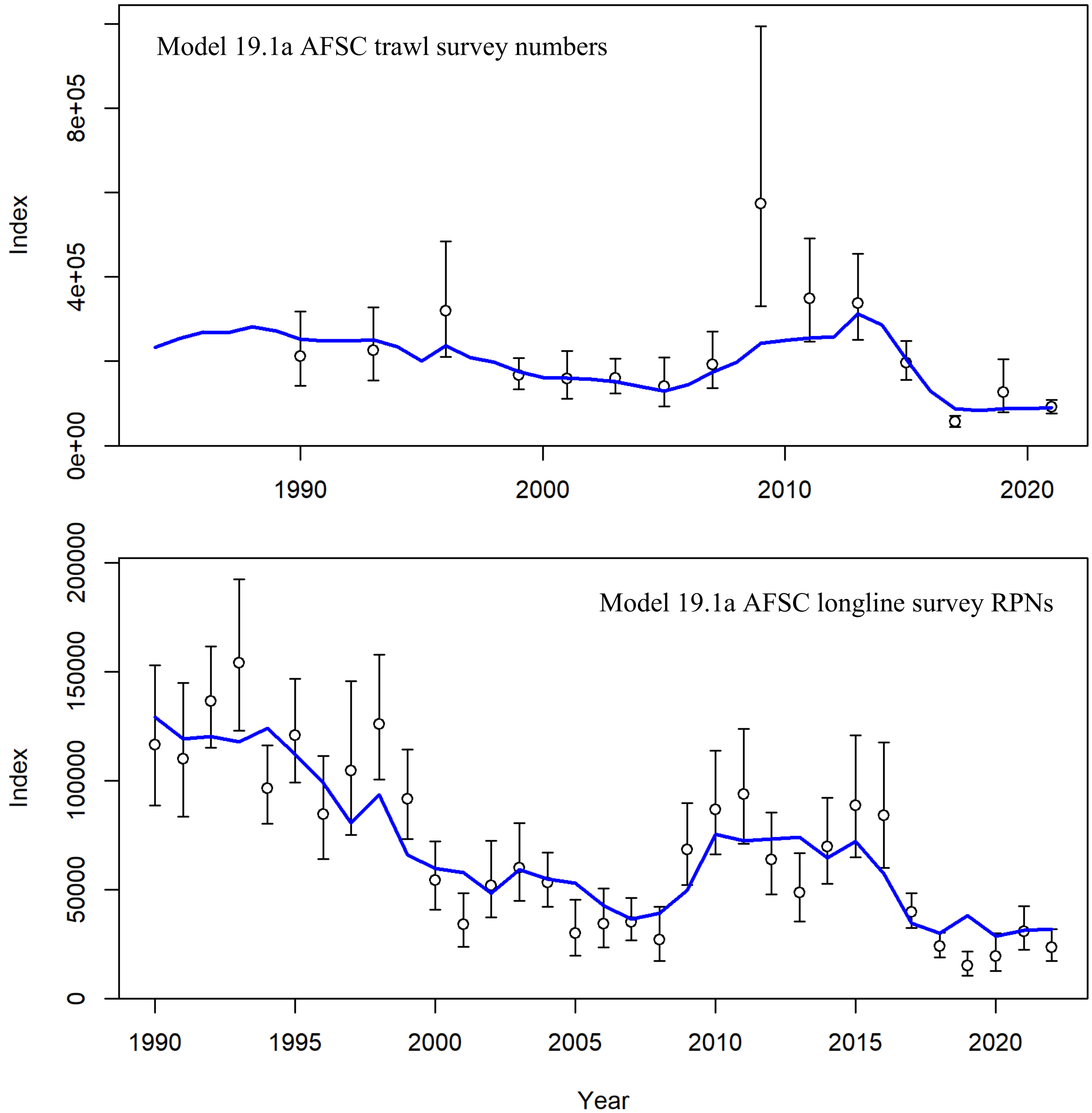

Figure 2.33. Model fits to AFSC bottom trawl survey numbers (top) and AFSC longline survey relative population numbers (RPNs, bottom).

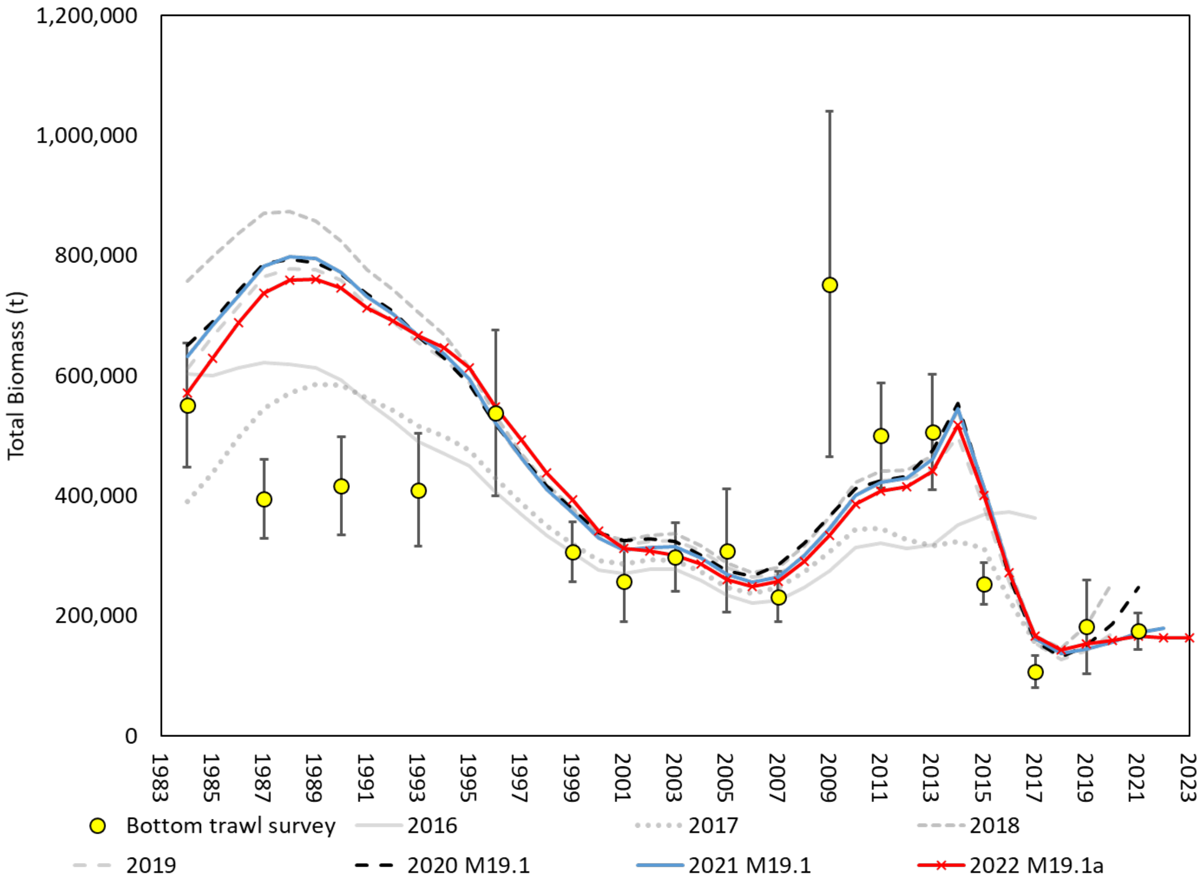

Figure 2.34. Total biomass estimates from 2016 through 2022 stock assessments and NMFS bottom trawl survey biomass estimates with 95% confidence bounds.

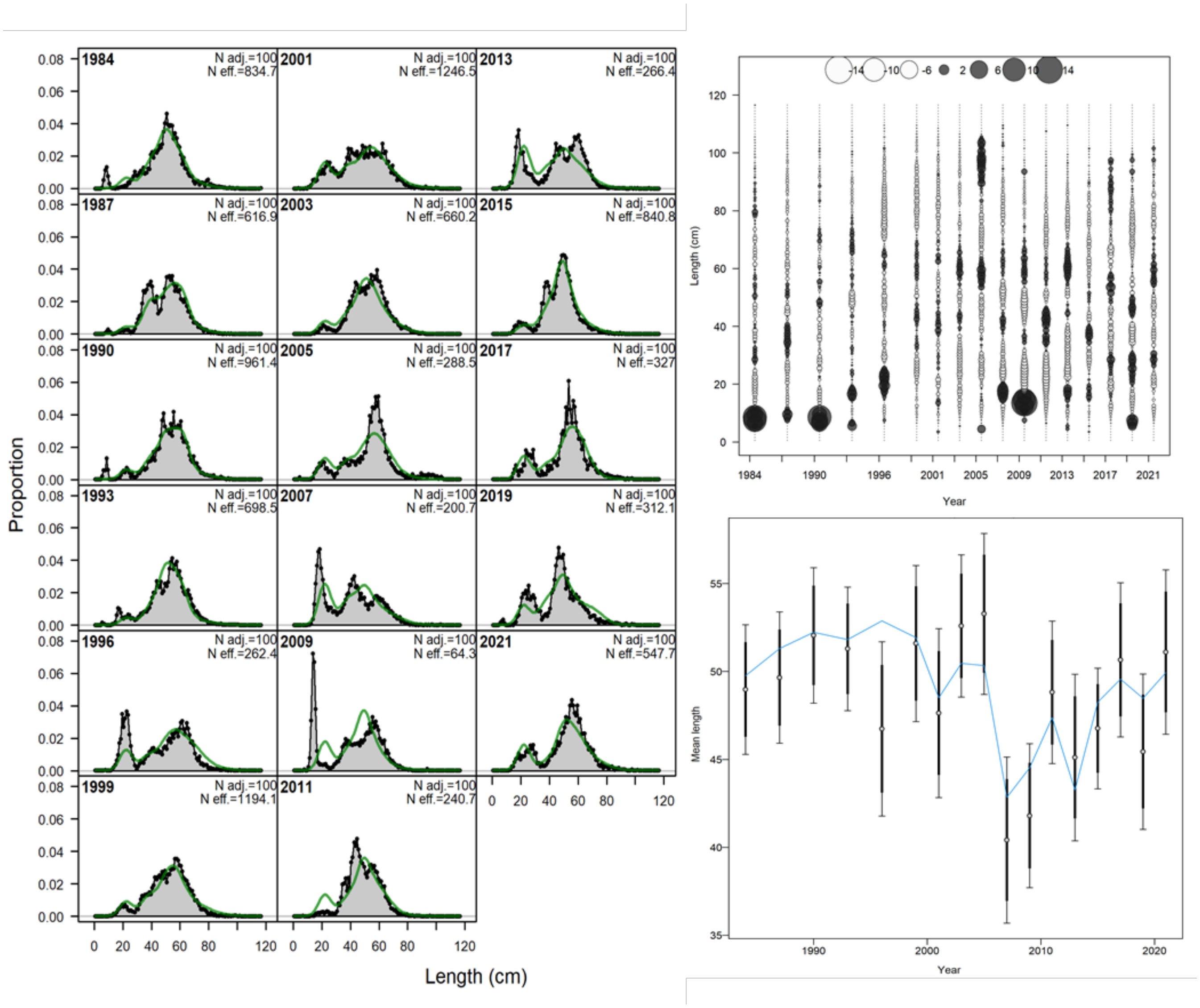

Figure 2.35. NMFS bottom trawl survey length composition and Model 19.1a fit (left), Pearson residuals (top right), and mean length (cm; bottom right).

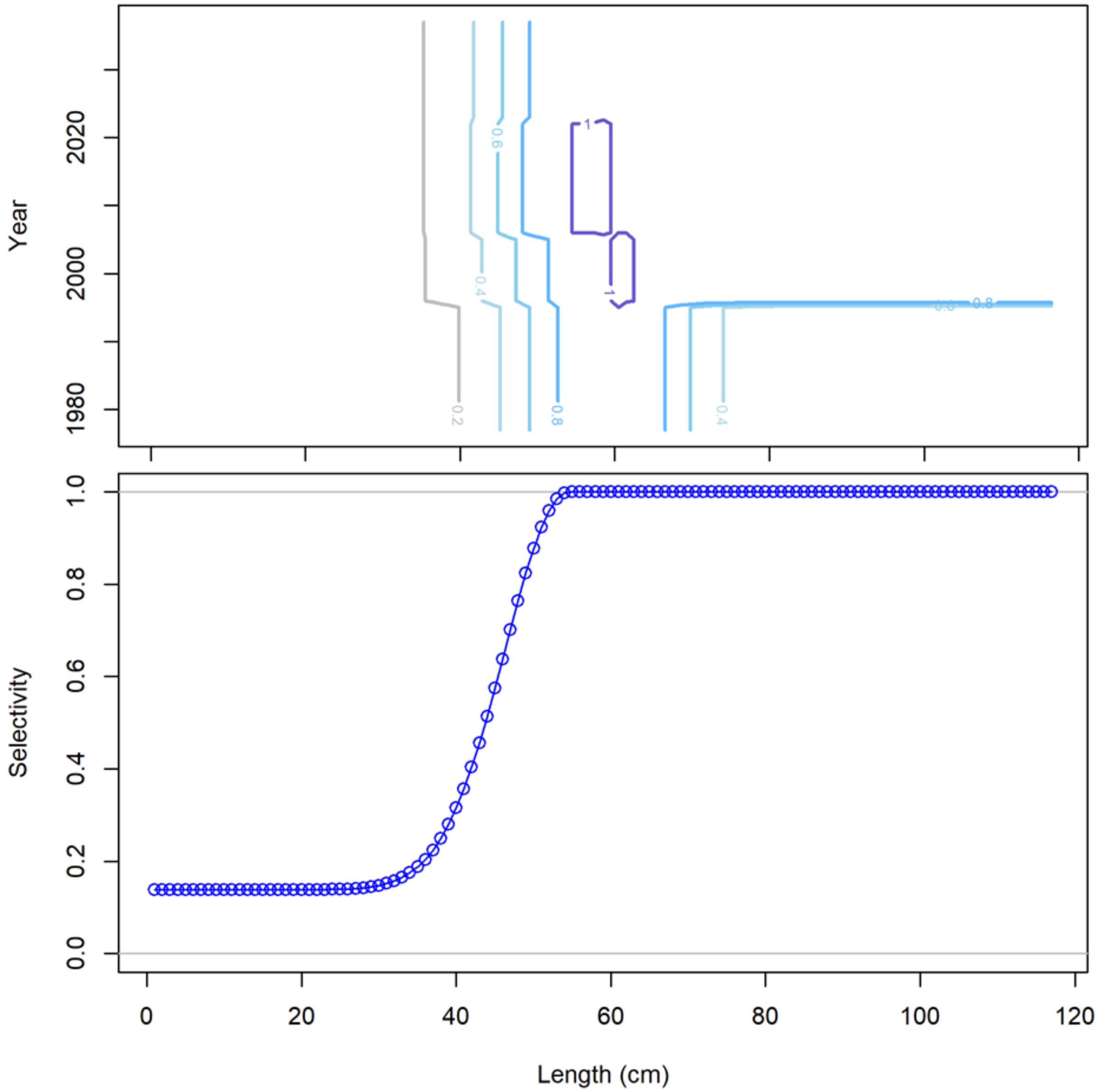

Figure 2.36. NMFS bottom trawl survey selectivity at length from Model 19.1a across time (top), and in final year of model (bottom).

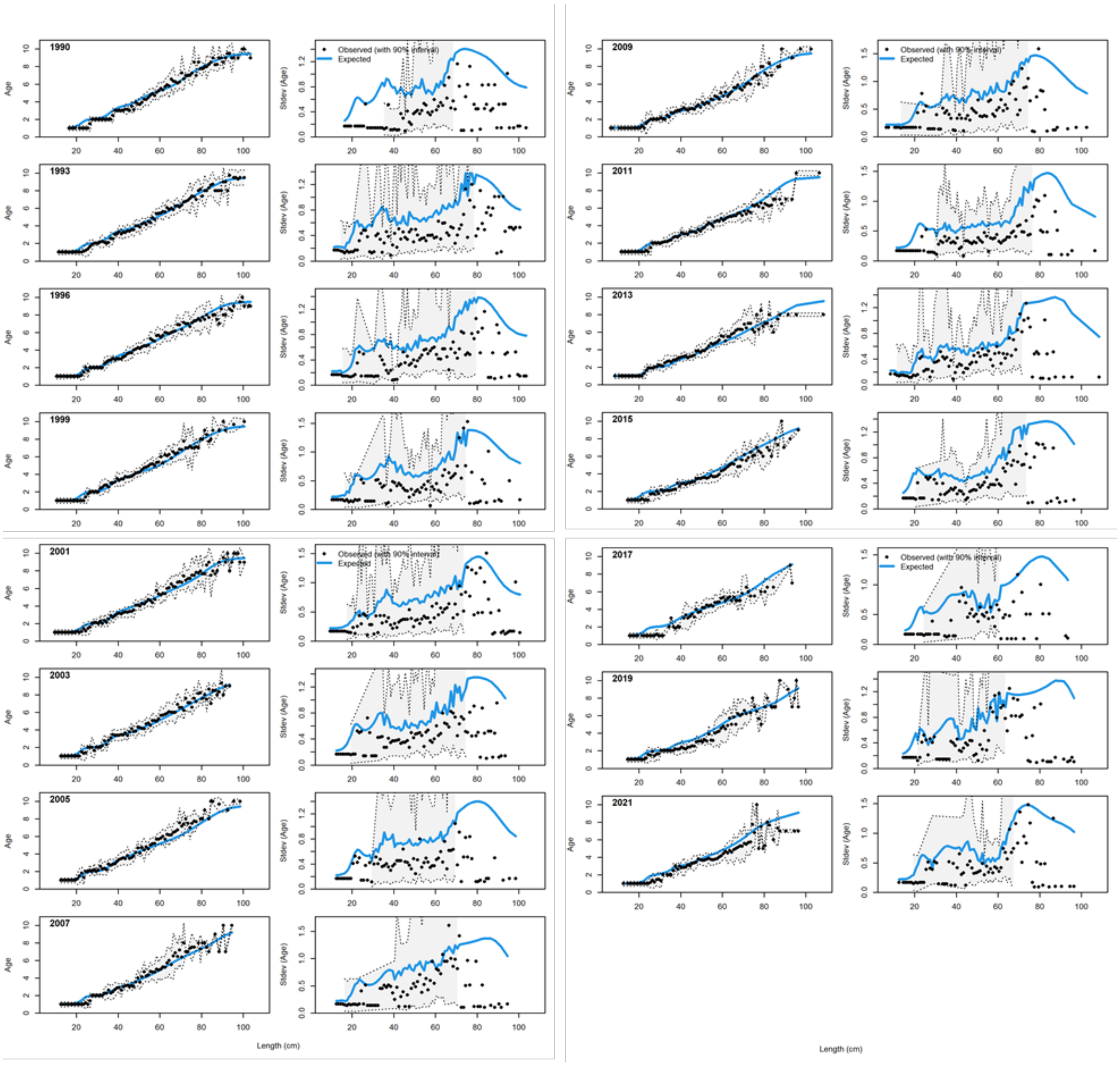

Figure 2.37. NMFS bottom trawl survey conditional age at length data and standard deviation with Model 19.1a fit (blue line).

