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

Steven Barbeaux, Kerim Aydin, Ben Fissel, Kirstin Holsman, Ben Laurel, Wayne Palsson,

Kalei Shotwell, Qiong Yang, and Stephani Zador

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Alaska Fisheries Science Center
7600 Sand Point Way NE., Seattle, WA 98115-6349

Executive Summary

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 2017 were updated and preliminary federal and state catch data for 2018 were included;
2. Commercial federal and state fishery size composition data for 2017 were updated, and preliminary commercial federal and state fishery size composition data for 2018 were included;
3. AFSC longline survey Pacific cod abundance index and length composition data for the GOA for 2018 were included;
4. Age composition and conditional length-at-age data for the 2017 AFSC bottom trawl survey were added to the model
5. Age composition and conditional length-at-age data for the 2012-2017 fisheries were added to the model.

Changes in the methodology

Model 17.09.35 is last year's reference model with the addition of the 2017 AFSC bottom trawl survey age data, and 2018 longline survey and fishery data including fishery age composition and conditional length-at-age data. There are two new data configurations and three new model series explored this year (see below). Model18.10.46 uses an environmental index to drive natural mortality and no satisfactory method has been yet fully vetted to conduct standard projections.

Model configurations:

Model	Data	SS version	M- block	Maturity	Marine heatwave index	Selectivity	Prior CV on M	VB prior (l_{inf}/K)
17.09.35	Same as 2017	2.24	15-16	Age-based		Length-based	0.10	Uniform
18.09.35	Same as 2017	3.30	14-16	Age-based		Length-based	0.10	Uniform
18.09.38A	Same as 2017	3.30	14-16	Length-based		Length-based	0.10	Uniform
18.10.38A	No age data pre-2007	3.30	14-16	Length-based		Length-based	0.10	Uniform
18.10.38B	No age data pre-2007	3.30	14-16	Length-based		Length-based	0.10	Normal 99.46/0.197
18.10.44	No age data pre-2007	3.30	14-16	Length-based		Length-based	0.41	Normal 99.46/0.197
18.10.46	No age data pre-2007	3.30	NA	Length-based	✓	Length-based	0.41	Normal 99.46/0.197
18.11.38B	No age data	3.30	14-16	Length-based		Length-based	0.10	Normal 99.46/0.197

All proposed models presented were single sex age-based models with length-based selectivity. The models have 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 indices. Growth was parameterized using the standard three parameter von Bertalanffy growth curve. Recruitment was parameterized as a standard Beverton-Holt with steepness fixed at 1.0 and sigma R at 0.44. All selectivities were fit using six parameter double-normal selectivity curves.

Model 17.09.35 performed well and is last year's reference model with the additionally available data described above. However, Model 18.10.44 is the best fit model, has less influential priors on natural mortality and is most consistent with last year's reference model used for management while considering the aging bias in the pre-2007 read ages. This model further expands the heatwave to include 2014 as suggested through a heatwave analysis. In addition, maturity is length instead of age based. Like Model 17.09.35 it suggests a moderate increase in M for 2014-2016 and has a retrospective index within reasonable bounds for both spawning biomass and recruitment. Therefore Model 18.10.44 was selected as the Authors' preferred method. A reduction of the ABC below Max ABC to 17,000 t in 2019 was proposed so that the stock continues to have a greater than 50% probability of remaining above $B_{20\%}$ for 2020 in projections. Results are summarized below:

Quantity	As estimated or *specified last* year for: 2018	2019	As estimated or *specified this* year for: 2019	2020
M (natural mortality rate)	0.49	0.49	0.50	0.50
Tier	3b	3b	3b	3b
Projected total (age 0+) biomass (t)	170,565	198,942	266,066	329,133
Female spawning biomass (t)				
Projected	36,209	34,424	34,701	34,774
$B_{100\%}$	168,583	168,583	172,240	172,240
$B_{40\%}$	67,433	67,433	68,896	68,896
$B_{35\%}$	59,004	59,004	60,284	60,284
F_{OFL}	0.42	0.40	0.36	0.36
$maxF_{ABC}$	0.34	0.32	0.29	0.29
F_{ABC}	0.31	0.31	0.25	0.29
OFL (t)	23,565	21,412	23,669	26,078
maxABC (t)	19,401	17,634	19,665	21,592
ABC (t)	18,000	17,000	*17,000	21,592
Status	As determined *this* year for: 2016	2017	2017	2018
Overfishing	No	n/a	No	n/a
Overfished	n/a	no	n/a	No
Approaching overfished	n/a	no	n/a	No

*Reduction from max to 17,000t to maintain stock above $B_{20\%}$ in 2020 based on estimated end of year catch in 2018 of 13,096 t.

Area apportionment

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 2017, the area-apportioned ABCs are:

	Western	Central	Eastern	Total
Random effects area apportionment	44.9%	45.1%	10.0%	100%
2019 ABC	7,633	7,667	1,700	17,000
2020 ABC	9,695	9,738	2,159	21,592

Responses to SSC and Plan Team Comments Specific to this Assessment

November 2016 Plan Team

The Team recommends that the author examine and incorporate where possible relevant data from the IPHC and ADFG surveys. Specific to the ADFG survey, the Team recommended coordinating with planned studies for alternative evaluation of these data to develop a refined index for pollock.

> *The CIE reviewers in 2018 concurred that the IPHC survey should be considered for use in the assessment. However length composition data were not yet available for model development for the September Plan team. The IPHC longline survey index and length composition are presented in this assessment below. There was disagreement among the CIE reviewers as to whether the ADFG large mesh trawl surveys should be used in the assessment and further analysis of these data is required before it is considered for use in a production model. The data through 2018 are presented in this assessment. It should be noted that both surveys indicated a decline in the cod abundance since 2015.*

The Team recommends that fishery otoliths be aged to support this stock assessment and this should include resolving past data which may have been subjected to biased age-determination methods. In particular, the Team recommends that the otoliths used in the Stark 2007 maturity-at-age study be re-evaluated for potential bias in the age-determination method used.

> *Fishery otoliths for 2008-2017 have been aged and included in this year's models for both age composition and conditional length-at-age. The Stark (2007) otoliths have been re-aged, they indicated an aging bias in the otoliths aged prior to 2007. Attempts at modeling this bias were not successful. Models presented this year include runs without age data aged prior to 2007 (Series Model18.10.xx). There is also a model run without any age data included (Model 18.11.38).*

December 2017 SSC

The SSC noted that the estimated value for M in the author's preferred model was 0.47, using a prior with a mean of 0.38 and a CV of 0.1. A number of studies were referenced suggesting a range of M that is potentially broader than implied by the current prior. All three Pacific cod assessments could benefit from a consistent formal prior on M based on the variety of studies referenced in each. The SSC recommends that a prior for use in all Pacific cod assessments be developed for 2017 and explored for use in the GOA Pacific model.

> *Models were explored this year using a prior for M developed by Grant Thompson for the EBS cod stock (see Thompson et al. 2017), lognormal with a mean of -0.81 and cv of 0.42.*

The SSC recommends that ageing additional fishery otoliths for this assessment be a priority, noting that the AFSC has an ongoing ageing-prioritization analysis which may guide their future efforts, and the author has recommended working with the age and growth lab on this project. Along these lines, ages underlying the study defining current maturity schedules (Stark, 2007) should be re-aged, and the data re-analyzed in light of recent information regarding ageing bias (i.e., Kastelle et al., 2017).

> *Fishery otoliths for 2008-2017 have been aged and included in this year's models for both age composition and conditional length-at-age. The Stark (2007) otoliths have been re-aged, they indicated an aging bias in the otoliths aged prior to 2007. Attempts at modeling this bias were not successful. Models presented this year include runs without age data aged prior to 2007 (Series Model18.10.xx). There is also a model run without any age data included (Model 18.11.38).Aging bias should be explicitly included in the next assessment.*
>
> *Aging error was explored in several model configurations last year. Substantial time and effort were put into exploring model runs with aging error and aging bias this year. However, there are*

substantial performance issues when implemented that requires additional work before a model with these features will be ready to present for management. Neither aging error nor aging bias were included in the suite of models presented this year. Models without the problematic age data were included. The authors are currently working with the Age and Growth program at the AFSC to develop aging error and aging bias alternatives for the stock synthesis model. Sandi Neidetcher is re-evaluating the ovary samples for maturity stage processed during the Stark (2007) study. The models presented this year use size-based maturity instead of age-based maturity.

September 2018 Plan Team

The Team discussed that the percent agreement between the age reader and the tester be examined to see if there are any indications of bias that may contribute to this problem. For presentation, the Team suggested that length at age data may be examined in aggregate pre- and post-2007 to better understand the implications of the changed methods.

Length at age data pre- and post- 2007 are presented below. The analysis indicates that there was likely a reader effect in the aging of the cod otoliths.

October 2018 SSC

The SSC in its September 2018 minutes recommended that assessment authors and plan teams use the Dorn risk matrix when determining whether to recommend an ABC lower than the maximum permissible.

Assessment considerations. *The GOA Pacific cod assessment does not show a strong retrospective bias, and fits to the size composition data for the fisheries and AFSC longline survey well. The fit to the bottom trawl survey size composition does not capture some of the dynamics of the sub-27 cm fish, often underestimating the small fish from the survey. The GOA Pacific cod assessment is fit to two surveys the AFSC bottom trawl survey and AFSC longline survey. These surveys tend to agree in trend, the AFSC longline survey at times has a delay due to lower selectivity on younger fish which is captured by model selectivity well. One issue for consideration is that estimates for 1977-1989 recruitment (and hence abundance), particularly the 1977 year class, are sensitive to assumptions on fishery selectivity. As early recruitment values have a direct result on estimates of the reference values, a review of the models presented in 2016-2018 shows substantial modeling uncertainty. We rated the assessment-related concern as level 2, a substantially increased concern, because of the modeling uncertainty in the early recruitment estimates and model sensitivity relative to other North Pacific assessments where this is not an issue. However other aspects of the assessment seem relatively robust, so we could not justify going to a higher risk level.*

Population dynamics considerations. *Female spawning biomass is currently estimated to be at its lowest point in the 41-year time series considered in this assessment. This following three years of poor recruitment in 2014-2016 and increased natural mortality during the 2014-2016 GOA marine heat wave. There are no data in the assessment to estimate recruitment post-2016 and therefore recruitment for these years is estimated at average. With average recruitment it is expected that the stock status will improve, however there are no data to inform Pacific cod recruitment for these years. Information from beach seine surveys suggests a strong 2018 year class at age-0 is showing up in some near-shore habitats, but how this relates to overall recruitment into the fishery is currently unknown. Overall, we rated the population-dynamic concern as level 4, Extreme concern.*

Environmental/Ecosystem considerations. *It is likely that the poor recruitment in 2014-2016 and increased natural mortality of the entire stock are due to the intense and long-lasting 2014-2016 marine heat wave. In general, environmental conditions in 2017 and early 2018 appeared to be substantially improved, with cooler sea temperatures prevailing. For example, early May sea temperature to 100m depths in the northern Gulf of Alaska across the shelf along the Seward Line returned to the long-term 22 year mean during 2017 and 2018. However, in September of 2018 surface temperature patterns exceeded the Hobday threshold for a heatwave (See below). At the time this assessment was completed, the intensity of the heatwave is lower than for 2014-2016, although the duration is unknown. Short-term heatwaves are expected to have a greater negative impact on lower trophic organisms than apex predators. It is reasonable to expect that the current heat wave may negatively impact age-0 cod during a time when they are growing to a size that promotes over winter survival. In addition, climate models predict anomalously warm sea surface temperatures and a 70% probability of an El Niño through the 2018-19 winter. These portend warmer conditions in the near future in the Gulf of Alaska and hence poor conditions for age-0 survival.*

Foraging conditions for juvenile cod appear to be favorable in 2018. Copepod community size anomalies were larger for the Alaskan Shelf and oceanic habitats in 2017, after a period of smaller size copepods during the marine heat wave (2014-2016). Biomass of copepods and euphausiids were above the long-term mean during May 2018 along the Seward Line. A suite of indicators suggests that while small copepods were abundant during the heat wave, the more lipid-rich large copepods and euphausiids were less so. Thus, increases in large copepods and euphausiids suggest improved foraging conditions. The lipid content of all zooplankton taxa examined increased from 2017 to 2018, indicating an increase in the nutritional quality of the prey field utilized by larval and juvenile fish in Icy Strait, northern southeast Alaska.

Foraging conditions for adult cod can be inferred to some degree by looking at other forage fish predators. Fish-eating seabirds in the Gulf of Alaska had generally normal reproductive success at monitored colonies in 2018. Murres had better colony attendance and fledging rates that during 2015-2016, but the overall numbers of breeding birds was still low. Timing of breeding was normal for most species at Chowiet (Semidi Islands), late for murres at East Amatuli (Barren Islands), and late for murres and gulls at St. Lazaria (Southeast Alaska). Murre and cod survival appeared to be somewhat correlated during the marine heat wave with higher mortality in both. A return to more normal environmental conditions may suggest better conditions for piscivores in general in the Gulf of Alaska. However, some of the larger apex predators (e.g., humpback whales) appear to have not fully recovered. For now we rated the Environmental /Ecosystem considerations to be at Level 2: Substantially increased concerns because while the 2017 and early 2018 environment looks positive for cod, projections of late 2018 and 2019 do not look promising.

These results are summarized in the table below:

Assessment-related considerations	Population dynamics considerations	Environmental/ecosystem considerations	Overall score (highest of the individual scores)
Level 2: Substantially increased	Level 4: Extreme concern	Level 2: Substantially increased	Level 4: Extreme concern

The overall score of level 4 suggests that setting the ABC below the maximum permissible is warranted. The SSC recommended against using a table that showed example alternatives to select buffers based on that risk level. Thompson (unpublished Sept 2018 plan team document) tabulated the magnitude of buffers applied by the plan teams for the period 2003-2017, and found that the mode of the buffers recommended was 10-20 percent. Taking this as guideline, we recommend the reduction of the ABC to the value recommended in last year's assessment of 17,000 t, this is a 13.6% buffer from the maximum ABC of 19,665 t.

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 4500 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.

Tagging studies (e.g., Shimada and Kimura 1994) have demonstrated significant migration both within and between the EBS, AI, and GOA (Fig. 2.2). For the GOA it appears there is substantial migration between the southern Bering Sea and the western GOA, however little movement has been observed from the central GOA to the Western GOA. Two recent genetics studies using Restriction-site Associated DNA sequencing have indicated significant genetic differentiation among spawning stocks of Pacific cod in the Gulf of Alaska and the Bering Sea (Drinan et al. 2018; Spies et al. In Prep). The first study (Drinan et al. 2018) used 6,425 SNP loci to show high assignment success >80% of five spawning populations of Pacific cod throughout their range off Alaska. Further work using Alaskan samples in Drinan et al. (2018) as well as spawning fish near Unimak Pass, Pervenets Canyon, and Pribilof Island in the Eastern Bering Sea 2016-2018 and a sample from the Northern Bering Sea in August 2017 showed similar levels of differentiation among spawning groups (Spies et al. In Prep), using 3,599 SNP loci. The three spawning groups examined in the Gulf of Alaska, Hecate Strait, Kodiak Island, and Prince William Sound, were all genetically distinct and could be assigned to their population of origin with 80-90% accuracy (Fig. 2.3; Drinan et al. 2018). Cod that spawned at Unimak Pass in 2003 and 2018 were genetically distinct from the Kodiak Sample (spawning year 2003), FST=0.004 and FST=0.001. There was strong evidence for selective differentiation of some loci, including one which aligned to the zona pellucida glycoprotein 3 (ZP3) in the Atlantic cod genome. This locus had the level of differentiation of any locus examined (FST=0.071). ZP3 is known to undergo rapid selection (Drinan et al. 2018), and further work is needed to characterize this gene among spawning populations of cod in the Gulf of Alaska and the Bering Sea.

Although there appears to be some genetic differentiation within the GOA management area and some cross migration between the Western GOA and southeastern Bering Sea the Pacific cod stock in the GOA region is currently managed as a single stock.

Review of Life History

Pacific cod release all their eggs near the bottom in a single event during the late winter/ early spring period in the Gulf of Alaska (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). 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) over a broad range of salinities

(Alderdice and Forrester 1971). Eggs hatch into 4 mm larvae in ~2 wks at 5°C (Laurel et al 2008) and become surface oriented and available to pelagic icthyoplankton 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 Gulf of Alaska (Doyle et al. 2009, Doyle and Mier 2016). Laboratory studies suggest warm temperatures can 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 undergo a significant developmental change ('flexion') between 10-15 mm and gradually become more competent swimmers with increasing size (Voesenek et al. 2018). Very late stage larvae (aka 'pelagic juveniles') eventually settle to the bottom in early July around 40 mm and use nearshore nurseries through the summer and early fall in the Gulf of Alaska (Laurel et al. 2017).

Shallow, coastal nursery areas provide age-0 juvenile Pacific cod ideal conditions for rapid growth and refuge from predators (Laurel et al. 2007). Settled juvenile cod associate with bottom habitats (e.g., macrophytes) 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 microhabitat features and gradually move into deeper water in the fall (Laurel et al. 2009). Overwintering dynamics are currently unknown for Pacific cod, although laboratory held age-0 juveniles are capable of growth and survival at very low temperature (0°C) for extended periods (Laurel et al. 2016a)

Pelagic age-0 juvenile surveys of Pacific cod have been conducted in some years (Moss et al. 2016), but they are prone to significant measurement error if they are conducted across the settlement period (Mukhina et al. 2003). Therefore, 1st year assessments of Pacific cod in the Gulf of Alaska are better suited during the early larval or later post-settled juvenile period. There are two surveys that routinely survey early life stages of Pacific cod in the Gulf of Alaska during these phases: 1) the RACE EcoFOCI ichthyoplankton survey in the western GOA (1979 – present; https://access.afsc.noaa.gov/ichthyo/index.php), and 2) the RACE FBE nearshore seine survey in Kodiak (2006 – present). The EcoFOCI ichthyoplankton survey is focused in the vicinity of Kodiak Island, Shelikof Strait and Shelikof Sea Valley and captures Pacific cod larvae primarily in May when they are 5-8 mm in size (Fig. 2.4 and Fig. 2.5; Matarese et al. 2003). The Kodiak seine survey occurs in two embayments and is focused on post-settled age-0 juveniles later in the year (mid-July to late August) when fish are 40-100 mm in length (Laurel et al. 2016b). In 2018, Cooperative Research between the AFSC and UAF spatially extended the Kodiak seine survey to include 14 different bays on Kodiak Island, the Alaska Peninsula, and the Shumagin Islands (Fig 2.6; Litzow and Abookire 2018)

The summer thermal conditions in the Central/Western GOA have been historically been well-suited for high growth and survival potential for juvenile Pacific cod (Laurel et al. 2017), but were likely sub-optimal during the 2014-16 marine heatwave (Fig. 2.7 and Fig. 2.8). The Kodiak seine survey indicated that age-0 juvenile abundance was very low during this period. However, age 0 abundance returned to relatively high numbers following a period of relative cooling in 2017 and 2018 (Fig 2.9). A strong 2018 age-0 cohort was also observed across the WGOA in the new Cooperative Research survey (Fig. 2.10).

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). In the earliest stages (eggs, yolk-sac larvae), individuals have less flexibility to behaviorally adapt and have finite energetic reserves (non-feeding). In later juvenile stages, individuals can move to more favorable thermal or food habitats that better suit their metabolic demands. Changes in seasonal temperatures also influence how energy is allocated. A recent laboratory study indicated age-0 juvenile Pacific cod shift more energy to lipid storage than to growth as temperatures drop, possibly as a strategy to offset limited food access during the winter (Copeman et al. 2017).

The AFSC will be investigating environmental regulation of 1st year of life processes in Pacific cod to better understand the interrelationship between processes occurring during pre-settlement (spawning/larvae), settlement (summer growth) and post-settlement (1st overwintering) phases. Transport processes and connectivity between larval and juveniles nursery areas will continue to be an important area of research as the Regional Oceanographic Model (ROMS) for the GOA is updated.

Fishery

General description

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 are shown in Table 2.2; 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 (not counting 2017, for which data are not yet complete). Figure 2.11 shows landings by gear since 1977. Table 2.2 shows the catch by jurisdiction and gear type.

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 2.3. 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 2005b), 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 MFCMA (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, 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 all but three 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 trawl surveys or management responses to local concerns. Currently the area-specific ABC allocation is derived from the random effects model (which is similar to the Kalman filter approach). The complete history of allocation (in percentage terms) by regulatory area within the GOA is shown in Table 2.4. Table 2.2 and Table 2.3 include discarded Pacific cod, estimated retained and discarded amounts are shown in Table 2.5.

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 and observer data (Cahalan *et al.* 2014).

The distribution of directed cod fishing is distinct to gear type, Figure 2.12 shows the distribution of catch from 1990-2015 for the three major gear types. Figure 2.13 and Figure 2.14 show the distribution of catch for 2017 and 2018 through October 17, 2018 for the three major gear types. 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 Pacific cod 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 2.2 and Fig. 2.11). 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 by 2011 through 2018 the pot sector caught more than half the total catch of Pacific cod in the Gulf of Alaska.

In 2015 combined state and federal catch was 77,772 t (24%) below the ABC while in 2016 combined catch was 64,071 t (35% below the ABC) and in 2017 catch was 48,734 t (45% below the ABC) (Table 2.3). The ABC was substantially reduced for 2018 to 18,000 t from 88,342 t in 2017, an 80% reduction. This was a 65% reduction from the realized 2017 catch. As of October 17, the 2018 combined fishery has caught 11,965 t which is 65% of the ABC.

The largest component of incidental catch of other targeted groundfish species in the Pacific cod fisheries by weight are skate species in combination followed by arrowtooth flounder and walleye pollock (Table 2.6). Rockfish, octopus, rock sole, sculpin species, and shark 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 2.7.

<u>Longline</u>

For 1990-2015 the longline fishery has been dispersed across the Central and Western GOA, however more longline catch taken to the west of Kodiak, with some longline fishing occurring in Barnabus trough and a small concentration of sets along the Seward Peninsula (Fig. 2.12). The 2017 longline fishery was predominantly conducted on the border of are 620 and 610 in deeper waters south of the Shumagin Islands and South of Unimak Island to the western edge of the 610 GOA management area shelf (Fig. 2.13). In 2018 with the drastic cut in TAC the fishery has shown very little effort the majority of catch being south of the Shumagin Islands straddling the 610 and 620 management area edges (Fig. 2.14). The longline fishery tends to catch larger fish on average than the other fisheries (Fig. 2.15). The mean size of Pacific cod caught in the longline fishery is 64cm (annual mean varies from 58cm to 70cm). 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 (Fig. 2.16). In the Central GOA the Longline fishery the 2017 A season had a slower start than previous years, but eventually caught the A-season TAC by mid-April; a point reached in 2016 three weeks earlier (Fig. 2.21). In 2018 fewer boats participated in the fishery and catch was substantially slower and lower than previous years. The A season CPUE in the Central GOA longline fishery in 2018 was substantially lower than the previous years (Fig. 2.23) below 2008 catch rates when stock abundance had been at it previously lowest level (Fig. 2.25). The A- season longline fishery in the Western GOA appears to have started later than the previous 5 years, effort was lower and CPUE this year appears to have declined (Fig. 2.22, Fig. 2.24, and Fig. 2.25).

Pot

The pot fishery is a relatively recent development (Table 2.2) and predominately pursued using smaller catcher vessels. The Alaska state managed fishery is predominantly conducted using pots with on average 84% of the state catch coming from pot fishing vessels. In 2016 60% of the overall GOA Pacific cod catch was made using pots. Pot fishing occurs close to the major ports of Kodiak, Sand Point and on either side of the Seward Peninsula (Fig. 2.12). In 2017 the observer coverage rate of pot fishing vessels was greatly reduced from 14% to ~4% this impacts 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 (Fig.2.13), however this may be due to low observer coverage. In 2018 there were few observed hauls throughout the GOA, this is likely due to the lower TAC and low fishing levels. The pot fishery in the Central GOA appears to have moved to deeper water in 2017 and 2018 than in 2016. The 2017 pot fishery in both the Central and Western GOA showed a mark decrease in CPUE (Fig. 2.23) from 2016 and 2018 declined even further (Fig. 2.23 Fig. 2.24, and Fig.2.25).

The pot fishery generally catches fish greater than 40 cm (Fig. 2.17), 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 (Fig. 2.18). The 2017 and 2018 fishery data show an increase in length, potentially due to a combination of the fishery moving to deeper water and an apparent lack of smaller fish in the population.

In 2017 the pot fishery in the Central GOA was slower than previous years and did not take the full TAC for the A season (Fig. 2.21). The 2017 pot fishery in the Western GOA appears to have been slower than 2015 but similar to 2016 (Fig. 2.22). In 2018 the Pot fishery in both regions were slower than the previous three years. In the Western GOA, approximately half the catch was caught in a single week in March. CPUE during the A season (January-April) in both the Central and Western GOA was lower than the previous three years (Fig. 2.23 and Fig. 2.24), on par with CPUE during 2013 and 2008-2010 (Fig. 2.25).

Trawl

The Gulf of Alaska Pacific cod trawl fishery rapidly developed starting in 1987, quickly 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 mid-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 Alaska state 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. 2.12) 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 shows a shift away from the Shumigan Islands further to the west around Sanak Island and near the Alaska Peninsula, this continued through 2017 (Fig.2.13). Trawl fishing in 2018 for the A season shows a similar pattern as 2017 with large catches from around Sanak Island, but some increased effort on Portlock Banks to the southeast of Kodiak. Overall 2018 shoes substantially less catch and observed effort (Fig. 2.14) than previous years.

The trawl fishery catches smaller fish than the other two gear types with fish as small as 10 cm appearing in the observed length composition samples (Fig. 2.19). The average size of Pacific cod caught by trawl in the 1980's was on average smaller than those caught later (Fig. 2.20). The trawl fishery shows 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 2018. The change to deeper depth and a larger proportion of the catch coming from the Western GOA might partially explain this recent increase.

The directed A-season trawl fishery in the Central GOA started much later than previous years, catch rates were lower and the fishery did not take the full TAC (Fig. 2.21). The mean CPUE for Pacific cod in both the Central and Western GOA has been stable to increasing over the past 10 years. The distribution of CPUE by tow is highly right skewed with a few very large tows increasing the overall mean CPUE. Although the mode of the distribution has gone down over time there has been an increase in the number of very large tows recently which has caused the mean CPUE to increase.

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

There is a small jig fishery for Pacific cod in the GOA, this 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 and 2018 the jig fishery was nearly non-existent with catch at less than 290 t. Catch in both the Central and Western GOA was exceptionally low as were catch rates.

Pacific cod is also caught as bycatch in other commercial fisheries. Although historically the shallow water flatfish fishery caught the most Pacific cod, since 2014 Pacific cod bycatch in the Arrowtooth flounder target fishery has surpassed it (Table 2.8). The weight of Pacific cod catch summed for all other target fisheries was 3,239 t in 2016 a low for recent fisheries, 2017 will likely be lower. This following an all-time high of 10,780 t in 2015 with 1/3 of this from the Arrowtooth flounder target fishery.

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 2015 (Table 2.9). The largest component of this catch comes from the recreational fishery, generally taking one-third to 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 fishery A season (January-April) data for 1992-2018. 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 in there being lower condition during 2014-2016 for fish less than 80 cm (Fig. 2.26, Fig.2.27, Fig. 2.28, and Fig. 2.29). In 2018 there is in general an improvement in condition of fish in both the Central and Western GOA.

Incidental catch of Pacific cod in other targeted groundfish fisheries is provided in Table 2.8 and noncommercial catch of Pacific cod are listed in Table 2.9.

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 2011). Instead we show the occurrence of Pacific cod in other directed fisheries. 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. 2.30). In the shallow water flatfish fishery, catch rates in tons of Pacific cod per ton of all species catch were examined (Fig. 2.31). For the pollock fishery the 2017 value is the lowest in the series (2000-2018) with an slight increase in 2018 in areas 610 and 620. For the shallow water flatfish fishery, 2016 was the lowest value with a slight increase in 2017 and 2018. It should be noted that none of these indices are controlled for gear, vessel, or fishing practice changes.

Surveys

Bottom trawl survey

The Alaska Fisheries Science Center (AFSC) has been conducting standardized bottom trawl surveys for groundfish and crab in the Gulf of Alaska since 1984. From 1984-1997 these were conducted every third year, and every two years between 1999 and 2017. 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 fact that trawl duration 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, and 2017 deeper strata had fewer stations sampled than in other years due to budget and/or vessel constraints.

The 2017 survey was conducted with two chartered vessels that accomplished 536 stations (von Szalay and Raring 2018). While the GOA Bottom Trawl Survey optimally employs three chartered vessels and targets 825 stations, the 2017 likely captured the trend and magnitude of the cod abundance in the GOA. The 2017 survey covered all strata; regions; and shelf, gully, and upper slope habitats to 700 m. The percent standard error of 12.8% was lower than the historic average of 16.7%. The 2017 survey was comparable to the 2013 survey that was also conducted with two vessels and achieved 548 stations. The 2013 Pacific cod survey estimate was almost five times higher than the 2017 survey.

The Pacific cod biomass estimates from the bottom trawl survey are highly variable between survey years (Table 2.10 and Fig. 2.32). 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. Subsequent surveys showed a decline through 2017. 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). The 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; Fig. 2.33). The mean length in the trawl survey generally increased from 1984-2005 excepting the 1997 and 2001 surveys (Fig. 2.34). 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 although the mean remains below the 1984-2005 overall average.

The distribution of Pacific cod in the survey has been highly variable (Fig. 2.35) 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 next lowest survey, 2007, had high spikes of density in the Central GOA west of Kodiak and along the Alaska Peninsula, as well as numerous mid-density spikes throughout the Central and Western GOA.

AFSC sablefish longline survey

Japan and the United States conducted a cooperative longline survey 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 Alaska Fisheries Science Center 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 et al. 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

A Relative Population Number (RPN) index of Pacific cod abundance and length compositions for 1990 through (Table 2.11 and Fig 2.36). Details about these data and a description of the methods for the AFSC sablefish longline survey can be found in Hanselman et al. (2015) 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 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. In Revision). In 2014-2016 the index increases but this may reflect increased availability with warmer conditions. The index shows a sharp drop (53%) in abundance from 2016 to 2017 and again (40%) from 2017 to 2018. The 2018 estimate was 73% lower than the 2015 abundance estimate.

Unlike the bottom trawl survey, the longline survey encounters few small fish (Fig. 2.37). The size composition data show consistent and steep unimodal distributions with a stepped decreasing trend in mean size between 1990 and 2015 (Fig. 2.38) and then increasing mean size from 2015-2018. 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. 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 warmest year on record for the time series.

Since 1990, when the AFSC longline survey time series begins, there is an increasing trend in temperature, a decreasing trend in both AFSC longline RPN and mean length of Pacific cod in this survey (Fig. 2.39). Once linearly de-trended the RPN index and CFSR 10 cm bottom temperature index (See below) has a Pearson's correlation coefficient R = 0.30, (p-value of 0.12). Conversely the mean size of Pacific cod caught in the survey has r = -0.23 with temperature, and mean length is negatively correlated with RPN (r = -0.49) over the time series from 1990-2016 suggesting smaller fish being selected by the survey in warmer years as the abundance estimate is increased.

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 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 verus 13/0) than the AFSC longline survey which may prevent very small Pacific cod from getting hooked. To compare, to IPHC relative population number's (RPN) were calculated using the same methods as the AFSC longline survey data (but using different depth strata). Stratum areas (km^2) from the RACE trawl surveys were used for IPHC RPN calculations. Length data on Gulf of Alaska Pacific cod started being collected during this survey in 2018 and became available in October.

The IPHC survey estimates of Pacific cod tracks well with both the AFSC sablefish longline and AFSC bottom trawl surveys (Table 2.12 and Fig. 2.40). There was an apparent drop in abundance from 1997-1999 with 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 other two surveys. The 2017 RPN is the lowest on record for the 20-year time series. This index shows a slight increase of the population abundance in 2018 to values slightly higher than 2016, but remain the fourth lowest estimate on record after 2001, 2016, and 2017. The length composition (Fig. 2.41) shows the survey encounters fish greater than 40cm. The length data shows a mode at approximately 60 cm in the 610 management area. The other management areas have modes slightly higher between 65 and 75 cm.

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 (2012).

To develop an index from these data, a simple delta GLM model was applied covering 1988-2018. 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 (ΔAIC= 2023.8). 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 0.07 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. 42). 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 5% higher than the 2016 survey index. 2018 increased by 30% from 2017. The length composition data (Fig. 2.43) shows a wide multi-modal length composition distribution with modes at 10 cm, 25cm, and 60 cm.

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 1979-2018 (Fig. 2.44 and Table 2.14).

The mean depth of Pacific cod at 10 cm and 40cm 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 10 cm and 40 cm Pacific cod in the CFSR indices are highly correlated ($R^2 = 0.88$) with the larger fish in deeper and slightly colder waters 7.49 °C vs. 6.00 °C in the Central GOA and 4.78 °C vs. 4.75 °C in the Western GOA. The shallower index is more variable (CV_{10cm} 0.10 vs. CV_{40cm}=0.07). There are high peaks temperature in 1981, 1987, 1998, 2015 and 2016 with 2015 being the highest in both the 10 cm and 40 cm indices. There are low valleys in temperature in 1982, 1989, 2009, 2012, and 2013. The coldest temperature in the 10cm index was in 2009 and in the 40cm index in 2012. The trend is insignificant for both indices.

Sum of annual marine heatwave cumulative intensity index (MHWCI)

The daily sea surface temperatures for 1981 through June 2018 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 (MHWCI; 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 1983 through 31 December 2012 time series. The MHWCI were then summed for each year to create an annual index of MHWCI and summed for each year for the months of January through March, November, and December to create an annual winter index of MHWCI.

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. 2.7). 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 (Imax) of 3.02°C. The heatwave had a summed cumulative intensity (Icum) for 2016 of 635.26°C days, more than 25% of the sum of the Icum 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 Icum for the time series.

There were three periods of increased winter heatwave activity in the Central GOA, the first in 1983-1986, second in 1997-2006 and the third 2014-2016. The Imax of each event for these periods appears to have a linear increasing trend over time (Imax= 0.000006D+1.0016 where D is the day in the timeline; R2 = 0.22) while the cumulative intensity increased exponentially (Icum= 5.82e0.0002D; R2 = 0.40). 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 Icum 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 Imax 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 Imax 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.

Data

This section describes data used in the current assessment (Fig. 2.45). It does not attempt to summarize all available data pertaining to Pacific cod in the GOA. All data used are provided here (http://www.afsc.noaa.gov/REFM/Docs/2018/GOApcod_Appendix2.3.zip). Descriptions of the trends in these data were provided above in the pertinent sections.

Data	Source	Type	Years included
Federal and state fishery catch, by gear type	AKFIN	metric tons	1977 – 2018
Federal fishery catch-at-length, by gear type	AKFIN / FMA	number, by cm bin	1977 – 2018
State fishery catch-at-length, by gear type	ADF&G	number, by cm bin	1997 – 2018
GOA NMFS bottom trawl survey biomass and abundance estimates	AFSC	metric tons, numbers	1984 – 2017
AFSC Sablefish Longline survey Pacific cod RPN	AFSC	RPN	1990 – 2018
GOA NMFS bottom trawl survey length composition	AFSC	number, by cm bin	1984 – 2017
GOA NMFS bottom trawl survey age composition	AFSC	number, by age	1990 – 2017
GOA NMFS bottom trawl survey mean length-at-age and conditional age-at-length	AFSC	mean value and number	1990 – 2017
AFSC Sablefish Longline survey Pacific Cod length composition	AFSC	Number, by cm bin	1990 – 2018
CFSR bottom temperature indices	National Center for Atmospheric Research	Temperature anomaly at mean depth for P. cod size bins 10 cm and 40 cm.	1979-2016

Fishery

Catch Biomass

Catches for the period 1991-2018 are shown for the three main gear types in Table 2.2, with the catches for 2018 presented through October 09, 2018. For the assessment model the Oct – Dec catch was estimated given the average fraction of annual catch by gear type and FMP subarea for this period in 2017. The fishery was set in three gear type, trawl (all trawl types), longline (longline and jig) and pot. The weight of catch of other commercial species caught in the Pacific cod targeted fisheries for 2013 through 2017 are shown in Table 2.6, and incidental catch of non-commercial species for 2014 – 2018 are shown in Table 2.7. Non-commercial catch of Pacific cod in other activities is provided in Table 2.9.

Catch 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 2018. 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. The trawl fishery length composition data are in Figures 2.15 – 2.20 and provided in Appendix 2.2 in an Excel spreadsheet.

(http://www.afsc.noaa.gov/REFM/Docs/2018/GOApcod_Appendix2_2.xlsx)

Size composition proportioning

For the 2016 assessment models and assessment model series Model17.08.xx in the 2017 assessment, 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.

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*.

For 2017 and 2018 for post-1991 length composition (series Model xx.09-11.xx) we estimated the length compositions 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.

Model xx.09-11.xx method (post-1991): $p_{ygl} = \sum_{t,a}\left(\left(\frac{\sum_h \frac{n_{ytaghl}}{\sum_l n_{ytaghl}} N_{ytagh}}{\sum_h N_{ytag}}\right)\left(\frac{W_{ytag}}{\sum_{tag} W_{ytag}}\right)\right)$

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 for gear type *g*, NMFS area *a*, trimester *t,* and year *y*.

Addition of ADFG port sampling for Pot fishery data

In 2017 observer coverage changed as managers established electronic monitoring (EM) as a substitute for observer coverage. This reduced observer coverage of the GOA Pacific cod pot fishery to ~4% compared to 14.7% coverage in 2016 (Craig Faunce, personal comm. 25 July 2017). The EM program is currently unable to measure fish for length composition (and obviously is unable to include age structure sampling). In 2016 the pot fishery caught 59% of the total allocation of GOA Pacific cod with 75% of this caught in state waters. This leaves a large proportion of the catch without observer collected length composition data. To mitigate this loss of data, other sources of pot fishery length composition data are being considered. The ADFG has routinely collected length data from Pacific cod landings since 1997. As such, adding these data is a way to augment the pot fishery length composition data for the stock assessment.

The ADFG port sampling and NMFS at-sea observer methods are follow different sampling frames so combining them poses some challenges. We propose to use ADF&G data from the pot fishery for trimester/areas in which observer data were missing. The resolution of the ADF&G data required the assumption that all of the samples collected in an area/trimester were representative of the overall catch for that 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 (Fig. 2.45). The age data was also used to develop an annual conditional length-at-age matrix for each fishery (Fig. 2.47-49). Both of these datasets have been added to the models explored in 2018.

Surveys

NMFS Gulf of Alaska Bottom Trawl Survey

Abundance Estimates

Bottom trawl survey estimates of total abundance used in the assessment models examined this year are shown in Table 2.10 and Fig. 2.2, together with their respective coefficients of variation.

Length Composition

The relative length compositions used in the assessment models examined this year from 1984-2017 are shown in Figure 2.50 and provided in Appendix 2.2 in an Excel spreadsheet (http://www.afsc.noaa.gov/REFM/Docs/2018/GOApcod_Appendix2_2.xlsx).

Age Composition

Age compositions (Fig. 2.50) and conditional length at age (Fig. 2.51) from each trawl survey since 1990 are available and included in this year's assessment models. The age compositions and conditional length at age data are provided in Appendix 2.2 in an Excel spreadsheet. (http://www.afsc.noaa.gov/REFM/Docs/2018/GOApcod_Appendix2_2.xlsx)

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 (Fig. 2.52). 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 (Fig. 2.53). 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. Further investigation shows this may be due to age reader bias where the ages pre-2007 were read by a single reader. Data were identified by age reader and trimester and plotted. There is general agreement in the length at age from the otoliths read in the first trimester (Fig. 2.55). These tended to be fisheries and specialty surveys. This agreement diverges in the second quarter (Fig. 2.56) with Reader 3 tending to age fish older at size than other readers in the same year. This becomes even more apparent in the third quarter (Fig. 2.57). Reader 3 was the predominant age reader for the AFSC GOA bottom trawl surveys from 1990-2007. The apparent change in growth observed post-2007 with fish becoming larger at age may likely be a change in reading criteria and predominant age readers.

AFSC Longline Survey for the Gulf of Alaska

Relative Population Numbers Index and Length Composition
The AFSC longline survey for the Gulf of Alaska survey data on relative Pacific cod abundance together with their respective coefficients of variation used in the assessment models examined this year are shown in Table 2.12 and Fig. 2.36.

Length Composition
The length composition data for the AFSC longline survey data are shown in Figure 2.37 and provided in Appendix 2.2 in an Excel spreadsheet.

(http://www.afsc.noaa.gov/REFM/Docs/2018/GOApcod_Appendix2_2.xlsx)

Environmental indices

CFSR bottom temperature indices

The CFSR bottom temperature indices for 10 cm Pacific cod were used in this assessment (see description above; Table 2.14).

Analytic Approach

Model Structure

This year's proposed models apply refinements to last year's model in consideration of the review conducted this year by the Center for Independent Experts (CIE), changes to SS3.30, issues encountered with aging bias discovered in the age data prior to 2007, and implementation of findings from marine heat wave index analysis. To see the history of models used in this assessment refer to A'mar and Palsson (2015). Stock Synthesis version 3.24U (Methot and Wetzel 2013; Methot 2013) was used for the Model 17.xx.xx series models as in last year. New models for this year, Model18.xx.xx series models were run in Stock Synthesis version 3.30.12. For consistency, we include the 2017 accepted model (Model17.09.35) with updated data.

All models presented were single sex, age-based models with length-based selectivity. The models have 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 indices. Age composition and conditional length at age were available for the three fisheries and AFSC bottom trawl survey. Growth was parameterized using the standard three parameter von Bertalanffy growth curve. Recruitment was modeled as varying about a mean with standard deviation fixed at sigma R = 0.44 (Barbeaux *et al.* 2016). All selectivities were fit using six parameter double-normal selectivity curves.

New models presented in this assessment were first reviewed by the NPFMC GOA Groundfish Plan Team in September 2018 (this is provided in Appendix 2.1 http://www.afsc.noaa.gov/REFM/Docs/2018/GOApcod_Appendix2_1.pdf). The major difference in the models considered following the CIE review is that we transitioned to SS v3.30 from SS v3.24. All models presented in consideration for use in management have been developed in SS v3.30. There are two new data configurations and three new model series explored this year (see below). Model18.10.46 uses the winter marine heat wave index to drive the natural mortality estimate, however no satisfactory method has been yet fully vetted to conduct standard projections, so this model will not be considered for management at this time. All model configurations are shown below:

Model configurations:

Model	Data	SS version	M- block	Maturity	Marine heatwave index	Selectivity	Prior CV on M	VB prior (l_{inf}/K)
17.09.35	Same as 2017	2.24	15-16	Age-based		Length-based	0.10	Uniform
18.09.35	Same as 2017	3.30	14-16	Age-based		Length-based	0.10	Uniform
18.09.38A	Same as 2017	3.30	14-16	Length-based		Length-based	0.10	Uniform
18.10.38A	No age data pre-2007	3.30	14-16	Length-based		Length-based	0.10	Uniform
18.10.38B	No age data pre-2007	3.30	14-16	Length-based		Length-based	0.10	Normal 99.46/0.197
18.10.44	No age data pre-2007	3.30	14-16	Length-based		Length-based	0.41	Normal 99.46/0.197
18.10.46	No age data pre-2007	3.30	NA	Length-based	✓	Length-based	0.41	Normal 99.46/0.197
18.11.38A	No age data	3.30	14-16	Length-based		Length-based	0.10	Normal 99.46/0.197

Time varying selectivity components for all models:

Component	Temporal Blocks/Devs
Longline Fishery	Annually variable 1978-1989 Blocks – 1996-2004, 2005-2006, 2007-2016, 2017-2018
Trawl Fishery	
Pot Fishery	Blocks – 1977-2012 and 2013-2018
Bottom trawl survey	Blocks – 1977-1995, 1996-2006, 2007-2018

All Stock synthesis files are provided in a zip file in Appendix 2.3:
(http://www.afsc.noaa.gov/REFM/Docs/2018/GOApcod_Appendix2.3.zip)

Parameters Estimated Outside the Assessment Model

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 2.1) for the Bering Sea stock assessment (Thompson et al. 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. All models presented were fit with this prior on M.

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 natural mortality. 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 expand the natural mortality block to 2014-2016. For this $M_{standard}$ is fit separate from $M_{2014\text{-}2016}$ with a lognormal prior of μ=-0.81 and a σ of either 0.1 or 0.41. The use of special mortality periods have been proposed and approved for use in several Bering Sea crab assessments.

Model 18.10.46 is experimental and intended to explore the impact of marine heatwaves on Pacific cod mortality. In this model *M* is fit with a lognormal prior of μ=-0.81 and a σ =0.41, but a parameter is then fit to scale the annual natural mortality to the winter marine heatwave index.

Growth

A three parameter von Bertalanffy growth model is used in the model. For Model 18.10.38B, 18.10.44, 18.10.46 and 18.11.38 the growth parameters were set to values based on a nonlinear least squares regression of the 2007-2015 AFSC GOA bottom trawl survey length at age data (Fig. 2.58). The *nls* function form the **nlstools** library (Baty *et al.* 2015) in R was used to fit the formula $FL = L_{inf}\left(1 - e^{(-K(Age-t_0))}\right)$ where FL is the fork length, Linf is the asymptotic length, K is the growth rate, Age is the age of the fish, and t_0 is the age where the fish had size 0. 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, t_0 was -0.11 CV=0.25.

Variability in Estimated Age

Variability in estimated age in SS 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

A detailed history and evaluation of parameter values used to describe the maturity schedule for GOA Pacific cod was presented in the 2005 assessment (Thompson and Dorn 2005). A length-based maturity schedule was used for many years. The parameter values used for this schedule in the 2005 and 2006 assessments were set on the basis of a study by Stark (2007) at the following values: length at 50% maturity = 50 cm and slope of linearized logistic equation = –0.222. However, in 2007, changes in SS allowed for use of either a length-based or an age-based maturity schedule. Beginning with the 2007 assessment, the accepted model has used an age-based schedule with intercept = 4.3 years and slope = –1.963 (Stark 2007). The use of an age-based rather than a length-based schedule follows a recommendation from the maturity study's author (James Stark, ret., Alaska Fisheries Science Center, personal communication). The age-based parameters were retained through the 2017 assessment. The re-reading of the Stark (2007) otoliths revealed that the parameters for maturity at age derived in this study are not correct. It was therefore determined that management model should revert back to a length-based maturity until the study can be reanalyzed. The decision to use length-based maturity was also made to accommodate model options that will incorporate environmental effects on growth. 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 (Fig. 2.59).

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 von Bertalanffy growth parameters, annual recruitment deviations, initial fishing mortality, gear-specific fishery selectivity parameters, and survey selectivity parameters (Table 2.15).

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.

In this year's models 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.

In addition to the above, the full set of year- and gear-specific fishing mortality rates were also estimated conditionally, but not in the same sense as the above 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.

Catchability

For all models the catchability for the AFSC bottom trawl survey was fit with a non-informative prior. All prior. In all models presented this year, the AFSC longline survey catchability included a parameter, P, which was used to additively adjust annual catchability values based on an annual temperature index, Iy, as $\log(Q_y) = (\bar{Q} + PI_y)$ where Q_y is catchability for a given year, and Q is the expected catchability across all time. We used an index of mean annual temperature at depth for cod developed from the Climate Forecast System Reanalysis (CFSR) as our temperature index (see description above). An analysis introducing this methodology was presented last year (Barbeaux *et al.* 2017) and a new method validating this methodology was presented at the 2018 September Plan team meeting and provided in Appendix 2.1. It can be seen from the bottom trawl survey data below that the centroid of distribution for Pacific cod greater than 34 cm shifts to deeper water in years with warmer shelf temperatures. This shift would make these size categories of Pacific cod more available to the AFSC longline survey which starts at 150 m.

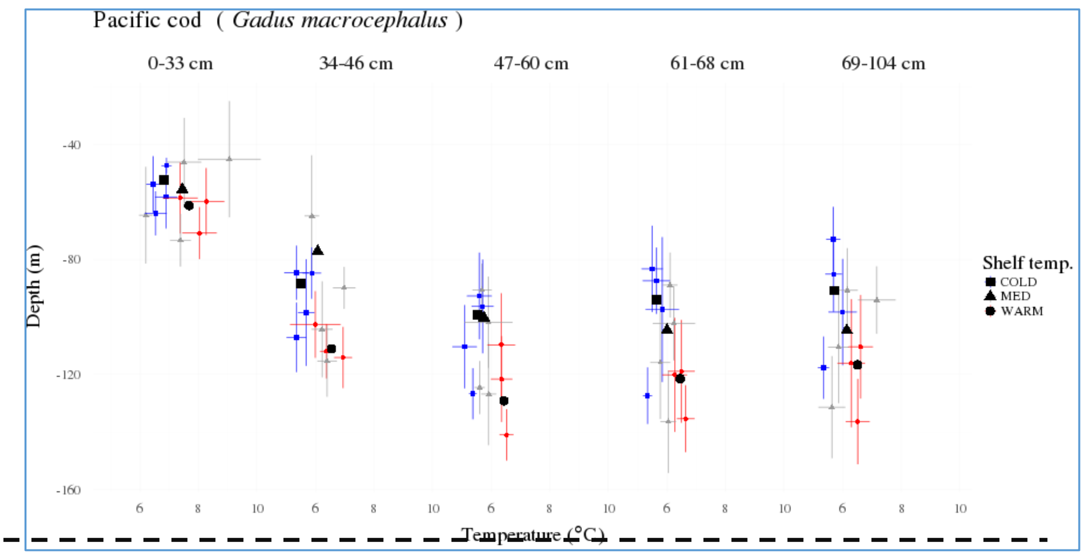


Figure: AFSC bottom trawl survey Pacific cod centroids of distribution for the Central GOA by shelf temperature and Pacific cod size category. Dashed line shows starting depth of AFSC longline survey (150 M).

Likelihood Components

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

For all models presented there were no parameters near bounds and the likelihoods appear well defined with the gradient of the objective function at less than $10e^{-4}$. All models were examined by "jittering" starting parameters by 10% over 50 runs to evaluate if models had converged to local minima.

Use of Size and Age Composition Data in Parameter Estimation

Size and age composition data are 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 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 are assumed to be drawn. 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 initially set at 100.

Results

Model Evaluation

The 2017 final model with data from 2018, and new model configurations are presented. All new models presented would be considered major model changes from the 2017 base model with ADSB values greater than 0.1. Model evaluation criteria included AIC where applicable, model adherence to biological principles and assumptions, the relative sizes of the likelihood components, and how well the model estimates fit to the survey indices, the survey and fishery age composition and conditional age-at-length data, reasonable curves for fishery and survey selectivity, and retrospective pattern. All models presented adequately estimated the variance-covariance matrix. Model likelihoods and key parameter estimates are provided in Table 2.16. Likelihoods by fleet are provided in Table 2.17. It should be noted that not all models can be compared directly using likelihoods or AIC due to differences in data. Retrospective results, index RMSE and composition mean effective sample sizes are provided in Table 2.18.

Comparing and Contrasting Model Configurations

The Model 17.09.38 -2018 was the same configuration as Model 17.09.35 -2017 with the addition of the 2018 catch and survey data. Model 17.09.35 - 2018 and all other models included the addition of fishery age composition data. The Model 18.10.xx series has the same data as the earlier models, except the conditional length at age data and all age composition data are excluded prior to 2007. Model 18.11.38 excludes all age data. The results from the GOA Pacific cod stock assessment has been particularly volatile with a wide-array of models presented over the past 17 years (A'mar and Palsson 2015). The models presented this year are well within the bounds of models presented in previous years for the spawning stock biomass time series (Fig. 2.60). The female spawning biomass and age-0 recruitment for all the models considered this year are provided in Figure 2.61. All the models show a similar fit, and similar recruitment and biomass trends. Tradeoffs in model selection pivot on fits to the surveys versus fits to the age and size composition data where there are conflicts. Adding the extra year to the heatwave block for natural mortality allows M to be reduced in the remainder of the time series. The other pivot point is the fit of the model to the high 2009 bottom trawl survey estimate to the low 2017 estimate. When growth is allowed to be free the models increase growth to reach the 2009 high, increase natural mortality during the heatwave, and increases catchability to reduce the overall abundance throughout the timeline. The alternative models presented this year make tradeoffs between fitting the 2009 estimate and the 2017 estimate in light of the low 2018 AFSC longline survey.

Model17.09.35-2017 and Model17.09A.35-2018

Model17.09A.35-2018 is simply last year's base model with the addition of the AFSC longline survey index value and length composition, fishery catch data as well as length composition from the fisheries, and the 2017 AFSC bottom trawl survey age composition and conditional length at age data. It does not include any of the newly acquired fishery age composition data. The 2018 AFSC longline survey index value was the lowest in the time series, a 40% decline from 2017. To accommodate this drop, the model fits a higher natural mortality (Table 2.17 and Fig. 2.62) for both the generic and heatwave M values and survey catchability for both surveys. With these changes the model provides a better fit to the surveys overall than in last year's base model, but the fits to the length and age data are degraded. Although recruitment remains approximately the same, the increase in catchability causes the overall population to be estimated lower than in last year's base model (Fig. 2.63). The survey age composition data and fishery size composition data suggest a stronger 2016 year class than last year's data and an even weaker 2014 and 2015 year classes.

Model17.09.35-2018

The addition of the fishery age composition and conditional length at age data in Model 17.09.35-2018 causes a degradation in fit to all of the other data components (Table 2.16, Table 2.17, and Table 2.18). This suggests that the growth model is not consistent with what was observed in the age and length data. Overall the model performs well in comparison with last year's base model. Retrospective analysis performs adequately with a Rho value on SSB at 0.08 (Table 2.19). The fishery age composition data suggests a stronger 2012 year class than was projected from the survey and length composition data alone. The increase in the 2012 year class requires an increase in natural mortality (Table 2.16 and Table 2.17) during the heat wave (2015-2016 in this model). The increase in natural mortality during the heat wave time block allows the model to reduce the natural mortality for the rest of the time series. Previous assessments have highlighted the high degree of uncertainty in the pre-1989 population estimates as there are few data on which to anchor these values. Slight changes in the assumptions on natural mortality and catchability cause substantial differences in the estimated recruitment for this time period, in particular the 1977 year class. In Model17.09.35-2018 the 1977 year class is inflated compared to last year's base model and Model17.09A.35-2018 causing an overall increase in population estimates throughout the 1980's. **It should be noted that because the reference points are set in part based on these early recruitments, there is substantial modeling uncertainty in our reference point and current status estimates that are not captured in individual model runs.** This year's modeling effort once again highlights this uncertainty. There is currently an effort to age otoliths collected from the GOA Pacific cod fishery in the 1980's, this effort should help reduce uncertainty in the earlier recruitment estimates.

Model 18.09.35 and Model 18.09.38A

Model 18.xx.xx series of models migrates to SS 3.30 where previous models had been run in SS2.24U. The new version of SS provides an improved methodology for fitting deviations for annual variability, in this case implemented for the pre-1989 longline and trawl fishery selectivities. In addition to the SS version change, the marine heat wave natural mortality block was expanded to include 2014 because of findings of the marine heat wave intensity analysis presented in September The slight change in how the deviances are modeled between SS versions results in a larger weight on selectivity deviations in the more recent version. The change in deviation weighting in the likelihood results in small changes in selectivity in the trawl fishery (Fig. 2.64) to smoother curves as there are higher constraints on annual variability than in the previous version. This change tipped the balance towards fitting the early survey index values and away from fitting the early catch composition data. Here the model found the lowest objective value at an overall higher natural mortality and lower survey catchability. The expansion of the marine heat wave block allowed the model to fit a lower overall natural mortality during the heat wave fitting the recent drops in survey abundance while increasing the estimate of the 2012 year class and improving the fit to the fishery age composition data. Model 18.09.35 has a better fit to both surveys than Model 17.09.35-2018 (Fig. 2.67 and Fig. 2.68) and all fishery age composition, but a worse fit to the AFSC bottom trawl survey age and length composition data (Table 2.18). These changes in fit and parameter estimates results in an overall increase in estimated recruitment overall (Fig. 2.65), it also suggests a higher abundance in this model compared Model 17.09.35-2018 for all years except 2016-2018, the last year of and two years following the increased mortality event hypothesized to have occurred during the 2014-2016 marine heat wave. Model

18.09.38A changes maturity to length-based instead of age-based because of bias in the age reading process. There is no difference in fit between the two models, however there is a drop in the resulting spawning biomass and reference points as fish mature at a slightly older age/larger size in the length-based maturity schedule than in the age-base maturity schedule (Fig. 2.65 and Table 2.16). The retrospective analysis performance for both these models are the same, similar to the Model17.09.xx models (Table 2.19), all were within acceptable bounds for the SSB. The high values for the recruitment Mohn's rho is driven by the high recruitment in 2012 and lows in 2014-2016 contrasting with mean recruitment forecast in the models.

<u>Model 18.10.38A and Model 18.10.38B</u>

In the Model 18.10.xx series the pre-2007 age data are not used. For Model18.10.38A this is the only difference from Model18.09.38. There is an apparent conflict between the pre-2007 age data and the growth model as removing these data improve the fits to the length composition for all but the longline fishery and both survey indices with the greatest improvement to the AFSC longline survey index (Table 2.18, Fig. 2.67, and Fig. 2.68). Natural mortality and catchability are both reduced in the model as is the L_{inf}, while growth rate, K, is increased (Table 2.16). The increase in K was due to removal of the older ages where it can be shown that aging bias in these older ages caused Pacific cod to be smaller at age. Lower natural mortality led to lower estimates of recruitment while lower catchability and an increased growth rate led to higher spawning biomass (Fig. 2.69) for most of the time series except at the beginning and end. Selectivity for all fleets shifted to smaller fish (Fig. 2.66 and Fig. 2.70). Model 18.10.38B changes to a higher growth rate based on the post-2007 survey length at age data. This model improves the fit to both survey indices, but degrades the fit to the remaining age data and all of the length composition data, except the longline fishing length composition. The fit to data for these two models is only 4.19 likelihood points different. Although the $SSB_{100\%}$ is 8,727 t higher in Model18.10.38B from Model 18.10.38A the estimated 2018 spawning biomass is only 234 t higher. A likelihood profile (Fig. 2.71) on natural mortality for Model 18.10.38B shows that the fit for natural mortality is likely overly constrained by an informative prior (cv = 0.1). Both models perform equally well in the retrospective analysis (Table 2.19), however their performances were slightly worse than that of the xx.09.xx series of models.

<u>Model 18.10.44</u>

Model 18.10.44 is the same as Model 18.10.39B and in addition loosens the prior on natural mortality setting the CV to the meta-analysis estimated prior value of 0.41 (Table 2.1). Releasing the constraints on natural mortality substantially improves the fit to both survey indices (Fig. 2.67 and Fig. 2.68) while degrading the fit to all of the age composition data and the trawl fishery length composition data (ΣΔ–LL of 3.4) (Table 2.16 and 2.18). The fit improves to the AFSC longline survey, longline fishery, and pot fishery length composition data. There was little change to the AFSC bottom trawl survey length composition data fit (Δ -LL of +0.09). Although the trend in recruitment and biomass are similar in the two models, the higher natural mortality led to higher estimates of recruitment across the time series and lower catchability estimates for the two surveys resulted in higher biomass estimates (Table 2.16 and Fig. 2.72). Likelihood profiles on natural mortality and AFSC trawl survey catchability (Fig. 2.73) show that the prior on natural mortality has much less influence on the posterior than the previous series of models and both natural mortality and catchability are well defined in the likelihood (Fig. 2.74). Jitter analyses showed the model to perform well repeatedly reaching the same objective function with a jitter set to 0.1. The general natural mortality was estimated at 0.5 and the 2014-2016 heat wave natural mortality at 0.87. Catchability for the AFSC bottom trawl survey was estimated at 1.07 and for the AFSC longline survey at 1.22. The retrospective analysis performed the best out of all models with a Mohn's Rho of -0.02 for spawning biomass and 0.00 for age-0 recruitment (Table 2.19 and Fig. 2.75). Of the three models evaluated using the same dataset, this model had the lowest AIC. Model 18.10.44 estimates of spawning biomass diverge from the 2017 base model (Fig.2.77) with an ADSB score of 0.27.

Model 18.10.46

This model is the same as Model 18.10.44 except the winter heat wave intensity index (Table 2.14 and Fig. 2.7) is used to scale natural mortality. Overall this model fits the data better than Model 18.10.44 with a lower objective function (Δ-LL of -8.64). The improvements in model fit were in the Trawl and longline fishery and AFSC bottom trawl survey length composition data. The fits to both survey indices were slightly degraded from Model18.10.44 (Δ-LL of +2.18). The change in fits to the age composition were minor (Δ-LL of +1.03). Natural mortality in this model has a base of 0.49 but increased with the winter heat wave index during the four notable winter heat waves in the GOA (Fig. 2.62). The most intense was the 2014-2016 heat wave where natural mortality was estimated to have spiked to an all-time high of 1.02 in 2016 and second highest in 2015 of 0.98. The changes in model fit result in fairly minor changes in model results with a slightly higher estimate of recruitment and spawning biomass during the mid-1990's, slightly lower during the high recruitments in the late 2000s (Fig. 2.72). Recruitment post-2015 is largely based on the mean and therefore resulted in slightly higher estimates of recruitment for this period. Retrospective analysis results show a slightly less stable model with increases in Mohn's Rho for SSB. Retrospective results remain at acceptable levels. The main issue with using this model for management is in what to use for recruitment and natural mortality for projection purposes under Tier 3B. For demonstration purposes here the overall mean natural mortality of 0.54 and recruitment assuming a static natural mortality was used in the projections presented in Table 2.17.

Model 18.11.38B

Model18.11.38B is the same configuration as Model18.10.38B without age composition or conditional length at age data included. The removal of the age data improves the fit to the length composition and survey index data for all likelihood components from Model 18.10.38B, except the AFSC longline survey length composition data. This suggests there is some disagreement between the age data and the growth model leading to a tradeoff of fits between the age and length composition data. This is likely due to annual variability in Pacific cod growth that is not captured in these models. The largest difference between Model 18.10.38B and Model 18.11.38B is a reduction in survey catchabilities (Table 2.16). With the reduction in catchability estimates, the overall scale of biomass estimate increased. Although the peaks and valleys of recruitment line up between the two models, they are increased in Model 18.11.38B compared to Model 18.10.38B. The retrospective analysis results are within acceptable bounds with a slight improvement over Model 18.10.38B.

Selection of Final Model

Comparing likelihoods or AIC was not appropriate for all models. Likelihoods could be compared across all models for fits to the Survey indices and length composition and for all components among models within a data series (e.g. series Model xx.09.xx, Model xx.10.xx). Model 18.10.46 will not be considered for management as we have not validated a means to properly project this model. The results from all of the models evaluated this year are very similar with a range of SSB status for 2019 between $B_{17.9\%}$ and $B_{20.9\%}$. The lowest estimate is from the 2017 base model run without the new fishery age composition data and with the restricted 2015-2016 heatwave block on natural mortality. Given the results of the marine heatwave intensity analysis, the evidence strongly supports adding 2014 to the marine heatwave natural mortality block. This eliminates the series Model 17.xx.xx models from consideration. The fit to the data improves in all models considered using the expanded marine heatwave natural mortality block. There is unaccounted for aging bias in the Model xx.09.xx series where the pre-2007 data are included. The bias appears to substantially impact the models' ability to fit the indices and size composition data. Although models were explored to deal with this bias within the model, none of the methods attempted improved model fits and we suspect the bias may not have been consistent from year to year and likely dependent on age reader. Post-2007 data appear to be more consistently read and in agreement with isotope analysis conducted to verify age. Removing these data completely (Model 18.11.38B) improved the fit to the survey indices and size composition data, however gains to model fit are small and there is not an external reason not to include these data. Of the three remaining Model18.10.xx series models Model 18.10.44 has the best fit overall with the lowest AIC and had the best retrospective performance. This model incorporates a less precise prior on natural mortality, but tight (essentially fixed) parameters in the growth model.

We recommend using Model 18.10.44 as the reference model for 2019. Due to the lower catchability in this model the overall biomass and reference point estimates are higher than the 2017 base model (Fig. 2.77), however the status of the stock remains the same. All Stock Synthesis files for Model 18.10.44 are provided in a linked zip file here:

(http://www.afsc.noaa.gov/REFM/Docs/2018/GOApcod_Appendix2.3.zip).

