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, Lauren Rogers, Kalei Shotwell,
Qiong Yang, and Stephani Zador

November 2019

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 2018 were updated and preliminary federal and state catch data for 2019 were included;
2. Commercial federal and state fishery size composition data for 2018 were updated, and preliminary commercial federal and state fishery size composition data for 2019 were included;
3. AFSC bottom trawl survey Pacific cod abundance index and length composition data for the GOA for 2019 were included;
4. AFSC longline survey Pacific cod abundance index and length composition data for the GOA for 2019 were included;
5. Conditional length-at-age data for the 2010-2011 fisheries were added to the model.

Changes in the methodology

Model 18.10.44 is last year's accepted model with the addition of the 2019 AFSC bottom trawl and longline survey indices and length composition data, and fishery catch, length composition and age data including conditional length-at-age data. There is one new data configuration and one new model explored this year (see below).

Model configurations:

Model	Data	Plus group	Aging error	Aging bias
18.10.44	No age data pre-2007	20+	No	No
19.11.44	No age data pre-2007	10+	Yes	No
19.14.48c	All Cond. length at age	10+	Yes	Pre-2007 fit, 2007+ fixed at 0

All proposed models presented for management 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 18.10.44 performed well and is last year's reference model, Model 19.11.44 is last year's model with this year's data, a change to a 10+ age group instead of 20+, and the addition of aging error. Model 19.14.48c assumes aging bias in the pre-2007 age data. Kastelle et al. (2017) suggests only a limited positive bias. This is best reflected in Model 19.14.48c and is therefore the Authors' preferred model. Model 19.14.48c results, like those of Model 18.10.44, includes a moderate increase in M for 2014-2016 and has a retrospective index within reasonable bounds for both spawning biomass and recruitment.

Summary of results

The data as interpreted through Model 19.14.48c indicates that the stock has been lower in abundance than previously thought. It shows that the stock was likely below $B_{20\%}$ since 2018 and will remain below until 2021. Model 19.14.48c is nearly identical to last year's model, the biggest influences in the model were the drop in the AFSC longline survey index value and the lower than predicted value for the AFSC trawl survey. Although the AFSC bottom trawl survey index value did increase, the increase was not as high as last year's model had predicted. To accommodate these new data the model estimated the spawning biomass to have been lower than what was estimated last year relative to the unfished biomass. This not only drove 2018-2019 to be below $B_{20\%}$, but also, despite an increasing trend, predicted that the stock would remain below $B_{20\%}$ in 2020. For 2020 the stock is estimated to be at $B_{17.6\%}$, above, but very near the overfished determination level. The beginning of the year 2020 spawning biomass level is projected to be the lowest of the time series and with the 2017 and 2018 year classes should see an increase above $B_{20\%}$ at the start of 2021.

Key results are tabulated below:

	As estimated or *specified last* year for:		As estimated or *specified this* year for:	
Quantity	2019	2020	2020	2021
M (natural mortality rate)	0.50	0.50	0.49	0.49
Tier	3b	3b	3b	3b
Projected total (age 0+) biomass (t)	207,198	266,066	203,373	261,484
Female spawning biomass (t)				
Projected	34,701	34,774	32,958	42,026
$B_{100\%}$	172,240	172,240	187,780	187,780
$B_{40\%}$	68,896	68,896	75,112	75,112
$B_{35\%}$	60,284	60,284	65,723	65,723
F_{OFL}	0.36	0.36	0.27	0.36
$maxF_{ABC}$	0.29	0.29	0.22	0.29
F_{ABC}	0.25	0.29	0.22	0.29
OFL (t)	23,669	26,078	17,794	30,099
maxABC (t)	19,665	21,592	14,621	24,820
ABC (t)	*17,000	21,592	**14,621	**24,820
Status	2017	2018	2018	2019
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.*

*** Assumes 15,000 t catch in 2019 and no directed fishery in 2020 as reference level is below $B_{20\%}$. For 2021 projections the 2020 catch was assumed to be 3,300 from state fisheries and 3,000 t from non-directed fishery bycatch.*

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 2019, the area-apportioned ABCs are:

	Western	Central	Eastern	Total
Random effects area apportionment	22.7%	70.6%	6.7%	100%
2020 ABC	3,319	10,322	980	14,621
2021 ABC	5,634	17,523	1,663	24,820

It should be noted that for 2020 there would be no federal directed fishery allowed due to the stock being below $B_{20\%}$. Catch was set at 3,300 t for state fishery and 3,000 t for bycatch in non-target fisheries.

Responses to SSC and Plan Team Comments Specific to this Assessment

September 2019 Plan Team

The Team agrees with the author and recommends for the November meeting that models addressing aging error, aging-bias, the 10+ age group, asymptotic selectivity for age, further explore whether inclusion of the IPHC length composition data are appropriate (how many tows/sample sizes, etc.).

The model presented this year as the alternative (Model 19.14.48c) has all of these features. The IPHC survey was not available until much too late to include in the assessment model this year. It will be included in alternatives next year.

October 2019 SSC

In agreement with the author and the PT, the SSC would like to have models addressing aging bias and error, a change to the maximum age bin, and asymptotic age selectivity be brought forward in November.

The model presented this year as the authors' recommendation, Model 19.14.48c, includes all of these features.

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 outside of spawning season (Fig. 2.2). There appears to be substantial migration between the southern Bering Sea and the western GOA based on tagging data, 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. 2019). The first study (Drinan et al. 2018) used 6,425 single-nucleotide polymorphism (SNP) loci to show high assignment success >80% of five spawning populations of Pacific cod throughout their range off Alaska. Further work using using 3,599 SNP loci and spawning samples throughout the range of Pacific cod off Alaska, as well as a summer sample from the Northern Bering Sea in August 2017 showed significant differentiation among all spawning groups (Spies et al. 2019). 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), F_{ST}=0.004 and F_{ST}=0.001. There was strong evidence for selective differentiation of some loci, including one that aligned to the zona pellucida glycoprotein 3 (ZP3) in the Atlantic cod genome. This locus had the level of differentiation of any locus examined (F_{ST}=0.071). ZP3 is known to undergo rapid selection (Drinan *et al.* 2018), and completely distinct haplotypes have been observed in spawning cod from Kodiak Island westward vs. Prince William Sound and samples to the east.

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. Further work is needed to understand the genetic stock structure of cod in the GOA and its relationship with the Bering Sea stock of cod during spawning and feeding periods.

Review of Early 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 survival 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 ichthyoplankton nets during the spring (Doyle and Mier 2016). During this period, Pacific cod larvae are feeding principally on eggs, nauplii and early copepodite stages of copepod prey <300 um (Strasburger *et al.* 2014). Field observations show that larvae achieve a larger size by late May in warm years compared to cooler years. Warm surface waters can accelerate larval growth when prey are abundant (Hurst *et al.* 2010), while warm temperatures at depth may shift the timing of spawning to earlier in the year as well as accelerate egg development, leading to earlier timing of hatching. However, there is 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), suggesting that increased size does not translate into benefits for survival. 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, currently conducted during only odd-numbered years; 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). In 2019 this study was continued across nearly the same region at most of the original 2018 locations (13 bays, 72 seine sets).

The summer thermal conditions in the Central/Western GOA have historically been well-suited for high growth and survival potential for juvenile Pacific cod (Laurel *et al.* 2017), but 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). With the warm conditions in 2019 both the surveys once again indicated very low abundance of the 2019 year class. For perspective, 240 age-0 Pacific cod were captured in the Cooperative Research beach seine survey this year, compared with 18,600 Pacific cod in 130 sets in 2018. The strong 2018 cohort was also not evident in either of the 2019 beach seine surveys, although older juveniles may have shifted to cooler depths beyond the gear. Ichthyoplankton surveys confirm the patterns observed in the beach seine surveys, with the lowest and second-lowest larval abundance on record observed in 2015 and 2019 respectively.

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), making them especially sensitive to changes in thermal conditions. For instance, hatching success of Pacific cod eggs is temperature-dependent, and drops rapidly as temperatures rise above ~6 °C. In most years, temperature does not appear to be a limiting factor for eggs, but during the recent heatwave, bottom temperatures were above optimal for successful hatching and may have reduced the reproductive potential of the stock (Lauren and Rogers, in review). 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 2005), at which time age-based data began to enter the assessment. Several changes have been made to the model within the SS2 framework (renamed "Stock Synthesis," or SS3, in 2008) each year since then.

For the first year of management under the 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, observer, and electronic monitoring 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 2018 and 2019 through October 17, 2019 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 2019 the pot sector caught approximately 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. In 2018 the total catch was 15,247 t. For 2019 the ABC was set below the maximum ABC at 17,000t and as of October 1, the 2019 combined fishery has caught 13,373 t which is 79% 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 shark species, arrowtooth flounder, octopus, and walleye pollock (Table 2.6). Rockfish, rock sole, and sculpin species also make up a major component of the bycatch in these fisheries. Incidental catch of non-target species in the GOA Pacific cod fishery are listed in Table 2.7.

Longline

For 1990-2015 the longline fishery had 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. In 2018 and 2019 with the drastic cut in TAC the fishery showed very little effort the majority of catch being south of the Shumagin Islands straddling the 610 and 620 management area edges (Fig. 2.13 and 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 64 cm (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 and 2019 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 its previously lowest level. For both 2018 and 2019 the A- season longline fishery in the Western GOA appears to have started later than the previous 4 years, effort was lower and CPUE in January through March of 2019 declined in the Western GOA but was up in the Central GOA (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. In the Alaska state managed fishery an average of 84% of the state catch comes from pot fishing vessels. In 2016 60% of the overall GOA Pacific cod catch was 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, however this may be due to low observer coverage. In 2018 and 2019 there were few observed hauls throughout the GOA (Fig. 2.13 and Fig. 2.14), this is likely due to the lower TAC and low fishing levels. The pot fishery in the Central GOA moved to deeper water in 2017 through 2019 than previous years. 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, however 2019 shows a marked increase in CPUE in both the Central and Western GOA (Fig. 2.23).

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 through 2019 fishery data show a sharp increase in mean length, potentially due to a combination of the fishery moving to deeper water and lower recruitment since 2014.

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. The 2017 pot fishery in the Western GOA appears to have been similar to 2016 (Fig. 2.22). In 2018 and 2019 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. In 2018 CPUE during the A season (January-April) in both the Central and Western GOA was lower than the previous three years (Fig. 2.23), on par with CPUE during 2013 and 2008-2010 (Fig. 2.23). In January – March 2019 there was an increase in the pot fishery CPUE in both regions.

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. 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. There was substantially less catch and observed effort in 2018 and 2019 (Fig. 2.13 and 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 2019. The change to deeper depth and a larger proportion of the catch coming from the Western GOA might partially explain this recent increase.

The 2018-2019 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). Prior to 2018 the mean CPUE for Pacific cod in both the Central and Western GOA had been stable to increasing over the previous 10 years (Fig. 2.23). In 2018 there was no observed effort in the Central GOA. In the western GOA there was very little observed effort, however where observed CPUE remained near 2017 levels. In 2019 there was little observed effort, however the effort observed showed a decrease in CPUE in both regions from 2018.

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 through 2019 the jig fishery has remained low with catch at less than 500 t for all regions.

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, 2,726 in 2017, 2,786 in 2018, and as of October 1 2,682 t in 2019.

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 2017 (Table 2.9). The largest component of this catch comes from the recreational fishery, generally taking approximately 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 1992-2019. 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 2015-2016 (Fig. 2.24 -2.27). In 2018 and 2019 the condition of fish in both the Central and Western GOA are mixed with differences in condition by gear and season. The Central GOA longline fishery shows improving condition in January through April (Fig. 2.24), however in 2019 the condition of Pacific cod returned to a poor condition. The Central GOA pot fishery shows improvement in 2018 in January through April as well (Fig 2.25), but lack of data availability in May through September limit our ability to evaluate condition. In the Western GOA longline fishery cod condition in 2019 returned to average in January through April (Fig. 2.26), but again like in the Central GOA we see worse than average condition in the summer fishery. The Western GOA pot fishery shows improved cod condition in 2017 and 2018 following the heatwave (Fig. 2.27), but then again in the winter of 2019 cod condition once again drops to below average. There were not enough data in the summer of 2019 to evaluate condition in the Western GOA pot fishery.

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 1999). 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. 2.28). In the shallow water flatfish fishery, catch rates in tons of Pacific cod per ton of all species catch were examined (Fig. 2.29). For the pollock fishery the 2017 value is the lowest in the series (2008-2019) with a slight increase in 2018 and continued increase in 2019 in areas 610 and 620. For the shallow water flatfish fishery, 2017 was the lowest value with a slight increase in 2018 and 2019. 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 2019. Two or three commercial fishing vessels are contracted to conduct the surveys with fishermen working alongside AFSC scientists. Survey design is stratified random with the strata based on depth and distance along the shelf, with some concentrated strata in troughs and canyons (Raring *et al.* 2016). There are generally between 500 and 825 stations completed during each survey conducted between June and August starting in the western and ending in the southeastern Gulf of Alaska. Some changes in methods have occurred over the years with the addition of electronics to monitor how well the net is tending on-bottom, also to measure differences in net and trawl door dynamics and detect when general problems with the trawl gear occur. Surveys conducted prior to 1996 are considered to have more uncertainty given changes in gear mensuration. Also, the trawl duration was changed in 1996 to be 15 minutes instead of 30. Since 1996, methods have been consistent but in some years the extent of the survey has varied. In 2001 the Southeastern portion of the survey was omitted and in 2011, 2013, 2017, and 2019 deeper strata had fewer stations sampled than in other years due to budget and/or vessel constraints.

The 2019 survey was conducted with two chartered vessels that accomplished 541 stations following the protocols of Stauffer (2004) and von Szalay and Raring (2018). While the GOA Bottom Trawl Survey optimally employs three chartered vessels and targets 825 stations, the reduced 2019 survey likely captured the trend and magnitude of the cod abundance in the GOA. The 2019 survey covered all strata; regions; and shelf, gully, and upper slope habitats to 700 m. The percent standard error of the biomass estimate was 21.8% and was higher than the historic average of 17.7%. The 2019 survey design was comparable to the 2013 and 2017 surveys that were also conducted with two vessels and achieved 548 and 536 stations, respectively. The 2013 Pacific cod survey biomass estimate was 3.5 times higher than the 2019 estimate, and the 2019 biomass estimate was 69% greater than the 2017 estimate.

The Pacific cod biomass estimates from the bottom trawl survey are highly variable between survey years (Table 2.10 and Fig. 2.30). 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 with a slight uptick in 2019. The 2017 estimates for abundance and biomass estimates were the lowest in the time series (a 71% drop in abundance and 58% drop in biomass compared to the 2015 estimate). Although the 2019 survey resulted in a 126% increase in abundance over 2017, the estimate remains the second lowest in the time series at 127 million fish. 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. 2.31). The mean length in the trawl survey generally increased from 1984-2005 excepting the 1997 and 2001 surveys (Fig. 2.32). The decline in mean length in 2007 and 2009 were apparently due to the large incoming 2005-2008 year classes. The mean length in the survey increased in the 2011-2017 survey then dropped again in 2019. The average length of fish for 2007-2019 remains below the 1984-2005 overall average.

The distribution of Pacific cod in the survey has been highly variable (Fig. 2.33) with inconsistent peaks in CPUE. In 2017 the survey had the lowest average density of the time series, but also no high density peaks in CPUE were observed in any survey station. There were some higher than average densities for the 2017 survey located along the Alaska Peninsula and south of Unimak island, but for the most part CPUE was universally low throughout the Gulf of Alaska. The 2019 survey showed in increase in cod in the area of the Central GOA east of Kodiak Island on Portlock Bank and South of Marmot Island, but fewer cod in the Eastern and Western GOA.

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 2.34). Details about these data and a description of the methods for the AFSC sablefish longline survey can be found in Hanselman *et al.* (2016) and Echave *et al.* (2012). This RPN index follows the trend observed in the bottom trawl survey for 1990 through 2018 with a decline in abundance from 1990 through 2008 and a sharp increase (154%) in 2009 and continued increase through 2011 with the maturation of the large 2005-2008 year classes. In 2012-2013 there appears a decline in the abundance index concurrent with a drop in overall shelf temperature potentially due to changes in availability of Pacific cod in these years as the population moved to shallower areas (Yang *et al.* 2019). In 2014-2016 the index increases but this may reflect increased availability with warmer conditions. The index shows a sharp drop (53%) in abundance from 2016 to 2017, again (40%) from 2017 to 2018, and yet again (37%) from 2018 to 2019. The 2019 estimate was 83% lower than the 2015 abundance estimate.