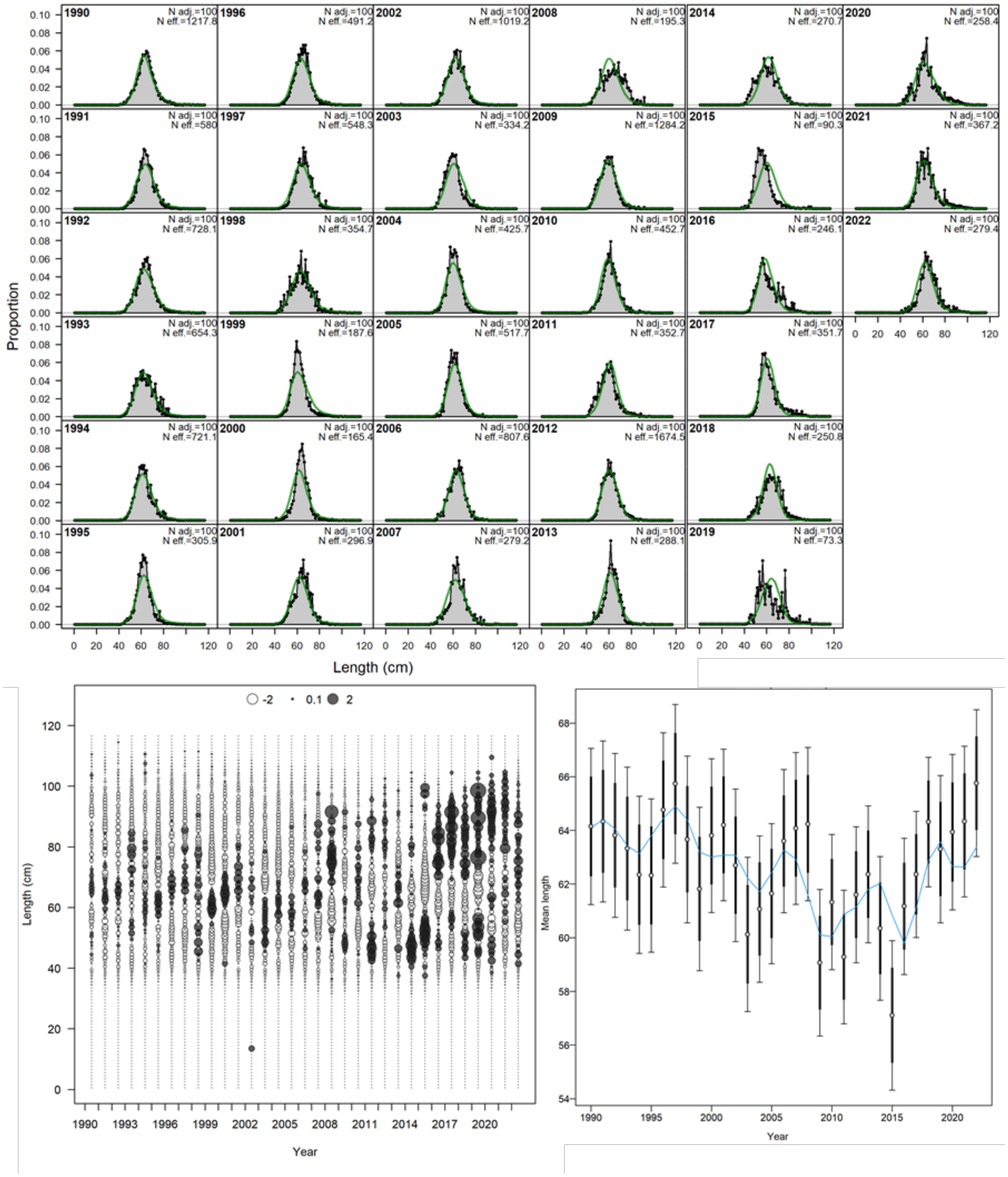

Figure 2.38. AFSC Longline survey length composition and Model 19.1a fit (top), Pearson residuals (left bottom), and mean length (cm; right bottom).

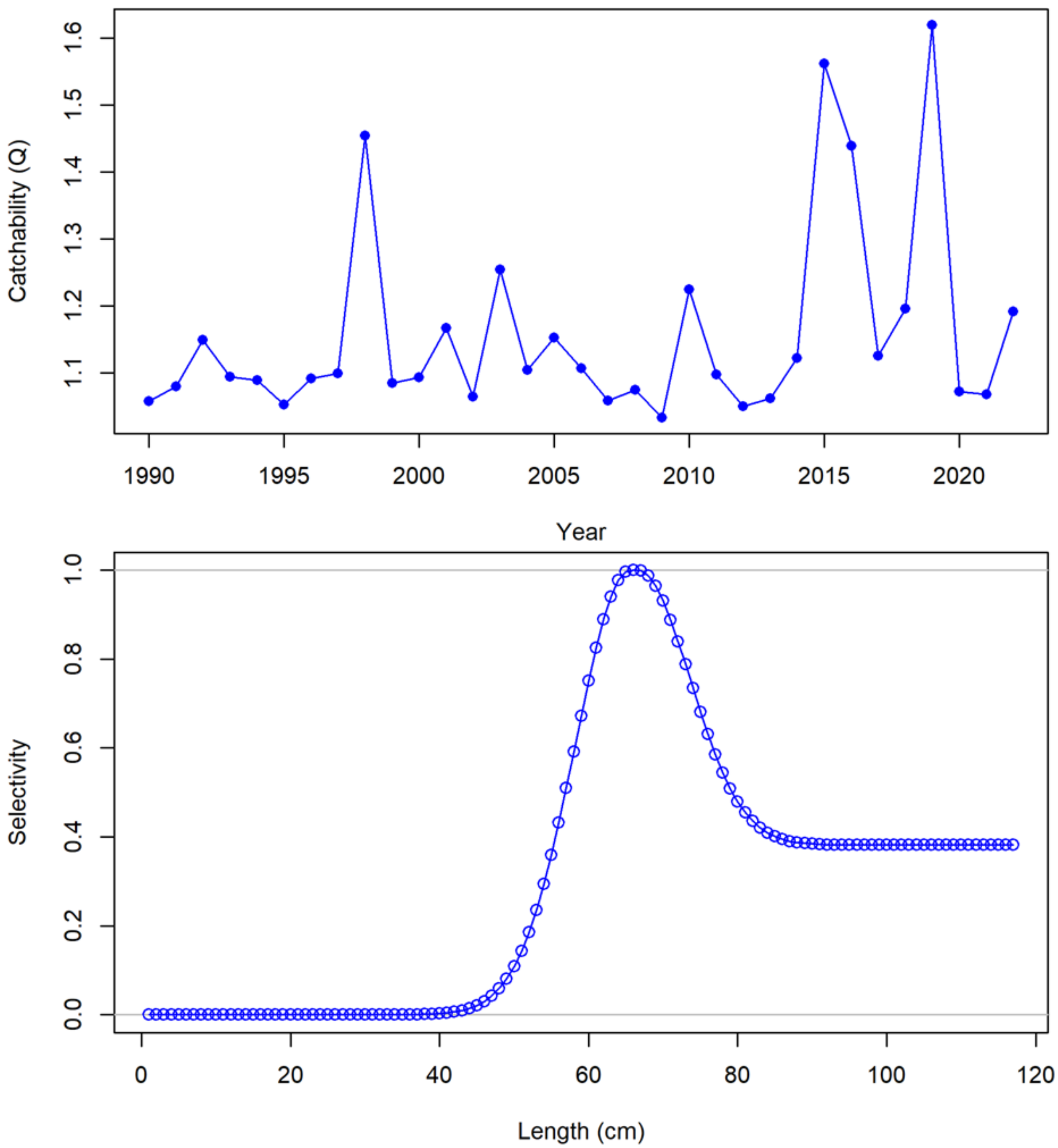

Figure 2.39. AFSC Longline survey time-dependent catchability (top; as estimated with CFSR anomaly covariate) and selectivity at length (bottom) from Model 19.1a.

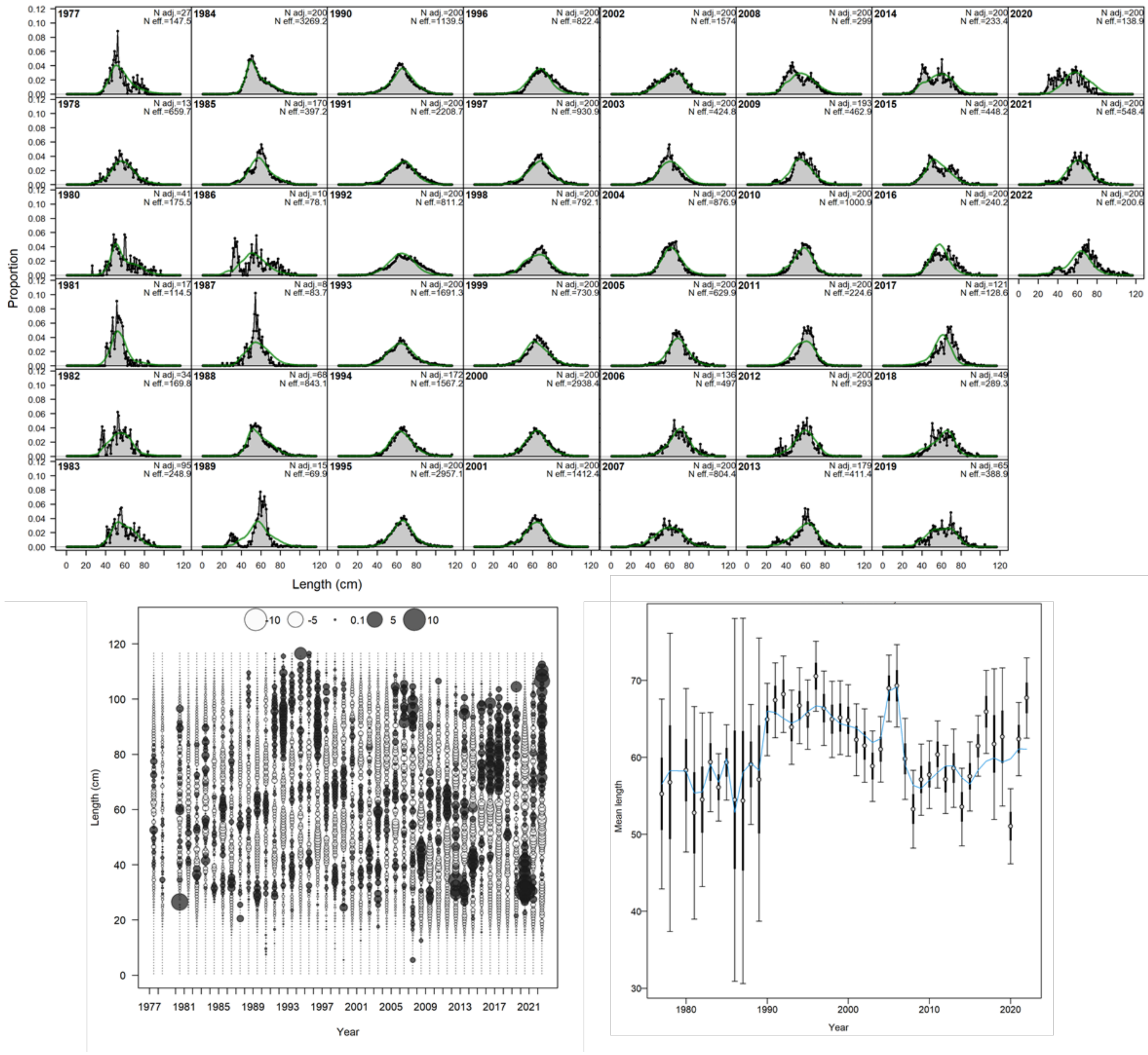

Figure 2.40. Trawl fishery length composition and Model 19.1a fit (top), Pearson residuals (left bottom), and mean length (cm; right bottom).

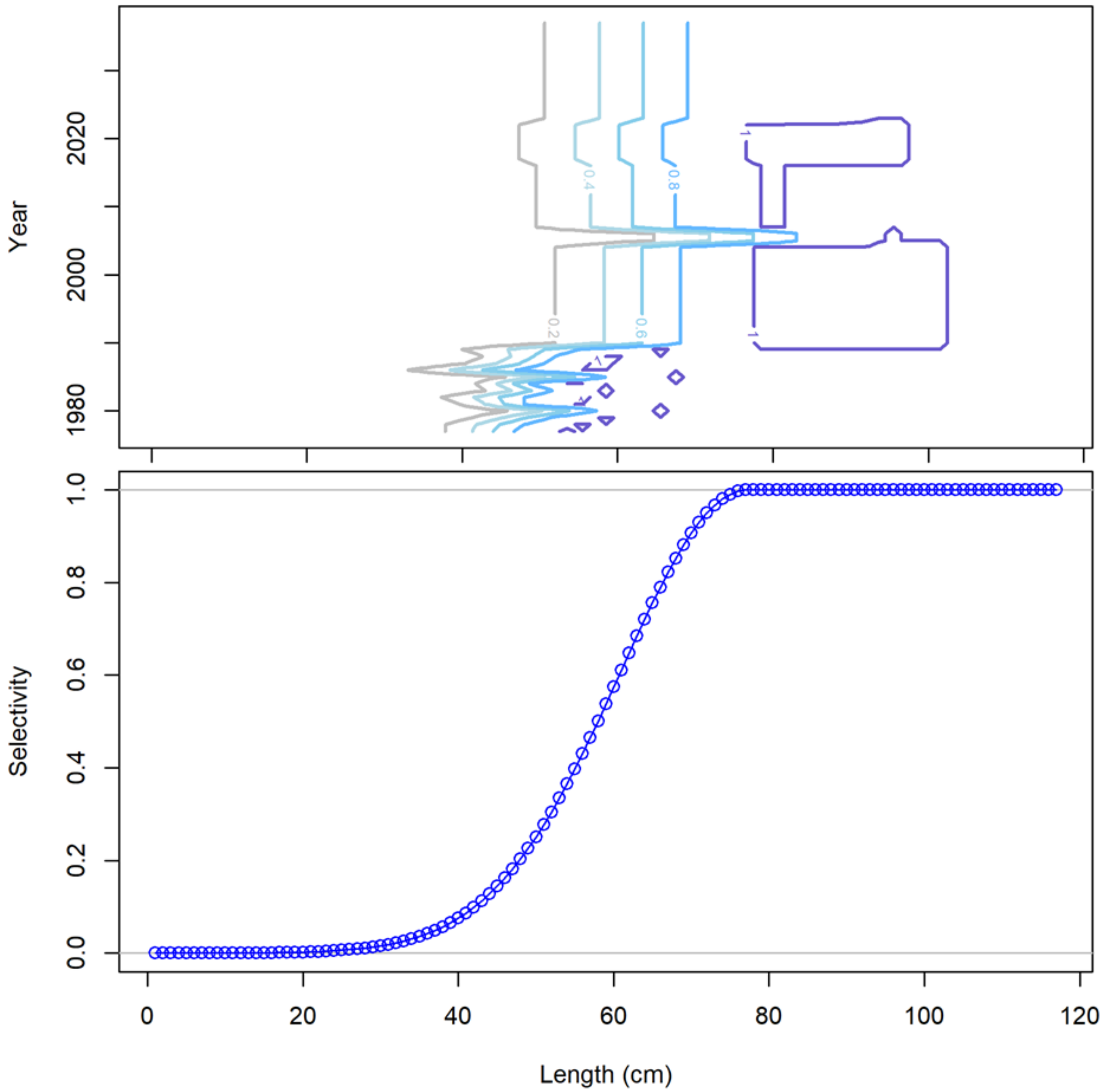

Figure 2.41. Trawl fishery selectivity at length from Model 19.1a across time (top), and in final year of model (bottom).

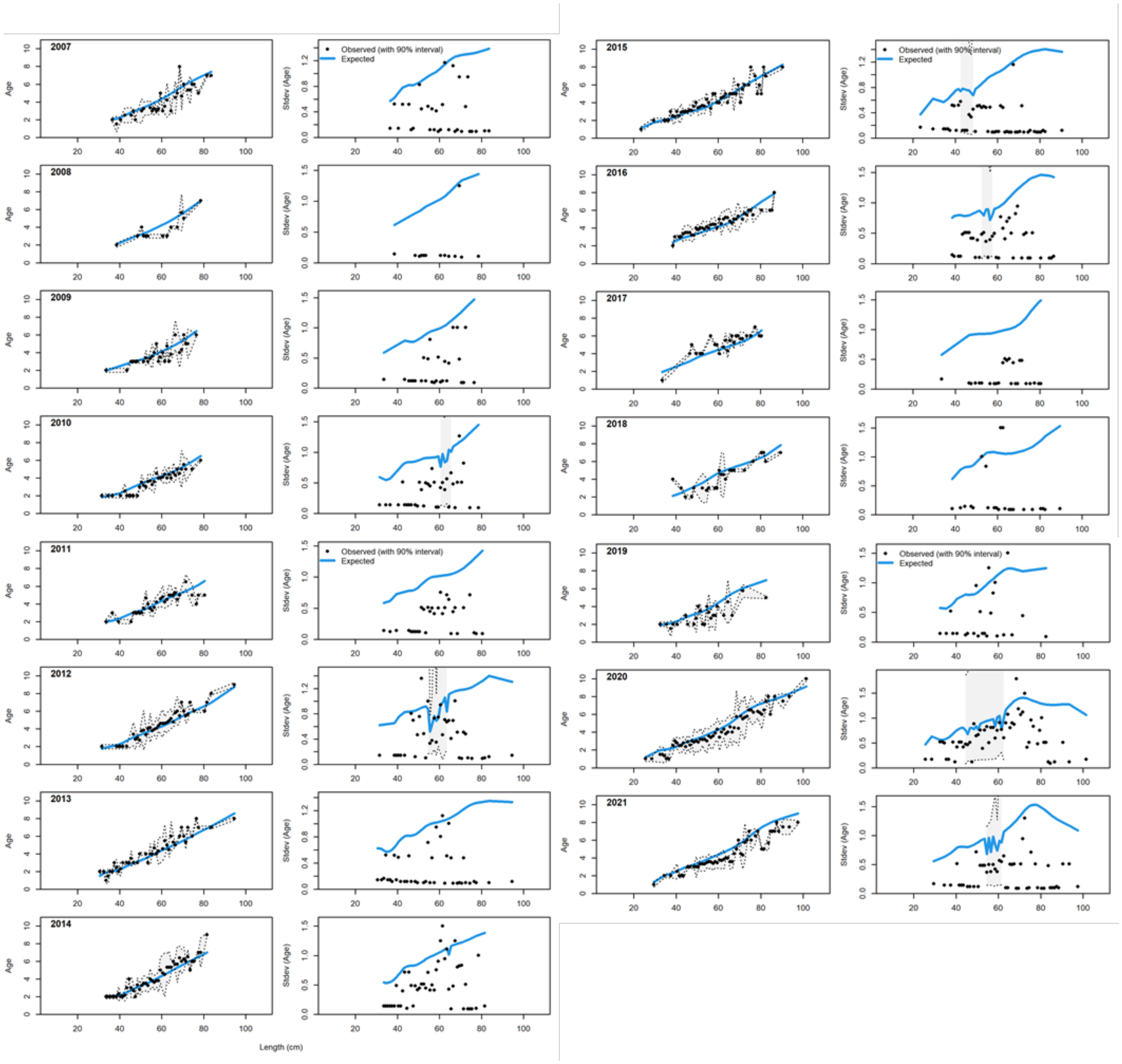

Figure 2.42. Trawl fishery conditional age at length data and standard deviation with Model 19.1a fit (blue line).