Model 18.10.44 diagnostics and Suggestions for Future Improvement

Survey Indices

Model 18.10.44 fit to the NMFS bottom trawl survey was similar to previous base model fits (Fig. 2.67), missing the 2009 survey and still not meeting the low 2017 estimate. Like previous models given the available length and age composition data, the model was not able to increase abundance enough between 2007 and 2009 to match the large increase in abundance between these two surveys and the model could also not fit the steepness of the decrease in abundance between 2013 and 2017 and retain a good fit to the longline survey RPN index which had a relatively high value for 2016. Comparison of total biomass predictions and AFSC bottom trawl survey abundance estimates are relatively closely matched for the 1996-2017 values with predictions at 1.60 times the survey estimates (Fig. 2.78), an effective "catchability" of 0.62.

Model 18.10.44 fits the AFSC longline index well (Fig. 2.68). The improvement was primarily due to fitting it with the 10cm CFSR bottom temperature index. This addition allowed the model to increase overall biomass in warm years and decrease it in cold year, better fitting the spikes and valleys observed in the index as well as the overall decreasing trend observed with the warming trend in the temperature index for 1990-2016.

Both the IPHC longline (Fig. 2.40) and ADFG large mesh bottom trawl (Fig. 2.42) surveys show a small uptick in abundance. Neither of these surveys are included in the model at this time. The length data for the IPHC longline survey have been collected for 2018, however they were not available for model development and validation in time for the September plan team meeting. The IPHC survey will be added to model runs for next year's assessment model development and presented in September 2019.

Length Composition

Selectivities in Model 18.10.44 were allowed to be dome-shaped, except for the 1990-2018 longline fisheries and 2013-2018 trawl fisheries (Fig. 2.79). Overall model predictions of the length compositions closely match the data for all components (Fig. 2.80). For the trawl fishery the model predictions (Fig. Fig. 2.81 and Fig. 2.82) although matching the mean length well, tended to underestimate the high peaks of the distributions and overestimate either side of the peaks. The addition of the 2005-2006 block on the fit selectivity parameters allowed the model to fit these two years well. Predictions of the longline fishery length composition (Fig. 2.83 and Fig. 2.84) were well fit but similarly underestimated the high peaks of some of the distributions, but matched the mean length very well. In addition, when the distributions tended to be bimodal, the model tended to predict a single mode between the two modes. Predictions of the pot fishery length composition (Fig. 2.85) were also very well fit, again, like the trawl and longline fisheries the high peaks of the distributions tended to be underestimated. The mean length for the pot fishery data were well matched for all years. For the fishery length composition, there really is no need for improvement, residuals were small even for the minimal discrepancies noted above for the peak modes.

Model 18.10.44 matched the NMFS bottom trawl survey length composition data mean lengths well (Fig. 2.86), however small fish (sub-27 cm) high modes although identified were not always matched in magnitude. The sub-27 cm modes in 1996, 2007, and 2009 were estimated lower than observed while a predicted mode for sub-27 cm fish in 2011 was not observed in the data. A few peak modes were underestimated, but in general the larger fish were well predicted by the model. In future years, we may use models similar to last year's Model 17.09.37 with age and year specific M to examine how these missed peaks correlate with mortality events and how these impact overall model performance (Barbeaux et al. 2017).

Although the selectivity for Model 18.10.44 AFSC Longline survey length composition data (Fig. 2.87) was not time varying, the predictions matched the data well. The 2008 and 2015 predictions were the only ones that didn't fit within the 95% confidence bounds of the mean length. For 2015 this was likely due to smaller fish moving to deeper waters in this very warm year. For this survey in the future, fitting the selectivity parameters on the CFSR temperature index, similar to how catchability is parameterized, should be explored.

Age Composition and Length-at-Age

Even though the AFSC bottom trawl survey age composition data were not fit in the model and did not contribute to the objective function we are able to examine how consistent the projected fit is to the data (Fig. 2.88). As suggested in other analysis there appears to be a bias in the aging where aged fish pre-2007 are older than what the model would predict them to be. This is generally not the case for fish aged post-2007. The data fits to the post-2007 are consistent and generally well matched.

Model 18.10.44 has time-invariant growth (Fig. 2.89). Fits to the length-at-age data are within the error bounds for most ages (Fig. 2.90, Fig. 2.91, Fig. 2.92, and Fig. 2.93), however there appears to be some inter-annual variability that was not captured in this model. For instance, Pacific cod in 2011 and 2015 AFSC bottom trawl survey were predicted in Model 18.10.44 to be larger at age than the data show for the oldest fish, while 2013 the opposite was true. The fishery data appear more consistent, except for 2017 where the larger Pacific cod in both the longline and pot fisheries are predicted to be older at size than the data suggests. This was not observed in the 2017 trawl survey data. Fitting these data may be improved with annually varying growth, however reliable data for pre-2007 data are not available, and therefore modeling inter-annual variability prior to 2007 may not be possible.

Mean length and weight at age from Model 18.10.44 are provided in Table 2.21.

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 was defined as numbers of age-0 fish in a given year; actual recruitment to fishery and survey depends on selectivities as estimated (noting that there are no indices involving age-0 Pacific cod). All results presented are from Model 18.10.44.

Biomass

Estimates of total biomass were on average 160% higher than the NMFS bottom trawl survey total biomass estimates. Total biomass estimates show a long decline from their peak of 873,994 t in 1988 (Table 2.22 and Fig. 2.94) to 272,454 in 2006 and then an increase to another peak in 2014 of 541,959 t then decrease continuously through 2018. With average recruitment in 2017 and 2018 total biomass is expected to begin to increase again in 2019 (note that there is no information currently on the 2017 recruitment size). Spawning biomass (Table 2.22) shows a similar trend of decline since the late 1980s with a peak in 1989 at 263,761 t to a low in 2008 of 59,467 t. There was then a short increase in spawning biomass coincident with the maturation of the 2005-2008 year classes through 2014 to 109,814 t, after which the decline continued to lowest level of 34,701 t projected for 2019. With future fishing in 2019 limited to 17,000 t the projected spawning biomass for 2020 is projected to be $B_{20.2\%}$ at 34,774 t, with fishing at Max ABC (19,665 t) in 2019 the 2020 projected spawning biomass would expected to be $B_{19.7\%}$ at 34,008 t.

Numbers at age and length are given in Appendix 2.2 and shown in Figure 2.95 and available online at: (http://www.afsc.noaa.gov/REFM/Docs/2017/GOApcod_Appendix2_2.xlsx)

Recruitment and Numbers at Age

The recruitment predictions in Model 18.10.44 (Table 2.23, Fig. 2.96 and Fig. 2.97) show large 1977, 1980-1982,1984-1985, 1987,1990, and 2012 year-classes width more than 1.0 billion (at age-0) fish for each, although uncertainty on the 1977 and 1984 year-class estimates were large (σ_{1977} = 0.65 and $\sigma_{1984\text{-}1990}$ > 0.19). Between 1991 and 2010 the average recruitment was estimated at 0.551 billion, 47% lower than the 1977-1989 mean recruitment of 1.04 billion and 27% lower than the 1977-2016 mean recruitment of 0.759 billion.

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 2.24). This period 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. 2.98). In 2018 there was a sharp decrease in fishing mortality coincident with the drastic cut in ABC. The phase plane plot (Fig. 2.99) shows that F was estimated to have been above the ABC control rule advised levels for 2008 through 2011 and 2014 through 2017 and biomass was below $B_{35\%}$ in 2008 and 2009 and again 2015 through 2018, and projected to continue to be below through 2020, very near $B_{20\%}$. It should be noted that this plot shows what the current model predicts not what the past assessments had estimated.

Retrospective analysis

Estimates of spawning biomass for Model 18.10.44 with an ending year of 2008 through 2018 are not consistently biased from 1984 through 2000, have a consistent negative bias from 2009-2016 and a positive bias post-2017 as more data are included (Fig. 2.70). The Mohn's Rho for SSB ends up at -0.02, a Woods Hole Rho of 0.02 and an RMSE of 0.05. The Mohn's Rho for recruitment is 0.00 as the time series although wavers to either side over time is perfectly balanced in sum. Similarly, the Woods Hole Rho is 0.00 and the RMSE is 0.16. All of the models examined this year had acceptable retrospective patterns.

MCMC results

MCMC were conducted with 1,000,000 iterations with 150,000 burn-in and thinned to every 1000^{th} iteration leaving 850 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 (Fig. 2.100). Posterior distributions of key parameters appear well defined and bracket the MLE estimates (Table 2.26, Fig. 2.101, and Fig. 2.102). Posterior distributions based on beginning of the year values shows a 20.7% probability of the spawning stock biomass being below $B_{20\%}$ and a 1.1% probability of being below $B_{17.5\%}$ at the start of 2019 (Fig. 2.102).

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 18.10.44:

Reference point:	$B_{35\%}$	$B_{40\%}$	$B_{100\%}$
Spawning biomass:	60,284 t	68,896 t	172,240 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 (2012-2017). The average fishing mortality rates implied that total fishing mortality was divided among the three main gear types according to the following percentages: trawl 30%, longline 20%, and pot 50%. This apportionment of catch given the projected selectivity for each gear results in estimates of $F_{35\%}$ and $F_{40\%}$ of 0.762 and 0.616 in aggregate.

Specification of OFL and Maximum Permissible ABC

Spawning biomass for 2019 is estimated by this year's model to be 34,701 t at spawning. This is below the $B_{40\%}$ value of 68,895 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 2019 and 2020 as follows (2020 values are predicated on the assumption that 2019 catch will be 17,000 t, below maximum permissible ABC):

Units	Year	Overfishing Level (OFL)	Maximum Permissible ABC
Harvest amount	2019	23,669	19,665
Harvest amount	2020	26,078	21,592
Fishing mortality rate	2019	0.358	0.292
Fishing mortality rate	2020	0.362	0.294

The age 0+ biomass projections for 2019 and 2020 from this year's model are 266,066 t and 329,133 t, respectively.

ABC Recommendation

From 2008-2017 the GOA Plan Team and SSC recommended setting the ABC at the maximum permissible level under Tier 3. For 2018 an ABC was recommended below the maximum ABC in order to ensure the 2019 and 2020 SSB would remain above $B_{20\%}$. Biological reference points from GOA Pacific cod SAFE documents for years 2001 – 2018 are provided in Table 2.26.

Like last year this year's maximum ABC for 2019 is projected to reduce the stock below $B_{20\%}$ in 2020, therefore we recommend reducing the recommended ABC to 17,000 to maintain the stock above $B_{20\%}$ in 2020 (Fig. 2.104). With average recruitment in 2017 and 2018 the model the spawning stock biomass is projected to increase and therefore we recommend fishing at the maximum ABC for 2020.

Area Allocation of Harvests

For the past several years, ABC has been allocated among regulatory areas on the basis of the three most recent surveys. The previous proportions based on the 2009-2013 surveys were 33% Western, 64% Central, and 3% Eastern. In the 2013 assessment, the random effects model was used for the 2014 ABC apportionment. Using this method with the trawl survey biomass estimates through 2017, the area-apportioned ABCs are:

	Western	Central	Eastern	Total
Random effects area apportionment	44.9%	45.1%	10.0%	100%
2019 ABC	7,633	7,667	1,700	17,000
2020 ABC	9,695	9,738	2,159	21,592

Standard Harvest and Recruitment Scenarios and Projection Methodology

A standard set of projections for population status under alternatives were conducted to comply with Amendment 56 of the FMP. This set of projections encompasses seven harvest scenarios designed to satisfy the requirements of Amendment 56, the National Environmental Protection Act, and the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA).

For each scenario, the projections begin with the vector of 2018 numbers at age estimated in the assessment. This vector is then projected forward to the beginning of 2018 using the schedules of natural mortality and selectivity described in the assessment and the best available estimate of total (year-end) catch for 2018 (here assumed to be 13,096 t). In each subsequent year, the fishing mortality rate is prescribed based on the spawning biomass in that year and the respective harvest scenario. In each year, recruitment is drawn from an inverse Gaussian distribution whose parameters consist of maximum likelihood estimates determined from recruitments estimated in the assessment. This year the recruitments were pulled from Model 18.10.44 with the 2014-2016 natural mortality block was set at the standard M value (Fig. 2.103 and Table 2.27). This is thought to be consistent with past practices for models with single Ms throughout. Spawning biomass is computed in each year based on the time of peak spawning and the maturity and weight schedules described in the assessment. Total catch is assumed to equal the catch associated with the respective harvest scenario in all years. This projection scheme is run 1,000 times to obtain distributions of possible future stock sizes, fishing mortality rates, and catches.

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 2019, 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. 17,000 in 2019 and max ABC afterwards.

Scenario 3: In all future years, *F* is set equal to the 2013-2017 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 2018 and above its B_{MSY} level in 2028 under this scenario, then the stock is not overfished.)

Scenario 7: In 2019 and 2020, F is set equal to max FABC, and in all subsequent years, F is set equal to FOFL. (Rationale: This scenario determines whether a stock is approaching an overfished condition. If the stock is 1) above its MSY level in 2020 or 2) above 1/2 of its MSY level in 2020 and expected to be above its MSY level in 2030 under this scenario, then the stock is not approaching an overfished condition.)

Scenarios 1 through 7 were projected 13 years from 2018 in Model 18.10.44 (Table 2.28). All scenarios including scenario 5 (no fishing) project the stock to be below $B_{35\%}$ until 2022, scenarios 1, 2, 6, and 7 have the stock below $B_{35\%}$ until 2022. Fishing at the maximum permissible rate indicate that the spawning stock (Fig. 2.104) will be below $B_{35\%}$ in 2019 through 2021 due to poor recruitment and high natural mortality post-2008. Under an assumption of mean recruitment, the stock recovers above $B_{35\%}$ by 2022.

Our projection model run under these conditions indicates that for Scenario 6, the GOA Pacific cod stock although below $B_{35\%}$ in 2018 at 35,740 will be above its MSY value in 2023 at 64,148 t and therefore is not overfished.

Projections 7 with fishing at the OFL after 2020 results in an expected spawning biomass of 64,276 t by 2030. These projections illustrate the impact of the low recruitment in 2014 and 2015. For example, under all scenarios, the spawning biomass is expected to continue to drop in 2019 due to the low recruitments post-2008 and high mortality of the 2011-2013 recruitments and decreasing influence of the high 2005-2008 year classes and then levels off as the projection relies on mean recruitment post-2017.

Under Scenarios 6 (Fig. 2.104) and 7 of the 2018 Model 18.10.44 the projected spawning biomass for Gulf of Alaska Pacific cod is not currently overfished, nor is it approaching an overfished status.

Ecosystem Considerations

Ecosystem Effects on the Stock

Food-web dynamics in the Gulf of Alaska (GOA) are structured by climate-driven changes to circulation and water temperature, which can impact the distribution of key predators in the system and mediate trophic interactions. Recent evaluation finds evidence for strong food-web responses to perturbation in the GOA and indicates a dominance of destabilizing forces in the system that suggest a "dynamic ecosystem structure, perhaps more prone to dramatic reorganization than the [Bering Sea], and perhaps inherently less predictable" (Gaichas et al., 2015).

Predation is a major structuring pressure in the GOA ecosystem. Prey and predators of Pacific cod have been described or reviewed by Albers and Anderson (1985), Livingston (1989, 1991), Lang et al. (2003), Westrheim (1996), Yang (2004), and Gaichas et al. 2015. The composition of Pacific cod prey varies spatially and with changing environmental conditions. In terms of percent occurrence, some of the most important items in the diet of Pacific cod in the BSAI and GOA have been polychaetes, amphipods, and crangonid shrimp. In terms of numbers of individual organisms consumed, some of the most important dietary items have been euphausids, miscellaneous fishes, and amphipods. In terms of weight of organisms consumed, some of the most important dietary items have been walleye pollock, fishery offal, yellowfin sole, and crustaceans (including Pandalidae and Chionoecetes bairdi). Predators of Pacific cod include Pacific cod, halibut, salmon shark, northern fur seals, Steller sea lions, harbor porpoises, various whale species, and tufted puffin. Major trends in the most important prey or predator species can be expected to affect the dynamics of Pacific cod (Gaichas et al. 2015).

The marine heat wave of 2014-2016 in the Northeast Pacific was unusual in the degree of temperature increase, the maintenance of warm water through the winters and the depth to which the warm temperatures reached (Bond et al 2015). Metabolic demand for ectothermic fish like Pacific cod is largely a function of thermal experience and tends to increase exponentially with increasing temperatures. Fish can minimize metabolic costs through behaviors such as movement to thermally optimal temperatures, or can increase consumption of food energy to meet increasing metabolic demands. The former requires access to thermally optimal temperatures, which may have been impacted by the recent marine heat wave. The latter requires sufficient access to abundant or high energy prey resources. Thus, if either is limiting, metabolic costs may exceed energetic consumption and decreases in growth or increases in mortality may occur.

In fact, for Pacific cod in the GOA during the anomalously warm years of 2014-2016, prey demand was elevated above long-term mean estimates, and peaked in 2016, according to adult bioenergetic model estimates of relative energetic demand (Fig. 2.105). Based on water temperatures at preferred depth, metabolic demand was greatest for 10 cm fish and >40 cm fish but lowest for 30 cm fish (Fig. 2.105). Bioenergetic model estimates of Pacific cod growth and respiration also suggest poor thermal conditions for growth in 1998 (following the record El Niño of 1997/98) and 2016 (top panel Fig. 2.103) that were driven by high metabolic demand during those years (bottom panel, Fig. 2.106). Prey energetic demand based on mean energy densities and annual shifts in diet composition show moderate changes in diet energy density over time, with highest cumulative diet energy densities in 2013, which occurred at the end of a seven year cold temperature stanza in the GOA, and slightly lower values in 2015 near the long-term mean (Fig. 2.107). Stomach fullness of Pacific cod sampled from the GOA summer bottom trawl survey was lowest to date in 2015 (Fig. 2.108), and diet composition varied from previous years, with a 47.8 % drop in *Chionoecetes bairdi* relative to previous years (Figs. 2.109 and 2.110) and an absence of capelin which had been abundant, particularly in smaller Pacific cod, during 2011 and 2013. The proportion of *C. bairdi* in the diets of 40-80 cm cod dropped from the long-term mean of about 13.8% to 6.6% in 2015, but increased again to mean levels in 2017. The average specific weight of diets in 2017 increased from a historical low in 2015 to above average for 40-80 cm fish, but remained low for 20-40 cm fish (Fig. 2.108).

The increase in metabolic demand in 2015 has two important implications: (1) Pacific cod would have had to consume an additional 6-12% of prey per day ($g\ g^{-1}d^{-1}$) over average (i.e., based on mean estimates for years 1980-2014) to maintain growth and body condition, or (2) Pacific cod would have had to access energetic reserves leading to net body mass loss. The protracted warm conditions from 2014-2016 may have exceeded both adaptive options, potentially leading to starvation and mortality. In addition, other ectothermic fish species would be expected to have similarly elevated metabolic demands during the warm conditions, increasing the potential for broad scale prey limitations.

There are a few lines of evidence to support this potential mechanism for declines in Pacific cod abundance, including low fish condition observed in 2015 (i.e., fish that were lighter than average for a given length; Zador et al. 2017), lowest potential growth based on mean relative foraging rates reported in Holsman and Aydin (2015; Fig 2.106 top), highest recorded metabolic demands in 2015 (Fig. 2.106, bottom), below average diet energy density (lowest since 2007) based on diet composition of survey collected stomach samples (Fig. 2.108), and reports in 2015-2106 of widespread mortality events from starvation for avian and marine mammal predators that share prey resources with Pacific cod in the GOA. Also of important note is the potential absence of capelin (an important prey item) in the diets of Pacific cod from 2015 (Fig. 2.108), and the overall lower mean stomach fullness for fish in 2015 (height of columns in Fig. 2.101; note that these data are aggregated across regions and fish sizes). Considered collectively, these lines of evidence suggest that persistent anomalously warm conditions that extended from surface waters to depth, may have contributed to high mortality rates for juvenile and adult Pacific cod from the years 2014-2016. Additional analysis of these patterns is needed to further evaluate spatial differences in energetic demand and potential factors influencing Pacific cod survival across the region.

Fishery Effects on the Ecosystem

Potentially, fisheries for Pacific cod can have effects on other species in the ecosystem through a variety of mechanisms, for example by relieving predation pressure on shared prey species (i.e., species which serve as prey for both Pacific cod and other species), by reducing prey availability for predators of Pacific cod, by altering habitat, by imposing bycatch mortality, or by “ghost fishing” caused by lost fishing gear.

Incidental Catch of Nontarget Species

Incidental catches of nontarget species in each year 2014-2018 are shown Table 2.7. In terms of average catch over the time series, only sea stars account for more than 250 t per year.

Steller Sea Lions

Sinclair and Zeppelin (2002) showed that Pacific cod was one of the four most important prey items of Steller sea lions in terms of frequency of occurrence averaged over years, seasons, and sites, and was especially important in winter. Pitcher (1981) and Calkins (1998) also showed Pacific cod to be an important winter prey item in the GOA and BSAI, respectively. Furthermore, the size ranges of Pacific cod harvested by the fisheries and consumed by Steller sea lions overlap, and the fishery operates to some extent in the same geographic areas used by Steller sea lion as foraging grounds (Livingston (ed.), 2002).

The Fisheries Interaction Team of the Alaska Fisheries Science Center has been engaged in research to determine the effectiveness of recent management measures designed to mitigate the impacts of the Pacific cod fisheries (among others) on Steller sea lions. Results from studies conducted in 2002-2003 were summarized by Conners et al. (2004). These studies included a tagging feasibility study, which may evolve into an ongoing research effort capable of providing information on the extent and rate to which Pacific cod move in and out of various portions of Steller sea lion critical habitat. Nearly 6,000 cod with spaghetti tags were released, of which approximately 1,000 had been returned as of September 2003.

Seabirds

The following is a summary of information provided by Livingston (ed., 2002): In both the BSAI and GOA, the northern fulmar (*Fulmarus glacialis*) comprises the majority of seabird bycatch, which occurs primarily in the longline fisheries, including the hook and line fishery for Pacific cod Shearwater (*Puffinus* spp.) distribution overlaps with the Pacific cod longline fishery in the Bering Sea, and with trawl fisheries in general in both the Bering Sea and GOA. Black-footed albatross (*Phoebastria nigripes*) is taken in much greater numbers in the GOA longline fisheries than the Bering Sea longline fisheries, but is not taken in the trawl fisheries. The distribution of Laysan albatross (*Phoebastria immutabilis*) appears to overlap with the longline fisheries in the central and western Aleutians. The distribution of short-tailed albatross (*Phoebastria albatrus*) also overlaps with the Pacific cod longline fishery along the Aleutian chain, although the majority of the bycatch has taken place along the northern portion of the Bering Sea shelf edge (in contrast, only two takes have been recorded in the GOA). Some success has been obtained in devising measures to mitigate fishery-seabird interactions. For example, on vessels larger than 60 ft. LOA, paired streamer lines of specified performance and material standards have been found to reduce seabird incidental take significantly.

Fishery Usage of Habitat

The following is a summary of information provided by Livingston (ed., 2002): The longline and trawl fisheries for Pacific cod each comprise an important component of the combined fisheries associated with the respective gear type in each of the three major management regions (BS, AI, and GOA). Looking at each gear type in each region as a whole (i.e., aggregating across all target species) during the period 1998-2001, the total number of observed sets was as follows:

Gear	BS	AI	GOA
Trawl	240,347	43,585	68,436
Longline	65,286	13,462	7,139

In the BS, both longline and trawl effort was concentrated north of False Pass (Unimak Island) and along the shelf edge represented by the boundary of areas 513, 517 (in addition, longline effort was concentrated along the shelf edge represented by the boundary of areas 521-533). In the AI, both longline and trawl effort were dispersed over a wide area along the shelf edge. The catcher vessel longline fishery in the AI occurred primarily over mud bottoms. Longline catcher-processors in the AI tended to fish more over rocky bottoms. In the GOA, fishing effort was also dispersed over a wide area along the shelf, though pockets of trawl effort were located near Chirikof, Cape Barnabus, Cape Chiniak and Marmot Flats. The GOA longline fishery for Pacific cod generally took place over gravel, cobble, mud, sand, and rocky bottoms, in depths of 25 fathoms to 140 fathoms.

Impacts of the Pacific cod fisheries on essential fish habitat were further analyzed in an environmental impact statement by NMFS (2005).

Gulf of Alaska Pacific cod Economic Performance Report for 2017

Pacific cod is a critical species in the catch portfolio of the Gulf of Alaska (GOA) fisheries. Pacific cod typically accounts for just under 30% of the GOA's FMP groundfish harvest and over 20% of the total Pacific cod catch in Alaska. In 2017 these shares fell to approximately 16% as the GOA cod catch as poor fishing conditions from low abundance resulted in roughly 75% of the TAC being harvested. Catch of Pacific cod in the GOA was down 24% from 2016 with a total catch of 48.7 thousand t and retained catch 48 thousand t. Retained catch is below the recent high of 79 thousand t in 2014, and is just under the 2007-2011 average of 63 thousand t (Table 2.29). Catches in 2018 will be substantially lower due to a 80% conservation reduction in the 2018 TAC. Preliminary stock assessment estimates as of Oct. 2018 suggest continued restraint in the 2019 catch specifications. Ex-vessel revenues in 2017 were down 14% to $35 million with the reduction in catch (Table 2.29). The products made from GOA Pacific cod had a first-wholesale value was $72 million in 2017, which was down 20% from 2015 and below the 2008-2012 average of $105 million (Table 2.30).

The fishery for cod is an iconic fishery with a long history, particularly in the North Atlantic. Global catch was consistently over 2 million t through the 1980s, but began to taper off in the 1990s as cod stocks began to collapse in the northwest Atlantic Ocean. Over roughly the same period, the U.S. catch of Pacific cod (caught in Alaska) grew to approximately 250 thousand tons where it remained throughout the early to mid-2000s. European catch of Atlantic cod in the Barents Sea (conducted mostly by Russia, Norway, and Iceland) slowed and global catch hit a low in 2007 at 1.13 million t. U.S. Pacific cod's share of global catch was at a high at just over 20% in the early 2000s. Since 2007 global catch has grown to roughly 1.8 million t in recent years as catch in the Barents Sea has rebounded and U.S. catch has remained strong at over 300 thousand t since 2011 (Table 2.31). European Atlantic cod and U.S. Pacific cod remain the two major sources supplying the cod market over the past decade accounting for roughly 75% and 20%, respectively. Atlantic cod and Pacific cod are substitutes in the global market. Because of cod's long history, global demand is present in a number of geographical regions, but Europe and the U.S. are the primary consumer markets for many of the Pacific cod products. The market for cod is also indirectly affected by activity in the pollock fisheries which experienced a similar period of decline in 2008-2010 before rebounding. Cod and pollock are commonly used to produce breaded fish portions. Alaska caught Pacific cod in the GOA became certified by the Marine Stewardship Council (MSC) in 2010, a NGO based third-party sustainability certification, which some buyers seek. Changes in global catch and production account for much of the broader time trends in the cod markets. In particular, the average first-wholesale prices peak approximately $1.90 per pound in 2008 and subsequently declined precipitously to approximately $1.50 per pound in 2009-2010 as markets priced in consecutive years of approximately 100 thousand t increases in the Barents Sea cod catch in 2009-2011; coupled with reduced demand from the recession.

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. Almost all of the GOA Pacific cod fisheries is caught by CVs which make deliveries to shore-based processors and accounts for 90% of the total GOA Pacific cod catch (Table 2.29). Approximately 40% is caught by the trawl, 40% is caught by pot gear, and 20% caught by hook and line, though the number of hook and line vessels is far greater. Poor fishing conditions in 2017 may have contributed to the significant reduction in jig fleet participation in 2017. In recent years approximately 60% of the retained catch volume and value is in the Central Gulf fisheries, 40% in the Western Gulf, and 1-2% occurring in other region of the GOA. In 2017 this shifted as the share of catch in the Central Gulf fell to 43% with reduced fishing opportunities. Harvests from catcher vessels that deliver to shoreside processors account for approximately 90% of the retained catch. The 2017 retained catch in the GOA decreased 24% to 48 thousand t. In most years the fisheries harvest the entire TAC, however, in 2016 only approximately 75% of the TAC was harvested, poor fishing conditions were a contributing factor. The ex-vessel value totaled $35 million in 2017, which was down from $41 million in 2016 (Table 2.29). Ex-vessel prices increased 14% to $0.33 per pound in 2017. 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, has recently been about $0.04 per pound, but fell to $0.01 in 2017.

The first-wholesale value of Pacific cod products was down 20% to $71.9 million in 2017 (Table 2.30). Despite lower prices through 2014 and 2015 revenues were strong as result of increased catch levels. In contrast, in 2016 and 2017 prices were up and the decrease in revenues were the result of reduced production volumes. The two primary product forms produced from cod in the GOA are fillets and H&G, which comprised approximately 60% and 30% of the value on average in 2017, though the relative share can fluctuate year over year depending on relative prices and processing decisions. The average price of GOA Pacific cod products in 2017 showed little change decreased 1% to $1.81 as fillet prices decrease 12% to $2.97 per pound and H&G prices increased 34% to $1.46 per pound (Table 2.30). Media reports indicate that prior to the announcement of reduction in the Pacific cod catch in 2018 prices were high with tight supplies and strong demand. Following the announcement of significant catch reductions for 2018 prices escalated to higher level. These price increases are reflected in the highly exported H&G product type which rose 34%.

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 (Table 2.31). China's rise as re-processor is fairly recent. Between 2001 and 2011 exports to China have increased nearly 10 fold. Japan and Europe (mostly Germany and the Netherlands) are also important export destinations. Approximately 30% of Alaska's cod production is estimated to remain in the U.S. Because U.S. cod production is approximately 20% of global production and the GOA is approximately 20% of U.S. production, the GOA Pacific cod is a relatively small component of the broader cod market. However, strong demand and tight supply in 2017-2018 from the U.S. and globally have contributed to strong prices. With the Barents Sea quota reduced by 13% 2018 the global cod supply will remain constrained which has resulted in high price levels continuing through 2018. High cod prices have incentivized increased demand for substitute products such haddock and pollock which cod relieve some of the upward pressure of cod prices. Furthermore, media reports indicate that significant price increase have yet to filter through to the retail level.

Data Gaps and Research Priorities

Understanding of the above ecosystem considerations would be improved if future research were directed toward closing certain data gaps. Such research would have several foci, including the following: 1) ecology of the Pacific cod stock, including spatial dynamics, trophic and other interspecific relationships, and the relationship between climate and recruitment; 2) behavior of the Pacific cod fishery, including spatial dynamics; 3) determinants of trawl survey catchability and selectivity and relationship with environmental covariates; 4) age determination and effects of aging error and bias on model parameters including natural mortality; 5) ecology of species taken as bycatch in the Pacific cod fisheries, including estimation of biomass, carrying capacity, and resilience; and 6) ecology of species that interact with Pacific cod, including estimation of biomass, carrying capacity, and resilience.

Literature Cited

Abookire, A. A., J. T. Duffy-Anderson, and C. M. Jump. 2007. Habitat associations and diet of young-of-the-year Pacific cod (Gadus macrocephalus) near Kodiak, Alaska. Marine Biology 150:713-726.

Albers, W. D., and P. J. Anderson. 1985. Diet of Pacific cod, *Gadus macrocephalus*, and predation on the northern pink shrimp, *Pandalus borealis*, in Pavlof Bay, Alaska. Fish. Bull., U.S. 83:601-610.

Alderdice, D.F. and C. R. Forrester, 1971. Effects of salinity, temperature, and dissolved oxygen on early development of the Pacific cod (*Gadus macrocephalus*). Journal of the Fisheries Board of Canada, 28(6), pp.883-902.

A'mar, T. and W. Pallson 2015. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 173-296. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501

A'mar, T., G. Thompson, M. Martin, and W. Palsson. 2012. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 183-322. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501

Barbeaux. S. J., K. Aydin, B. Fissel, K. Holsman, W. Palsson, K. Shotwell, Q. Yang, and S. Zador. 2017. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 183-322. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501

Bakkala, R. G., and V. G. Wespestad. 1985. Pacific cod. *In* R. G. Bakkala and L. L. Low (editors), Condition of groundfish resources of the eastern Bering Sea and Aleutian Islands region in 1984, p. 37-49. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-83.

Betts, M., H. D. G. Maschner, and D. S. Clark 2011. Zooarchaeology of the 'Fish That Stops', in Madonna L. Moss and Aubrey Cannon, eds., *The Archaeology of North Pacific Fisheries*, University of Alaska Press, Fairbanks, Alaska, 188.

Bian, X. D., X. M. Zhang, Y. Sakurai, X. S. Jin, R. J. Wan, T. X. Gao, and J. Yamamoto. 2016. Interactive effects of incubation temperature and salinity on the early life stages of pacific cod Gadus macrocephalus. Deep-Sea Research Part Ii-Topical Studies in Oceanography 124:117-128.

Boldt, J. (editor). 2005. Ecosystem Considerations for 2006. North Pacific Fishery Management Council, 605 West 4th Ave., Suite 306, Anchorage, AK 99501.

Bond, N. A., M. F. Cronin, H. Freeland, and N. Mantua (2015), Causes and impacts of the 2014 warm anomaly in the NE Pacific. Geophys. Res. Lett., 42, 3414–3420

Cahalan, J., J. Gasper, and J. Mondragon. 2014. Catch sampling and estimation in the federal groundfish fisheries off Alaska, 2015 edition. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-286, 46 p.

Calkins, D. G. 1998. Prey of Steller sea lions in the Bering Sea. Biosphere Conservation 1:33-44.

Copeman, L. A., and B. J. Laurel. 2010. Experimental evidence of fatty acid limited growth and survival in Pacific cod larvae. Marine Ecology Progress Series 412:259-272.

Copeman, L. A., B. J. Laurel, M. Spencer, and A. Sremba. 2017. Temperature impacts on lipid allocation among juvenile gadid species at the Pacific Arctic-Boreal interface: an experimental laboratory approach. Marine Ecology Progress Series 566:183-198.

Doyle, M. J., and K. L. Mier. 2016. Early life history pelagic exposure profiles of selected commercially important fish species in the Gulf of Alaska. Deep-Sea Research Part Ii-Topical Studies in Oceanography 132:162-193.

Doyle, M. J., S. J. Picquelle, K. L. Mier, M. C. Spillane, and N. A. Bond. 2009. Larval fish abundance and physical forcing in the Gulf of Alaska, 1981-2003. Progress in Oceanography 80:163-187.

Faunce, C., J. Sullivan, S. Barbeaux, J. Cahalan, J. Gasper, S. Lowe, and R. Webster. 2017. Deployment performance review of the 2016 North Pacific Groundfish and Halibut Observer Program. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-358, 75 p.

Fournier, D. 1983. An analysis of the Hecate Strait Pacific cod fishery using an age-structured model incorporating density-dependent effects. Can. J. Fish. Aquat. Sci. 40:1233-1243.

Fournier, D., and C. P. Archibald. 1982. A general theory for analyzing catch at age data. Can. J. Fish. Aquat. Sci. 38:1195-1207.

Fournier, D.A., H. J. Skaug, J. Ancheta, J. Ianelli, A. Magnusson, M. N. Maunder, A. Nielsen, and J. Sibert. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optim. Methods Softw. 27:233-249.

Francis, R.I.C.C. (2011). Data weighting in statistical fisheries stock assessment models. Can. J. Fish. Aquat. Sci. 68: 1124-1138.

Gaichas, S., Aydin, K.Y. & Francis, R.C. 2015. Wasp waist or beer belly? Modeling food web structure and energetic control in Alaskan marine ecosystems, with implications for fishing and environmental forcing. Progress in Oceanography, 138: 1–17. https://doi.org/10.1016/j.pocean.2015.09.010

Geweke, J. Evaluating the accuracy of sampling-based approaches to calculating posterior moments. In Bayesian Statistics 4 (ed JM Bernado, JO Berger, AP Dawid and AFM Smith). Clarendon Press, Oxford, UK.

Greer-Walker, M. 1970. Growth and development of the skeletal muscle fibres of the cod (*Gadus morhua L.*). Journal du Conseil 33:228-244.

Gregory, R. S., C. Morris, and B. Newton. In review. Relative strength of the 2007 and 2008 year-classes, from nearshore surveys of demersal age 0 Atlantic cod in Newman Sound, Bonavista Bay. Can. Sci. Advis. Sec. Res. Doc. series./xxx.

Hare, S. R., and N. J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47:103-146.

Heidelberger P and Welch PD. Simulation run length control in the presence of an initial transient. Opns Res., 31, 1109-44 (1983)

Hiatt, T., R. Felthoven, M. Dalton, B. Garber-Yonts, A. Haynie, K. Herrmann, D. Lew, J. Sepez, C. Seung, L. Sievanen, and the staff of Northern Economics. 2007. Stock Assessment and Fishery Evaluation Report for the Groundfish Fisheries of the Gulf of Alaska and Bering Sea/Aleutian Islands Area: Economic Status of the Groundfish Fisheries off Alaska, 2006. Economic and Social Sciences Research Program, Resource Ecology and Fisheries Management Division, Alaska Fisheries Science Center, NMFS, NOAA, 7600 Sand Point Way N.E., Seattle, Washington 98115-6349. 353p.

Hobday, A.J., Oliver, E.C., Sen Gupta, A., Benthuysen, J.A., Burrows, M.T., Donat, M.G., Holbrook, N.J., Moore, P.J., Thomsen, M.S., Wernberg, T. and Smale, D.A., 2018. Categorizing and naming marine heatwaves. Oceanography, 31(2), pp.1-13.

Holsman, KK and K Aydin. (2015). Comparative methods for evaluating climate change impacts on the foraging ecology of Alaskan groundfish. Mar Ecol Prog Ser doi: 521:217-23510.3354/ meps11102

Hurst, T. P., D. W. Cooper, J. S. Scheingross, E. M. Seale, B. J. Laurel, and M. L. Spencer. 2009. Effects of ontogeny, temperature, and light on vertical movements of larval Pacific cod (Gadus macrocephalus). Fisheries Oceanography 18:301-311.

Hurst, T. P., B. J. Laurel, and L. Ciannelli. 2010. Ontogenetic patterns and temperature-dependent growth rates in early life stages of Pacific cod (Gadus macrocephalus). Fishery Bulletin 108:382-392.

Jung, S., I. Choi, H. Jin, D.-w. Lee, H.-k. Cha, Y. Kim, and J.-y. Lee. 2009. Size-dependent mortality formulation for isochronal fish species based on their fecundity: an example of Pacific cod (*Gadus macrocephalus*) in the eastern coastal areas of Korea. Fisheries Research 97:77-85.

Kastelle, C. R., Helser, T. E., McKay, J. L., Johnston, C. G., Anderl, D. M., Matta, M. E., & Nichol, D. G. 2017. Age validation of Pacific cod (Gadus macrocephalus) using high-resolution stable oxygen isotope (δ 18O) chronologies in otoliths. Fisheries Research, 185, 43-53.

Ketchen, K.S. 1964. Preliminary results of studies on a growth and mortality of Pacific cod (*Gadus macrocephalus*) in Hecate Strait, British Columbia. J. Fish. Res. Bd. Canada 21:1051-1067.

Lang, G. M., C. W. Derrah, and P. A. Livingston. 2003. Groundfish food habits and predation on commercially important prey species in the Eastern Bering Sea from 1993 through 1996. Alaska Fisheries Science Center Processed Report 2003-04. Alaska Fisheries Science Center, 7600 Sand Point Way NE., Seattle, WA 98115-6349. 351 p.

Laurel, B., M. Spencer, P. Iseri, and L. Copeman. 2016a. Temperature-dependent growth and behavior of juvenile Arctic cod (Boreogadus saida) and co-occurring North Pacific gadids. Polar Biology 39:1127-1135.

Laurel, B. J., D. Cote, R. S. Gregory, L. Rogers, H. Knutsen, and E. M. Olsen. 2017. Recruitment signals in juvenile cod surveys depend on thermal growth conditions. Canadian Journal of Fisheries and Aquatic Sciences 74:511-523.

Laurel, B. J., T. P. Hurst, and L. Ciannelli. 2011. An experimental examination of temperature interactions in the match-mismatch hypothesis for Pacific cod larvae. Canadian Journal of Fisheries and Aquatic Sciences 68:51-61.

Laurel, B. J., T. P. Hurst, L. A. Copeman, and M. W. Davis. 2008. The role of temperature on the growth and survival of early and late hatching Pacific cod larvae (Gadus macrocephalus). Journal of Plankton Research 30:1051-1060.

Laurel, B. J., B. A. Knoth, and C. H. Ryer. 2016b. Growth, mortality, and recruitment signals in age-0 gadids settling in coastal Gulf of Alaska. ICES Journal of Marine Science 73:2227-2237.

Laurel, B. J., C. H. Ryer, B. Knoth, and A. W. Stoner. 2009. Temporal and ontogenetic shifts in habitat use of juvenile Pacific cod (Gadus macrocephalus). Journal of Experimental Marine Biology and Ecology 377:28-35.

Laurel, J., A. W. Stoner, C. H. Ryer, T. P. Hurst, and A. A. Abookire. 2007. Comparative habitat associations in juvenile Pacific cod and other gadids using seines, baited cameras and laboratory techniques. Journal of Experimental Marine Biology and Ecology 351:42-55.Livingston, P. A. 1989. Interannual trends in Pacific cod, Gadus macrocephalus, predation on three commercially important crab species in the eastern Bering Sea. Fish. Bull., U.S. 87:807-827.

Livingston, P. A. 1991. Pacific cod. *In* P. A. Livingston (editor), Groundfish food habits and predation on commercially important prey species in the eastern Bering Sea from 1984 to 1986, p. 31-88. U.S. Dept. Commer, NOAA Tech. Memo. NMFS F/NWC-207.

Livingston, P. A. (editor). 2003. Ecosystem Considerations for 2003. North Pacific Fishery Management Council, 605 West 4th Ave., Suite 306, Anchorage, AK 99501.

Livingston, P.A., Aydin, K., Buckley, T.W., Lang, G.M., Yang, M-S., Miller, B.S. (2017) Quantifying food web interactions in the North Pacific - a data-based approach. Environmental Biology of Fishes 100:443-470. doi: 10.1007/s10641-017-0587-0

Low, L. L. 1974. A study of four major groundfish fisheries of the Bering Sea. Ph.D. Thesis, Univ. Washington, Seattle, WA. 240 p.

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., & Francis, R. C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78, 1069-1079.

Matarese, A. C., D. M. Blood, S. J. Picquelle, and J. L. Benson. 2003. Atlas of abundance and distribution patterns of ichthyoplankton from the Northeast Pacific Ocean and Bering Sea ecosystems: based on research conducted by the Alaska Fisheries Science Center (1972–1996).

Methot, R. D. 1986. Synthetic estimates of historical abundance and mortality for northern anchovy, *Engraulis mordax*. NMFS, Southwest Fish. Cent., Admin. Rep. LJ 86-29, La Jolla, CA.

Methot, R. D. 1990. Synthesis model: An adaptable framework for analysis of diverse stock assessment data. Int. N. Pac. Fish. Comm. Bull. 50:259-277.

Methot, R. D. 1998. Application of stock synthesis to NRC test data sets. *In* V. R. Restrepo (editor), Analyses of simulated data sets in support of the NRC study on stock assessment methods, p. 59-80. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-F/SPO-30.

Methot, R. D. 2000. Technical description of the stock synthesis assessment program. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-NWFSC-43, 46 p.

Methot, R. D. 2005a. Technical description of the Stock Synthesis II Assessment Program. Unpubl. manuscr. National Marine Fisheries Service, Northwest Fisheries Science Center, 2725 Montlake Blvd. East, Seattle, WA 98112-2097. 54 p.

Methot, R. D. 2005b. User manual for the assessment program Strock Synthesis 2 (SS2), Model Version 1.19. National Marine Fisheries Service, Northwest Fisheries Science Center, 2725 Montlake Blvd. East, Seattle, WA 98112-2097. 47 p.

Methot, R. D. 2007. User manual for the integrated analysis program Stock Synthesis 2 (SS2), Model Version 2.00c. National Marine Fisheries Service, Northwest Fisheries Science Center, 2725 Montlake Blvd. East, Seattle, WA 98112-2097. 47 p.

Methot, R. D. 2013. User Manual for Stock Synthesis, Model Version 3.24q. Unpublished manuscript. 150 p.

Methot, R. D., and Wetzell, C. R. 2013. Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. Fish. Rsch. 142:86-99.

Moss, J. H., M. F. Zaleski, and R. A. Heintz. 2016. Distribution, diet, and energetic condition of age-0 walleye pollock (Gadus chalcogrammus) and pacific cod (Gadus macrocephalus) inhabiting the Gulf of Alaska. Deep-Sea Research Part Ii-Topical Studies in Oceanography 132:146-153.

National Marine Fisheries Service (NMFS). 2005. Final environmental impact statement for essential fish habitat identification and conservation in Alaska. National Marine Fisheries Service, Alaska Region. P.O. Box 21668, Juneau, AK 99802-1668.

Nichol, D. G., T. Honkalehto, and G. G. Thompson. 2007. Proximity of Pacific cod to the sea floor: Using archival tags to estimate fish availability to research bottom trawls. *Fisheries Research* 86:129-135.

Nichols, N. W., P. Converse, and K. Phillips. 2015. Annual management report for groundfish fisheries in the Kodiak, Chignik, and South Alaska Peninsula Management Areas, 2014. Alaska Department of Fish and Game, Fishery Management Report No. 15-41, Anchorage.

Ona, E., and O. R. Godø. 1990. Fish reaction to trawling noise: the significance for trawl sampling. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer 189: 159–166.

Pitcher, K. W. 1981. Prey of Steller sea lion, *Eumetopias jubatus*, in the Gulf of Alaska. Fishery Bulletin 79:467-472.

Martyn Plummer, Nicky Best, Kate Cowles and Karen Vines (2006). CODA: Convergence Diagnosis and Output Analysis for MCMC, R News, vol 6, 7-11

Raring, N. W., E. A. Laman, P. G. von Szalay, and M. H. Martin. 2016. Data report: 2011 Gulf of Alaska bottom trawl survey. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-330, 231 p. doi:10.7289/V5/TM-AFSC-330.

Rose, G.A. and Kulka, D.W., 1999. Hyperaggregation of fish and fisheries: how catch-per-unit-effort increased as the northern cod (*Gadus morhua*) declined. Canadian Journal of Fisheries and Aquatic Sciences, 56(S1), pp.118-127.

Saha, S., and Coauthors, 2010: The NCEP climate forecast system reanalysis. Bull. Amer. Meteor. Soc., 91, 1015-1057.

Savin, A. B. 2008. Seasonal distribution and Migrations of Pacific cod *Gadus macrocephalus* (Gadidae) in Anadyr Bay and adjacent waters. Journal of Ichythyology 48:610-621.

Shimada, A. M., and D. K. Kimura. 1994. Seasonal movements of Pacific cod (*Gadus macrocephalus*) in the eastern Bering Sea and adjacent waters based on tag-recapture data. U.S. Natl. Mar. Fish. Serv., Fish. Bull. 92:800-816.

Sinclair, E.S. and T. K. Zeppelin. 2002. Seasonal and spatial differences in diet in the western stock of Steller sea lions (*Eumetopias jubatus*). Journal of Mammalogy 83(4).

Smith, R.L., Paul, A.J. and Paul, J.M., 1990. Seasonal changes in energy and the energy cost of spawning in Gulf of Alaska Pacific cod. Journal of Fish Biology, 36(3), pp.307-316.

Spies I. 2012. Landscape genetics reveals population subdivision in Bering Sea and Aleutian Islands Pacific cod. *Transactions of the American Fisheries Society* 141:1557-1573.

Stark, J. W. 2007. Geographic and seasonal variations in maturation and growth of female Pacific cod (*Gadus macrocephalus*) in the Gulf of Alaska and Bering Sea. Fish. Bull. 105:396–407.

Strasburger, W. W., N. Hillgruber, A. I. Pinchuk, and F. J. Mueter. 2014. Feeding ecology of age-0 walleye pollock (Gadus chalcogrammus) and Pacific cod (Gadus macrocephalus) in the southeastern Bering Sea. Deep-Sea Research Part Ii-Topical Studies in Oceanography 109:172-180.

Thompson, G., T. A'mar, and W. Palsson. 2011. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 161-306. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501

Thompson, G. G., and M. E. Conners. 2007. Report of the Pacific cod technical workshop held at the Alaska Fisheries Science Center, April 24-25, 2007. Unpubl. manuscr., Alaska Fisheries Science Center, Resource Ecology and Fisheries Management Division, 7600 Sand Point Way NE., Seattle, WA 98115-6349. 56 p.

Thompson, G. G., and M. W. Dorn. 2005. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 155-244. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G., M. Dorn, and D. Nichol. 2006. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 147-220. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G., J. Ianelli, M. Dorn, D. Nichol, S. Gaichas, and K. Aydin. 2007a. Assessment of the Pacific cod stock in the Eastern Bering Sea and Aleutian Islands Area. *In* Plan Team for Groundfish Fisheries of the Bering Sea/Aleutian Islands (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands regions, p. 209-327. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G., J. Ianelli, M. Dorn, and M. Wilkins. 2007b. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 169-194. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G., J. Ianelli, M. Dorn, and M. Wilkins. 2009. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 165-352. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G., J. Ianelli, M. Dorn, and M. Wilkins. 2010. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 157-328. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G. G., and R. D. Methot. 1993. Pacific cod. *In* Plan Team for Groundfish Fisheries of the Bering Sea/Aleutian Islands (editor), Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands region as projected for 1994, chapter 2. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G. G., and A. M. Shimada. 1990. Pacific cod. *In* L. L. Low and R. E. Narita (editors), Condition of groundfish resources of the eastern Bering Sea-Aleutian Islands region as assessed in 1988, p. 44-66. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-178.

Thompson, G. G, and H. H. Zenger. 1993. Pacific cod. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (editor), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska as projected for 1994, chapter 2. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G. G, and H. H. Zenger. 1994. Pacific cod. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (editor), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska as projected for 1995, chapter 2. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G. G., and H. H. Zenger. 1995. Pacific cod. *In* Plan Team for the Groundfish Fisheries of the Gulf of Alaska (editor), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska as projected for 1996, chapter 2. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G. G., H. H. Zenger, and M. K. Dorn. 2002. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for the Groundfish Fisheries of the Gulf of Alaska (compiler), Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Gulf of Alaska p. 89-167. North Pacific Fishery Management Council, 605 West 4th Ave., Suite 306, Anchorage, AK 99501.

Thompson, G. G., H. H. Zenger, and M. K. Dorn. 2004. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for the Groundfish Fisheries of the Gulf of Alaska (compiler), Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Gulf of Alaska p. 131-232. North Pacific Fishery Management Council, 605 West 4th Ave., Suite 306, Anchorage, AK 99501.

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

Vollenweider, J.J., Heintz, R.A., Schaufler, L. & Bradshaw, R. 2011. Seasonal cycles in whole-body proximate composition and energy content of forage fish vary with water depth. Marine Biology, 158(2): 413–427. https://doi.org/10.1007/s00227-010-1569-3

Voesenek, C. J., F. T. Muijres, and J. L. van Leeuwen. 2018. Biomechanics of swimming in developing larval fish. Journal of Experimental Biology 221.

von Szalay, P.G., and N.W. Raring. 2018. Data report: 2017 Gulf of Alaska bottom trawl survey. NOAA Tech. Mem NMFS-AFSC-374. 260 p.

Walters, C., 2003. Folly and fantasy in the analysis of spatial catch rate data. Canadian Journal of Fisheries and Aquatic Sciences, 60(12), pp.1433-1436.

Wespestad, V., R. Bakkala, and J. June. 1982. Current abundance of Pacific cod (*Gadus macrocephalus*) in the eastern Bering Sea and expected abundance in 1982-1986. NOAA Tech. Memo. NMFS F/NWC-25, 26 p.

Westrheim, S. J. 1996. On the Pacific cod (*Gadus macrocephalus*) in British Columbia waters, and a comparison with Pacific cod elsewhere, and Atlantic cod (*G. morhua*). Can. Tech. Rep. Fish. Aquat. Sci. 2092. 390 p.

Yang, M-S. 2004. Diet changes of Pacific cod (Gadus macrocephalus) in Pavlof Bay associated with climate changes in the Gulf of Alaska between 1980 and 1995. U.S. Natl. Mar. Fish. Serv., Fish. Bull. 102:400-405.

Zador et al. 2017. Ecosystem considerations for the Gulf of Alaska. 2017 SAFE report.

Tables

Table 2.1. Studies of Pacific cod natural mortality and statistics on the combined values. Use? Column indicates whether the value was used in developing this year's assessment model prior on natural mortality.

Area	Author	Year	Value	ln(value)	Use?	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 et al.	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 2.2. Catch (t) for 1991 through 2018 by jurisdiction and gear type (as of 2018-10-09)

	Federal					State				
Year	Trawl	Long-line	Pot	Other	Subtotal	Long-line	Pot	Other	Subtotal	Total
1991	58,093	7,656	10,464	115	76,328	0	0	0	0	76,328
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	47,485	0	0	0	0	47,485
1995	41,875	10,978	16,055	77	68,985	0	0	0	0	68,985
1996	45,991	10,196	12,040	53	68,280	0	0	0	0	68,280
1997	48,406	10,978	9,065	26	68,476	0	7,224	1,319	8,542	77,018
1998	41,570	10,012	10,510	29	62,121	0	9,088	1,316	10,404	72,525
1999	37,167	12,363	19,015	70	68,614	0	12,075	1,096	13,171	81,785
2000	25,443	11,660	17,351	54	54,508	0	10,388	1,643	12,031	66,560
2001	24,383	9,910	7,171	155	41,619	0	7,836	2,084	9,920	51,542
2002	19,810	14,666	7,694	176	42,345	0	10,423	1,714	12,137	54,483
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	13,419	56,624
2005	14,549	5,732	14,749	203	35,233	26	9,653	2,673	12,351	47,584
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	39,932	270	11,378	682	12,329	52,261
2008	20,293	12,106	11,230	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	13,096	53,196
2010	21,765	16,540	20,116	429	58,850	826	14,604	4,045	19,475	78,325,
2011	16,453	16,668	29,233	722	63,076	1,035	16,675	4,627	22,337	85,412
2012	20,072	14,467	21,238	722	56,499	866	15,940	4,613	21,419	77,918
2013	21,700	12,866	17,011	476	52,053	1,089	14,156	1,303	16,547	68,600
2014	26,798	14,749	19,957	1,046	62,550	1,007	18,445	2,838	22,290	84,841
2015	22,269	13,054	20,653	408	56,384	578	19,719	2,808	23,104	79,489
2016	15,217	8,153	19,248	346	42,964	806	18,609	1,708	21,123	64,087
2017	13,041	8,978	13,426	67	35,512	149	13,011	62	13,222	48,734
2018*	2,882	2,537	2,393	95	7,907	205	3,659	195	4,058	11,965

Table 2.3 History of Pacific cod catch (t, includes catch from State waters), Federal TAC (does not include State guideline harvest level), ABC, and OFL. ABC was not used in management of GOA groundfish prior to 1986. Catch for 2018 is current through 2018-10-09. 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. The ABC value listed for 1987 is the upper bound of the range. Source: NPFMC staff.

Year	Catch	TAC	ABC	OFL
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	76,328	77,900	77,900	-
1992	80,747	63,500	63,500	87,600
1993	56,488	56,700	56,700	78,100
1994	47,485	50,400	50,400	71,100
1995	68,985	69,200	69,200	126,000
1996	68,280	65,000	65,000	88,000
1997	68,476	69,115	81,500	180,000
1998	62,121	66,060	77,900	141,000
1999	68,614	67,835	84,400	134,000
2000	54,508	59,800	76,400	102,000
2001	41,619	52,110	67,800	91,200
2002	42,345	44,230	57,600	77,100
2003	52,582	40,540	52,800	70,100
2004	56,624	48,033	62,810	102,000
2005	47,584	44,433	58,100	86,200
2006	47,897	52,264	68,859	95,500
2007	52,261	52,264	68,859	97,600
2008	59,014	50,269	64,493	88,660
2009	53,196	41,807	55,300	66,000
2010	78,325	59,563	79,100	94,100
2011	85,412	65,100	86,800	102,600
2012	77,918	65,700	87,600	104,000
2013	68,600	60,600	80,800	97,200
2014	84,840	64.738	88,500	107,300
2015	79,489	75,202	102,850	140,300
2016	64,087	71,925	98,600	116,700
2017	48,734	64,442	88,342	105,378
2018*	11,965	13,096	17,000	23,565

*As of 10/09/2018

Table 2.4. History of GOA Pacific cod allocations by regulatory area (in percent).

Year(s)	Western	Central	Eastern
1977-1985	28	56	16
1986	40	44	16
1987	27	56	17
1988-1989	19	73	8
1990	33	66	1
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

Table 2.5 Estimated retained-and discarded GOA Pacific cod from federal waters (source: AKFIN; *as of 2018-10-09)

Year	Discarded	Retained	Grand Total
1991	1,429	74,899	76,328
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	63,647	68,476
1998	1,732	60,389	62,121
1999	1,645	66,970	68,614
2000	1,378	53,130	54,508
2001	1,904	39,715	41,619
2002	3,715	38,631	42,345
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	2,871	75,454	78,325
2011	2,243	83,170	85,412
2012	973	76,945	77,918
2013	4,625	63,975	68,600
2014	5,234	79,606	84,840
2015	1,764	77,725	79,489
2016	896	63,191	64,087
2017	734	48,001	48,734
2018*	448	11,518	11,965

Table 2.6 Weight of groundfish bycatch (t), discarded (D) and retained (R), for 2014 2018 for GOA Pacific cod as target species (AKFIN; as of 2018-10-09)

	2014		2015		2016		2017		2018	
	D	R	D	R	D	R	D	R	D	R
Arrowtooth Flounder	823	499	455	659	568	809	217	273	83	13
Atka Mackerel	7	0.26	146	11	31	8	352	32	3	6
Flathead Sole	120	180	98	241	78	245	53	100	21	5
GOA Deep Water Flatfish	1	9	26	15	17	4	19	1	0.03	0.13
GOA Demersal Shelf Rockfish	0.03	2	0.46	2	1	2	0.40	0.38		0.43
GOA Dusky Rockfish	10	39	11	16	60	19	78	18	3	4
GOA Rex Sole	12	73	8	113	23	147	3	16	5	0.37
GOA Rougheye Rockfish	1	5	0.12	13	2	5	10	7	6	2

GOA Shallow Water Flatfish	323	595	298	715	181	565	279	563	25	8
GOA Shortraker Rockfish	3	5	0.16	11	1	4	5	4	7	1
GOA Skate, Big	759	180	603	205	438	257	449	171	54	22
GOA Skate, Longnose	105	364	154	565	384	181	301	105	38	35
GOA Skate, Other	1,016	59	1,063	81	1,002	73	894	106	161	15
GOA Thornyhead Rockfish	3	16	5	4	3	7	11	25	1	3
Halibut	10	41	32	52	8	38	11	30	9	12
Northern Rockfish	13	59	12	35	61	17	45	9	4	1
Octopus	674	517	524	380	154	207	29	195	9	54
Other Rockfish	28	27	22	70	44	69	66	53	6	22
Pacific Ocean Perch	0.41	14	104	62	781	15	46	31	0.07	1
Pollock	92	1,423	133	1,003	64	350	343	487	10	45
Sablefish	12	45	43	37	101	31	81	32	44	13
Sculpin	539	7	635	3	865	11	919	2	65	0.36
Shark	402	0.48	207	0.29	424	0.18	364		35	
Squid		0.02	0.21	1	0.03	1	0.012	0.11		

Table 2.7 - Incidental catch (t or birds by number) of non-target species groups by GOA Pacific cod fisheries, 2014-2018 (as of 2018-10-09).

	2014	2015	2016	2017	2018
Benthic urochordata	0.1	4.3	0.0	1.5	0.0
Birds	***123***	***98***	***167***	***232***	***273***
Bivalves	1.6	1.4	0.6	1.3	2.6
Brittle star unidentified	0.0	0.0	0.0	0.0	0.0
Corals Bryozoans - Corals Bryozoans Unidentified	1.5	1.2	0.4	2.3	1.3
Corals Bryozoans - Red Tree Coral	0.1	0.5	-	-	-
Eelpouts	0.1	0.3	0.1	0.1	-
Eulachon	0.2	0.0	-	0.0	-
Giant Grenadier	187.9	105.7	84.9	18.6	0.1
Greenlings	1.4	2.6	4.7	5.8	0.8
Grenadier - Rattail Grenadier Unidentified	15.6	0.1	1.2	-	0.5
Hermit crab unidentified	0.4	2.8	0.6	0.1	0.1
Invertebrate unidentified	0.5	0.2	1.1	0.2	0.0
Misc crabs	2.9	1.0	1.0	0.8	0.3
Misc crustaceans	0.0	0.5	-	0.0	-
Misc fish	120.5	108.3	154.2	169.2	19.8
Misc inverts (worms etc)	-	0.0	-	-	-
Other osmerids	-	-	0.0	-	-
Pacific Hake	-	-	0.0	-	-
Pacific Sand lance	0.0	-	-	0.0	-
Pandalid shrimp	-	0.0	0.0	-	-

Polychaete unidentified	-	-	0.0	-	-
Scypho jellies	1.2	4.1	21.5	0.9	-
Sea anemone unidentified	6.7	5.6	21.2	13.3	1.6
Sea pens whips	2.9	1.8	0.7	0.6	0.2
Sea star	872.0	1,218.2	891.8	383.8	29.7
Snails	23.9	11.9	14.6	9.6	0.5
Sponge unidentified	0.3	1.3	1.6	2.6	2.4
State-managed Rockfish	13.6	14.5	47.2	75.5	3.1
Stichaeidae	-	-	-	0.3	-
urchins dollars cucumbers	1.4	4.2	2.0	4.6	0.3

Table 2.8 Pacific cod catch (t) by trip target in Gulf of Alaska groundfish fisheries. *Data for 2018 is as of 10/09/2018.

Trip Target	2014	2015	2016	2017	2018
Arrowtooth Flounder	3,030	1,384	1,346	1,266	735
Atka Mackerel	-	-	10	5	2
Deep Water Flatfish - GOA	2	-	-	-	-
Flathead Sole	64	1	39	2	2
Halibut	1,195	541	325	368	299
Other Species	1	12	-	2	1
Pacific Cod	***73,978***	***74,052***	***60,789***	***46,008***	***10,506***
Pollock - bottom	2,811	1,090	624	557	261
Pollock - midwater	476	622	230	55	49
Rex Sole - GOA	273	162	25	6	64
Rockfish	628	786	366	253	375
Sablefish	114	127	108	88	27
Shallow Water Flatfish - GOA	2,267	711	225	123	199
TOTAL	84,840	79,489	64,087	48,734	12,520
Non Pacific cod trip target total	10,862	5,437	3,297	2,726	2,014

Table 2.9 Noncommercial fishery catch (in kg); total source amounts less than 1 mt were omitted (AFSC for GOA bottom trawl survey values; AKFIN for other values, as of 2018-10-09)

Source	2009	2010	2011	2012	2013	2014	2015
Annual Longline Survey	30,987	33,224	27,069	30,505	22,734	33,370	39,824
Bait for Crab Fishery					16,444	7,348	1,616
Golden King Crab Pot Survey				12			
Gulf of Alaska Bottom Trawl Survey			29,393		26,221		18,945
IPHC Annual Longline Survey		142,300	124,356	85,595	123,197	138,091	77,044
Large-Mesh Trawl Survey	958	11,702	17,015	20,500	18,577	13,090	8,072
Salmon EFP 13-01					2,647	8,316	
Scallop Dredge Survey	14				8		0
Shelikof Acoustic Survey		14					
Shelikof and Chirikof EIT				4			
Shumagin and Sanak EIT				583			
Shumigans Acoustic Survey		1,030					
Small-Mesh Trawl Survey		1,887	1,654	2,662	1,678	1,424	1,412
Sport Fishery		113,660	155,527	143,762	131,133	199,263	183,813
Spot Shrimp Survey			3			12	10
Structure of Gulf of Alaska Forage Fish Communities		136					
Western Gulf of Alaska Pollock Acoustic Cooperative Survey		59					
Total	31,959	304,011	355,017	283,622	342,639	400,913	330,736

Table 2.10 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

Table 2.11 ABL Longline 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			
2003	59,952	0.150			
2004	53,108	0.118			
2005	29,864	0.214			
2006	34,316	0.197			

Table 2.12 IPHC Longline Relative Population Numbers (RPNs) and CVs for Pacific cod.