Unlike the bottom trawl survey, the longline survey encounters few small fish (Fig. 2.35). The size composition data show consistent and steep unimodal distributions with a stepped decreasing trend in mean size between 1990 and 2015 (Fig. 2.36) and then increasing mean size from 2015-2018 and a leveling off in 2019. 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 second warmest year on record for the time series. In 2019 we would have expected both a more severe drop in average length due to the increased temperatures on the shelf and an increase in abundance due to increased availability. That we observed neither portends either very few small fish available in the population, or a change in behavior.

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 although as of the writing of this document (10/30/2019) the 2019 length data are not available.

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. 2.37). 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 (28% from 2017) to values slightly higher than 2016, but remain the fourth lowest estimate on record after 2001, 2016, and 2017. The 2019 survey again sees a slight increase above 2018 (8%), however the uncertainty in the estimate is high. The length composition data available from 2018 (Fig. 2.38) show the survey encounters fish greater than 40cm. The length data have 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 (2006).

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= 2068.99). Comparison of delta GLM indices with the area-swept estimates indicated similar trends. Variances were based on a bootstrap procedure, and CVs for the annual index values ranged from 0.06 to 0.14. These values underestimate uncertainty relative to population trends since the area covered by the survey is a small percentage of the GOA shelf area where Pacific cod have been observed.

The ADFG survey index follows the other three indices presented above with a drop in abundance between 1998 and 1999 (-45%) and relatively low abundance throughout the 2000s (Table 2.13 and Fig. 2.39). 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 2019 survey showed a slight decline (15.7%) from 2018. Length composition data (Fig. 2.40) from this survey show wide multi-modal length distributions are common with modes of age-0 fish at times available at near 10cm, however the 2019 survey had no fish smaller than 22cm. The 2018 year class is apparent as a mode at between 29 cm and 36 cm and the 2017 year class at between 44 cm and 54 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 1979-2019 (Fig. 2.41 and Table 2.14).

The mean depth of Pacific cod at 0 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 in water temperature in 1981, 1987, 1998, 2015, 2016 and 2019 with 2019 being the highest in both the 10 cm and 40 cm indices. There are low valleys in temperature in 1982, 1989, 1995, 2002, 2009, 2012, and 2013. The coldest temperature in the 10 cm index was in 2009 and in the 40 cm 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 September 2019 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 1982 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 have been four periods of increased winter heatwave activity in the Central GOA, the first in 1983-1986, second in 1997-2006, the third 2014-2016, and the fourth 2018-2019. 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. The most recent heatwave began September 9, 2018 to the current date. There are six distinct events making up the 2018-2019 heatwave with a maximum intensity of 2.75°C for the most recent heatwave period from June 23, 2019 through September 10, 2019. The cumulative intensity of the 2018-2019 marine heatwave is lower than the 2014-2016 heatwave, however the heatwave is still extant and may intensify.

Data

This section describes data used in the current assessment (Fig. 2.42). 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/2019/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 – 2019
Federal fishery catch-at-length, by gear type	AKFIN / FMA	number, by cm bin	1977 – 2019
State fishery catch-at-length, by gear type	ADF&G	number, by cm bin	1997 – 2019
GOA NMFS bottom trawl survey biomass and abundance estimates	AFSC	metric tons, numbers	1984 – 2019
AFSC Sablefish Longline survey Pacific cod RPN	AFSC	RPN	1990 – 2019
GOA NMFS bottom trawl survey length composition	AFSC	number, by cm bin	1984 – 2019
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 – 2019
CFSR bottom temperature indices	National Center for Atmospheric Research	Temperature anomaly at mean depth for P. cod size bins 10 cm and 40 cm.	1979-2019

Fishery

Catch Biomass

Catches for the period 1991-2019 are shown for the three main gear types in Table 2.2, with the catches for 2019 presented through October 02, 2019. 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 2018. 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 – 2019 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 2019. 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/2019/GOApcod_Appendix2_2.xlsx)

Size composition proportioning

For the 2016 assessment models 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 through 2019 for post-1991 length composition 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.

"New" 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 used 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. 2.43). The age data was also used to develop an annual conditional length-at-age matrix for each fishery (Fig. 2.44-46).

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. 2.30, together with their respective coefficients of variation.

Length Composition

The relative length compositions used in the assessment models examined this year from 1984-2019 are shown in Figure 2.47 and provided in Appendix 2.2 in an Excel spreadsheet (http://www.afsc.noaa.gov/REFM/Docs/2019/GOApcod_Appendix2_2.xlsx).

Age Composition

Age compositions (Fig. 2.47) and conditional length at age (Fig. 2.48) from 1990-2017 trawl surveys 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/2019/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. 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. 2.49). Plotting all of the GOA AFSC bottom trawl survey age at length data for 1996-2017 as pre- and post-2007 shows the bias is most apparent from ages 3 onward with at least one year between length categories. Upon further investigation the apparent change in growth observed post-

2007 with fish becoming larger at age may have been due to a change in reading criteria and predominant age readers. Aging bias for the pre-2007 ages were explored in this year's proposed model configuration.

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. 2.34.

Length Composition

The length composition data for the AFSC longline survey data are shown in Figure 2.35 and provided in Appendix 2.2 in an Excel spreadsheet.

(http://www.afsc.noaa.gov/REFM/Docs/2019/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 model applies refinements to last year's model in consideration of issues encountered with aging error and aging bias discovered in the age data prior to 2007. To see the history of models used in this assessment refer to A'mar and Palsson (2015). All models were run in Stock Synthesis version 3.30.13.10 (Methot and Wetzell 2013). For consistency, we include the 2018 accepted model (Model18.10.44) and the 2018 accepted model with updated data and a change in the age plus group from 20+ to 10+.

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 survey indices. 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 2019 (this is provided in Appendix 2.1 http://www.afsc.noaa.gov/REFM/Docs/2019/GOApcod2019_Appendix2_1.pdf). All models presented in consideration for use in management have been developed in SS v3.30. There is one new model series explored this year (see below). All model configurations are shown below:

Model configurations:

Model	Data	Plus group	Aging error	Aging bias
18.10.44	No age data pre-2007	20+	No	No
19.11.44	No age data pre-2007	10+	Yes	No
19.14.48c	All Cond. length at age	10+	Yes	Pre-2007 fit, 2007+ fixed at 0

Time varying selectivity components for all models:

Component	**Temporal Blocks/Devs**
Longline Fishery	Annually variable 1978-1989 Blocks – 1996-2004, 2005-2006, 2007-2016, 2017-2019
Trawl Fishery	
Pot Fishery	Blocks – 1977-2012 and 2013-2019
Bottom trawl survey	Blocks – 1977-1995, 1996-2006, 2007-2019

All Stock synthesis files are provided in a zip file in Appendix 2.3:
(http://www.afsc.noaa.gov/REFM/Docs/2019/GOApcod2019_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 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 expanded the natural mortality block to 2014-2016. For this $M_{standard}$ is fit separate from $M_{2014\text{-}2016}$ with a lognormal prior of μ=-0.81 and a σ of either 0.1 or 0.41. This configuration was used in the 2019 proposed models as well. The use of special mortality periods have been proposed and approved for use in several Bering Sea crab assessments.

Growth

A three parameter von Bertalanffy growth model is used in the model. 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. 2.50). The *nls* function form the **nlstools** library (Baty *et al.* 2015) in R was used to fit the formula $FL = L_{inf}\left(1 - e^{\left(-K(Age - t_0)\right)}\right)$ 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 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. 2.51).

Aging Error

Aging error matrices were included in Models 19.11.44 and 19.14.48c (Fig. 2.52). These were developed from age reader agreement testing results for otoliths read from the 2007-2017 bottom trawl surveys. The standard deviation at age 3 was 0.57 and at age 10 was 1.16, the model assumed a linear interpolation between these values and no error at ages 1 and 2.

Parameters Estimated Inside the Assessment Model

Parameters estimated conditionally (i.e., within individual SS runs, based on the data and the parameters estimated independently) in the model include the von Bertalanffy growth parameters, annual recruitment deviations, initial fishing mortality, gear-specific fishery selectivity parameters, aging bias adjustment 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.

For Model 19.14.48c aging bias was estimated for ages 3+ with two parameters, bias at age 3 and bias at age 10, with a linear interpolation between the two, applied to all age data collected prior to 2007 (aged prior to 2008). Age data from post 2007 were assumed to be aged without bias (Fig. 2.52).

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 $\log\left(Q_y\right) = \left(\bar{Q} + PI_y\right)$ 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 in 2017 (Barbeaux et al. 2017) and a new method validating this methodology was presented at the 2018 September Plan team meeting and provided in Barbeaux et al. (2018) 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 relationship was verified in Yang et al. 2019 with a shift to deeper depths in all size classes examined during warm years and shift to shallower waters in cold years. This shift would make Pacific cod more available to the AFSC longline survey which starts at 150 m.

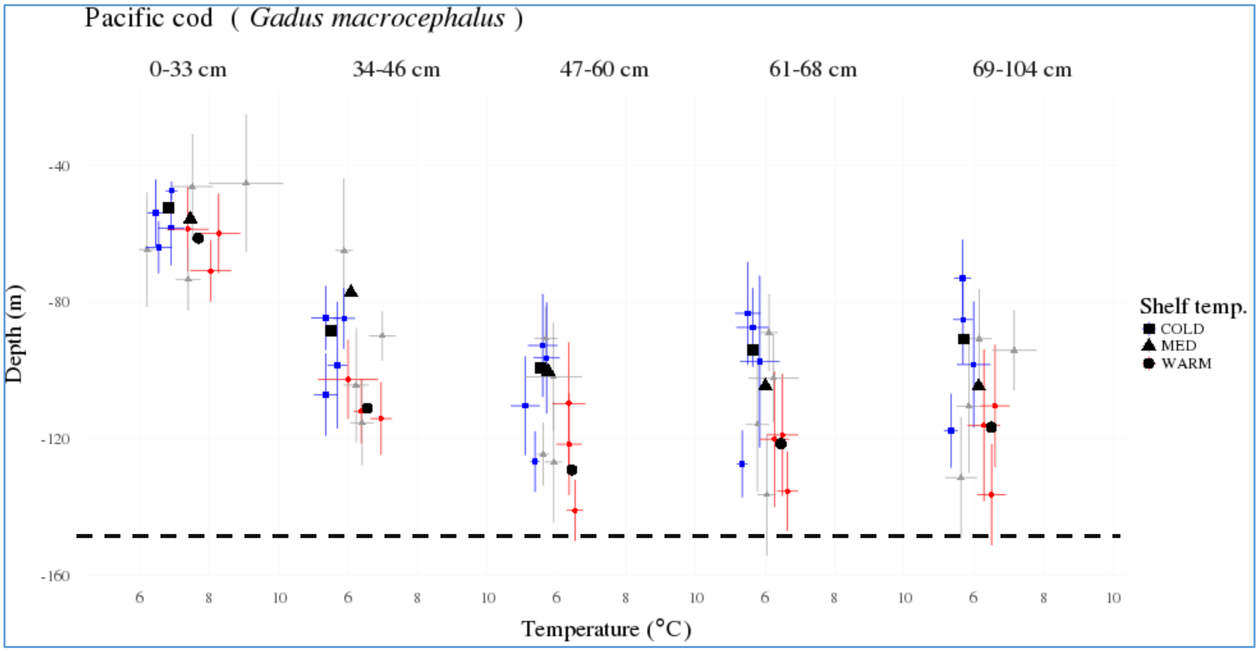


Figure: AFSC bottom trawl survey Pacific cod centroids of distribution for the Central GOA by shelf temperature and Pacific cod size category. Dashed line shows starting depth of AFSC longline survey (150 M).

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 2018 final model with data from 2019, and new model configuration are presented. The new model presented would be considered major model changes from the 2018 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 models cannot be compared directly using likelihoods due to differences in data and aging error assumptions. Retrospective results, index RMSE and composition mean effective sample sizes are provided in Table 2.18.

Comparing and Contrasting Model Configurations

The Model 18.10.44 was the same configuration as last year's author's preferred model and Model 19.11.44 was the same as that model with the addition of the 2019 data and a plus group at age 10 instead of 20 and aging error. The Model 19.14.48c is the same as Model 19.11.44 except all conditional age at length data are used and aging bias is fit for pre-2007 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 18 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. 2.53). The female spawning biomass and age-0 recruitment for all the models considered this year are provided in Figure 2.54. All the models show a similar fit, and similar recruitment and biomass trends. The size based selectivity (Fig. 2.55 and Fig. 2.56 are nearly indistinguishable among the three models. The difference between Model 18.10.44 and Model 19.14.48c comes down to the use of an age 10+ instead of 20+ maximum age, application of aging error, the use of pre-2007 conditional age at length data, and fitted aging bias for the pre-2007 data. There is no easy means of quantitatively comparing the two models. As expected the introduction of aging error allows the model to have a slightly worse fit to the size composition and conditional length at age data. None of the changes in fit are easily discernable by eye. Both models have a similar fit to the indices. Model 19.11.44 provides a better fit to the survey indices. The slight degradation of fit to both the length composition and the conditional age at length data is a result of allowing aging error and placing slightly less emphasis on the composition data versus the indices. Model 19.14.48c adds aging bias and the pre-2007 conditional age at length data. The additional conditional age at length data causes a small change in fit to both survey indices (+0.39 LL) and the length composition (+17.8 LL). There is little differences in fit among the three models except changes in weighting of the different data components as more data are added and additional uncertainty is quantified within the model.

Selection of Final Model

Comparing likelihoods or AIC was not appropriate for these models as there were changes in both data and model error structure impacting weighting of data components. The retrospectives for Model 19.14.48c (Fig. 2.59) are marginally better than Model 18.10.44 (Table 2.18).

We recommend using Model 19.14.48c as the reference model for 2019 as the model allows for the use of the pre-2007 age data using a temporally distinct aging bias and implements aging error as requested by both the GOA Plan Team and SSC. This is a better treatment of uncertainty within the model. All Stock Synthesis files for Model 19.14.48c are provided in a linked zip file here:

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

Model 19.14.48c diagnostics and Suggestions for Future Improvement

Survey Indices

Model 19.14.48c fit to the NMFS bottom trawl survey was similar to previous base model fits (Fig. 2.55), missing the 2009 bottom trawl survey 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 1.07 times the survey estimates (Fig. 2.60), an effective “catchability” of 0.94.

Model 19.14.48c fits the AFSC longline index well (Fig. 2.57). The inclusion of the 10cm CFSR bottom temperature index 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. However the 2019 survey estimate is not fit well, the index value was much lower than expected, the warmer temperatures should have increased the availability of cod to the survey and the model was expecting a higher index. Given that the mean size of fish also did not decrease with the warmer temperatures this indicates that either cod did not become more available in 2019 due to warmer temperatures or there were few middle-aged fish and the population is at a lower abundance than modeled.

Length Composition

Selectivities in Model 19.14.48c were not allowed to be dome-shaped, except for the pot fishery and surveys (Fig. 2.61). Overall model predictions of the length compositions closely match the data for all components (Fig. 2.62). For the trawl fishery the model predictions (Fig. 2.63 and Fig. 2.64) 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. 2.65 and Fig. 2.66) 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. 2.67) were generally well fit, again, like the trawl and longline fisheries the high peaks of the distributions tended to be underestimated. In addition the 2018 and 2019 fishery fits miss the largest fish. This is likely due to the fishery moving to deeper waters and a change in selectivity that is not accounted for in the model. The mean length for the pot fishery data were well matched for all years except 2018 and 2019 where the mean was expected to be smaller. For the fishery length composition, generally there is no need for improvement, residuals were small even for the minimal discrepancies noted above for the peak modes. The authors will consider creating another block in the pot fishery for 2018 and 2019 for the 2020 assessment cycle.

Model 19.14.48c matched the NMFS bottom trawl survey length composition data mean lengths well (Fig. 2.68), however like previous years small fish (sub-27 cm) the dominant length modes 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.

Although the selectivity for Model 19.14.48c AFSC Longline survey length composition data (Fig. 2.69) 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 model expectations are to the data (Fig. 2.70). The aging bias adjustment appears to have corrected the problem identified in previous assessments with poor fits to the pre-2007 age composition data. The model expectations for age composition are consistent with the data for all years except 1987.