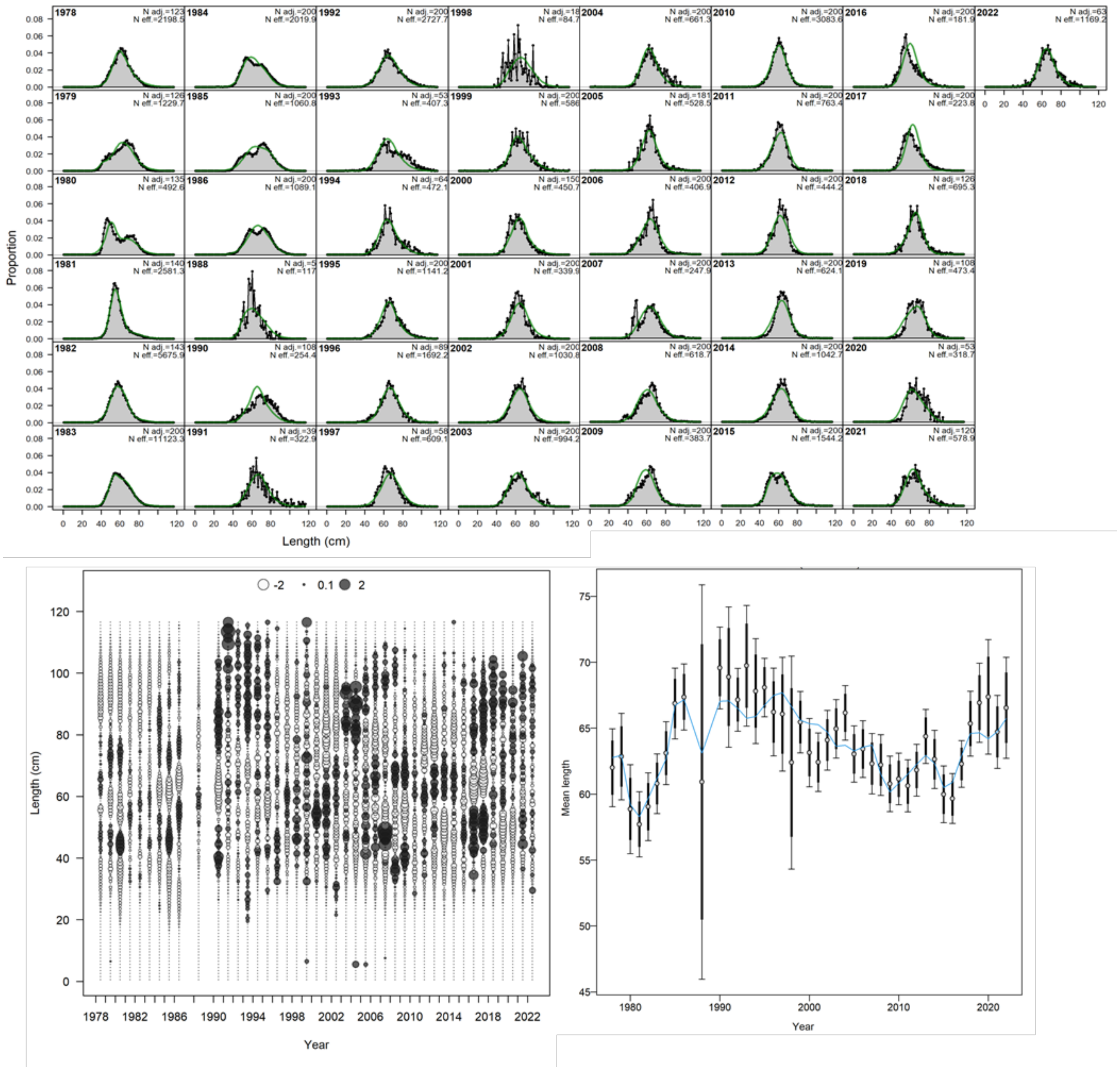

Figure 2.43. Longline fishery length composition and Model 19.1a fit (top), Pearson residuals (left bottom), and mean length (cm; right bottom).

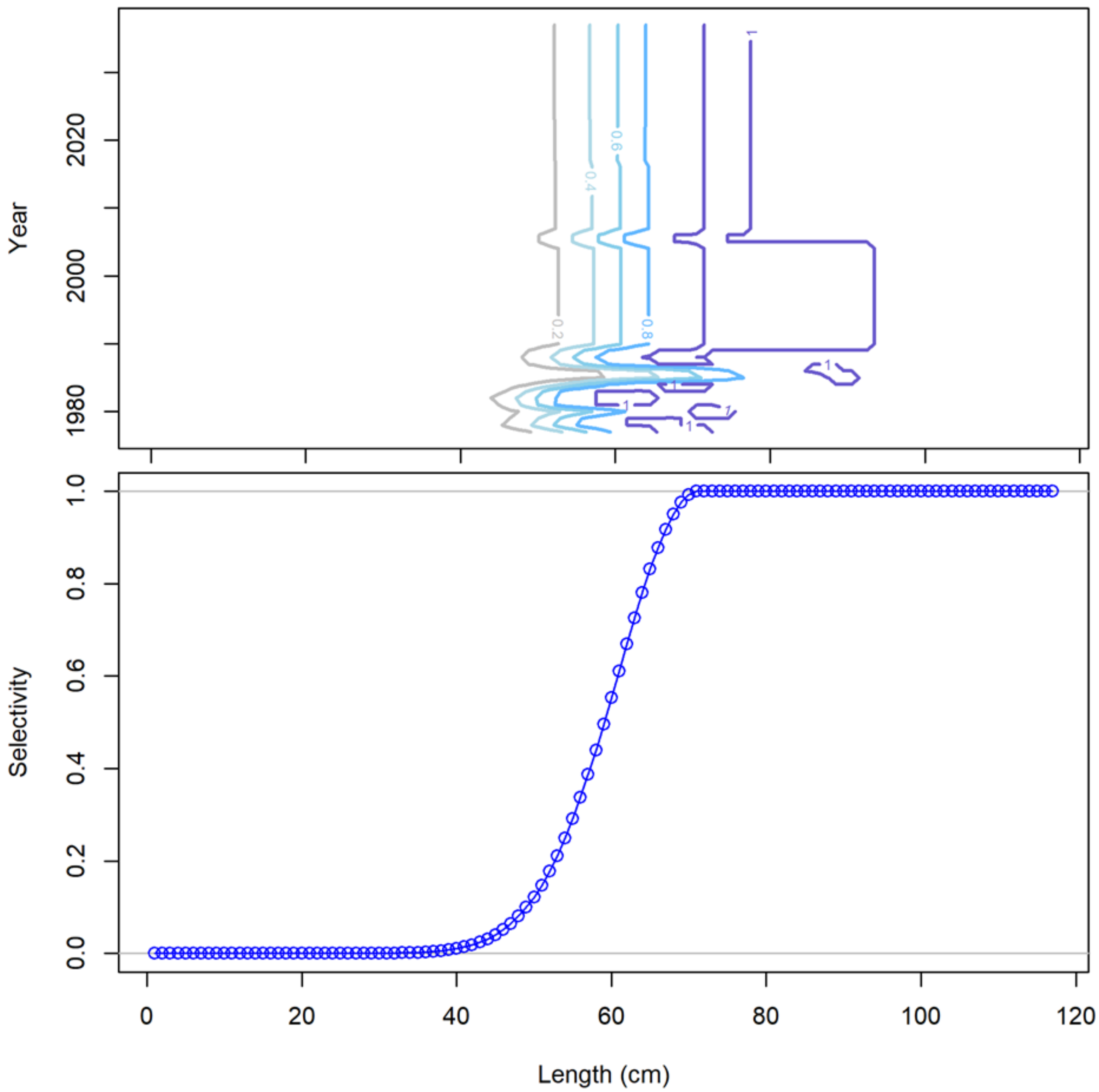

Figure 2.44. Longline fishery selectivity at length from Model 19.1a across time (top), and in final year of model (bottom).

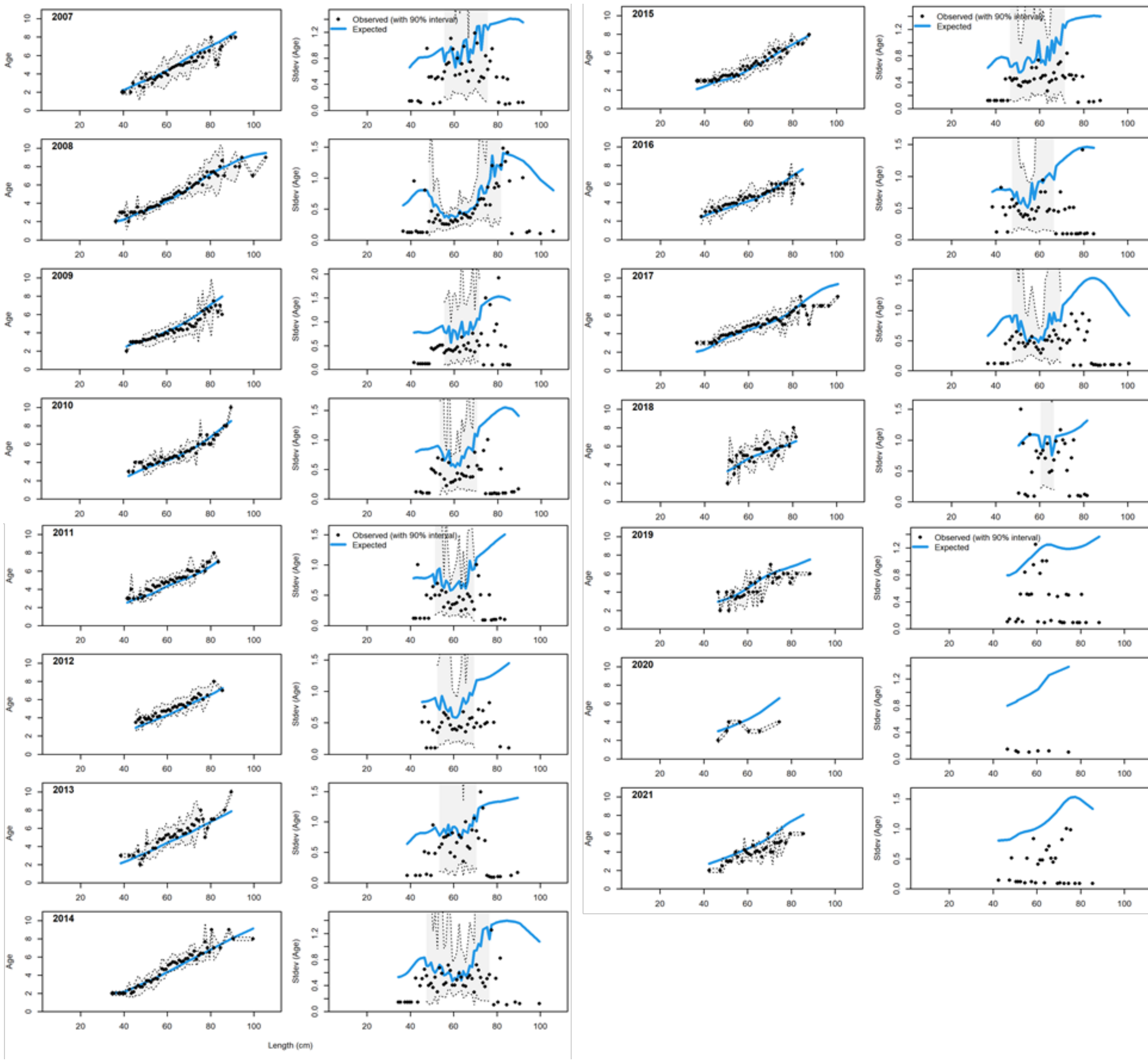

Figure 2.45. Longline fishery conditional age at length data and standard deviation with Model 19.1a fit (blue line).

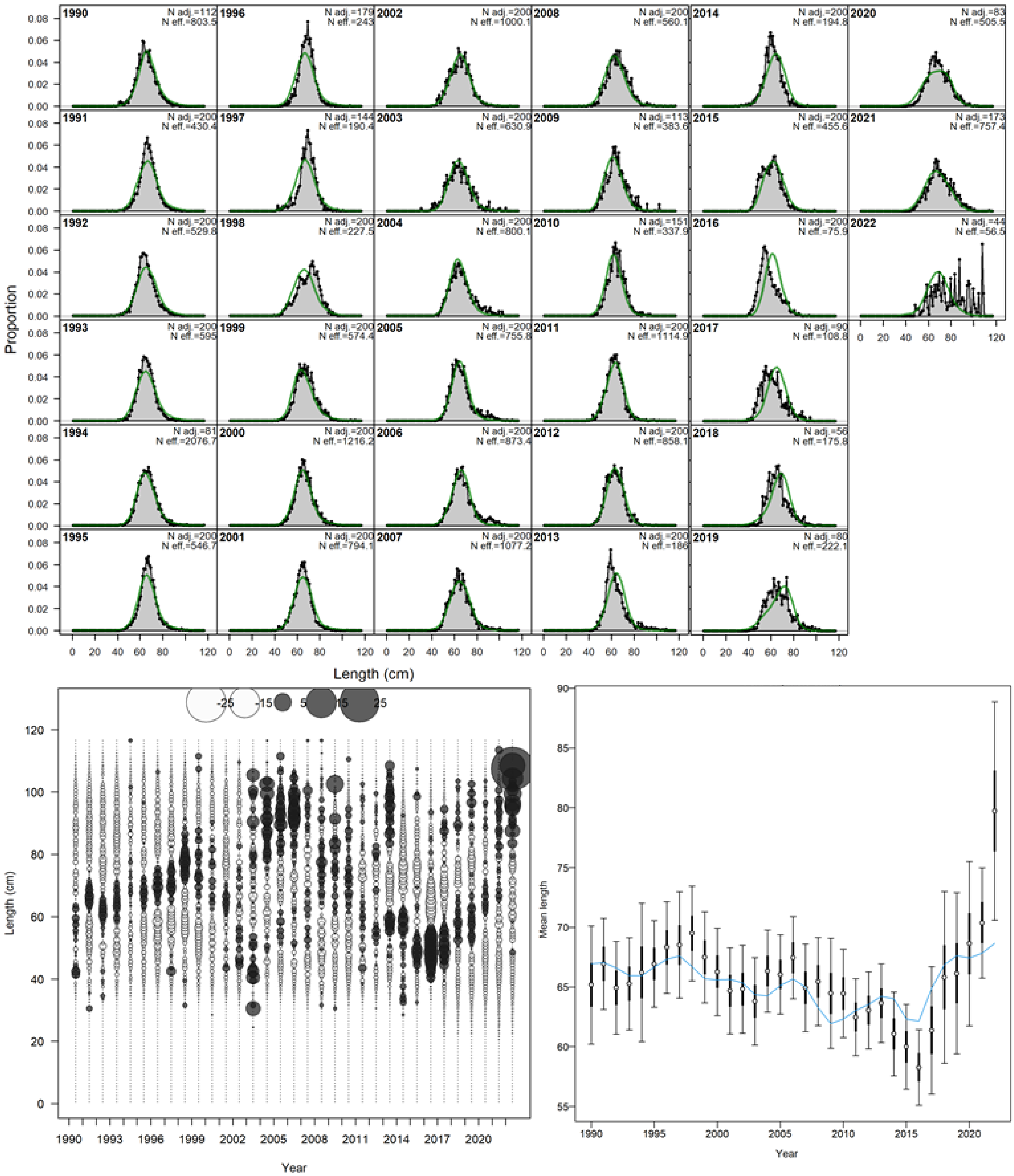

Figure 2.46. Pot fishery length composition and Model 19.1a fit (top), Pearson residuals (left bottom), and mean length (cm; right bottom).

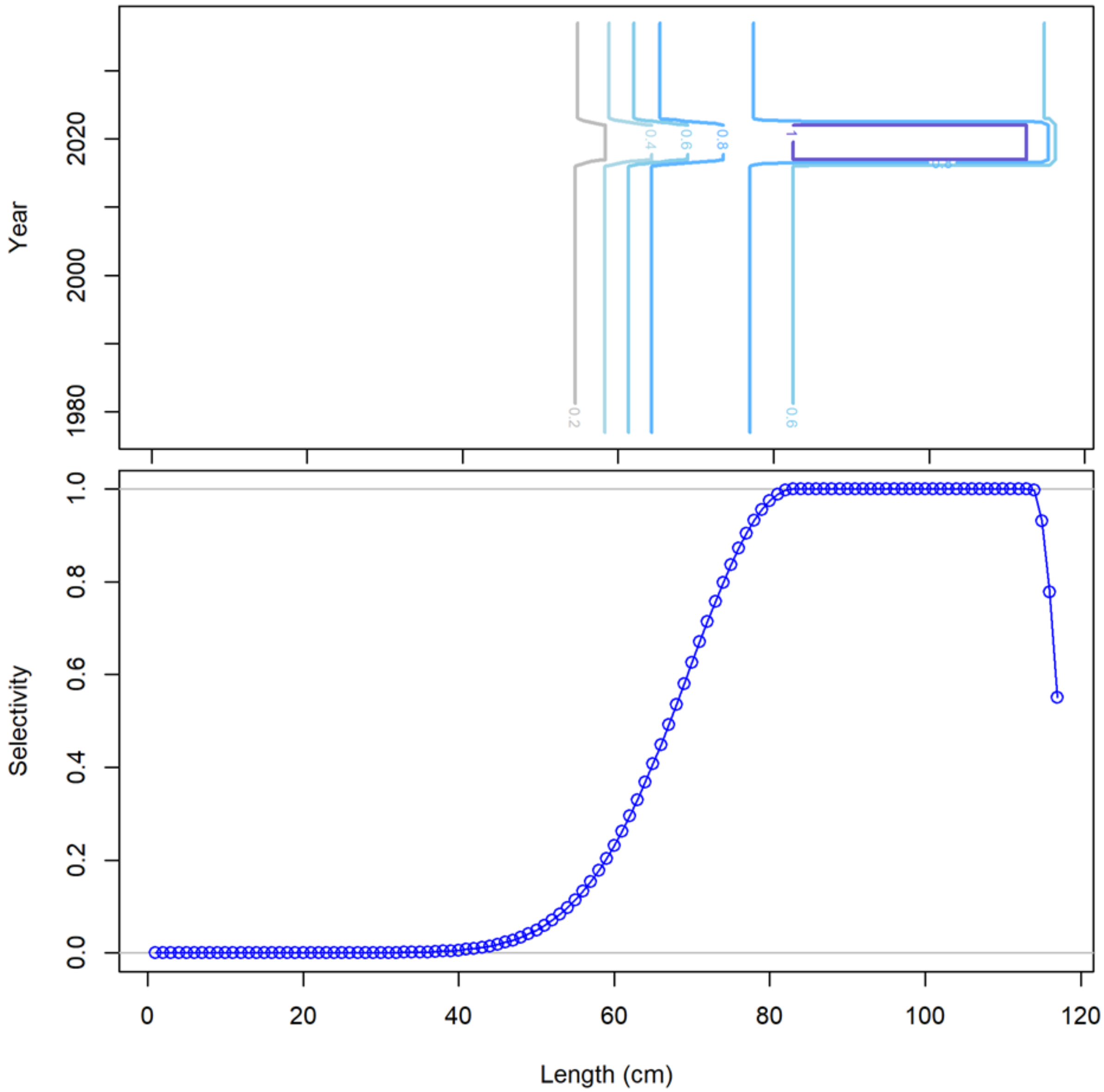

Figure 2.47. Pot fishery selectivity at length from Model 19.1a across time (top), and in final year of model (bottom).