Year	RPN	CV	Year	RPN	CV
1997	29,431.29	0.24	2008	22,201.86	0.17
1998	16,389.47	0.20	2009	30,228.94	0.16
1999	12,387.02	0.21	2010	27,836.75	0.16
2000	14,599.59	0.22	2011	31,728.38	0.15
2001	12,192.47	0.23	2012	23,604.72	0.17
2002	16,372.69	0.21	2013	26,333.14	0.18
2003	15,361.62	0.22	2014	27,789.64	0.16
2004	16,075.93	0.20	2015	16,853.72	0.20
2005	16,397.51	0.23	2016	11,888.02	0.23
2006	15,761.12	0.20	2017	10,241.65	0.23
2007	18,196.23	0.19	2018	13,198.32	0.16

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

Year	Index	CV	Year	Index	CV
1988	2.85	0.09	2005	1.08	0.09
1989	3.79	0.09	2006	0.93	0.09
1990	2.82	0.08	2007	1.11	0.08
1991	1.93	0.14	2008	1.28	0.07
1992	2.93	0.08	2009	1.29	0.07
1993	2.37	0.09	2010	1.09	0.07
1994	2.13	0.08	2011	1.40	0.07
1995	2.36	0.11	2012	2.65	0.09
1996	2.39	0.09	2013	2.00	0.10
1997	2.57	0.08	2014	1.37	0.10
1998	2.32	0.09	2015	1.24	0.10
1999	1.28	0.07	2016	0.85	0.11
2000	1.00	0.08	2017	0.90	0.11
2001	0.88	0.08	2018	1.17	0.10
2002	1.11	0.07			
2003	0.89	0.08			
2004	1.37	0.07			

Table 2.14 CFSR bottom temperature index for 10 cm and 40 cm Pacific cod and Hobday (2018) marine heatwave intensity index (MHWI) in °C days for full year and for winter for 1979-2018.

Year	10cm	40cm	Annual MHWI	Winter MHWI		Year	10cm	40cm	Annual MHWI	Winter MHWI
1979	5.16	5.10	0	0		1999	4.85	5.02	0	0
1980	5.23	5.03	0	0		2000	4.88	4.88	0	0
1981	6.13	5.45	0	0		2001	5.19	5.07	35.5	16.7
1982	4.44	4.65	0	0		2002	4.54	4.44	50.3	49.4
1983	5.33	5.33	24.8	8.7		2003	5.54	5.44	201.1	123
1984	5.04	5.32	75.6	38.4		2004	4.95	5.10	115.6	0
1985	4.90	5.24	22.2	19.2		2005	5.17	5.33	276.5	0
1986	5.06	5.09	15.7	14.7		2006	5.03	5.06	35	5.1
1987	5.87	5.42	5.5	0		2007	4.46	4.37	0	0
1988	5.18	5.03	0	0		2008	4.55	4.65	0	0
1989	4.40	4.51	0	0		2009	4.02	4.39	0	0
1990	4.46	4.56	8.6	0		2010	5.46	5.19	6.5	0
1991	4.62	4.64	0	0		2011	4.75	4.78	0	0
1992	5.15	4.96	0	0		2012	4.41	4.29	0	0
1993	4.80	4.80	19	0		2013	4.40	4.76	0	0
1994	4.72	4.91	0	0		2014	5.11	5.00	257.7	82.3
1995	4.35	4.68	0	0		2015	6.17	5.69	378.9	246.4
1996	4.79	4.87	0	0		2016	5.79	4.97	632.8	266.3
1997	4.80	4.96	138.6	15.4		2017	5.15	4.65	39.3	22.5
1998	5.92	5.57	152.4	88.5		2018	5.47	5.19	0	0

Table 2.15 Number of parameters by category for model configurations presented.

	M17.09.35	M18.09.xx	M18.10.xx	M18.11.38
Recruitment				
Early Rec. Devs (1962-1977)	16	16	16	16
Main Rec. Devs (1978-2014)	37	37	37	37
Late Rec. Devs (2015-2017)	4	4	4	4
Future Rec. Devs. (2018-2022)	5	5	5	5
R_0	1	1	1	1
R_1 offset	2	***0***	***0***	***0***
1976 R reg.	0	***1***	***1***	***1***
Natural mortality	2	2	2	2
Growth	5	5	5	5
Catchability				
Q_{trawl}	1	1	1	1
$Q_{longline}$				
$Q_{longline}$ env. offset				
Initial F	2	2	2	2
Selectivity				
Trawl Survey	16	16	16	16
Longline survey	5	5	5	5
Trawl Fishery	60 (39 dev)	60 (39 dev)	60(39 dev)	60(39 dev)
Longline Fishery	40 (24 dev)	40 (24 dev)	40 (24 dev)	40 (24 dev)
Pot Fishery	8	8	8	8
Total	204	203	203	203

Table 2.16 Model fit statistics and results. Note that likelihoods between model series are not completely comparable. 2020 (top) estimates based on full take of max ABC, (***bottom in bold italics***) on 3,000 t catch (shaded) for those models below $B_{20\%}$ and 17,000 t for those above $B_{20\%}$ in 2019. Preferred model in green.

	M17.09.35 -2018	M18.09.35	M18.09.38A	M18.10.38A	M18.10.38B	M18.10.44	M18.11.38B
ADSB	0.12	0.13	0.14	0.13	0.16	0.27	0.29
AIC	6719.86	6554.38	6552.38	4155.96	4167.58	4150.66	2682.40
Likelihoods Total	3155.93	3073.19	3073.19	1874.98	1880.79	1872.33	1138.20
Survey	0.42	-4.98	-4.98	-14.06	-15.77	-19.19	-17.70
Length Comp.	1272.60	1299.80	1299.80	1255.04	1257.24	1259.08	1240.74
Age Comp.	1862.66	1861.39	1861.39	719.97	725.98	727.61	0.00
Recruitment	-11.23	-10.94	-10.94	-6.38	-5.10	-4.54	-2.29
Parameter priors	22.25	19.26	19.26	11.72	9.29	1.70	9.19
Parameter Devs.	4.33	-96.92	-96.92	-96.14	-95.68	-95.72	-95.68
Parameters							
R_0 billions	0.560	0.674	0.674	0.523	0.424	0.703	0.487
Steepness	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Natural Mortality	0.51	0.53	0.53	0.49	0.45	0.50	0.45
M14-16	M15-16 0.86	0.81	0.81	0.72	0.68	0.87	0.67
q_{Shelf}	1.63	1.42	1.42	1.27	1.25	1.07	1.00
$q_{longline}$	1.86	1.62	1.62	1.48	1.43	1.22	1.14
L_{min}	7.20	6.90	6.90	6.27	5.09	4.91	7.16
L_{max}	115.76	116.11	116.11	107.86	99.46	99.46	99.46
Von Bert K	0.13	0.13	0.13	0.15	0.17	0.17	0.16
Results							
SSB_{1978} (t)	66,025	96,577	90,714	88,751	100,707	130,267	133,325
$SSB_{100\%}$ (t)	155,842	155,325	147,748	160,525	169,252	172,240	192,072
SSB_{2018} (t)	32,030	33,950	30,998	31,529	31,763	35,740	41,286
$SSB_{2018\%}$	20.6	21.9	21.0	19.6	18.8	20.8	21.5
SSB_{2019}(t)	30,375	32,220	30,144	30,990	31,499	34,515	40,217
$SSB_{2019\%}$	19.5	20.7	20.4	19.3	18.6	20.0	20.9
SSB_{2020}(t)	28,408	29,855	28,668	30,760	31,885	34,008	38,453
$SSB_{2020\%}$	18.2	19.2	19.4	19.2	18.5	19.7	20.0
$F_{35\%}$	1.04	0.916	0.871	0.684	0.633	0.762	0.608
$F_{40\%}$	0.824	0.731	0.696	0.552	0.513	0.615	0.496
2019 ABC (t)	16,554	19,619	18,419	15,600	14,287	19,665	19,473
F_{ABC}	0.379	0.360	0.337	0.252	0.224	0.292	0.247
OFL (t)	21,062	23,709	22,279	18,804	17,216	23,669	23,292
F_{OFL}	0.473	0.447	0.417	0.309	0.275	0.358	0.301
2020* ABC (t)	15,333 ***20,282***	17,931 ***23,110***	17,468 ***17,956***	16,301 ***20,424***	15,579 ***19,038***	20,697 ***21,592***	18,796
F_{ABC}	0.352 ***0.410***	0.249 ***0.336***	0.319 ***0.324***	0.250 ***0.284***	0.227 ***0.255***	0.287 ***0.294***	0.235
OFL (t)	18,747 ***24,649***	21,799 ***27,921***	21,229 ***21,810***	19,704 ***24,595***	18,808 ***22,916***	25,017 ***26,078***	22,561
F_{OFL}	0.440 ***0.512***	0.411 ***0.461***	0.417 ***0.401***	0.307 ***0.349***	0.279 ***0.314***	0.327 ***0.362***	0.286

Table 2.17 Model fit statistics and results. Note that likelihoods between model series are not completely comparable. 2020 (top) estimates based on full take of max ABC, (*bottom in bold italics*) on 3,000 t catch (shaded) for those models below $B_{20\%}$. M18.10.46 projection estimates based on average M of 0.54.

	M17.09.35-2017	**M17.09A.35**	**M18.10.46**
ADSB		0.12	0.29
AIC	3526.78	4138.26	4133.38
Likelihoods Total	1559.39	1866.13	1863.69
Survey	0.80	-2.00	-17.02
Length Composition	1005.46	1260.09	1252.94
Age Composition	531.37	588.80	728.64
Recruitment	-4.14	-7.77	-9.14
Parameter priors	11.64	16.60	0.35
Parameter Devs.	4.80	4.74	-94.52
Parameters			
R_0 billions	0.470	0.559	0.747
Steepness	0.44	0.44	0.44
Natural Mortality	0.49	0.54	$\mu = 0.54$
	M15-16 0.71	M15-16 0.77	M14,15,16 0.65/0.98/1.02
q_{Shelf}	1.47	1.87	1.03
$q_{longline}$	1.4	2.08	1.19
L_{min}	7.08	5.53	4.94
L_{max}	123.98	121.07	99.46
Von Bert K	0.11	0.13	0.17
Results			
SSB_{1978} (t)	74,472	85,133	131,898
Projection			
$SSB_{100\%}$ (t)	168,583	154,554	172,326
SSB_{2018} (t)	35,824	29,238	35,141
$SSB_{2018\%}$	21.3	18.9	20.4
SSB_{2019}(t)	34,444	27,675	32,471
$SSB_{2019\%}$	20.4	17.9	18.9
SSB_{2020}(t)	[redacted]	26,547	30,759
$SSB_{2020\%}$	[redacted]	17.1	17.8
$F_{35\%}$	0.804	0.915	0.841
$F_{40\%}$	1.018	0.730	0.677
2019 ABC (t)	17,635	12,937	18,769
F_{ABC}	0.393	0.305	0.300
OFL (t)	20,953	15,739	22,605
F_{OFL}	0.477	0.379	0.369
2020* ABC (t)	[redacted]	12,577 ***15,835***	18,505 ***23,896***
F_{ABC}	[redacted]	0.291 ***0..331***	0.282 ***0.329***
OFL (t)	[redacted]	15,348 ***19,243***	22,416 ***28,808***
F_{OFL}	[redacted]	0.362 ***0.411***	0.348 ***0.404***

Table 2.18 Likelihood components by fleet for all proposed models. Note that Model17.09.35 is Model17.09.35-2018.

Model	Label	ALL	FshTrawl	FshLL	FshPot	Srv	LLSrv
Model17.09.35	Age_like	1862.66	525.12	326.88	331.62	679.04	-
Model18.09.35	Age_like	1861.39	524.22	326.30	329.00	681.87	-
Model18.09.38	Age_like	1861.39	524.22	326.30	329.00	681.87	-
Model18.10.38A	Age_like	719.93	175.89	190.54	139.95	213.55	-
Model18.10.38B	Age_like	725.98	178.63	192.13	140.66	214.56	-
Model18.10.44	Age_like	727.61	178.99	192.67	140.81	215.14	-
Model18.10.46	Age_like	728.64	179.52	193.29	140.93	214.90	-
Model18.11.38	Age_like	-	-	-	-	-	-
Model17.09.35	Catch_like	6.03E-11	1.92E-11	2.12E-11	1.99E-11	-	-
Model18.09.35	Catch_like	1.51E-11	4.70E-12	5.25E-12	5.19E-12	-	-
Model18.09.38	Catch_like	1.51E-11	4.70E-12	5.25E-12	5.19E-12	-	-
Model18.10.38A	Catch_like	2.04E-11	6.59E-12	7.26E-12	6.57E-12		
Model18.10.38B	Catch_like	2.07E-11	6.71E-12	7.34E-12	6.69E-12	-	-
Model18.10.44	Catch_like	9.54E-13	3.18E-13	3.20E-13	3.15E-13	-	-
Model18.10.46	Catch_like	9.44E-13	3.05E-13	3.12E-13	3.26E-13	-	-
Model18.11.38	Catch_like	4.93E-13	1.69E-13	1.72E-13	1.52E-13	-	-
Model17.09.35	Length_like	1272.60	393.62	273.06	298.42	111.21	196.29
Model18.09.35	Length_like	1299.80	393.36	272.84	299.27	137.91	196.44
Model18.09.38	Length_like	1299.80	393.36	272.84	299.27	137.91	196.44
Model18.10.38A	Length_like	1255.27	377.04	273.53	282.03	129.55	193.13
Model18.10.38B	Length_like	1257.24	379.50	274.02	281.40	129.83	192.49
Model18.10.44	Length_like	1259.08	384.76	273.43	280.86	129.92	190.11
Model18.10.46	Length_like	1252.94	377.71	271.40	284.65	128.48	190.71
Model18.11.38	Length_like	1240.46	378.04	271.38	273.93	126.27	190.86
Model17.09.35	Surv_like	0.42	-	-	-	-1.03	1.45
Model18.09.35	Surv_like	-4.98	-	-	-	-1.65	-3.33
Model18.09.38	Surv_like	-4.98	-	-	-	-1.65	-3.33
Model18.10.38A	Surv_like	-14.16	-	-	-	-4.71	-9.46
Model18.10.38B	Surv_like	-15.77	-	-	-	-4.96	-10.80
Model18.10.44	Surv_like	-19.19	-	-	-	-7.15	-12.04
Model18.10.46	Surv_like	-17.02	-	-	-	-5.04	-11.99
Model18.11.38	Surv_like	-17.61	-	-	-	-6.42	-11.19

Table 2.19 Retrospective analysis, index RMSE, harmonic mean effective N for length and age compositions, and recruitment variability for selected assessed models. Note that Model17.09.35 is Model17.09.35-2018.

		M17.09.35	M18.09.35/ 38A	M18.10.38 A	M18.10.38 B	M18.10.44	M18.10.46	M18.11.38 B
Retrospective								
Spawning biomass	Mohn's ρ	0.08	0.07	0.09	0.10	-0.02	0.13	0.06
	Woods Hole ρ	0.04	0.04	0.08	0.06	0.02	0.07	0.05
	RMSE	0.07	0.05	0.10	0.07	0.05	0.08	0.07
Recruit. (age -0)	Mohn's ρ	0.56	0.70	0.61	0.54	0.00	0.29	0.58
	Woods Hole ρ	0.05	0.06	0.11	0.09	0.00	0.07	0.06
	RMSE	0.19	0.17	0.18	0.17	0.16	0.15	0.17
	Index RMSE Shelf	0.32	0.32	0.31	0.31	0.31	0.30	0.29
	ABL Longline	0.31	0.30	0.28	0.28	0.27	0.28	0.28
Size Comp								
Har. Mean EffN	Trawl	321.50	322.00	328.29	324.54	321.56	321.35	323.42
	Longline	471.70	471.25	457.16	455.71	456.60	462.58	458.27
	Pot	441.97	440.95	463.82	466.08	462.77	454.52	479.48
	Trawl Survey	315.67	326.89	336.89	338.94	341.24	344.82	332.67
	ABL Longline	306.80	307.47	310.39	312.16	314.70	313.06	310.45
Mean input N	Trawl	149.56	149.56	149.56	149.56	149.56	149.56	149.56
	Longline	155.72	155.72	155.72	155.72	155.72	155.72	155.72
	Pot	175.97	175.97	175.97	175.97	175.97	175.97	175.97
	Trawl Survey	94	94	94	94	94	94	94
	ABL Longline	100	100	100	100	100	100	100
Age Data								
Har. Mean EffN	Trawl	1.65	1.66	1.67	1.66	1.66	1.65	-
	Longline	2.36	2.36	2.98	2.98	2.98	2.98	-
	Pot	1.93	1.95	2.56	2.59	2.59	2.59	-
	Trawl Survey	2.87	2.89	3.15	3.14	3.12	3.11	-
Mean input N	Trawl	5.45	3.64	1.03	1.03	1.03	1.03	-
	Longline	5.98	5.18	1.66	1.66	1.66	1.66	-
	Pot	5.92	4.55	1.21	1.21	1.21	1.21	-
	Trawl Survey	2.59	2.60	1.40	1.40	1.40	1.40	-
Rec. Var. (1977-2016)								
	Std.dev(ln(No. Age 1))	0.37	0.39	0.42	0.43	0.46	0.40	0.48

Table 2.20 Hobday annual and winter heatwave intensity indices in °C days. The index for 2018 is through 11 June 2018.

Year	Annual	Winter		Year	Annual	Winter
1979	0	0		2001	35.5	16.7
1980	0	0		2002	50.3	49.4
1981	0	0		2003	201.1	123
1982	0	0		2004	115.6	0
1983	24.8	8.7		2005	276.5	0
1984	75.6	38.4		2006	35	5.1
1985	22.2	19.2		2007	0	0
1986	15.7	14.7		2008	0	0
1987	5.5	0		2009	0	0
1988	0	0		2010	6.5	0
1989	0	0		2011	0	0
1990	8.6	0		2012	0	0
1991	0	0		2013	0	0
1992	0	0		2014	257.7	82.3
1993	19	0		2015	378.9	246.4
1994	0	0		2016	632.8	266.3
1995	0	0		2017	39.3	22.5
1996	0	0		2018	0	0
1997	138.6	15.4				
1998	152.4	88.5				
1999	0	0				
2000	0	0				

Table 2.21 Estimated beginning year weight and length at age from Model 18.10.44.

Age	Weight (kg)	Length (cm)	Age	Weight (kg)	Length (cm)
0	0.000	0.500	11	6.201	84.052
1	0.021	12.742	12	6.778	86.497
2	0.178	26.502	13	7.291	88.554
3	0.537	38.079	14	7.741	90.285
4	1.081	47.818	15	8.133	91.741
5	1.762	56.013	16	8.472	92.966
6	2.523	62.907	17	8.763	93.996
7	3.317	68.707	18	9.011	94.863
8	4.103	73.587	19	9.223	95.593
9	4.856	77.692	20	9.612	96.889
10	5.559	81.146			

Table 2.22 Estimated female spawning biomass (t) from the last year's assessment and this year's assessment from Models 17.09.35 and the author's recommended Model 18.10.44.

	Last Year's Model			Model18.10.44		
	Sp.Bio	St.dev	Tot. Bio. 0+	Sp.Bio	St.dev	Tot. Bio. 0+
1977	67,950	12,982	211,386	120,453	28,059	403,588
1978	74,475	13,342	234,741	130,267	29,204	422,439
1979	71,785	12,529	270,065	126,010	27,365	504,136
1980	72,545	12,284	304,973	123,733	25,682	593,197
1981	82,590	14,613	317,916	151,436	30,339	635,060
1982	98,600	17,205	333,039	188,497	36,725	668,967
1983	101,520	17,580	360,125	197,736	37,047	713,828
1984	101,765	17,838	390,651	200,333	35,954	758,519
1985	116,150	18,910	438,030	218,129	35,924	798,787
1986	138,020	19,415	498,477	242,500	35,204	837,433
1987	157,635	19,245	545,294	254,206	32,877	871,227
1988	171,305	18,348	571,580	255,330	29,508	873,994
1989	186,405	17,373	585,726	263,180	26,925	857,974
1990	190,465	15,852	583,689	260,761	23,944	823,846
1991	176,205	14,214	561,688	236,943	20,755	776,061
1992	164,150	13,138	542,783	215,133	18,336	743,411
1993	154,270	12,518	516,572	199,049	16,766	705,219
1994	159,545	12,248	498,812	200,625	15,889	667,998
1995	164,135	11,395	475,335	201,299	14,614	613,486
1996	148,525	9,751	429,089	180,727	12,558	533,819
1997	127,535	8,063	387,341	151,465	10,273	470,311
1998	108,470	6,867	349,568	122,877	8,463	418,822
1999	97,520	6,265	320,068	107,276	7,598	379,079
2000	87,170	5,917	292,025	95,443	7,154	338,390
2001	80,405	5,476	285,986	87,620	6,642	325,728
2002	78,825	5,112	293,479	82,855	6,079	334,660
2003	81,325	5,048	292,427	82,785	5,910	336,484
2004	83,360	5,145	273,329	85,552	6,116	317,059
2005	79,250	4,899	247,080	83,110	5,936	288,103
2006	71,040	4,306	236,684	76,069	5,264	272,454
2007	61,235	3,818	246,165	66,572	4,594	281,250
2008	54,470	3,718	273,080	59,467	4,316	316,237
2009	57,740	4,201	306,193	62,478	4,809	364,318
2010	75,775	5,124	342,798	81,083	6,076	421,953
2011	86,915	5,897	343,212	95,334	7,507	441,055
2012	89,920	6,314	324,950	105,408	8,952	442,457
2013	88,915	6,312	314,781	109,747	9,903	467,634
2014	81,125	5,996	322,031	109,814	10,778	541,959
2015	69,555	6,518	311,495	76,280	6,691	413,621
2016	56,455	4,941	227,406	60,085	5,033	278,457
2017	47,326	4,375	154,605	45,374	4,036	166,636
2018	**35,824**		132,812	39,723	4,208	146,433
2019				**34,701**	4,075	183,503

Table 2.23 Age-0 recruitment and standard deviation of age-0 recruits by year for last year's model and Model18.10.44. Highlighted are the 1977 and 2012 year classes.

	Last Year's Model		M18.10.44	
Year	**Age-0 x 10^9**	**Stdev**	**Age-0 x 10^9**	**Stdev**
1977	0.945	0.255	2.234	0.650
1978	0.290	0.101	0.504	0.197
1979	0.388	0.122	0.539	0.196
1980	0.695	0.187	1.220	0.381
1981	0.612	0.169	1.080	0.341
1982	0.881	0.227	1.273	0.377
1983	0.631	0.169	0.767	0.276
1984	0.975	0.221	1.047	0.343
1985	0.841	0.181	1.515	0.376
1986	0.611	0.132	0.544	0.190
1987	0.797	0.162	1.012	0.245
1988	0.660	0.138	0.800	0.214
1989	0.842	0.171	0.983	0.238
1990	0.826	0.165	1.094	0.252
1991	0.550	0.112	0.676	0.176
1992	0.450	0.090	0.539	0.135
1993	0.430	0.084	0.375	0.101
1994	0.474	0.090	0.456	0.109
1995	0.542	0.099	0.689	0.138
1996	0.398	0.076	0.410	0.094
1997	0.369	0.070	0.450	0.096
1998	0.441	0.080	0.318	0.073
1999	0.576	0.103	0.670	0.127
2000	0.505	0.090	0.586	0.112
2001	0.280	0.054	0.355	0.072
2002	0.294	0.054	0.298	0.058
2003	0.276	0.052	0.345	0.063
2004	0.431	0.078	0.372	0.067
2005	0.697	0.121	0.734	0.127
2006	0.799	0.136	0.869	0.153
2007	0.639	0.114	0.761	0.138
2008	0.727	0.126	0.942	0.171
2009	0.370	0.069	0.490	0.095
2010	0.425	0.079	0.678	0.132
2011	0.603	0.116	0.989	0.205
2012	0.902	0.180	1.703	0.382
2013	0.421	0.102	1.002	0.254
2014	0.182	0.052	0.379	0.110
2015	0.278	0.094	0.247	0.083
2016	0.208	0.068	0.400	0.126
2017	0.531	0.257	0.693	0.335
2018			0.703	0.341
Mean 1977-2015	0.562		0.768	
Stdev(Ln(x))		0.407		0.588

Table 2.24 Estimated fishing mortality in Apical F and Total exploitation for Model 18.10.44.

	Sum Apical F		Total		Sum Apical F		Total
Year	F	σ	**Exploitation**	**Year**	F	σ	**Exploitation**
1977	0.009	0.002	0.006	2001	0.335	0.028	0.151
1978	0.043	0.010	0.033	2002	0.357	0.028	0.145
1979	0.057	0.014	0.042	2003	0.467	0.035	0.170
1980	0.137	0.033	0.064	2004	0.494	0.037	0.193
1981	0.082	0.017	0.062	2005	0.568	0.084	0.182
1982	0.062	0.012	0.051	2006	0.600	0.080	0.201
1983	0.081	0.015	0.058	2007	0.590	0.047	0.235
1984	0.054	0.010	0.036	2008	0.741	0.064	0.236
1985	0.049	0.011	0.020	2009	0.594	0.051	0.176
1986	0.072	0.014	0.033	2010	0.693	0.059	0.221
1987	0.057	0.013	0.043	2011	0.652	0.057	0.213
1988	0.059	0.007	0.041	2012	0.527	0.049	0.202
1989	0.073	0.011	0.055	2013	0.372	0.037	0.180
1990	0.190	0.019	0.096	2014	0.552	0.055	0.203
1991	0.222	0.021	0.109	2015	0.723	0.069	0.218
1992	0.259	0.024	0.122	2016	0.718	0.068	0.242
1993	0.193	0.017	0.086	2017	0.732	0.087	0.314
1994	0.162	0.014	0.076	2018	0.184	0.022	0.100
1995	0.241	0.019	0.118				
1996	0.267	0.020	0.138				
1997	0.321	0.025	0.163				
1998	0.361	0.028	0.161				
1999	0.478	0.039	0.198				
2000	0.420	0.035	0.176				

Table 2.25 Model 18.10.44 parameters and reference estimates MLE and MCMC derived. SSB is calculated for January 1 in this table.

	MLE estimates		MCMC posterior distribution		
	MLE	σ	50%	2.5%	97.5%
$M_{Standard}$	0.5049	0.0223	0.4956	0.4470	0.5347
$M_{2014\text{-}2016}$	0.8687	0.0550	0.8507	0.7394	0.9525
Von Bert K	0.1728	0.0023	0.1725	0.1680	0.1769
Lmin	4.9177	0.5995	4.9176	3.6908	6.0062
Lmax	99.4604	0.0150	99.4619	99.4298	99.4893
$Ln(Q_{Trawl\ survey})$	0.0852	0.0920	0.1036	-0.0660	0.2864
$Ln(Q_{ll\ survey})$	0.1997	0.0813	0.2302	0.1074	0.4351
$Ln(Q_{ll\ survey\ envir.\ link})$	1.3720	0.0718	NA	NA	NA
$FSSB_{1978}$	130,267	29,204	125,924	82,969	184,758
$FSSB_{2019}$	39,298	4074.955	37,962	30,743	45,524
Recr_1977	2,233,830	649,894	2,011,525	1,059,680	3,492,533
Recr_2012	1,702,890	382,349	1,568,765	967,289	2,341,290
$SSB_{100\%}$	187,361	NA	177,288	154,191	199,553
$SSB_{2019}/SSB_{100\%}$	20.97%	2.74%	21.45%	17.98%	25.00%

Table 2.26 Biological reference points from GOA Pacific cod SAFE documents for years 2001 2018

Year	$SB_{100\%}$	$SB_{40\%}$	$F_{40\%}$	SB_{y+1}	ABC_{y+1}
2001	212,000	85,000	0.41	82,000	57,600
2002	226,000	90,300	0.35	88,300	52,800
2003	222,000	88,900	0.34	103,000	62,810
2004	211,000	84,400	0.31	91,700	58,100
2005	329,000	132,000	0.56	165,000	68,859
2006	259,000	103,000	0.46	136,000	68,859
2007	302,000	121,000	0.49	108,000	66,493
2008	255,500	102,200	0.52	88,000	55,300
2009	291,500	116,600	0.49	117,600	79,100
2010	256,300	102,500	0.42	124,100	86,800
2011	261,000	104,000	0.44	121,000	87,600
2012	234,800	93,900	0.49	111,000	80,800
2013	227,800	91,100	0.54	120,100	88,500
2014	316,500	126,600	0.50	155,400	102,850
2015	325,200	130,000	0.41	116,600	98,600
2016	196,776	78,711	0.53	105,378	88,342
2017	168,583	67,433	0.80	35,973	18,972
2018	172,240	68,896	0.76	34,515	19,665

Table 2.27 Number of fish at age-1 from Model 18.10.44 with the M 2014-2016 block fixed at the standard M value used in projection model.

Year	Age-1		Year	Age-1
1977	217,912		2000	389,677
1978	1,210,570		2001	351,641
1979	281,304		2002	218,893
1980	297,863		2003	179,014
1981	651,420		2004	205,029
1982	615,514		2005	209,076
1983	726,058		2006	402,274
1984	447,090		2007	458,134
1985	575,923		2008	383,353
1986	915,472		2009	427,581
1987	302,412		2010	197,516
1988	587,916		2011	231,734
1989	464,836		2012	277,833
1990	560,620		2013	397,156
1991	637,950		2014	202,813
1992	404,404		2015	75,952
1993	319,750		2016	71,682
1994	220,722			
1995	260,328			
1996	405,972			
1997	239,077			
1998	269,097			
1999	184,214			

Table 2.28 Results for the projection scenarios from Model 18.10.44. Female spawning stock biomass (SSB) SSB, fishing mortality (F), and catch for the 7 standard projection scenarios.

SSB	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
2018	35,740	35,740	35,740	35,740	35,740	35,740	35,740
2019	34,515	34,701	34,847	34,597	35,806	34,227	34,515
2020	34,008	34,774	35,737	34,413	41,359	32,626	34,008
2021	45,039	45,396	48,107	46,033	57,673	43,120	44,654
2022	60,546	60,650	68,211	65,142	82,891	57,565	58,073
2023	68,822	68,826	85,746	81,253	107,664	64,148	64,204
2024	71,358	71,348	97,520	91,538	127,614	65,313	65,287
2025	72,111	72,104	104,856	97,638	142,599	65,414	65,396
2026	72,701	72,699	109,560	101,438	153,690	65,745	65,738
2027	72,525	72,524	111,881	103,135	161,018	65,467	65,465
2028	71,834	71,833	112,471	103,336	165,261	64,801	64,801
2029	71,442	71,442	112,517	103,182	167,741	64,506	64,506
2030	71,134	71,134	112,284	102,859	169,041	64,276	64,276
2031	71,390	71,390	112,449	102,996	170,115	64,588	64,588
F							
2018	0.18	0.18	0.18	0.18	0.18	0.18	0.18
2019	0.29	0.25	0.22	0.27	0.00	0.36	0.29
2020	0.29	0.29	0.22	0.27	0.00	0.34	0.29
2021	0.39	0.39	0.22	0.27	0.00	0.46	0.48
2022	0.53	0.53	0.22	0.27	0.00	0.62	0.63
2023	0.56	0.56	0.22	0.27	0.00	0.67	0.67
2024	0.57	0.57	0.22	0.27	0.00	0.67	0.67
2025	0.57	0.57	0.22	0.27	0.00	0.67	0.67
2026	0.57	0.57	0.22	0.27	0.00	0.67	0.67
2027	0.57	0.57	0.22	0.27	0.00	0.67	0.67
2028	0.56	0.56	0.22	0.27	0.00	0.66	0.66
2029	0.56	0.56	0.22	0.27	0.00	0.66	0.66
2030	0.56	0.56	0.22	0.27	0.00	0.66	0.66
2031	0.56	0.56	0.22	0.27	0.00	0.66	0.66
Catch							
2018	13,096	13,096	13,096	13,096	13,096	13,096	13,096
2019	19,665	17,000	14,868	18,495	0	23,669	19,665
2020	20,697	21,592	16,398	19,917	0	23,464	20,697
2021	38,171	38,714	22,763	27,560	0	43,166	45,986
2022	66,499	66,670	31,217	37,653	0	74,515	75,559
2023	78,576	78,576	38,100	45,558	0	86,701	86,783
2024	81,445	81,428	42,613	50,480	0	88,224	88,166
2025	82,429	82,420	45,423	53,410	0	88,626	88,591
2026	83,058	83,054	47,160	55,160	0	88,985	88,974
2027	82,442	82,441	47,915	55,811	0	88,014	88,012
2028	81,514	81,513	48,087	55,850	0	86,892	86,892
2029	81,039	81,039	48,062	55,730	0	86,421	86,421
2030	80,705	80,705	47,984	55,595	0	86,130	86,130
2031	81,066	81,066	48,107	55,740	0	86,596	86,596

Table 2.29 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; 2008-2012 average and 2013-2017.

	Avg 08-12	2013	2014	2015	2016	2017
Total catch K mt	70.74	68.6	84.8	79.5	64.1	48.7
Retained catch K mt	68.0	63.9	79.5	77.6	63.2	48.0
Ex-vessel value M $	$52.1	$37.2	$52.0	$50.3	$41.0	$35.3
Ex-vessel price lb $	$0.348	$0.264	$0.297	$0.293	$0.294	$0.334
Hook & line share of catch	28%	21%	23%	21%	17%	18%
Pot gear share of catch	48%	49%	48%	52%	60%	55%
Central Gulf share of catch	62%	58%	59%	60%	53%	43%
Shoreside share of catch	89%	93%	91%	92%	92%	87%
Vessels #	458.6	350	341	382	358	246

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 2.30 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; 2008-2012 average and 2013-2017.

		Avg 08-12	2013	2014	2015	2016	2017
All Products	**volume K mt**	29.52	23.80	31.07	32.00	21.65	17.39
All Products	**value M $**	$105.0	$94.2	$118.1	$102.9	$90.2	$71.9
All Products	**price lb $**	$1.61	$1.80	$1.72	$1.46	$1.89	$1.88
Fillets	**volume K mt**	8.03	9.70	9.85	6.39	7.87	6.52
Fillets	**value share**	50.0%	71.3%	57.1%	36.2%	64.6%	59.5%
Fillets	**price lb $**	$2.96	$3.14	$3.10	$2.64	$3.36	$2.97
Head & Gut	**volume K mt**	13.14	6.63	13.95	19.05	8.43	6.11
Head & Gut	**value share**	36.1%	15.6%	32.6%	51.1%	22.4%	27.3%
Head & Gut	**price lb $**	$1.31	$1.01	$1.25	$1.25	$1.09	$1.46

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 2.31 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; 2008-2012 average and 2013-2018.

		Avg 08-12	2013	2014	2015	2016	2017	2018 (thru July)
Global cod catch K mt		1,366	1,831	1,853	1,763	1,792	-	-
U.S. P. cod share of global catch		19.3%	16.9%	17.6%	18.0%	17.9%	-	-
Europe share of global catch		72.8%	76.7%	75.9%	74.8%	74.8%	-	-
Pacific cod share of U.S. catch		97.2%	99.3%	99.3%	99.5%	99.5%	-	-
U.S. cod consumption K mt (est.)		83	105	115	108	114	119	-
Share of U.S. cod not exported		27%	31%	31%	26%	29%	33%	-
Export volume K mt		94.4	101.8	107.3	113.2	105.3	92.8	51.6
Export value M US$		$302.9	$308.0	$314.2	$335.0	$312.0	$295.3	$176.1
Export price lb US$		$1.456	$1.373	$1.328	$1.342	$1.344	$1.444	$1.547
Frozen (H&G)	**volume Share**	69%	91%	92%	91%	94%	94%	92%
	value share	69%	89%	91%	90%	92%	92%	92%
Fillets	**volume Share**	12%	4%	2%	3%	3%	4%	5%
	value share	15%	5%	4%	4%	4%	5%	6%
China	**volume Share**	33%	51%	54%	53%	55%	52%	53%
	value share	31%	48%	51%	51%	52%	50%	52%
Japan	**volume Share**	18%	13%	16%	13%	14%	16%	13%
	value share	18%	13%	16%	14%	15%	18%	15%
Netherlands & Germany	**volume Share**	10%	8%	9%	8%	5%	3%	1%
	value share	11%	9%	10%	8%	5%	3%	1%

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.
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.

Figures

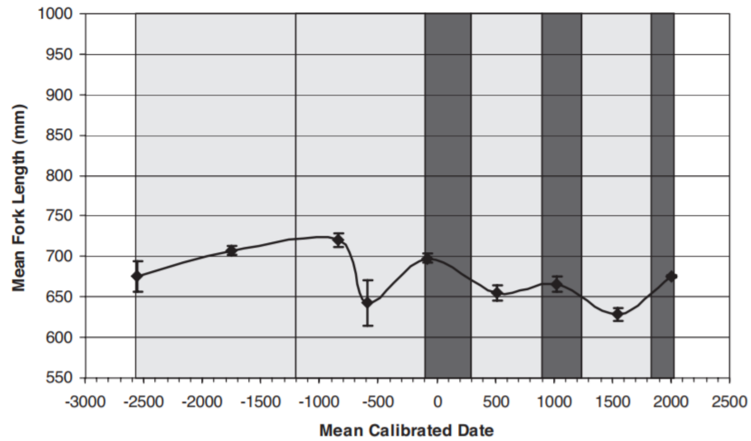


Figure 2.1 Gulf of Alaska mean lengths with climate reconstruction. The shaded boxes represent periods of significant changes in air temperature, sea surface temperature, storminess, and ocean circulation that drive ocean productivity. The lightly shaded boxes represent periods of cooler and stormier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

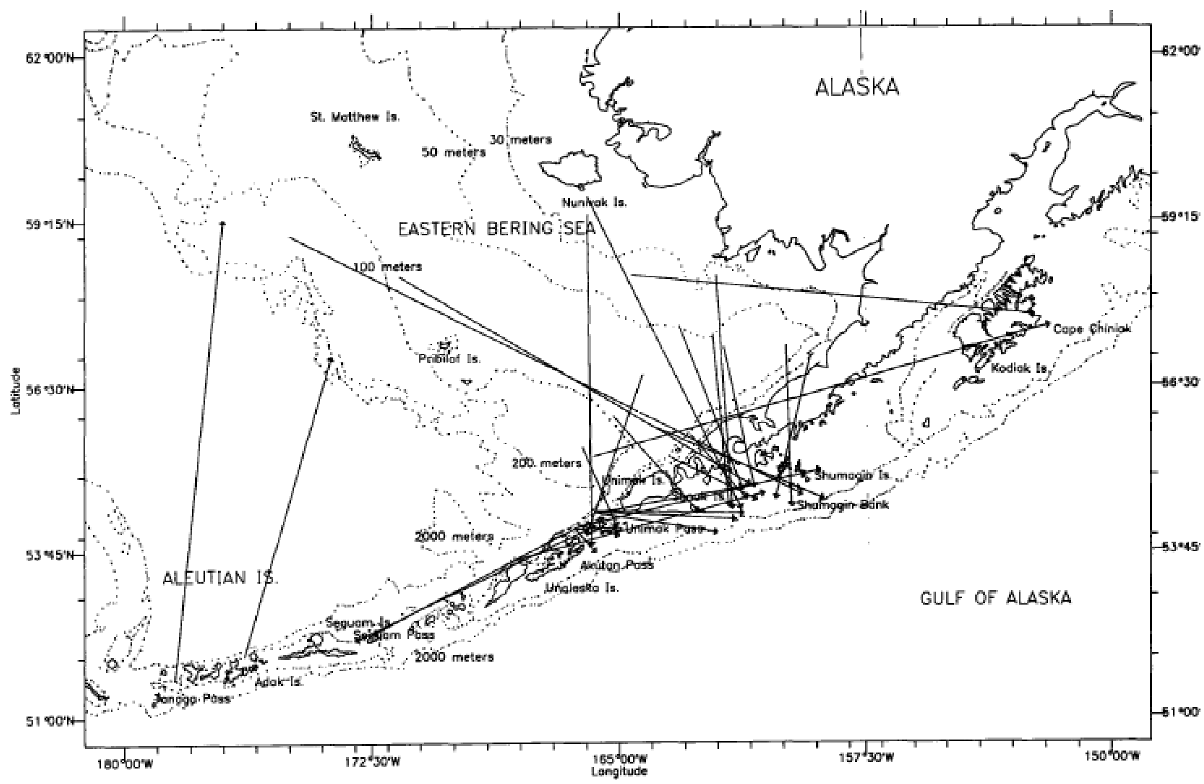


Figure 2.2 Tag recoveries from Shimada and Kimura 1994 (Figure 8), showing movement of individual tagged Pacific cod from eastern Bering Sea into the Gulf of Alaska and other interregional migrations.

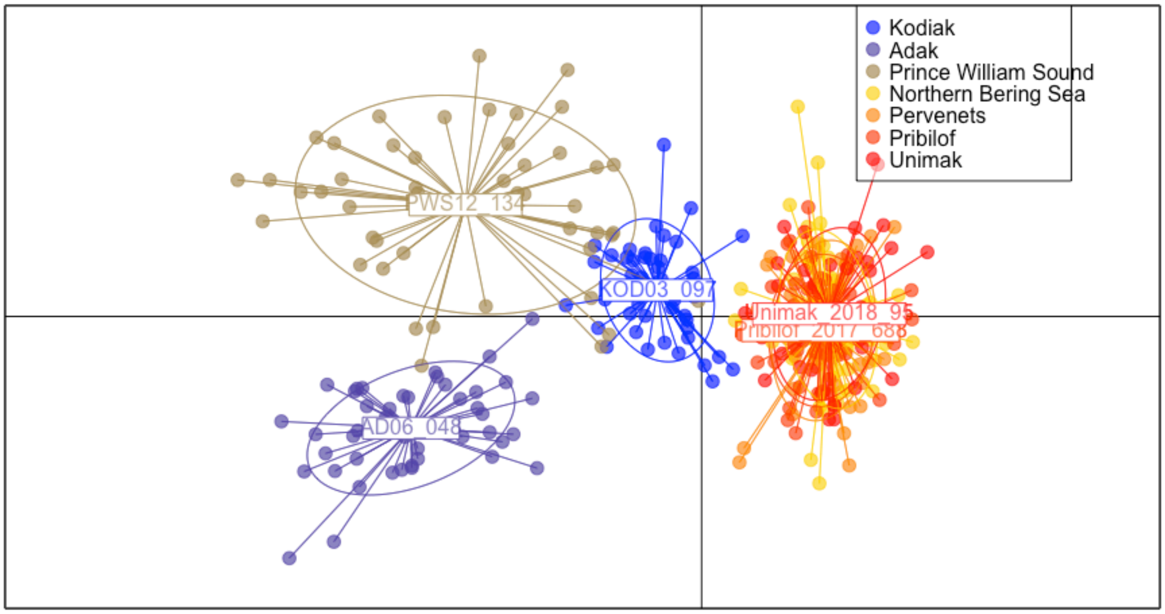
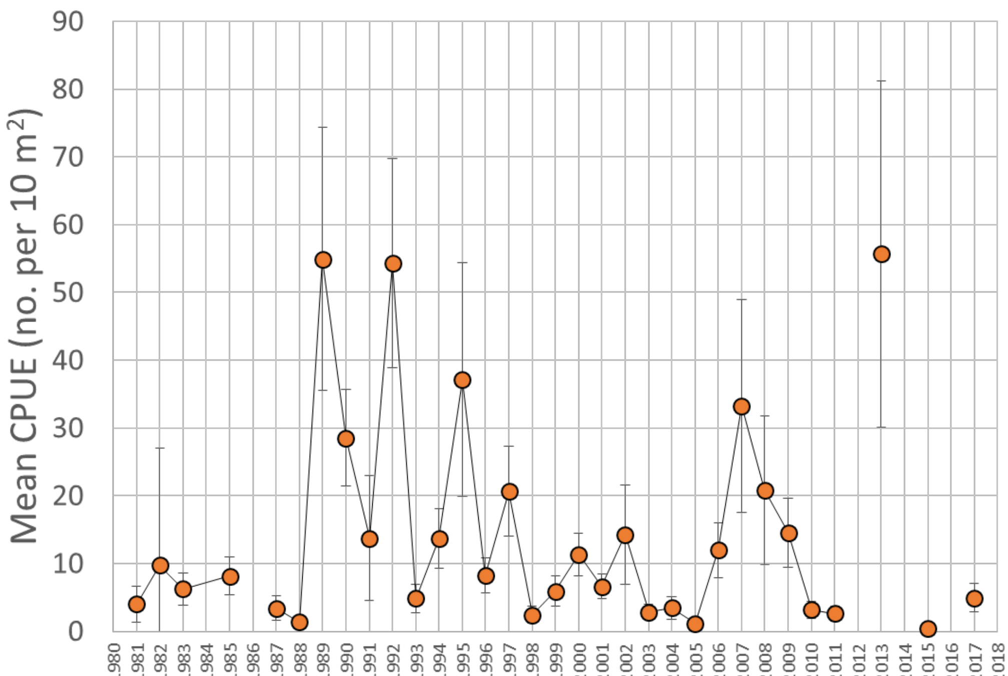


Figure 2.3 Discriminant analysis of principal components (DAPC) scatterplot with the following populations represented: Adak (2006), Prince William Sound, PWS (2012), Kodiak (2003), Unimak (2018), Pervenets (2016), Pribilof (2017), and Norton Sound, NBS (2017). All populations represent spawning groups except the Norton Sound sample, which was sampled in August, 2017. Note: The Norton Sound sample in panel b. is behind the Unimak and Pribilof labels, and barely visible.



.

Figure 2.4. Pacific cod larval abundance from late spring icthyoplankton surveys in the Gulf of Alaska using all stations within a core area covering the Shelikof Sea valley and Semidi bank area.

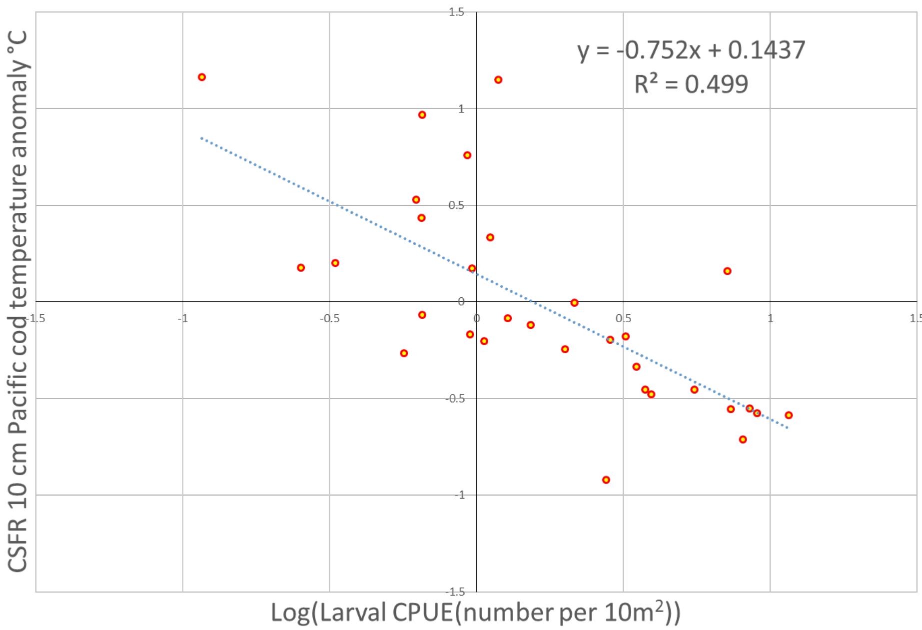


Figure 2.5 Log larval area weighted CPUE from late spring icthyoplankton surveys in the Gulf of Alaska using all stations within a core area covering the Shelikof Sea valley and Semidi bank area by mean annual temperature at 48m bottom depth in the Central GOA from the CFSR reanalysis data.

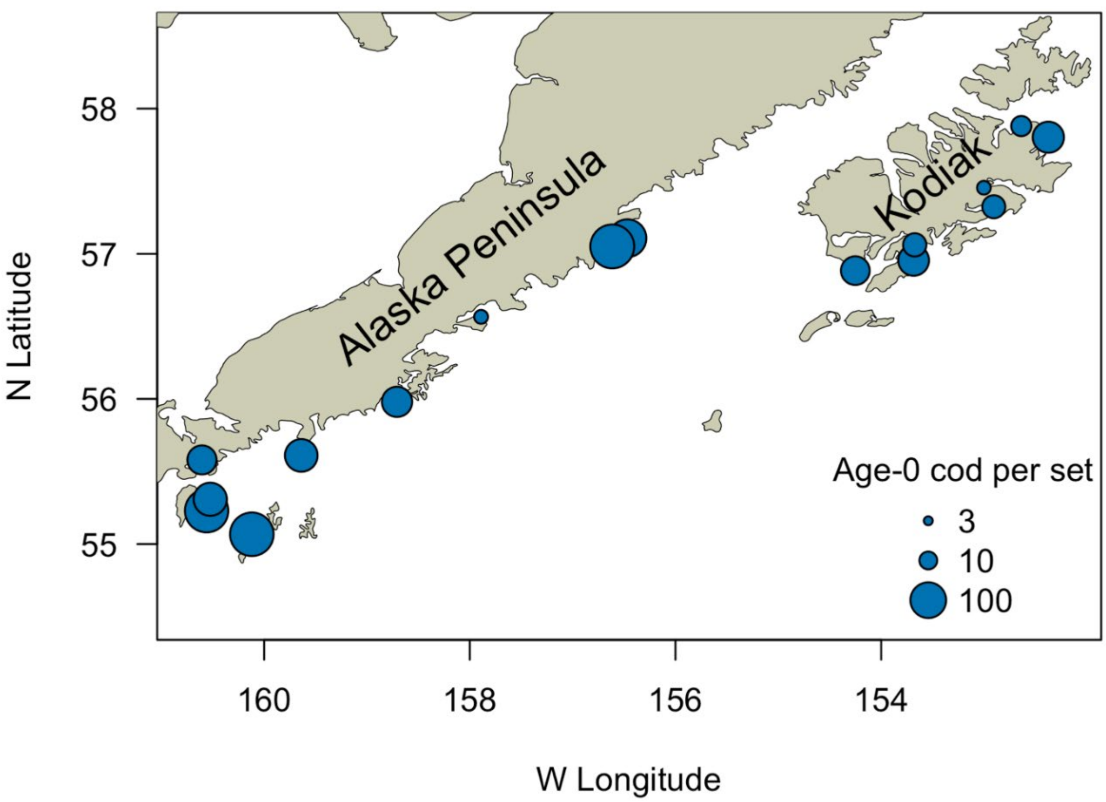


Figure 2.6 Abundance (catch per set, where present) of age-0 cod in beach seines, summer 2018. Each point plots the average abundance for a given bay, with 4-16 individual sets within each bay.

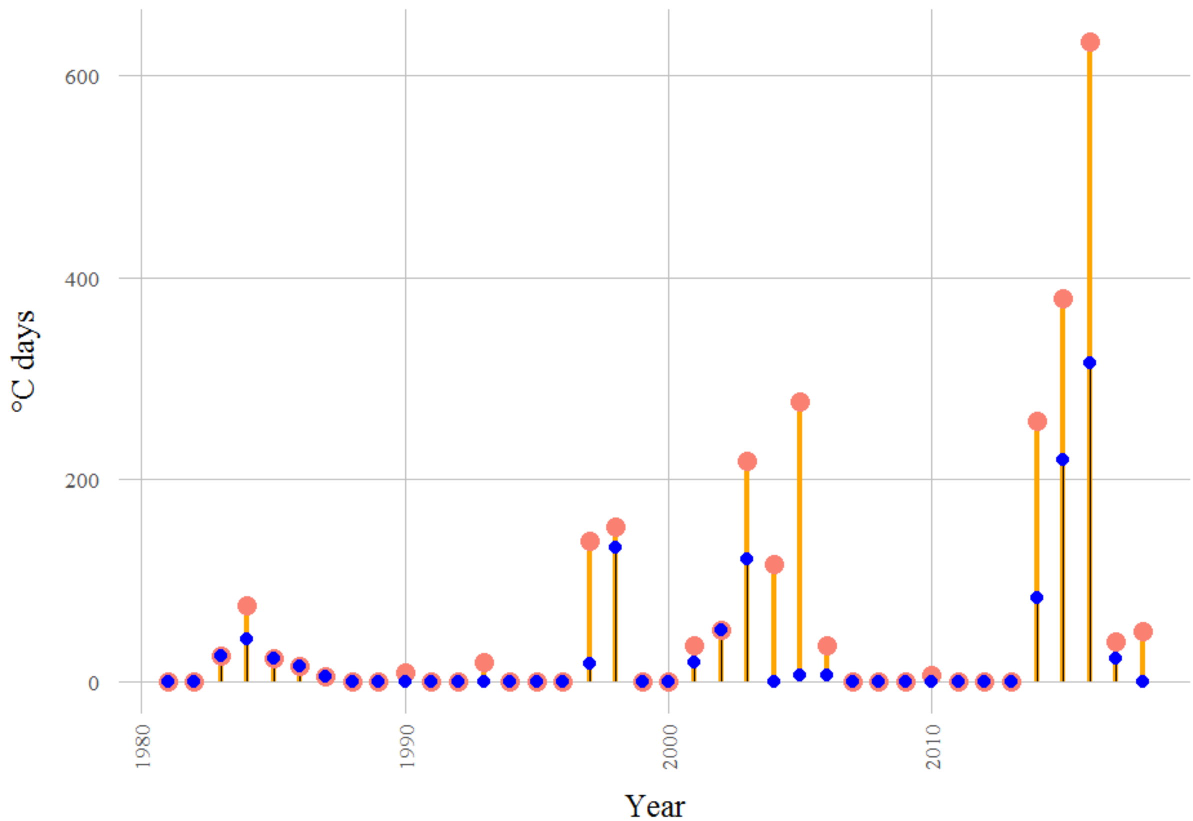


Figure 2.7 Index of the sum of the annual marine heatwave cumulative intensity (℃ days) for 1981-2018 (larger red points) and index of the sum of the annual winter marine heatwave cumulative intensity for 1981-2018 (smaller blue points) from the daily mean sea surface temperatures NOAA high resolution blended analysis data for the Central Gulf of Alaska. The 2018 index value is the sum through 21 October 2018.

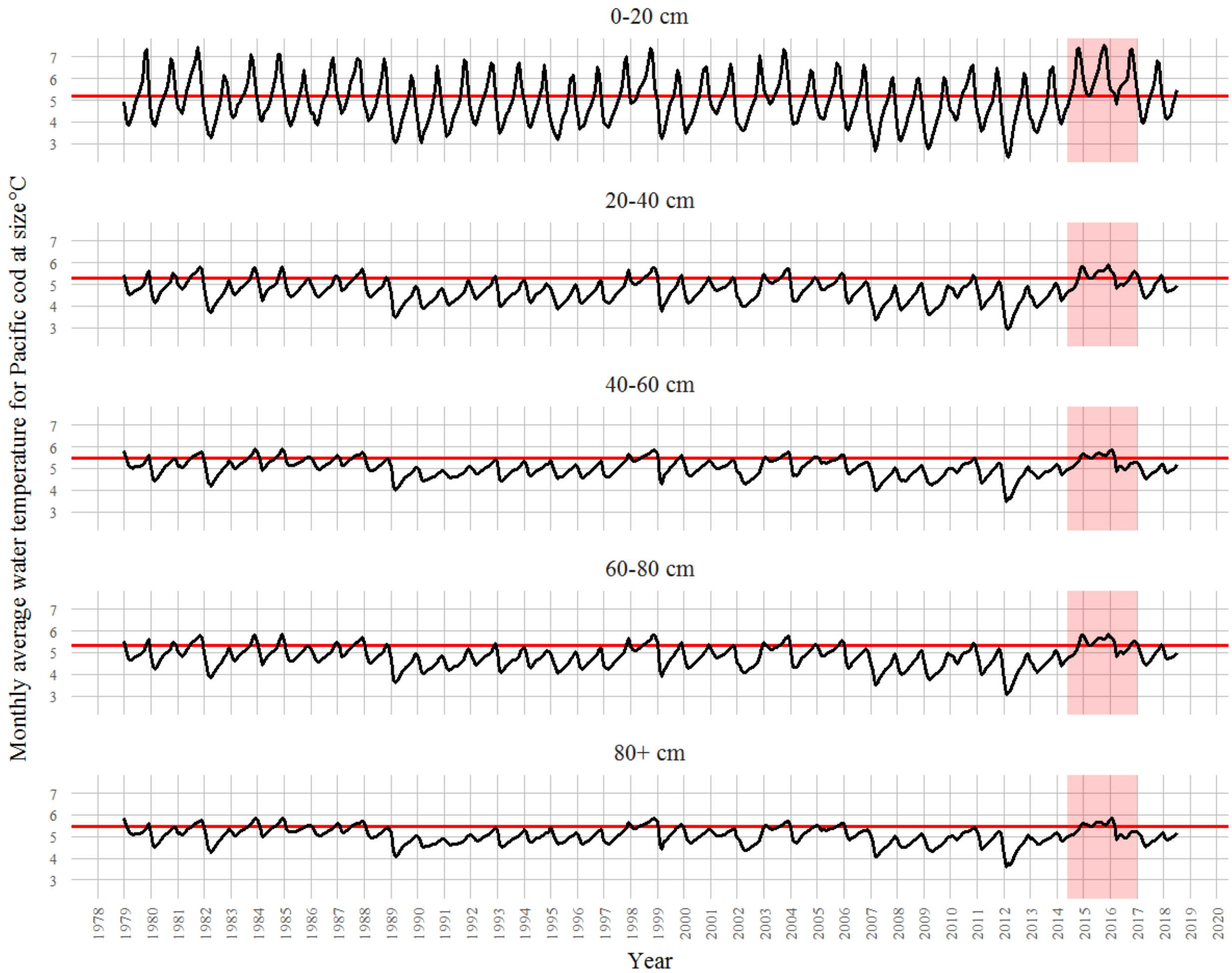


Figure 2.8 Temperature at mean depth of cod grouped by 20 cm size class bins from the Climate Forecast System Reanalysis (CFSR) output. Red lines are the minimum monthly mean temperatures in 2015 encountered by each size bin and the red block indicates the time frame of the 2014-2016 marine heatwave. Plotted through July 2018.

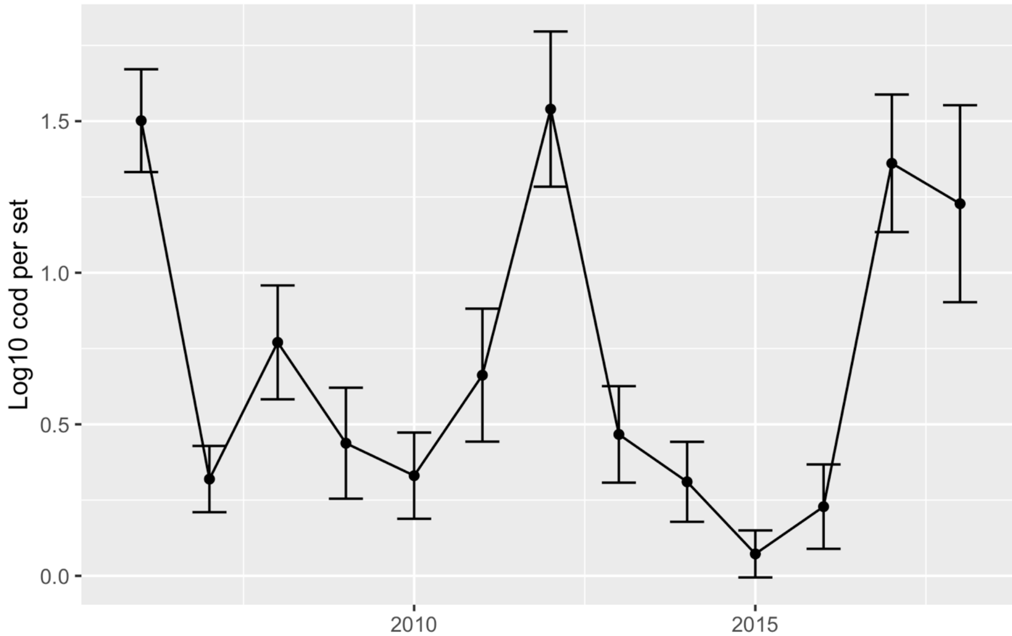


Figure 2.9 Catch per unit effort (log cod per set, including sets where absent) at Kodiak long-term sampling sites, 2006-2018 (mean and 95% CI).

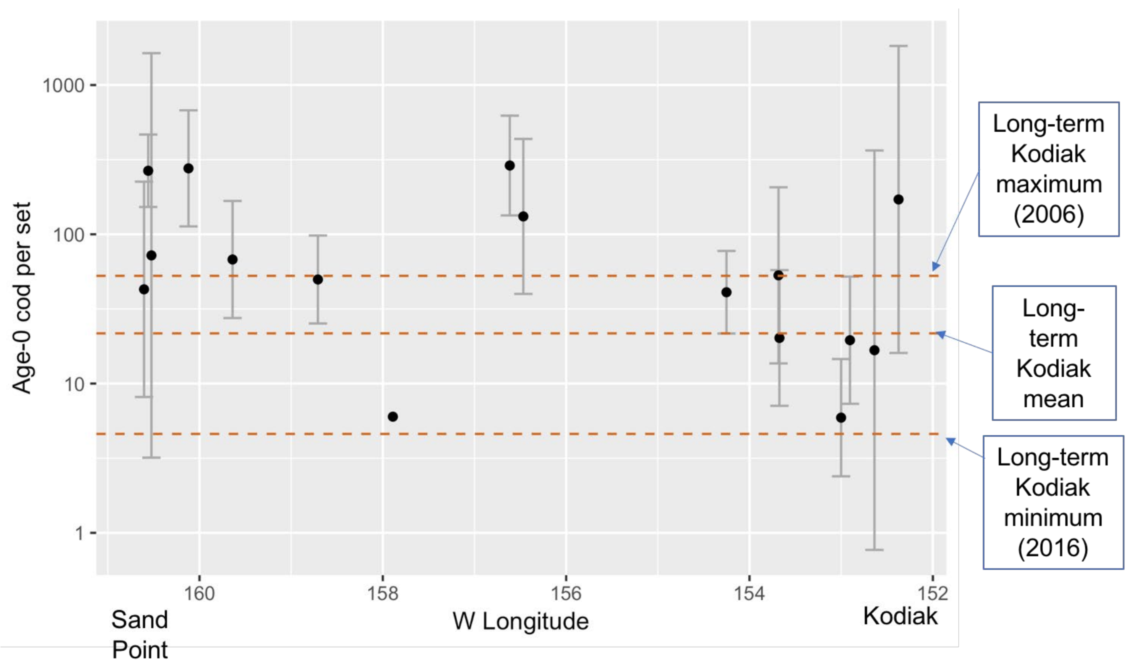


Figure 2.10 Age-0 cod abundance (catch per set, where present) from 2018 western Gulf of Alaska beach seine survey, compared to the range of abundances observed during 2006-2018 NOAA survey of two Kodiak bays. Each point plots mean abundance and 95% confidence intervals for 16 bays sampled in 2018. This very preliminary analysis suggests that the 2018 cohort is strong across the sampling area when compared to the historical range observed around Kodiak.

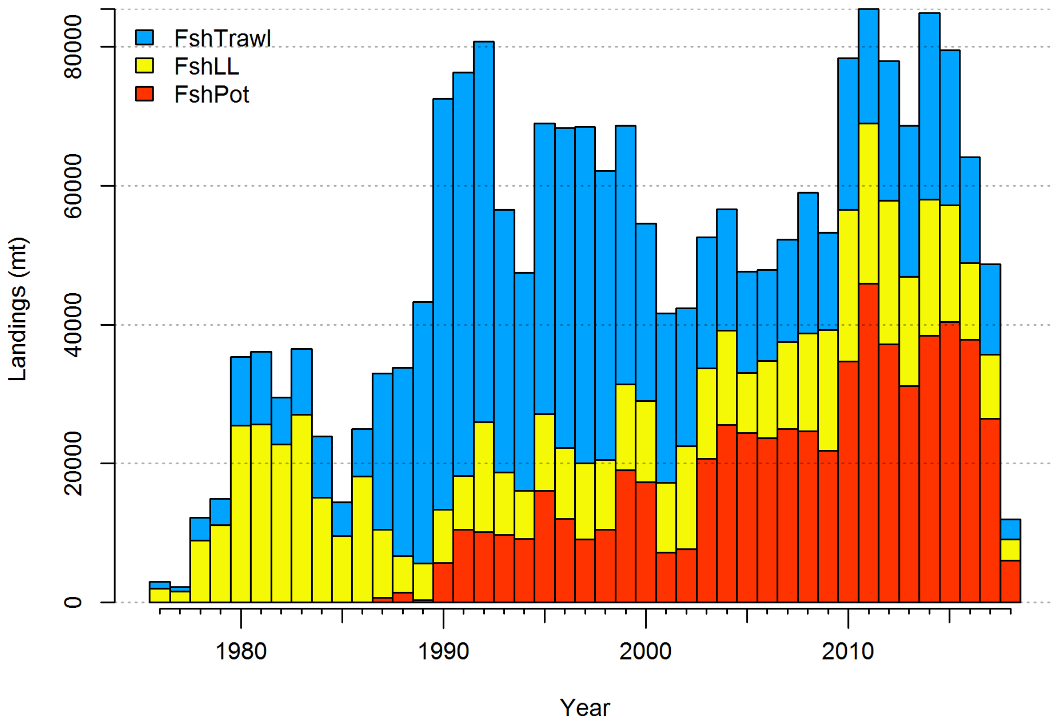


Figure 2.11 Gulf of Alaska Pacific cod catch from 1977-2018. Note that 2018 catch was estimated.