Model 19.14.48c has time-invariant growth (Fig. 2.71). Fits to the conditional length-at-age data are within the error bounds for most ages (Fig. 2.72, Fig. 2.73, Fig. 2.74, and Fig. 2.75), 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 19.14.48c to be larger at age than the data shown 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 19.14.48c are provided in Table 2.19.

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 19.14.48c.

Biomass

Estimates of total biomass were on average 107% higher than the NMFS bottom trawl survey total biomass estimates. Total biomass estimates show a long decline from their peak of 778,122 t in 1988 (Table 2.20 and Fig. 2.76) to 264,538 in 2006 and then an increase to another peak in 2014 of 498,565 t then decrease continuously through 2018. With improved recruitment in 2017 and 2018 total biomass began to increase again in 2019. Spawning biomass (Table 2.20) shows a similar trend of decline since the late 1980s with a peak in 1990 at 248,915 t to a low in 2008 of 61,215 t. There was then a short increase in spawning biomass coincident with the maturation of the 2005-2008 year classes through 2014 to 113,830 t, after which the decline continued to lowest level of 32,957 t projected for 2020. Projections of Model 19.14.48c indicate that the stock has been below $B_{20\%}$ since the beginning of the year 2018 and will be projected to below $B_{20\%}$ until the beginning of the year 2021.

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/GOApcod2019_Appendix2.2.xlsx)

Recruitment and Numbers at Age

The recruitment predictions in Model 19.14.48c (Table 2.21, Fig. 2.78 and Fig. 2.79) show large 1977, 1980-1982,1984-1985, 1987,1989-1990, 2008, and 2011-2012 year-classes with more than 0.8 billion (at age-0) fish for each, although uncertainty on the 1977 and 1984 year-class estimates were large (σ_{1977} =

0.37 and $\sigma_{1984\text{-}1990} > 0.14$). Between 1991 and 2010 the average recruitment was estimated at 0.492 billion, 40% lower than the 1977-1989 mean recruitment of 0.82 billion and 20% lower than the 1977-2017 mean recruitment of 0.619 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 2.22). 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. 2.80). There is a steep rise in F in 2016 and 2017 following the sharp population drop during the 2014-2016 marine heatwave. In 2018 and 2019 there was a sharp decrease in fishing mortality coincident with the drastic cuts in ABC. The phase plane plot (Fig. 2. 81) shows that F was estimated to retrospectively have been above the ABC control rule advised levels for 2005 through 2011 and 2015 through 2017 and biomass was below $B_{35\%}$ in 2008 and 2009 and again 2016 through 2019, and projected to continue to be below through 2021. The spawning biomass in 2018 through 2020 is projected to be below $B_{20\%}$. 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 19.14.48c with an ending year of 2009 through 2019 are consistently positively biased from 1984 through 2000, but have inconsistent bias post-2000 (Fig. 2.59). The Mohn's ρ for SSB ends up at 0.118, a Woods Hole ρ of 0.148 and an RMSE of 0.174 (Table 2.18). All of the models examined this year had retrospective patterns within reasonable bounds.

MCMC results

MCMC were conducted with 1,000,000 iterations with 150,000 burn-in and thinned to every 1000th 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. 2.82). Posterior distributions of key parameters appear well defined and bracket the MLE estimates (Table 2.23). Using the projection model estimate for unfished spawning biomass (187,780 t) then there is an 85.3% probability that the stock was below $B_{20\%}$ in 2019 and a 39.8% probability the stock was below $B_{17.5\%}$ (Fig 2.83 and Fig. 2.84). For 2020 there is a 73.3% probability of the stock being below $B_{20\%}$ and 27.7% probability of it being below $B_{17.5\%}$.

Harvest Recommendations

Amendment 56 Reference Points

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

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

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

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

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

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

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

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

$F_{OFL} = 0$

$F_{ABC} = 0$

Other useful biomass reference points which can be calculated using this assumption are $B_{100\%}$ and $B_{35\%}$, defined analogously to $B_{40\%}$. These reference points are estimated as follows, based on this year's model, Model 19.14.48c:

Reference point:	$B_{35\%}$	$B_{40\%}$	$B_{100\%}$
Spawning biomass:	65,723t	75,112 t	187,780 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 (2013-2018). 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 0.67 and 0.54 in aggregate.

Specification of OFL and Maximum Permissible ABC

Spawning biomass for 2020 is estimated by this year's model to be 32,958 t at spawning. This is below the $B_{40\%}$ value of 75,112 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 2020 and 2021 as follows (2021 values are predicated on the assumption of 15,000 t catch in 2019 and that the 2020 catch will be state fishery and bycatch only at 6,300 t):

Units	Year	Overfishing Level (OFL)	Maximum Permissible ABC
Harvest amount	2020	17,794	14,621
Harvest amount	2021	30,099	24,820
Fishing mortality rate	2020	0.274	0.221
Fishing mortality rate	2021	0.359	0.290

The age 1+ biomass projections for 2020 and 2021 from this year's model are 200,899 t and 257,606 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 and 2019 an ABC was recommended below the maximum ABC in an attempt to ensure the 2019 and 2020 SSB would remain above $B_{20\%}$. Biological reference points from GOA Pacific cod SAFE documents for years 2001 – 2019 are provided in Table 2.24.

For 2020 the stock is expected to be below $B_{20\%}$, because of the rules in place to protect forage for Steller sea lions the directed fishery will be required to remain closed if any of the models presented in this assessment are accepted. The ABC recommendation will be for non-directed fisheries that encounter

Pacific cod as bycatch. Here we recommend a maximum ABC of 14,621 t for 2020 and with the expectation of a 6,300 t catch the maximum ABC for 2021 is recommended at 24,820 t.

Should the ABC be reduced below the maximum permissible ABC?

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 2016-2019 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 second lowest point in the 42-year time series considered in this assessment following last year's record low. 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-2018 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. There appears to be a small increase in the 2017 and 2018 recruitment over the record lows during the heatwave, however information from spring ichthyoplankton and beach seine surveys suggests a very weak 2019 year class at age-0. How these indices relate to overall recruitment into the fishery is currently unknown. Currently for the projection model the 2019 year class is assumed to be average. Overall, we rated the population-dynamic concern as level 2, a substantially increased concern.

Environmental/Ecosystem considerations. During the 2019 bottom trawl survey, the average condition (defined as weight-length residuals) of sampled cod was above the time series mean, in contrast to the other groundfish examined by this method, which showed average to below-average condition. This difference potentially indicates that Pacific cod were more successful at meeting energetic demands via foraging than the other species. Condition was at or below the time series mean in the Yakutat and Southeastern survey areas, but above the time series mean from Kodiak to the west, indicating the potential for regional variation in prey abundance. However, the western GOA shelf area largely experienced heatwave conditions from September 2018 to October 2019. Based on knowledge gained from the 2014-2016 heatwave, we consider this to be unfavorable for Pacific cod as the prolonged increased temperatures likely increased their metabolic demands as well as the metabolic demands of their groundfish predators. Although as of 1 November 2019 the heatwave appears to have ended 12 October, it is unknown whether these lower temperatures will persist, particularly given the NMME forecast for warm conditions throughout the North Pacific through the upcoming winter.

Both juvenile and adult arrowtooth flounder eat euphausiids, polychaetes, forage fish (including walleye pollock), amphipods and crangonid shrimp. While euphausiids were at record abundance during the September 2018 Seward Line sampling, abundance estimates were low in May 2019.

Acoustically-derived estimates of euphausiid abundance during summer 2019 were moderate to low. Additionally, the reproductive success of planktivorous auklets at the Semedi Islands was average. Taken together, these euphausiid indicators suggest moderate to low euphausiid abundance during 2019. Forage fish indicators suggest mixed signals for abundance during 2019. Spring and late summer surveys for young-of-year groundfish found very few. However, forage-fish eating seabirds at the Semidis had strong reproductive success, although observations indicated that diets were unusual relative to other years where typical forage fish such as age-0 gadids, capelin, and sand lance predominate. Taken together these indicators suggest poor forage fish prey abundance in 2019, although abundance of age-1 and age-2 pollock appear strong. In general predators of Pacific cod (including Pacific cod, halibut, salmon shark, northern fur seals, Steller sea lions, harbor porpoises, various whale species, and tufted puffin) appear to be stable or declining. Steller sea lion trends have stabilized or continued to decline in the Gulf of Alaska. Pacific halibut, large Pacific cod (representing cannibalistic predation) are estimated at low biomass. Together these suggest no apparent concern for an increase in juvenile Pacific cod predator populations.

We consider the concern level to be 2-3—some indicators showing adverse signals relevant to the stock but the pattern is not consistent across all indicators. Fishery Performance. Where data were available catch per unit effort measures in the GOA fisheries showed mixed signals with CPUE improved in the Central GOA longline and pot and Western GOA pot fisheries in 2019 over 2018, but dropping in the Western GOA bottom trawl and longline fisheries. Condition of fish in the fisheries were above average in the winter and spring fisheries, but showed a worsening trend in the summer fisheries over previous years. It should be noted that catch levels and fishery participation have been low over the past 3 years in comparison with previous years. Bycatch in other fisheries show increasing amounts of cod, but still remaining low compared to prior to the 2014-2016 marine heatwave.

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

These results are summarized in the table below:

Assessment-related considerations	Population dynamics considerations	Environmental/ecosystem considerations	Fishery Performance	Overall score (highest of the individual scores)
Level 2: Substantially increased	Level 2: Substantially increased	Level 2: Substantially increased	Level 1: Normal	Level 2: Substantially increased

The overall score of level 2 suggests that setting the ABC below the maximum. For 2019 the GOA Pacific cod stock is below $B_{20\%}$ in the projection models and therefore there will not be a federal directed GOA Pacific cod fishery. It is expected that Pacific cod bycatch in the non-target fisheries will be near 3,000 t as it has the previous 3 years. The state has the option to open a directed fishery, this would be approximately 3,300 t if they chose to take the allocation from the maximum ABC. Although a level 2 overall rating may warrant a reduction in ABC no specific ABC reduction is recommended. A complete evaluation is provided in order to allow the SSC to come up with a reduction if it chooses to do so.

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 2019, the area-apportioned ABCs are:

	Western	Central	Eastern	Total
Random effects area apportionment	22.7%	70.6%	6.7%	100%
2020 ABC	3,319	10,322	980	14,621
2021 ABC	5,634	17,523	1,663	24,820

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 2019 numbers at age estimated in the assessment. This vector is then projected forward to the beginning of 2020 using the schedules of natural mortality and selectivity described in the assessment and the best available estimate of total (year-end) catch for 2019 (here assumed to be 15,000 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 19.14.48c with the 2014-2016 natural mortality block was set at the standard M value (Fig. 2.85 and Table 2.25). 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 2020, are as follow ("*max* F_{ABC} " refers to the maximum permissible value of F_{ABC} under Amendment 56):

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

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

Scenario 3: In all future years, F is set equal to the 2014-2018 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 2019 and above its B_{MSY} level in 2029 under this scenario, then the stock is not overfished.)

Scenario 7: In 2020 and 2021, 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 2021 or 2) above 1/2 of its MSY level in 2021 and expected to be above its MSY level in 2031 under this scenario, then the stock is not approaching an overfished condition.)

Scenarios 1 through 7 were projected 13 years from 2019 in Model 19.14.48c (Table 2.28). Scenarios 3 and 5 (no fishing) project the stock to be below $B_{35\%}$ until 2023, scenarios 1 and 2 have the stock below $B_{35\%}$ until 2024, and scenarios 6 and 7 have the stock below $B_{35\%}$ until 2025. Fishing at the maximum permissible rate indicate that the spawning stock (Fig. 2.86) will be below $B_{35\%}$ in 2020 through 2024 due to poor recruitment and high natural mortality post-2008. Under an assumption of mean recruitment, the stock recovers above $B_{35\%}$ by 2025.

Our projection model run under these conditions indicates that for Scenario 6, the GOA Pacific cod stock although below $B_{35\%}$ in 2020 at 32,957 t will be above its MSY value in 2030 at 70,555 t and therefore is not overfished.

Projections 7 with fishing at the OFL after 2021 results in an expected spawning biomass of 70,313 t by 2031. These projections illustrate the impact of the low recruitment in 2015 and 2016. For example, under all scenarios, the spawning biomass is expected to continue to drop in 2020 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-2018.

Under Scenarios 6 (Fig. 2.86) and 7 of the 2019 Model 19.14.48c the projected spawning biomass for Gulf of Alaska Pacific cod is not currently overfished, nor is it approaching an overfished status. However the stock is below $B_{20\%}$ triggering a closure of the directed Pacific cod fisheries managed under the GOA FMP for 2020.

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), Westerheim (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 euphausiids, 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 unprecedented in intensity, duration (especially persistence of warm water through the winter months), and extent spatially and at depth (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 (behavioral thermoregulation), or can increase consumption of food energy to meet increasing metabolic demands. The former requires sensory and swimming capability to move to favorable habitats (eggs and larvae generally cannot), whereas the latter requires sufficient access to abundant or high energy prey resources. The latter requires sufficient access to abundant or high energy prey resources. The former also requires access to thermally optimal temperatures, which may not be available due to the recent marine heat wave. Thus, metabolic costs due to warming may lead to decreased growth and survival when there is limited access and availability to alternate food and thermal habitats.

When prey is readily available, Pacific cod consumption rates exhibit a non-linear relationship with temperature, this non-linear response can limit foraging potential at very low and high temperatures. A cumulative (over months) index based on this relationship indicates high potential foraging needs in the GOA during the anomalously warm years of 2016-2019 (Fig. 2.87). Based on water temperatures at preferred depth, foraging demand is greatest for smallest fish (Fig. 2.88), consistent with bioenergetic estimates of metabolic demand from groundfish trawl surveys (diets, fish length, and bottom-temperature) suggest higher metabolic demand for smaller fish (Fig 2.89).

Recent declines in Pacific cod biomass are most consistent with poor conditions for growth for 20-40 cm fish (as well as 0-20cm fish). For this size range, bioenergetic model estimates of Pacific cod growth and respiration suggest poor conditions for growth in 1998 (following the record El Niño of 1997/98), 2015, and 2017 (middle panel Fig. 2.90) that were driven by high metabolic demand during those years (middle panel, Fig. 2.89) and lower mean stomach fullness in recent years (height of columns in Fig. 2.91). Prey energetic demand based on mean energy densities and annual shifts in diet composition show moderate changes in diet energy density over time, with a general decline observed for 20-40 cm fish while recent peaks in 2015 and 2017 are observed for 0-20 cm fish (Fig. 2.92). These could represent switching to more energetic valuable prey and or increased rations (e.g., 2019). Stomach fullness (rations) in 2019 for 0-20 cm fish are the some of the highest observed (and follow one of the lowest levels observed in 2017); for 20-40 cm fish 2019 rations continue to increase over 2015 and 2017 levels; there is no appreciable trend in rations for 40-60 cm fish.

There are a few lines of evidence to support poor energetic conditions as a potential mechanism for declines in Pacific cod abundance. First, poor fish condition was observed in 2015 (i.e., fish that were lighter than average for a given length; Zador et al. 2017), potential growth in 2015 and 2016 is the lowest in the time series, metabolic demands for 20-40 cm fish in 2015-2019 are the highest estimated (Fig. 2.89), and for 20-40 cm fish 2015-2019 diet energy density are below average (Fig. 2.92). Additionally reports there have been numerous multi-trophic reports from 2015 to present day of mortality events from starvation for avian and marine mammal predators that share prey resources with Pacific cod in the GOA. 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 and overall population decline for juvenile and adult Pacific cod from the years 2014-2019. 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.

From 9 September 2018 through 10 October 2019, the Gulf of Alaska again experienced heatwave conditions above a 90th percentile threshold defined by Hobday et al. (2016). It's reasonable to assume that Pacific cod and other groundfish experienced similar metabolic pressures as during the beginning of the 2014-2016 heatwave. The temperature profiles from the Gulf of Alaska bottom trawl survey suggest that water temperatures in 2019 may have been as warm or warmer than those observed in 2015 and 2017, particularly near the surface in the western Gulf of Alaska (as reported by N. Laman in the 2019 GOA ESR). The 2019 anomaly profiles were most similar to 2015 profiles with warmer anomalies ($\geq 7.0_{o}$C) consistently observed across the entire survey area and penetrating to 200 m depths.