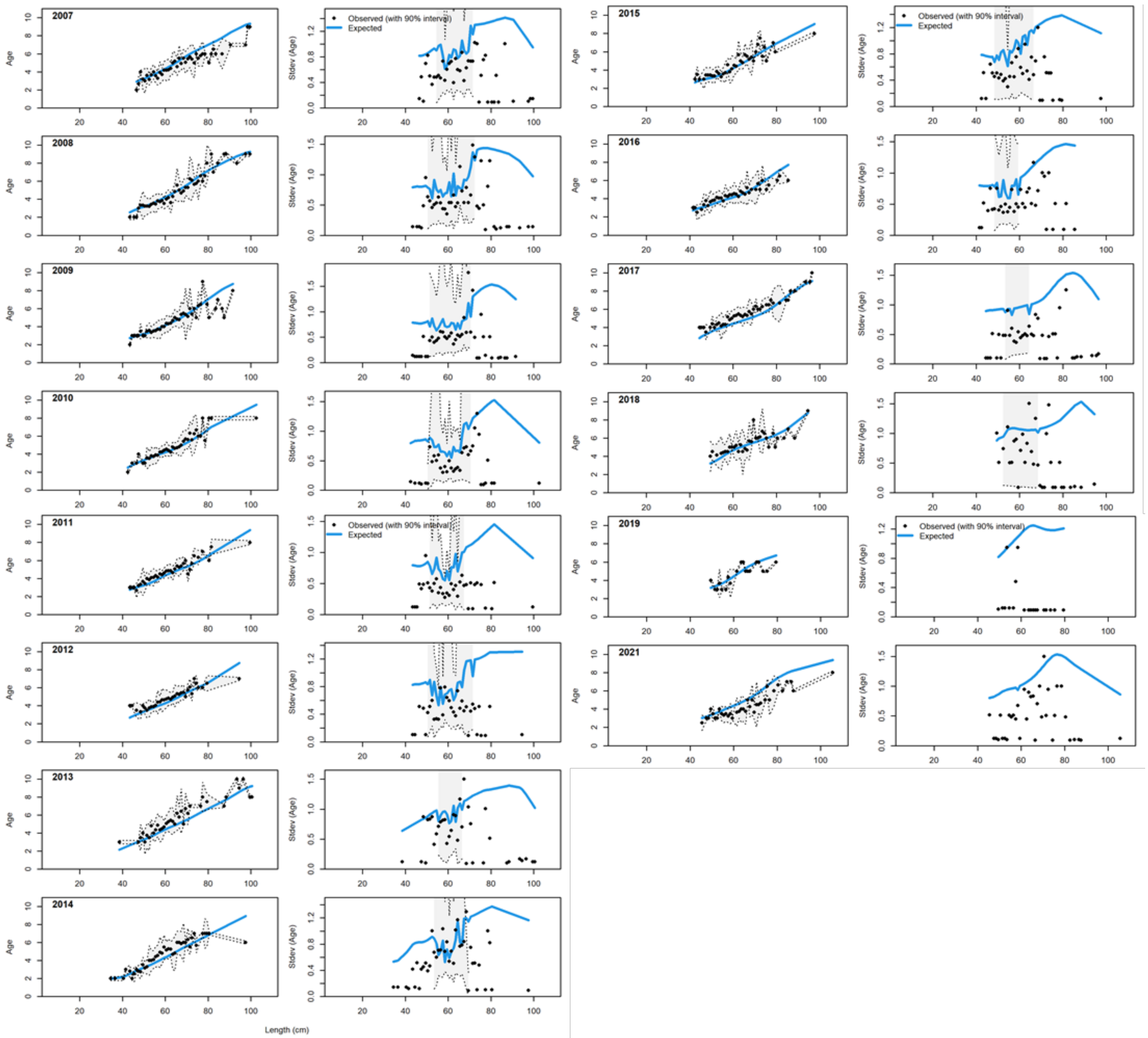

Figure 2.48. Pot fishery conditional age at length data and standard deviation with Model 19.1a fit (blue line).

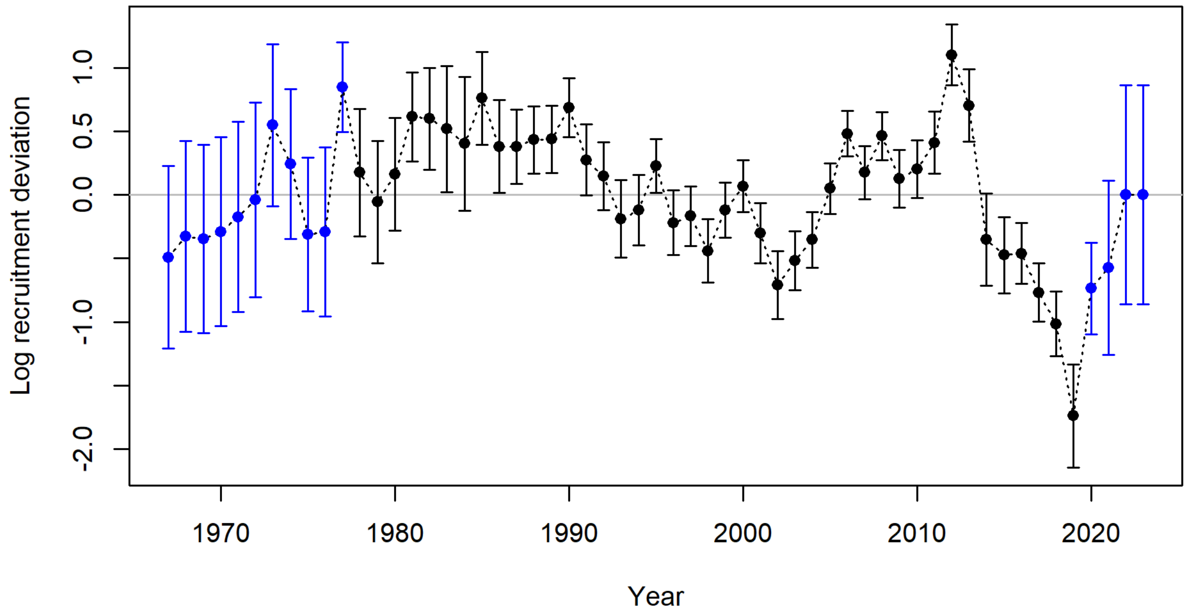

Figure 2.49. Model 19.1a log recruitment deviations with 95% asymtotic error intervals.

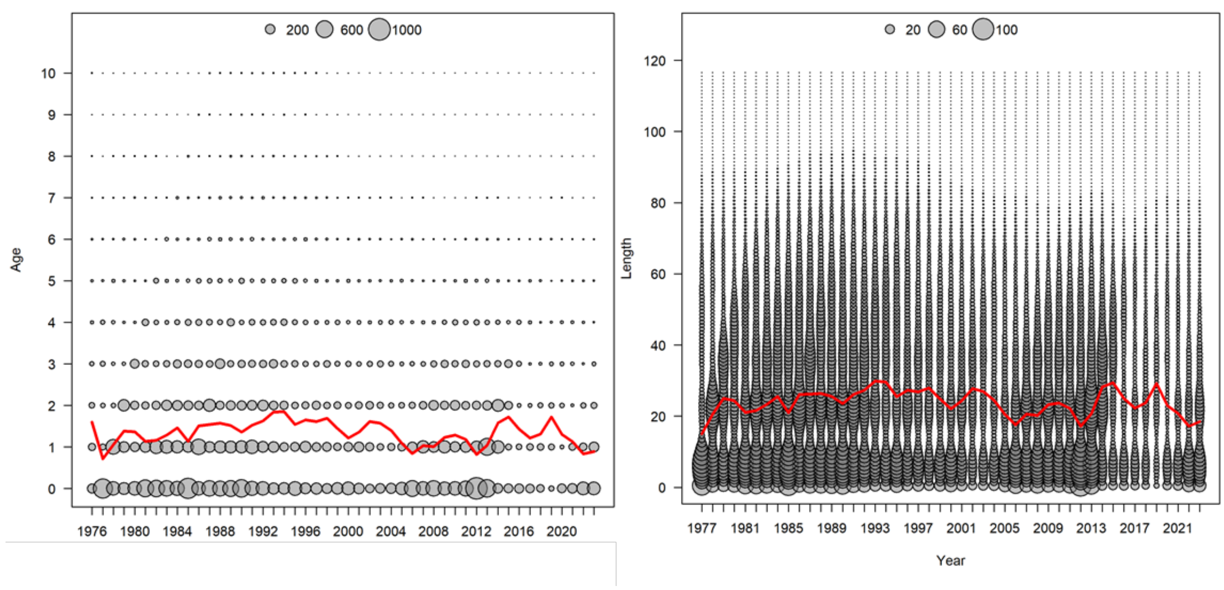

Figure 2.50. Model 19.1a predictions of middle of the year number at age (left) with mean age (red line) and number-at-length (right)with mean length (red line).

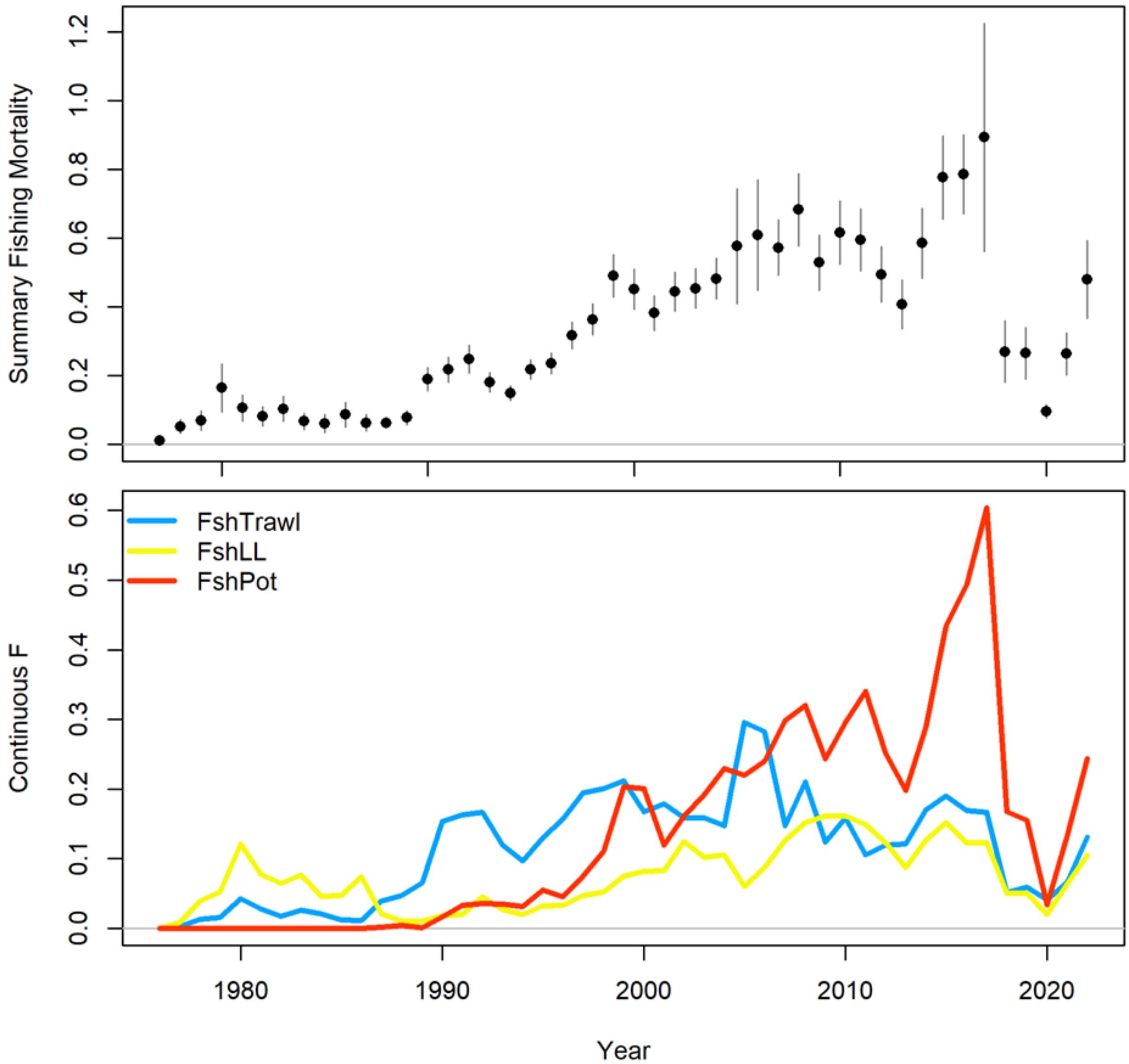

Figure 2.51. Model 19.1a sum of apical fishing mortality (top) and continuos fishing mortality by trawl (FshTrawl), longline (FshLL) and pot (FshPot) fisheries (bottom).

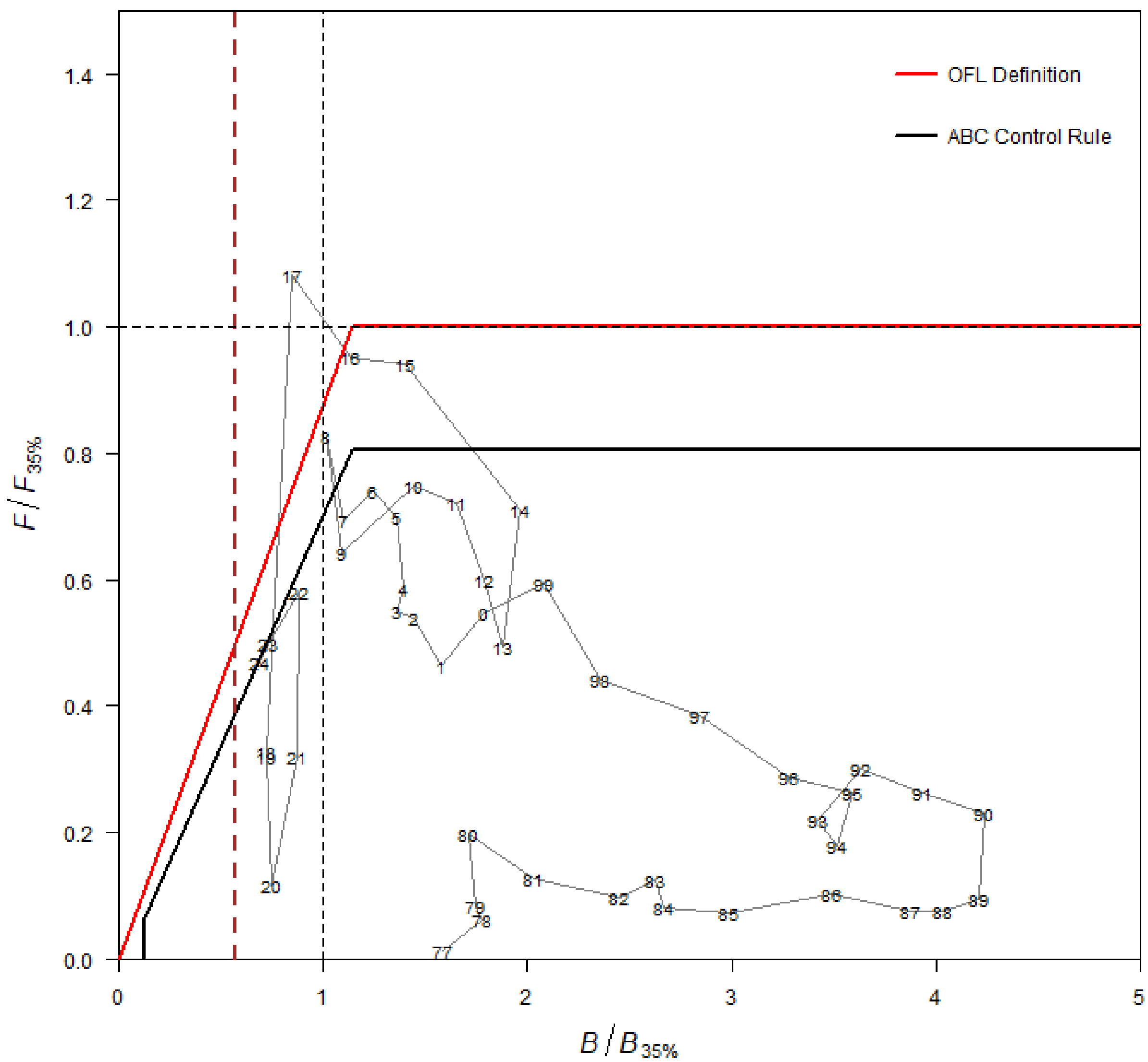

Figure 2.52. For Model 19.1a ratio of historical $F/F_{35\%}$ versus female spawning biomass relative to $B_{35\%}$ for GOA pacific cod, 1977-2024. The Fs presented are the sum of the full Fs across fleets. Dashed red line is at $B_{20\%}$, Steller sea lion closure rule for GOA Pacific cod.

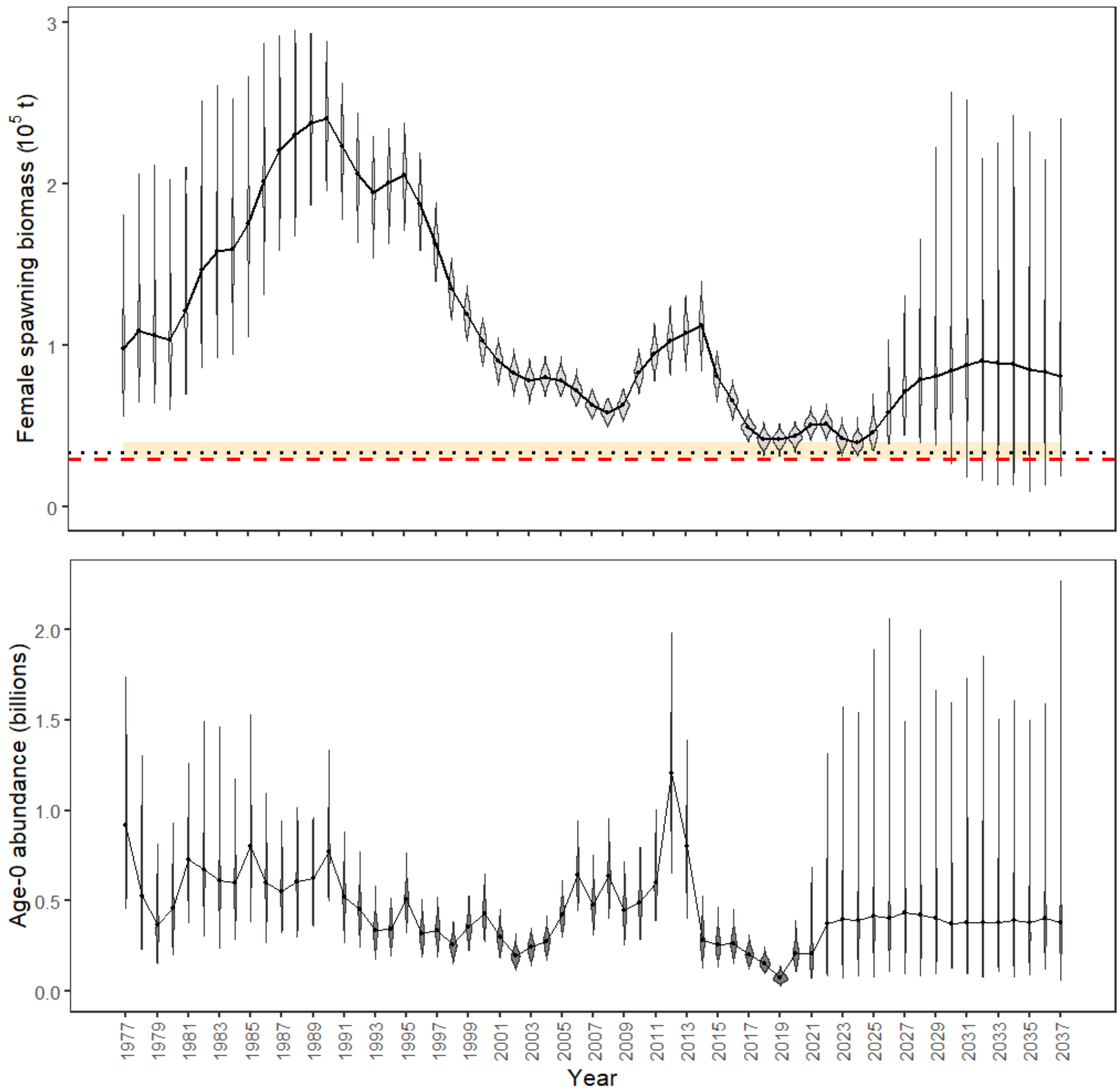

Figure 2.53. Model 19.1a MCMC posterior distribitions of beginning of the year female spawning biomass (top) and age-0 abundance (bottom) for 1977-2037. Dotted line is the projected $SSB_{20\%}$ with 95% confidence interval in orange and the red dashed line is $SSB_{17.5\%}$.