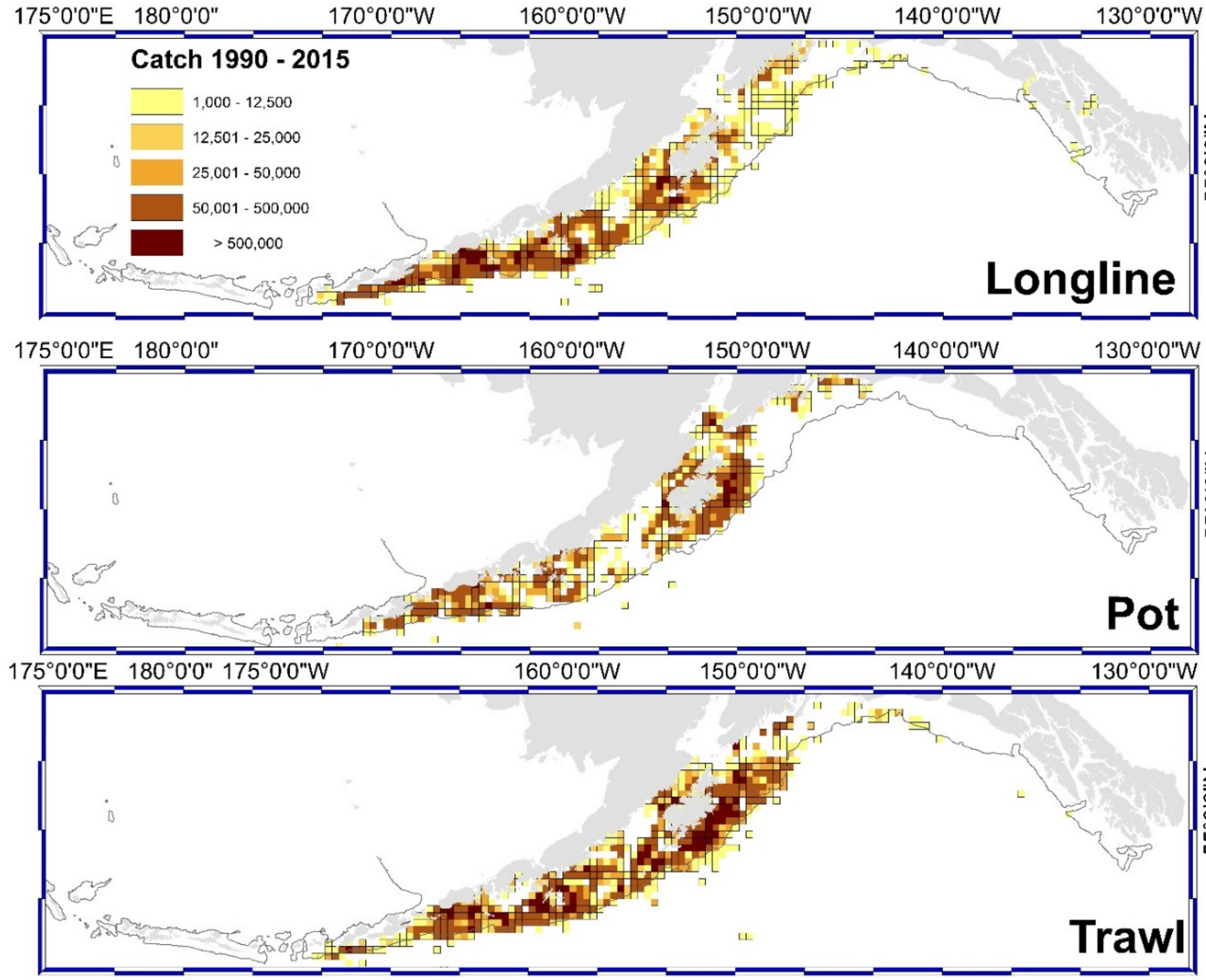


Figure 2.12 Commercial catch of Pacific cod in the Gulf of Alaska by 20km^2 grid for 1990-2015.

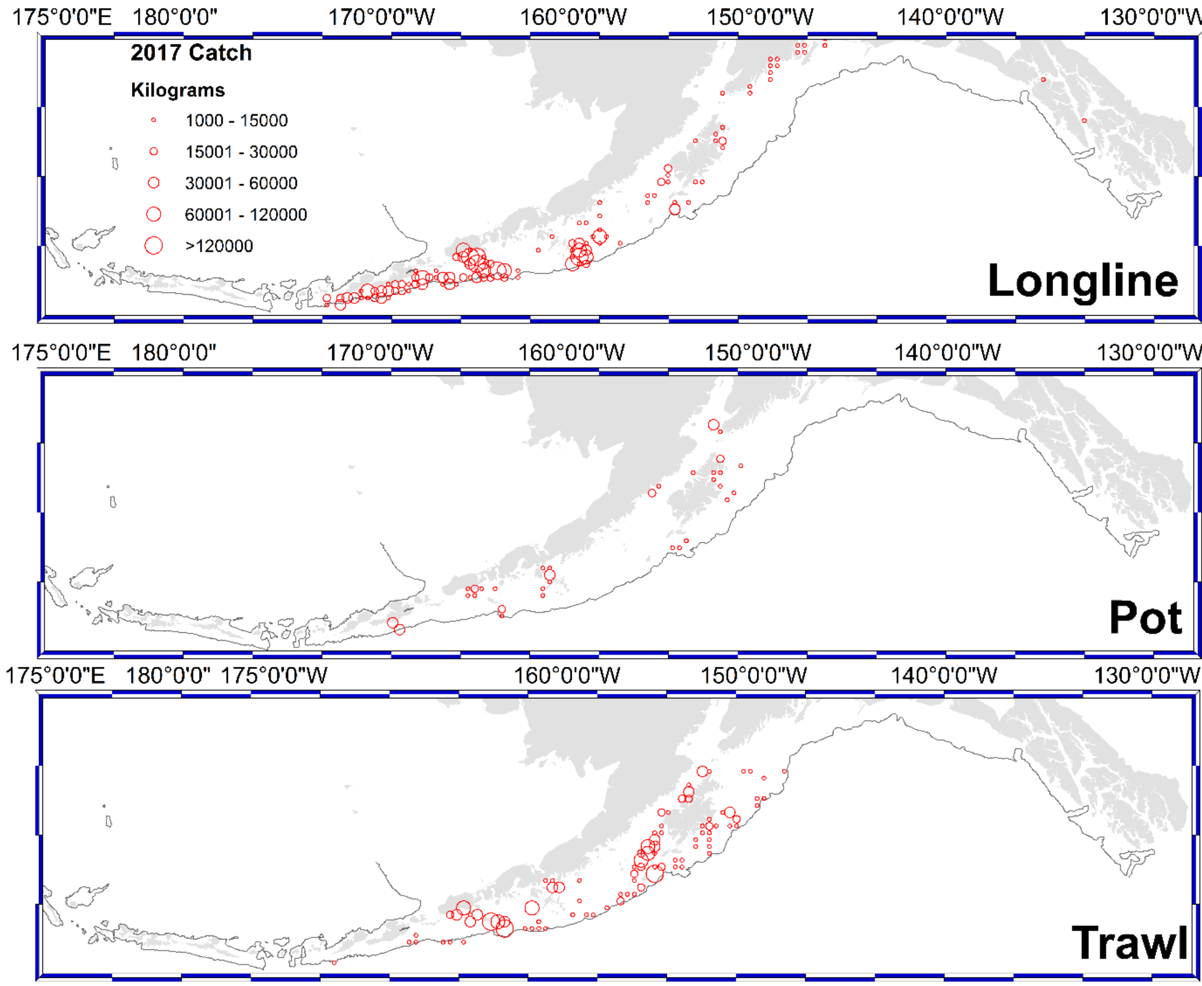


Figure 2.13 Commercial catch of Pacific cod in the Gulf of Alaska by 20km² grid for 2017.

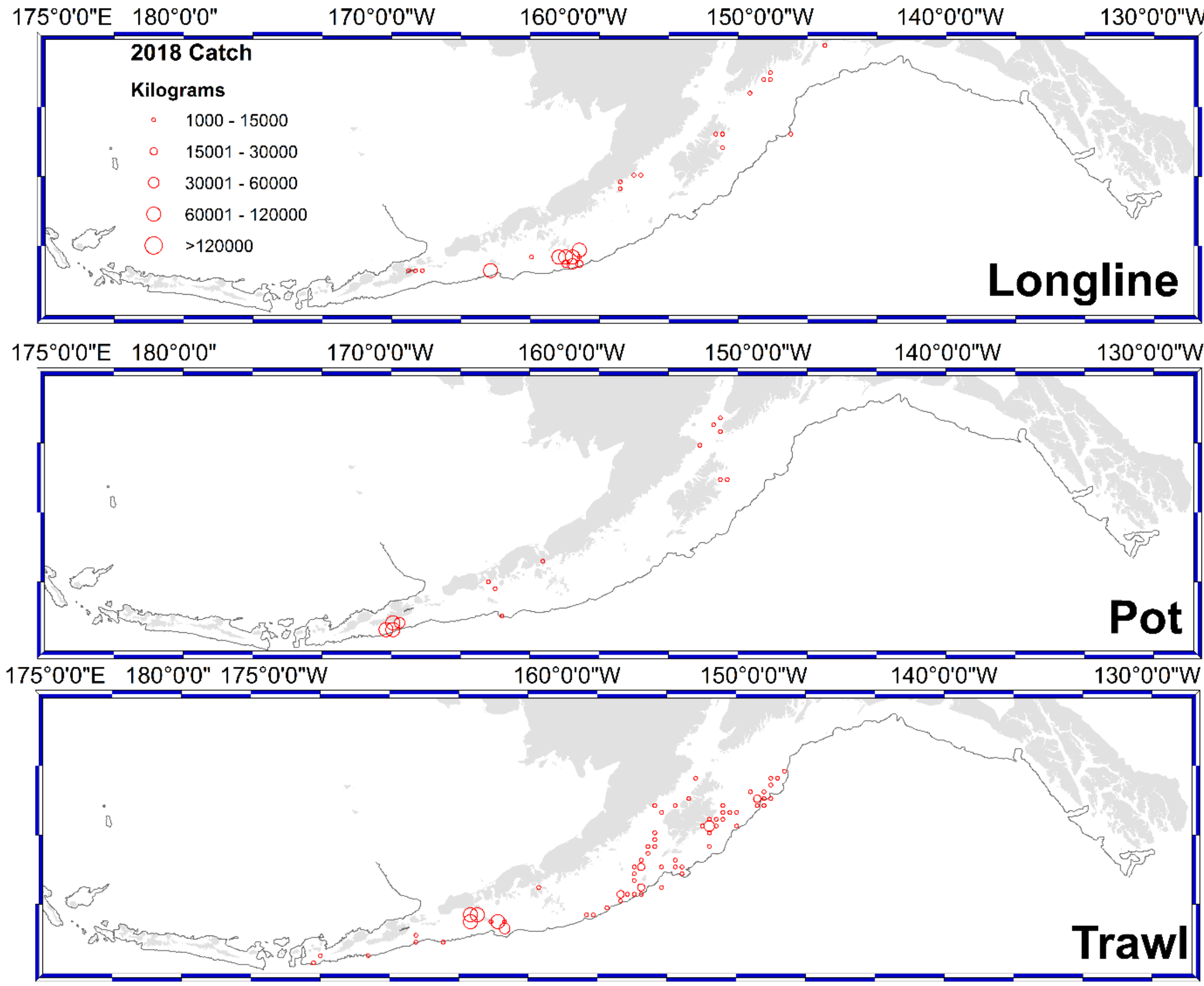


Figure 2.14 Commercial catch of Pacific cod in the Gulf of Alaska by 20km^2 grid for 2018 as of October 17, 2018.

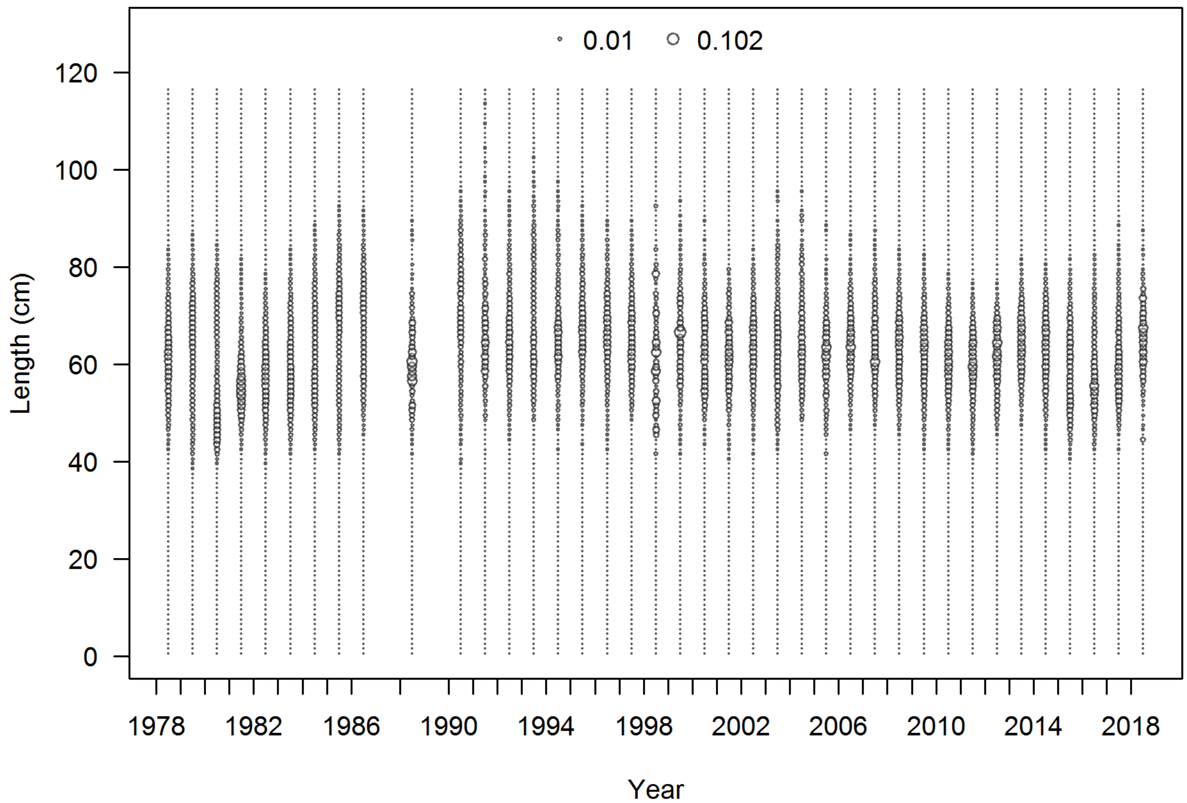


Figure 2.15 Pacific cod length composition by annual proportion from the Gulf of Alaska longline fishery (max=0.102).

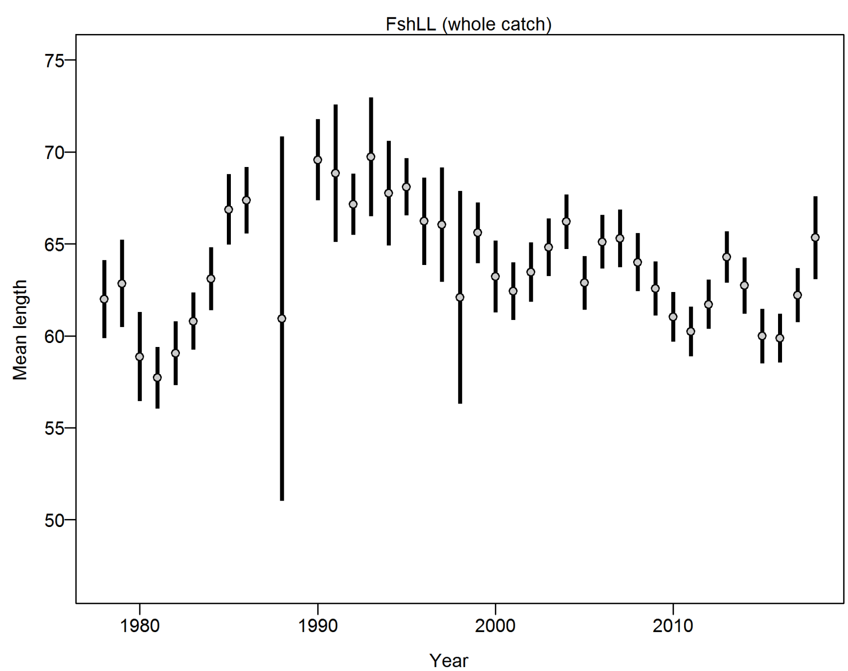


Figure 2.16 Mean length (cm) of Pacific cod from the Gulf of Alaska longline fishery.

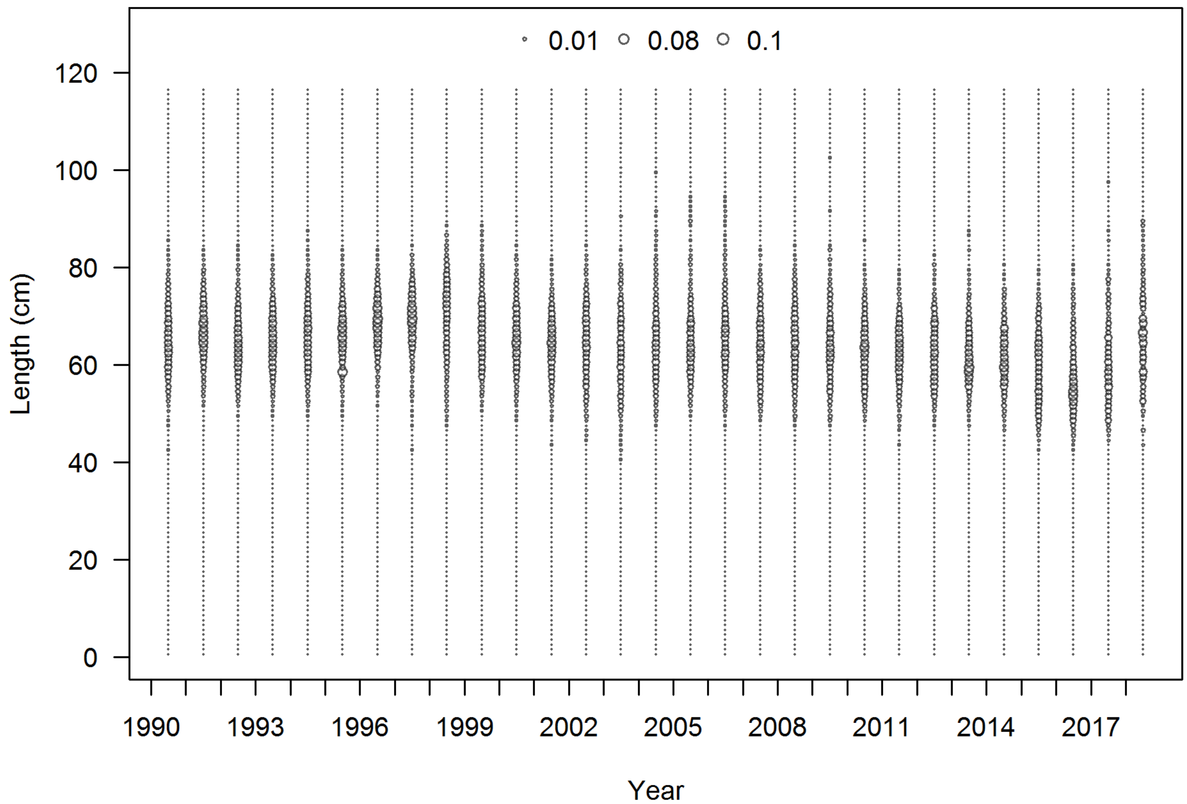


Figure 2.17 Pacific cod length composition by annual proportion from the Gulf of Alaska pot fishery (max=0.1).

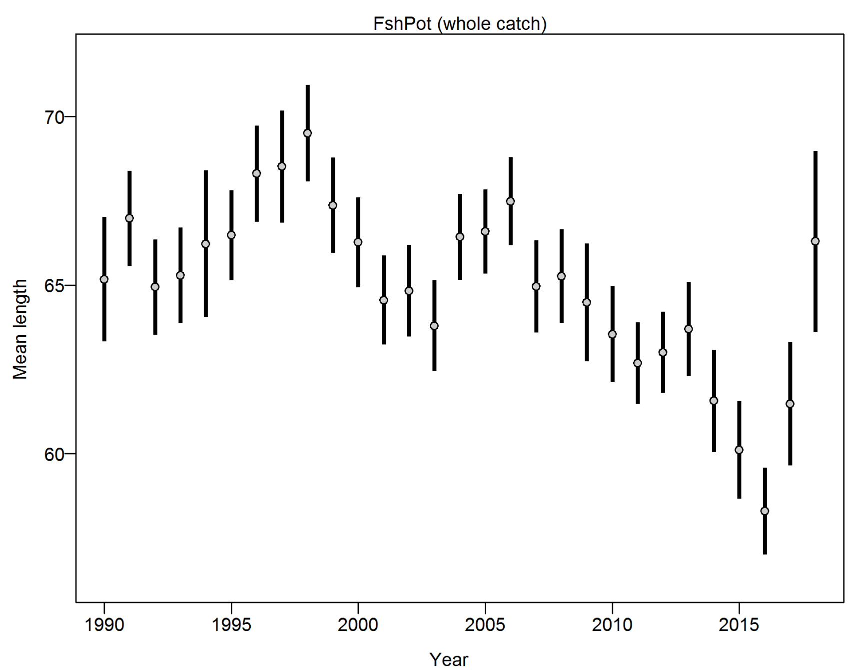


Figure 2.18 Mean length (cm) of Pacific cod from the Gulf of Alaska pot fishery.

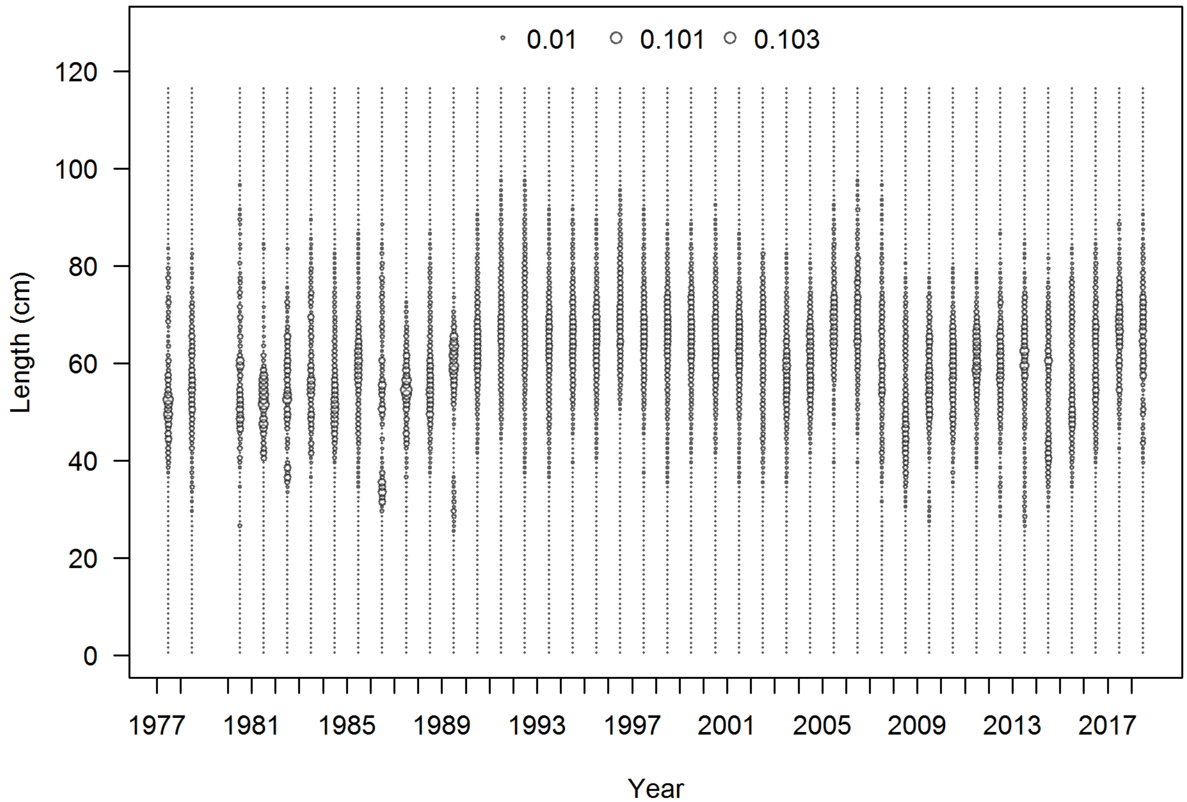


Figure 2.19 Pacific cod length composition by annual proportion from the Gulf of Alaska trawl fishery (max=0.1).

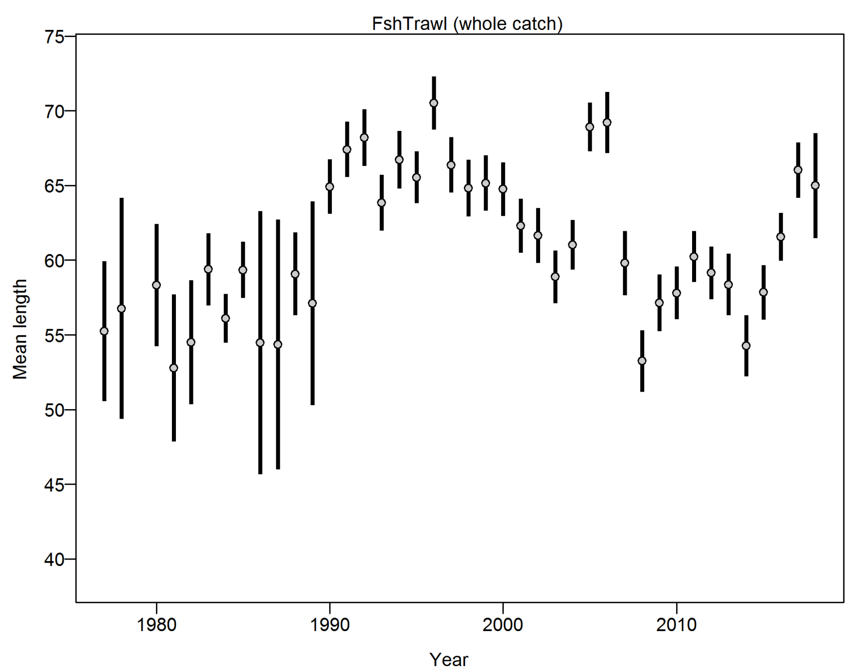


Figure 2.20 Mean length (cm) of Pacific cod from the Gulf of Alaska trawl fishery.

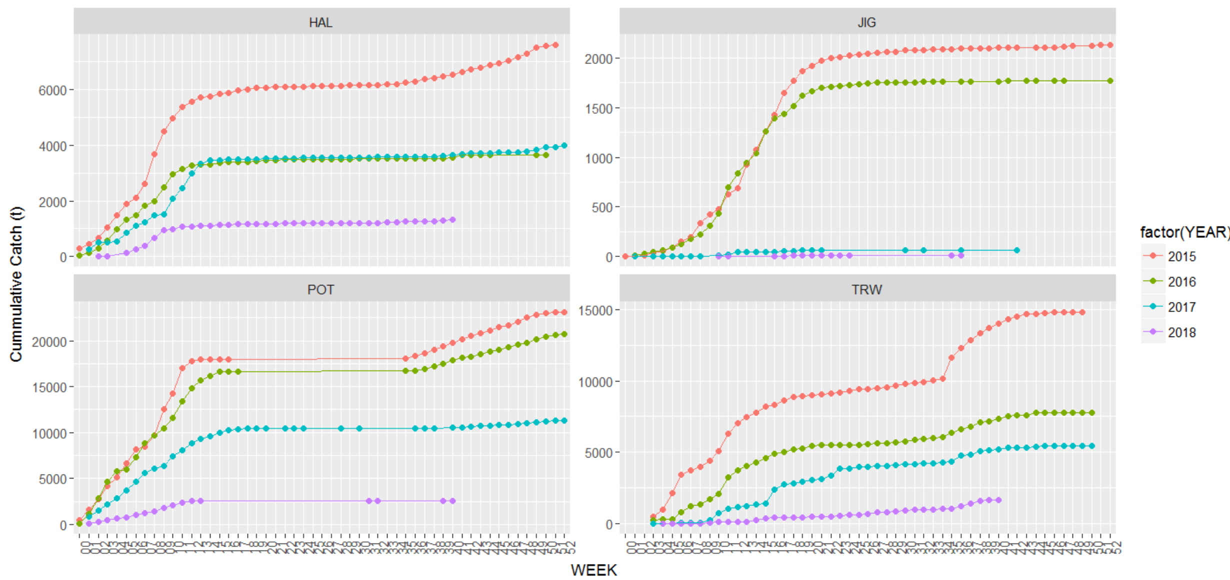


Figure 2.21 Cumulative catch by week of the year and gear for 2015-2018 in the Central regulatory area. 2017 data are through October 17, 2018.

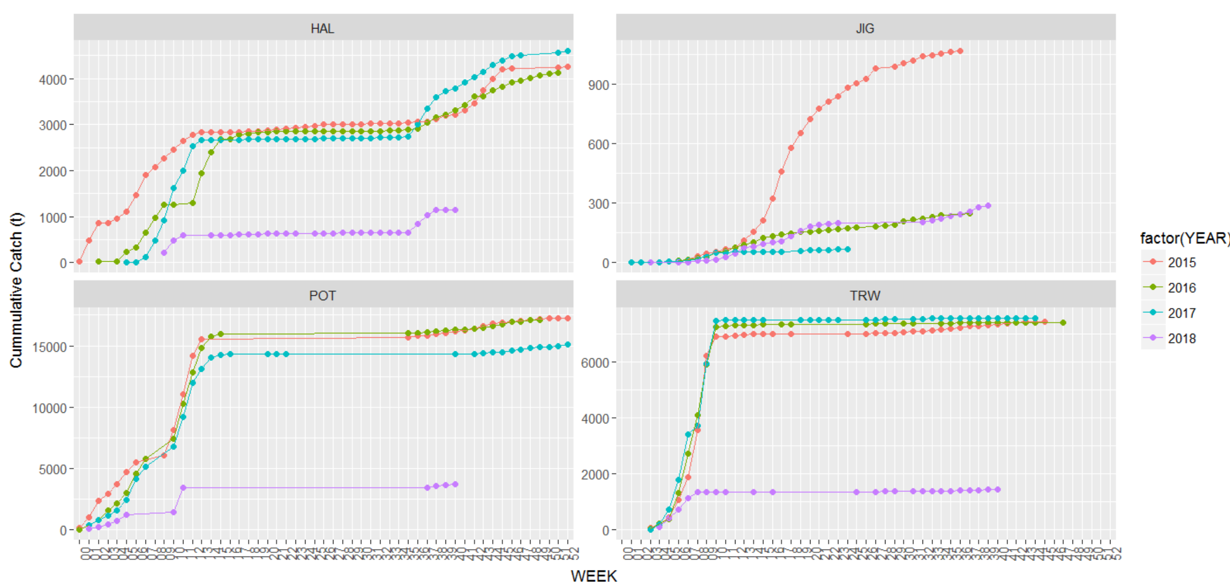


Figure 2.22 Cumulative catch by week of the year and gear for 2015-2018 in the Western regulatory area. The 2018 data are through October 17, 2018.

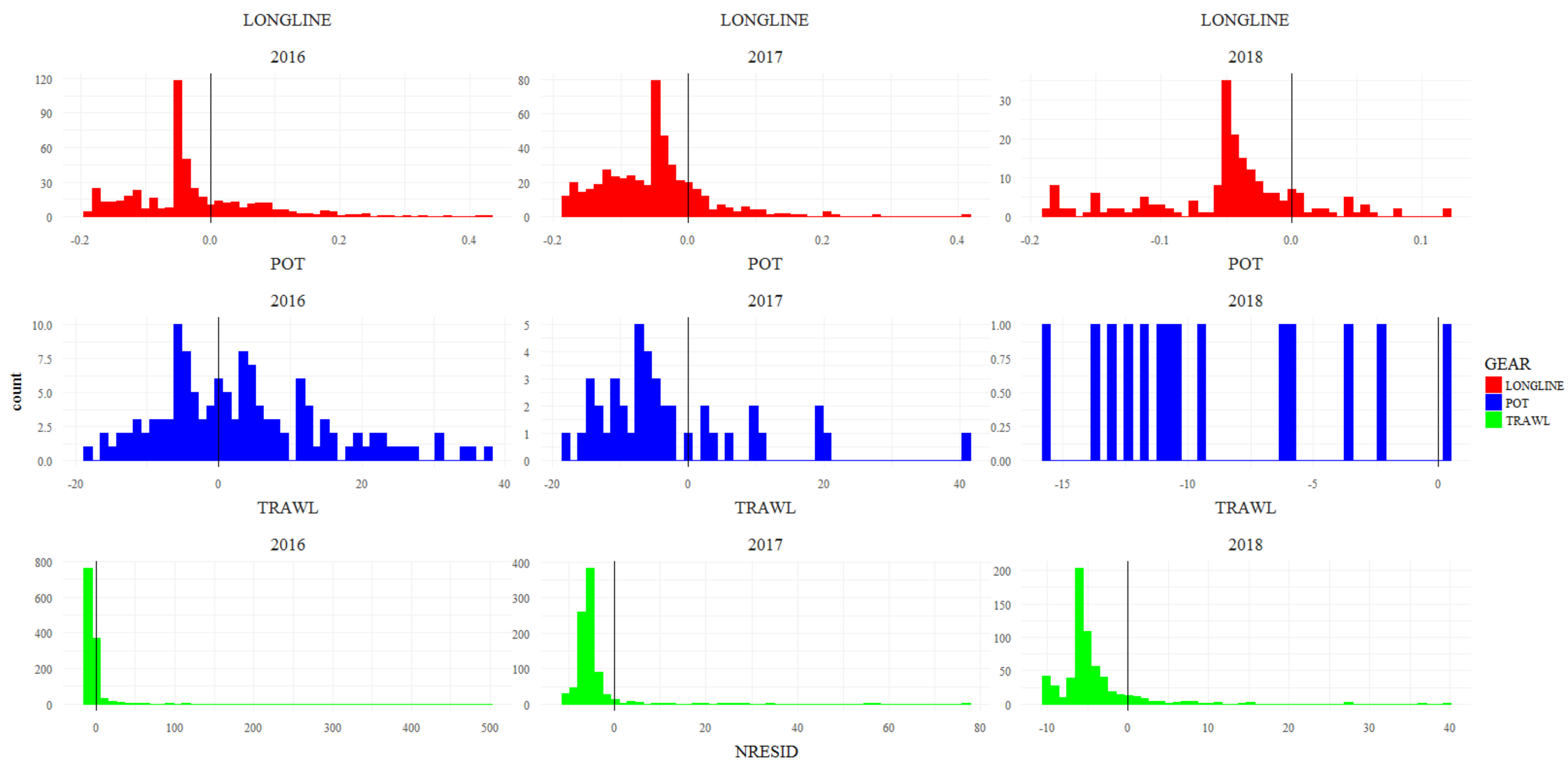


Figure 2.23 Central regulatory area distribution of residual CPUE by number of hauls from the 2015-2018 January-August directed cod fishery in longline (top; catch per hook), pot (middle; catch per pot), and trawl (bottom; catch per minute) fisheries. The time series used for average was 2008-2018. Note that both x and y axis differ among graphs.

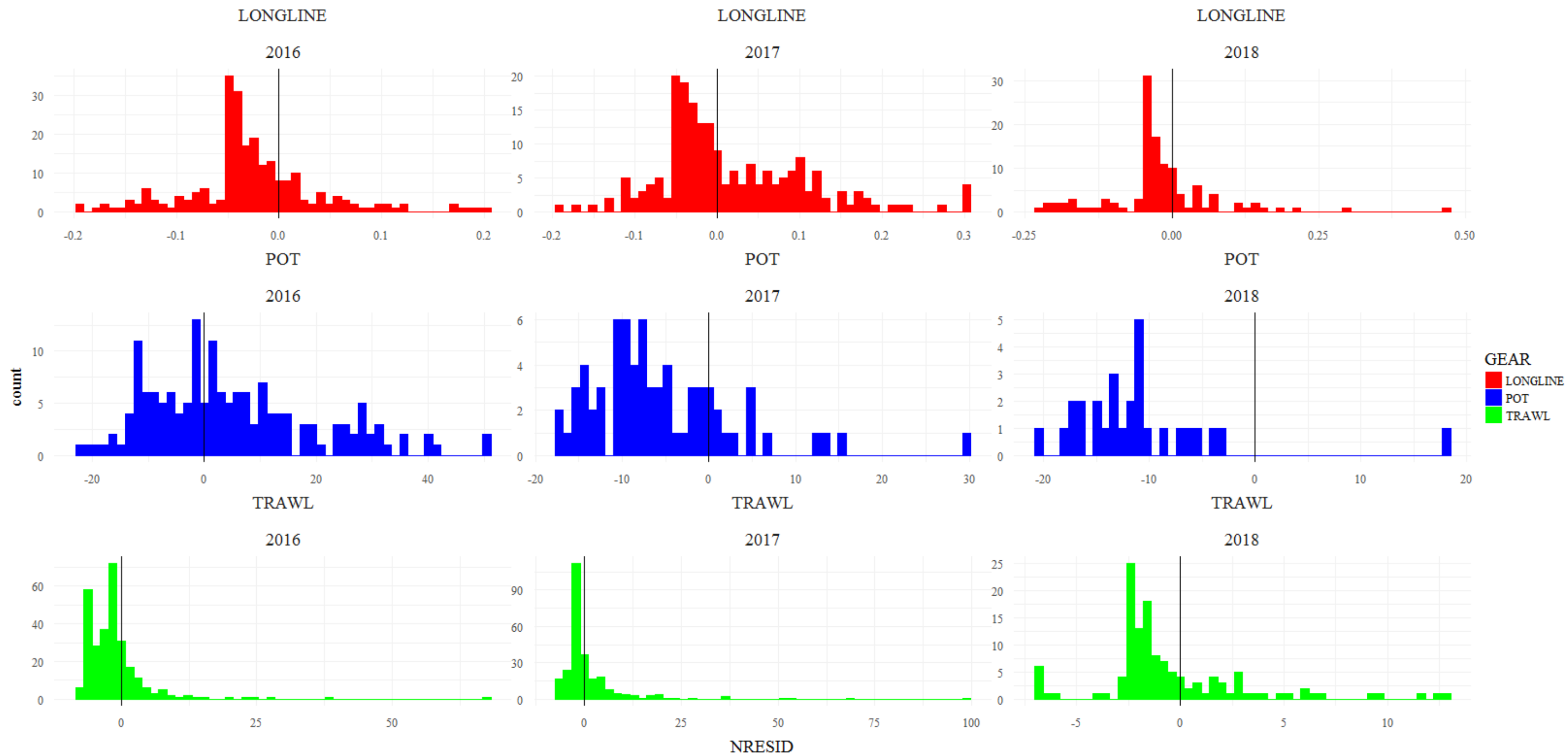


Figure 2.24 Western regulatory area distribution of residual CPUE by number of hauls from the 2015-2018 January-August directed cod fishery in longline (top; catch per hook), pot (middle; catch per pot), and trawl (bottom; catch per minute) fisheries. The time series used for average was 2008-2018. Note that both x and y axis differ among graphs.

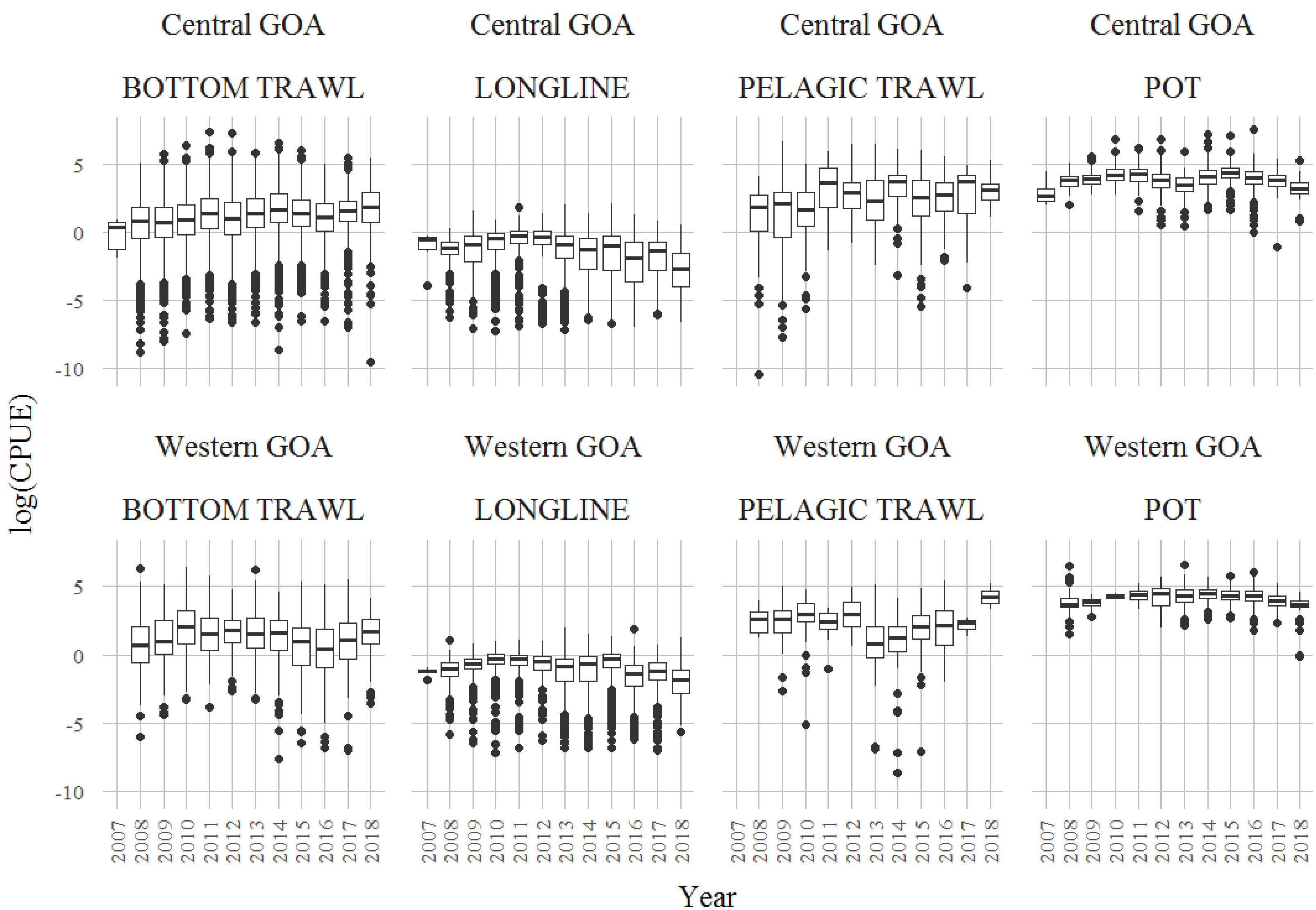


Figure 2.25 Boxplot of CPUE by number from the 2007-2018 Pacific cod CPUE for January-April for the Central (top) and Western (bottom) regulatory areas. Note that the data in these figures are not controlled for vessel or gear differences within a gear type across time, but shows the raw CPUE data distribution. These represent all catches and is not limited to the directed cod fishery.

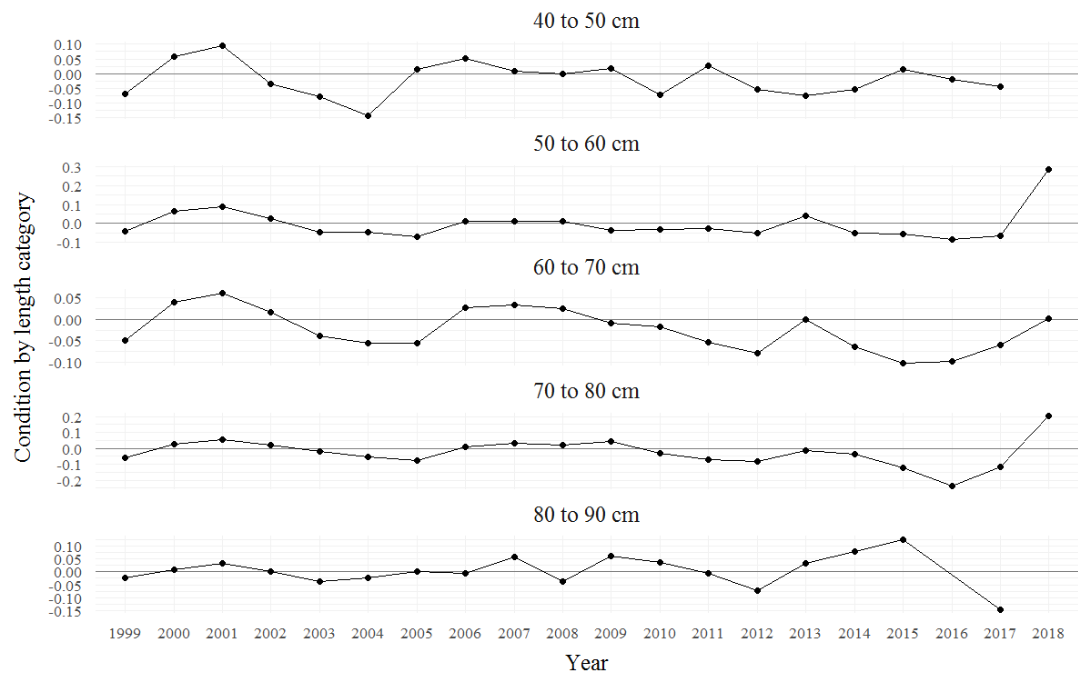


Figure 2.26 Condition of Pacific cod by length category and year in the Central GOA for the longline A-season fisheries (January-April).

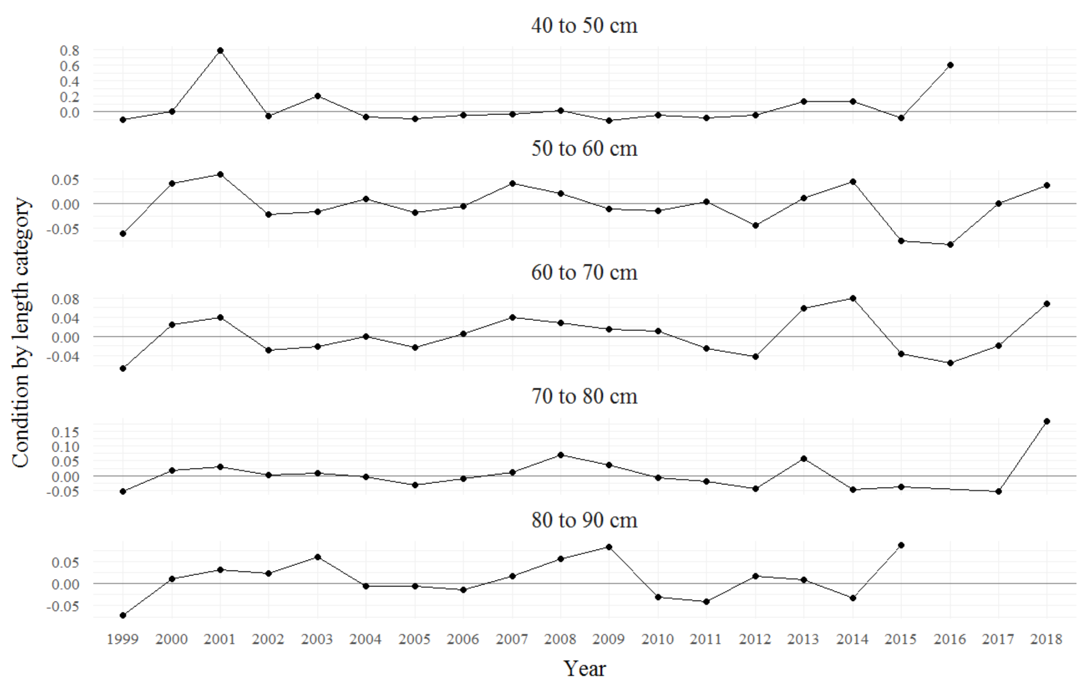


Figure 2.27 Condition of Pacific cod by length category and year in the Central GOA for the pot A-season fisheries (January-April).

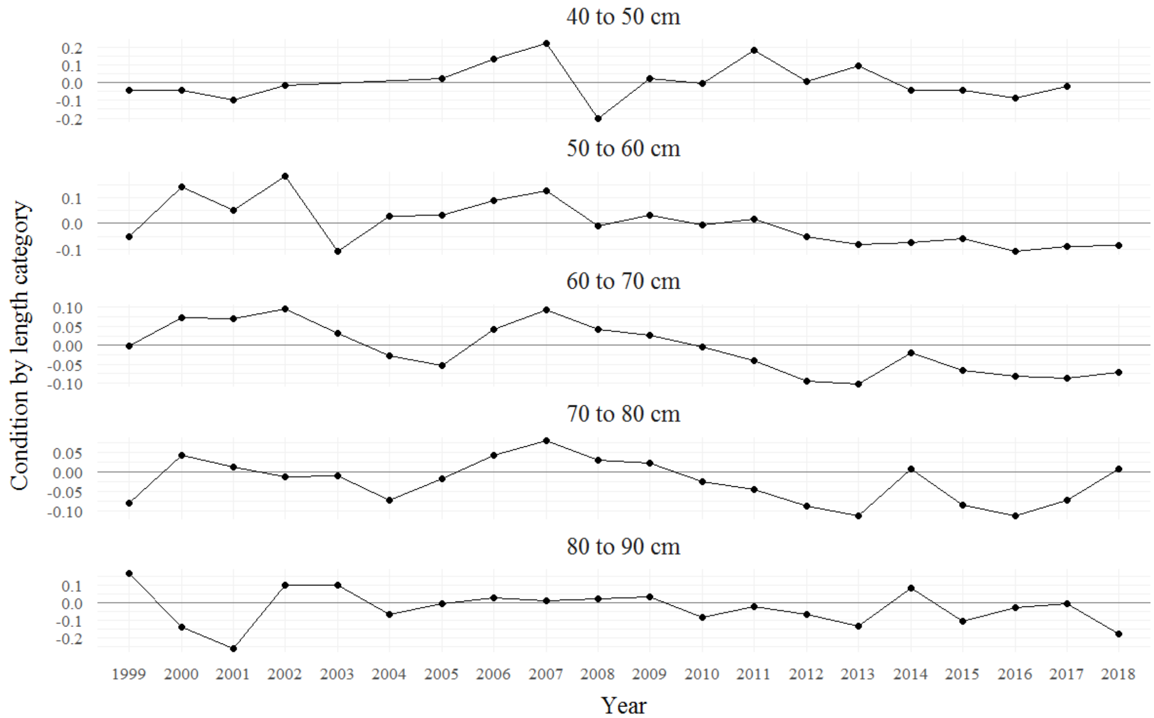


Figure 2.28 Condition of Pacific cod by length category and year in the Western GOA for the longline A-season fisheries (January-April).

Figure 2.29 Condition of Pacific cod by length category and year in the Western GOA for pot A-season fisheries (January-April).

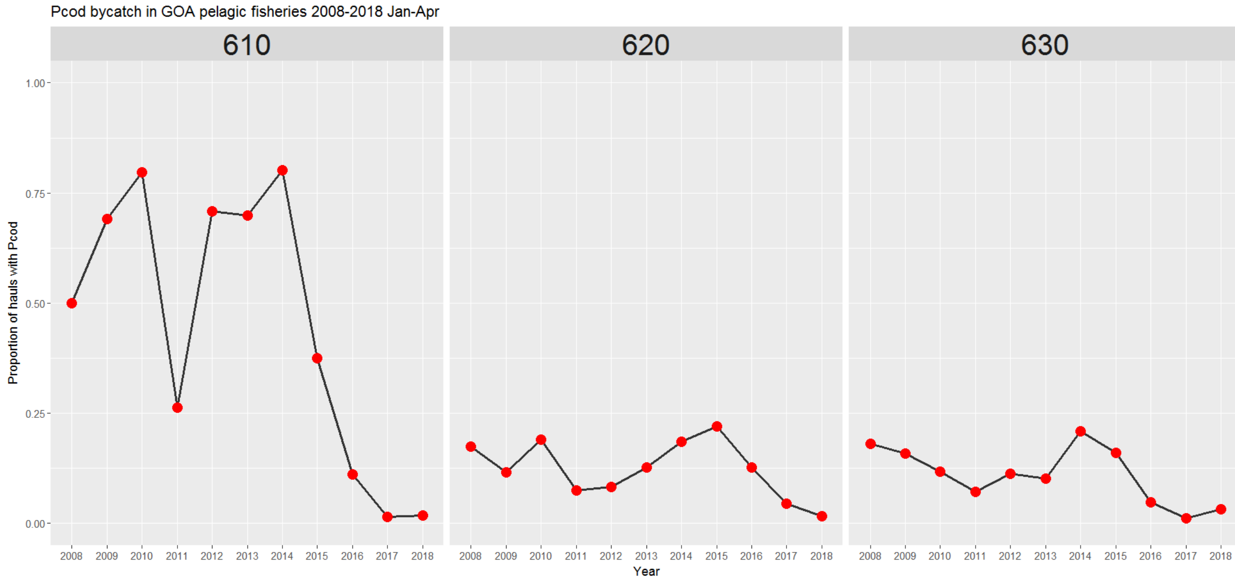


Figure 2.30 Proportion of pelagic trawls in the A Season (January-April) walleye pollock fishery with Pacific cod present by region.

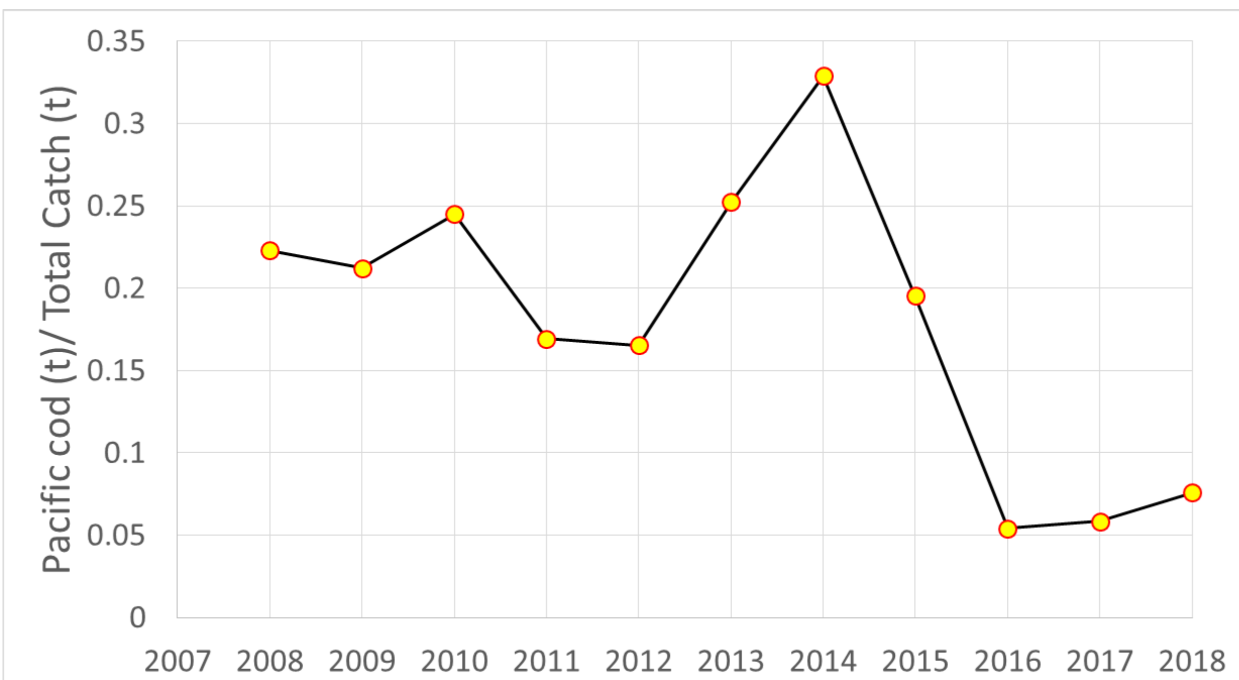


Figure 2.31 Pacific cod bycatch in the Gulf of Alaska shallow water flatfish fishery as tons of Pacific cod per tons of total catch in the fishery by year.

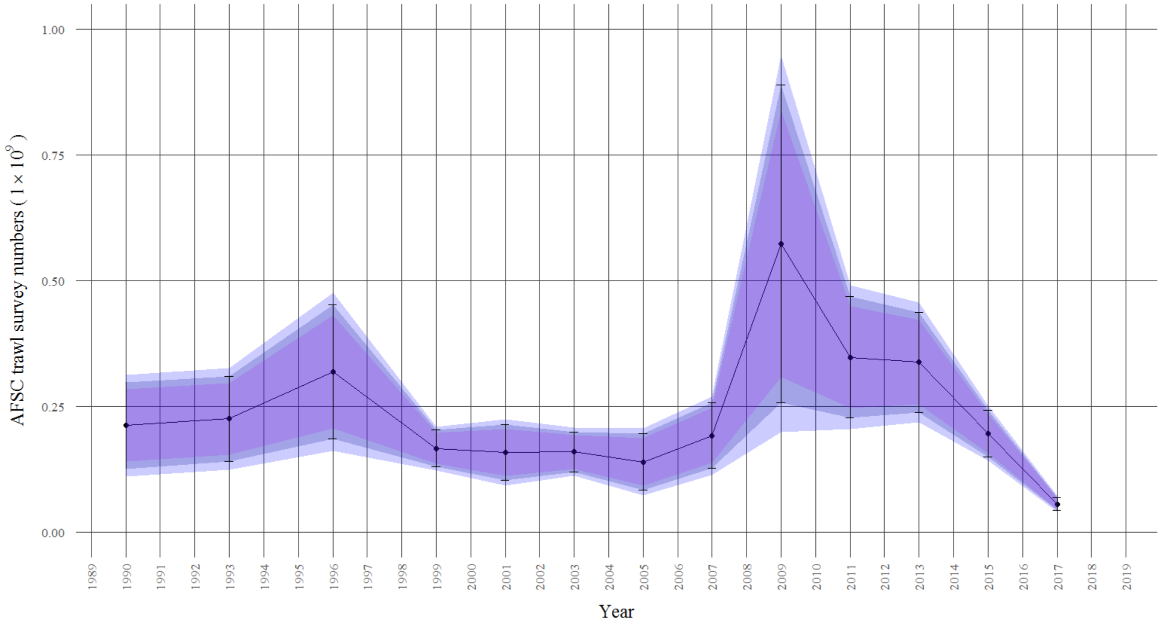


Figure 2.32 GOA bottom trawl survey abundance (numbers) estimate. Bars indicate the 95th percentile confidence intervals, the color changes from 99th percentile (light), 95th percentile (medium) to 90th percentile (darkest) confidence intervals.

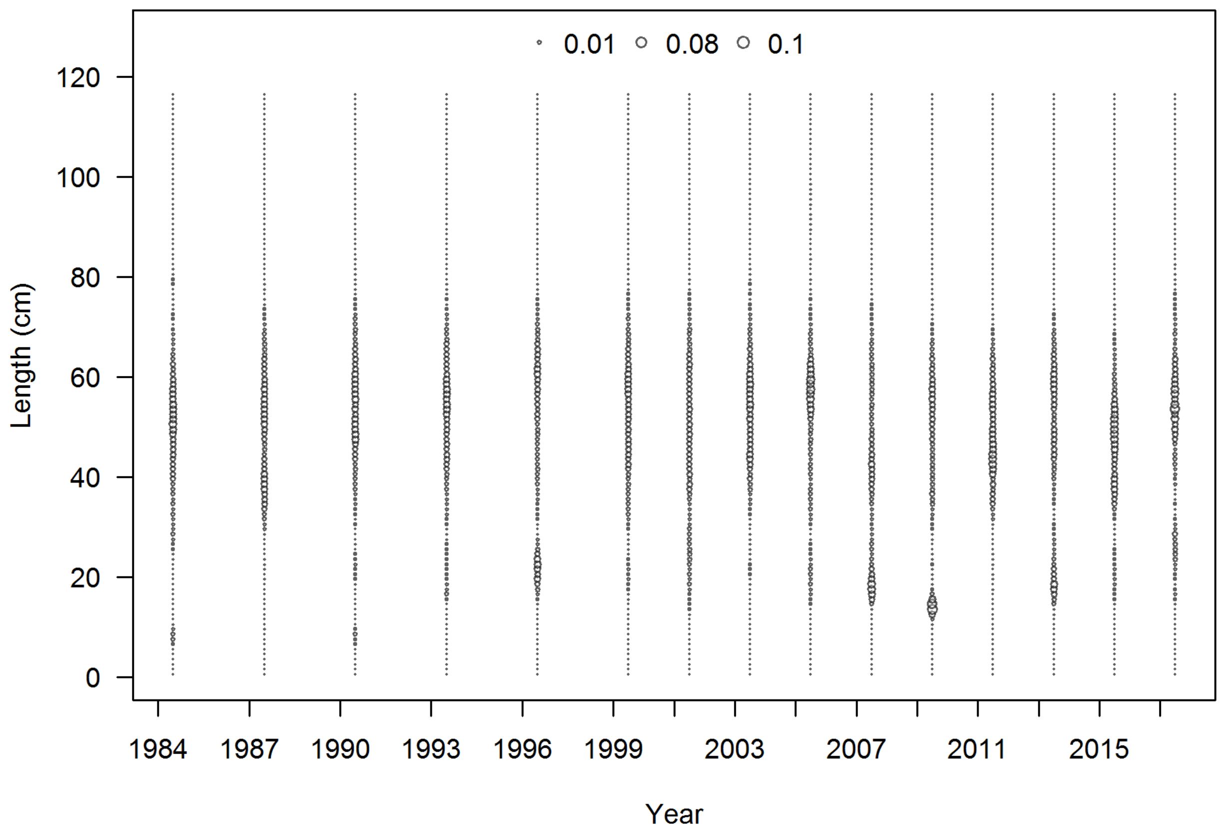


Figure 2.33 GOA bottom trawl survey Pacific cod population numbers at length estimates (max =0.07).

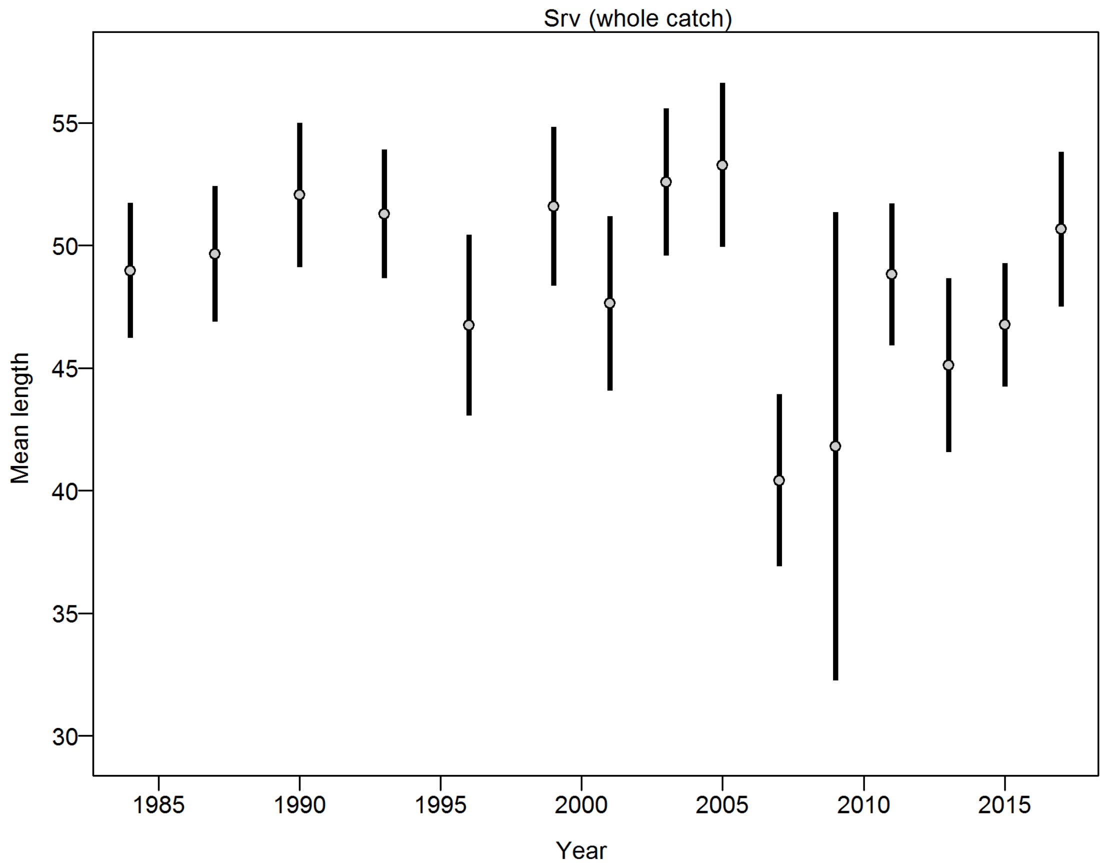


Figure 2.34 Mean length (cm) of Pacific cod in the GOA bottom trawl survey.