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 2015-2019 are shown Table 2.7. In terms of average catch over the time series, only sea stars account for more than 170 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 was 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 and Munro (2008). 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 has been a critical species in the catch portfolio of the Gulf of Alaska (GOA) fisheries. Starting in 2017, conservation reductions in the TAC have resulted in substantially reduced catch levels. Between 2009-2016, Pacific cod typically accounted for just under 30% of the GOA's FMP groundfish harvest and over 20% of the total Pacific cod catch in Alaska. By 2018 these shares fell to approximately 6%. Catch of Pacific cod in the GOA was down 70% from 2017 with a total catch of 15.2 thousand t and retained catch 14.4 thousand t (Table 2.27). Catches in 2019 are expected to be similarly constrained. Ex-vessel revenues in 2018 were down 59% to $14.5 million with the reduction in catch (Table 2.27). The products made from GOA Pacific cod had a first-wholesale value was $32 million in 2018, which was down 58% from 2017 and below the 2009-2013 average of $102 million (Table 2.28).

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 2.29). 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. The majority of GOA Pacific cod is caught by CVs which make deliveries to shore-based processors and accounts for 90% of the total GOA Pacific cod catch (Table 1). Approximately 25% is caught by the trawl, 55% is caught by pot gear, and 20% caught by hook and line, though the number of hook and line vessels is far greater. Poor fishing conditions in 2017 may have contributed to the significant reduction in jig fleet participation in 2017. Prior to 2016, 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. Since 2016 the distribution has shifted to about 50% with proportionally more cod is being caught in the Western Gulf. Harvests from catcher vessels that deliver to shoreside processors account for approximately 90% of the retained catch. The 2018 retained catch in the GOA decreased 70% to 14.4 thousand t. The ex-vessel value totaled $14.5 million in 2018, which was down from $35 million in 2017 (Table 2.27). Ex-vessel prices increased 35% to $0.45 per pound in 2018. 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. This price differential was $0.05 per pound in 2018.

The first-wholesale value of Pacific cod products was down 58% to $32 million in 2018 (Table 2.28). Despite lower prices through 2014 and 2015 revenues were strong as result of increased catch levels. In contrast, in 2016-2018 prices were up and there was a decrease in revenues as a 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 in 2018, 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 2018 increased 32% to $2.60 per pound as fillet prices increase 38% to $4.35 per pound and H&G prices increased 36% to $2.05 per pound (Table 2.28). Since 2016 reductions in global supply have put upward pressure on prices resulting in significant year over year price increases in 2017 and 2018. Available information on 2019 prices indicate that prices may be leveling off as reflected in the highly exported H&G product type where the price through June of 2019 fell 2%.

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 2.29). China’s rise as re-processor is fairly recent. Between 2001 and 2011 exports to China have increased nearly 10 fold and continued to increase up to 2016. Since 2017 China’s share of exports has declined slightly going from 55% in 2016 to 47% in 2018. The cod industry has largely avoided U.S. tariffs that would have a significant negative impact on them in the U.S.-China trade war. However, Chinese tariffs on U.S. products could inhibit growth in that market. Japan and Europe (mostly Germany and the Netherlands) are also important export destinations. Japan and Europe accounted for 15% and 16% of the export volume respectively. 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 6% of U.S. production, the GOA Pacific cod is a relatively small component of the broader cod market. Strong demand and tight supply in 2017-2018 from the U.S. and globally have contributed to increasing prices. The Barents Sea quota was reduced by 13% 2018 and the global cod supply will remain constrained. Groundfish forum estimates for 2019 indicate global catches of Atlantic and Pacific cod will be reduced by approximately 100 thousand t. Markets may have incorporated these supply adjustments as export prices in 2019 have leveled off, decreasing slightly by 2% (Table 2.29). A portion of the Russian catch of Pacific cod became MSC certified in Oct. 2019 which could put further downward pressure on prices going forward.

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

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.

Barbeaux. S. J., K. Aydin, B. Fissel, K. Holsman, W. Palsson, K. Shotwell, Q. Yang, and S. Zador. 2018. 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. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501

Barbeaux. S. J., A'mar, T., and Palsson, W. 2016. 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. 175-324. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501

Baty, F., Ritz, C. Charles, S., Brutsche, M., Flandrois, J., Delignette-Muller, M. 2015. A Toolbox for Nonlinear Regression in R: The Package nlstools. Journal of Statistical Software, 66(5), 1-21. URL http://www.jstatsoft.org/v66/i05/

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.

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.

Conners, M.E. and Munro, P., 2008. Effects of commercial fishing on local abundance of Pacific cod (*Gadus macrocephalus*) in the Bering Sea. Fishery Bulletin, 106(3), pp.281-292.

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.

Drinan, D.P., Gruenthal, K.M., Canino, M.F., Lowry, D., Fisher, M.C. and Hauser, L., 2018. Population assignment and local adaptation along an isolation-by-distance gradient in Pacific cod (*Gadus macrocephalus*). Evolutionary applications, 11(8), pp.1448-1464.

Echave KB, Hanselman DH, Adkison MD, Sigler MF. 2012. Inter-decadal changes in sablefish, *Anoplopoma fimbria*, growth in the northeast Pacific Ocean. Fish. Bull. 210: 361-374

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.

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. 1992. 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.

Hanselman, D.H., C.R. Lunsford, C.J. Rodgveller, and M.J. Peterson. 2016. Assessment of the sablefish stock in Alaska. In Stock assessment and fishery evaluation report for the groundfish resources of the GOA and BS/AI. North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306 Anchorage, AK 99501. pp. 325-488.

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

Hobday, A.J., Alexander, L.V., Perkins, S.E., Smale, D.A., Straub, S.C., Oliver, E.C., Benthuysen, J.A., Burrows, M.T., Donat, M.G., Feng, M. and Holbrook, N.J., 2016. A hierarchical approach to defining marine heatwaves. Progress in Oceanography, 141, pp.227-238.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

Hobday, A.J., Oliver, E.C., Gupta, A.S., 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.162-173.

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.

Jensen, A.L., 1996. Beverton and Holt life history invariants result from optimal trade-off of reproduction and survival. Canadian Journal of Fisheries and Aquatic Sciences, 53(4), pp.820-822.

Kastelle, C.R., Helser, T.E., McKay, J.L., Johnston, C.G., Anderl, D.M., Matta, M.E. and 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, pp.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.

Kimura, D.K., Balsiger, J.W. and Ito, D.H., 1984. Generalized stock reduction analysis. Canadian Journal of Fisheries and Aquatic Sciences, 41(9), pp.1325-1333.

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 and Rogers (in revision) Loss of spawning habitat and pre-recruits of Pacific cod during a Gulf of Alaska heatwave. Can J Fish Aquat.

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.

Li, L., Hollowed, A.B., Cokelet, E.D., Barbeaux, S.J., Bond, N.A., Keller, A.A., King, J.R., McClure, M.M., Palsson, W.A., Stabeno, P.J. and Yang, Q., 2019. Subregional differences in groundfish distributional responses to anomalous ocean bottom temperatures in the northeast Pacific. Global change biology.

Litzow M, Abookire A. 2018. Kodiak and Alaska Peninsula Cruise Report, College of Fisheries and Ocean Sciences, University of Alaska Fairbanks pgs 1-3

Livingston, P.A., 1989. Interannual trends in Pacific cod, Gadus macrocephalus, predation on three commercially important crab species in the eastern Bering Sea. Fishery Bulletin, 87(4), pp.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.

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. 2005. 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., 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.

Mukhina, N.V., Marshall, C.T. and Yaragina, N.A., 2003. Tracking the signal in year-class strength of Northeast Arctic cod through multiple survey estimates of egg, larval and juvenile abundance. Journal of Sea Research, 50(1), pp.57-75.

Nash, R.D., Valencia, A.H. and Geffen, A.J., 2006. The origin of Fulton's condition factor—setting the record straight. Fisheries, 31(5), pp.236-238.

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.

National Oceanographic and Atmospheric Administration (NOAA). 2017. NOAA OI SST V2 High Resolution Dataset. Available: https://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.highres.html

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.

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

Plummer, M., Best, N., Cowles, K. and Vines K. 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.

Rutecki, T. L., and Varosi, E. R. 1997. Distribution, age, and growth of juvenile sablefish, *Anoplopoma fimbria*, in southeast Alaska. U.S. Dep. Commer., NOAA Technical Report NMFS, vol. 130, pp. 45– 54.

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

Sasaki, T., 1985. Studies on the sablefish resources in the North Pacific Ocean. Far Seas Fishery Laboratory Bulletin, 22, pp. 1–108. Shimizu, 424, Japan.

Schlegel, R.W. and Smit, A.J., 2018. heatwaveR: A central algorithm for the detection of heatwaves and cold-spells. J. Open Source Software, 3(27), p.821.

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.

Sigler, M. F. and Fujioka, J. T., 1988. Evaluation of variability in sablefish, Anoplopoma fimbria, abundance indices in the Gulf of Alaska using the boarstrap method. Fishery Bulletin, 86(3).

Sigler, M.F., and Zenger, H.H. 1989. Assessment of Gulf of Alaska sablefish and other groundfish based on the domestic longline survey, 1987. NOAA Tech. Memo. NMFS F/NWC-169.

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).

Soderlund, E., Dykstra, C., Geernaert, T., Anderson-Chao, E., Ranta, A. 2009. 2008 Standardized stock assessment survey. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2008: 469-496

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.

Spalinger, K., 2006. Bottom trawl survey of crab and groundfish: Kodiak, Chignik, South Peninsula, and eastern Aleutian management districts, 2005. Alaska Department of Fish and Game, Division of Sport Fish, Research and Technical Services.

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.

Spies, I., Gruenthal, K., Drinan, D., Hollowed, A., Stevenson, D., Tarpey, C., and Hauser, L. 2019. Genetic evidence of a northward range expansion in the eastern Bering Sea stock of Pacific cod. Evolutionary Applications. doi: 10.1111/EVA.12874.

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.

Stauffer, G. 2004. NOAA protocols for groundfish bottom trawl surveys of the Nation's fishery resources. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-F/SPO-65, 205 p.

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.G. 2017. Assessment of the Pacific Cod Stock in the Eastern Bering Sea. In Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska [online]. Compiled by The Plan Team for the Groundfish Fisheries of the Gulf of Alaska. North Pacific Fishery Management Council, Anchorage, Alaska.

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. 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.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 Biela, V.R., Arimitsu, M.L., Piatt, J.F., Heflin, B., Schoen, S.K., Trowbridge, J.L. and Clawson, C.M., 2019. Extreme reduction in nutritional value of a key forage fish during the Pacific marine heatwave of 2014-2016. Marine Ecology Progress Series, 613, pp.171-182.

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.

Yang, Q., Cokelet, E.D., Stabeno, P.J., Li, L., Hollowed, A.B., Palsson, W.A., Bond, N.A. and Barbeaux, S.J., 2019. How “The Blob” affected groundfish distributions in the Gulf of Alaska. Fisheries Oceanography, 28(4), pp.434-453.

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 2019 by jurisdiction and gear type (as of 2019-10-02)

	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	3,819	3,130	4,014	120	11,084	309	3,660	195	4,163	15,247
2019*	3,826	2,602	2,604	175	9,207	285	3,551	329	4,166	13,373

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 2019 is current through 2019-10-02 and includes catch from Alaska state waters fisheries and inside waters. The values in the column labeled “TAC” correspond to “optimum yield” for the years 1980-1986, “target quota” for the year 1987, and true TAC for the years 1988-present. 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	15,247	13,096	17,000	23,565
2019	13,372	12,368	17,000	23,669

*As of 10/02/2019

Table 2.4. History of GOA Pacific cod allocations by regulatory area (in percent) for 1991-2019. See Barbeaux et al. (2018) for 1977-1990.

Year(s)	Western	Central	Eastern
1991	33	62	5
1992	37	61	2
1993-1994	33	62	5
1995-1996	29	66	5
1997-1999	35	63	2
2000-2001	36	57	7
2002	39	55	6
2002	38	56	6
2003	39	55	6
2003	38	56	6
2004	36	57	7
2004	35.3	56.5	8.2
2005	36	57	7
2005	35.3	56.5	8.2
2006	39	55	6
2006	38.54	54.35	7.11
2007	39	55	6
2007	38.54	54.35	7.11
2008	39	57	4
2008	38.69	56.55	4.76
2009	39	57	4
2009	38.69	56.55	4.76
2010	35	62	3
2010	34.86	61.75	3.39
2011	35	62	3
2011	35	62	3
2012	35	62	3
2012	32	65	3
2013	38	60	3
2014	37	60	3
2015	38	60	3
2016	41	50	9
2017	41	50	9
2018	44.9	45.1	10
2019	44.9	45.1	10
2020	22.7	70.6	6.7

Table 2.5 Estimated retained-and discarded GOA Pacific cod from federal waters (source: AKFIN; *as of 2019-10-02)

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	704	48,030	48,734
2018	700	14,546	15,247
2019	671	12,702	13,372

Table 2.6 – Weight of groundfish bycatch (t), discarded (D) and retained (R), for 2015 – 2019 for GOA Pacific cod as target species (AKFIN; as of 2019-10-01). For 2018 and 2019 the discard of halibut bycatch is no longer reported in the AKFIN tables.

	2015		2016		2017		2018		2019	
	D	R	D	R	D	R	D	R	D	R
Arrowtooth Flounder	455	659	568	809	217	273	88	21	203	26
Atka Mackerel	146	11	31	8	352	32	3	7	33	0
Flathead Sole	98	241	78	245	53	100	22	8	90	7
GOA Deep Water Flatfish	26	15	17	4	19	1	0	0	2	0
GOA Demersal Shelf Rockfish	0.46	2	1	2	0.40	0.38	0	0	0	0
GOA Dusky Rockfish	11	16	60	19	78	18	4	4	2	5
GOA Rex Sole	8	113	23	147	3	16	5	1	28	0
GOA Rougheye Rockfish	0.12	13	2	5	10	7	6	4	1	2
GOA Shallow Water Flatfish	298	715	181	565	279	563	32	23	40	10
GOA Shortraker Rockfish	0.16	11	1	4	5	4	8	3	1	1
GOA Skate, Big	603	205	438	257	449	171	71	33	145	31
GOA Skate, Longnose	154	565	384	181	301	105	38	49	49	42
GOA Skate, Other	1,063	81	1,002	73	894	106	192	15	204	33
GOA Thornyhead Rockfish	5	4	3	7	11	25	1	2	1	1
Halibut	32	52	8	38	11	30	**60**		**57**	
Northern Rockfish	12	35	61	17	45	9	4	1	3	0
Octopus	524	380	154	207	29	195	10	142	27	111
Other Rockfish	22	70	44	69	66	53	10	24	6	21
Pacific Ocean Perch	104	62	781	15	46	31	0	3	0	3
Pollock	133	1,003	64	350	343	487	32	76	69	25
Sablefish	43	37	101	31	81	32	58	4	30	48
Sculpin	635	3	865	11	919	2	98	0	65	0
Shark	207	0.29	424	0.18	364		131	0	172	0
Squid	0.21	1	0.03	1	0.012	0.11	0	0	0	0

Table 2.7 - Incidental catch (t or *birds by number*) of non-target species groups by GOA Pacific cod fisheries, 2015-2019 (as of 2019-10-02). 0.0 indicates less and 0.05 tons, a blank indicates no catch.

	2015	2016	2017	2018	2019
Benthic urochordata	4.3	0.0	1.5	0.0	0.3
Birds	*98*	*167*	*232*	*399*	*31*
Bivalves	1.4	0.6	1.3	2.8	0.2
Brittle star unidentified	0.0	0.0	0.0	0.0	
Capelin	0.0				
Corals Bryozoans - Corals Bryozoans Unidentified	1.2	0.4	2.3	1.6	1.9
Corals Bryozoans - Red Tree Coral	0.5				
Eelpouts	0.3	0.1	0.1		0.2
Eulachon			0.0		
Giant Grenadier	105.7	84.9	18.6	0.1	0.2
Greenlings	2.6	4.7	5.8	0.9	0.9
Grenadier - Rattail Grenadier Unidentified	2.6	1.2		0.6	0.1
Hermit crab unidentified	2.8	0.6	0.1	0.1	1.2
Invertebrate unidentified	0.2	1.1	0.2	0.1	
Misc crabs	1.0	1.0	0.8	0.4	0.0
Misc crustaceans	0.5		0.0		
Misc fish	108.4	154.2	169.2	30.1	5.1
Misc inverts (worms etc)	0.0				
Other osmerids		0.0			
Pacific Hake		0.0			
Pacific Sand lance			0.0		
Pandalid shrimp	0.0	0.0			
Polychaete unidentified		0.0			
Scypho jellies	4.1	21.5	0.9		
Sea anemone unidentified	5.6	21.2	13.4	2.5	1.6
Sea pens whips	1.8	0.7	0.6	0.4	0.4
Sea star	1218.3	891.9	383.8	40.1	28.8
Snails	11.9	14.6	9.6	6.8	0.3
Sponge unidentified	1.3	1.6	2.6	2.3	6.3
State-managed Rockfish	14.5	47.2	75.5	3.5	4.2
Stichaeidae			0.3		
urchins dollars cucumbers	4.2	2.0	4.6	0.4	0.1

Table 2.8 – Pacific cod catch (t) by trip target in Gulf of Alaska groundfish fisheries. *Data for 2019 is as of 10/02/2019.