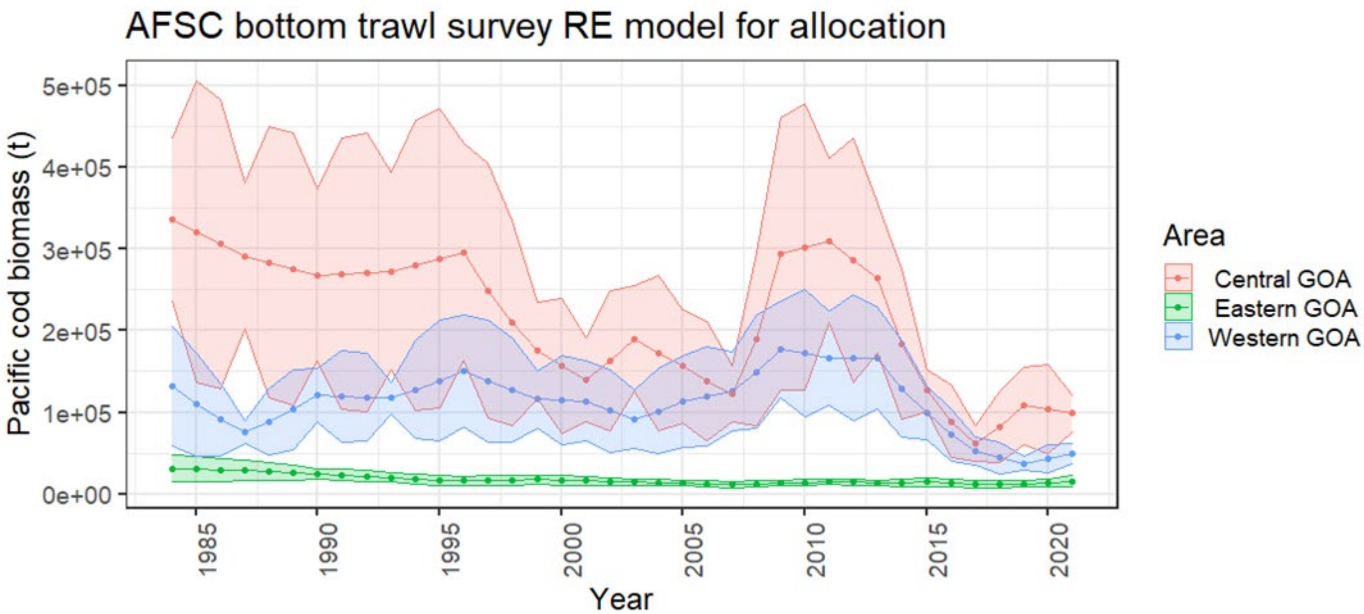

Figure 2.54. Random effects model results for the AFSC bottom trawl survey area used for area allocation.

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

S. Kalei Shotwell, Pete Hulson, Bridget Ferriss, Ben Laurel, and Lauren Rogers

November 2022

With Contributions from:

Kerim Aydin, Steven Barbeaux, Matt Callahan, Wei Cheng, Curry Cunningham, Kirstin Holsman, Sandi Neidetcher, Krista Oke, Patrick Ressler, Heather Renner, Sean Rohan, Elizabeth Siddon, Ingrid Spies, Katie Sweeney, Grant Thompson, Abigail Tyrell, Muyin Wang, Sarah Wise, Stephani Zador

Current Year Update

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

Please refer to the last full ESP for further information regarding the ecosystem and socioeconomic linkages for this stock (Shotwell et al., 2021a, available online within the Gulf of Alaska (GOA) Pacific cod stock assessment and fishery evaluation report of Barbeaux et al., 2021, Appendix 2.1, pp. 161-226).

Management Considerations

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

- Bottom temperature increased at depth to above average in 2022 but habitat suitability improved suggesting that bottom temperatures are within the suitability range for Pacific cod
- Annual eddy kinetic energy has shifted back to a lower energy system similar to 2016 to 2019 suggesting below average larval retention within mesoscale eddies
- Spring bloom timing is near average and high reproductive success of seabirds suggest sufficient forage fish prey resources
- There were few updates for upper trophic indicators as this is an off-cycle survey year but recent biomass estimates of arrowtooth flounder from the stock assessment remain low suggesting less competition or predation on juvenile Pacific cod
- Ex-vessel value remains low, price per pound is stable and near average, but revenue-per-unit-effort has increase to just below average
- Overall, physical indicators were average, and lower trophic indicators were above average in 2022, upper trophic indicators were above average and socioeconomic indicators were below average in 2021. It should be noted that fewer indicators were updated this year due to this being an off-cycle survey year.

Modeling Considerations

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

- Highest ranked predictors variables of GOA Pacific cod recruitment based on the importance methods in the intermediate stage indicator analysis were spawning habitat suitability index in the GOA, summer bottom temperature in the GOA, annual Steller sea lion adult counts, and annual arrowtooth biomass in the GOA (inclusion probability > 0.5)
- New research models are being evaluated as alternatives for the operational assessment using indicators of temperature, habitat suitability, and nearshore surveys of age-0 Pacific cod

Assessment

Ecosystem and Socioeconomic Processes

Figure 2.1.1 provides a life history conceptual model for GOA Pacific cod that summarizes ecological information and key ecosystem processes affecting survival by life stage. Pacific cod release all their eggs near the bottom in a single event during the late winter/ early spring period in the GOA (Stark, 2007). Unlike most cod species, Pacific cod eggs are negatively buoyant and are semi-adhesive to the ocean bottom substrate during development (Alderdice and Forrester, 1971, Ormseth and Norcross, 2009). Hatch timing/success is highly temperature-dependent (Laurel et al., 2008), with optimal hatch occurring in waters ranging between 4-6°C (Bian et al., 2016; Laurel and Rogers, 2020) over a broad range of salinities (Alderdice and Forrester 1971). Eggs hatch into 4 mm larvae in ~2 weeks at 5°C (Laurel et al., 2008) and become surface oriented and available to pelagic ichthyoplankton nets during the spring (Doyle and Mier 2016). During this period, Pacific cod larvae are feeding principally on eggs, nauplii and early copepodite stages of copepod prey <300 um (Strasburger et al., 2014). Warm surface waters can accelerate larval growth when prey are abundant (Hurst et al. 2010), but field observations indicate a negative correlation between temperature and abundance of Pacific cod larvae in the central and western GOA (Doyle et al., 2009, Doyle and Mier 2016). Laboratory studies suggest warm temperatures can also indirectly impact Pacific cod larvae by way of two mechanisms: 1) increased susceptibility to starvation when the timing and biomass of prey is 'mis-matched' under warm spring conditions (Laurel et al., 2011), and 2) reduced growth by way of changes in the lipid/fatty acid composition of the zooplankton assemblage (Copeman and Laurel 2010). The spatial-temporal distribution of Pacific cod larvae shifts with ontogeny and is dependent on a number of behavioral and oceanographic processes. In early April, Pacific cod larvae are most abundant around Kodiak Island before concentrations shift downstream to the SW in the Shumagin Islands in May and June (Doyle and Mier 2016). Newly hatched larvae are surface oriented and make extended diel vertical migrations with increased size and development (Hurst et al. 2009). Larvae reach a developmental milestone ('flexion') between 10-15 mm and gradually become more competent swimmers with increasing size (Voesenek et al., 2018). Very late stage larvae ('pelagic juveniles') eventually settle to the bottom in early summer around 30-40 mm and use nearshore nurseries through the summer and early fall in the GOA (Laurel et al., 2017). Cross-shelf transport may be an important process for assisting larvae and early juveniles to the nearshore nurseries for settlement. Sustained along shore currents may sweep eggs and larvae from the system before they can settle to the bottom as juveniles (Hinckley et al., 2019). Mesoscale oceanographic features such as eddies or gap winds may assist in entraining eggs and larvae in the system to allow time for growth to a large enough size to settle in preferred nearshore habitat (Sinclair and Crawford, 2005).

Shallow, coastal nursery areas provide age-0 juvenile Pacific cod ideal conditions for rapid growth and refuge from predators (Laurel et al., 2007). A fairly narrow and shallow depth range for the early juveniles suggesting the importance of these nearshore habitats for GOA Pacific cod. Tidal current also contributes to the spatial distribution in the early juvenile stage suggesting some influence of transport mechanisms in this stage as well. Settled juvenile cod associate with bottom habitats and feed on small calanoid copepods, mysids, and gammarid amphipods during this period (Abookire et al., 2007). At the end of August, age-0 cod become less associated with structural habitats and transition into deeper water in the fall (Laurel et al., 2009). Therefore, first year assessments of Pacific cod in the GOA are better suited during the early larval or later post-settled juvenile period. The summer thermal conditions in the central/western GOA have historically been well-suited for high growth and survival potential for juvenile Pacific cod (Laurel et al., 2017), but may have been suboptimal during the 2014-16 marine heatwave (Barbeaux et al., 2020). However, the absence of age-0 fish arriving to nurseries in years with warm springs strongly suggests pre-settlement processes (egg/larval) are determining annual cohort strength in the GOA. Reductions in spawning habitat from subsurface warming appears to be an important mechanism limiting reproductive output in the GOA (Laurel and Rogers 2020), but it is likely one of several mechanisms driving recruitment dynamics. The direct impacts of temperature on life history processes in Pacific cod are stage- and size-dependent but these relationships generally are 'dome shaped' like other cod species (e.g., Hurst et al. 2010; Laurel et al. 2016a). Pacific cod are opportunistic predators, eating a variety of zooplankton, crab, and fish species (Aydin et al., 2007). In the absence of abundance estimates of prey resources, the reproductive success of piscivorous and planktivorous seabirds in the GOA can be used to inform prey quality and quantity (e.g., Piatt, 2002). Walleye pollock and halibut account for the greatest sources of predation mortality for Pacific cod in the GOA, followed by sperm whales, Steller sea lions, and dogfish (Aydin et al., 2007).

Pacific cod has been a critical species in the catch portfolio of the GOA fisheries (Fissel et al., 2021). The Pacific cod total allowable catch (TAC) is allocated to multiple sectors. In the GOA, sectors are defined by gear type (hook and line, pot, trawl and jig) and processing capacity (catcher vessel (CV) and catcher processor (CP)). Within the sectoral allocations the fisheries effectively operate as open access with limited entry. The majority of GOA Pacific cod is caught by CVs which make deliveries to shore-based processors and accounts for 90% of the total GOA Pacific cod catch. Approximately 25% is caught by the trawl, 55% is caught by pot gear, and 20% caught by hook and line, though the number of hook and line vessels is far greater. Harvests from catcher vessels that deliver to shoreside processors account for approximately 90% of the retained catch.

Tables 2.1.1a-c provide a stock specific summary for GOA Pacific cod of the economic information presented in the current Economic SAFE (A. Ableman, *per. commun*.). Catch from the fixed gear vessels (which includes hook-and-line and pot gear) typically receive a slightly higher price from processors because they incur less damage when caught. The two primary product forms produced from cod in the GOA are fillets and head and gut (H&G) and the relative share can fluctuate year over year depending on relative prices and processing decisions. U.S. exports of cod are roughly proportional to U.S. cod production. More than 90% of the exports are H&G, much of which goes to China for secondary processing and re-export. The cod industry has largely avoided U.S. tariffs that would have a significant negative impact on them in the U.S.-China trade war. However, Chinese tariffs on U.S. products could be inhibiting growth in that market and putting downward pressure on Pacific cod export prices. Japan and Europe (mostly Germany and the Netherlands) are also important export destinations. Japan and Europe accounted for 12% and 22% of the export volume respectively. Approximately 35% of Alaska's cod production is estimated to remain in the U.S. Because U.S. cod production is approximately 15% of global production and the GOA is approximately 6% of U.S. production, the GOA Pacific cod is a relatively small component of the broader cod market. A portion of the Russian catch of Pacific cod became MSC certified in Oct. 2019 which could put further downward pressure on prices going forward.

An analysis of commercial processing and harvesting data may be conducted to examine sustained participation for those communities substantially engaged in a commercial fishery. The Annual Community Engagement and Participation Overview (ACEPO) is a new report that evaluates engagement at the community level and focuses on providing an overview of harvesting and processing sectors of identified highly engaged communities for groundfish and crab fisheries in Alaska (Wise et al., 2021). Within the processing sector four ports emerged as highly engaged: Akutan, King Cove, Kodiak, and Sand Point. In the last five years, Kodiak accounted for an average of 47% of GOA Pacific cod landings revenue, with Sand Point, King Cove, and Akutan combined landed 53% (Wise et al., 2021). Within the GOA Pacific cod harvesting sector, four communities emerged as highly engaged: Kodiak and Sand Point again, Homer, and Seattle MSA (metropolitan statistical area). Kodiak has historically had the highest harvest engagement, bringing in an average of 50% of all the GOA Pacific cod harvested since 2015. The number of vessels participating in the GOA Pacific cod fishery decreased across highly engaged communities by 70% since 2000. These decreases depict an overall decline in sustained participation (Wise et al., 2021).

Indicator Suite

The following list of indicators for GOA Pacific cod are organized by categories, three for ecosystem indicators (physical, lower trophic, and upper trophic) and three for socioeconomic indicators (fishery performance, economic, and community). A short description and contact name for the indicator contributor are provided. For ecosystem indicators, we also include the anticipated sign of the proposed relationship between the indicator and the stock population dynamics where relevant. Please refer to the full ESP document for detailed information regarding the ecosystem and socioeconomic indicator descriptions and proposed mechanistic linkages for this stock (Shotwell et al., 2021a). Time series of the ecosystem and socioeconomic indicators are provided in Figure 2.1.2a and Figure 2.1.2b, respectively.

<u>Ecosystem Indicators:</u>

Physical Indicators (Figure 2.1.2a.a-d)

- a.) Spawning marine heatwave cumulative index over the central GOA (contact: S. Barbeaux). Proposed sign of relationship is negative.
- b.) Winter spring spawning habitat suitability index from January to April in the central GOA shelf at GAK1 station (contact: L. Rogers). Proposed sign of relationship is positive and the time series is not lagged for the intermediate stage indicator analysis.
- c.) Summer bottom temperatures where small Pacific cod (0-20 cm) have been sampled by the AFSC GOA bottom trawl survey from the CFSR dataset (contact: M. Wang). Proposed sign of relationship is negative and the time series is not lagged for the intermediate stage indicator analysis.
- d.) Annual eddy kinetic energy (EKE) calculated from sea surface height in the Kodiak area (contact: W. Cheng). Proposed sign of relationship is positive and the time series is not lagged for the intermediate stage indicator analysis.

Lower Trophic Indicators (Figure 2.1.2a.e-i)

- e.) Peak timing of the spring bloom averaged across individual ADF&G statistical areas in the western and central GOA region from the MODIS satellite (contact: M. Callahan). Proposed sign of relationship is positive.
- f.) Summer large copepods for young-of-the-year (YOY) from the EcoFOCI summer survey (contact: L. Rogers). Proposed sign of relationship is positive.
- g.) Summer euphausiid abundance for the GOA from the AFSC acoustic survey (contact: P. Ressler). Proposed sign of relationship is positive.
- h.) Spring Pacific cod larvae catch-per-unit-of-effort (CPUE) from the EcoFOCI spring survey (contact: L. Rogers). Proposed sign of relationship is positive.
- i.) Common murre (piscivores) reproductive success at Chowiet Island (contact: S. Zador). Proposed sign of relationship is positive.

Upper Trophic Indicators (Figure 2.1.2a.j-o)

- j.) Summer condition for juvenile (<420 mm) Pacific cod from the AFSC GOA shelf bottom trawl survey (contact: S. Rohan). Proposed sign of relationship is positive.
- k.) Summer condition for adult (>=420 mm) Pacific cod from the AFSC GOA shelf bottom trawl survey (contact: S. Rohan). Proposed sign of relationship is positive.
- l.) Summer Pacific cod center of gravity northeastings estimated by a spatio-temporal model using the package VAST on AFSC GOA bottom trawl survey data (contact: Z. Oyafuso). Proposed sign of relationship is negative.
- m.) Summer Pacific cod area occupied estimated by a spatio-temporal model using the package VAST on AFSC GOA bottom trawl survey data (contact: Z. Oyafuso)
- n.) Arrowtooth flounder total biomass from the most recent stock assessment model in the GOA (contact: K. Shotwell). Proposed sign of relationship is negative and the time series is lagged two years for the intermediate stage indicator analysis.

o.) Steller sea lion non-pup estimates for the GOA portion of the western Distinct Population Segment (contact: K. Sweeney). Proposed sign of relationship is negative and the time series is lagged two years for the intermediate stage indicator analysis.

Socioeconomic Indicators:

Economic Indicators (Figure 2.1.2b.a-c)

a.) Annual estimated real ex-vessel value of GOA Pacific cod (contact: J. Lee)
b.) Annual real ex-vessel price per pound of GOA Pacific cod from fish ticket information (contact: J. Lee).
c.) Annual estimated real revenue per unit effort measured in weeks fished of GOA Pacific cod (contact: J. Lee)

Community Indicators (Figure 2.1.2b.d-g)

d.) Regional quotient of Pacific cod for harvesting revenue of the highly engaged community of Kodiak (contact: S. Wise)
e.) Regional quotient of Pacific cod for processing revenue of the highly engaged community of Kodiak (contact: S. Wise)
f.) Regional quotient of Pacific cod for harvesting revenue of three smaller highly engaged communities (Sand Point, King Cove, and Akutan) combined (contact: S. Wise)
g.) Regional quotient of Pacific cod for processing revenue of three smaller highly engaged communities (Sand Point, King Cove, and Akutan) combined (contact: S. Wise)

Indicator Monitoring Analysis

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

Beginning Stage: Traffic Light Test

We use a simple scoring calculation for this beginning stage traffic light evaluation. Indicator status is evaluated based on being greater than ("high"), less than ("low"), or within ("neutral") one standard deviation of the long-term mean. A sign based on the anticipated relationship between the indicator and the stock (generally shown in Figure 2.1.1 and specifically by indicator in the Indicator Suite, Ecosystem Indicators section) is also assigned to the indicator where possible. If a high value of an indicator generates good conditions for the stock and is also greater than one standard deviation above the mean, then that value receives a "+1" score. If a high value generates poor conditions for the stock and is greater than one standard deviation above the mean, then that value receives a "-1" score. All values less than or equal to one standard deviation from the long-term mean are average and receive a "0" score. The scores are summed by the three organizational categories within the ecosystem (physical, lower trophic, and upper trophic) or socioeconomic (fishery performance, economic, and community) indicators and divided by the total number of indicators available in that category for a given year. The scores over time allow for comparison of the indicator performance and the history of stock productivity (Figure 2.1.3). We also provide five year indicator status tables with a color (ecosystem indicators only) for the relationship with the stock (Tables 2.1.2a,b) and evaluate the current year status in the historical indicator time series graphic (Figures 2.1.2a,b) for each ecosystem and socioeconomic indicator.

We evaluate the status and trends of the ecosystem and socioeconomic indicators to understand the pressures on the GOA Pacific cod stock regarding recruitment, stock productivity, and stock health. We start with the physical indicators and proceed through the increasing trophic levels, economic, and community indicators as listed above. Here we concentrate on updates relative to the results presented in the last full ESP (Shotwell et al., 2021a). Overall both the physical indicators scored average and the lower trophic indicators scored average for 2022 (Figure 2.1.3). Compared to last year's results, this is the same for the physical indicators and an improvement for the lower trophic indicators. Two upper trophic indicators were updated for 2021 as the data are always lagged one year due to the timing of the stock assessment review and the marine mammal survey data review. The upper trophic indicators for 2021 were above average. We also note caution when comparing scores between odd to even years as there are many lower and upper trophic indicators missing in even years due to the off-cycle year surveys in the GOA. Also, there have been other cancellations due to COVID-19 or other survey delays in 2020 through 2022 that have limited production of several indicators. Economic and community indicators are all lagged by at least one year due to timing of the availability of the current year information and the production of this report. Economic indicators improved from last year but were still below average for 2021. There were no updates for community indicators.