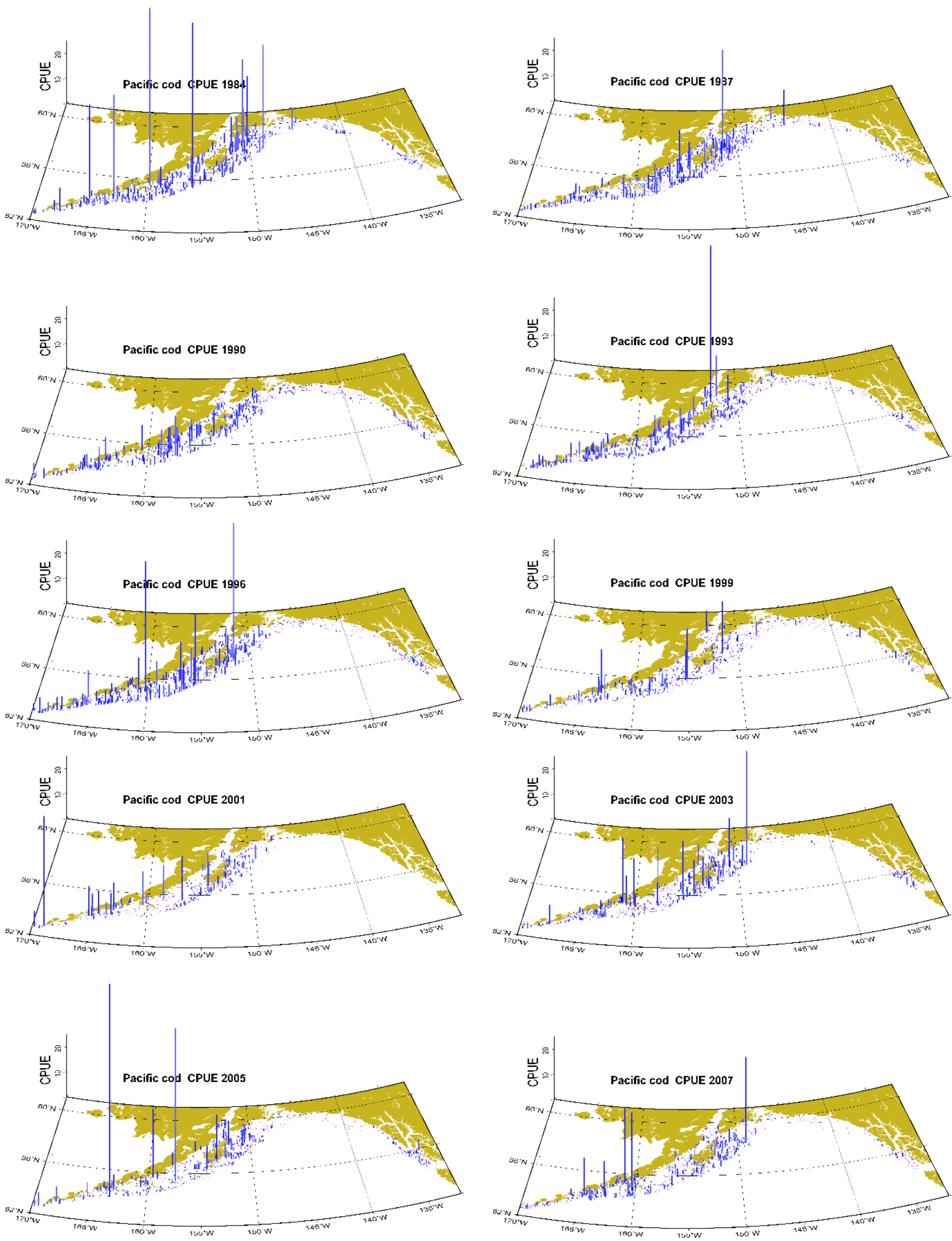


Figure 2.35 Distribution of AFSC bottom trawl survey CPUE of Pacific cod.

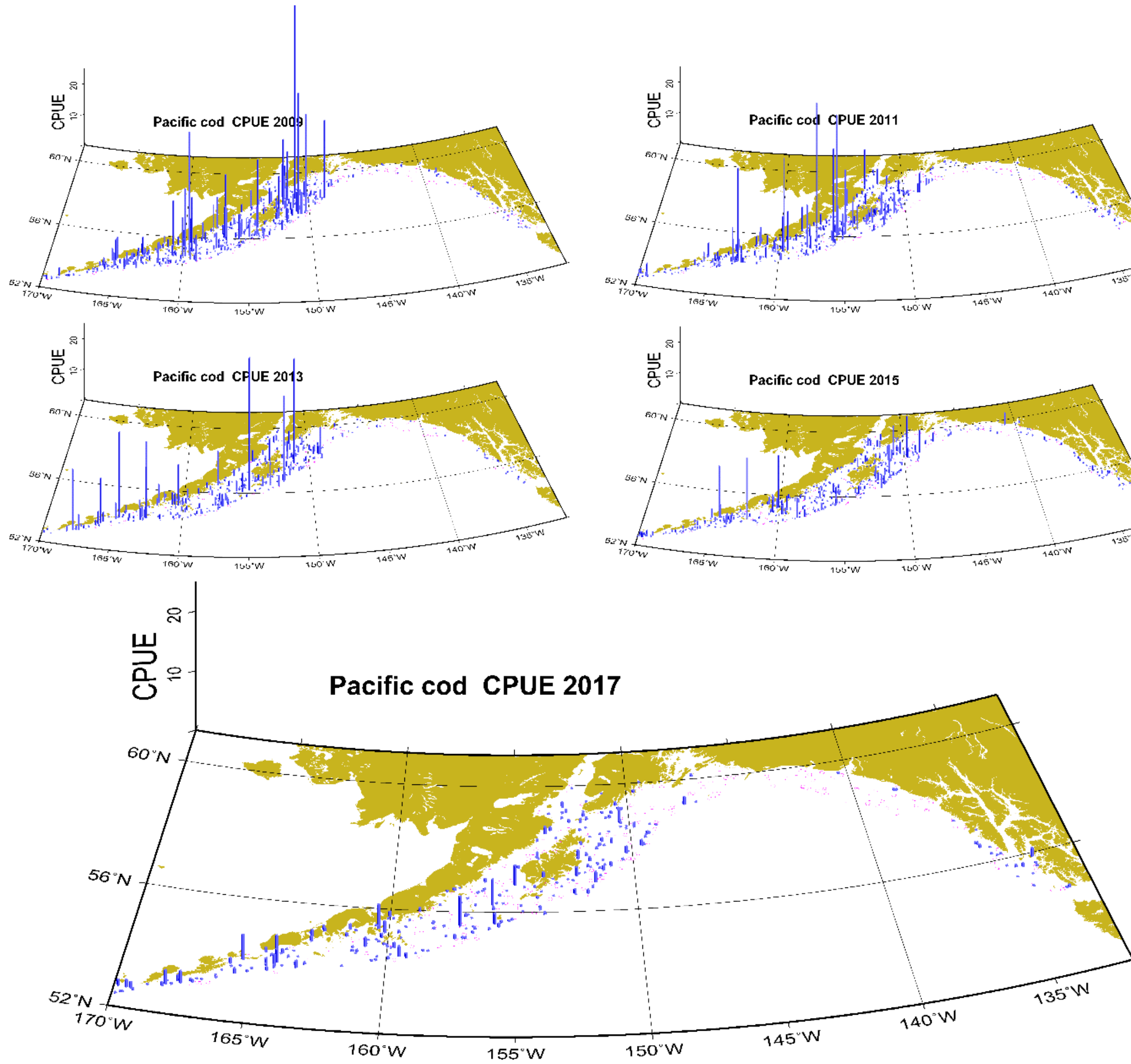


Figure 2.35 Cont. Distribution of AFSC bottom trawl survey CPUE of Pacific cod.

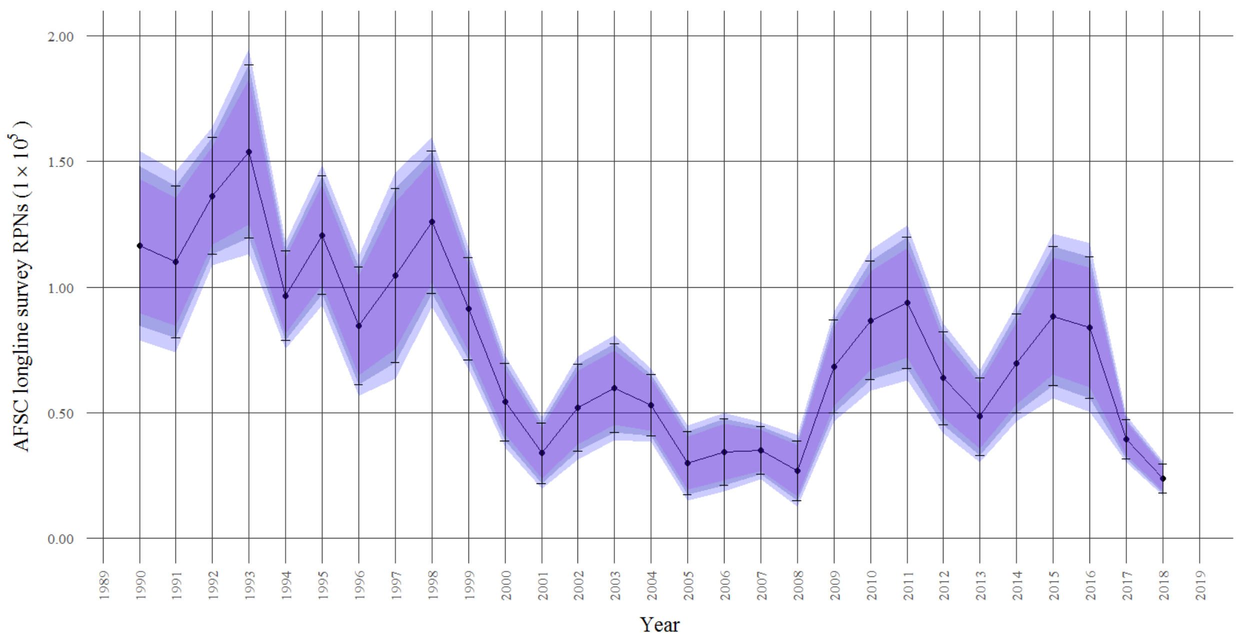


Figure 2.36AFSC longline survey Pacific cod relative population numbers (RPN) time series. Bars indicate the 95th percentile confidence intervals, the color changes from 99th percentile (light), 95th percentile (medium) to 90th percentile (darkest) confidence intervals.

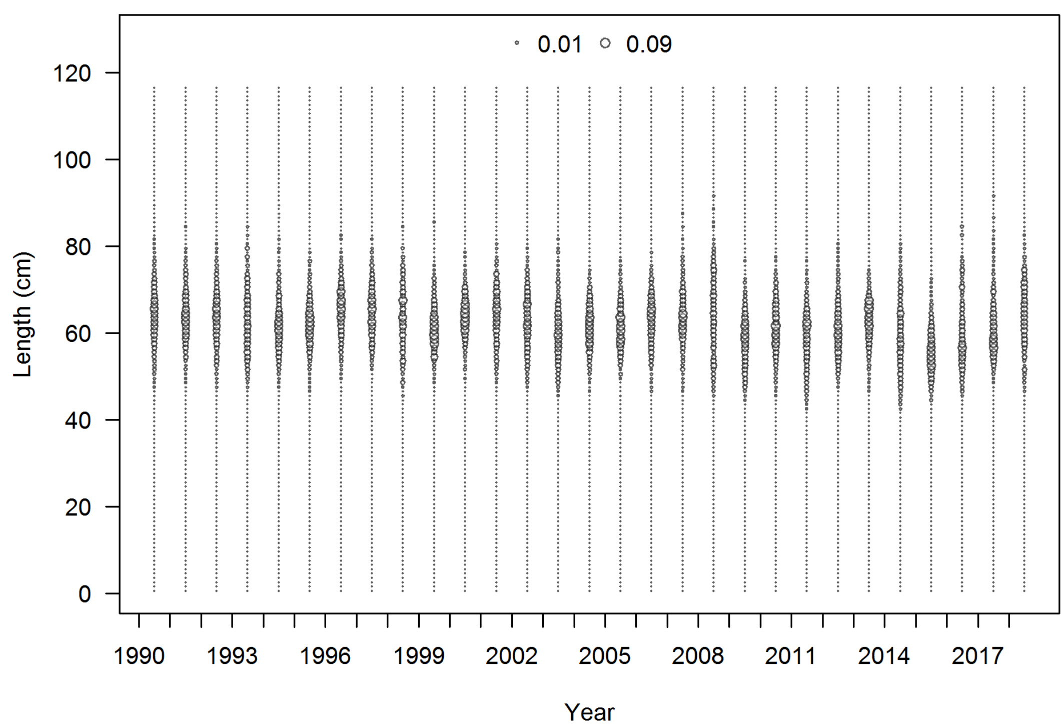


Figure 2.37AFSC longline survey Pacific cod size composition (max=0.09).

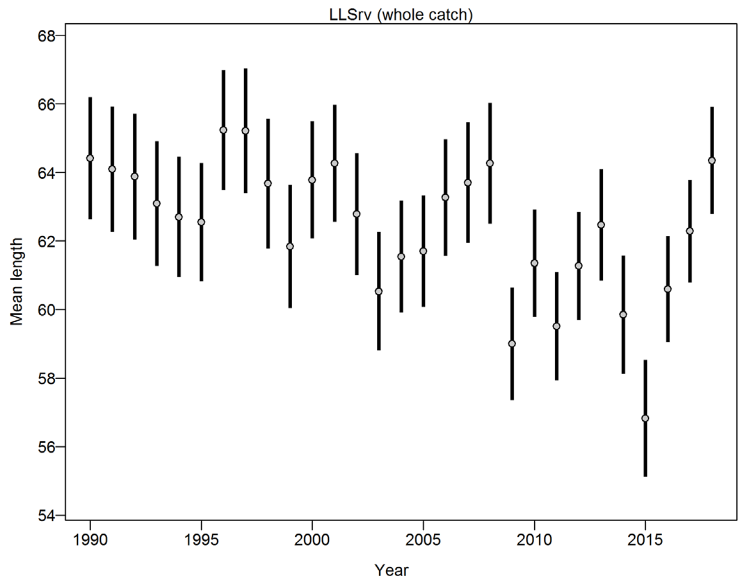


Figure 2.38Mean length (cm) of Pacific cod from the AFSC longline survey.

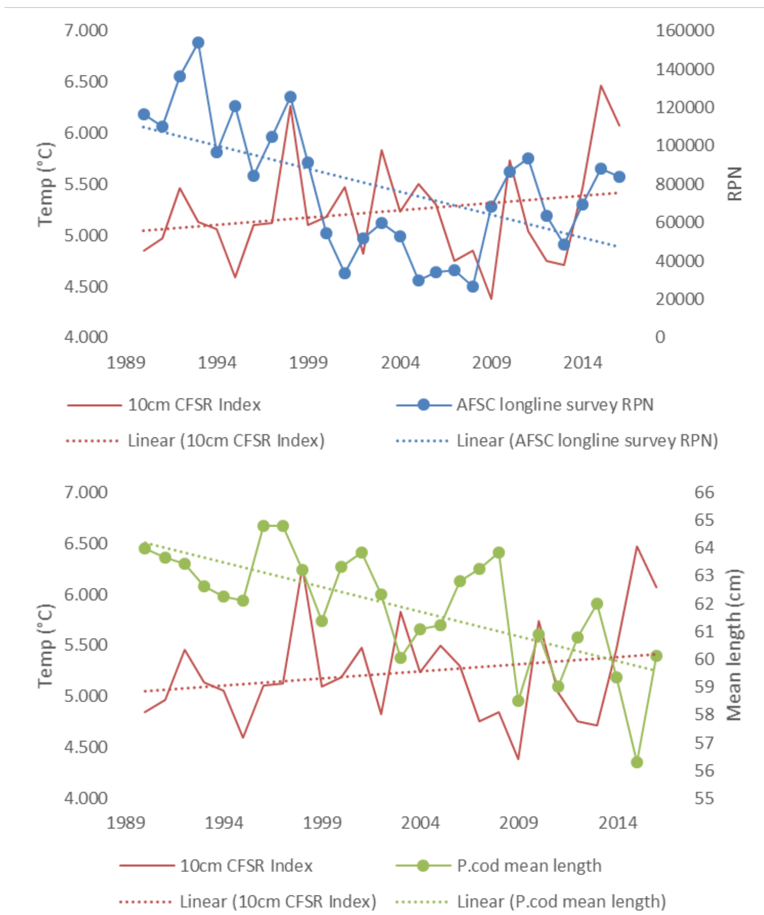


Figure 2.39 – AFSC longline survey Pacific cod RPN (top) and mean length (bottom) in comparison with the 10CM CFSR bottom temperature index.

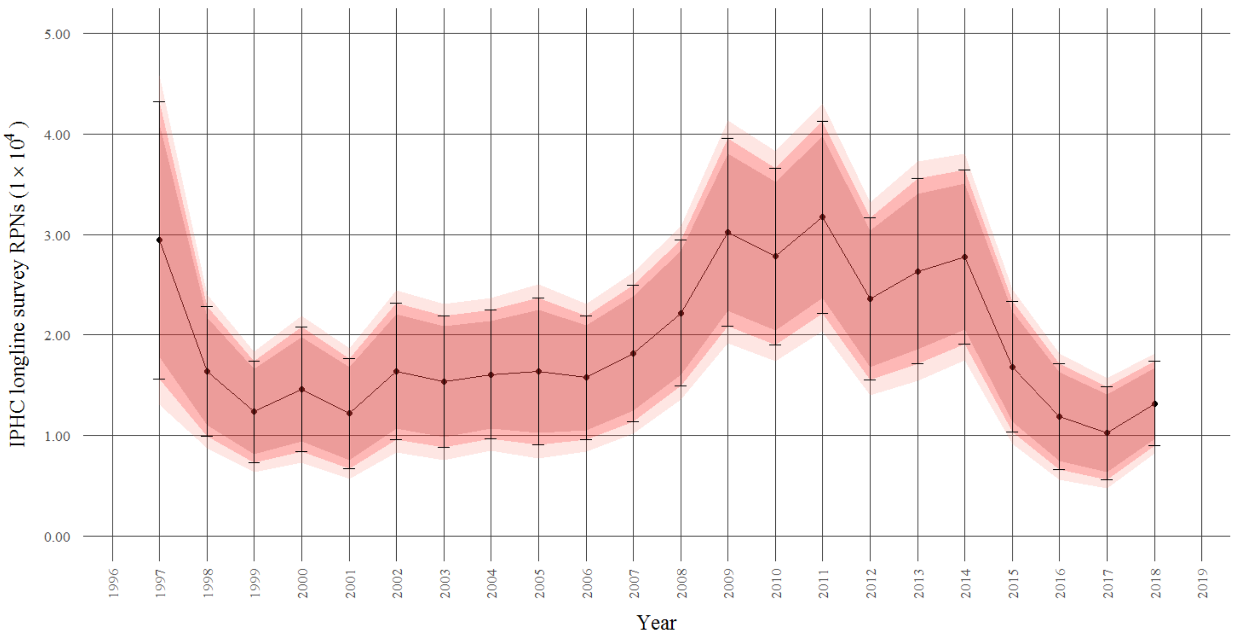


Figure 2.40 IPHC halibut longline survey Pacific cod RPN time series. Bars indicate the 95th percentile confidence intervals, the color changes from 99th percentile (light), 95th percentile (medium) to 90th percentile (darkest) confidence intervals.

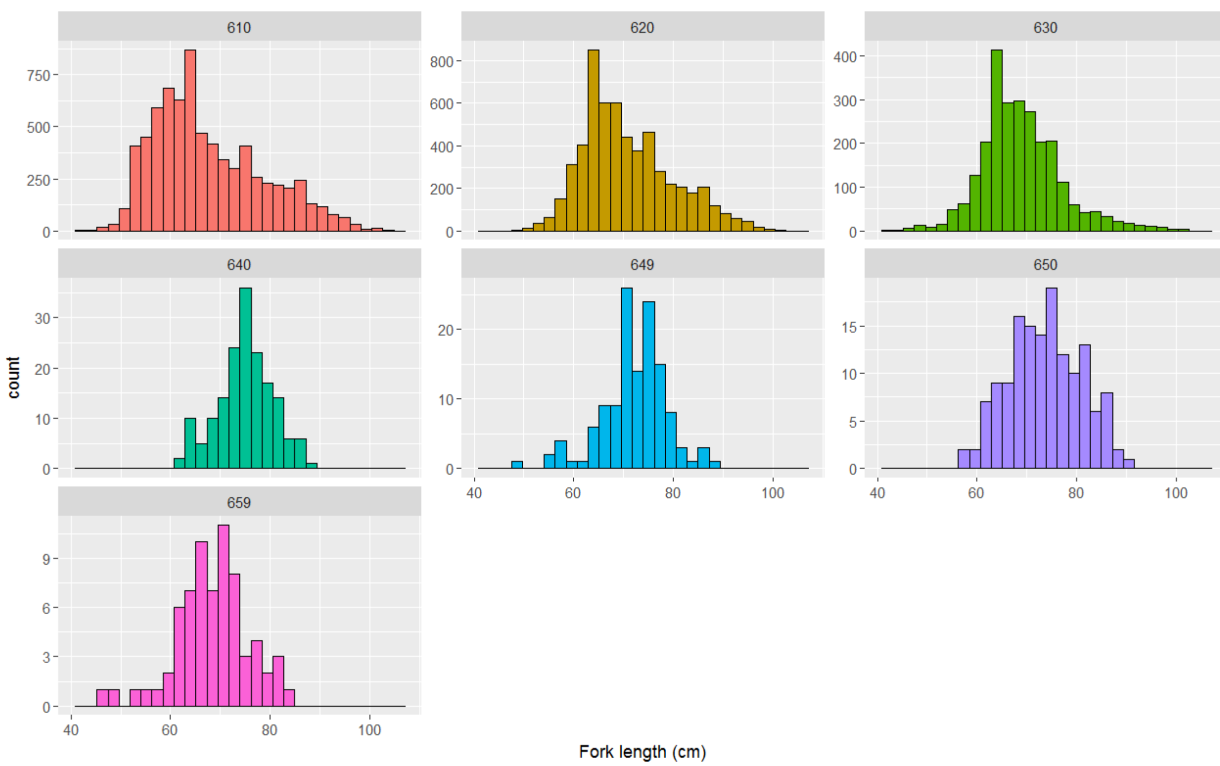


Figure 2.41 IPHC halibut longline survey Pacific cod RPN length composition collection for 2018 by NMFS management area.

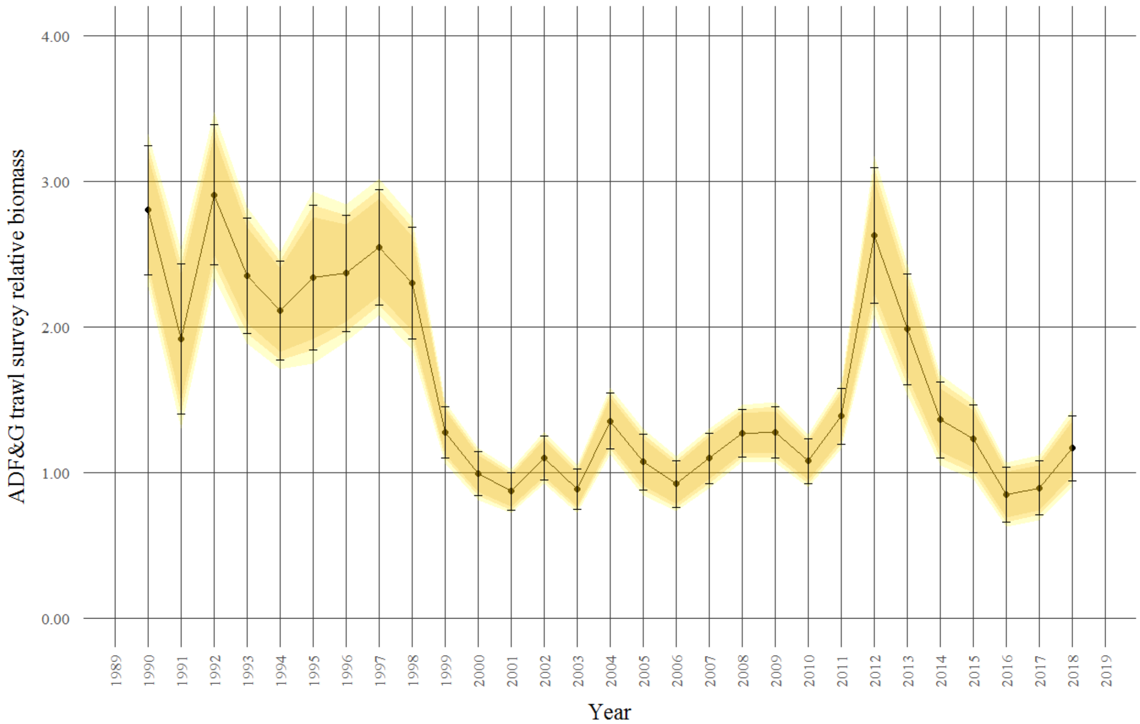


Figure 2.42 ADFG bottom trawl survey delta-glm Pacific cod density index time series. Bars indicate the 95th percentile confidence intervals, the color changes from 99th percentile (light), 95th percentile (medium) to 90th percentile (darkest) confidence intervals.

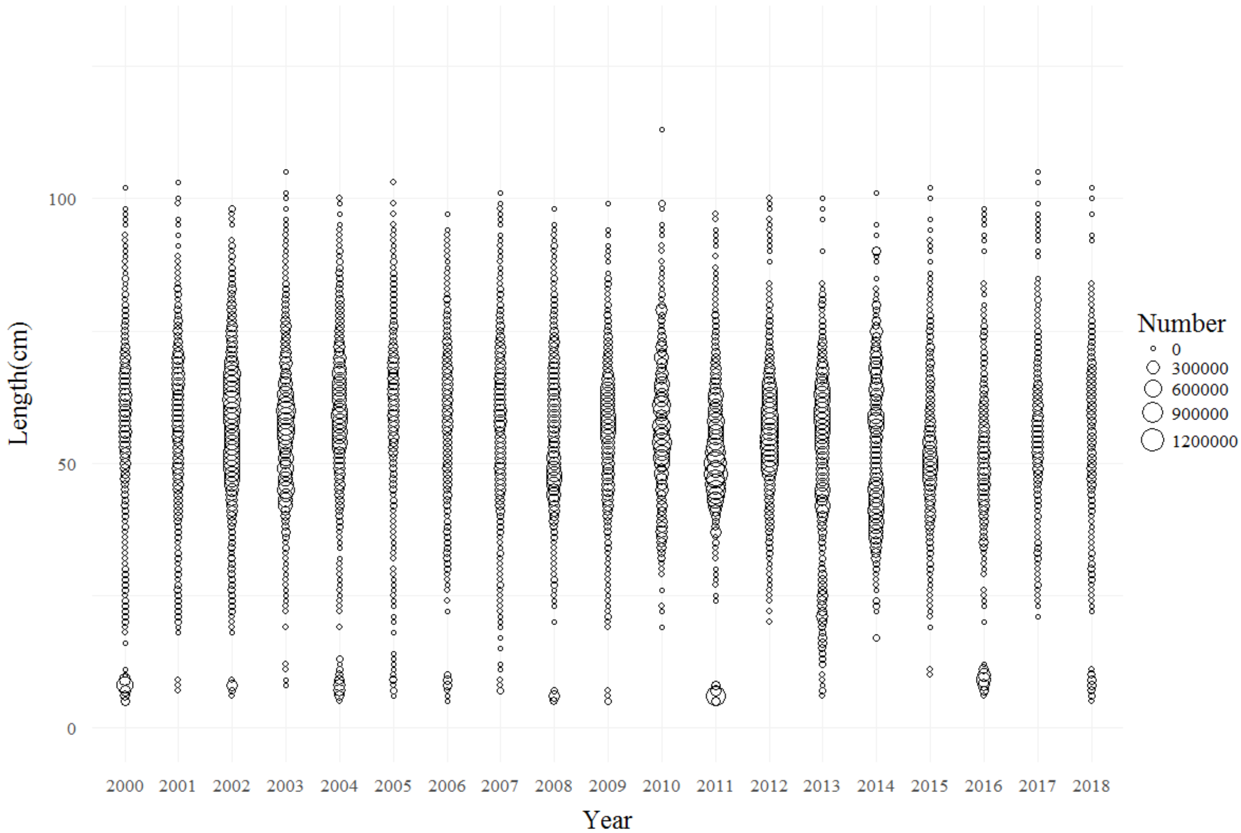


Figure 2.43 ADFG large-mesh trawl survey Pacific cod population numbers at length estimates.

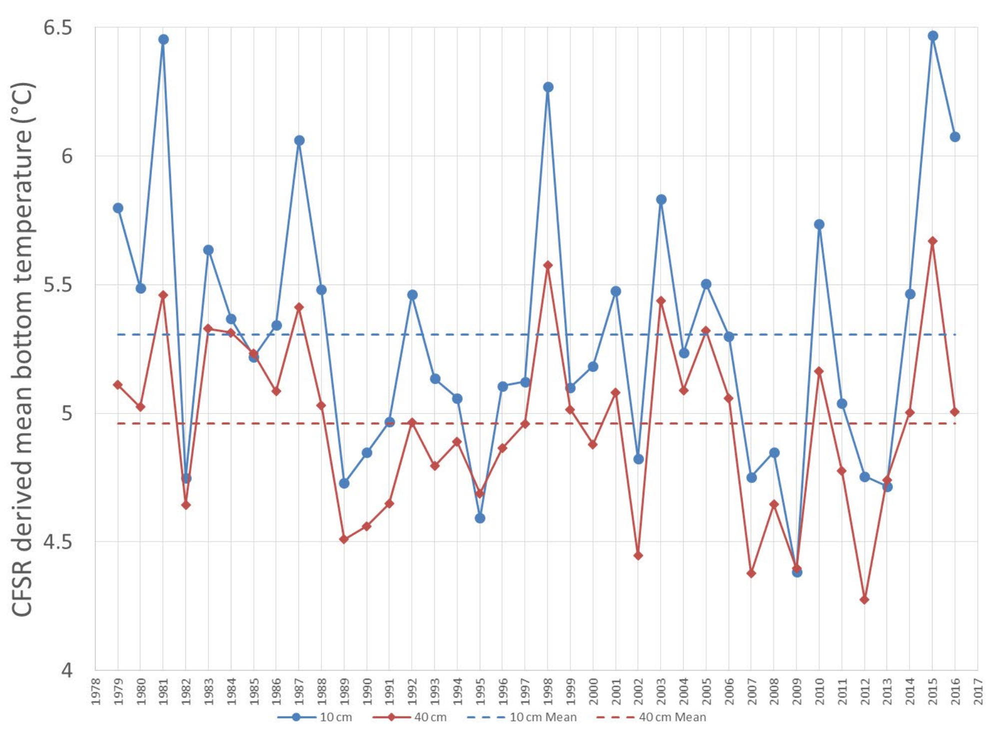


Figure 2.44 Climate Forcast System Reanalysis (CFSR) Central Gulf of Alaska bottom temperatures at the AFSC bottom trawl survey mean depths for 10 cm and 40 cm Pacific cod in July.

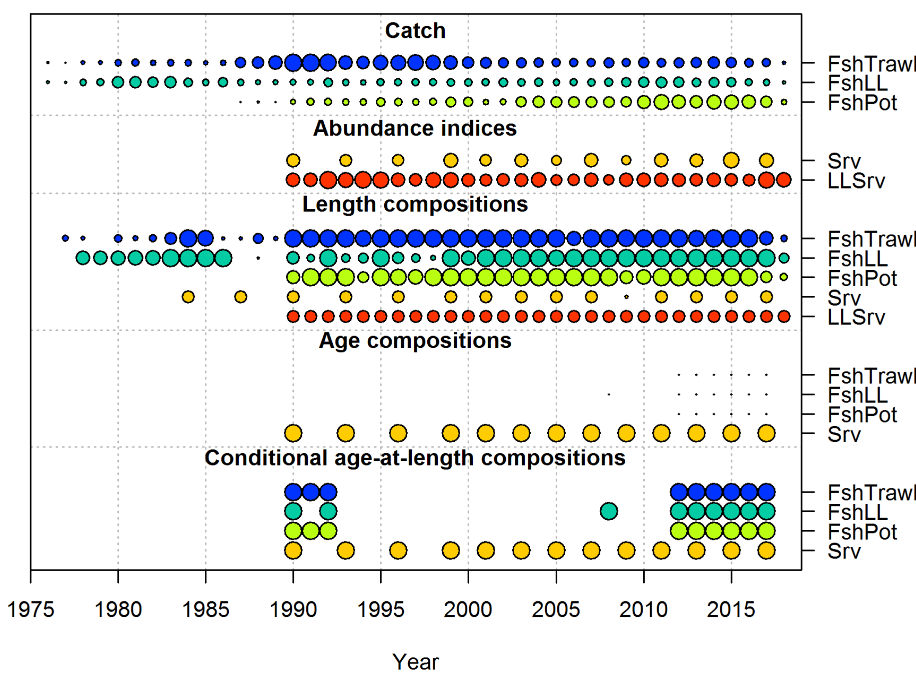


Figure 2.45 Data used in the 2018 models, circle area is relative to initial precision within data type.

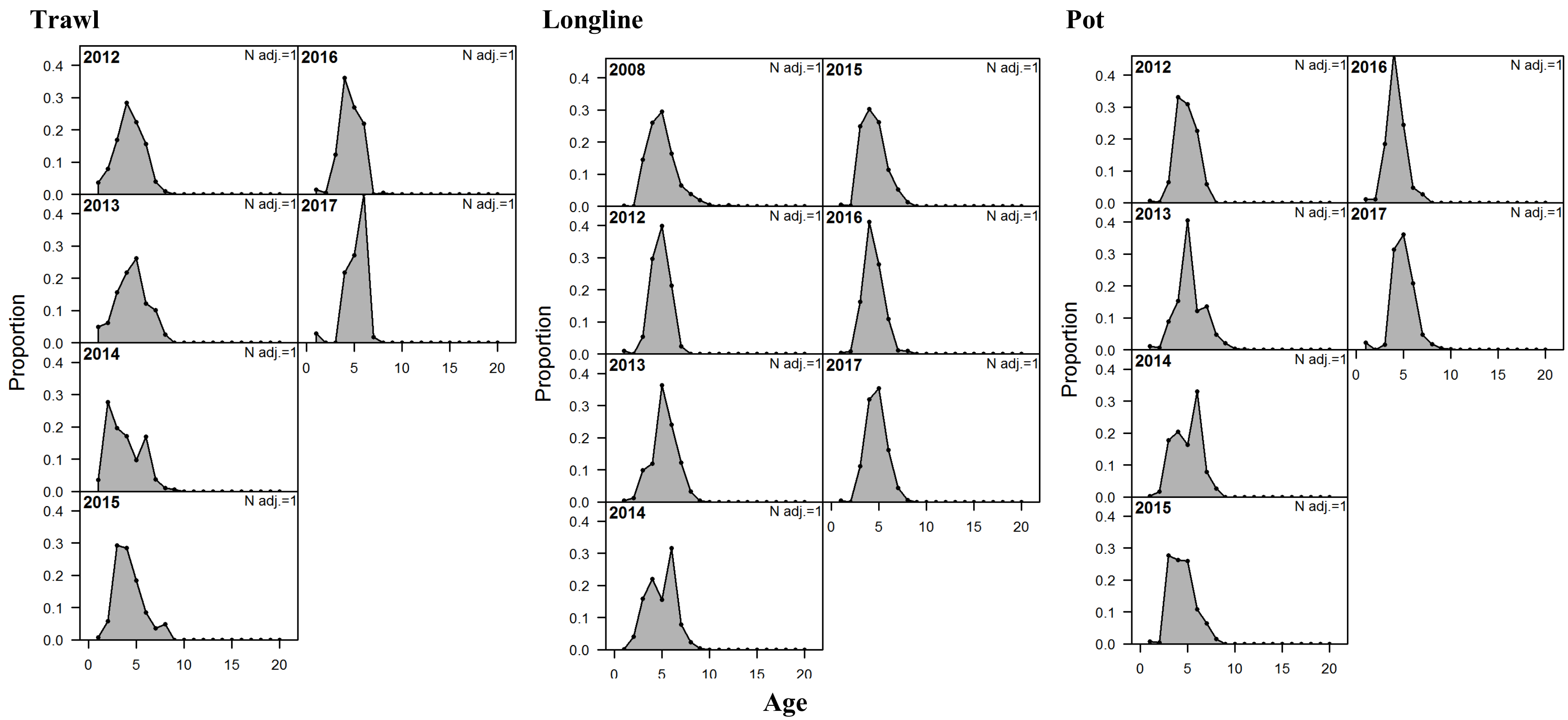


Figure 2.46 Pacific cod age composition data from the Gulf of Alaska fisheries by gear type.

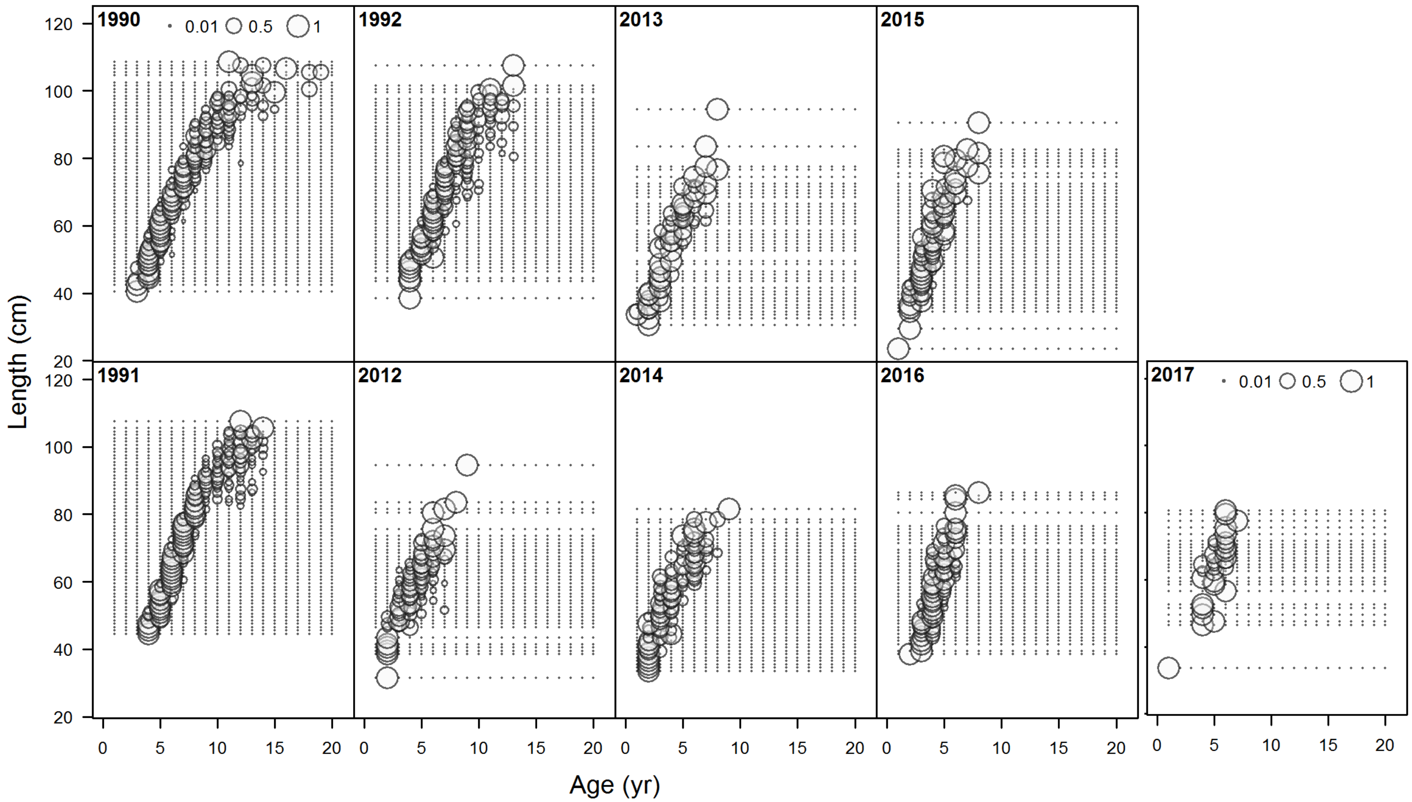


Figure 2.47 Pacific cod conditional length at age from the Gulf of Alaska trawl fishery.

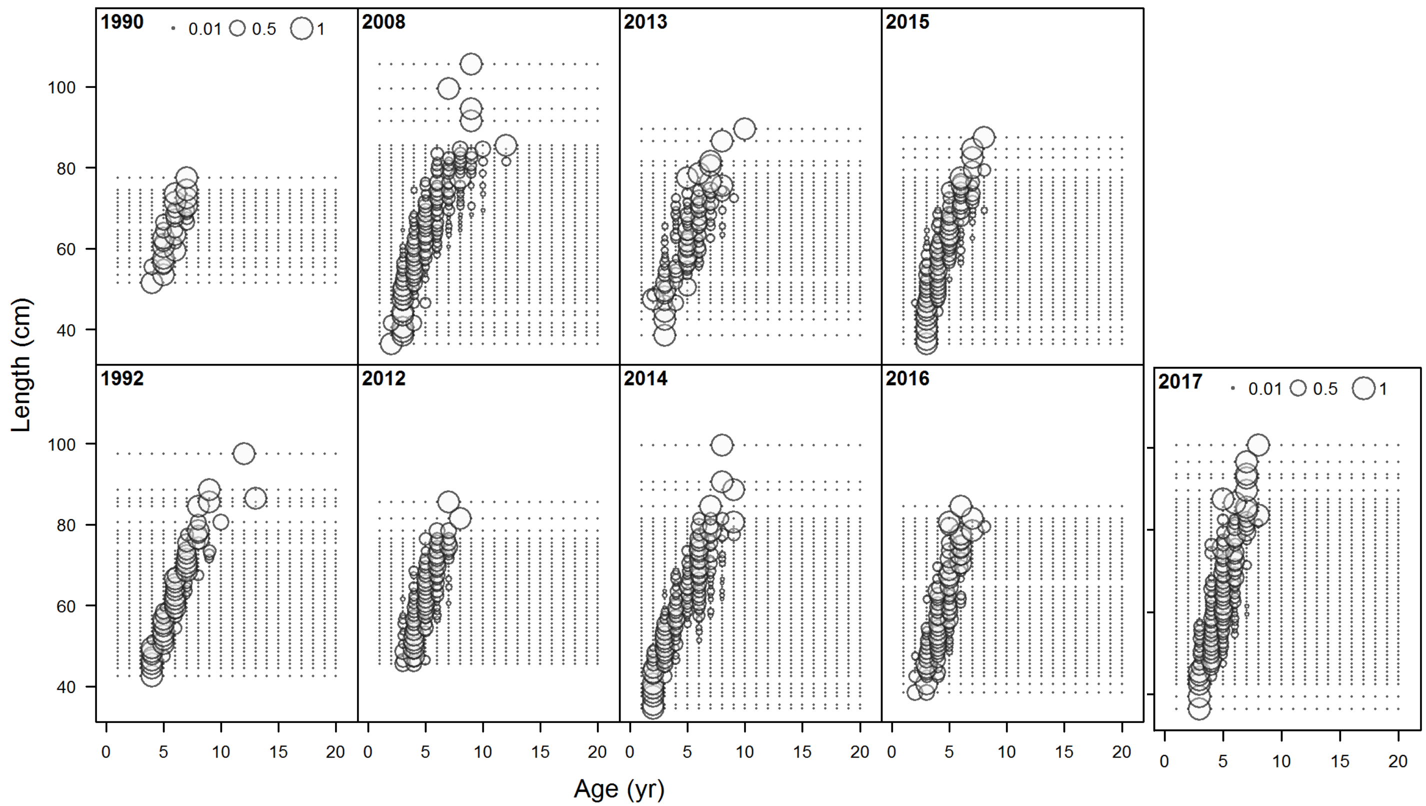


Figure 2.48 Pacific cod conditional length at age from the Gulf of Alaska bottom longline fishery.

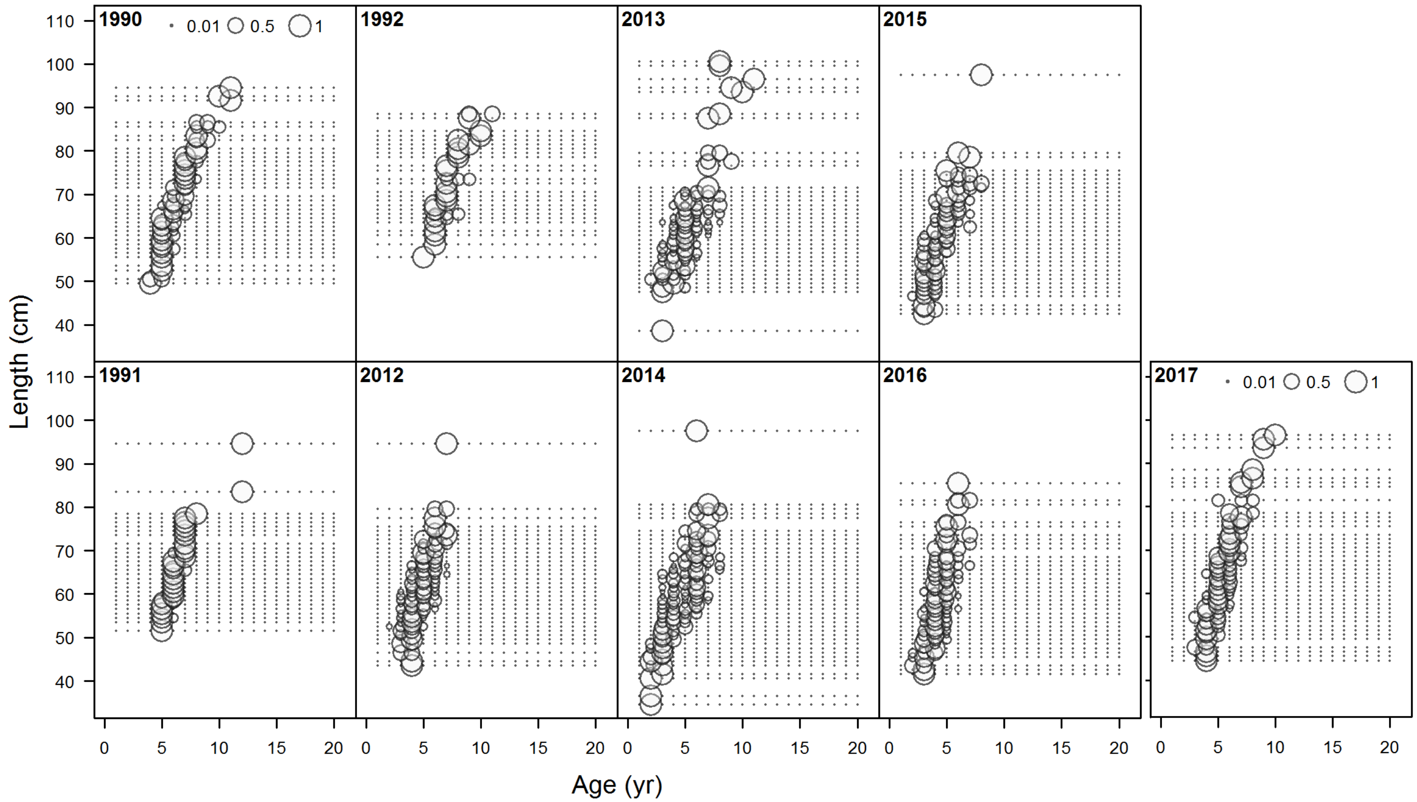


Figure 2.49 Pacific cod conditional length at age from the Gulf of Alaska pot fishery.

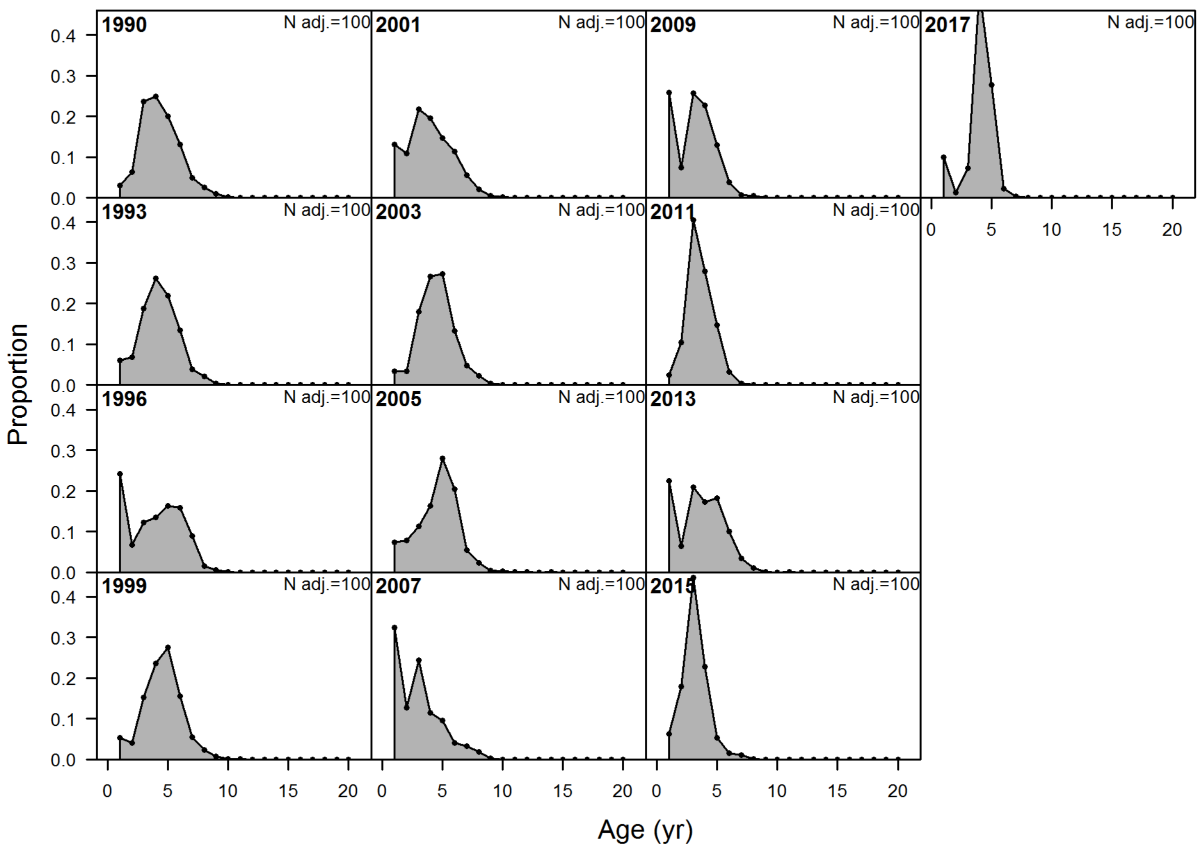


Figure 2.50 Pacific cod age composition data from the Gulf of Alaska bottom trawl survey 1990-2017.

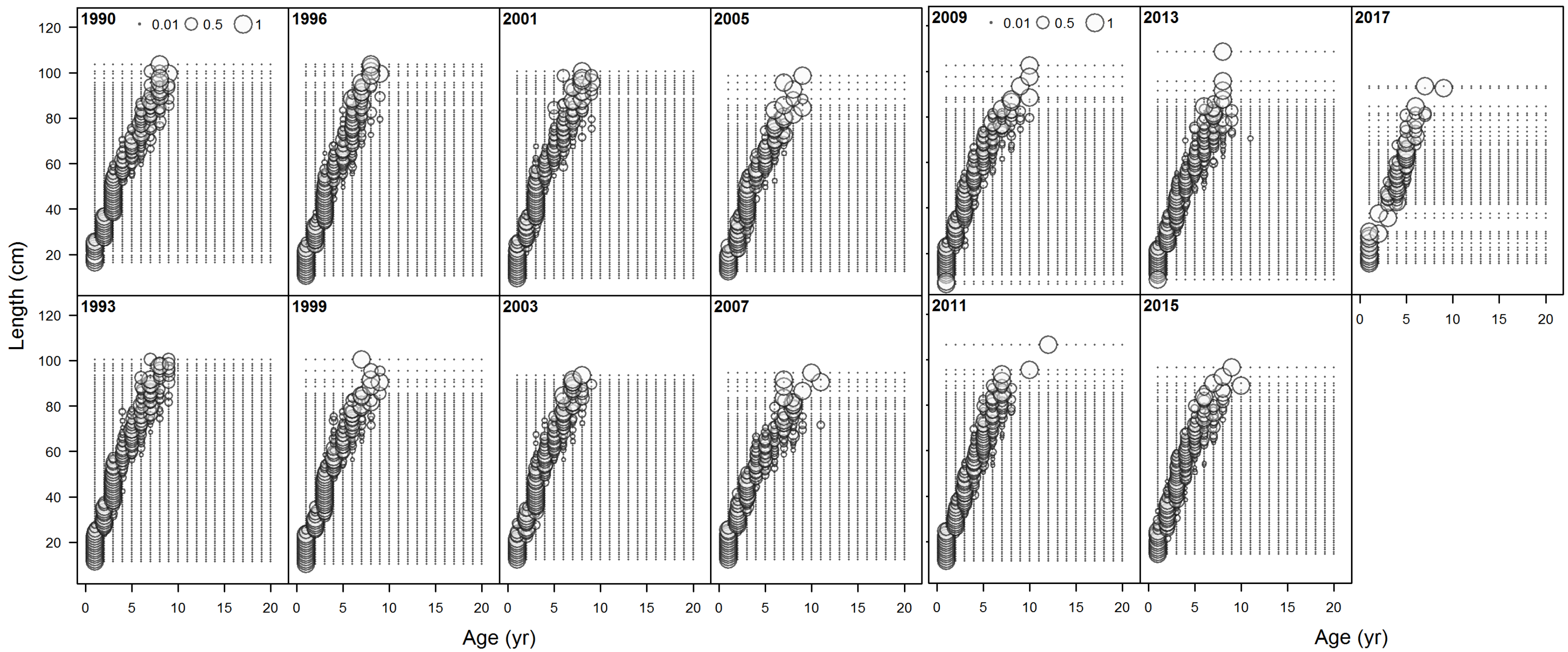


Figure 2.51 Pacific cod conditional length at age from the Gulf of Alaska bottom trawl survey 1987-2017.

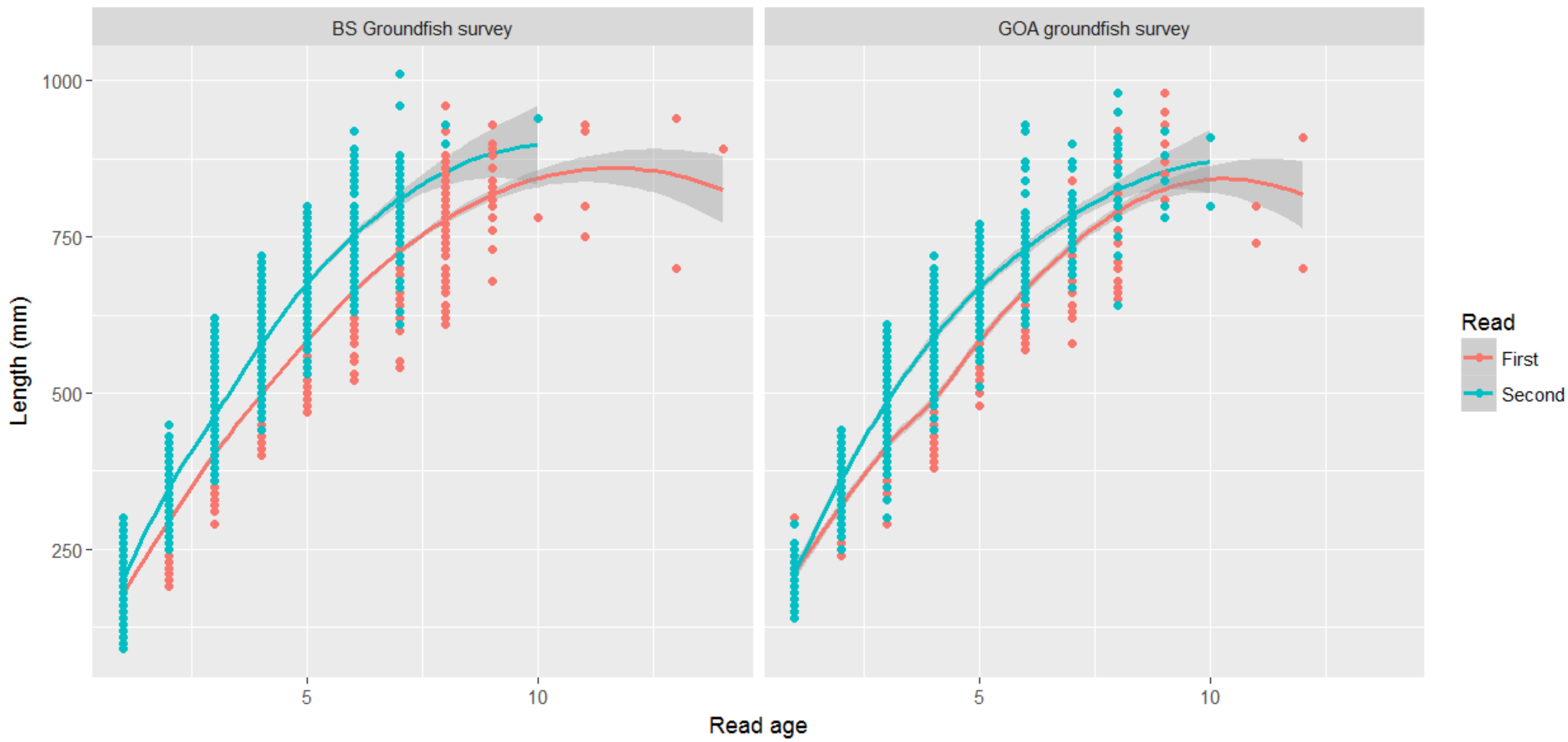


Figure 2.52 Length-at-age for otoliths from Stark (2007) analysis of Pacific cod growth and maturity showing the age from the original read (red) and a reread of the otoliths using the latest methods and criteria (blue).

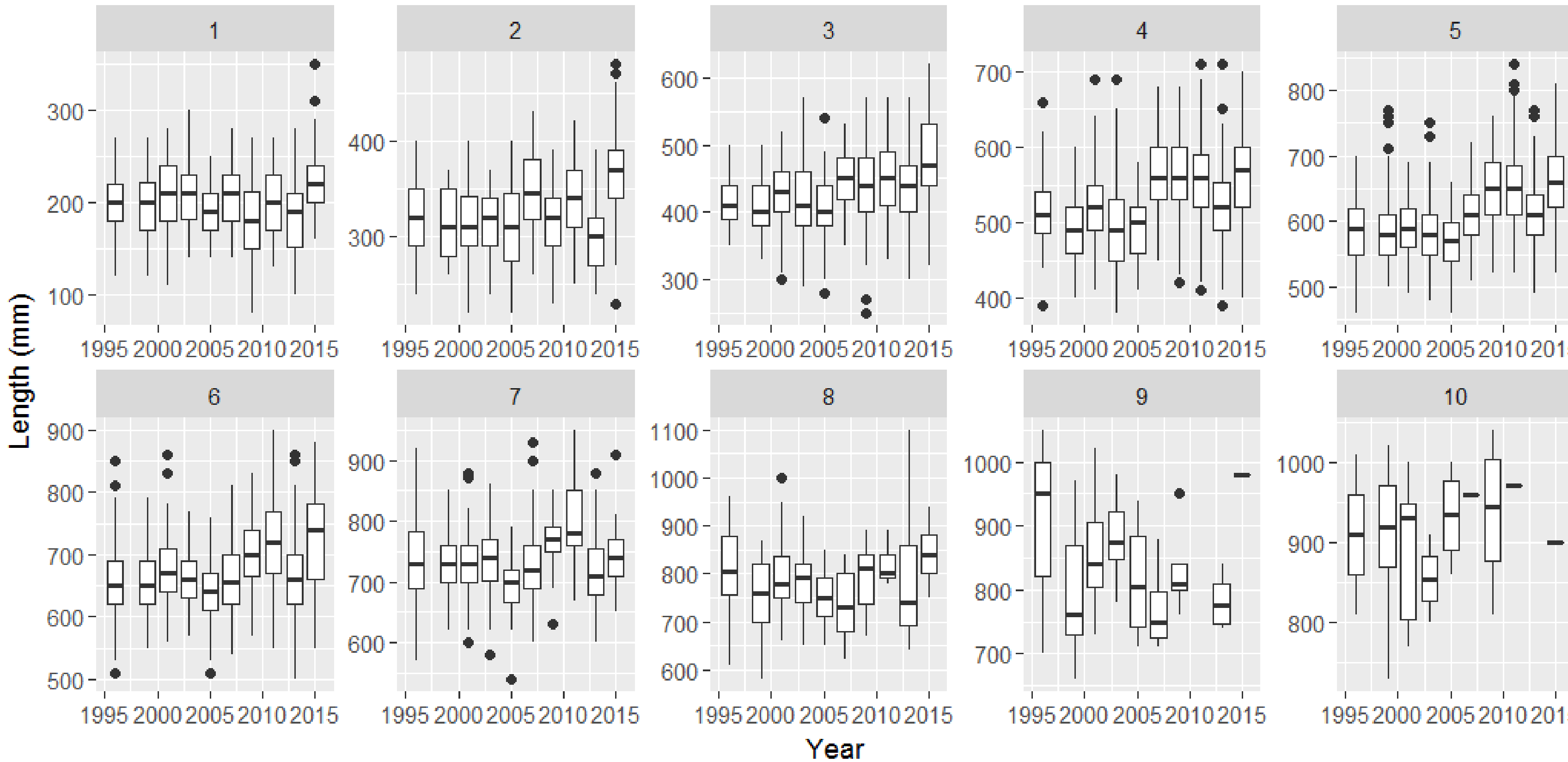


Figure 2.53 Length-at-age by year for each age 1 through 10 for Pacific cod otoliths collected during the summer bottom trawl surveys showing an increase in median length in 2007 for ages 2 through 6.