Trip Target	**2015**	**2016**	**2017**	**2018**	**2019**
Arrowtooth Flounder	1,384	1,346	1,266	960	1,302
Atka Mackerel	-	10	5	12	-
Deep Water Flatfish - GOA	-	-	-	-	-
Flathead Sole	1	39	2	2	18
Halibut	541	325	368	430	185
Other Species	12	-	2	1	-
Pacific Cod	***74,052***	***60,789***	***46,008***	***12,461***	***10,691***
Pollock - bottom	1,090	624	557	536	376
Pollock - midwater	622	230	55	64	58
Rex Sole - GOA	162	25	6	79	62
Rockfish	786	366	253	394	296
Sablefish	127	108	88	44	55
Shallow Water Flatfish - GOA	711	225	123	262	330
TOTAL	79,489	64,087	48,734	15,247	13,373
Non Pacific cod trip target total	5,437	3,297	2,726	2,786	2,682

Table 2.9 – Noncommercial fishery catch (in kg); total source amounts less than 1 kg were omitted (AFSC for GOA bottom trawl survey values; AKFIN for other values, as of 2019-10-09)

Source	**2014**	**2015**	**2016**	**2017**
AFSC Annual Longline Survey	33,370	39,824	24,240	15,598
Bait for Crab Fishery	7,348	1,616	2,006	988
GOA Shelf and Slope Walleye Pollock Acoustic-Trawl Survey				53
Gulf of Alaska Bottom Trawl Survey		18,945		5,197
IPHC Annual Longline Survey	138,091	77,044	46,273	38,927
Kachemak Bay Large Mesh Trawl Survey				1,254
Kenai/Prince William Sound Walleye Pollock Acoustic-Trawl Survey				15
Kodiak Scallop Dredge				1
Large-Mesh Trawl Survey	13,090	8,072	6,076	6,597
Prince William Sound Large Mesh Trawl Survey				164
Salmon EFP 13-01	8,316			
Scallop Dredge Survey				
Shumagin Islands Walleye Pollock Acoustic-Trawl Survey				11
Small-Mesh Trawl Survey	1,424	1,412	160	161
Sport Fishery	199,263	183,813	122,501	
Spot Shrimp Survey	12	10	2	
Total	400,913	330,736	201,257	68,966

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
2019	181,581	0.218	127,188	0.243

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	2019	14,933	0.185
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			
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
2008	22,201.86	0.17	2019	14,238.55	0.25

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

Year	Index	CV	Year	Index	CV
1988	2.80	0.09	2005	1.06	0.09
1989	3.72	0.09	2006	0.91	0.09
1990	2.77	0.08	2007	1.09	0.08
1991	1.89	0.14	2008	1.26	0.07
1992	2.88	0.08	2009	1.26	0.07
1993	2.33	0.09	2010	1.07	0.07
1994	2.09	0.08	2011	1.37	0.07
1995	2.31	0.11	2012	2.60	0.09
1996	2.34	0.09	2013	1.96	0.10
1997	2.52	0.08	2014	1.35	0.10
1998	2.27	0.09	2015	1.22	0.10
1999	1.26	0.07	2016	0.84	0.11
2000	0.98	0.08	2017	0.89	0.11
2001	0.86	0.08	2018	1.16	0.10
2002	1.09	0.07	2019	0.97	0.09
2003	0.87	0.08			
2004	1.34	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 1979-2019. Note that the MHWI for 2019 are only through October 30.

Year	10cm	40cm	Annual MHWI	Winter MHWI
1979	4.91	4.70	0	0
1980	5.03	4.74	0	0
1981	5.71	5.20	0	0
1982	4.00	4.08	0	0
1983	5.11	4.87	24.82	24.82
1984	4.73	4.75	75.56	41.44
1985	4.57	4.58	22.2	22.2
1986	4.73	4.53	15.67	15.67
1987	5.30	5.00	5.45	5.45
1988	4.70	4.60	0	0
1989	4.05	3.95	0	0
1990	4.12	4.11	8.56	0
1991	4.38	4.26	0	0
1992	4.89	4.60	0	0
1993	4.52	4.37	19.02	0
1994	4.47	4.46	0	0
1995	4.04	4.04	0	0
1996	4.50	4.40	0	0
1997	4.56	4.46	138.58	24.12
1998	5.73	5.20	152.42	152.42
1999	4.43	4.38	0	0
2000	4.51	4.43	0	0
2001	4.98	4.80	35.52	18.66
2002	4.20	4.10	50.34	50.34
2003	5.30	5.15	201.08	158.99
2004	4.60	4.58	115.59	0
2005	4.91	4.89	276.54	9.96
2006	4.63	4.57	35.03	5.97
2007	4.13	3.85	0	0
2008	4.33	4.17	0	0
2009	3.66	3.81	0	0
2010	5.21	4.78	6.54	0
2011	4.55	4.27	0	0
2012	4.00	3.64	0	0
2013	4.18	4.14	0	0
2014	4.73	4.62	257.74	104.06
2015	5.88	5.42	378.87	234.5
2016	5.71	4.99	632.81	368.28
2017	4.75	4.42	39.27	27.44
2018	5.10	4.79	93.68	69.59
2019	5.94	5.46	**368.06**	**144.65**

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

	M18.10.44	M19.11.44	M19.14.48c
Recruitment			
Early Init Ages	10	10	10
Early Rec. Devs (1977)	1	1	1
Main Rec. Devs (1978-2014)	37	37	37
Late Rec. Devs (2015-2018)	5	4	4
Future Rec. Devs. (2019-2023)	5	5	5
R_0	1	1	1
1976 R reg.	1	1	1
Natural mortality	2	2	2
Growth	5	5	5
Aging Bias	0	0	2
Catchability			
Q_{trawl}	1	1	1
$Q_{longline}$	1	1	1
$Q_{longline}$ env. offset	1	1	1
Initial F	2	2	2
Selectivity			
Trawl Survey	16	16	16
Longline survey	5	5	5
Trawl Fishery	58(39 dev)	58(39 dev)	58(39 dev)
Longline Fishery	39 (24 dev)	39 (24 dev)	39(24 dev)
Pot Fishery	8	8	8
Total	198	198	200

Table 2.16 – Model fit statistics and results. Note that likelihoods between model series are not completely comparable. Note 2019 SSB is beginning of year from Stock Synthesis, 2020 and 2021 SSB are March estimates from projection model assuming 6,300 t catch. Authors' preferred model in green.

	M18.10.44	M19.11.44	M19.14.48c
Likelihoods Total	2297.59	2349.20	2714.86
Survey	-9.59	-11.79	-11.38
Length Comp.	1337.18	1342.63	1360.43
Age Comp.	963.36	1013.33	1362.03
Recruitment	-6.34	-8.04	-9.00
Parameter priors	1.58	1.19	1.18
Parameter Devs.	5.83	6.09	6.10
Parameters			
R_0 billions	0.598	0.571	0.579
Steepness	1.0	1.0	1.0
Natural Mortality	0.49	0.49	0.49
M_{14-16}	0.85	0.81	0.81
q_{Shelf}	1.16	1.10	1.08
$q_{longline}$	1.23	1.16	1.15
L_{min}	5.29	3.49	2.3
L_{max}	99.46	99.46	99.46
Von Bert K	0.17	0.18	0.19
Results			
SSB_{1978} (t)	118,283	115,078	117,113
$SSB_{100\%}$ (t)	173,544	185,651	187,780
SSB_{2019} (t)	29,386	32,387	33,274
$SSB_{2019\%}$	16.9	17.4	17.7
SSB_{2020}(t)	29,782	31,840	32,958
$SSB_{2020\%}$	17.2	17.2	17.6
SSB_{2021}(t)	38,841	40,403	42,026
$SSB_{2021\%}$	22.4	21.8	22.4
$F_{35\%}$	0.750	0.676	0.668
$F_{40\%}$	0.603	0.546	0.540
2020 ABC (t)	14,838	14,042	14,620
F_{ABC}	0.240	0.218	0.221
OFL (t)	18,168	17,104	17,794
F_{OFL}	0.299	0.269	0.274
2021 ABC (t)	26,003	23,541	24,820
F_{ABC}	0.323	0.284	0.290
OFL (t)	31,705	28,574	30,099
F_{OFL}	0.402	0.351	0.359

Table 2.17 – Likelihood components by fleet for all proposed models.

Model	Label	ALL	FshTrawl	FshLL	FshPot	Srv	LLSrv
18.10.44	Age_like	963.36	258.38	264.82	210.90	229.27	
19.11.44	Age_like	1013.33	238.86	289.10	210.25	275.12	
19.14.48c	Age_like	1362.03	241.02	287.31	208.83	624.87	
18.10.44	Catch_like	4.38E-12	1.50E-12	1.48E-12	1.41E-12		
19.11.44	Catch_like	6.93E-12	2.33E-12	2.34E-12	2.26E-12		
19.14.48c	Catch_like	8.14E-12	2.73E-12	2.76E-12	2.66E-12		
18.10.44	Length_like	1337.18	393.66	289.72	291.74	144.13	217.94
19.11.44	Length_like	1342.63	397.32	284.38	290.74	153.93	216.25
19.14.48c	Length_like	1360.43	401.11	283.24	291.45	166.75	217.87
18.10.44	Surv_like	-9.60				-10.56	0.96
19.11.44	Surv_like	-11.79				-11.87	0.08
19.14.48c	Surv_like	-11.38				-11.80	0.42

Table 2.18 – Retrospective analysis, index RMSE, harmonic mean effective N for length and age compositions, and recruitment variability for selected assessed models.

		M18.10.44	M19.11.44	M19.14.48c
Retrospective				
Spawning biomass	Mohn's ρ	0.182	0.155	0.118
	Woods Hole ρ	0.190	0.177	0.148
	RMSE	0.195	0.185	0.174
Recruit. (age -0)	Mohn's ρ	0.347	0.246	0.197
	Woods Hole ρ	0.338	0.295	0.217
	RMSE	0.307	0.276	0.233
	Index RMSE			
	AFSC Trawl	0.290	0.277	0.277
	AFSC Longline	0.316	0.317	0.318
Size Comp				
Har. Mean EffN	Trawl	313.60	309.88	308.61.
	Longline	451.69	452.49	454.03
	Pot	414.64	416.45	413.66
	AFSC Trawl	327.37	313.64	305.71
	AFSC Longline	283.86	286.84	285.13
Mean input N	Trawl	147.45	147.45	147.45
	Longline	155.13	155.13	155.13
	Pot	171.00	171.00	171.00
	AFSC Trawl	94.38	94.38	94.38
	AFSC Longline	100.00	100.00	100.00
Age Data				
Har. Mean EffN	Trawl	1.64	1.84	1.81
	Longline	2.67	2.69	2.68
	Pot	2.35	2.53	2.51
	AFSC Trawl	2.81	2.90	2.93
Mean input N	Trawl	1.03	1.03	1.03
	Longline	1.59	1.59	1.59
	Pot	1.23	1.23	1.23
	AFSC Trawl	1.42	1.42	1.42
Rec. Var. (1977-2017)				
	Std.dev(ln(No. Age 1))	0.55	0.52	0.51

Table 2.19 – Estimated beginning year weight and length at age from Model 19.14.48c.

Age	Weight (kg)	Length (cm)
0	1.35E-04	0.5
1	0.013	10.919
2	0.161	25.914
3	0.536	38.369
4	1.121	48.715
5	1.856	57.309
6	2.672	64.447
7	3.513	70.377
8	4.336	75.302
9	5.113	79.394
10	7.082	88.036

Table 2.20 – Estimated female spawning biomass (t) from the last year's assessment and this year's assessment from Models 18.10.44 and the author's recommended Model 19.14.48c.

	Last Year's Model			Model19.14.48c		
	Sp.Bio	St.dev	Tot. Bio. 0+	Sp.Bio	St.dev	Tot. Bio. 0+
1977	120,453	28,059	403,588	104,750	23,105	340,687
1978	130,267	29,204	422,439	117,115	24,505	353,530
1979	126,010	27,365	504,136	114,285	23,198	401,961
1980	123,733	25,682	593,197	110,135	21,309	465,619
1981	151,436	30,339	635,060	125,320	23,684	496,767
1982	188,497	36,725	668,967	153,290	28,367	524,234
1983	197,736	37,047	713,828	162,280	29,274	565,329
1984	200,333	35,954	758,519	164,770	28,964	612,364
1985	218,129	35,924	798,787	182,455	29,559	664,827
1986	242,500	35,204	837,433	210,695	29,955	715,967
1987	254,206	32,877	871,227	232,910	29,421	764,445
1988	255,330	29,508	873,994	236,290	26,653	778,122
1989	263,180	26,925	857,974	245,590	24,537	777,175
1990	260,761	23,944	823,846	248,915	22,288	759,213
1991	236,943	20,755	776,061	228,490	19,601	717,933
1992	215,133	18,336	743,411	210,315	17,628	689,490
1993	199,049	16,766	705,219	193,725	16,084	654,597
1994	200,625	15,889	667,998	196,020	15,306	627,867
1995	201,299	14,614	613,486	199,155	14,210	588,782
1996	180,727	12,558	533,819	179,380	12,250	518,686
1997	151,465	10,273	470,311	153,285	10,210	461,210
1998	122,877	8,463	418,822	127,445	8,561	413,127
1999	107,276	7,598	379,079	112,615	7,674	375,787
2000	95,443	7,154	338,390	100,450	7,173	335,702
2001	87,620	6,642	325,728	91,975	6,585	318,708
2002	82,855	6,079	334,660	87,065	5,971	324,404
2003	82,785	5,910	336,484	85,975	5,663	325,922
2004	85,552	6,116	317,059	87,350	5,736	307,850
2005	83,110	5,936	288,103	84,680	5,590	280,816
2006	76,069	5,264	272,454	77,450	4,995	264,538
2007	66,572	4,594	281,250	68,365	4,420	268,873
2008	59,467	4,316	316,237	61,215	4,161	299,342
2009	62,478	4,809	364,318	62,835	4,557	342,596
2010	81,083	6,076	421,953	81,485	5,743	401,264
2011	95,334	7,507	441,055	94,895	7,039	425,866
2012	105,408	8,952	442,457	105,105	8,484	428,225
2013	109,747	9,903	467,634	113,350	9,743	445,224
2014	109,814	10,778	541,959	113,830	10,614	498,565
2015	76,280	6,691	413,621	80,020	6,587	381,875
2016	60,085	5,033	278,457	62,215	4,811	257,969
2017	45,374	4,036	166,636	46,080	3,787	155,394
2018	39,723	4,208	146,433	37,369	3,837	127,165
2019	34,701	4,075	183,503	35,231	3,711	141,458
2020				**33,274**		170,124

Table 2.21 – Age-0 recruitment and standard deviation of age-0 recruits by year for last year's model and Model19.14.48c. Highlighted are the 1977 and 2012 year classes.