For physical indicators (Table 2.1.2a, Figure 2.1.2a.a-d), the presence of a series of major marine heatwaves for the past several years has increased sea surface warming and reduced Pacific cod spawning habitat suitability in the GOA ecosystem (Figure 2.1.2a.a-c). However, from 2020 through 2021 there were reduced temperatures at the bottom and reduced annual marine heatwave events from the previous warm stanza. In 2022, the bottom temperatures increased again to above average, but the spawning habitat suitability also increased suggesting that the bottom temperature warming was still within a suitable physiological range for Pacific cod. We also see a shift in the annual eddy kinetic energy (EKE) near Kodiak from average to a lower energy period similar to 2016 to 2019 (Figure 2.1.2a.d). This EKE region near Kodiak has an opposite seasonal cycle phase than other regions in the GOA implying separate forcing mechanisms in the western GOA (Cheng, 2021). Sustained EKE may help retain larvae on the shelf and enhance cross-shelf transport of young-of-the-year Pacific cod to suitable nearshore nursery environments.

For the lower trophic level indicators (Table 2.1.2a, Figure 2.1.2a.e-j), the peak timing of the spring bloom appears highly variable since the onset of the marine heatwaves in 2014 but is now near average. This may have implications for mismatch between larval Pacific cod and the available plankton abundance. During warm years this may be particularly important for Pacific cod due to their increased metabolic requirements and the implications of a later bloom may be somewhat tempered in a cooler thermal environment such as in 2020 and 2021 (B. Laurel, *pers. commun*.). There were no updates for large copepods, euphausiid abundance, or CPUE of larvae in the spring EcoFOCI survey. Reproductive success of common Murre seabirds on Chowiet is now above one standard deviation of the time series mean suggesting sufficient forage fish prey resources (Figure 2.1.2a.i). The summer nearshore survey in Kodiak also increased to above one standard deviation of the time series mean suggesting good survival of the pelagic early life history phase of the 2022 year class (Figure 2.1.2a.j).

For the upper trophic indicators (Table 2.1.2a, Figure 2.1.2a.k-p) , there were no updates for the condition, center of gravity or area occupied indicators as this is an off-cycle survey year (Figure 2.1.2a.k-n). The 2021 biomass estimates of the most recent stock assessment for arrowtooth flounder biomass remain low (Shotwell et al., 2021b) and predicted counts of Steller sea lions decreased to slightly below average (Figure 2.1.2a.o-p).

For economic indicators (Table 2.1.2b, Figure 2.1.2b.a-c), ex-vessel value in 2021 remains below one standard deviation of the time series mean and has been low since 2018 (Figure 2.1.2b.a). Price per pound remains stable but revenue per unit effort increased to just below average in 2021 (Figure 2.1.2b.b-c). Since 2016 reductions in global supply have put upward pressure on prices resulting in significant year over year price increases in 2017 and 2018. In 2019 prices leveled off, decreasing slightly, as markets have adjusted. In 2020 COVID-19 closures resulted in increased demand for retail products and frozen products, and decreased food service and fresh products. Retail and food service are both significant components of the market for Pacific cod products. As such, the impact of COVID-19 on prices appears muted with only marginal changes in first-wholesale and export prices. Cost pressure from COVID-19 mitigation efforts likely had upstream impacts on ex-vessel prices, which decreased significantly.

The community indicators evaluated in the ESP are similar to those presented in the ACEPO report but on the stock level rather than the community level (Table 2.1.2b, Figure 2.1.2b.d-g). The indicators are separated into two categories of fisheries involvement: commercial processing and commercial harvesting (Wise et al., 2021). By separating commercial processing from commercial harvesting, the engagement indices highlight the importance of fisheries in communities that may not have a large amount of landings or processing in their community, but have a large number of fishers and/or vessel owners that participate in commercial fisheries who are based in the community. At this time there are no updates to the community indicators. In the future we plan to evaluate how to reference the products available in the ACEPO report for use in the ESPs to inform on stock health.

Intermediate Stage: Importance Test

Bayesian adaptive sampling (BAS) was used for the intermediate stage statistical test to quantify the association between hypothesized predictors and GOA Pacific cod recruitment and to assess the strength of support for each hypothesis. In this stage, the full set of indicators is first winnowed to the predictors that could directly relate to recruitment and highly correlated covariates are removed. We further restrict potential covariates to those that can provide the longest model run and through the most recent estimate of recruitment that is well estimated in the current operational stock assessment model (Figure 2.1.4a). This results in a model run from 1994 through the 2018 year-class. We then provide the mean relationship between each predictor variable and log GOA Pacific cod recruitment over time (Figure 2.1.4b, left side), with error bars describing the uncertainty (95% confidence intervals) in each estimated effect and the marginal inclusion probabilities for each predictor variable (Figure 2.1.4b, right side). A higher probability indicates that the variable is a better candidate predictor of GOA Pacific cod recruitment. The highest ranked predictor variables (inclusion probability > 0.5) based on this process are the spawning habitat suitability index in the GOA (same as last year), the summer bottom temperature in the GOA (new in 2022), the annual Steller sea lion adult counts (new in 2021), and the annual arrowtooth biomass in the GOA (new in 2021) (Figure 2.1.4).

Advanced Stage: Research Model Test

Further development continued in 2021 on the ecosystem research models (Barbeaux et al. 2021) that incorporated links for catchability, mortality, growth, and recruitment using CFSR predicted bottom temperatures, NOAA reanalysis predicted surface temperatures, and heatwave indices. These ecosystem linked models were presented at the same time as the operational stock assessment model but were not considered for use in tactical management of the stock at this time. However, projections based on CMIP 5 were provided to the end of the century for strategic considerations and evaluating the performance of the current control rules. At this time these models are being further developed and could be presented as alternatives in future stock assessment model evaluations.

In the future, mortality switches could be evaluated in the advanced stage statistical test, which is a modeling application that analyzes predictor performance and estimates risk probabilities within the operational stock assessment model. Output of two new model developments could be used to generate or enhance an ecosystem-linked model for GOA Pacific cod. First, a new multi-species statistical catch-at-age assessment model (known as CEATTLE; Climate- Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics; Holsman et al., 2016) has recently been developed for understanding trends in age-1 total mortality for Pacific cod, walleye pollock, and arrowtooth flounder from the GOA (Adams et al., 2022). Total mortality rates are based on residual mortality inputs (M1), model estimates of annual predation mortality (M2), and fishing mortality (F). CEATTLE has been modified for the GOA and implemented in Template Model Builder (Kristensen et al., 2015) to allow for the fitting of multiple sources of data, time-varying selectivity, time-varying catchability, and random effects. The model is based, in part, on the parameterization and data used for the most recent stock assessment model of each species (Barbeaux et al., 2021, Dorn et al., 2021, and Shotwell et al., 2021b). The model is fit to data from five fisheries and seven surveys, including both age and length composition assumed to come from a multinomial distribution. Model estimates of M2 are empirically driven by bioenergetics-based consumption information and diet data from the GOA to inform predator-prey suitability. The model was fit to data from 1977 to present.

A spatially-explicit individual-based model (IBM) for the early life stages of Pacific cod was developed as part of the GOA Integrated Ecosystem Research Program (GOAIERP) (Hinckley et al., 2019) using the DisMELS (Dispersal Model for Early Life Stages) IBM framework. It has since been updated to include temperature-dependent egg development and a better characterization of juvenile nursery habitat based on a Habitat Suitability Model. The IBM tracks the 3-dimensional location, growth, and other characteristics of simulated individuals from the egg stage to the benthic juvenile stage using stored 4-dimensional (3-d space and time) ROMS model output to provide the spatiotemporally-varying environment (e.g., 3-dimensional temperature, NPZ, and current fields) in which the individuals "exist". Egg development and larval/juvenile growth rates depend on *in situ* temperature. Vertical movement in the water column is also stage-specific, but horizontal dispersion is currently assumed to be passive. Individual location and other characteristics are updated using Lagrangian particle tracking with a 20-minute integration time step. It would be possible to derive several types of indices using the IBM and ROMS model output for the current year, including: 1) changes in connectivity between presumed spawning and juvenile nursery habitats; 2) spatiotemporally-averaged, temperature-dependent egg development success; and 3) life stage-specific, spatiotemporally-averaged, temperature-dependent growth rates. Once the ROMS model output is available, it takes several hours on a laptop to run the IBM for a year simulating ~100,000 individuals. Additional time would be required to calculate the desired indices, but turn-around could be reasonably quick.

The age-1 mortality index could provide a gap free estimate of predation mortality. Indeed, the age-specific mortality estimates from the GOA CEATTLE model are being tested as priors for age-specific mortality within the age-structured model, however fitting age-specific annually varying mortality within the model has proven to be challenging given the lack of data on younger fish (age 0-3) and will require further development. Additionally, the spawning habitat suitability index and the age-0 beach seine index continue to be explored for use in the most recent age-structured model as an age-0 index. Potentially in the future, other high importance indicators from the Intermediate Stage analysis could also be used directly to help explain the variability in recruitment deviations and predict pending recruitment events for GOA Pacific cod. The ecosystem indicators could also be used to explore linkages to time-varying growth patterns for GOA Pacific cod.

Data Gaps and Future Research Priorities

While the metric and indicator assessments provide a relevant set of proxy indicators for evaluation at this time, there are certainly areas for improvement. The majority of indicators collected for GOA Pacific cod have a fair number of gaps due to the biennial nature of survey sampling in the GOA. This causes issues with updating the ESP and the ecosystem considerations during off-cycle years and can lead to difficulty in identifying impending shifts in the ecosystem that may impact the GOA Pacific cod population. Development of high-resolution remote sensing (e.g., regional surface temperature, transport estimates, primary production estimates) or climate model indicators (e.g., bottom temperature, nutrient-phytoplankton-zooplankton variables) would assist with the current multi-year data gap for several indicators if they sufficiently capture the main trends of the survey data and are consistently and reliably available for use.

Refinements or updates to current indicators may also be helpful. More specific phytoplankton indicators tuned to the spatial and temporal distribution of GOA Pacific cod larvae as well as phytoplankton community structure information (e.g., hyperspectral information for size fractionation) could be more useful for understanding Pacific cod larval fluctuations. Current estimates of zooplankton biomass are only available at smaller spatial scales and regional to gulf-wide estimates of zooplankton biomass as well as offshore to nearshore monitoring of Pacific cod larvae and zooplankton are needed to elucidate prey trends at the spatial scales relevant to fisheries management. Emerging evidence for GOA Pacific cod also states that energy and trophic strategies are very different between Pacific cod and pollock after settlement; therefore, it will be important to align the spatial and temporal extent of available zooplankton or other productivity indicators to the specific needs of the GOA Pacific cod stock in the future (B. Laurel, *pers. commun*.). Demographic differences in the YOY population need to be evaluated within and among larval and juvenile surveys conducted in the Central and Western GOA (currently sampling ~1000km of coastline). Size shifts in the YOY population have already been observed in marine heatwave years, but it is unclear if one or more of the following processes are involved: 1) spawning (earlier); 2) larval/juvenile growth (higher); and/or 3) larval/juvenile mortality (higher/size-selective). Ongoing research seeks to understand how climate-driven changes in size and age may also impact survival trajectories of YOY cohorts and their potential to recruit to the fishery, which will guide further indicator development.

We currently lack an indicator of predation on YOY Pacific cod during their first autumn and winter, during a period when predation mortality is thought to be significant. Sampling of predator diets in fall and winter would help to fill this gap. An index of age-1 Pacific cod from the Kodiak beach seine survey is also available and could be useful for understanding overwinter survival in reference to the age-0 index explored for use in the operational model. The GOA CEATTLE model is now published and has potential to provide a gap-free index of predation mortality for age-1 GOA Pacific cod (Adams et al., 2022). The Pacific cod individual based model (IBM) is also currently being updated (Shotwell et al., *In prep.*) as part of the Essential Fish Habitat (EFH) update. Information on connectivity from spawning to nursery areas and dynamic spatial distribution of egg and larval EFH could be used to create indicators for understanding early life history dynamics. Additionally, evaluating condition and energy density of juvenile and adult Pacific cod samples at the outer edge of the population may be useful for understanding the impacts of shifting spatial statistics such as center of gravity and area occupied. Information is available from the GulfWatch Alaska program that could be helpful for evaluating the eastern edge of the GOA Pacific cod population. Also, a new project has recently been funded involving a multi-model approach including the development of the GOA Ecopath models and an Atlantis ecosystem model. This project is part of the GOA Regional Action Plan and will start in 2021 with the goal of evaluating the biological reference points used for status determination of individual stocks (e.g., Pacific cod) under projected climate scenarios (M. Dorn, *pers., commun*.). The project has a three-year timeline and we hope to incorporate the results of this effort as they become available.

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

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

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Tables

Table 2.1.1a. Gulf of Alaska Pacific cod catch and ex-vessel data. Total and retained catch (thousand metric tons), ex-vessel value (million US$) and price (US$ per pound), hook and line and pot gear share of catch, inshore sector share of catch, number of vessel 2012-2016 average and 2017-2021.

	2012-2016 Average	2017	2018	2019	2020	2021
Total catch K mt	75	48.7	15.2	15.7	6.8	19.2
Retained catch K mt	72.12	47.97	14.4	14.45	4.84	16.14
Ex-vessel value M $	$49.29	$35.23	$14.29	$15.74	$4.42	$15.35
Ex-vessel price lb $	$0.31	$0.33	$0.45	$0.49	$0.39	$0.39
Hook & line share of catch	21.81%	18.14%	22.93%	22.64%	19.21%	28.8%
Pot gear share of catch	50.96%	54.95%	53.05%	52.04%	34.57%	43.28%
Central Gulf share of catch	59.4%	42.77%	46.57%	47.23%	71.73%	62.55%
Shoreside share of catch	91.68%	87.28%	87.92%	89.27%	98.55%	98.95%
Vessels #	390	247	152	176	100	186

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

Table 2.1.1b. Gulf of Alaska Pacific cod first-wholesale market data. First-wholesale production (thousand metric tons), value (million US$), price (US$ per pound), fillet and head and gut volume (thousand metric tons), value share, and price (US$ per pound), inshore share of value; 2012-2016 average and 2017-2021.

	2012-2016 Average	2017	2018	2019	2020	2021
All Products volume K mt	28.52	17.39	5.58	7.47	2.97	6.54
All Products value M $	$103.94	$75.46	$31.91	$35.17	$15.03	$35.75
All Products price lb $	$1.65	$1.97	$2.59	$2.14	$2.3	$2.48
Fillets volume K mt	8.58	6.52	2	2.37	1.12	2.7
Fillets value share	55.05%	60.02%	60.07%	61.1%	67.41%	71.37%
Fillets price lb $	$3.03	$3.15	$4.35	$4.12	$4.09	$4.28
Head & Gut volume K mt	12.69	6.11	1.92	3.02	1.15	1.69
Head & Gut value share	32.28%	26.94%	27.06%	24.22%	23.42%	16.17%
Head & Gut price lb $	$1.2	$1.51	$2.04	$1.28	$1.39	$1.55

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

Table 2.1.1c. Cod U.S. trade and global market data. Global production (thousand metric tons), U.S. share of global production, and Europe's share of global production; U.S. export volume (thousand metric tons), value (million US$), and price (US$ per pound); U.S. cod consumption (estimated), and share of domestic production remaining in the U.S. (estimated); and the share of U.S. export volume and value for head and gut (H&G), fillets, China, Japan, and Germany and Netherlands; 2012-2016 average and 2017-2021.

	2012-2016 Average	2017	2018	2019	2020	2021
Global cod catch K mt	1763.16	1760.31	1636.16	1565.77	1483.09	-
U.S. P. cod share of global catch	18.7%	16.9%	14.2%	13.4%	11.6%	-
Europe Share of global catch	75.1%	75.9%	78.3%	78.5%	80.3%	-
Pacific cod share of U.S. catch	99.6%	99.8%	99.9%	99.8%	99.7%	-
U.S. cod consumption K mt (est.)	107.826	118.558	113.622	106.275	103.362	107.078
Share of U.S. cod not exported	29.4%	32.5%	35.5%	36.8%	45%	53.1%
Export volume K mt	107.74	92.79	73.14	65.1	44.48	32.52
Export value M US$	$326.55	$295.5	$253.37	$217.88	$139.4	$101.68
Export price lb US$	$1.37	$1.44	$1.57	$1.52	$1.42	$1.42
Frozen (H&G) volume share	89.49%	93.6%	90.95%	92.31%	92.32%	89.44%
Frozen (H&G) value share	88.19%	92.15%	90.42%	90.71%	89.83%	84.21%
Fillets volume share	4.34%	4.12%	4.97%	4.68%	5.86%	8.73%
Fillets value share	5.78%	5.33%	5.69%	5.84%	7.38%	12.93%
China volume share	51.63%	52.4%	47.55%	41.52%	39.52%	31.36%
China value share	49.01%	49.67%	46.46%	40.21%	37.35%	28.38%
Japan volume share	14.57%	16.09%	15.06%	11.86%	13.04%	10.99%
Japan value share	15.1%	18.36%	16.67%	12.97%	13.89%	11.78%
Europe* volume share	21.05%	17.35%	15.95%	21.6%	20.13%	11.53%
Europe* value share	22.65%	17.73%	17.67%	23.12%	20.69%	10.95%

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

Table 2.1.2a. First stage ecosystem indicator analysis for GOA Pacific cod, including indicator title and the indicator status of the last five years. The indicator status is designated with text, (greater than = "high", less than = "low", or within 1 standard deviation = "neutral" of long-term mean). Fill color of the cell is based on the sign of the anticipated relationship between the indicator and the stock (blue or italicized text = good conditions for the stock, red or bold text = poor conditions, white = average conditions). A gray fill and text = "NA" will appear if there were no data for that year.

Indicator category	Indicator	2018 Status	2019 Status	2020 Status	2021 Status	2022 Status
Physical	Spawning Heatwave GOA Model	neutral	**high**	neutral	neutral	neutral
	Winter Spring Pacific Cod Spawning Habitat Suitability GAK1 Model	neutral	**low**	neutral	neutral	neutral
	Summer Temperature Bottom GOA Model	neutral	**high**	neutral	neutral	neutral
	Annual Eddy Kinetic Energy Kodiak Satellite	neutral	neutral	*high*	neutral	neutral
Lower Trophic	Spring Chlorophyll a Peak WCGOA Satellite	**low**	*high*	**low**	neutral	neutral
	Summer Large Copepod Abundance Shelikof Survey	NA	neutral	NA	NA	NA
	Summer Euphausiid Abundance Kodiak Survey	NA	neutral	NA	NA	NA
	Spring Pacific Cod CPUE Larvae Shelikof Survey	NA	neutral	NA	neutral	NA
	Annual Common Murre Reproductive Success Chowiet Survey	neutral	*high*	NA	neutral	*high*
	Summer Pacific Cod CPUE YOY Nearshore Kodiak Survey	neutral	neutral	*high*	neutral	*high*
Upper Trophic	Summer Pacific Cod Condition Juvenile GOA Survey	NA	neutral	NA	neutral	NA
	Summer Pacific Cod Condition Adult GOA Survey	NA	neutral	NA	neutral	NA
	Summer Pacific Cod Center Gravity Northeast WCGOA Model	NA	**high**	NA	neutral	NA
	Summer Pacific Cod Area Occupied WCGOA Model	NA	*high*	NA	*high*	NA
	Annual Arrowtooth Biomass GOA Model	neutral	neutral	*low*	*low*	NA
	Annual Steller Sea Lion Adult GOA Survey	neutral	neutral	neutral	neutral	NA

Table 2.1.2b. First stage socioeconomic indicator analysis for GOA Pacific cod, including indicator title and the indicator status of the last five years. The indicator status is designated with text, (greater than = “high”, less than = “low”, or within 1 standard deviation = “neutral” of long-term mean). A gray fill and text = “NA” will appear if there were no data for that year.