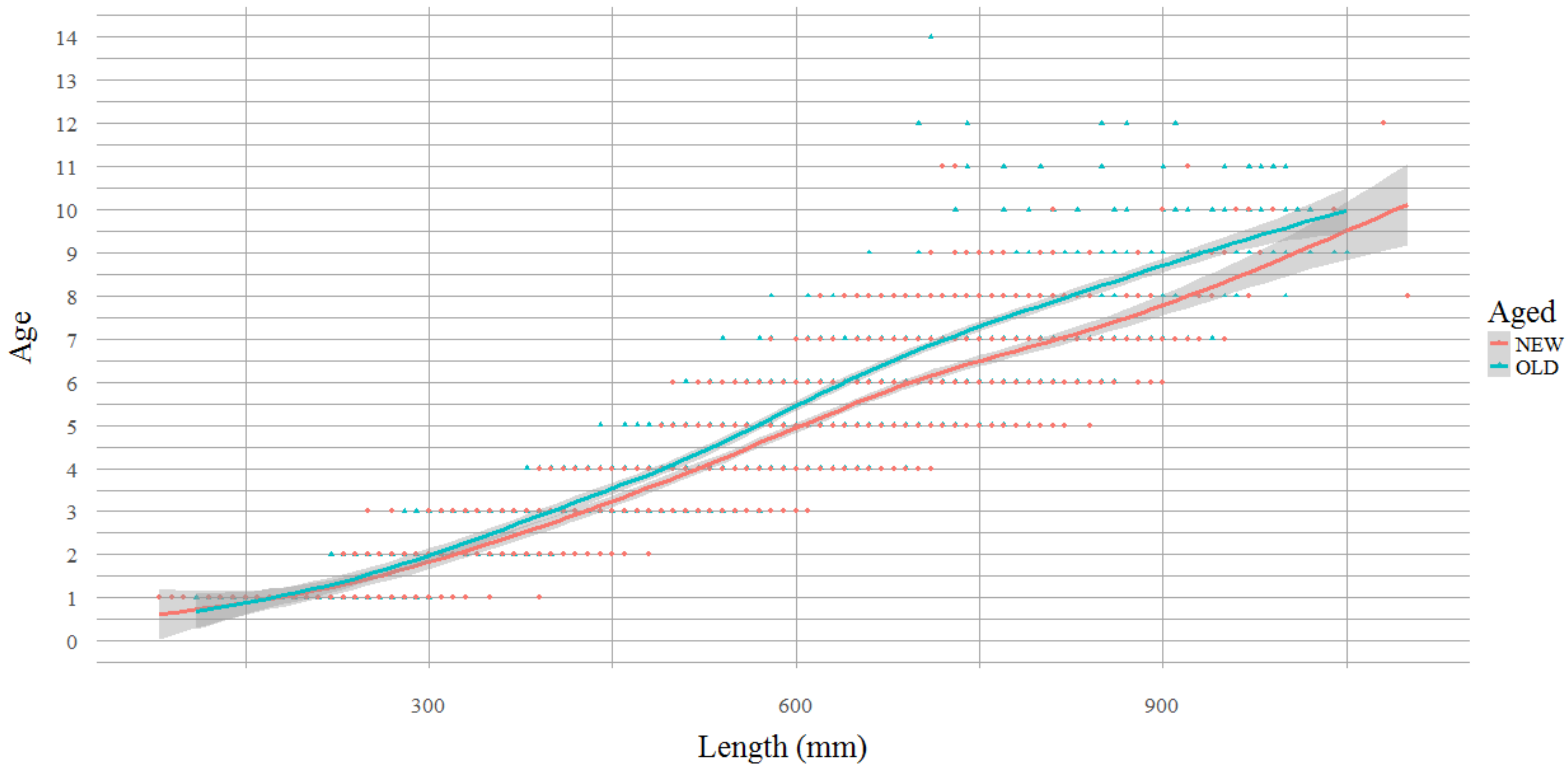


Figure 2.54 Pacific cod ages at length for survey data from 1996-2017 divided by pre-2007 (OLD; blue) and post-2007 (NEW; red) showing possible aging bias.

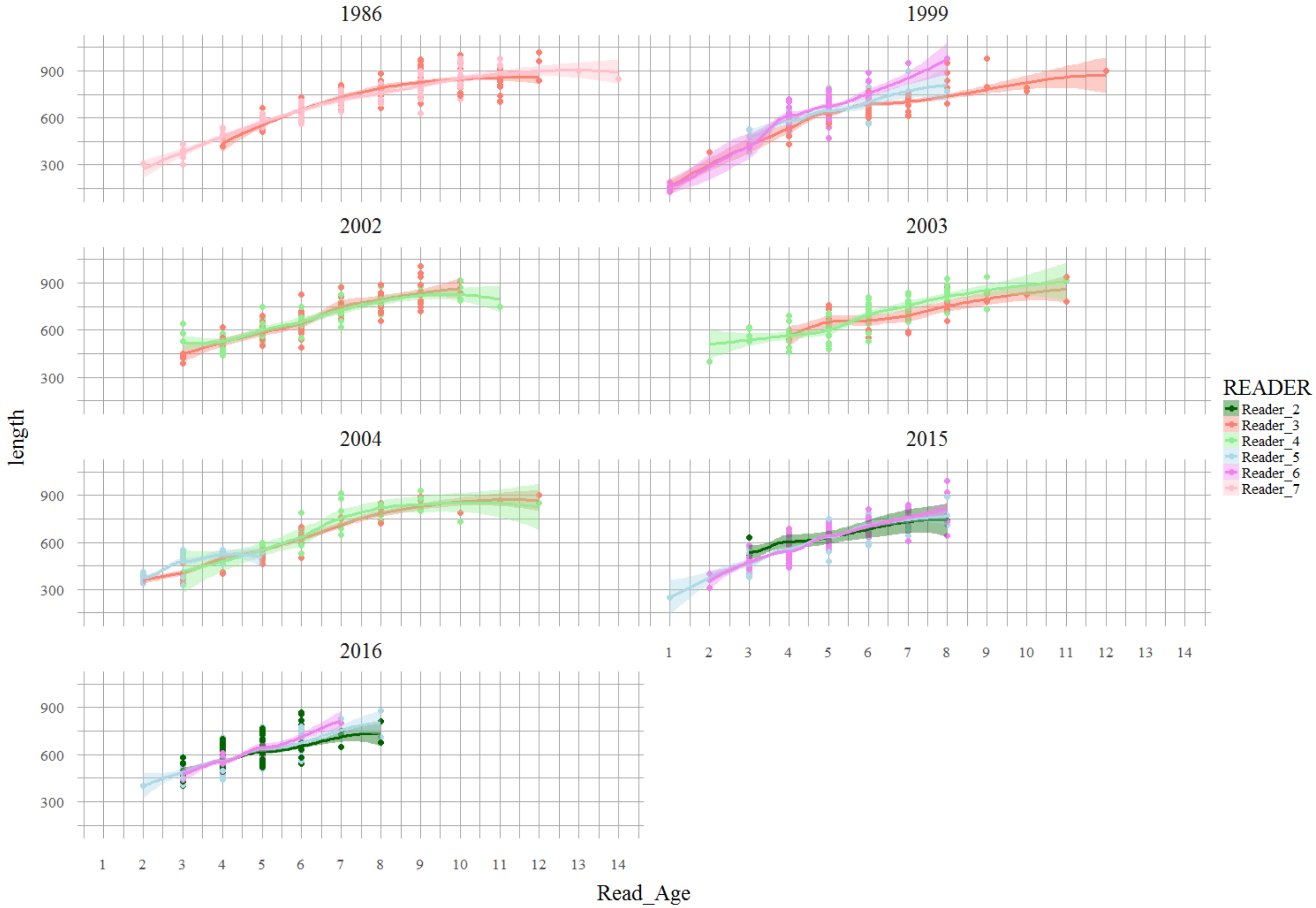


Figure 2.55 Pacific cod length at age for January-April for years with duplicate age readers showing possible age reader effect on aging.

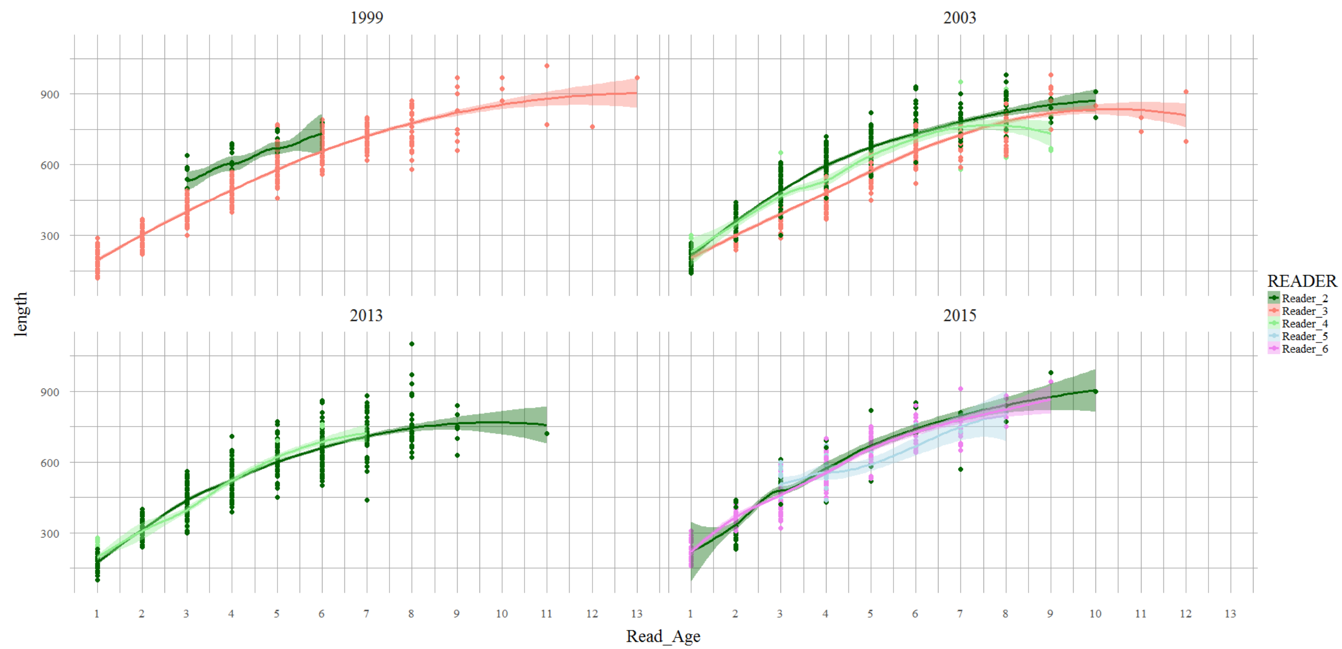


Figure 2.56 Pacific cod length at age for May-August for years with duplicate age readers showing possible age reader effect on aging.

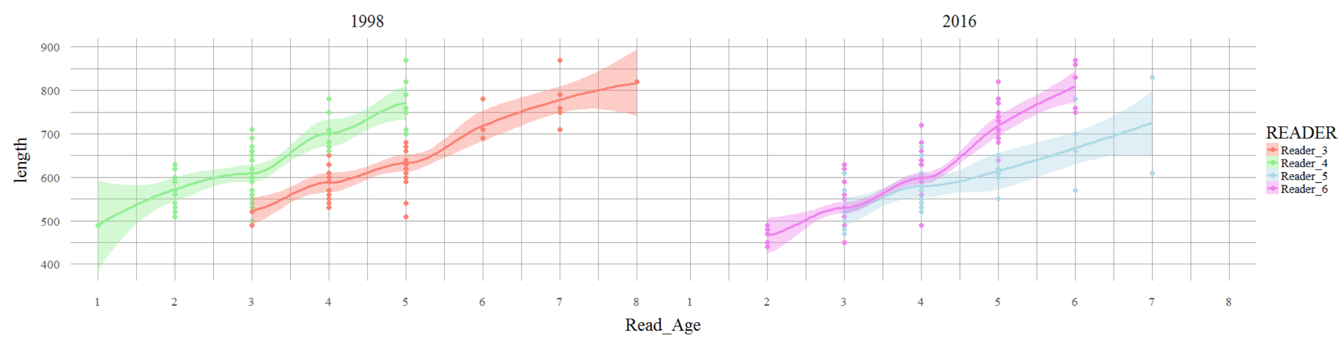


Figure 2.57 Pacific cod length at age for September-December for years with duplicate age readers showing possible age reader effect on aging.

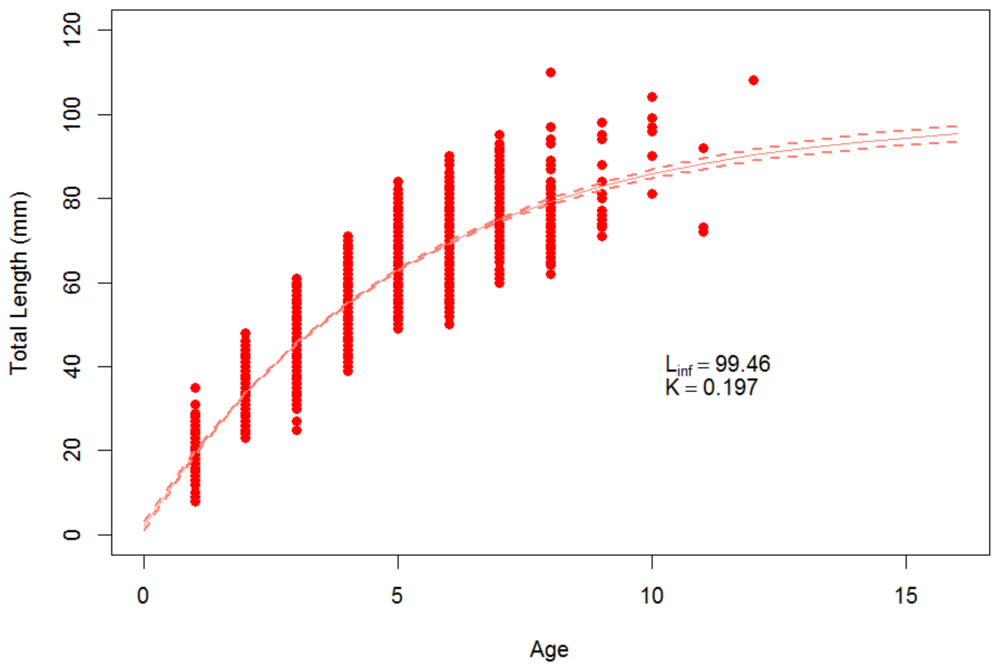


Figure 2.58 Fit to von Bertalanffy growth model for 2007-2015 length at age data from the AFSC bottom trawl surveys.

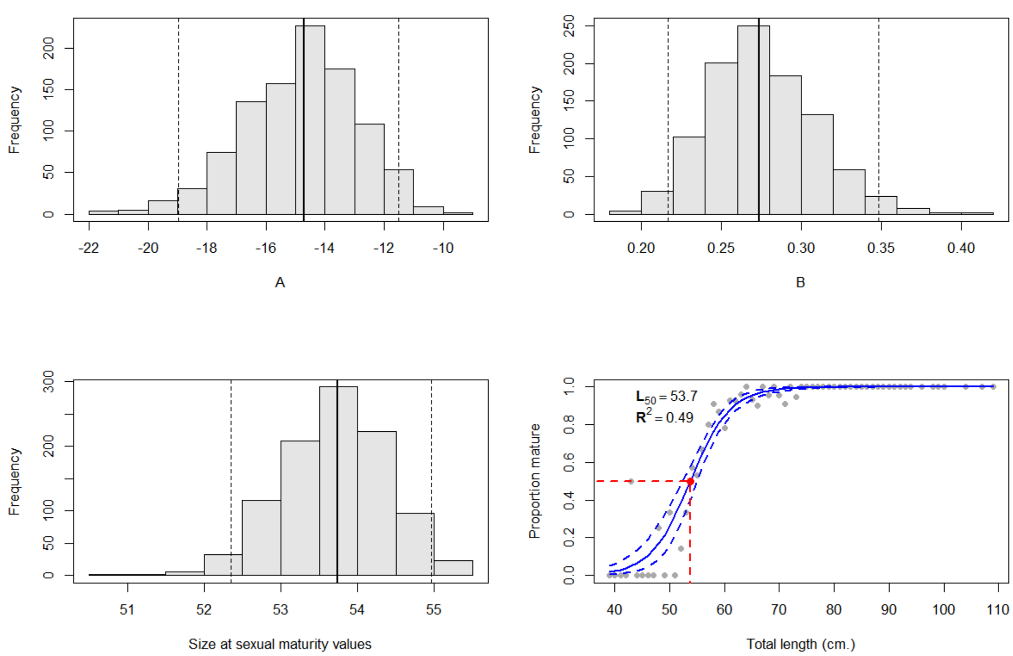


Figure 2.59 Bootstrapped (n=1000) parameters and results for the logistic length-based maturity using Stark (2007) reread otolith and maturity data. Proportion mature $P = {}^{1}/_{1+e^{-(A+BL)}}$ and L_{50} = A/-B

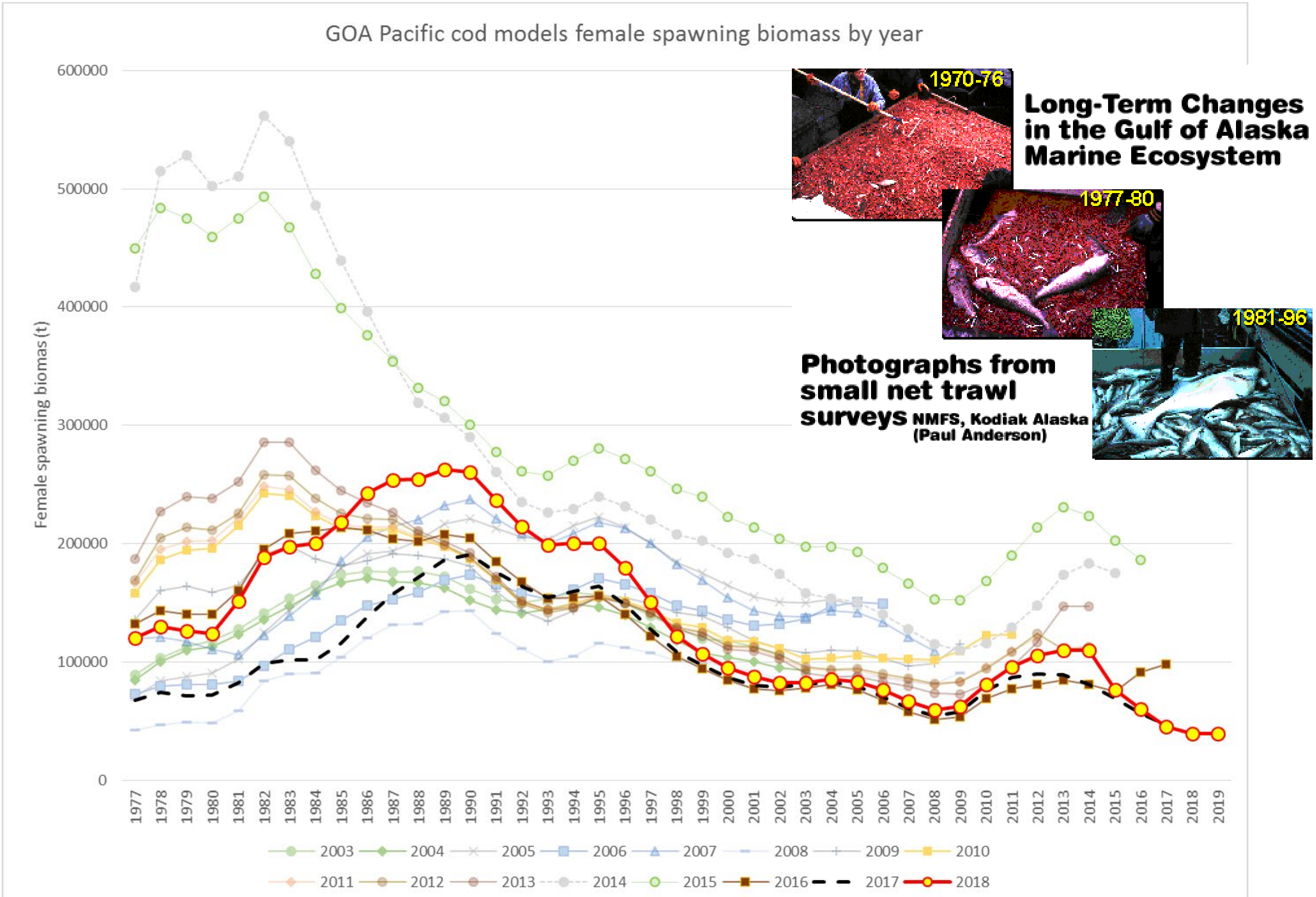


Figure 2.60 1977-2019 Gulf of Alaska Pacific cod female spawning biomass from the 2003 through 2018 stock assessments with the author's preferred Model 18.11.44 as the 2018 estimate and (inset) images from the NMFS small net surveys off Kodiak Alaska showing change in species composition over time from: http://www.thexxnakedscientists.com/HTML/articles/article/brucewrightcolumn1.htm/

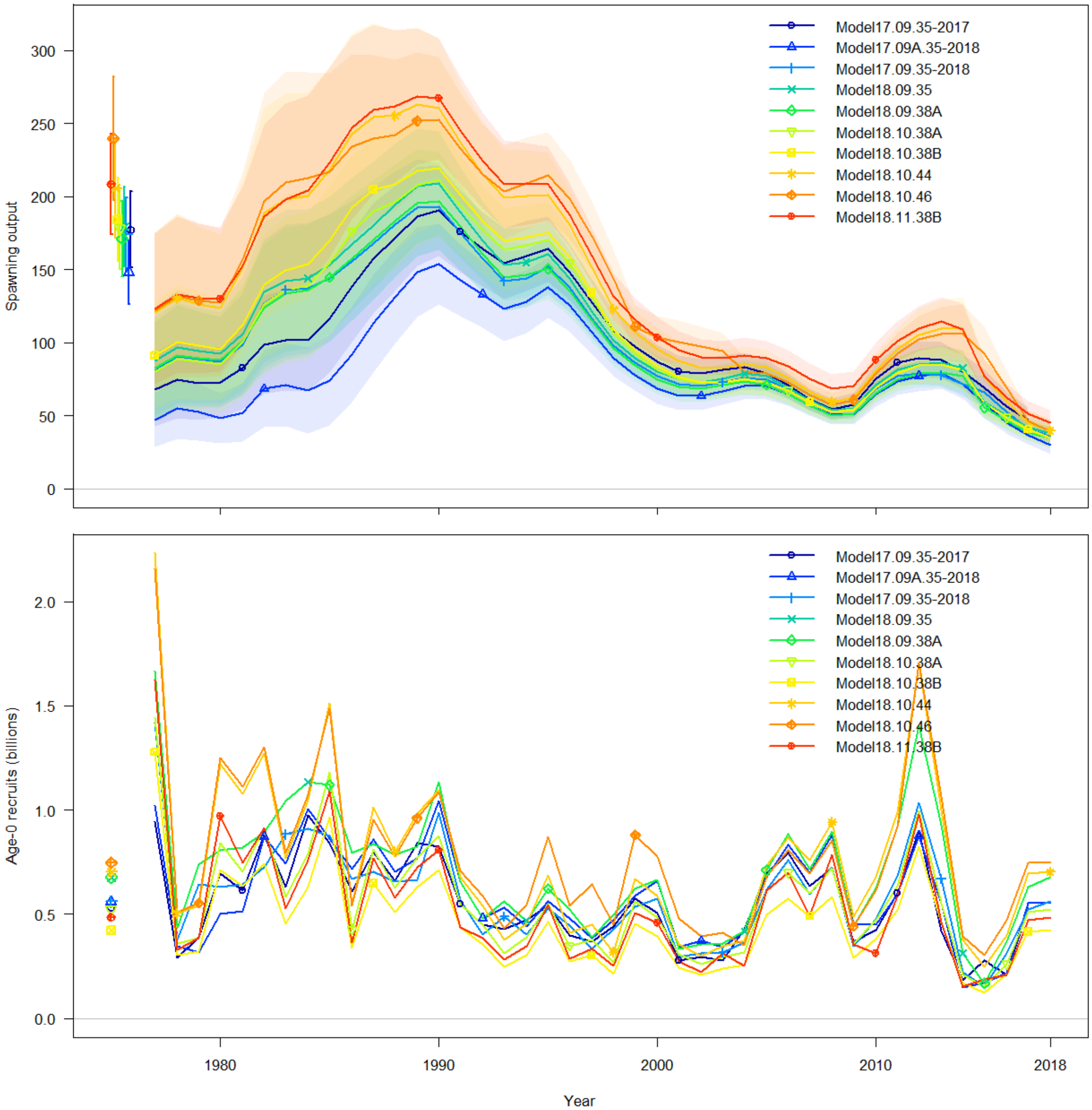


Figure 2.61 Estimates of female spawning biomass (t; top) and age-0 recruits (billions; bottom) for 2017 reference model without (Model 17.09.35 - 2017) and with 2018 data without fishery age data (Model 17.09A.35 - 2018), with all new 2018 data (Model17.09.38 – 2018) and the proposed alternative 2018 models.

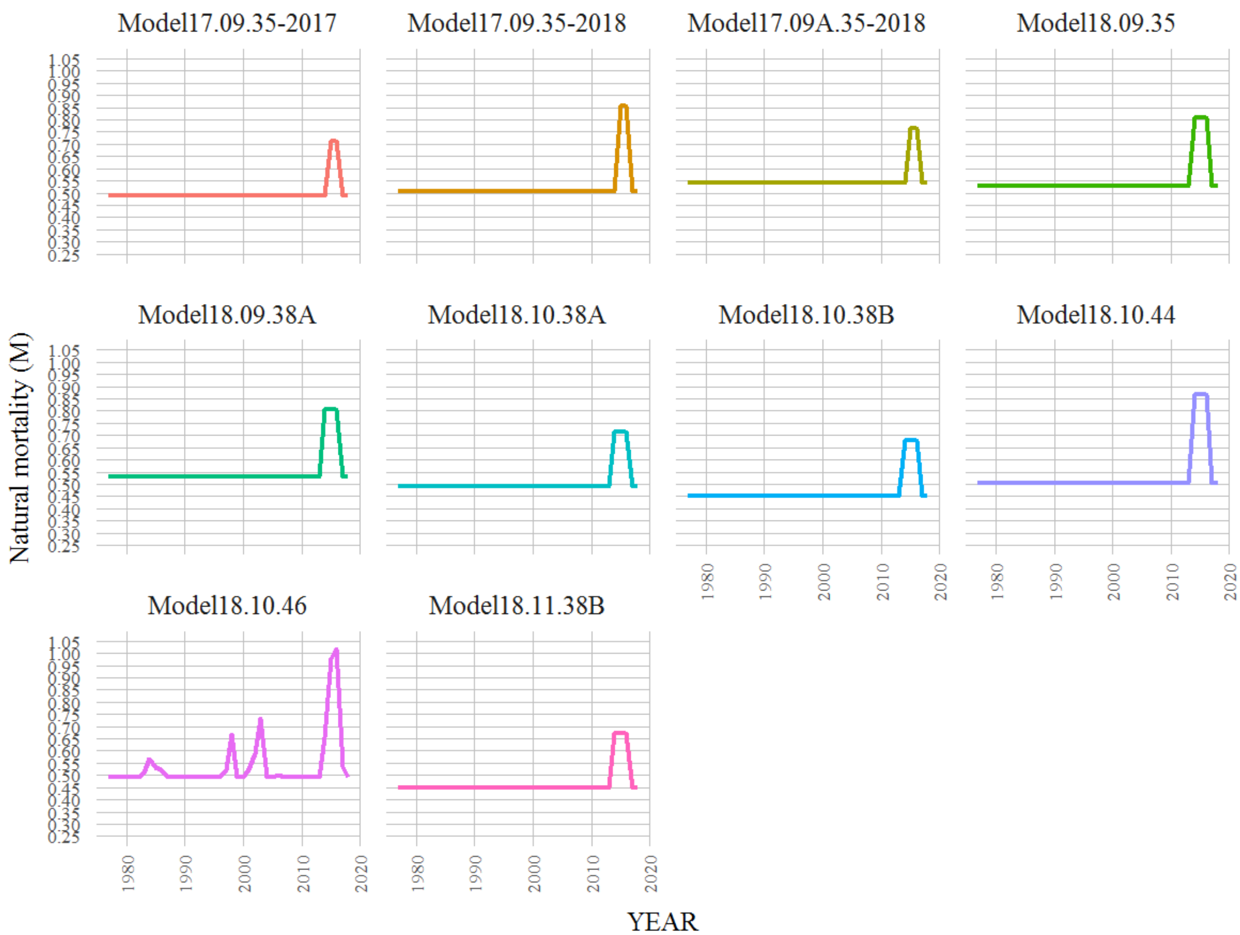
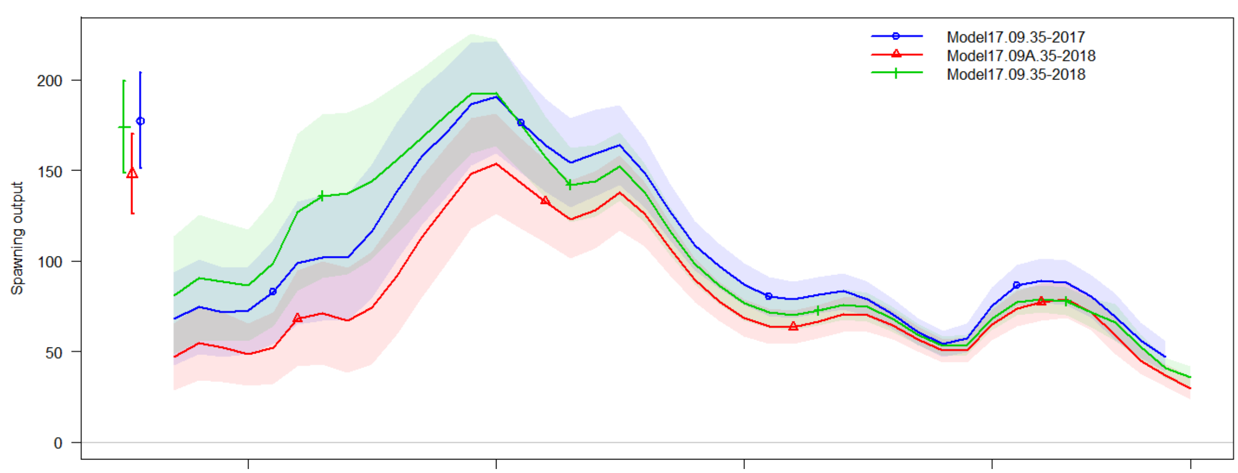


Figure 2.62 Natural mortality over time for all model configurations.



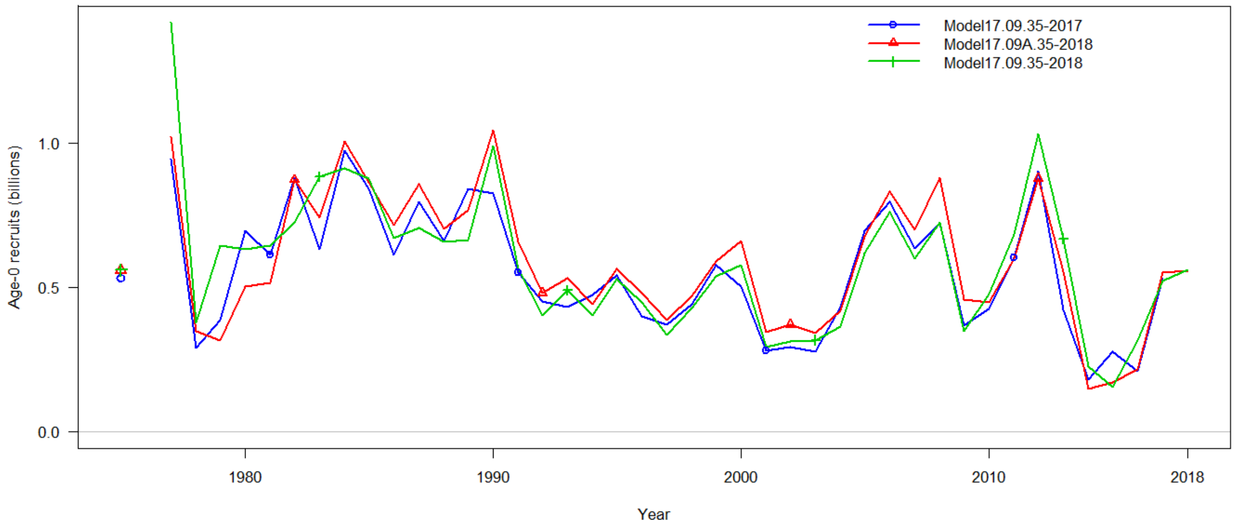


Figure 2.63 Estimates of female spawning biomass (t × 10^3; top) and age-0 recruits (billions; bottom) for Model 17.09.35 with and without 2018 data.

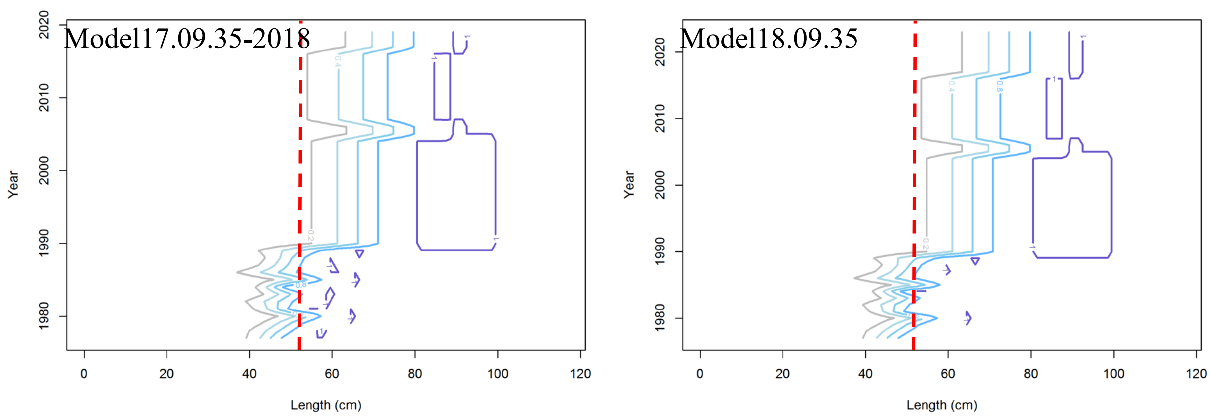


Figure 2.64 Estimates of trawl fishery selectivity for Model 17.09.35-2018 and Model 18.09.35. Red dashed line is the size at 50% mature

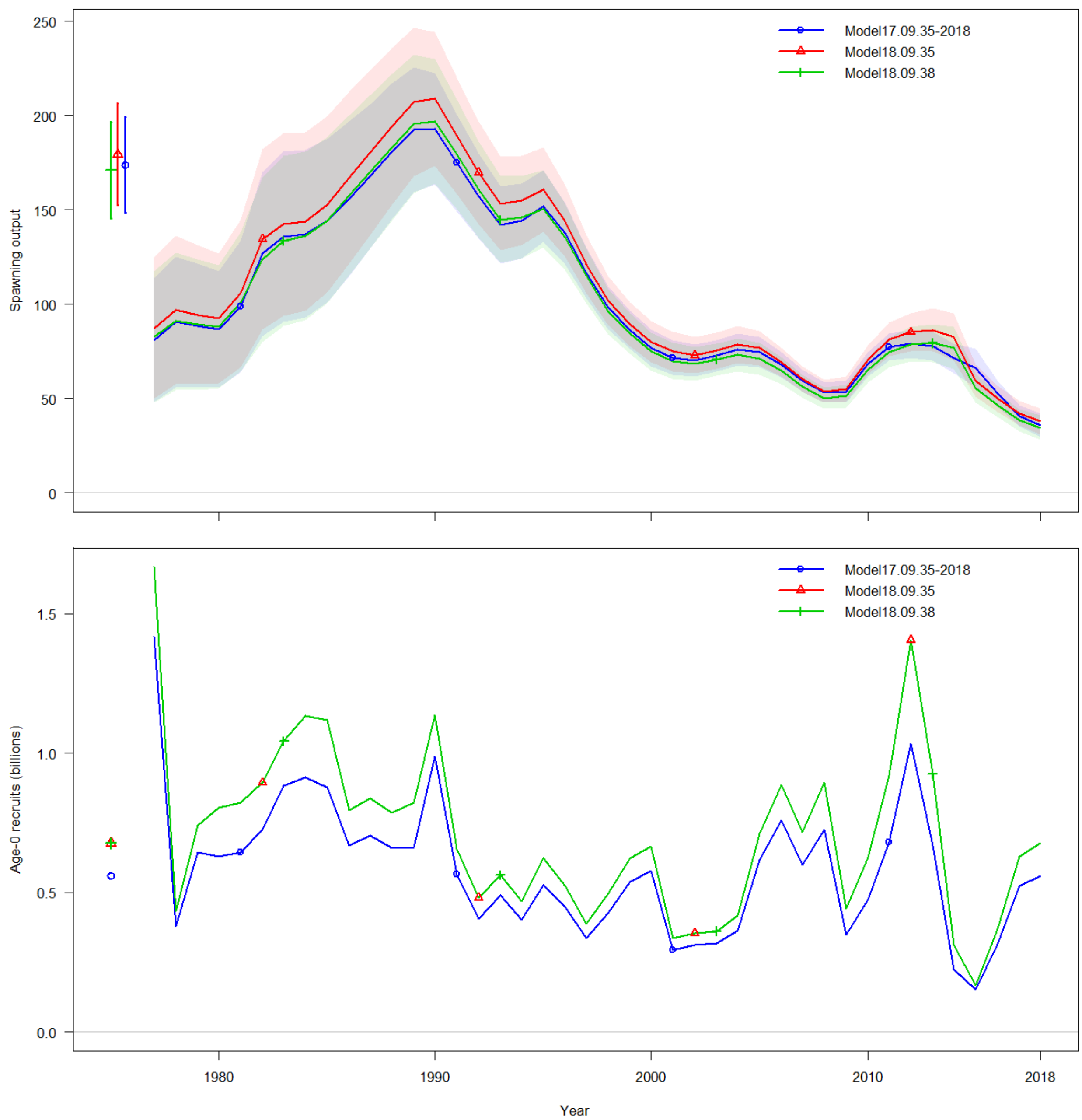


Figure 2.65 Estimates of female spawning biomass (t × 10^3; top) and age-0 recruits (billions; bottom) for Model 17.09.35-2018, Model 18.09.35, and Model 18.09.38A.

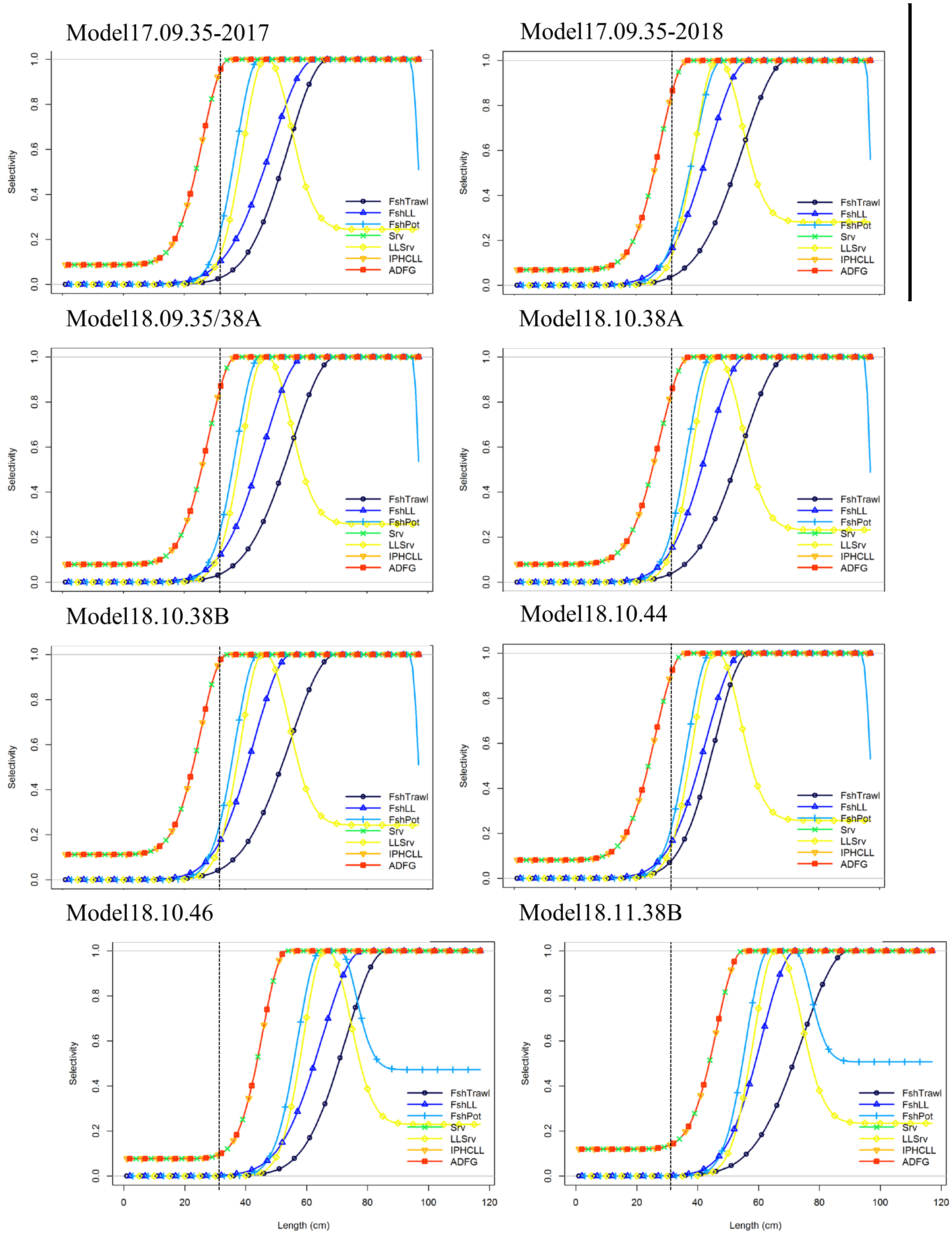


Figure 2.66 The 2017 (Model17.09.35-2017) and 2018 (all other models) selectivity for all size composition components for 2018. Dashed black line indicates size at 50% mature.

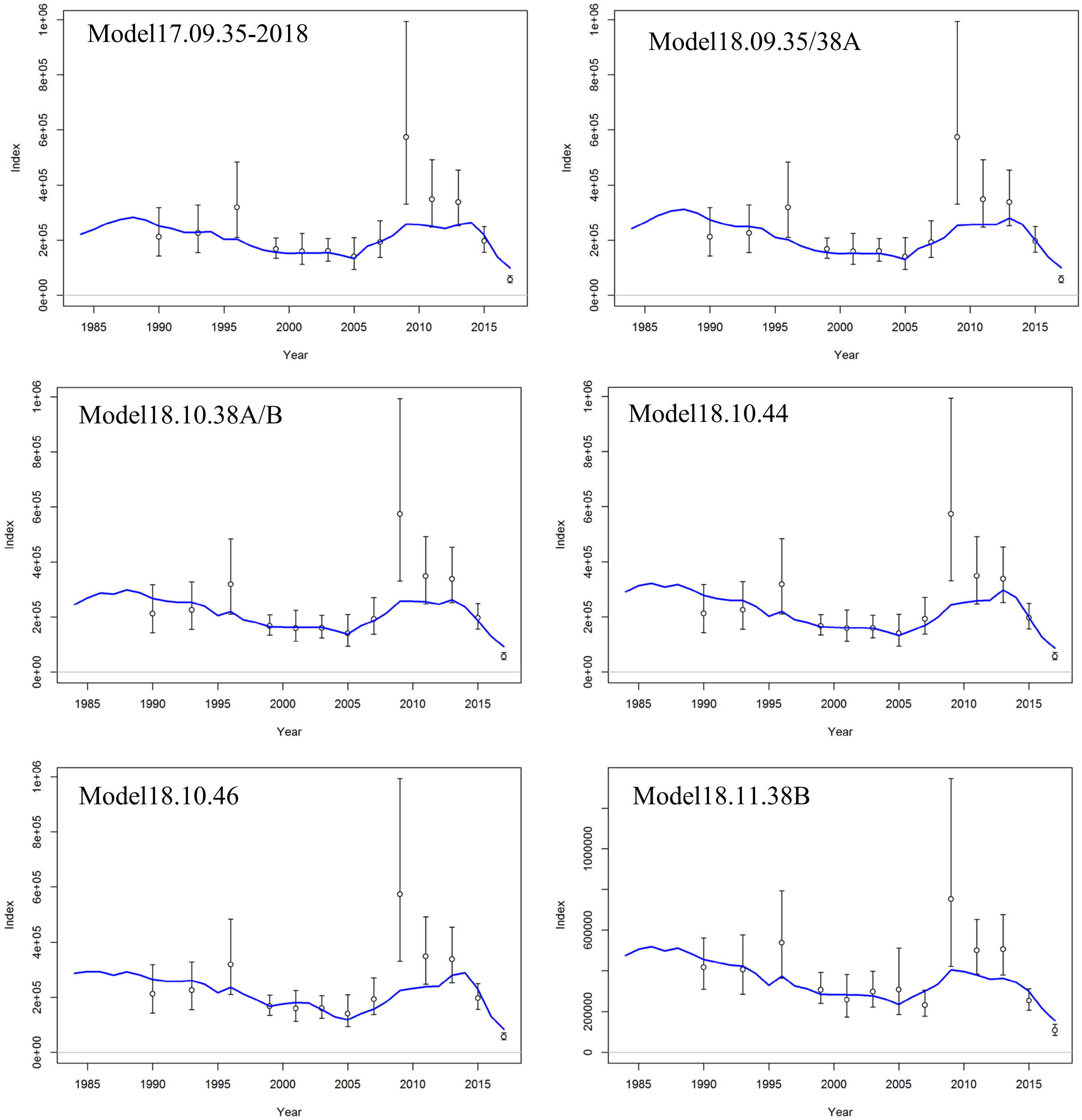


Figure 2.67 Model fits to AFSC bottom trawl survey index.

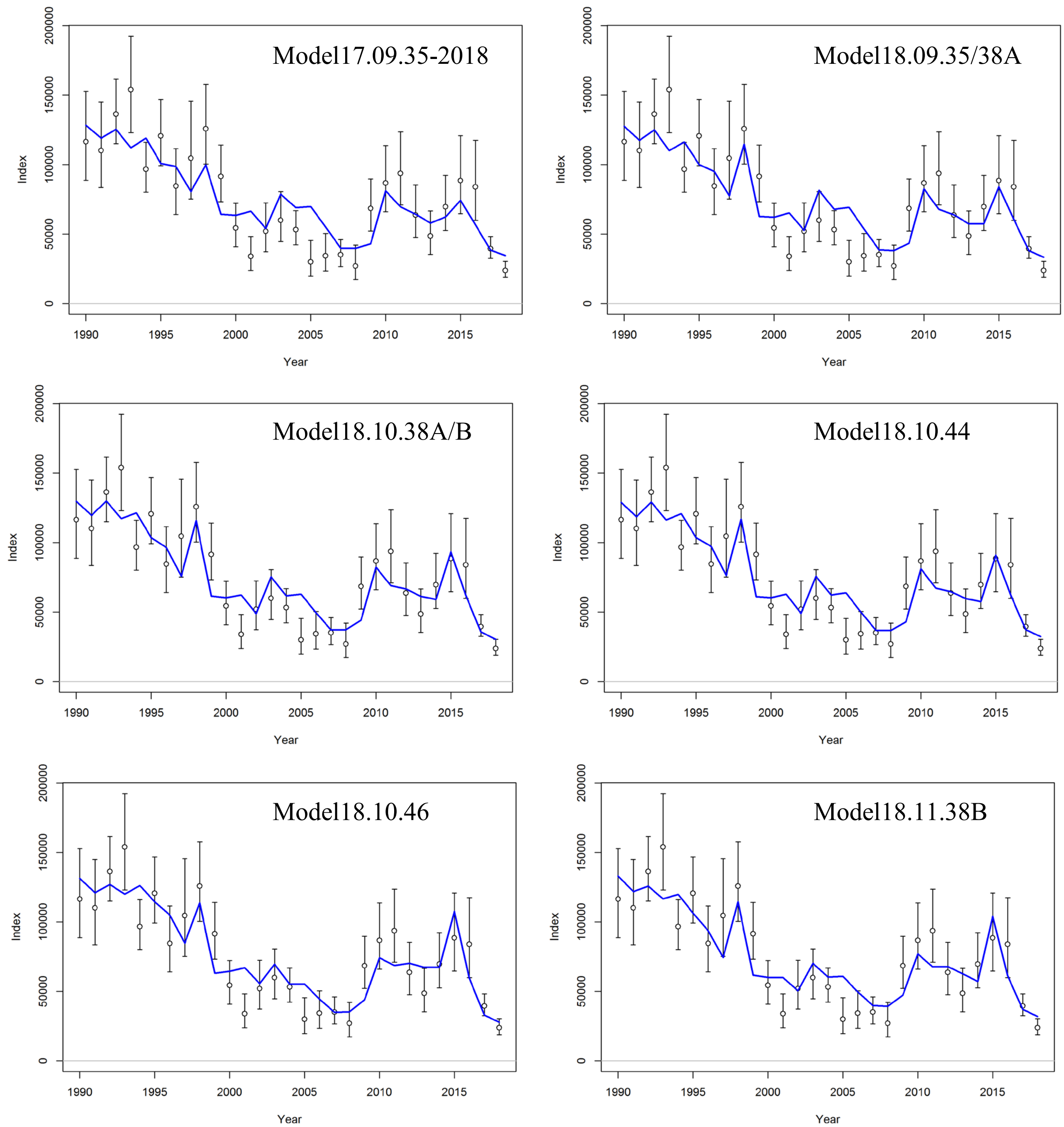


Figure 2.68 Model fits to AFSC longline survey index.

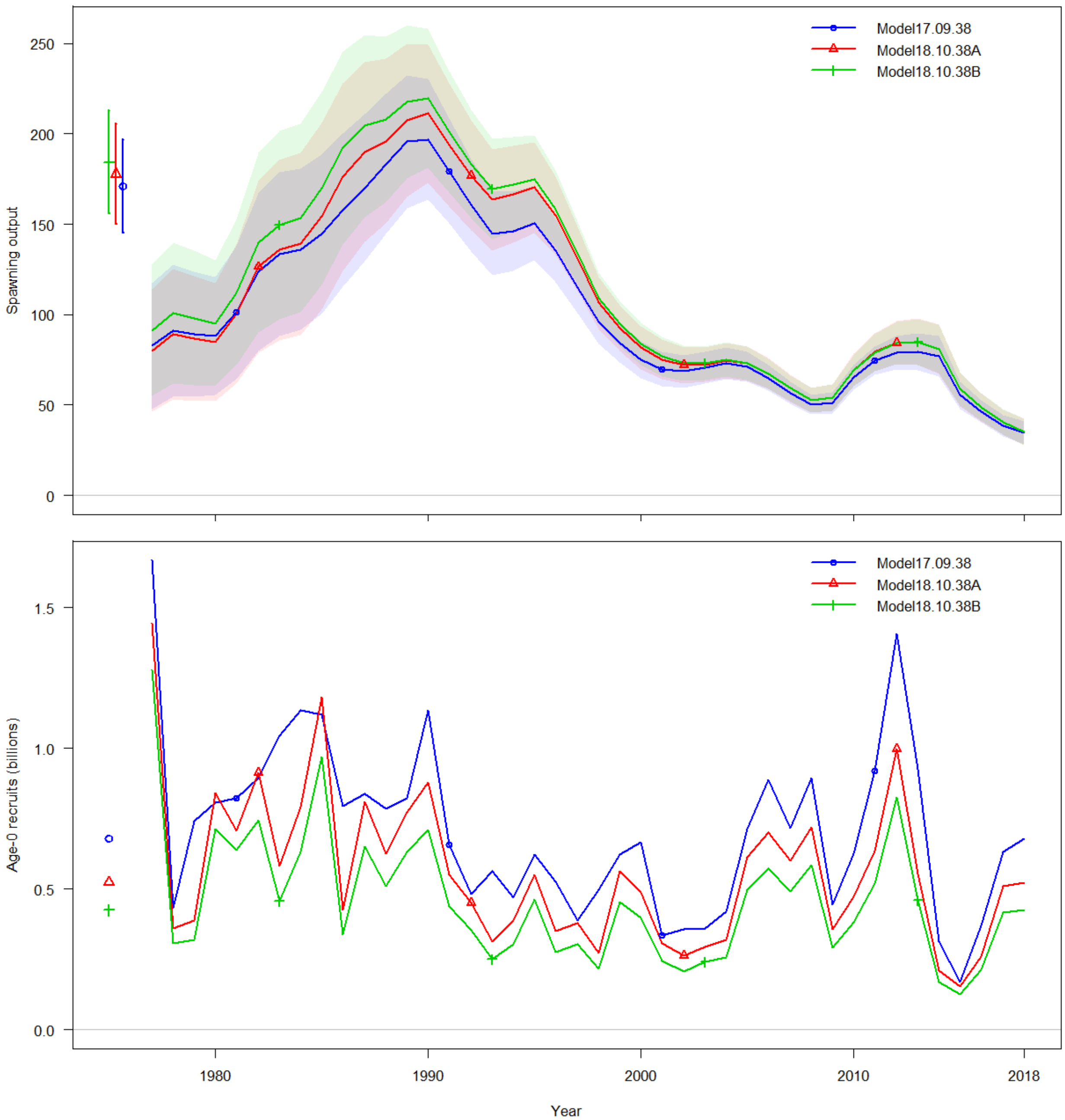


Figure 2.69 Estimates of female spawning biomass (t × 10^3; top) and age-0 recruits (billions; bottom) for Model 18.09.38A, Model 18.10.38A, and Model 18.10.38B.

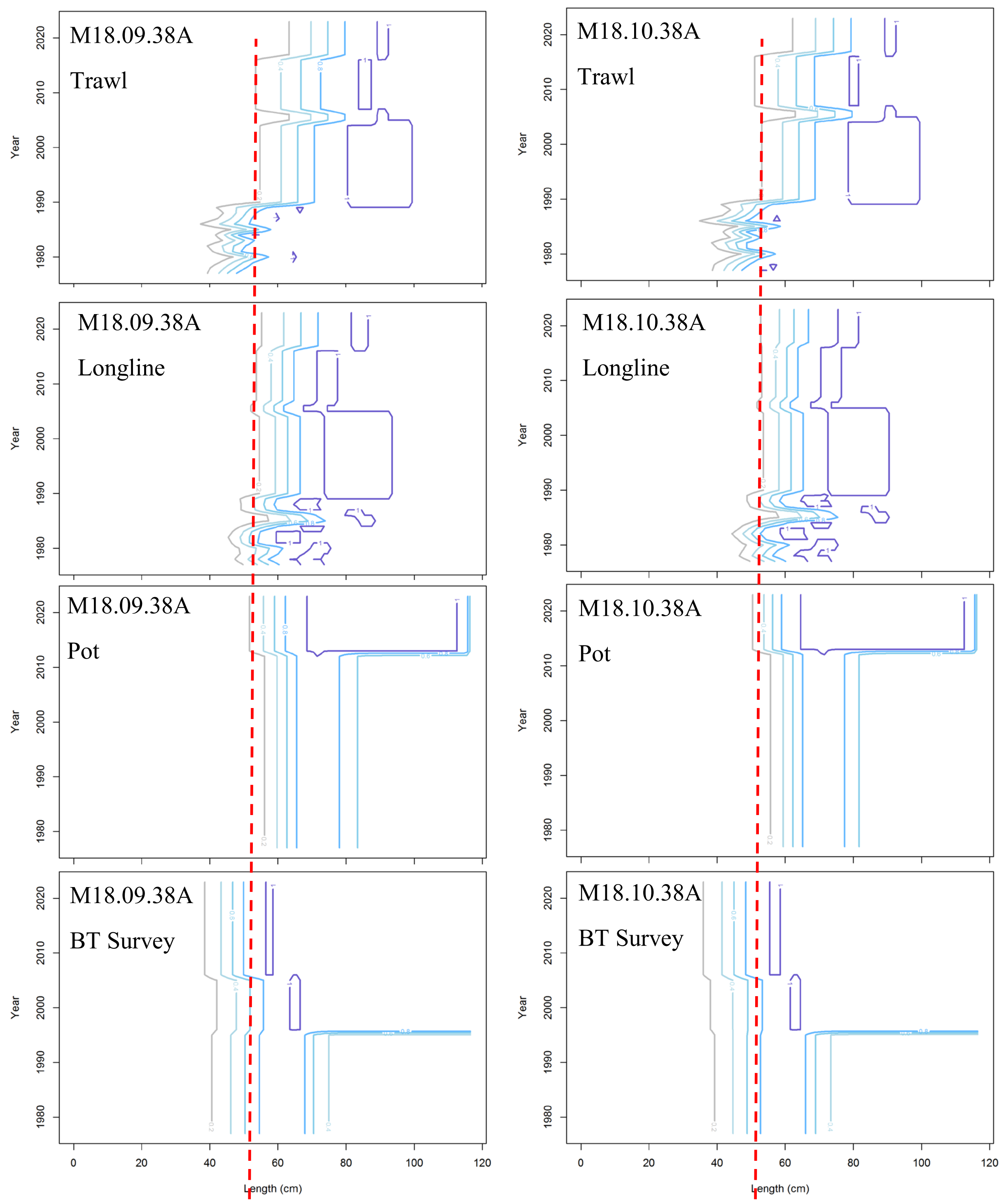


Figure 2.70 Estimates of fishery and AFSC bottom trawl survey selectivities for Model 18.09.38A and Model 18.10.38A. Red dashed line is the size at 50% mature.

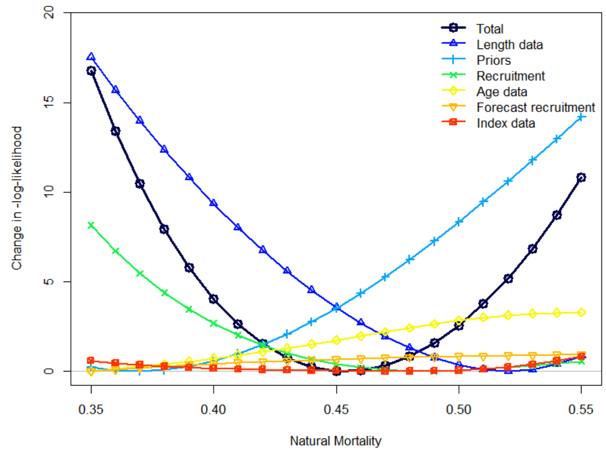


Figure 2.71 Likelihood profile on natural mortality in Model 18.10.38B.

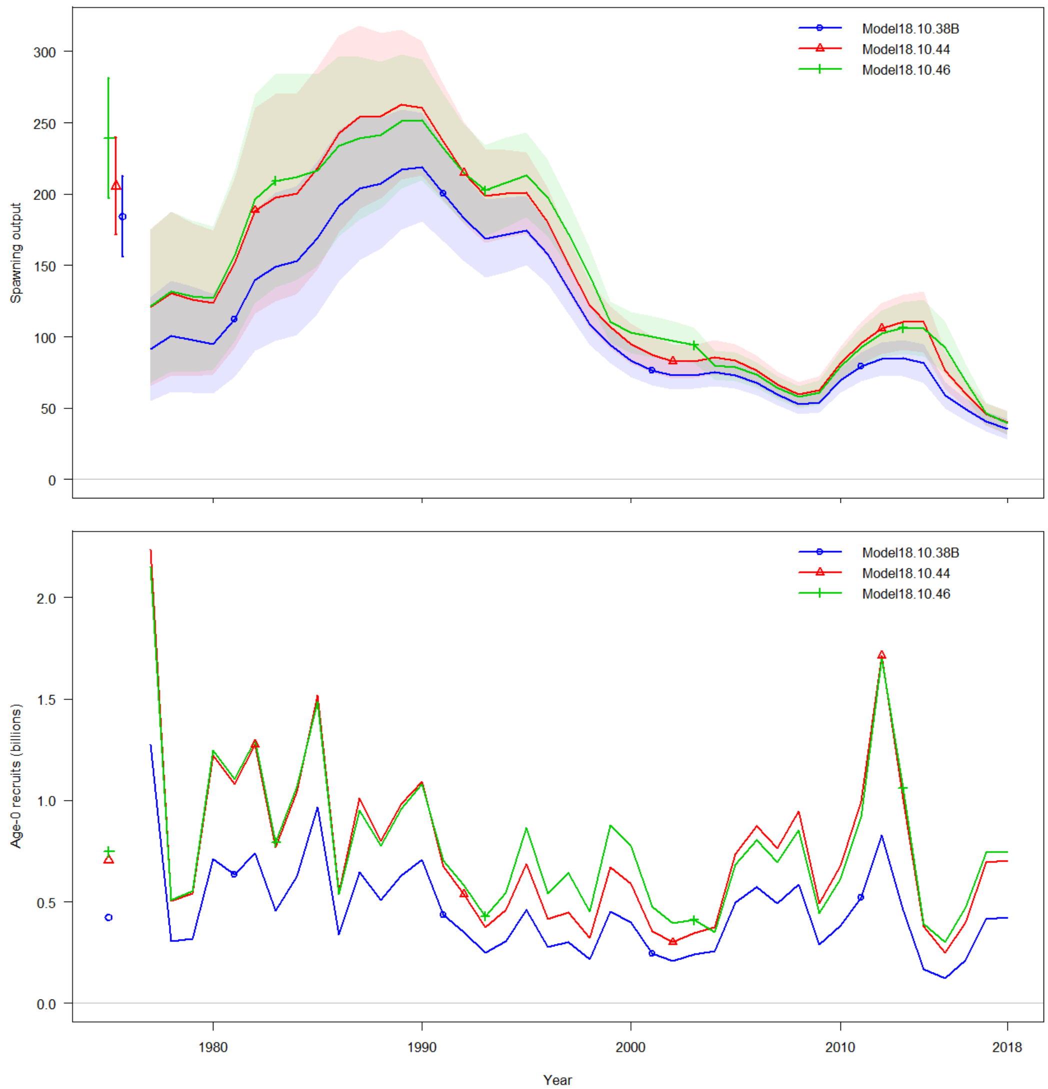


Figure 2.72 Estimates of female spawning biomass (t × 10^3; top) and age-0 recruits (billions; bottom) for Model 18.10.38B, Model 18.10.44, and Model 18.10.46.

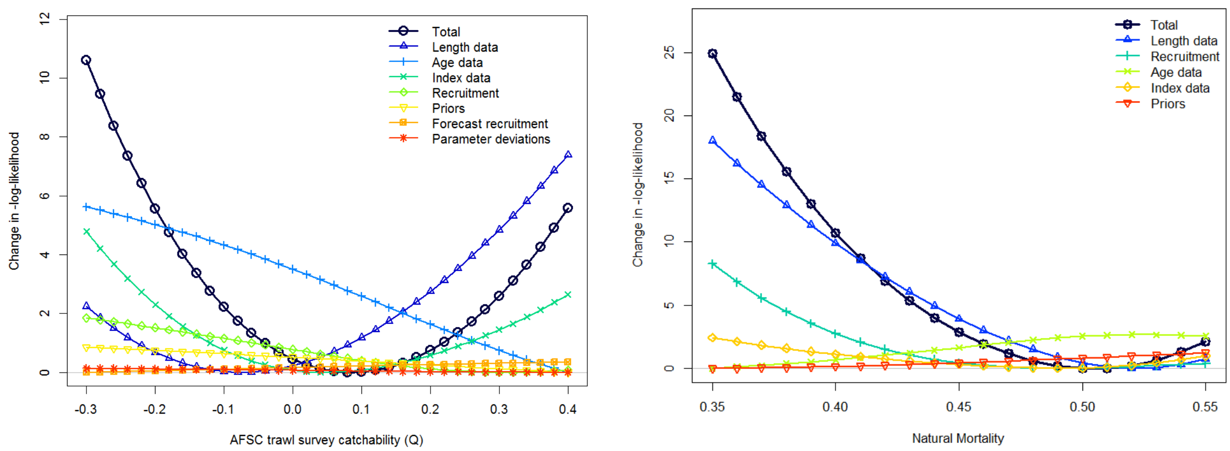


Figure 2.73 Likelihood profile on AFSC trawl survey catchability and natural mortality in Model 18.10.44.