	M18.10.44		M19.14.48c	
Year	Age-0 x 10^9	Stdev	Age-0 x 10^9	Stdev
1977	2.234	0.650	1.363	0.367
1978	0.504	0.197	0.441	0.144
1979	0.539	0.196	0.476	0.142
1980	1.220	0.381	0.880	0.235
1981	1.080	0.341	0.801	0.214
1982	1.273	0.377	1.105	0.282
1983	0.767	0.276	0.618	0.190
1984	1.047	0.343	0.875	0.228
1985	1.515	0.376	1.158	0.255
1986	0.544	0.190	0.543	0.140
1987	1.012	0.245	0.865	0.176
1988	0.800	0.214	0.668	0.144
1989	0.983	0.238	0.842	0.169
1990	1.094	0.252	0.882	0.173
1991	0.676	0.176	0.600	0.124
1992	0.539	0.135	0.467	0.097
1993	0.375	0.101	0.392	0.081
1994	0.456	0.109	0.440	0.086
1995	0.689	0.138	0.541	0.098
1996	0.410	0.094	0.416	0.077
1997	0.450	0.096	0.353	0.067
1998	0.318	0.073	0.356	0.065
1999	0.670	0.127	0.514	0.089
2000	0.586	0.112	0.530	0.090
2001	0.355	0.072	0.301	0.057
2002	0.298	0.058	0.284	0.052
2003	0.345	0.063	0.323	0.055
2004	0.372	0.067	0.330	0.057
2005	0.734	0.127	0.646	0.103
2006	0.869	0.153	0.777	0.126
2007	0.761	0.138	0.636	0.109
2008	0.942	0.171	0.893	0.152
2009	0.490	0.095	0.483	0.093
2010	0.678	0.132	0.558	0.105
2011	0.989	0.205	0.907	0.177
2012	1.703	0.382	1.250	0.266
2013	1.002	0.254	0.688	0.166
2014	0.379	0.110	0.200	0.057
2015	0.247	0.083	0.302	0.077
2016	0.400	0.126	0.269	0.069
2017	0.693	0.335	0.395	0.122
2018	0.703	0.341	0.297	0.095
2019			0.579	0.278
Mean 1977-2015	0.768		0.633	
Stdev(Ln(x))		0.588		0.517

Table 2.22 – Estimated fishing mortality in Apical F and Total exploitation for Model 19.14.48c.

	Sum Apical F		Total		Sum Apical F		Total
Year	F	σ	**Exploitation**	**Year**	F	σ	**Exploitation**
1977	0.005	0.001	0.007	2001	0.087	0.007	0.147
1978	0.032	0.007	0.038	2002	0.078	0.007	0.146
1979	0.033	0.008	0.047	2003	0.094	0.008	0.172
1980	0.043	0.009	0.081	2004	0.124	0.010	0.197
1981	0.064	0.012	0.078	2005	0.111	0.009	0.184
1982	0.053	0.010	0.063	2006	0.114	0.009	0.200
1983	0.049	0.009	0.072	2007	0.139	0.011	0.234
1984	0.030	0.005	0.044	2008	0.122	0.010	0.239
1985	0.012	0.002	0.023	2009	0.093	0.008	0.179
1986	0.023	0.003	0.038	2010	0.136	0.011	0.228
1987	0.036	0.007	0.048	2011	0.121	0.011	0.218
1988	0.032	0.004	0.046	2012	0.129	0.012	0.201
1989	0.049	0.007	0.060	2013	0.120	0.012	0.180
1990	0.058	0.006	0.102	2014	0.136	0.015	0.203
1991	0.067	0.007	0.116	2015	0.149	0.015	0.227
1992	0.071	0.007	0.128	2016	0.205	0.018	0.256
1993	0.050	0.005	0.092	2017	0.288	0.028	0.338
1994	0.047	0.004	0.080	2018	0.089	0.011	0.136
1995	0.079	0.007	0.123	2019	0.059	0.008	0.103
1996	0.091	0.008	0.140				
1997	0.098	0.008	0.161				
1998	0.088	0.007	0.161				
1999	0.113	0.009	0.195				
2000	0.106	0.009	0.176				

Table 2.23 – Model 19.14.48c parameters and reference estimates MLE and MCMC derived. SSB is calculated for January 1 in this table. FSSB100% is female unfished spawning biomass from Stock Synthesis calculated using 1977-2017 as reference.

	MLE estimates		MCMC posterior distribution		
	MLE	σ	50%	2.5%	97.5%
$M_{Standard}$	0.4886	0.0206	0.4819	0.4407	0.5214
$M_{2014\text{-}2016}$	0.8121	0.0521	0.8003	0.6822	0.8968
Von Bert K	0.1855	0.0021	0.1847	0.1807	0.1891
Lmin	2.3115	0.5625	2.3999	1.3236	3.4925
Lmax	99.4614	0.0150	99.4617	99.4342	99.4881
$Ln(Q_{Trawl\ survey})$	0.0799	0.0871	0.1112	-0.0552	0.2785
$Ln(Q_{ll\ survey})$	0.1378	0.0704	0.1772	0.0602	0.3145
$Ln(Q_{ll\ survey\ envir.})$	1.0829	0.0344	0.9263	0.5128	1.6020
$FSSB_{1978}$	117,115	24,505	112,872	77,648	165,303
$FSSB_{2019}$	35,231	3,711	33,803	27,940	40,690
Recr_1977	1,363,400	366,770	1,293,625	758,904	2,147,373
Recr_2012	1,250,100	265,600	1,177,775	767,083	1,740,844
$FSSB_{100\%}$	172,629	13,459	170,420	148,490	197,715
$FSSB_{2019}/FSSB_{100\%}$	20.4%		19.8%	16.2%	24.2%

Table 2.24 – Biological reference points from GOA Pacific cod SAFE documents for years 2001 – 2019

Year	$\mathbf{SB_{100\%}}$	$\mathbf{SB_{40\%}}$	$\mathbf{F_{40\%}}$	$\mathbf{SB_{y+1}}$	$\mathbf{ABC_{y+1}}$
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
2019	187,780	75,112	0.67	32,957	14,621

Table 2.25 – Number of fish at age-1 from Model 19.14.48c with the M 2014-2016 block fixed at the standard M value used in projection model.

Year	Age-1	Year	Age-1
1977	236,700	2000	317,328
1978	836,739	2001	328,025
1979	270,550	2002	187,192
1980	292,016	2003	176,125
1981	540,089	2004	198,647
1982	491,871	2005	196,316
1983	678,677	2006	376,135
1984	379,600	2007	428,542
1985	538,300	2008	338,917
1986	712,027	2009	428,897
1987	331,248	2010	206,826
1988	528,906	2011	210,410
1989	408,224	2012	283,787
1990	515,772	2013	331,254
1991	539,478	2014	161,998
1992	368,156	2015	51,013
1993	286,643	2016	101,296
1994	240,666	2017	109,078
1995	270,246		
1996	332,461		
1997	256,198		
1998	216,840		
1999	219,211		

Table 2.26 – Results for the projection scenarios from Model 19.14.48c. 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
2019	33,275	33,275	33,275	33,275	33,275	33,275	33,275
2020	32,958	32,958	32,958	32,958	32,958	32,958	32,958
2021	42,026	42,026	42,026	42,026	42,026	38,016	39,113
2022	50,180	50,180	52,321	51,443	58,806	46,629	48,707
2023	58,155	58,155	64,231	62,500	78,051	54,609	55,354
2024	68,231	68,231	80,075	77,551	101,500	64,141	64,243
2025	74,791	74,791	94,639	91,238	124,818	69,361	69,325
2026	77,556	77,556	104,922	100,685	144,009	70,987	70,957
2027	78,949	78,949	112,095	107,136	159,659	71,696	71,685
2028	79,089	79,089	115,910	110,459	169,823	71,542	71,538
2029	78,501	78,501	117,775	111,926	177,341	70,858	70,857
2030	78,127	78,127	118,428	112,372	181,586	70,555	70,556
2031	77,788	77,788	118,507	112,348	183,891	70,313	70,313
2032	77,881	77,881	118,698	112,492	185,435	70,457	70,458
F							
2019	0.24	0.24	0.24	0.24	0.24	0.24	0.24
2020	0.09	0.09	0.09	0.09	0.09	0.27	0.22
2021	0.29	0.29	0.21	0.24	0.00	0.32	0.27
2022	0.35	0.35	0.21	0.24	0.00	0.40	0.42
2023	0.41	0.41	0.21	0.24	0.00	0.48	0.48
2024	0.46	0.46	0.21	0.24	0.00	0.54	0.55
2025	0.49	0.49	0.21	0.24	0.00	0.58	0.58
2026	0.50	0.50	0.21	0.24	0.00	0.59	0.59
2027	0.50	0.50	0.21	0.24	0.00	0.59	0.59
2028	0.50	0.50	0.21	0.24	0.00	0.59	0.59
2029	0.50	0.50	0.21	0.24	0.00	0.58	0.58
2030	0.50	0.50	0.21	0.24	0.00	0.58	0.58
2031	0.50	0.50	0.21	0.24	0.00	0.58	0.58
2032	0.50	0.50	0.21	0.24	0.00	0.58	0.58
Catch							
2019	15,000	15,000	15,000	15,000	15,000	15,000	15,000
2020	6,300	6,300	6,300	6,300	6,300	17,794	14,621
2021	24,820	24,820	18,577	21,131	0	25,134	21,779
2022	35,127	35,127	22,845	25,616	0	37,368	40,339
2023	48,948	48,948	28,500	31,716	0	53,239	54,374
2024	63,700	63,700	34,897	38,665	0	70,164	70,283
2025	71,302	71,302	40,089	44,210	0	77,685	77,617
2026	74,438	74,438	43,660	47,940	0	80,203	80,159
2027	75,829	75,829	46,069	50,403	0	81,076	81,060
2028	75,365	75,365	47,160	51,453	0	80,132	80,128
2029	74,720	74,720	47,691	51,912	0	79,246	79,246
2030	74,442	74,442	47,859	52,028	0	78,901	78,901
2031	74,126	74,126	47,868	52,002	0	78,678	78,678
2032	74,386	74,386	48,035	52,178	0	79,066	79,066

Table 2.27 – 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; 2009-2013 average and 2014-2018.

	Avg 09-13	2014	2015	2016	2017	2018
Total catch K mt	72.7	84.9	79.5	64.1	48.7	15.2
Retained catch K mt	69.7	79.5	77.5	63.1	48.0	14.4
Ex-vessel value M $	$46.7	$52.1	$50.3	$41.0	$35.3	$14.5
Ex-vessel price lb $	$0.304	$0.297	$0.293	$0.294	$0.334	$0.452
Hook & line share of catch	27%	23%	21%	17%	18%	23%
Pot gear share of catch	49%	48%	52%	60%	55%	53%
Central Gulf share of catch	61%	59%	60%	53%	43%	47%
Shoreside share of catch	89%	91%	92%	92%	87%	88%
Vessels #	432.6	341	382	358	246	151

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 2.28 – 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; 2009-2013 average and 2014-2018.

		Avg 09-13	2014	2015	2016	2017	2018
All Products	**volume K mt**	29.11	31.07	32.00	21.65	17.39	5.58
All Products	**value M $**	$102.0	$118.0	$102.5	$91.8	$75.5	$32.0
All Products	**price lb $**	$1.59	$1.72	$1.45	$1.92	$1.97	$2.60
Fillets	**volume K mt**	8.79	9.85	6.39	7.87	6.52	2.00
Fillets	**value share**	54.8%	57.1%	36.3%	62.4%	60.0%	60.0%
Fillets	**price lb $**	$2.88	$3.10	$2.64	$3.30	$3.15	$4.35
Head & Gut	**volume K mt**	12.15	13.95	19.05	8.43	6.11	1.92
Head & Gut	**value share**	31.8%	32.5%	50.9%	24.7%	26.9%	27.2%
Head & Gut	**price lb $**	$1.21	$1.25	$1.24	$1.22	$1.51	$2.05

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 2.29 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; 2009-2013 average and 2014-2019.

		Avg 09-13	2014	2015	2016	2017	2018	2019 (thru June)
Global cod catch K mt		1,506	1,852	1,762	1,792	1,759	-	-
U.S. P. cod share of global catch		18.6%	17.6%	18.0%	17.9%	17.0%	-	-
Europe share of global catch		74.2%	75.9%	74.8%	74.8%	75.7%	-	-
Pacific cod share of U.S. catch		97.8%	99.3%	99.5%	99.5%	99.7%	-	-
U.S. cod consumption K mt (est.)		88	115	108	114	119	113	-
Share of U.S. cod not exported		27%	31%	26%	29%	32%	35%	-
Export volume K mt		98.3	107.3	113.2	105.3	92.8	73.2	39.4
Export value M US$		$309.9	$314.2	$335.0	$312.0	$295.5	$253.6	$133.6
Export price lb US$		$1.429	$1.328	$1.342	$1.344	$1.445	$1.570	$1.539
Frozen (H&G)	volume Share	74%	92%	91%	94%	94%	91%	90%
	value share	74%	91%	90%	92%	92%	90%	89%
Fillets	volume Share	10%	2%	3%	3%	4%	5%	6%
	value share	12%	4%	4%	4%	5%	6%	6%
China	volume Share	39%	54%	53%	55%	52%	47%	47%
	value share	37%	51%	51%	52%	50%	46%	45%
Japan	volume Share	17%	16%	13%	14%	16%	15%	7%
	value share	18%	16%	14%	15%	18%	17%	8%
Europe*	volume Share	30%	20%	19%	17%	17%	16%	20%
	value share	32%	22%	19%	18%	18%	18%	21%

Notes: Pacific cod in this table is for all U.S. Unless noted, `cod' in this table refers to Atlantic and Pacific cod. Russia, Norway, and Iceland account for the majority of Europe's cod catch which is largely focused in the Barents sea.

*Europe export statistics refers to: Austria, Belgium, Denmark, France, Germany, Greece, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and United Kingdom

Source: FAO Fisheries & Aquaculture Dept. Statistics http://www.fao.org/fishery/statistics/en. NOAA Fisheries, Fisheries Statistics Division, Foreign Trade Division of the U.S. Census Bureau, http://www.st.nmfs.noaa.gov/commercial-fisheries/foreign-trade/index. U.S. Department of Agriculture http://www.ers.usda.gov/data-products/agricultural-exchange-rate-data-set.aspx.

Figures

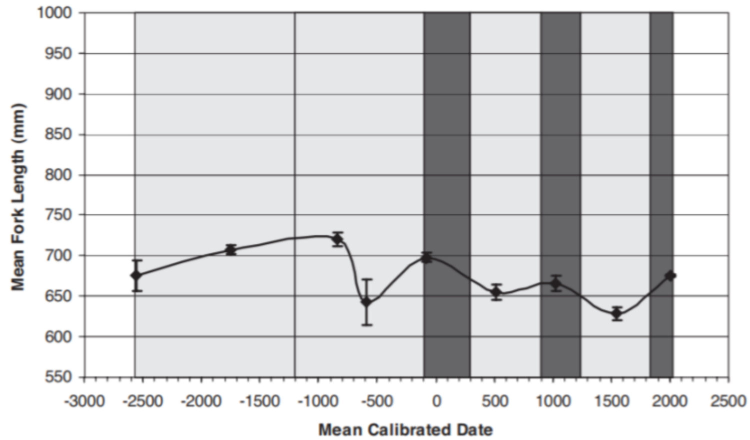


Figure 2.1 Gulf of Alaska mean lengths with climate reconstruction. The shaded boxes represent periods of significant changes in air temperature, sea surface temperature, storminess, and ocean circulation that drive ocean productivity. The lightly shaded boxes represent periods of cooler and stormier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

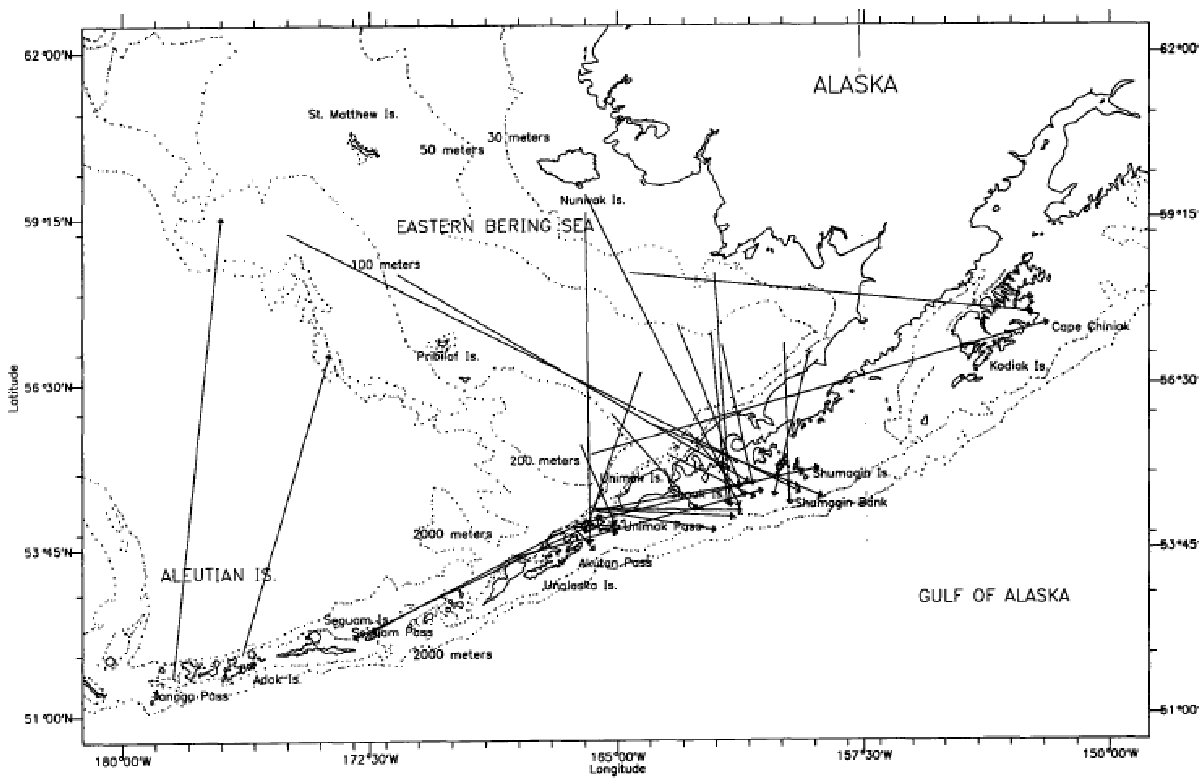


Figure 2.2 Tag recoveries from Shimada and Kimura 1994 (Figure 8), showing movement of individual tagged Pacific cod from eastern Bering Sea into the Gulf of Alaska and other interregional migrations.