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

Figures

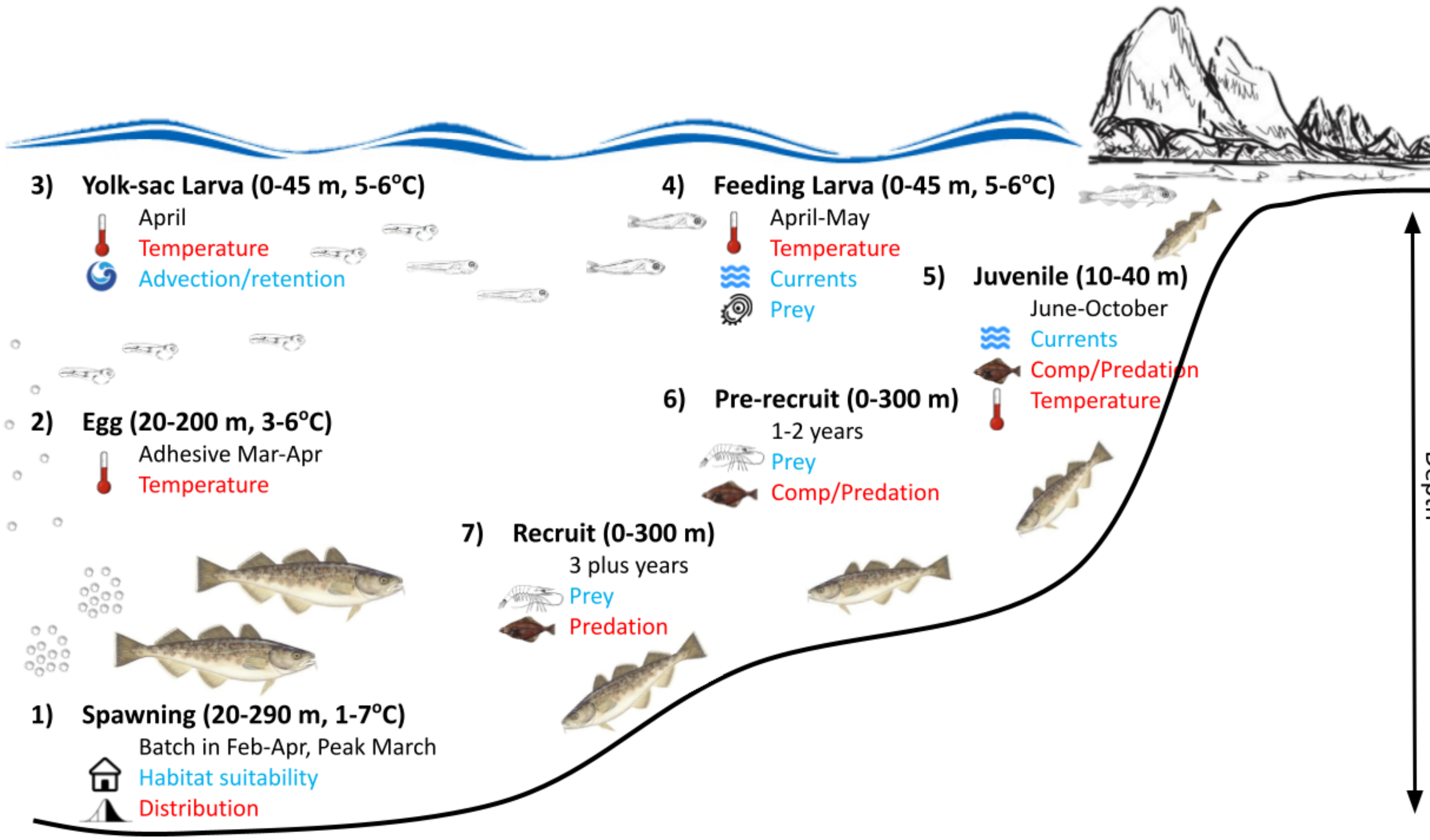


Figure 2.1.1: Life history conceptual model for GOA Pacific cod summarizing ecological information and key ecosystem processes affecting survival by life history stage. Red text means increases in the process negatively affect survival, while blue text means increases in the process positively affect survival.

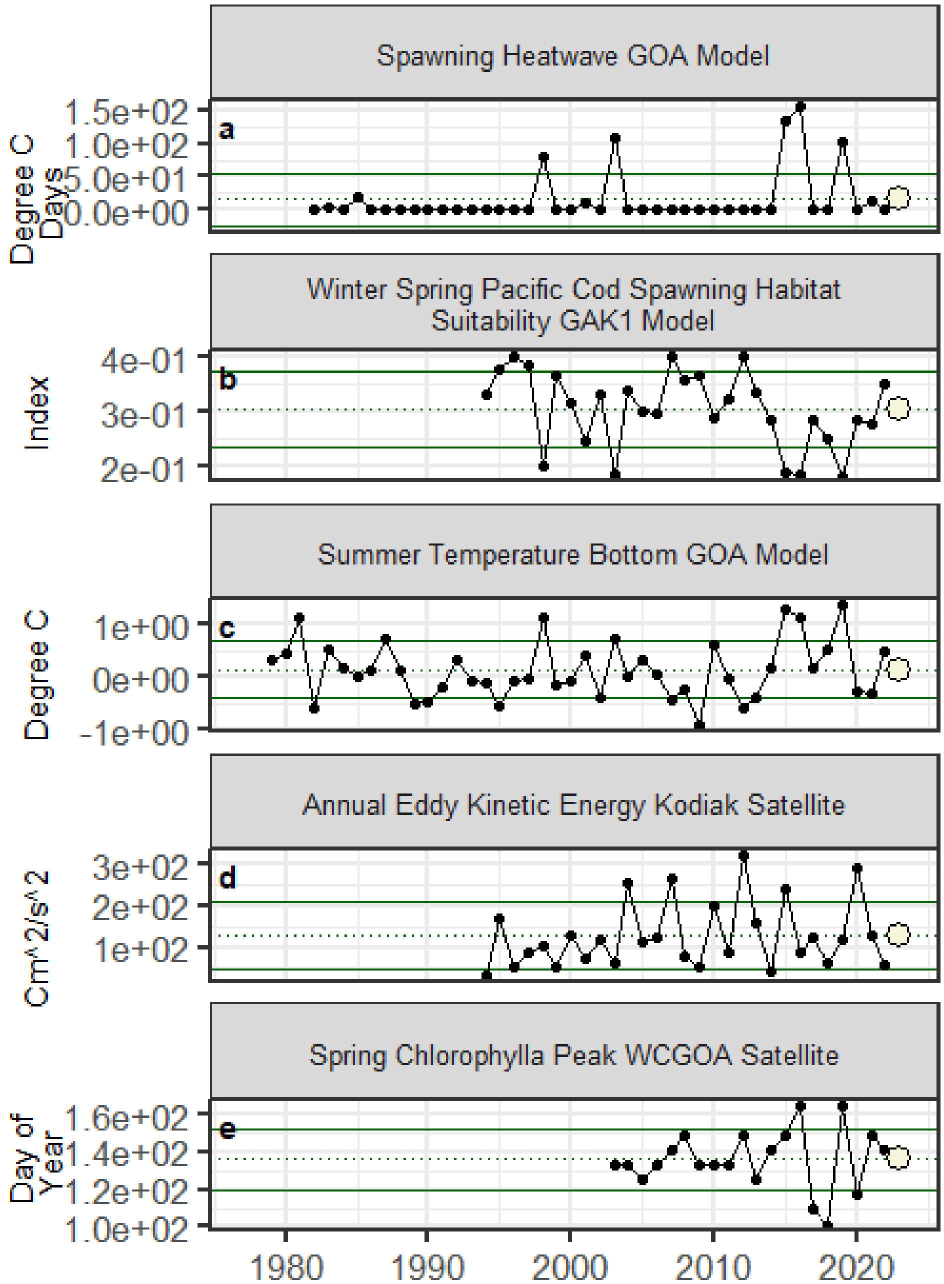


Figure 2.1.2a. Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. A symbol appears when current year data are available and follows the traffic light status table designations (triangle direction represents if above or below 1 standard deviation of the time series mean, color represents proposed relationship for stock with blue for good conditions, red for poor conditions, and a white circle is neutral).

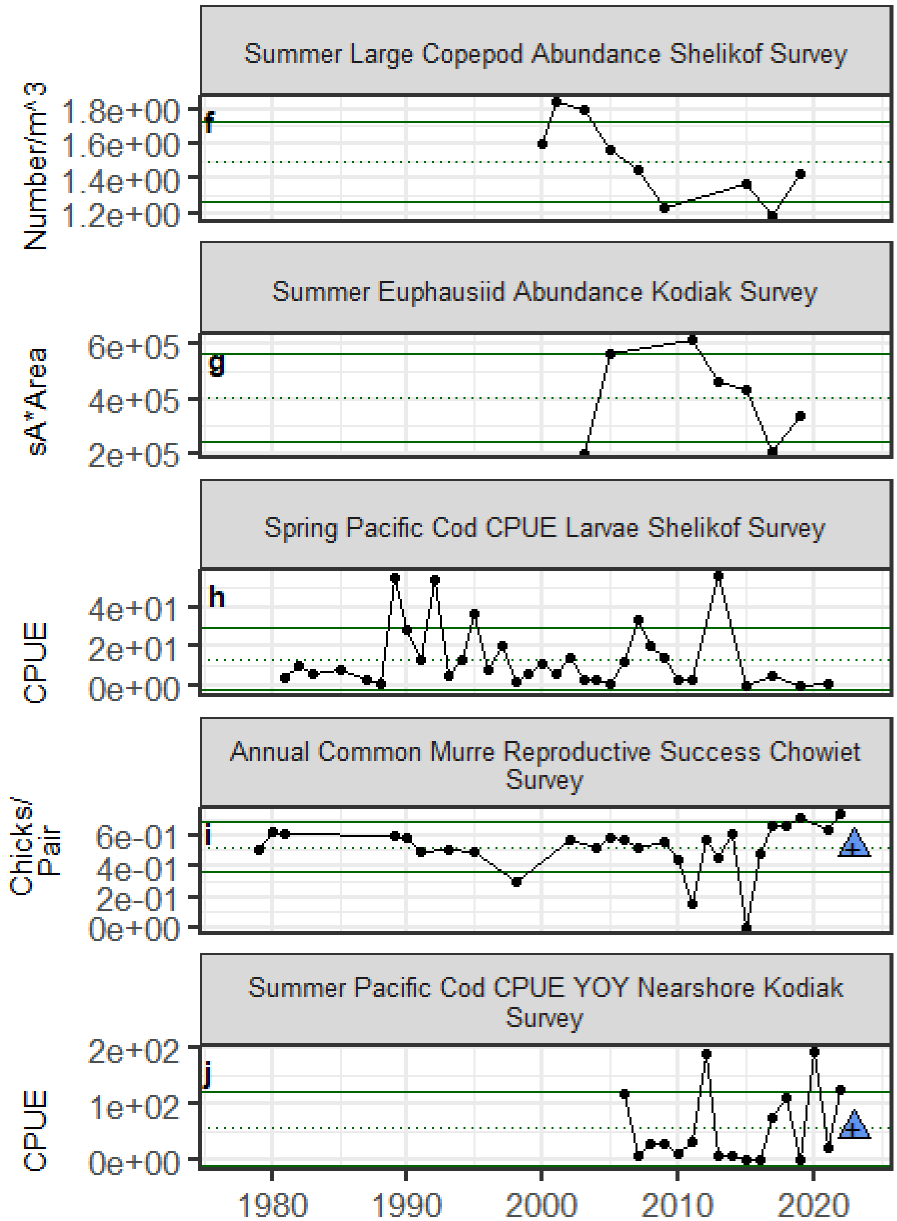


Figure 2.1.2a (cont.). Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. A symbol appears when current year data are available and follows the traffic light status table designations (triangle direction represents if above or below 1 standard deviation of the time series mean, color represents proposed relationship for stock with blue for good conditions, red for poor conditions, and a white circle is neutral).

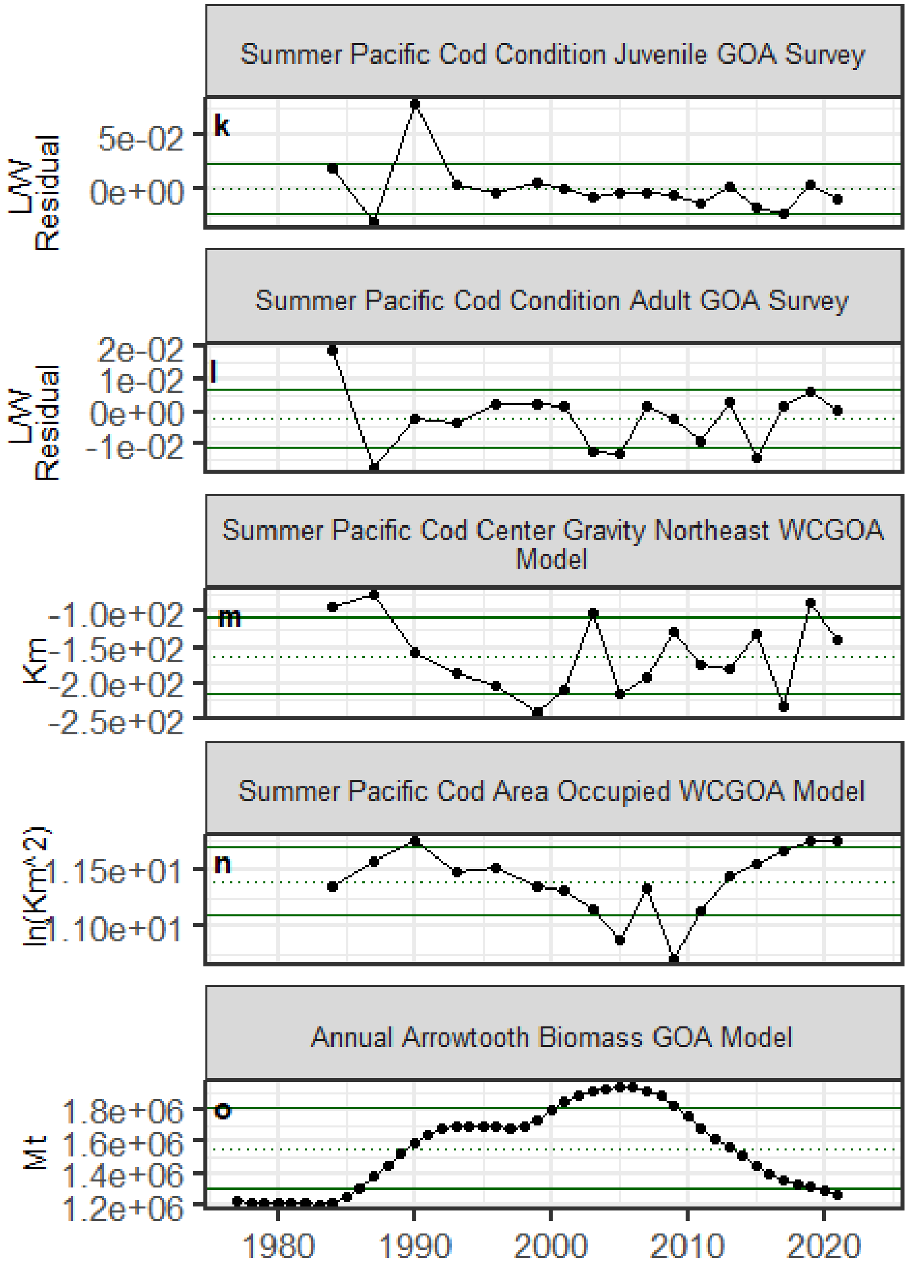


Figure 2.1.2a (cont.). Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. A symbol appears when current year data are available and follows the traffic light status table designations (triangle direction represents if above or below 1 standard deviation of the time series mean, color represents proposed relationship for stock with blue for good conditions, red for poor conditions, and a white circle is neutral).

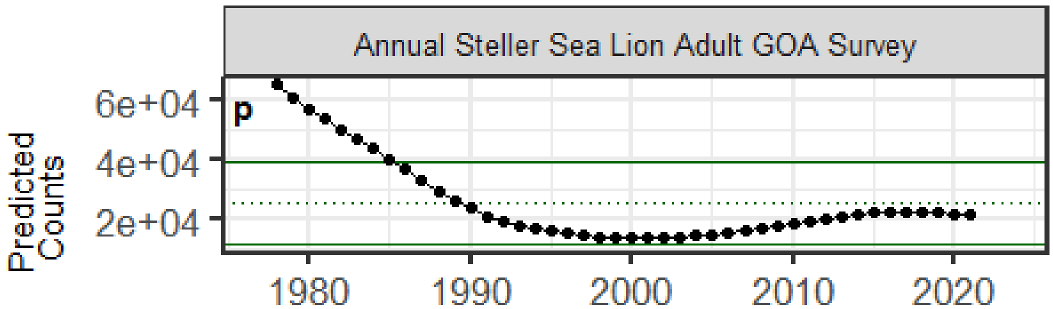


Figure 2.1.2a (cont.). Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. A symbol appears when current year data are available and follows the traffic light status table designations (triangle direction represents if above or below 1 standard deviation of the time series mean, color represents proposed relationship for stock with blue for good conditions, red for poor conditions, and a white circle is neutral).

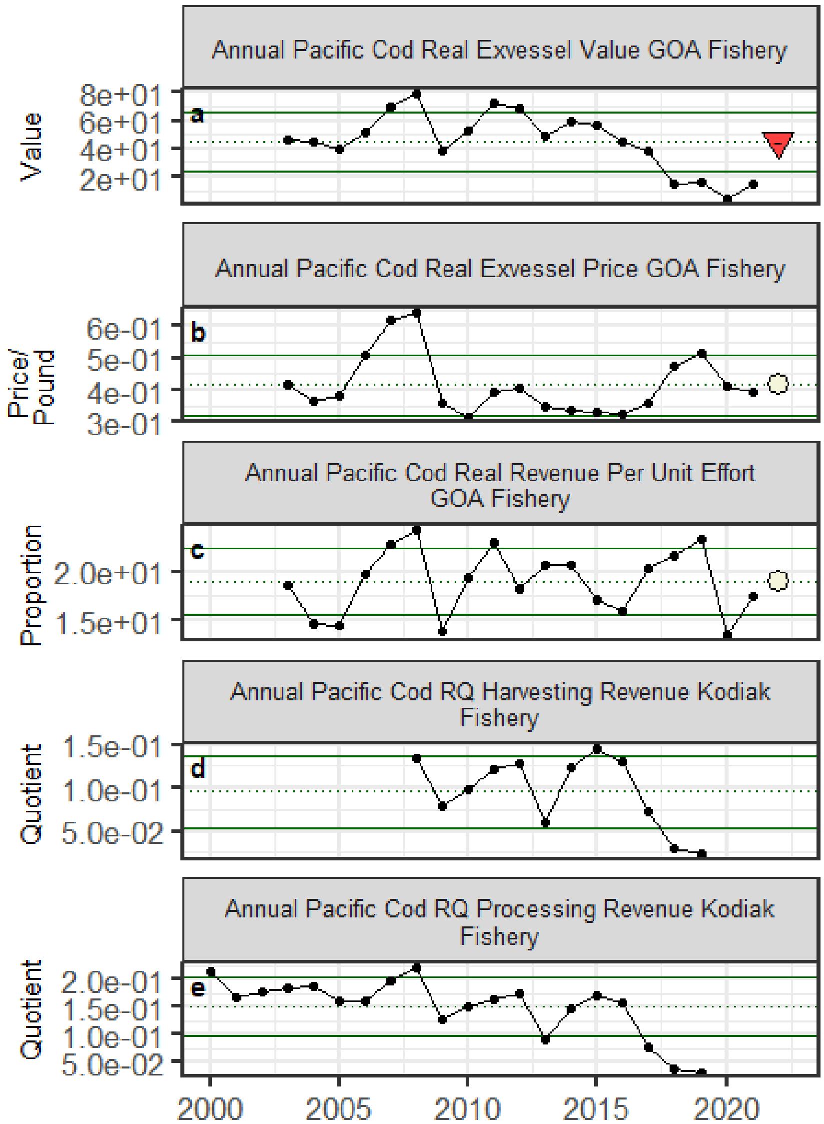


Figure 2.1.2b. Selected socioeconomic indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. A symbol appears when current year data are available and follows the traffic light status table designations (triangle direction represents if above or below 1 standard deviation of the time series mean, color only designates above (blue) or below (red) one standard deviation of the time series mean, no implied relationship with the stock).