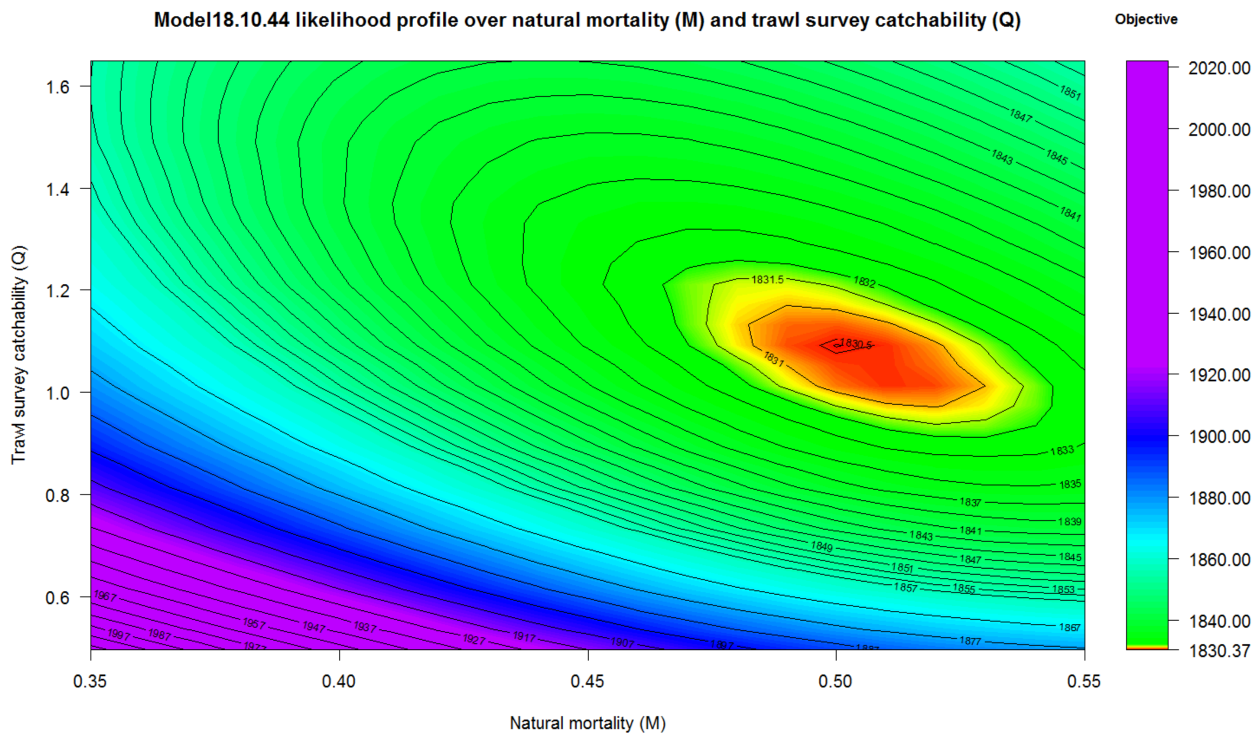


Figure 2.74 Likelihood profile on natural mortality and bottom trawl survey catchability in Model 18.10.44.

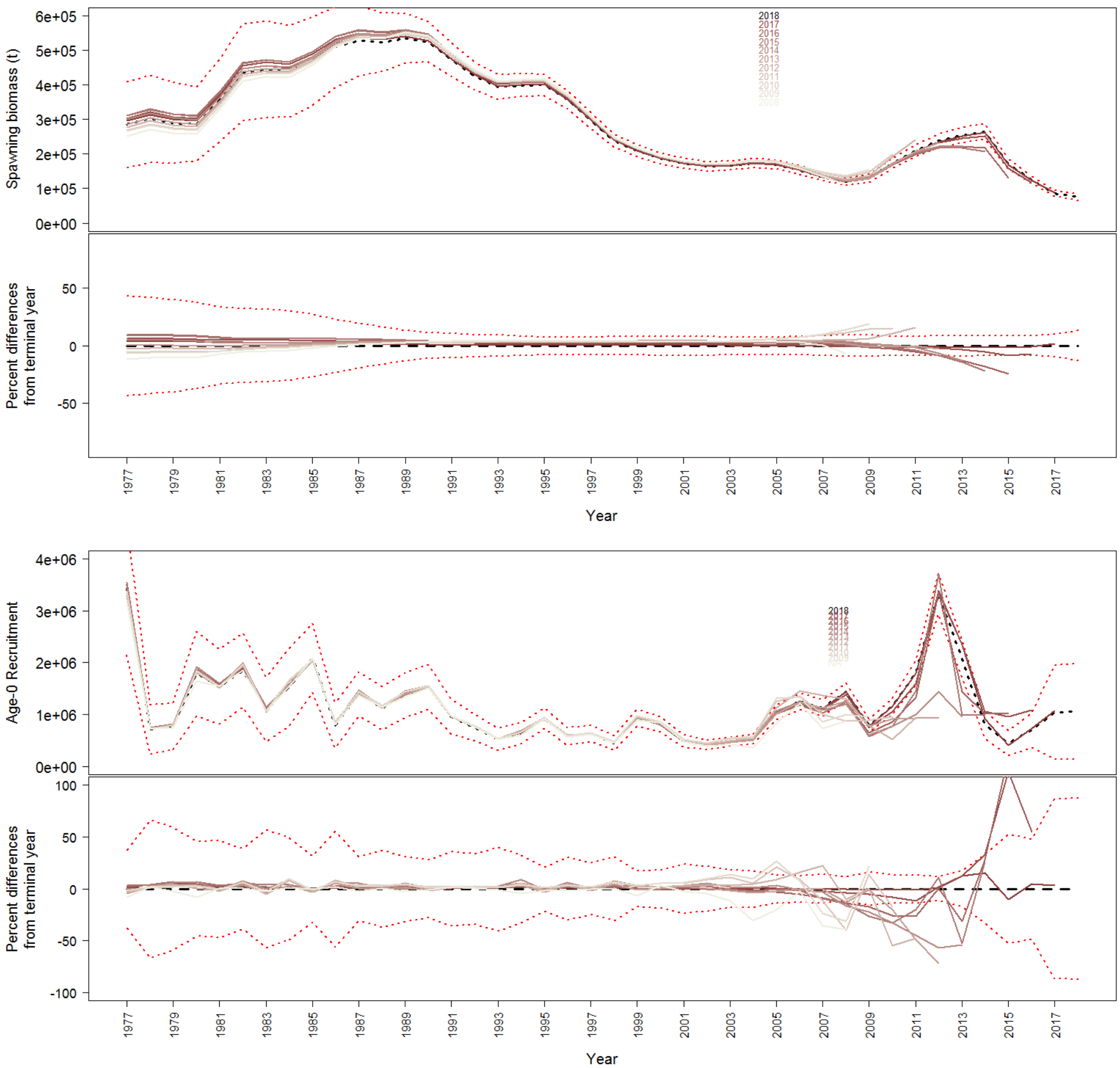


Figure 2.75 Retrospective analysis for Model 18.10.44 for Female spawning biomass (left) age-0 recruits (right).

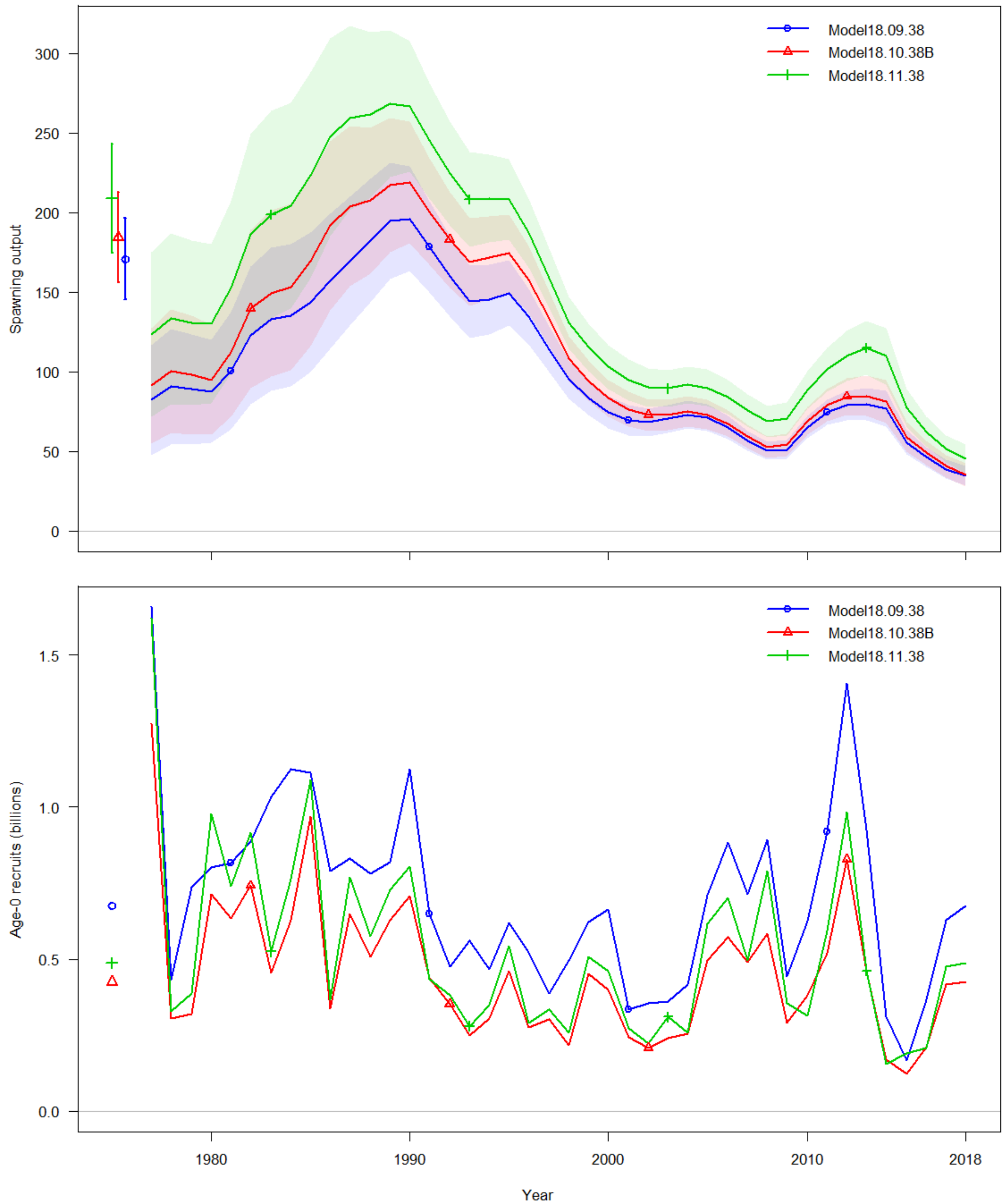


Figure 2.76 Estimates of female spawning biomass (t × 10^3; top) and age-0 recruits (billions; bottom) for Model 18.09.38A, Model 18.10.38B, and Model 18.11.38B.

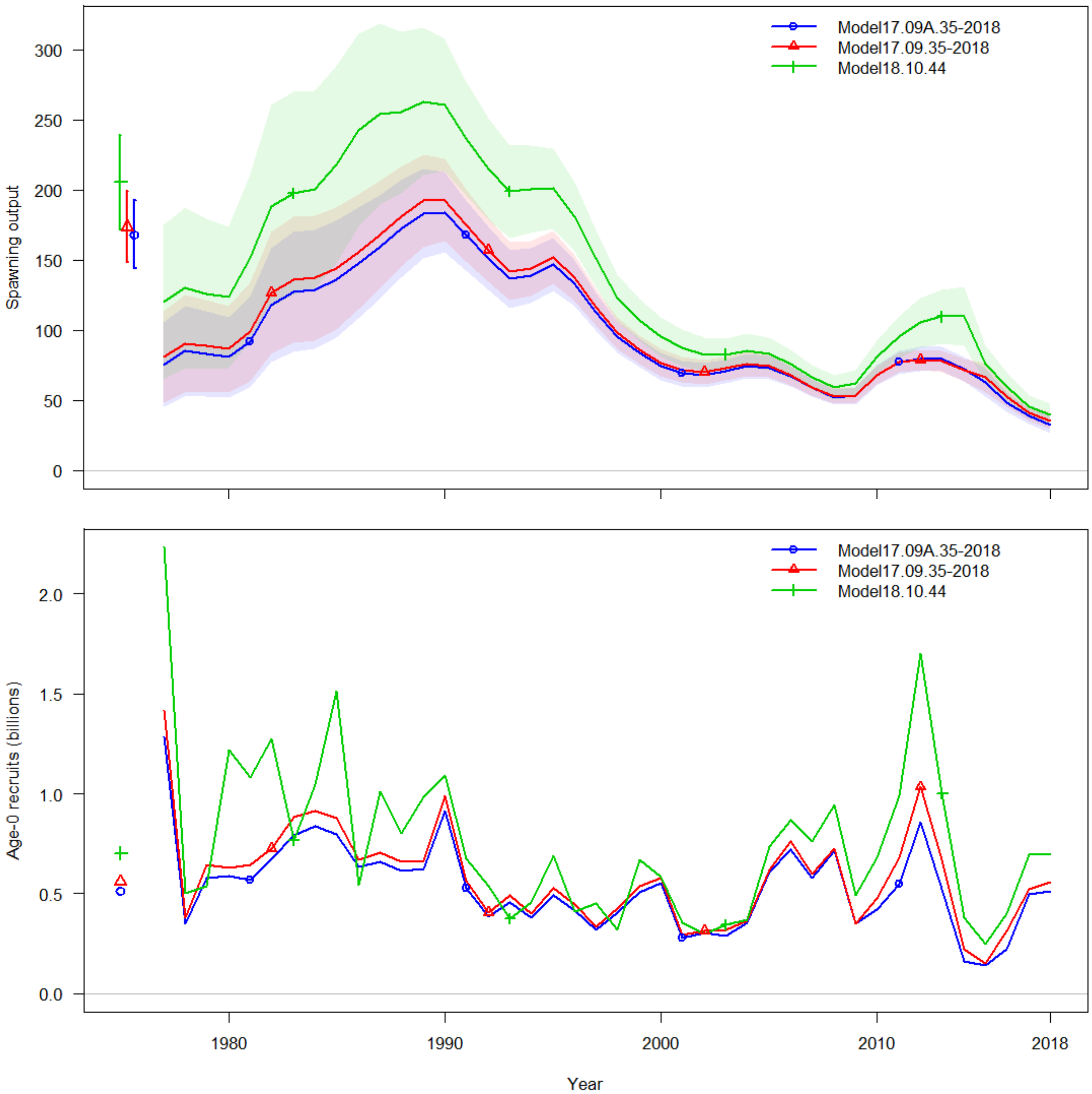


Figure 2.77 Estimates of female spawning biomass (t × 10^3; top) and age-0 recruits (billions; bottom) for Model 17.09A.35-2018, Model 17.09.35-2018, and Model 18.10.44.

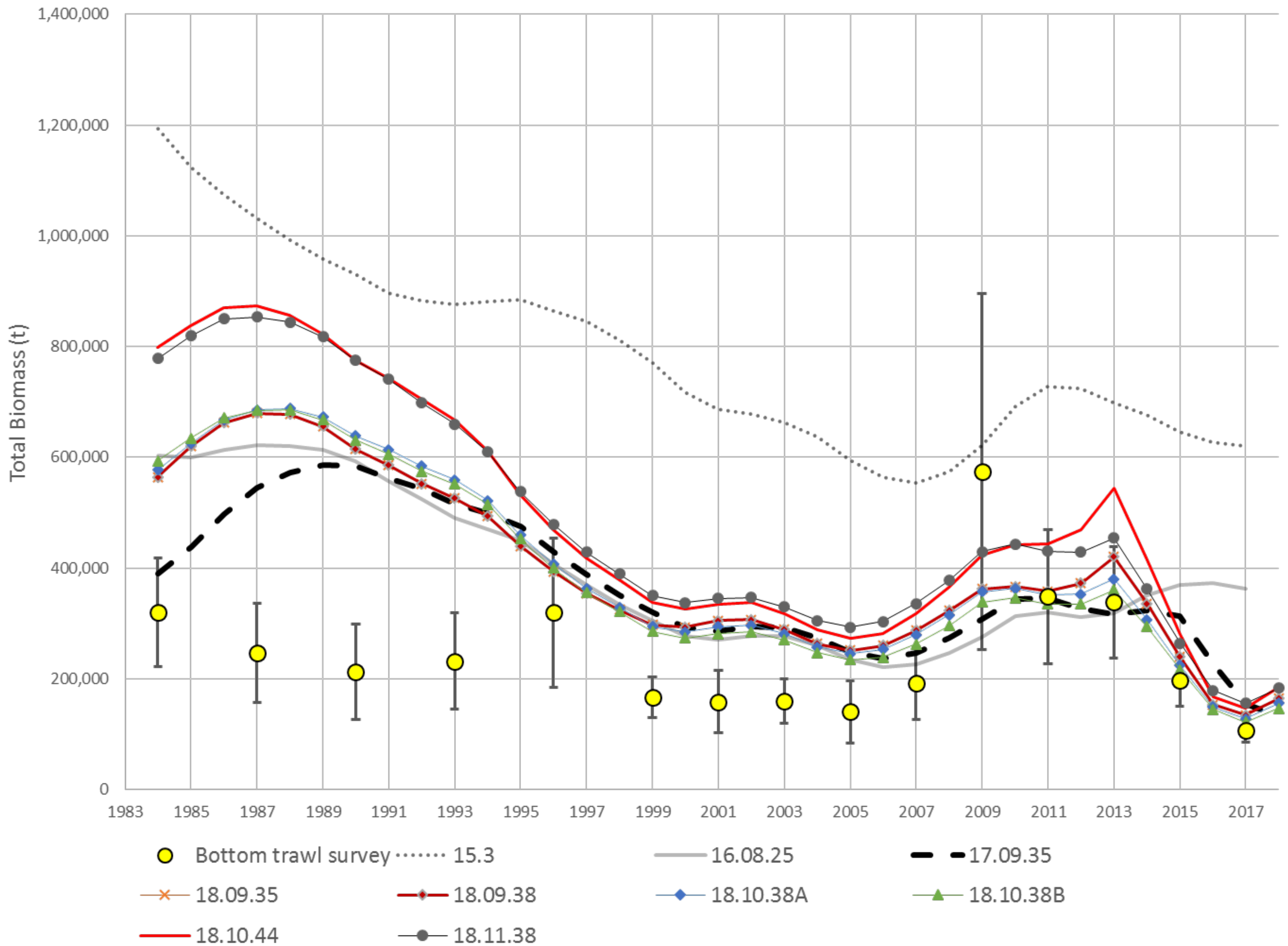


Figure 2.78 Total biomass estimates from reviewed models and NMFS bottom trawl survey biomass estimates with 95% confidence bounds.

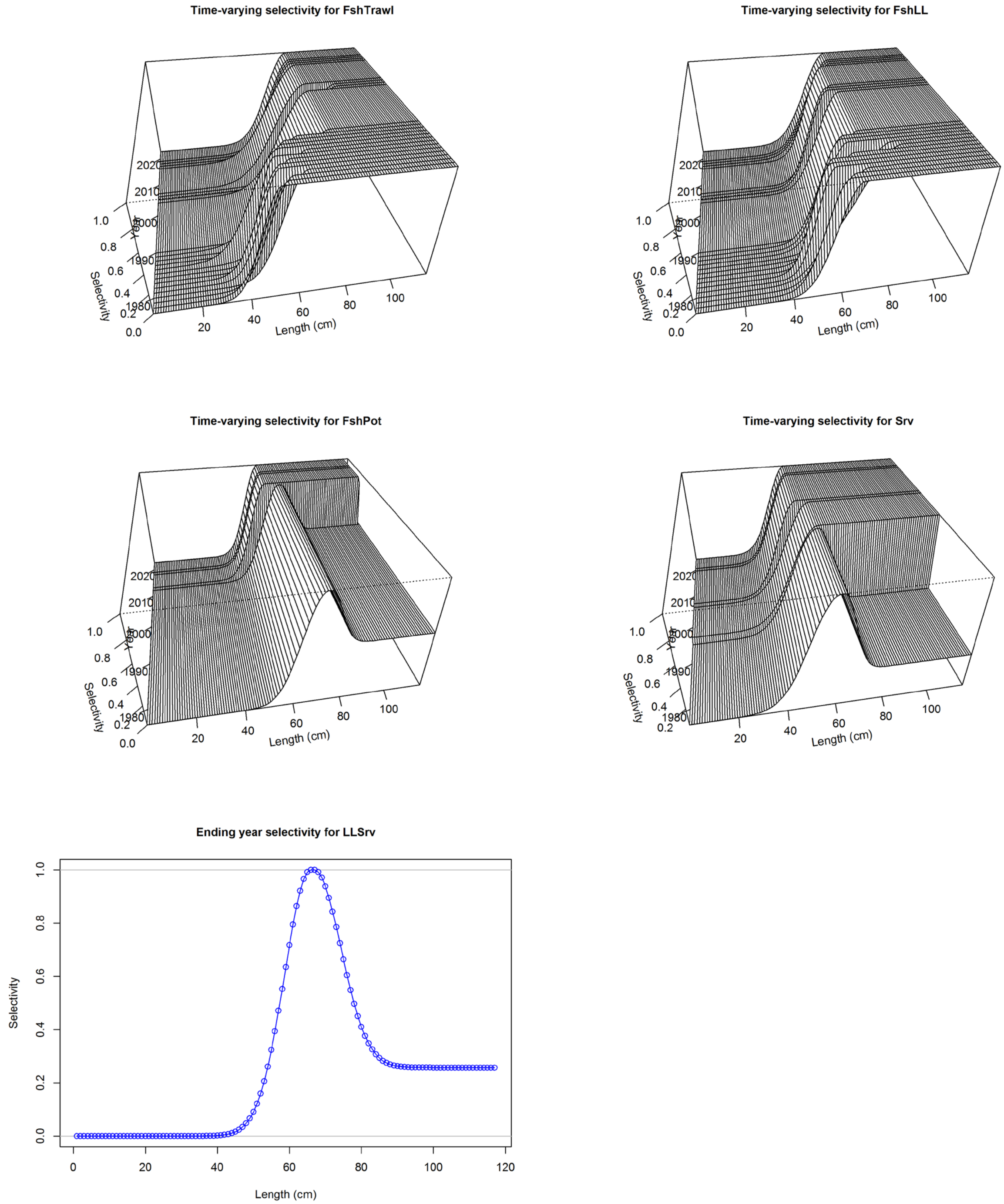


Figure 2.79 Selectivity curves for Model 18.10.44 Trawl fishery (FshTrawl), longline fishery (FshLL), pot fishery (FshPot), NMFS bottom trawl survey (Srv), and AFSC Longline survey (LLSrv) length composition data.

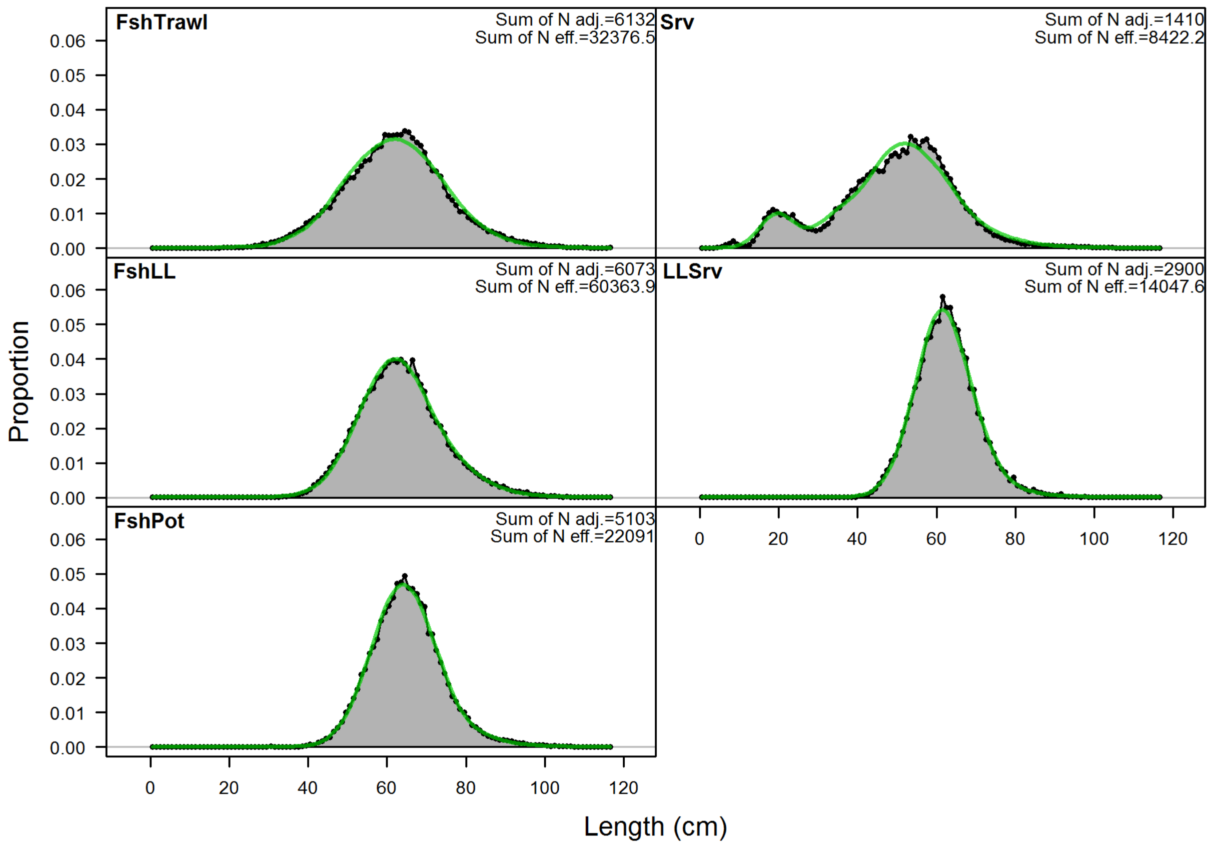


Figure 2.80 Overall Model 18.10.44 fits to Trawl fishery (FshTrawl), longline fishery (FshLL), pot fishery (FshPot), NMFS bottom trawl survey (Srv), and AFSC Longline survey (LLSrv) length composition data.

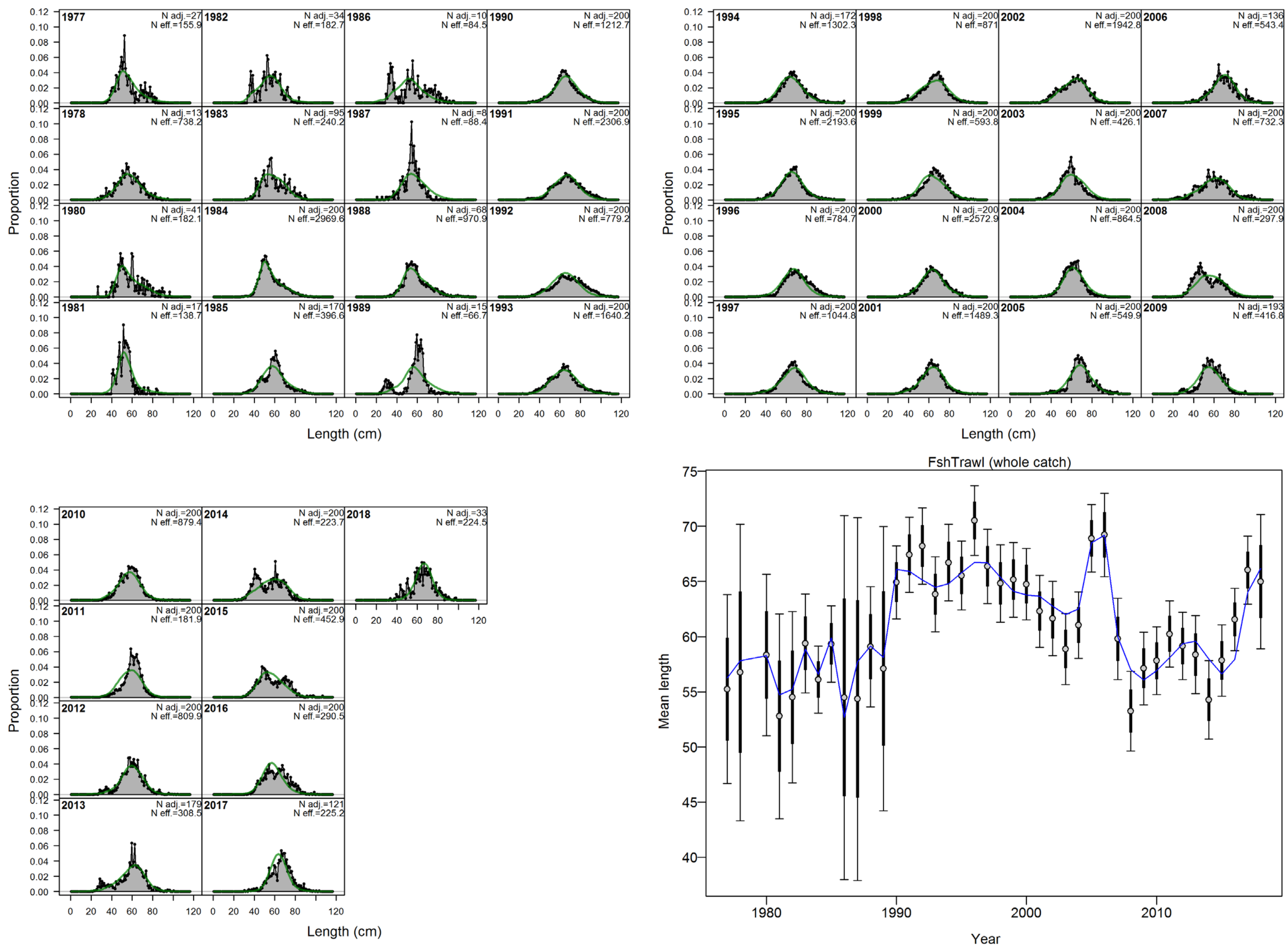


Figure 2.81 Trawl fishery length composition and Model 18.10.44 fit (top and left) and mean length (cm; right bottom).

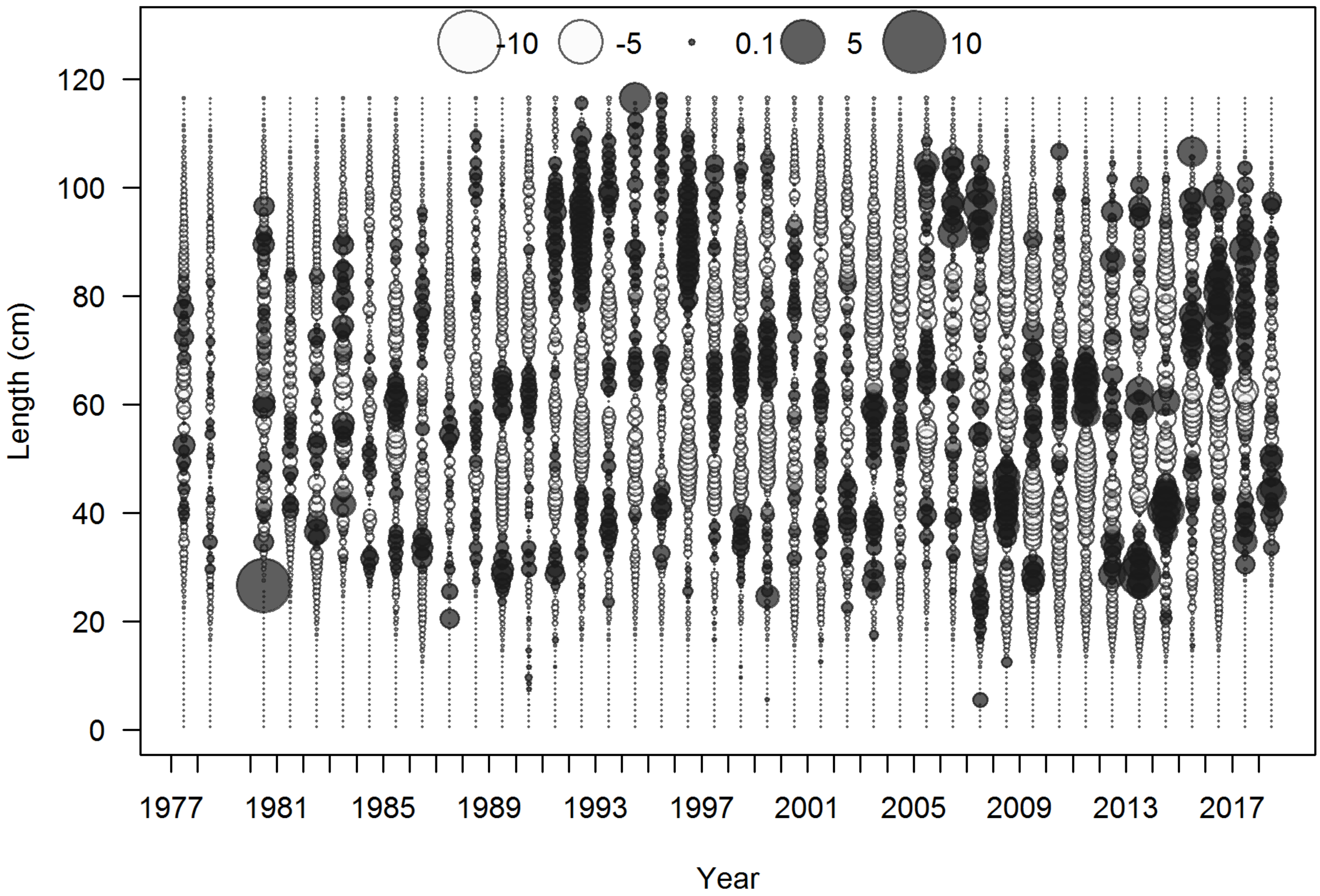


Figure 2.82 Trawl fishery length composition Pearson residuals (max = 7.59; right bottom).

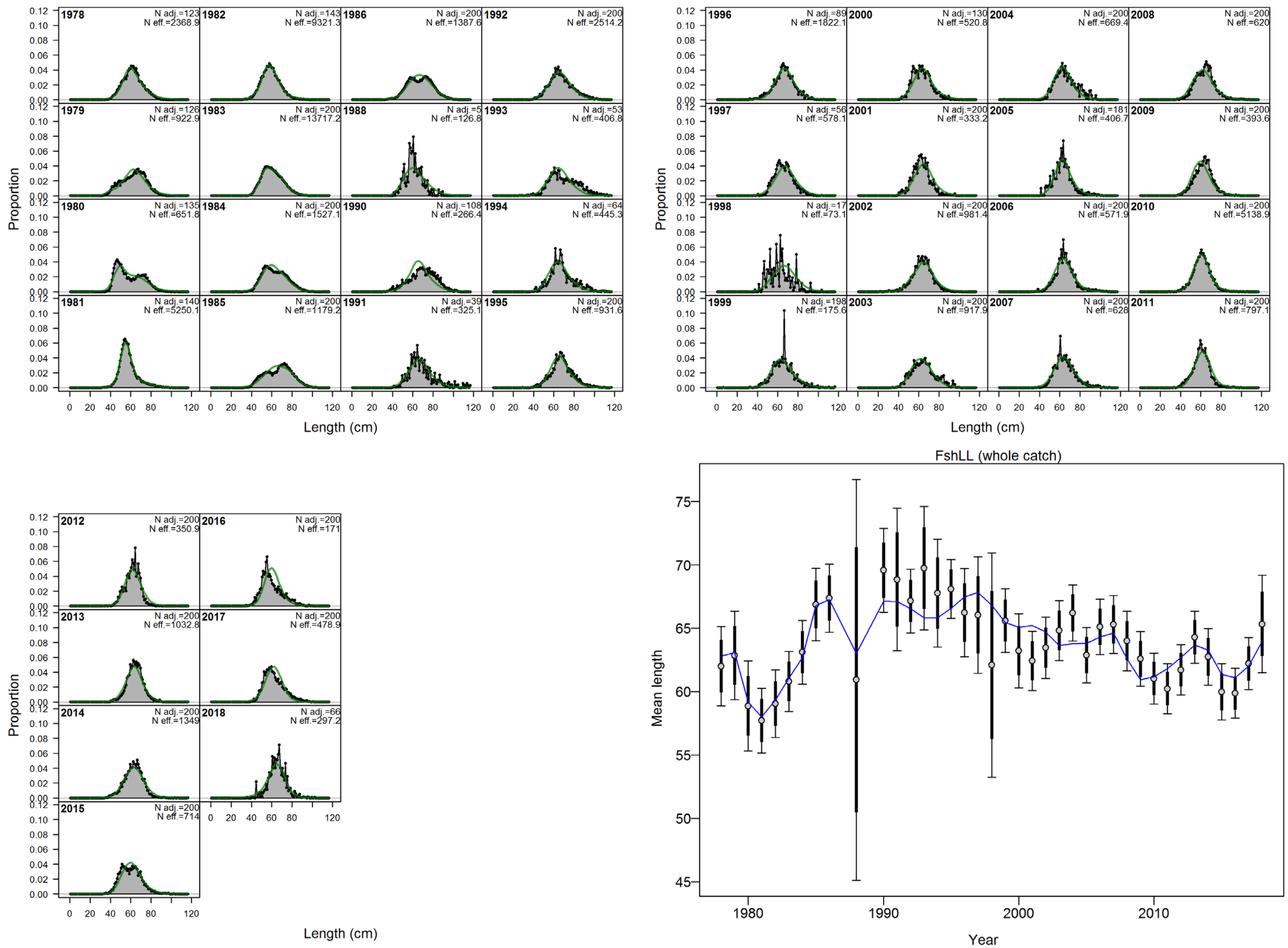


Figure 2.83 Longline fishery length composition and Model 18.10.44 fit (top and left) and mean length (cm; right bottom).

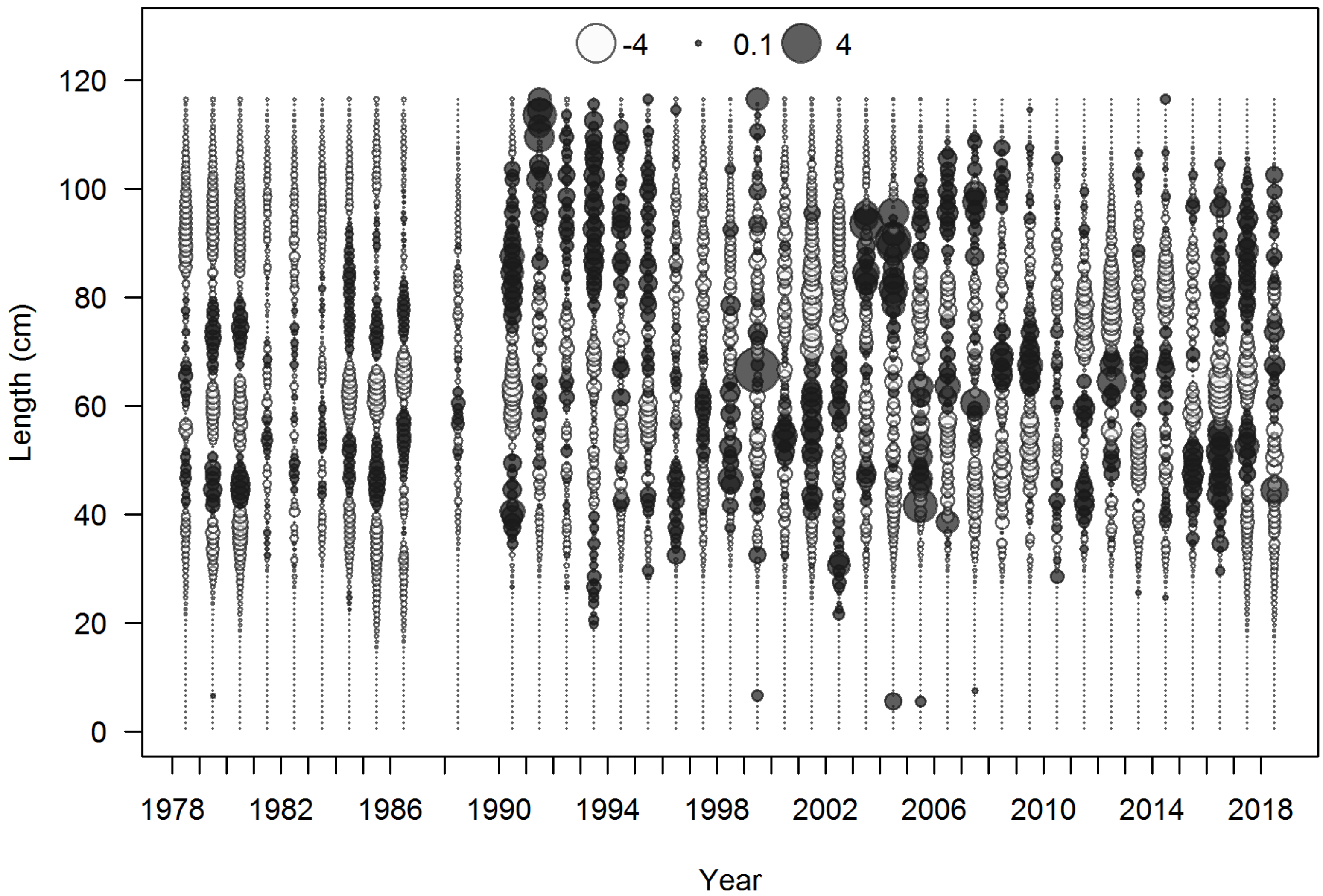


Figure 2.84 Longline fishery length composition and Model 18.10.44 fit (top and left) and Pearson residuals (max = 5.3; right bottom).

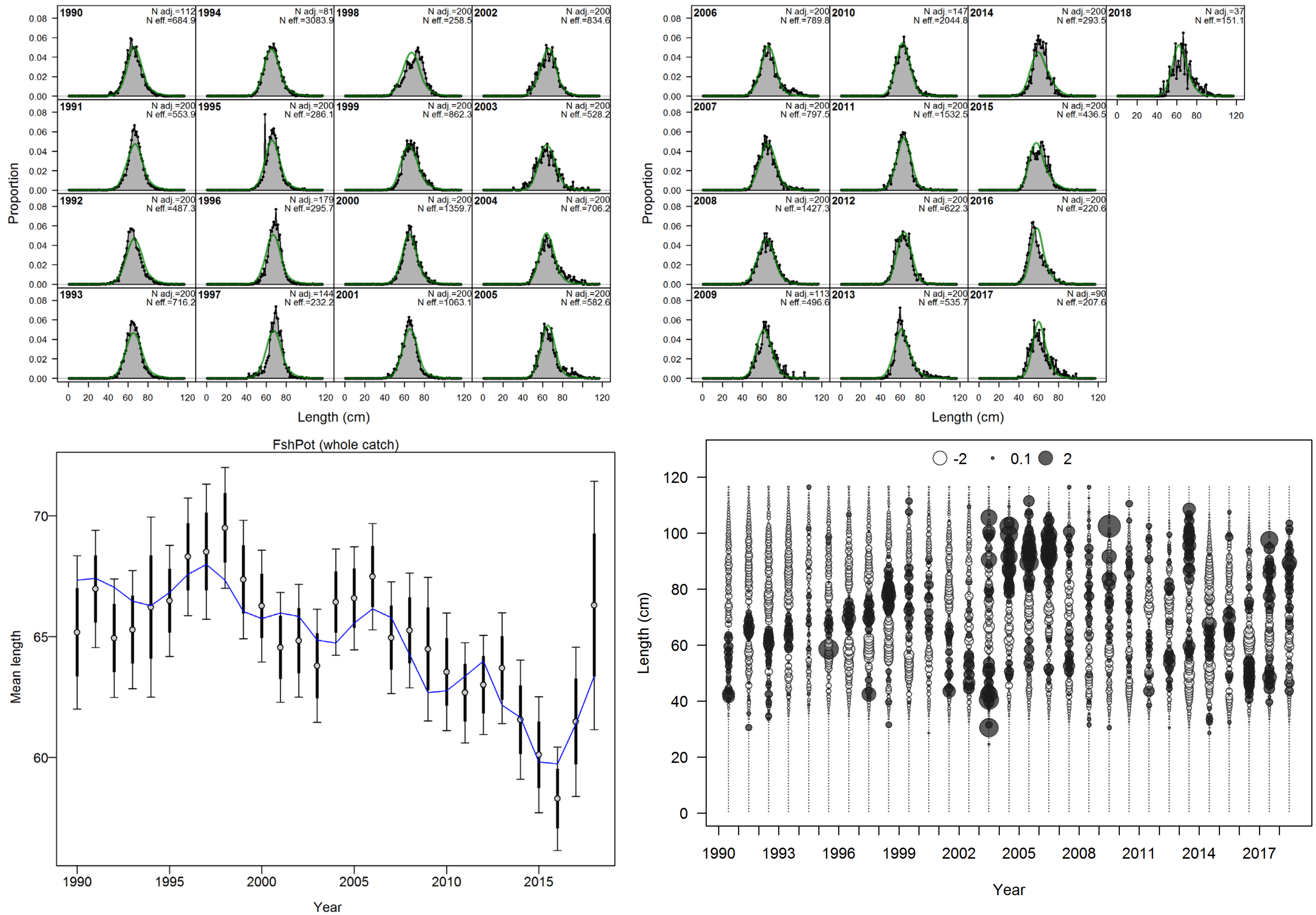


Figure 2.85 Pot fishery length composition and Model 18.10.44 fit (top), mean length (bottom left), and Pearson residuals (max=4.87; bottom right).

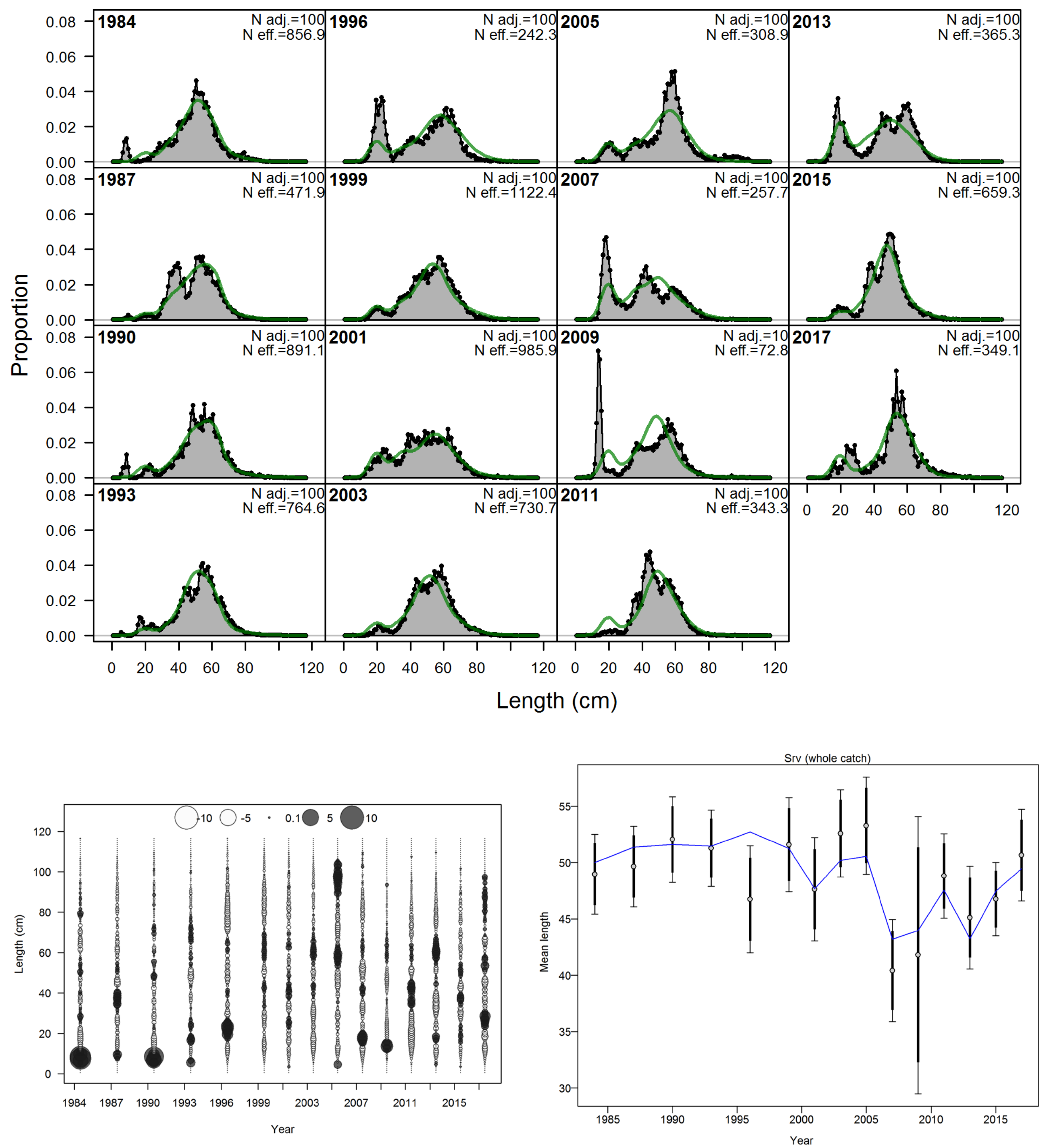


Figure 2.86 NMFS bottom trawl survey length composition and Model 18.10.44 fit (top), Pearson residuals (left bottom), and mean length (cm; right bottom).

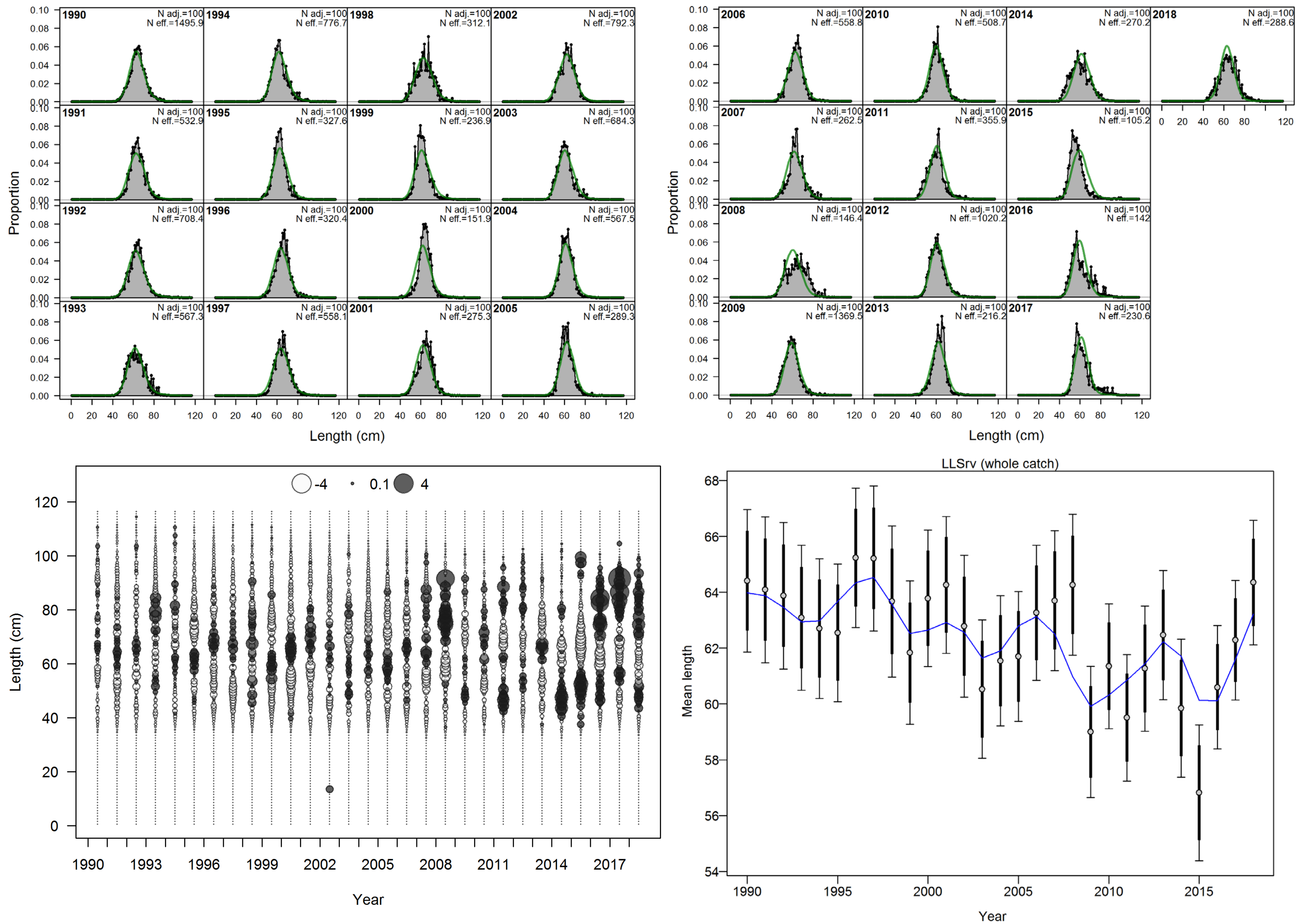


Figure 2.87 AFSC Longline survey length composition and Model 18.10.44 fit (top), Pearson residuals (left bottom), and mean length (cm; right bottom).

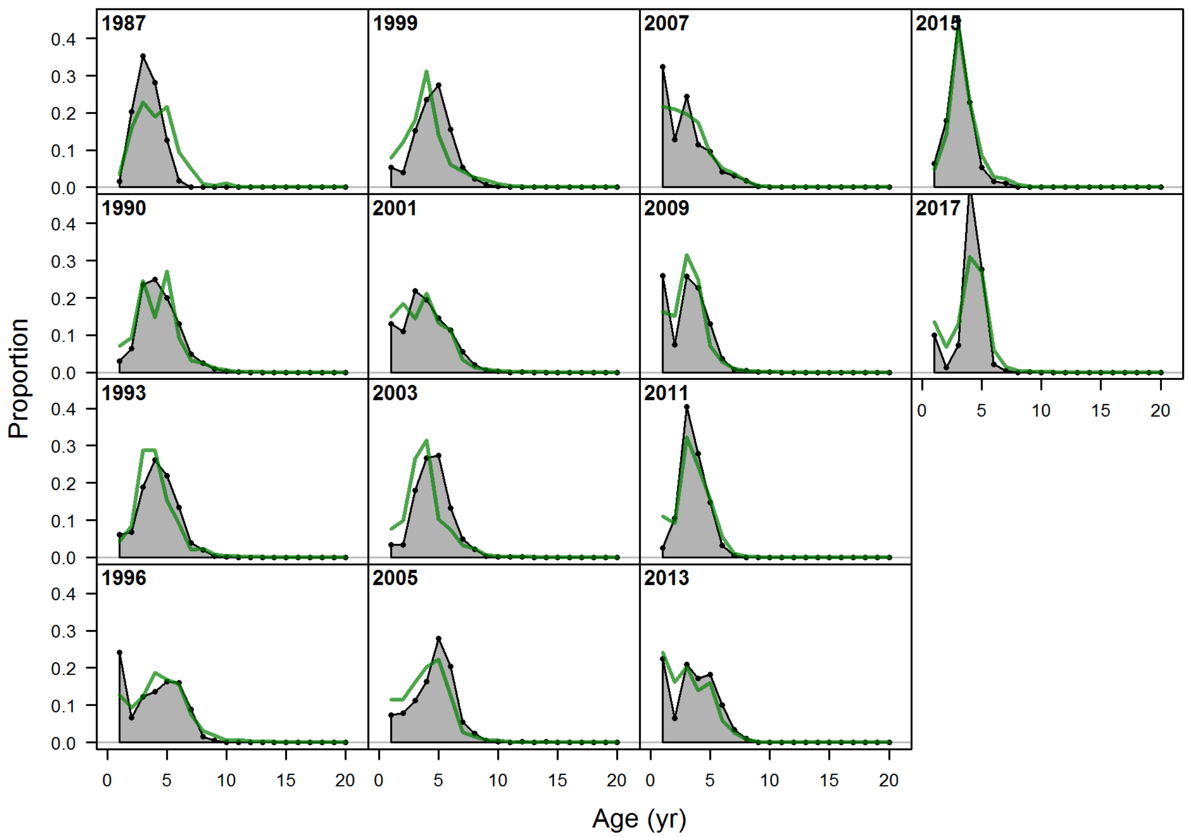


Figure 2.88 NMFS bottom trawl survey (Srv) age composition and Model 18.10.44 fit (left). Note the age data fits are not included in the objective function.

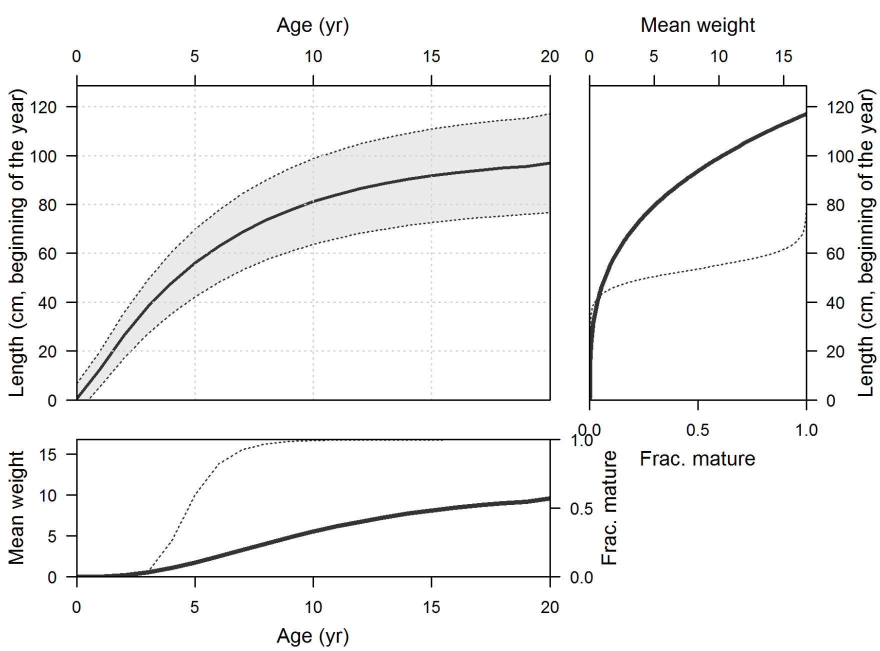


Figure 2.89 Model 18.10.44 length at age, weight at age, weight at length, and fraction mature at length, weight, and age.

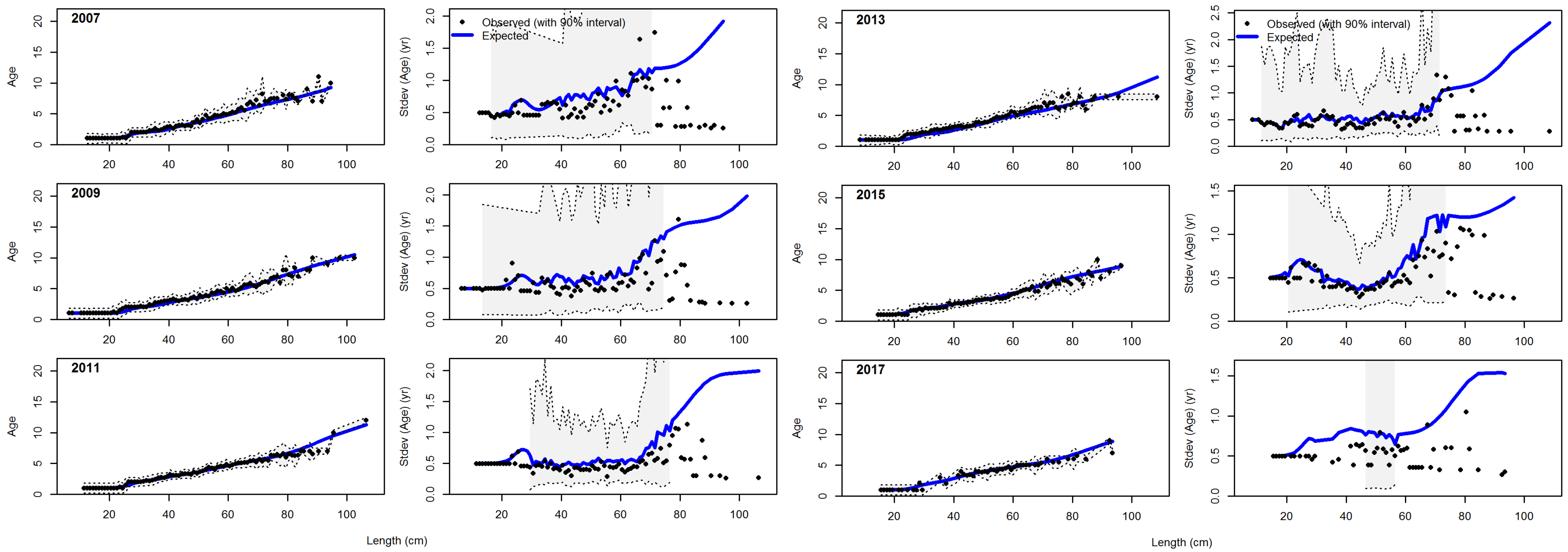


Figure 2.90 NMFS bottom trawl survey (Srv) conditional length-at-age data and Model 18.10.44 fit.

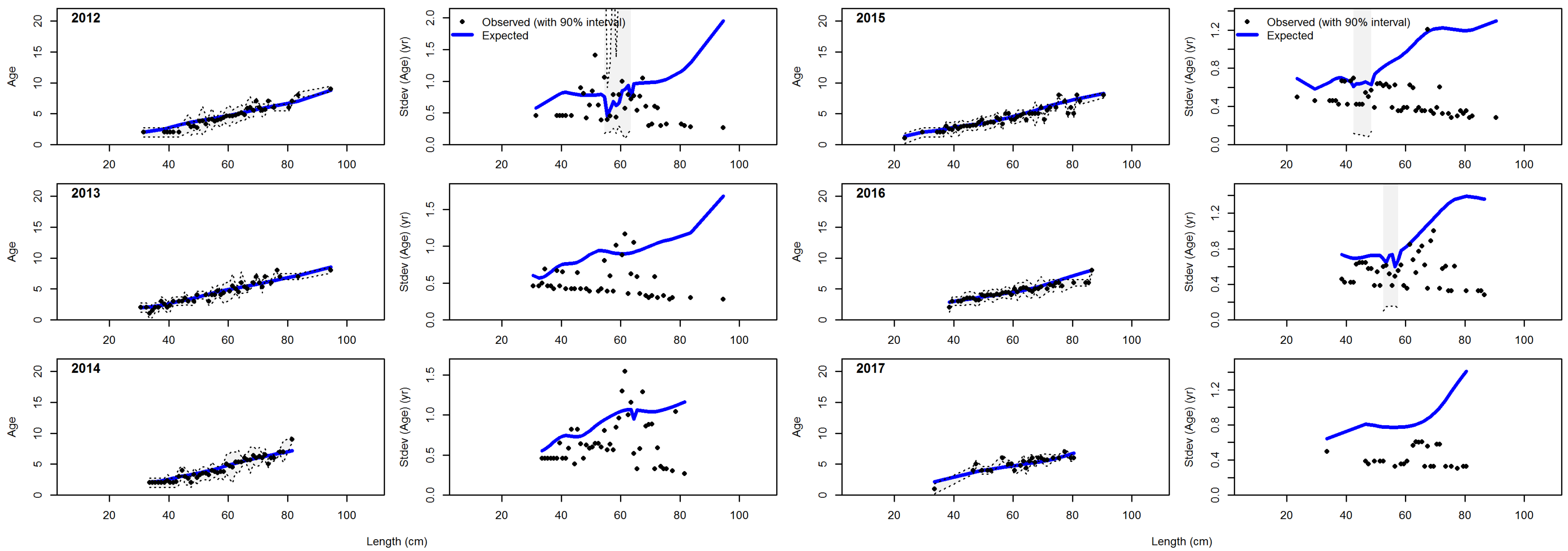


Figure 2.91 Trawl fishery conditional length-at-age data and Model 18.10.44 fit.