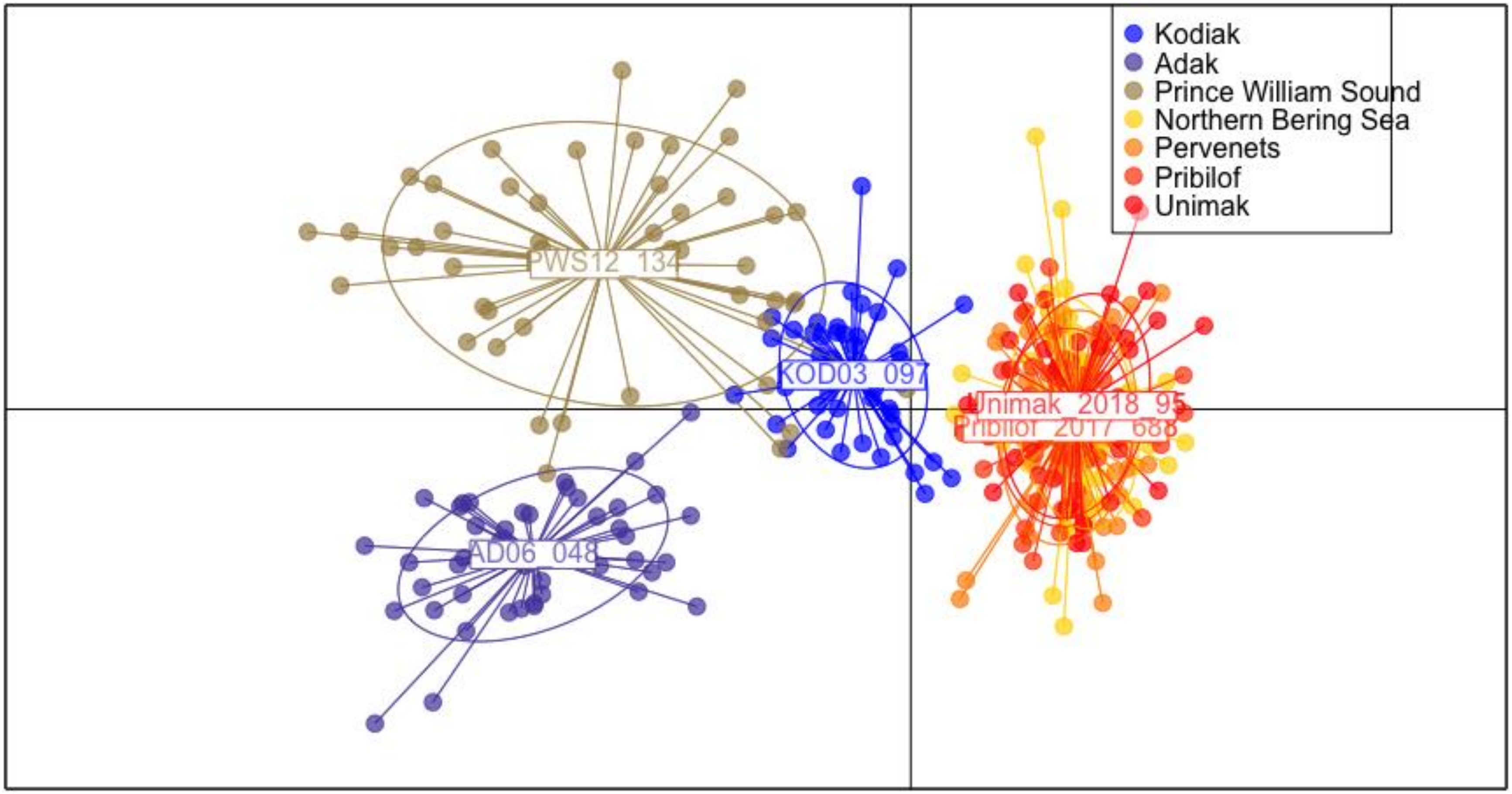


Figure 2.3 Discriminant analysis of principal components (DAPC) scatterplot with the following populations represented: Adak (2006), Prince William Sound, PWS (2012), Kodiak (2003), Unimak (2018), Pervenets (2016), Pribilof (2017), and Norton Sound, NBS (2017). All populations represent spawning groups 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.

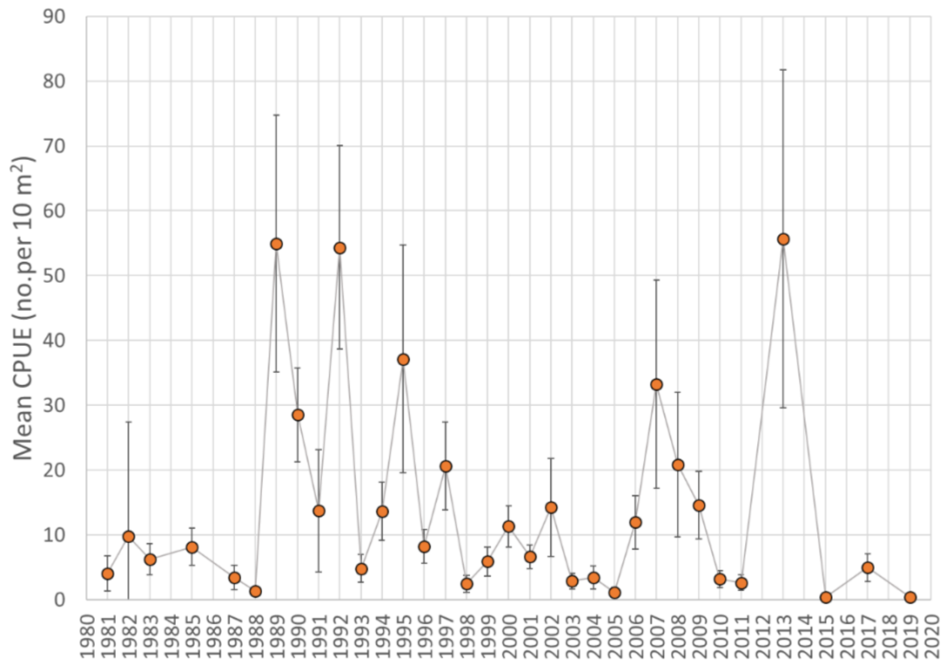


Figure 2.4. Pacific cod larval abundance from late spring ichthyoplankton surveys in the Gulf of Alaska using all stations within a core area covering the Shelikof Sea valley and Semidi bank area.

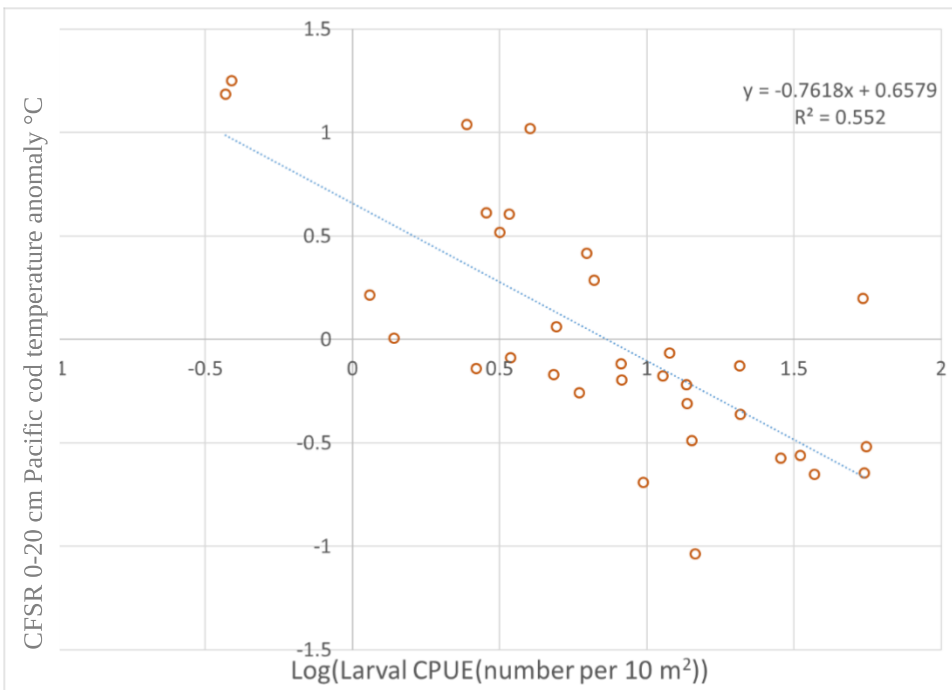


Figure 2.5 Log larval area weighted CPUE from late spring ichthyoplankton surveys in the Gulf of Alaska using all stations within a core area covering the Shelikof Sea valley and Semidi bank area by mean annual temperature at 48m bottom depth in the Central GOA from the CFSR reanalysis data.

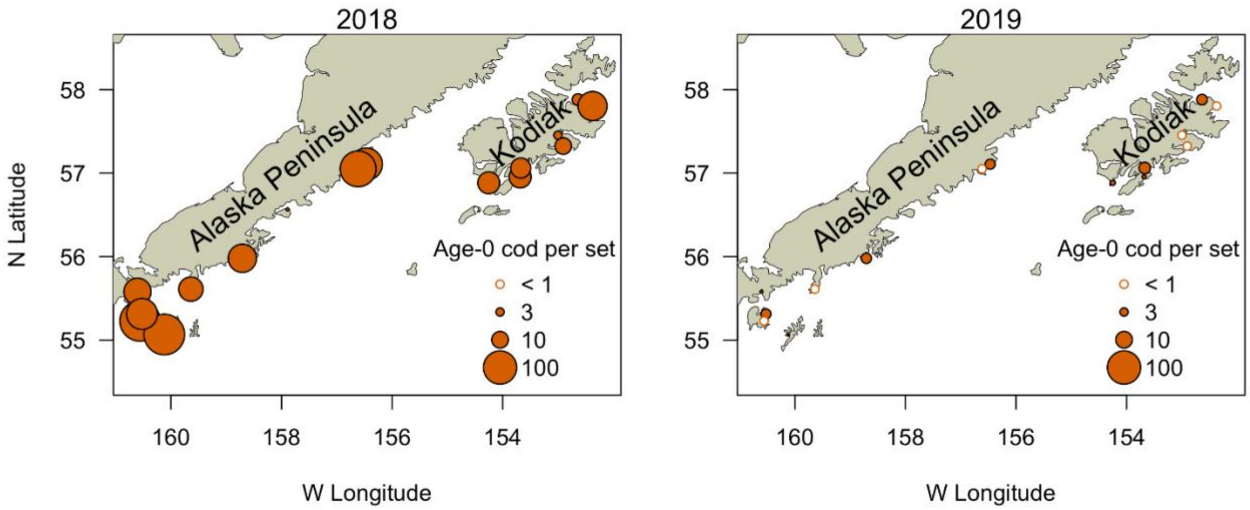


Figure 2.6 Abundance (catch per set, where present) of age-0 cod in beach seines, summer (left) 2018 and right (2019). Each point plots the average abundance for a given bay, with 4-16 individual sets within each bay.

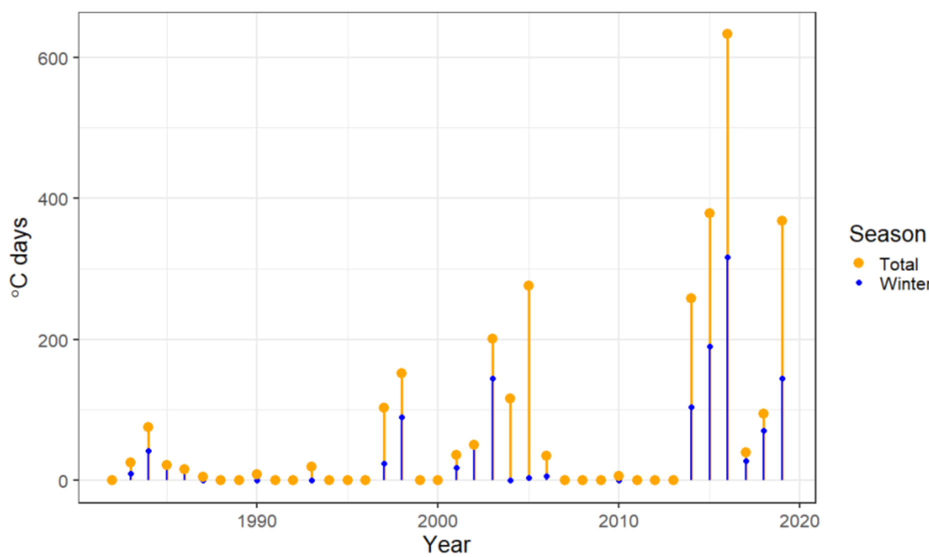


Figure 2.7 Index of the sum of the annual marine heatwave cumulative intensity (℃ days) for 1981-2019 (larger yellow points) and index of the sum of the annual winter marine heatwave cumulative intensity for 1981-2019 (smaller blue points) from the daily mean sea surface temperatures NOAA high resolution blended analysis data for the Central Gulf of Alaska. The 2019 index value is the sum through 30 October 2019.