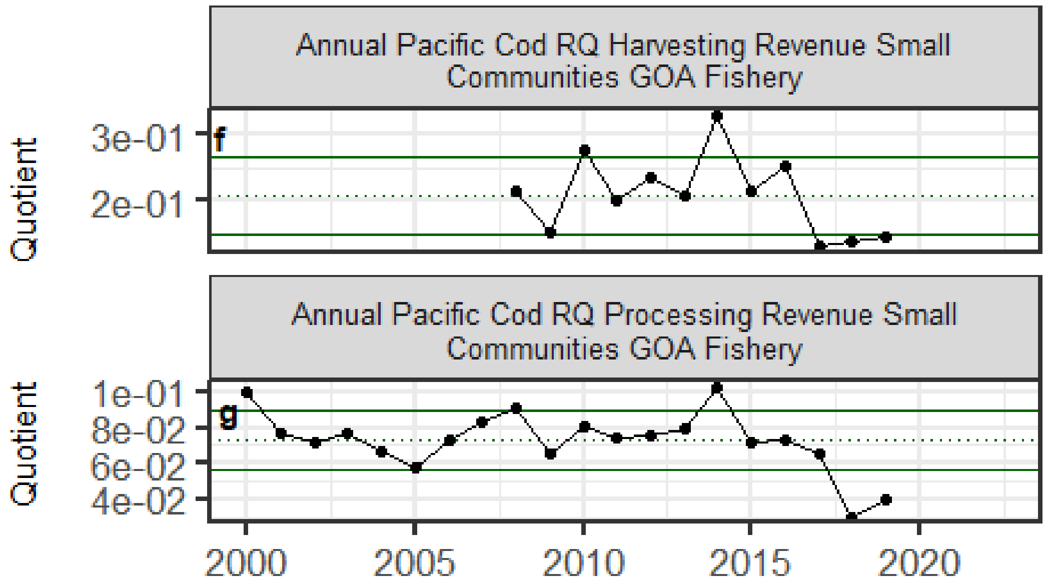


Figure 2.1.2b (cont.). Selected socioeconomic indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. A symbol appears when current year data are available and follows the traffic light status table designations (triangle direction represents if above or below 1 standard deviation of the time series mean, color only designates above (blue) or below (red) one standard deviation of the time series mean, no implied relationship with the stock).

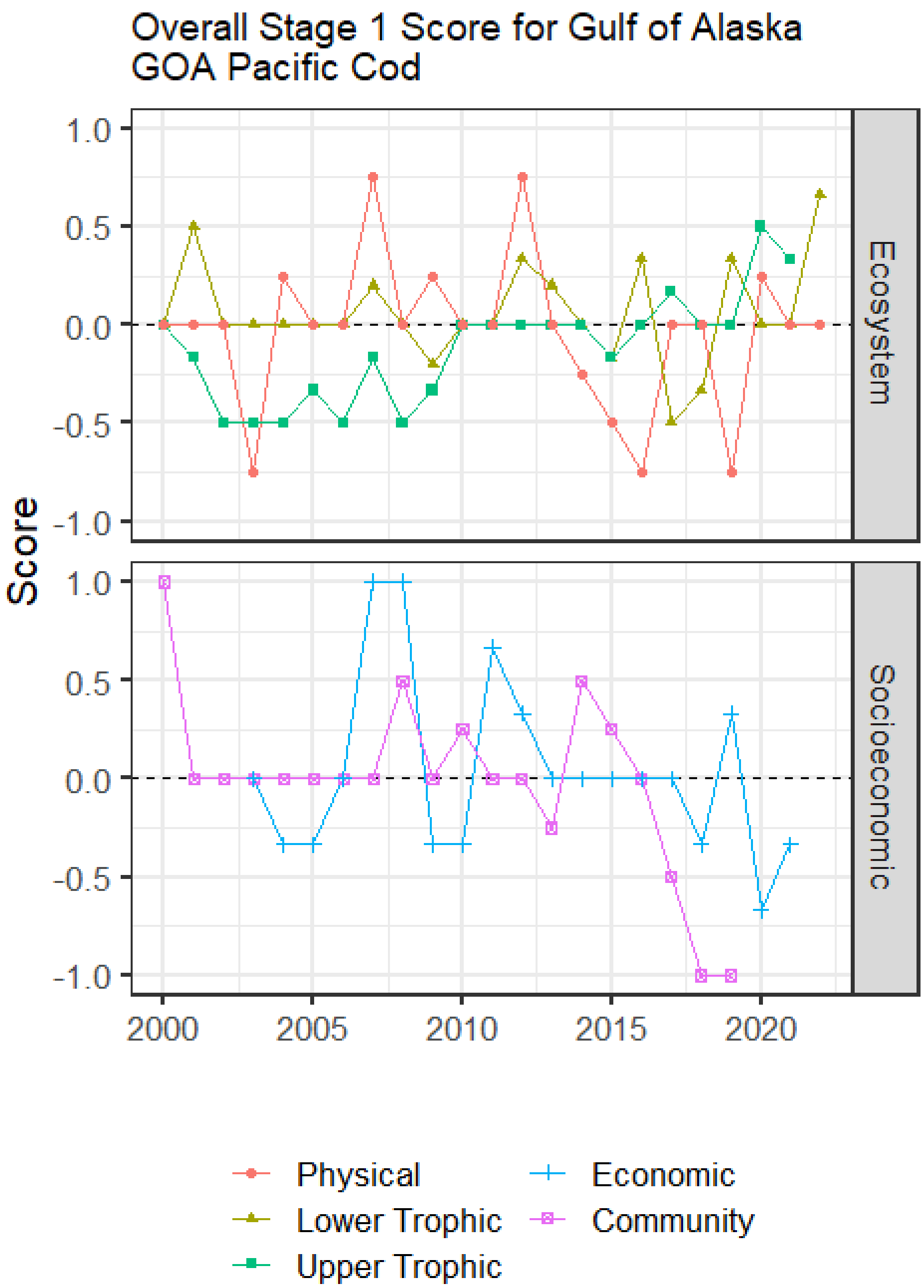
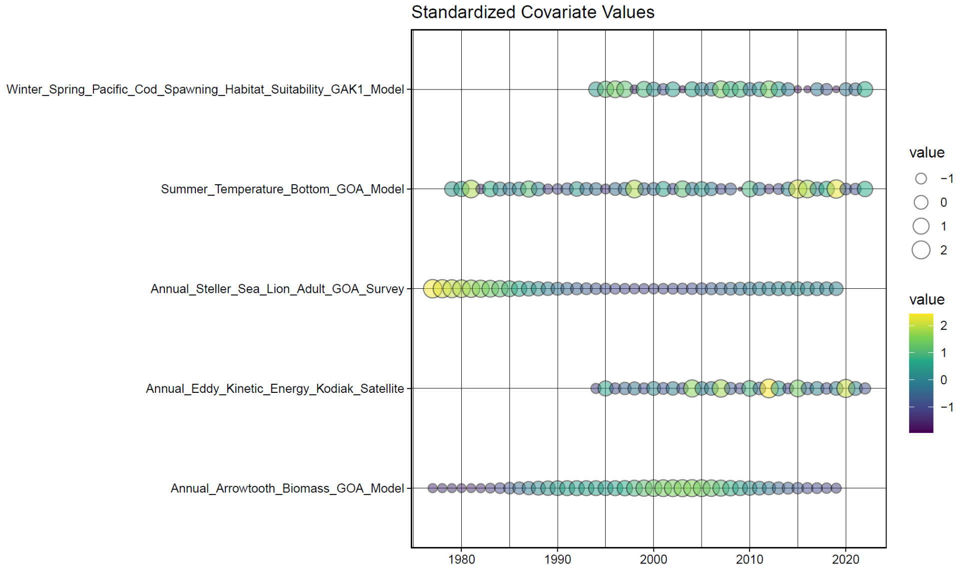


Figure 2.1.3: Simple summary traffic light score by category for ecosystem and socioeconomic indicators from 2000 to present.



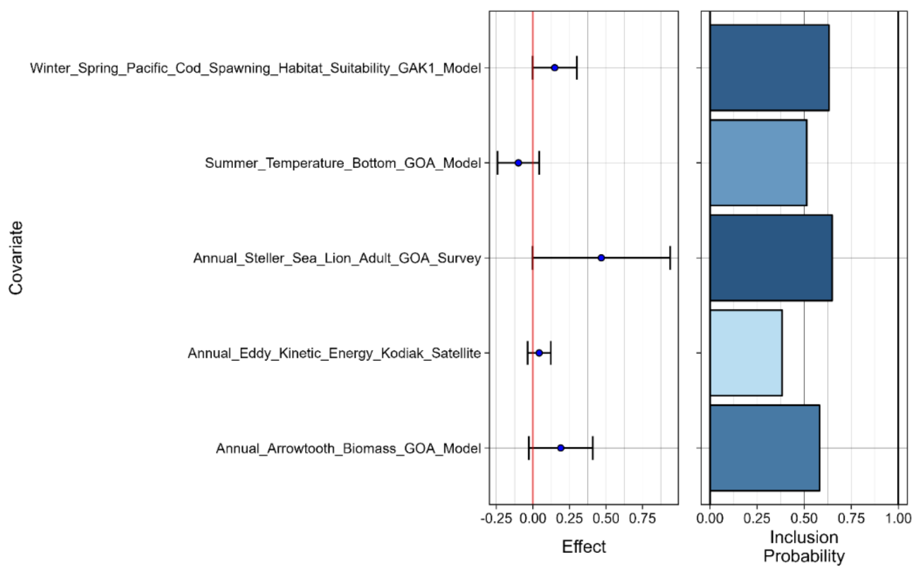


Figure 2.1.4: Bayesian adaptive sampling output showing (top graph) standardized covariates and (bottom graph) the mean relationship and uncertainty (95% confidence intervals) with log GOA Pacific cod recruitment, in each estimated effect (left bottom graph), and marginal inclusion probabilities (right bottom graph) for each predictor variable of the subsetted covariate set.

Appendix 2.2 Addition of 1997 – 2002 State GHL catches to model catch time-series

Introduction

In the process of compiling data for the 2022 assessment it was discovered that there was catch from the State GHL fishery in 1997 – 2002 (Table 2.1) that had been reported but not accounted for in the model's catch time-series within previous GOA Pacific cod assessments. This catch ranged from above 8,500 t to greater than 13,400 t, representing an average of 17% of the total harvest in those years. In this year's assessment we include this catch in the model's time-series of catch, and to denote this addition the recommended model this year will be denoted as Model 19.1a. We include this appendix to document this change, both in the model numbering but also in the model results.

Results

With the addition of the 1997 – 2002 State GHL fishery catch into Model 19.1a estimated fishing mortality during this period increased, as would be expected (Fig. 2.2.1). This resulted in a slight increase in spawning biomass (Fig. 2.2.2), which was driven by an increase in early recruitment estimates (Fig. 2.2.2). Overall, model estimates after 2010 remain largely unchanged in Model 19.1a compared to Model 19.1. We recommend that Model 19.1a be used in future assessments of GOA Pacific cod in order to account for this historical State GHL catch.

Figures

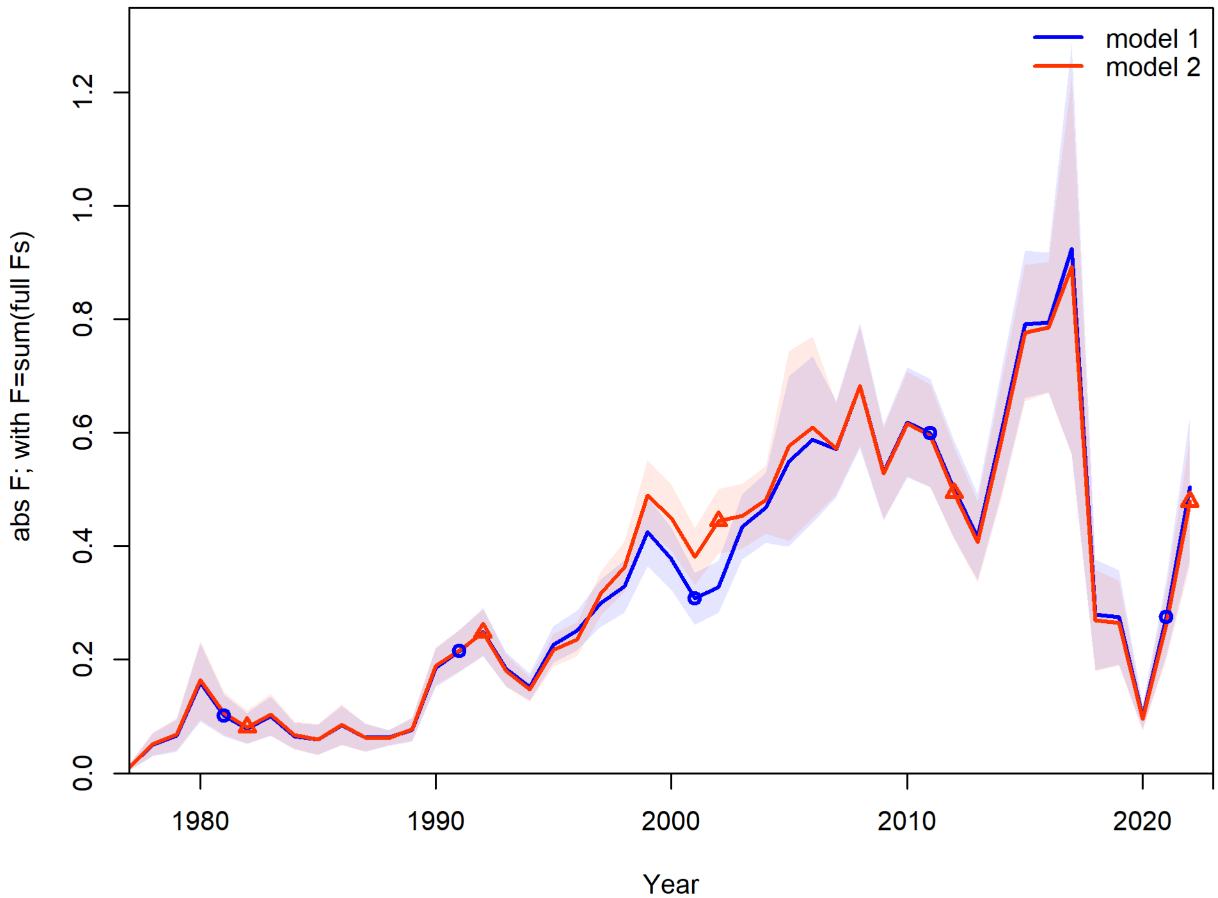


Figure 2.2.1. Estimated fishing mortality from Model 19.1 (model 1) compared to Model 19.1a (model 2).

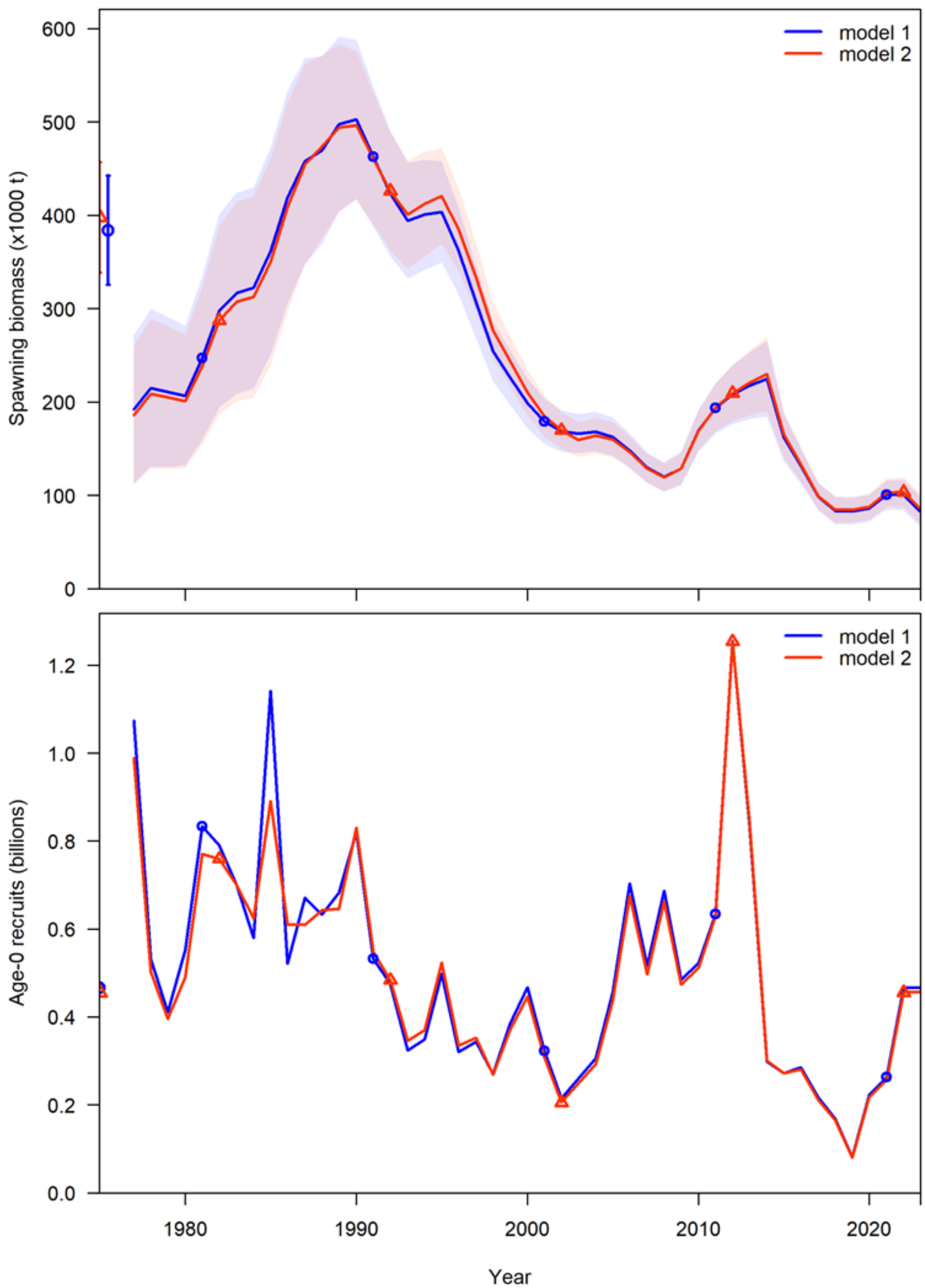


Figure 2.2.2. Estimated spawning biomass (top) and age-0 recruitment (bottom) from Model 19.1 (model 1) compared to Model 19.1a (model 2).