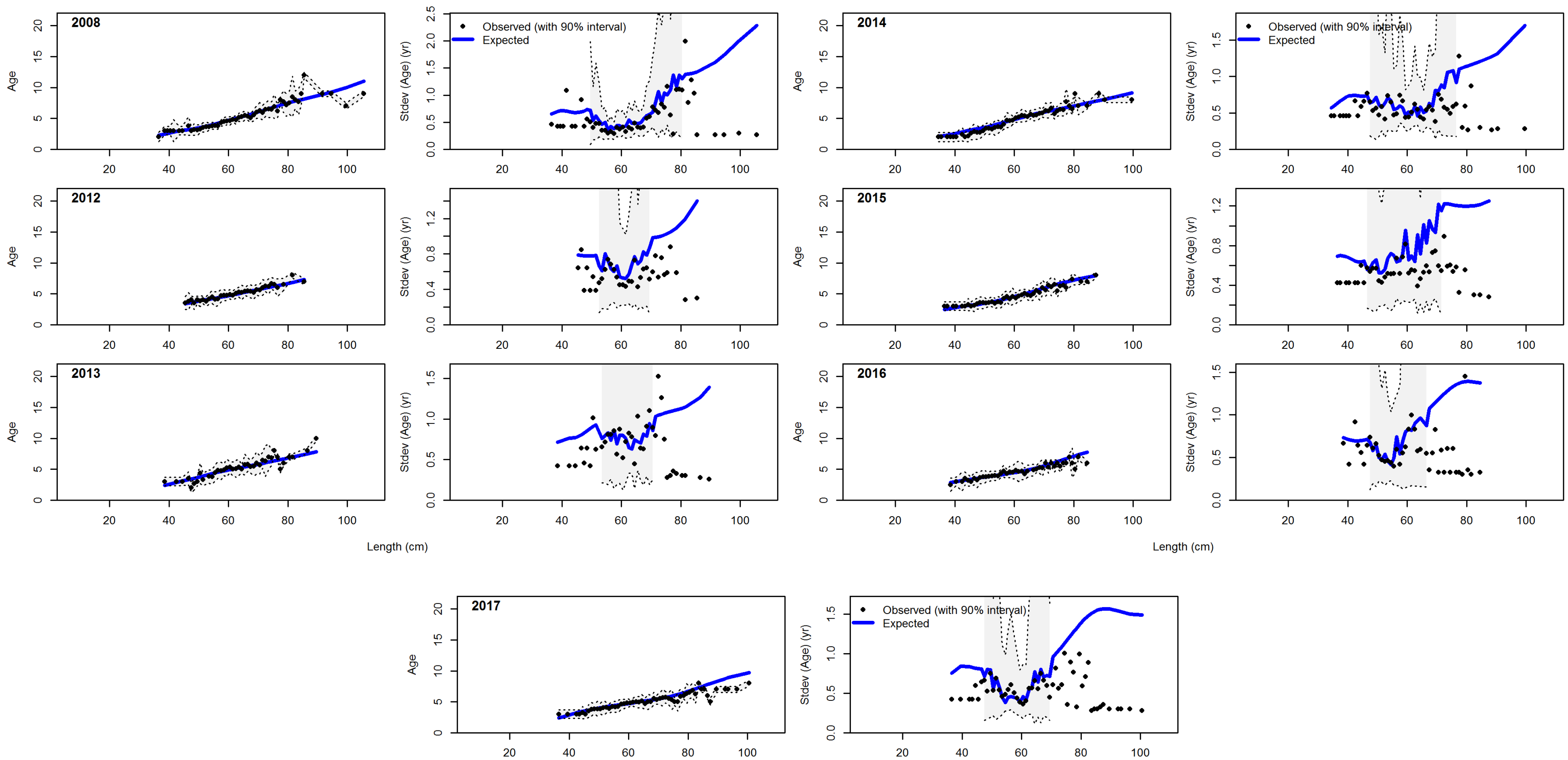


Figure 2.92 Longline fishery conditional length-at-age data and Model 18.10.44 fit.

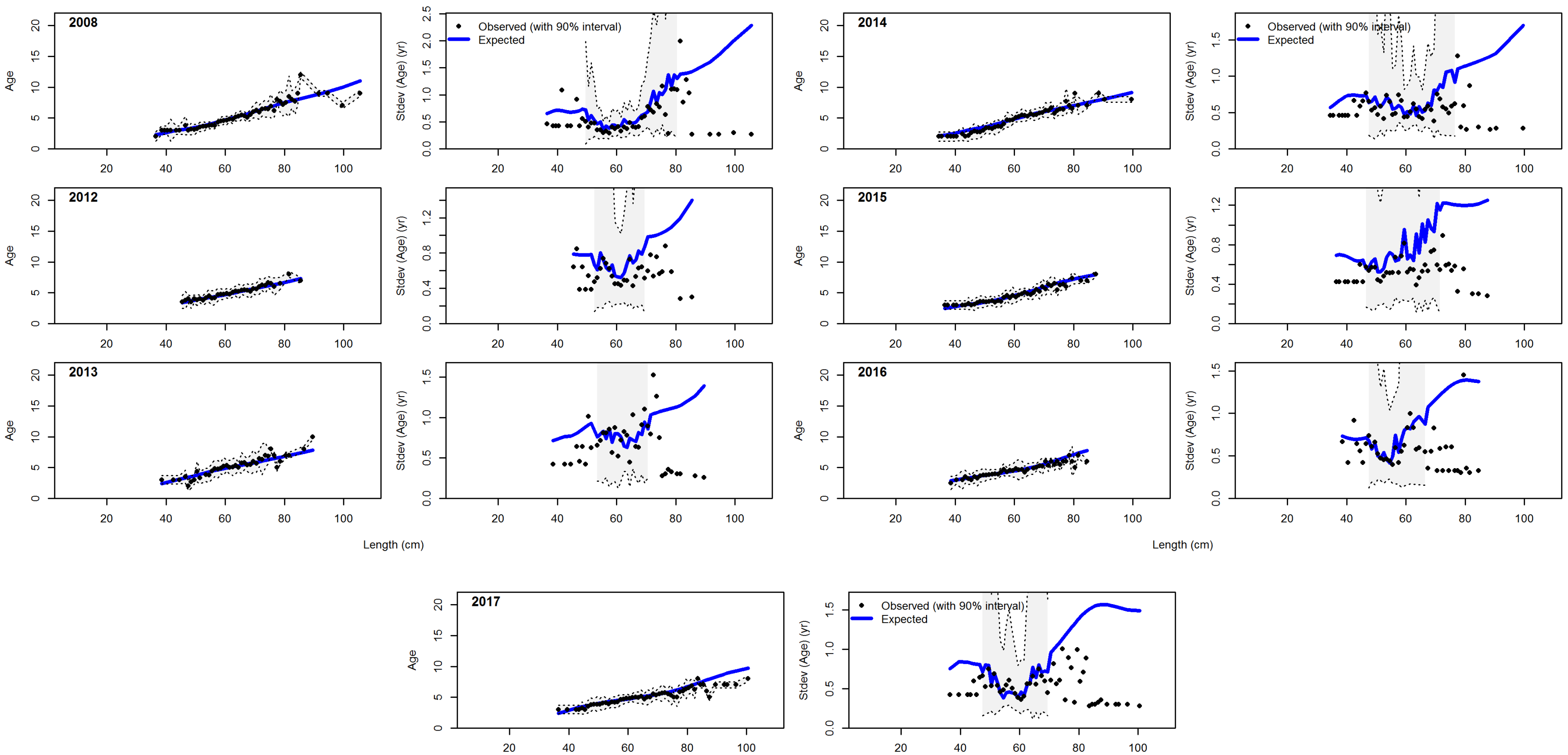


Figure 2.93 Pot fishery conditional length-at-age data and Model 18.10.44 fit.

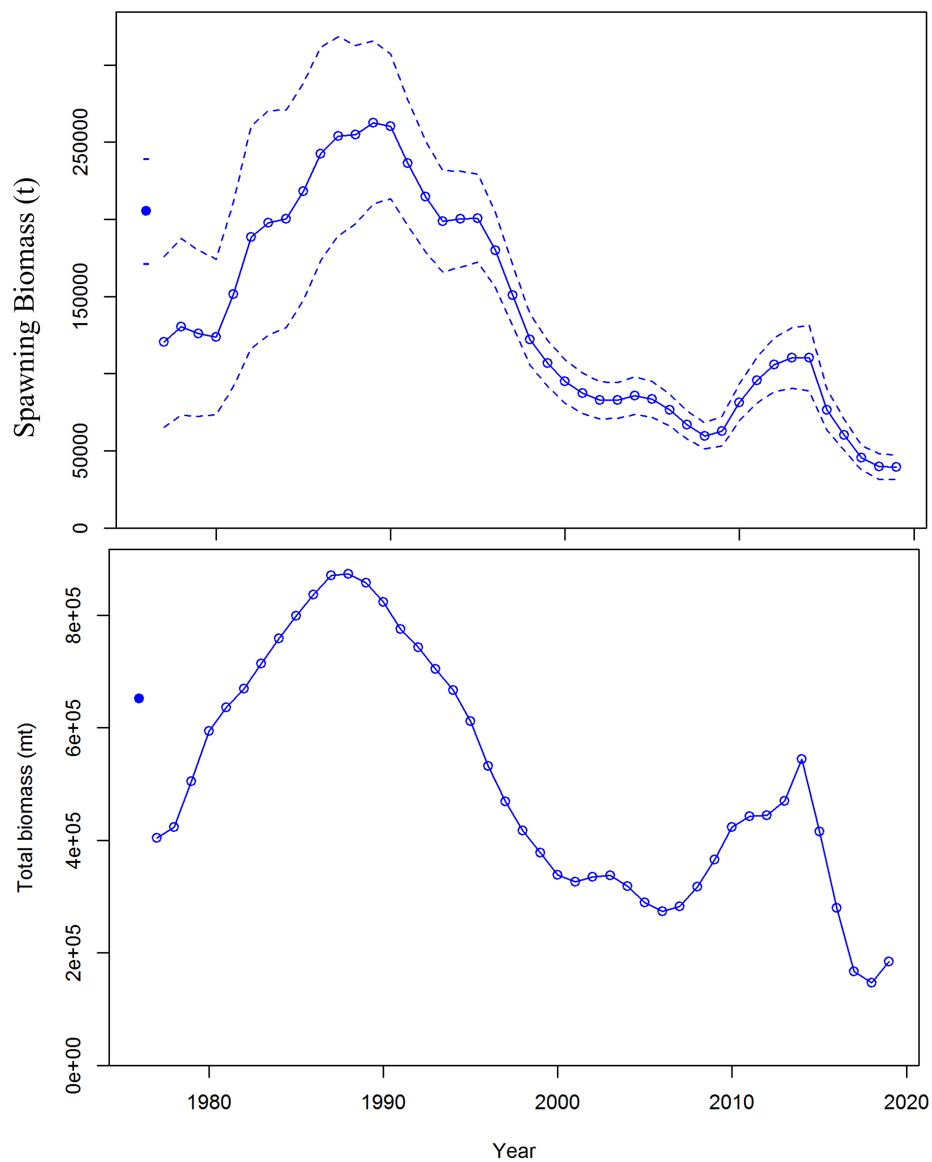


Figure 2.94 Model 18.10.44 predicted spawning output (femal spawning biomass; t) with 95% asymtotic error intervals (top) and total biomass (t).

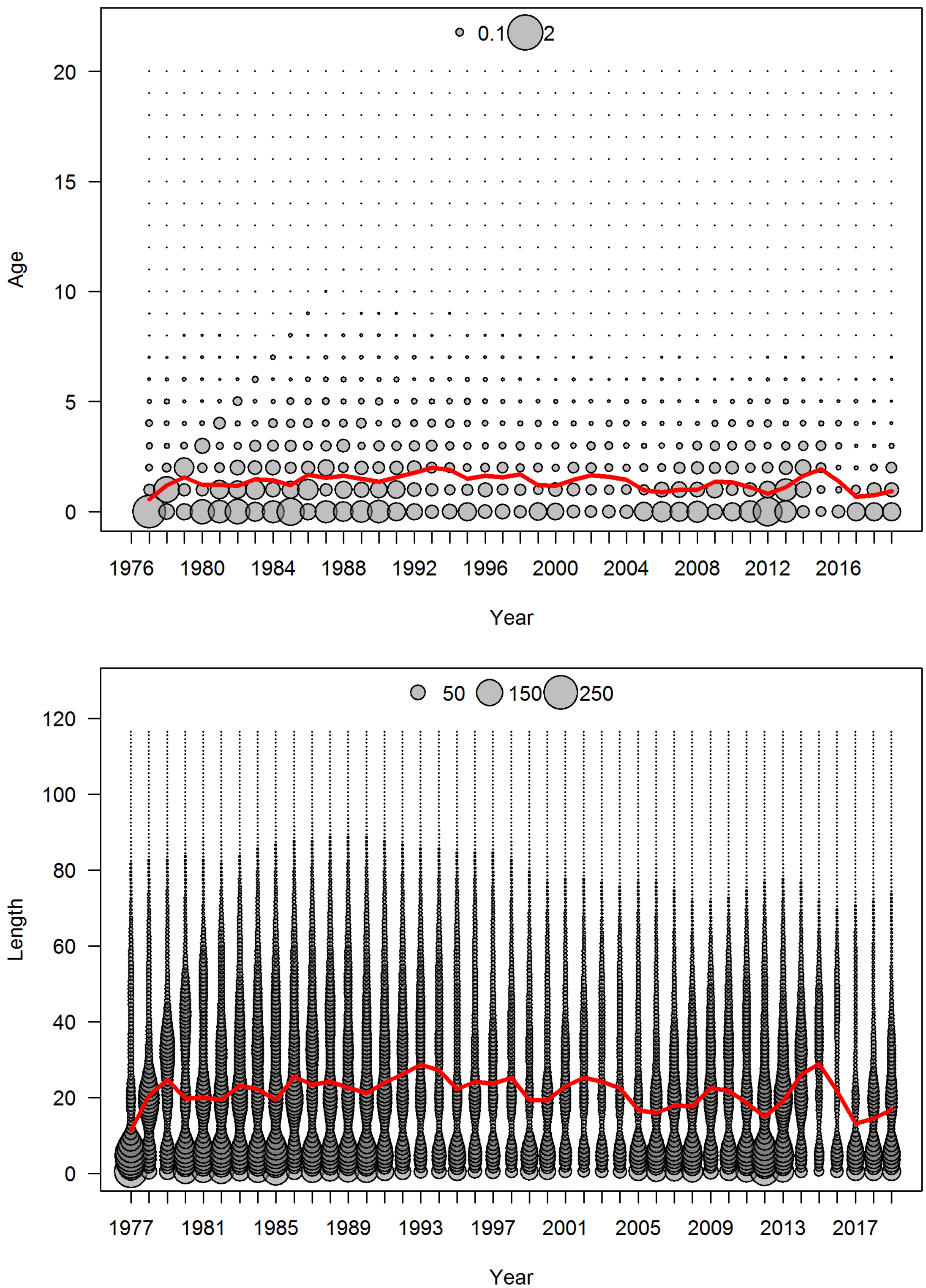


Figure 2.95 Model 18.10.44 predictions of middle of the year number at age (top) with mean age (red line) and numer at length (bottom)with mean length (red line).

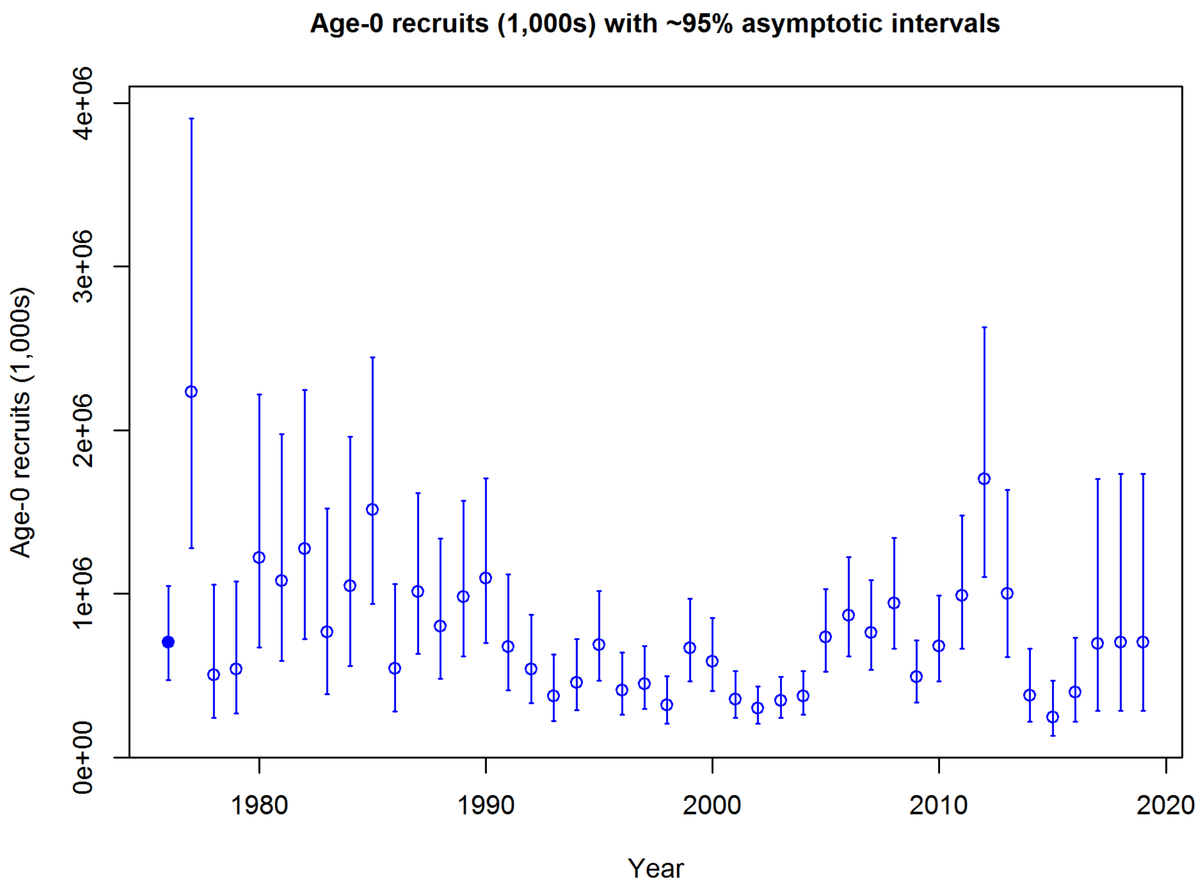


Figure 2.96 Model 18.10.44 age-0 recruitment (1000’s) with 95% asymtotic error intervals.

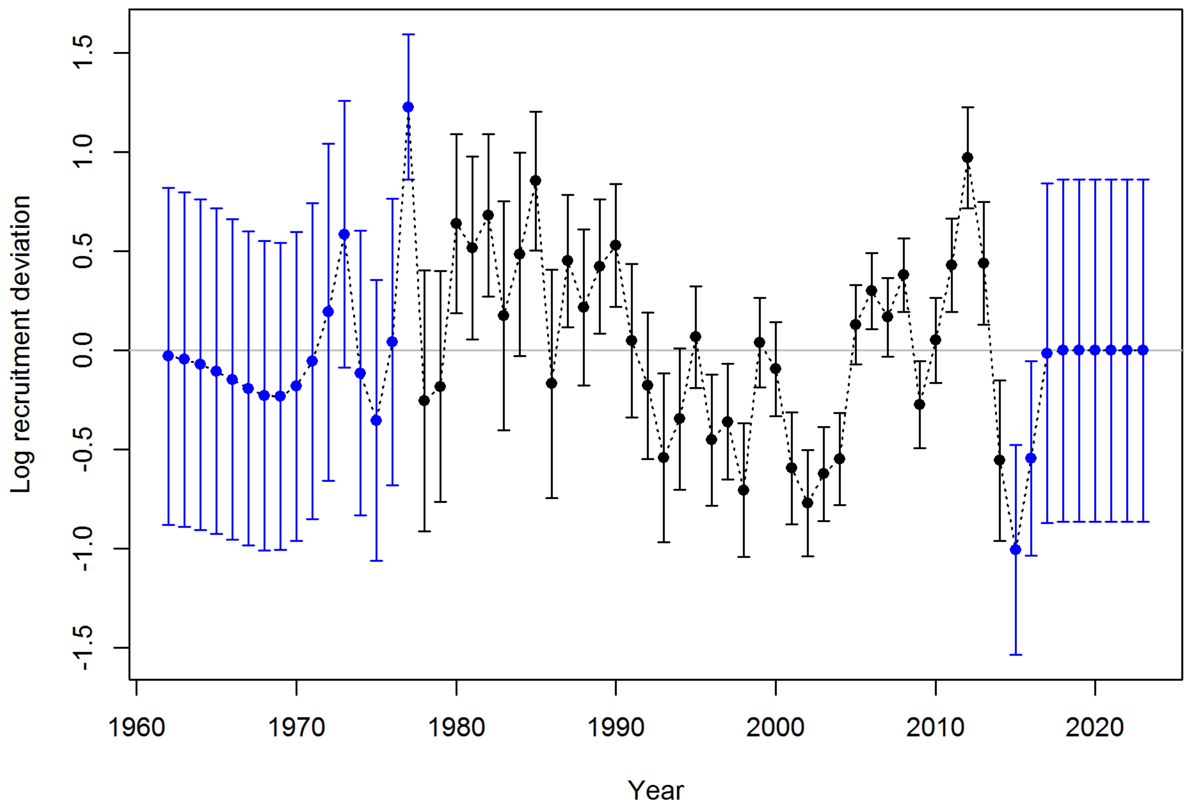


Figure 2.97 Model 18.10.44 log recruitment deviations with 95% asymtotic error intervals.

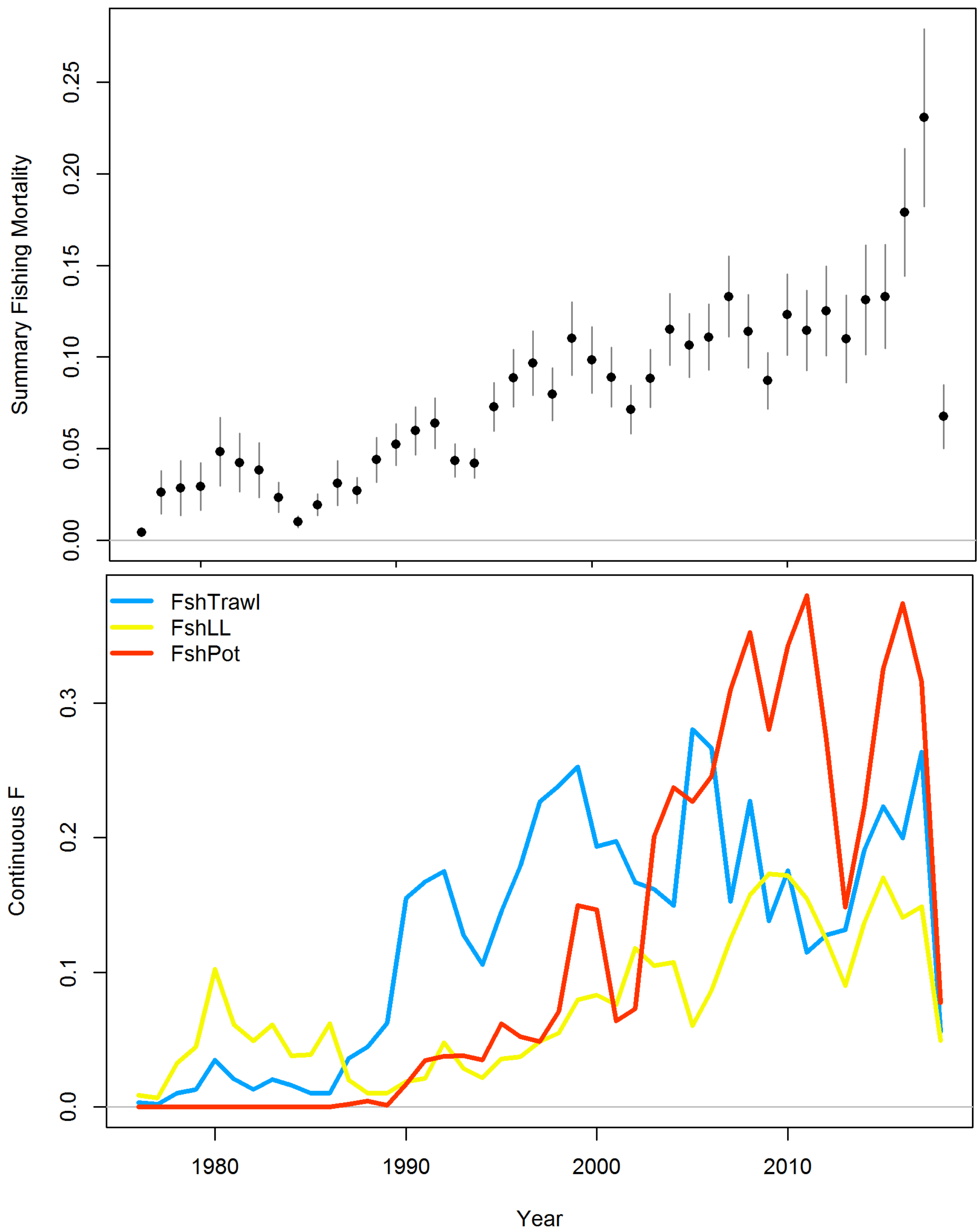


Figure 2.98 Model 18.10.44 age 3-8 true fishing mortality (top) and continuos fishing mortality by trawl (FshTrawl), longline (FshLL) and pot (FshPot) fisheries (bottom).

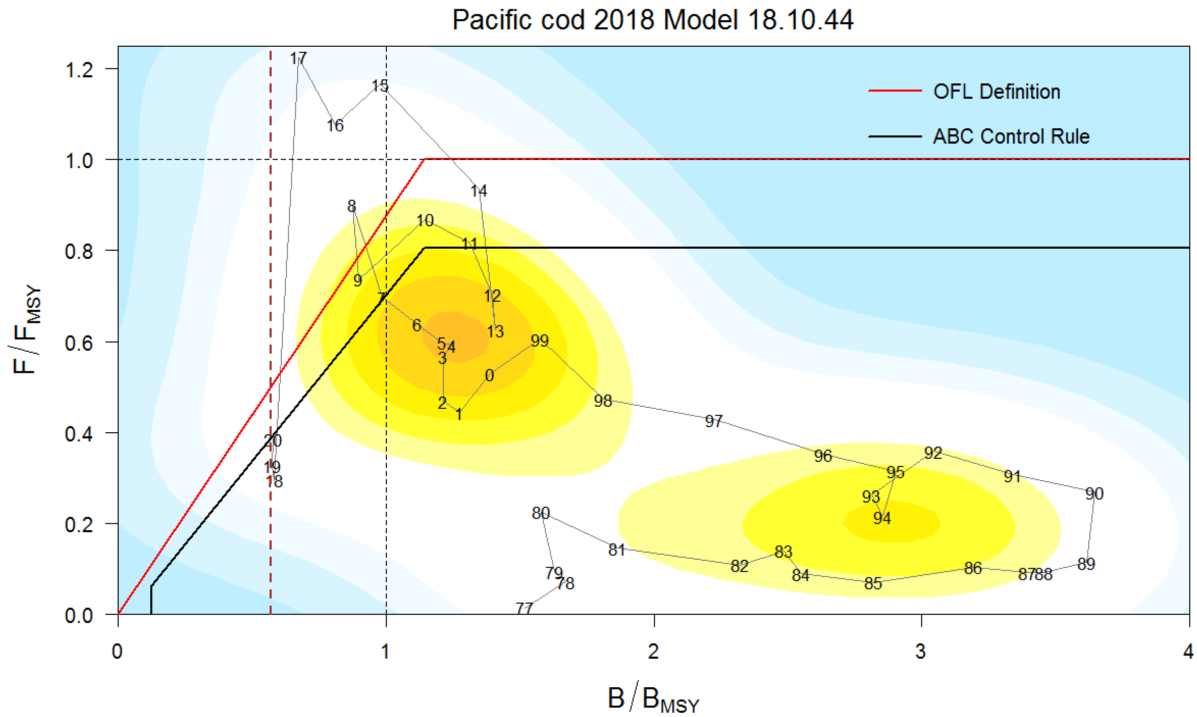


Figure 2.99 For Model 18.10.44 ratio of historical F/*Fmsy* versus female spawning biomass relative to *Bmsy* for GOA pacific cod, 1977-2020. Note that the proxies for *Fmsy* and *Bmsy* are *F35%* and *B35%*, respectively. The Fs presented are the sum of the full Fs across fleets. Dashed line is at $B_{20\%}$, Steller sea lion closure rule for GOA Pacific cod.

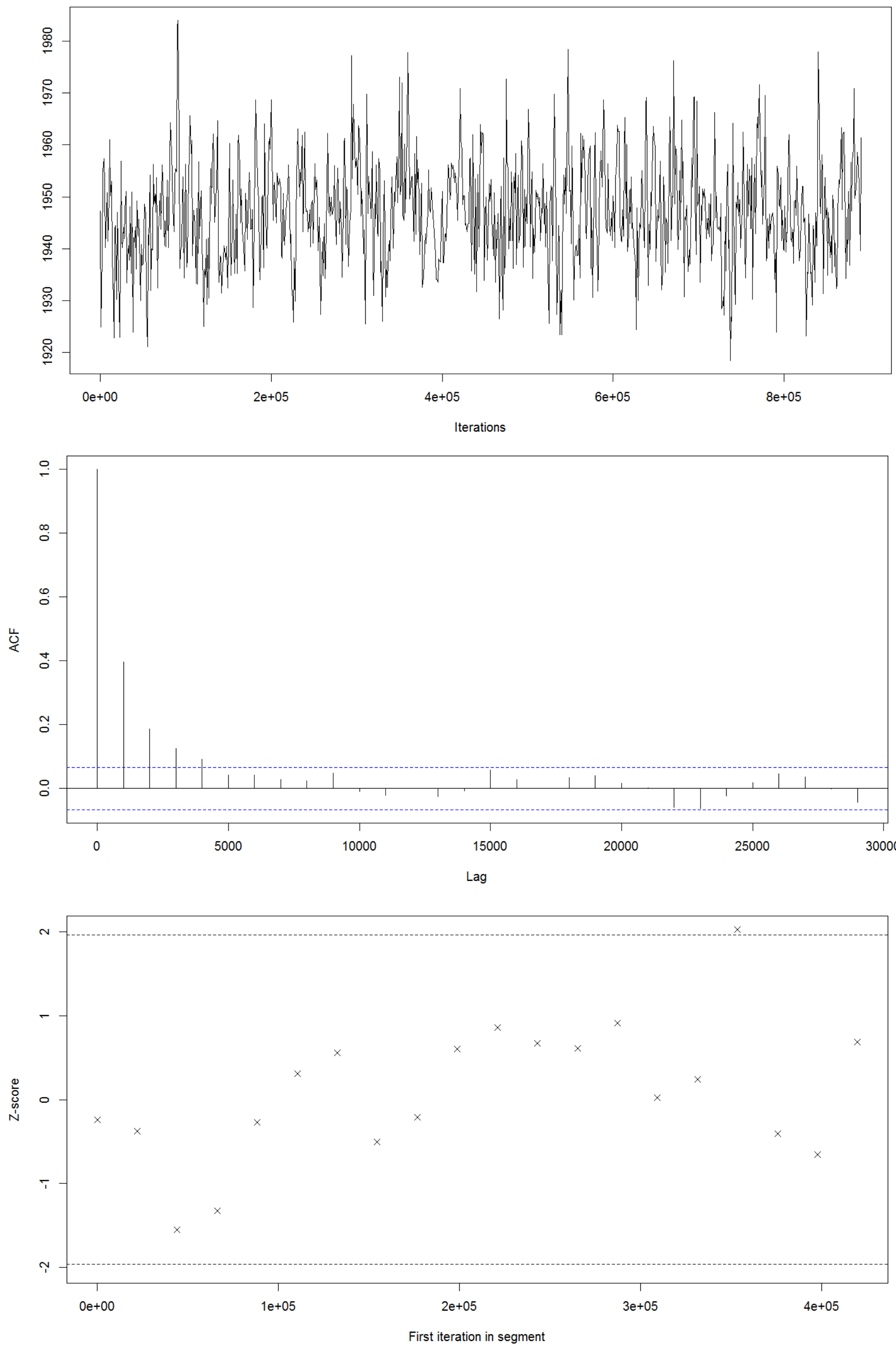


Figure 2.100 Model 18.10.44 MCMC trace (top), autocorrelation function plot (middle), Geweke diagnostic plot (bottom) for the objective function.

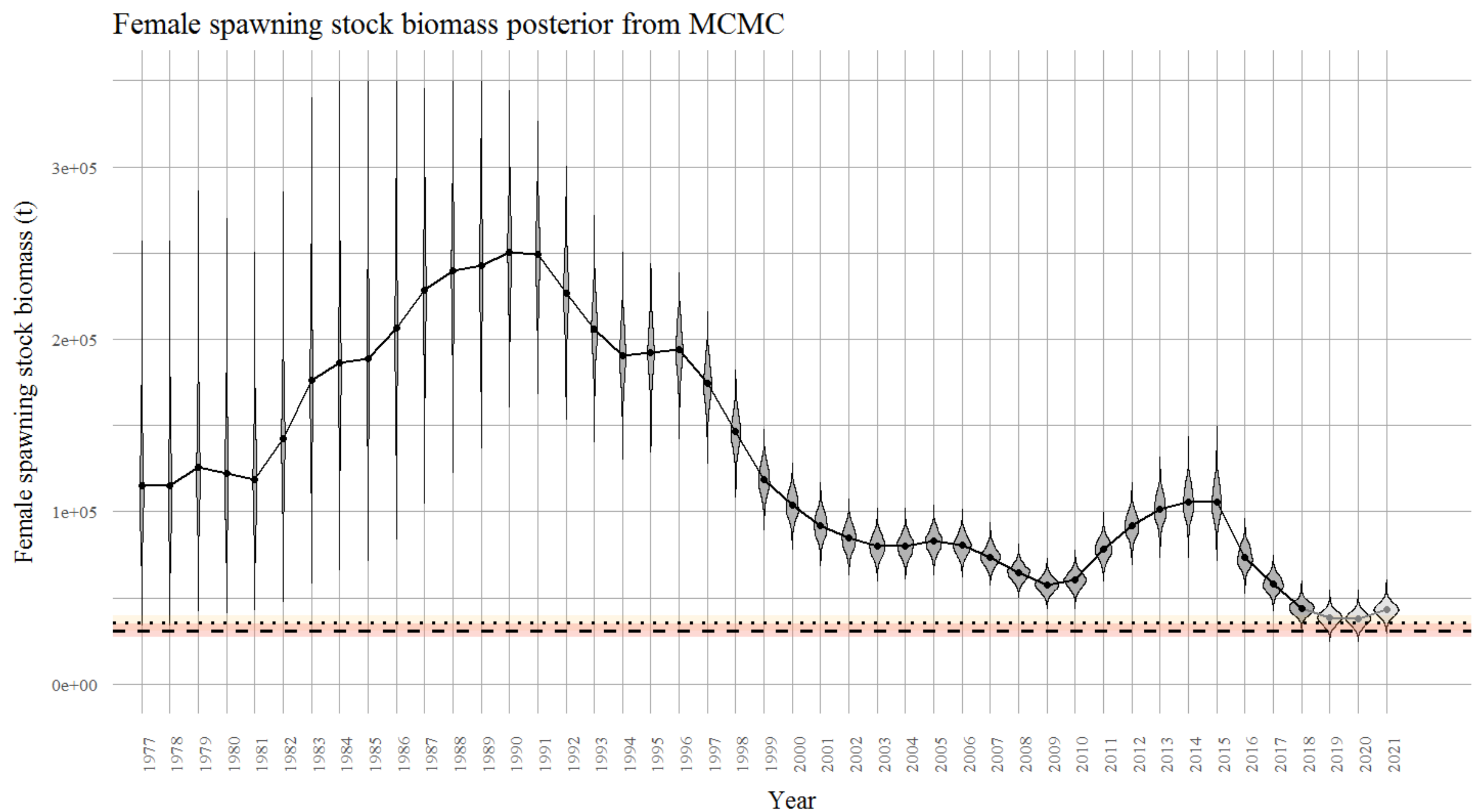


Figure 2.101 Model 18.10.44 MCMC posterior distributions of beginning of the year female spawning biomass 1977-2021. Dotted line is $SSB_{20\%}$ with yellow shaded 95% credible interval and dashed line is $SSB_{17.5\%}$ with orange shaded 95% credible interval.

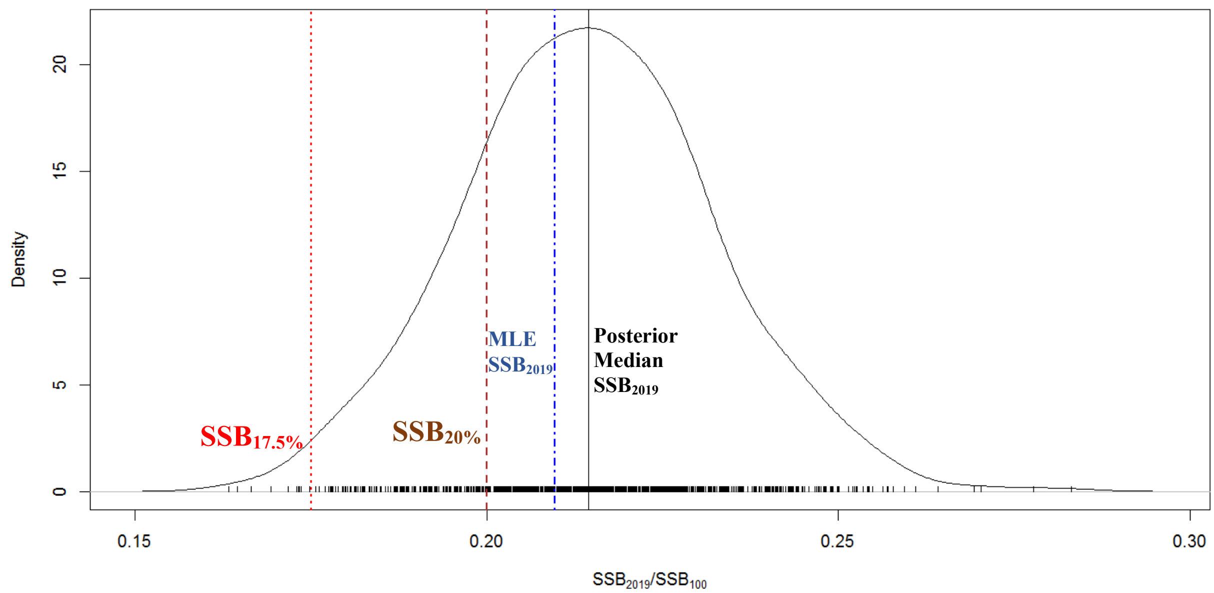


Figure 2.102 Model 18.10.44 MCMCposterior distribitions of the 2019 spawning stock biomass ratio with $SSB_{20\%}$ (brown dashed line) and $SSB_{17.5\%}$ (Red dotted line) from the projection model, MLE estimate (blue dashed line) and posterior median (black solid line) for beginning year 2019.

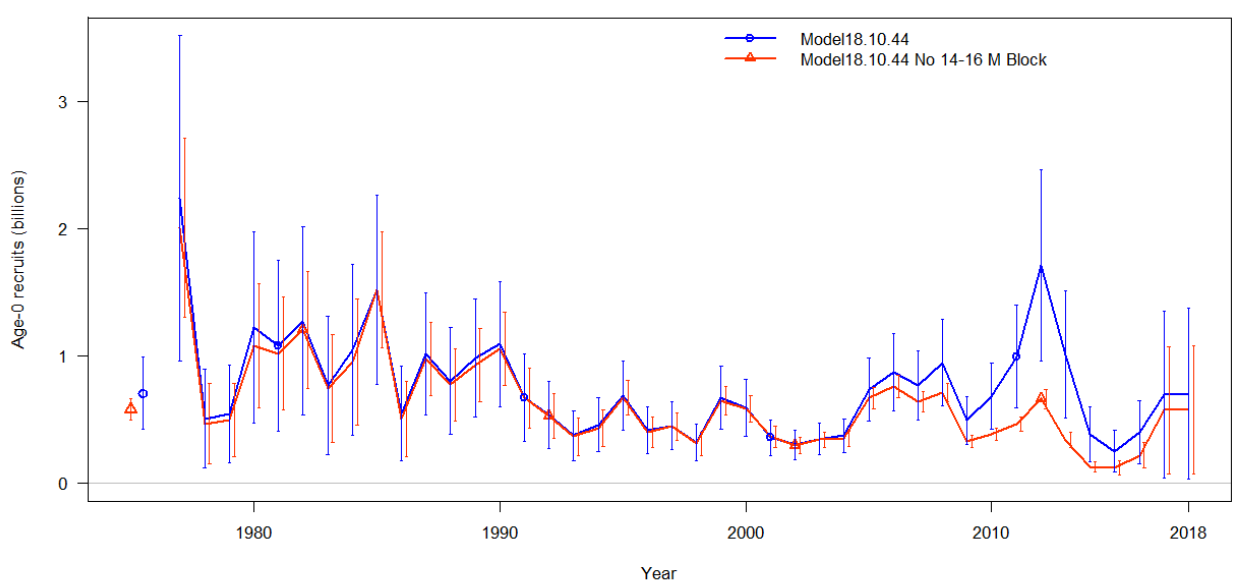


Figure 2.103 Model 18.10.44 Age-0 recruits with and without the 2014-2016 fitting block on natural mortality showing differences in estimated recruitment for 2005-2018.

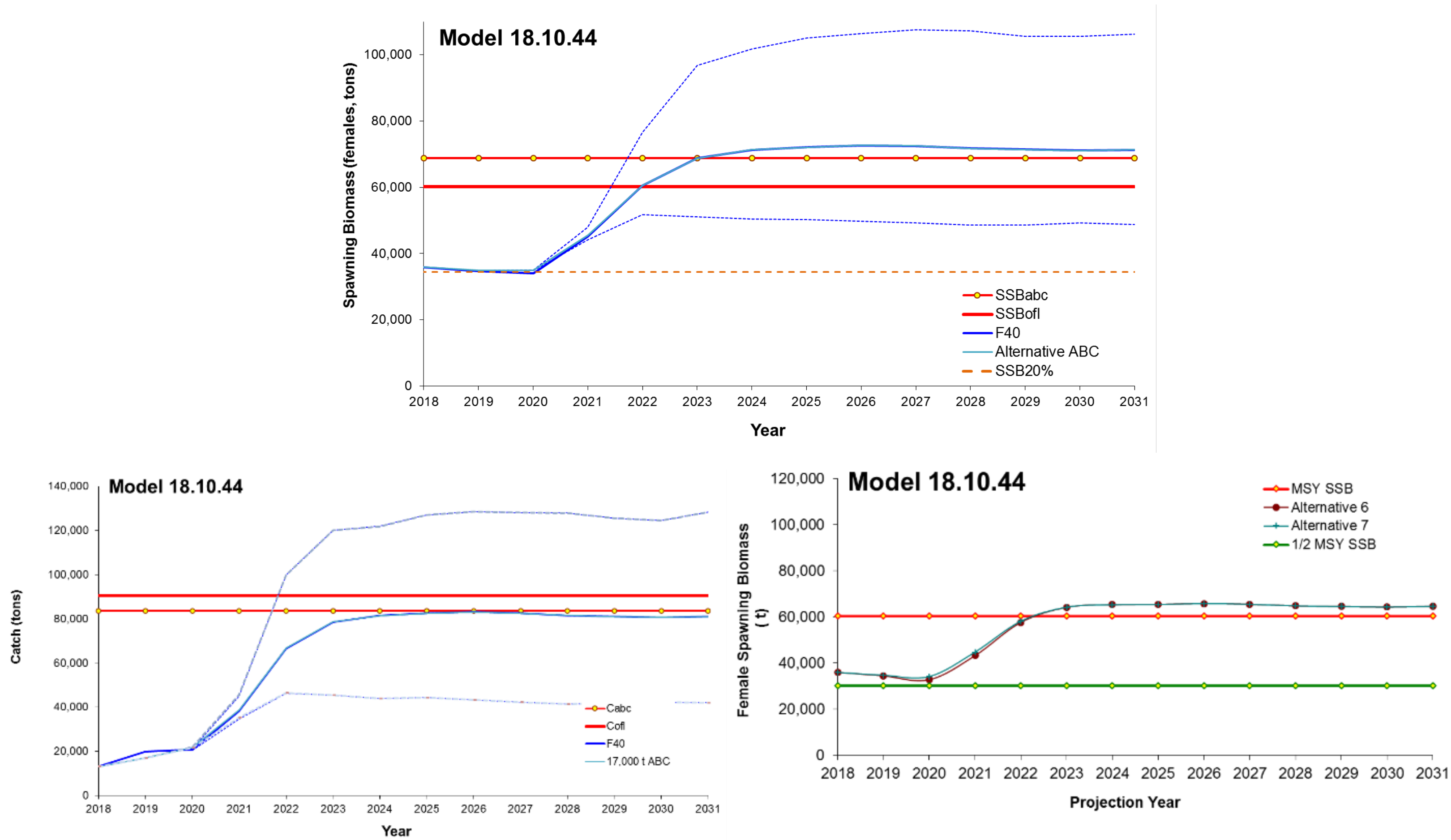


Figure 2.104 Model 18.10.44 projections of female spawning biomass (top), catch (bottom left), and female spawning biomass from scenarios 6 and 7 for status determination (bottom right).

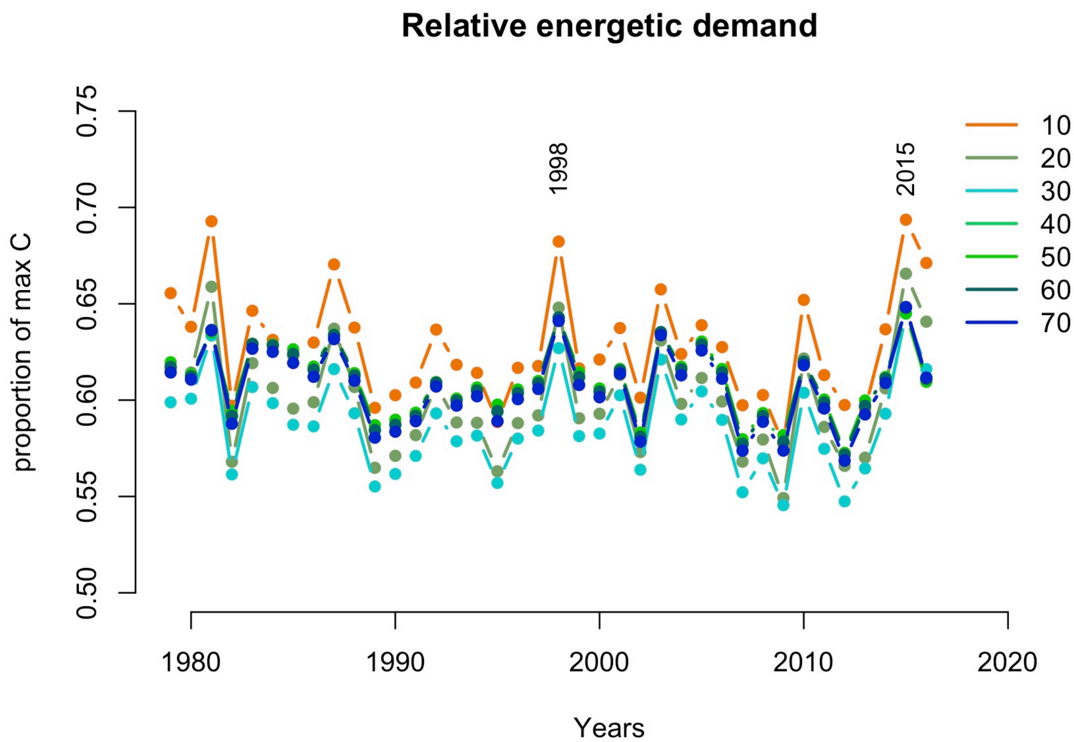
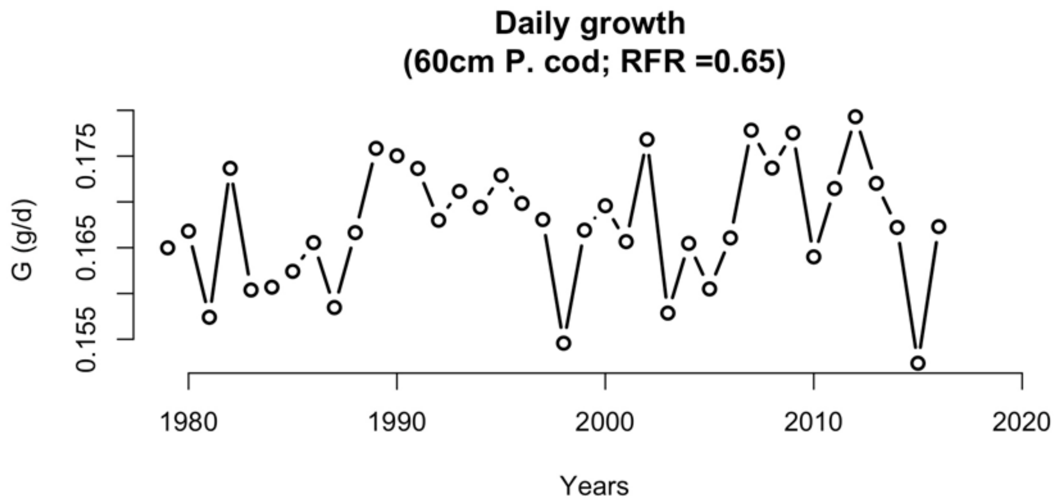


Figure 2.105 Relative energetic demand for Pacific cod of 10-70 cm FL based on the adult bioenergetic model for Pacific cod (Holsman and Aydin, 2015) and CFSR age-specific depth-preference corrected water temperatures (Barbeaux, unpublished data).



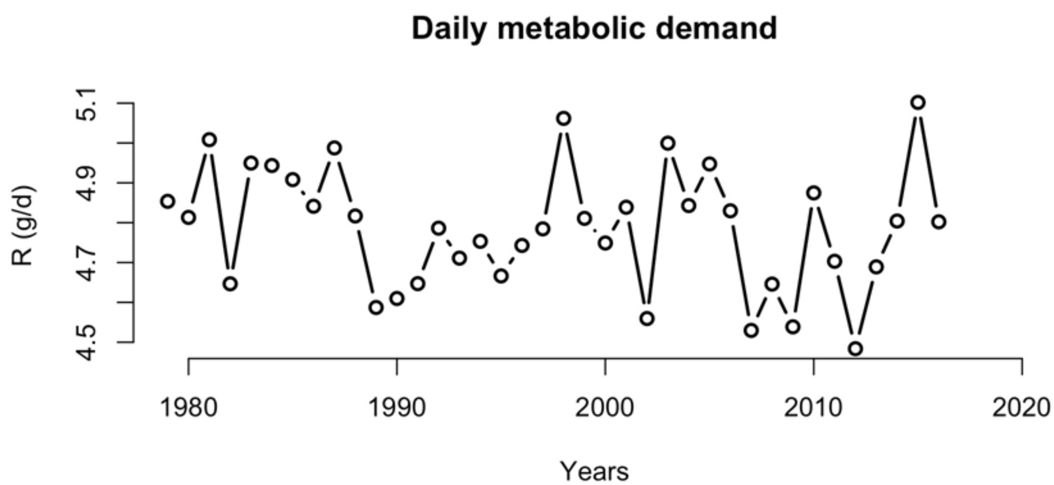


Figure 2.106 Daily model estimates of growth (top panel) and metabolic demand (bottom panel) based on the adult Pacific cod bioenergetics model (Holsman and Aydin, 2015), a fixed relative foraging rate (RFR) =0.65 (across years), annual indices of GOA prey eenergy density, and an intermediate P. cod energy density of 3.625 kJ/g reported in Vollenweider et al. 2011.

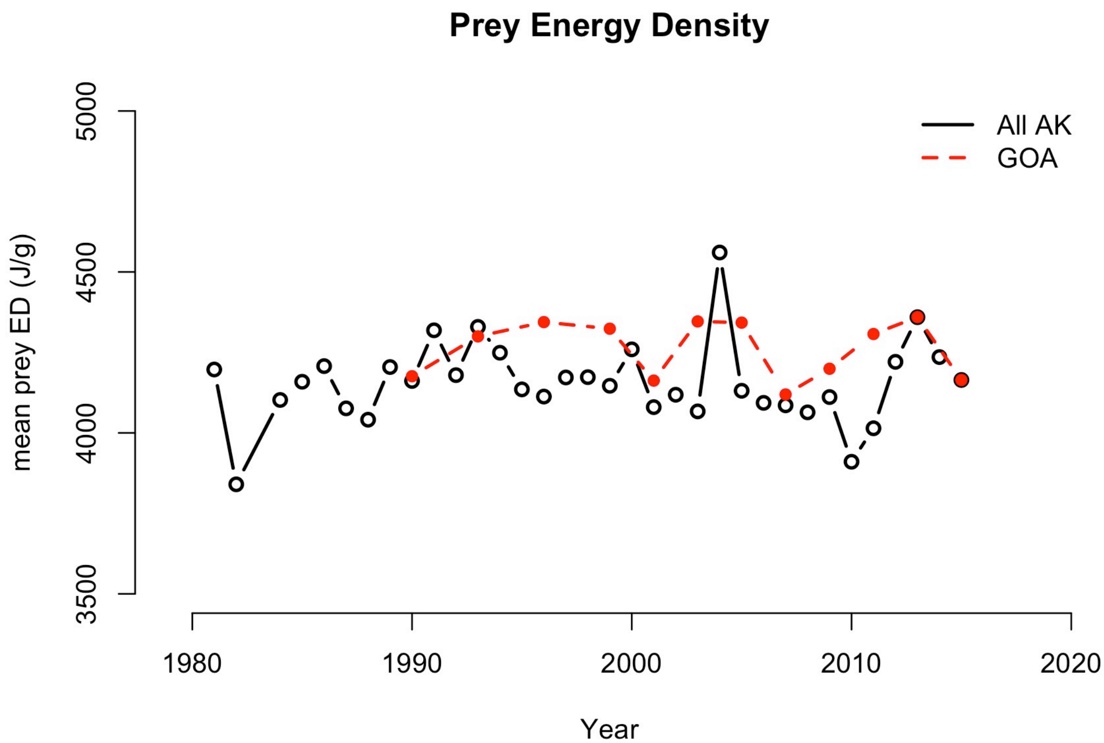


Figure 2.107 Average prey energy density based on mean energy density of prey items and diet composition from GOA Pacific cod stomach samples. Diet data from NOAA REEM Food Habits database.

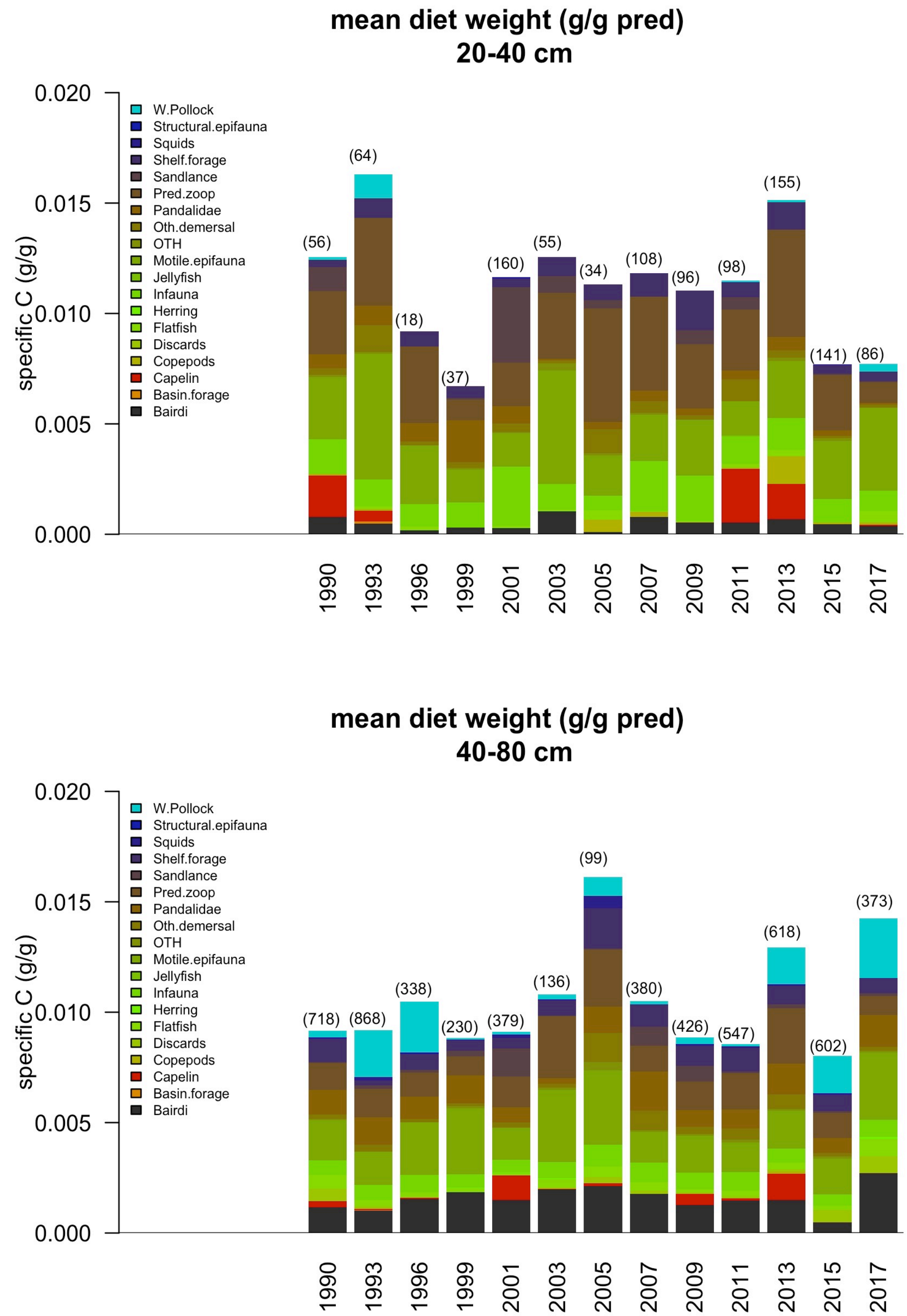


Figure 2.108 Specific weight (g prey/ g pred) of prey in the diets of GOA Pacific cod, averaged across all survey diet samples and fish sizes. Diet data from NOAA REEM Food Habits database.

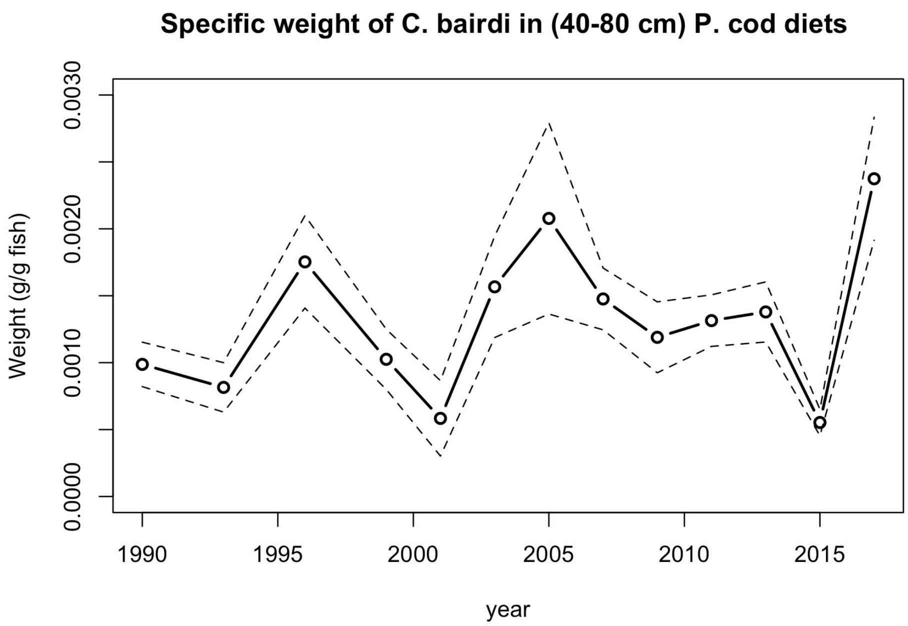


Figure 2.109 Specific weight (g prey/ g pred) of Chionoecetes bairdi in the diets of Pacific cod in the Gulf of Alaska, AK. Diet data from NOAA REEM Food Habits database.

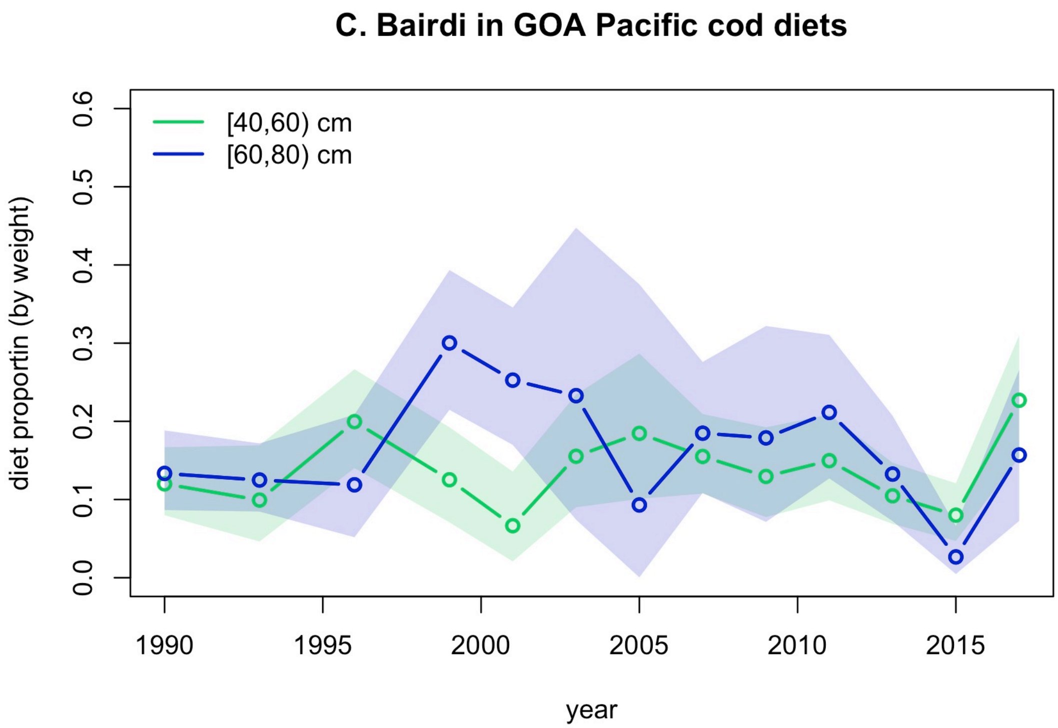


Figure 2.110 Proportion by weight of of Chionoecetes bairdi in the diets of different size classess of Pacific cod in the Gulf of Alaska, AK. Diet data from NOAA REEM Food Habits.

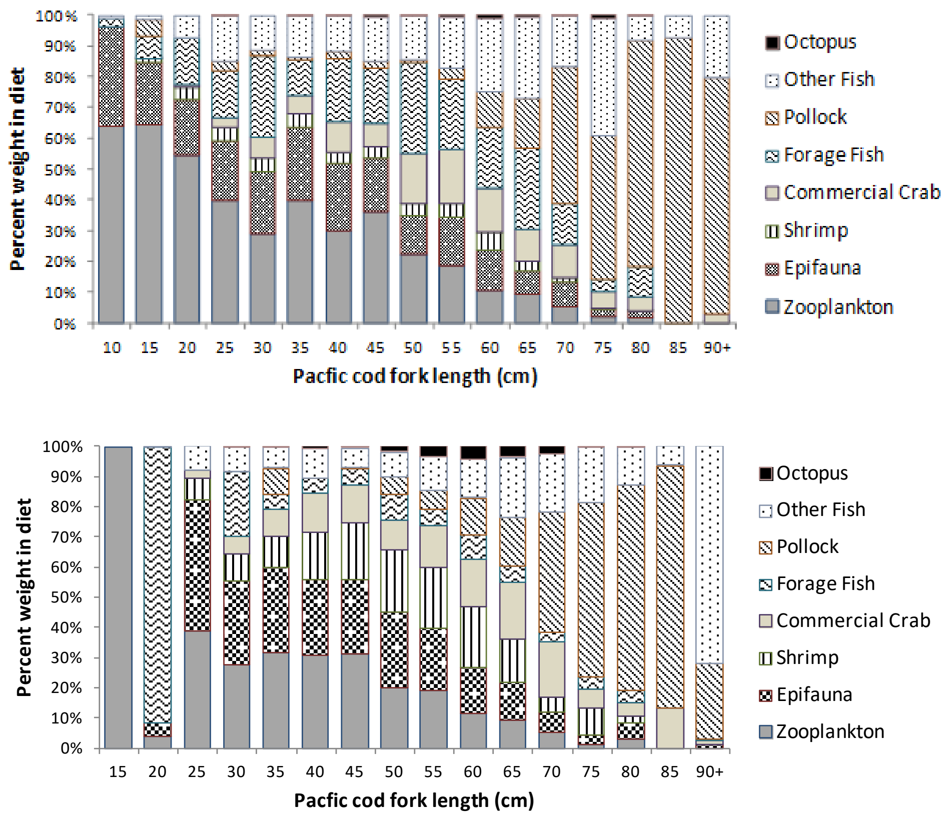


Figure 2.111 Percent diet by weight in Pacific cod stomachs sampled in water <100m (top) and >100m (bottom), all years and seasons, for Gulf of Alaska.