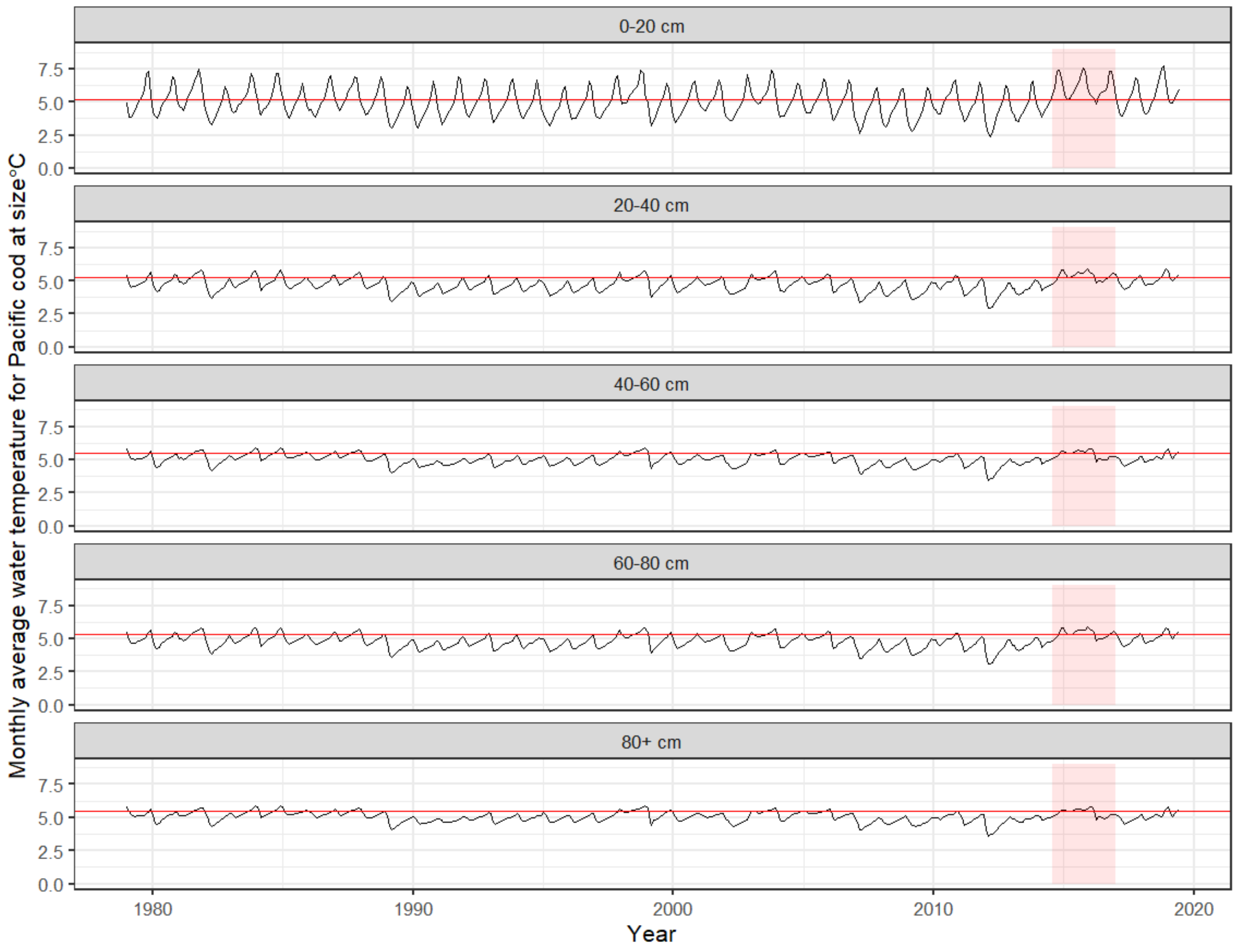


Figure 2.8 Temperature at mean depth of cod grouped by 20 cm size class bins from the Climate Forecast System Reanalysis (CFSR) output. Red lines are the minimum monthly mean temperatures in 2015 encountered by each size bin and the red block indicates the time frame of the 2014-2016 marine heatwave. Plotted through June 2019.

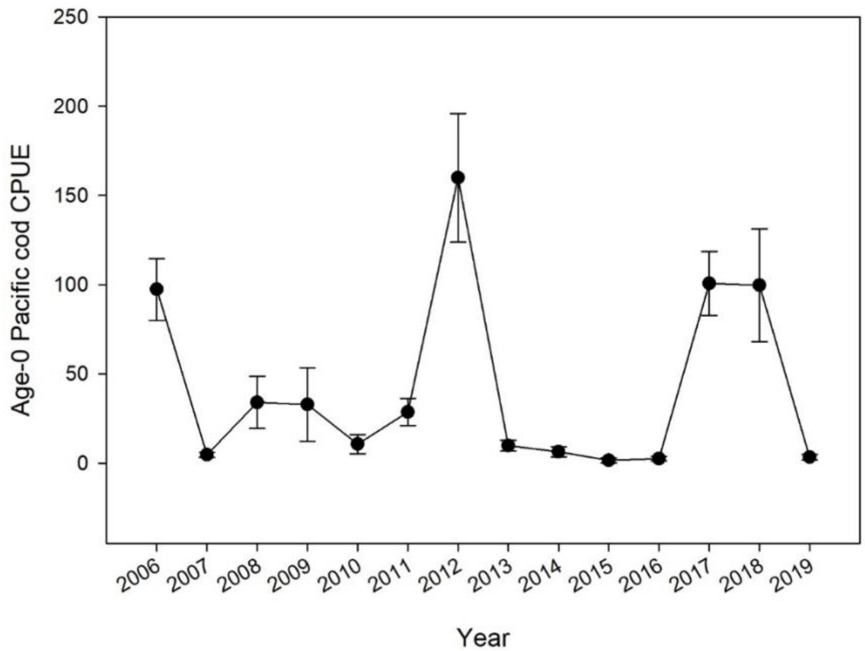


Figure 2.9 Catch per unit effort (log cod per set, including sets where absent) at Kodiak long-term sampling sites, 2006-2018 (mean and 95% CI).

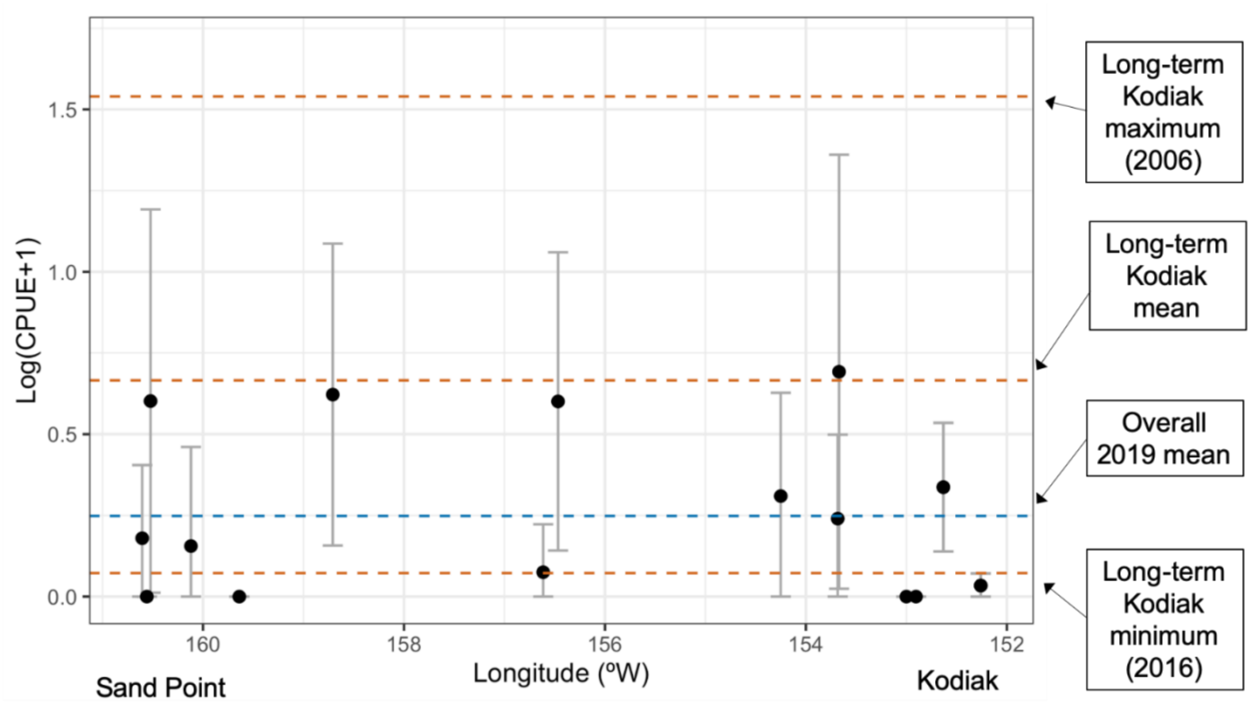


Figure 2.10 Age-0 cod abundance (catch per set, where present) from 2019 western Gulf of Alaska beach seine survey, compared to the range of abundances observed during 2006-2019 NOAA survey of two Kodiak bays. Each point plots mean abundance and 95% confidence intervals for 15 bays sampled in 2019. This very preliminary analysis suggests that the 2019 cohort is weak across the sampling area when compared to the historical range observed around Kodiak.

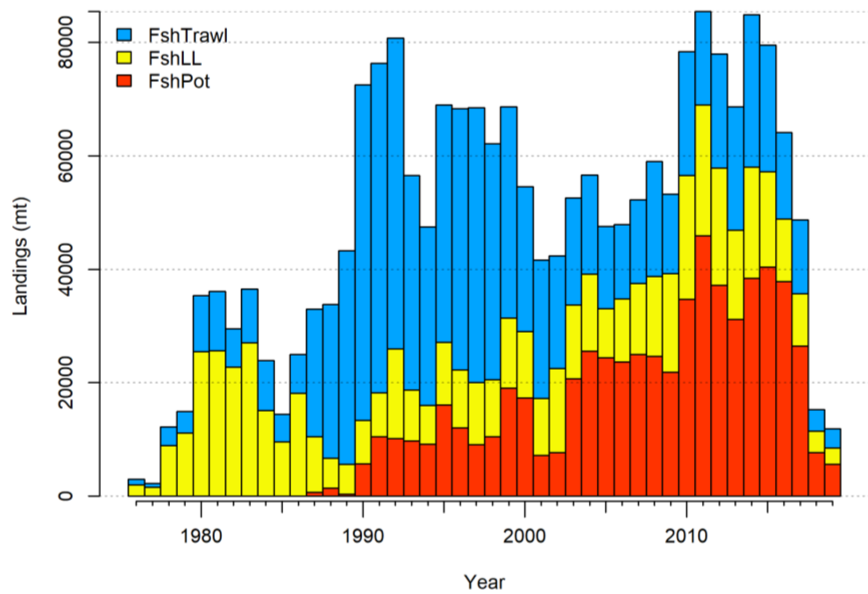


Figure 2.11 Gulf of Alaska Pacific cod catch from 1977-2019. Note that 2019 catch was through October 2.

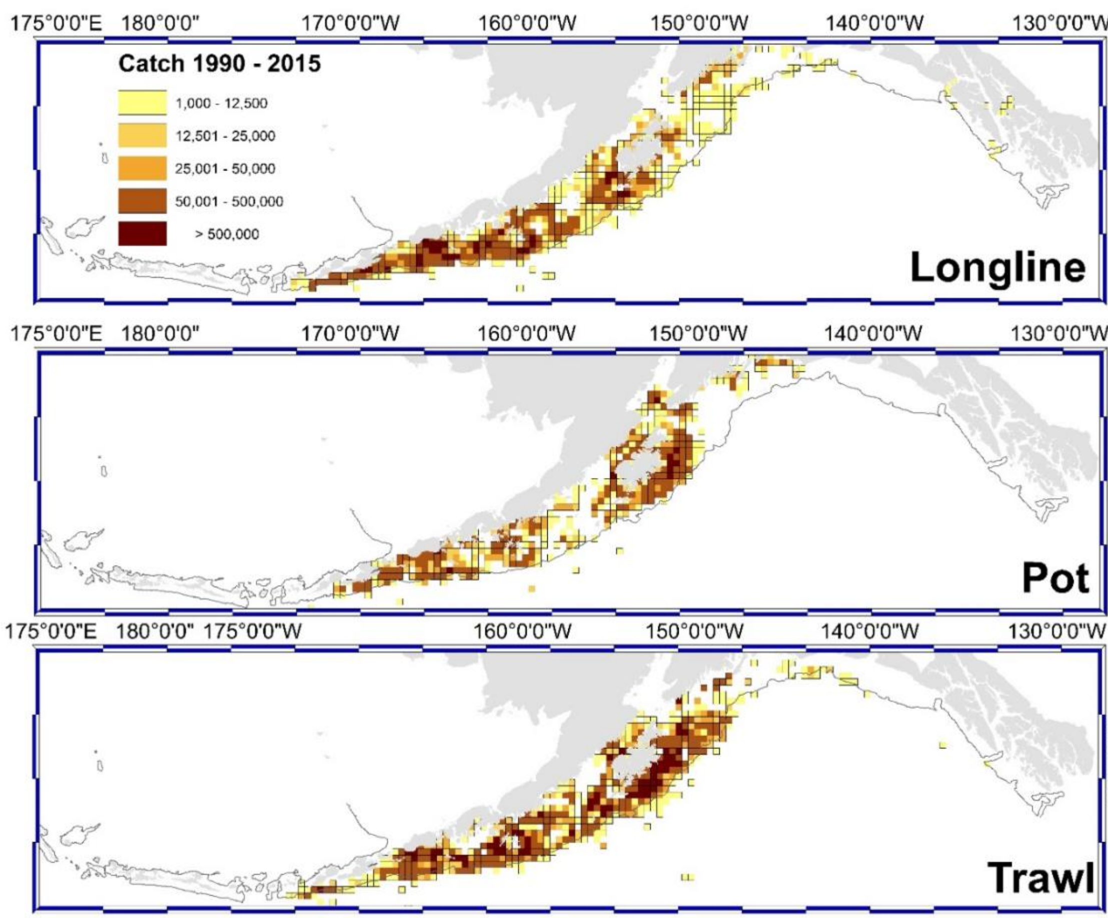


Figure 2.12 Commercial catch of Pacific cod in the Gulf of Alaska by 20km2 grid for 1990-2015.

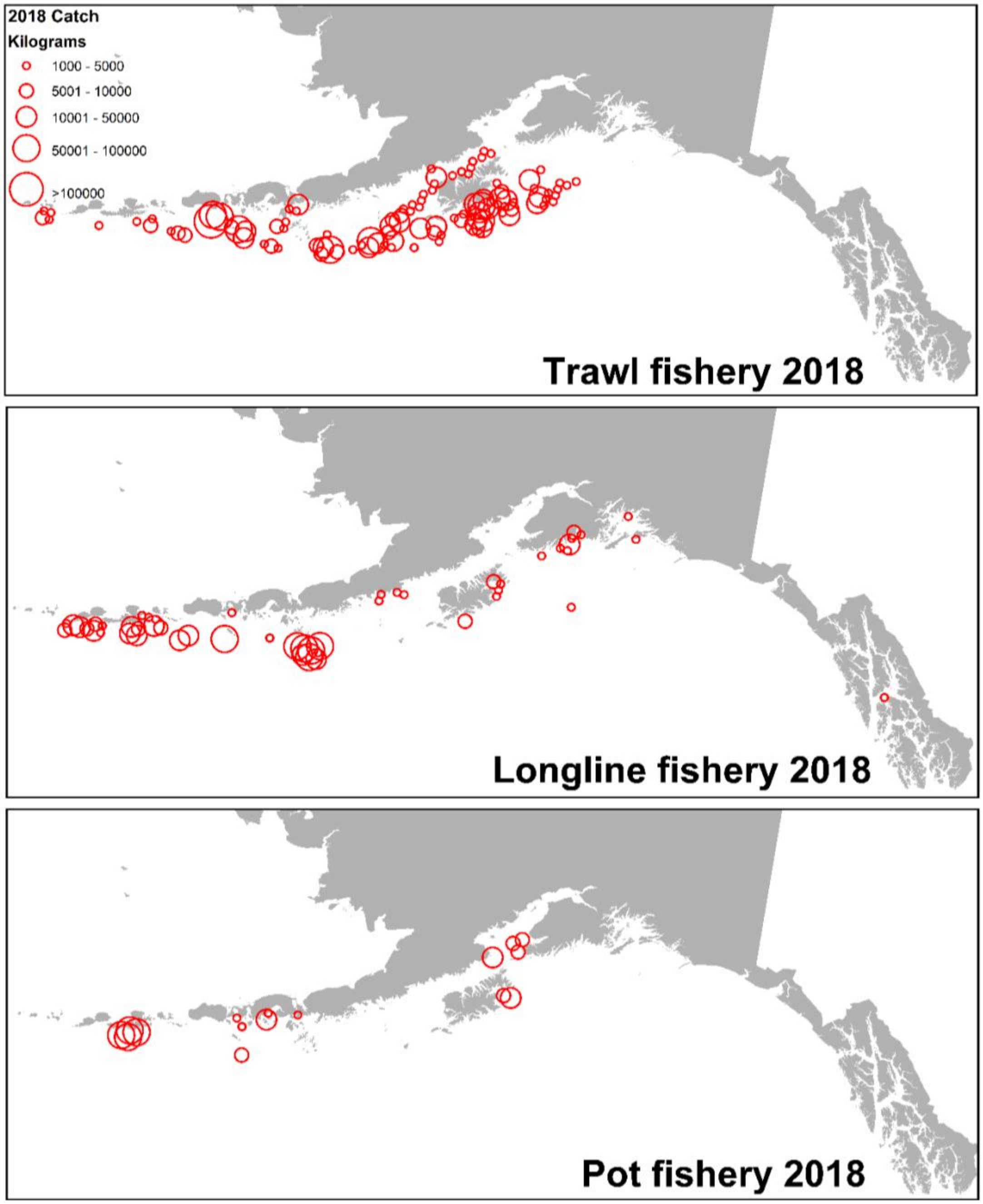


Figure 2.13 Commercial catch of Pacific cod in the Gulf of Alaska by 20km2 grid for 2018 for catch greater than 1000 kg.

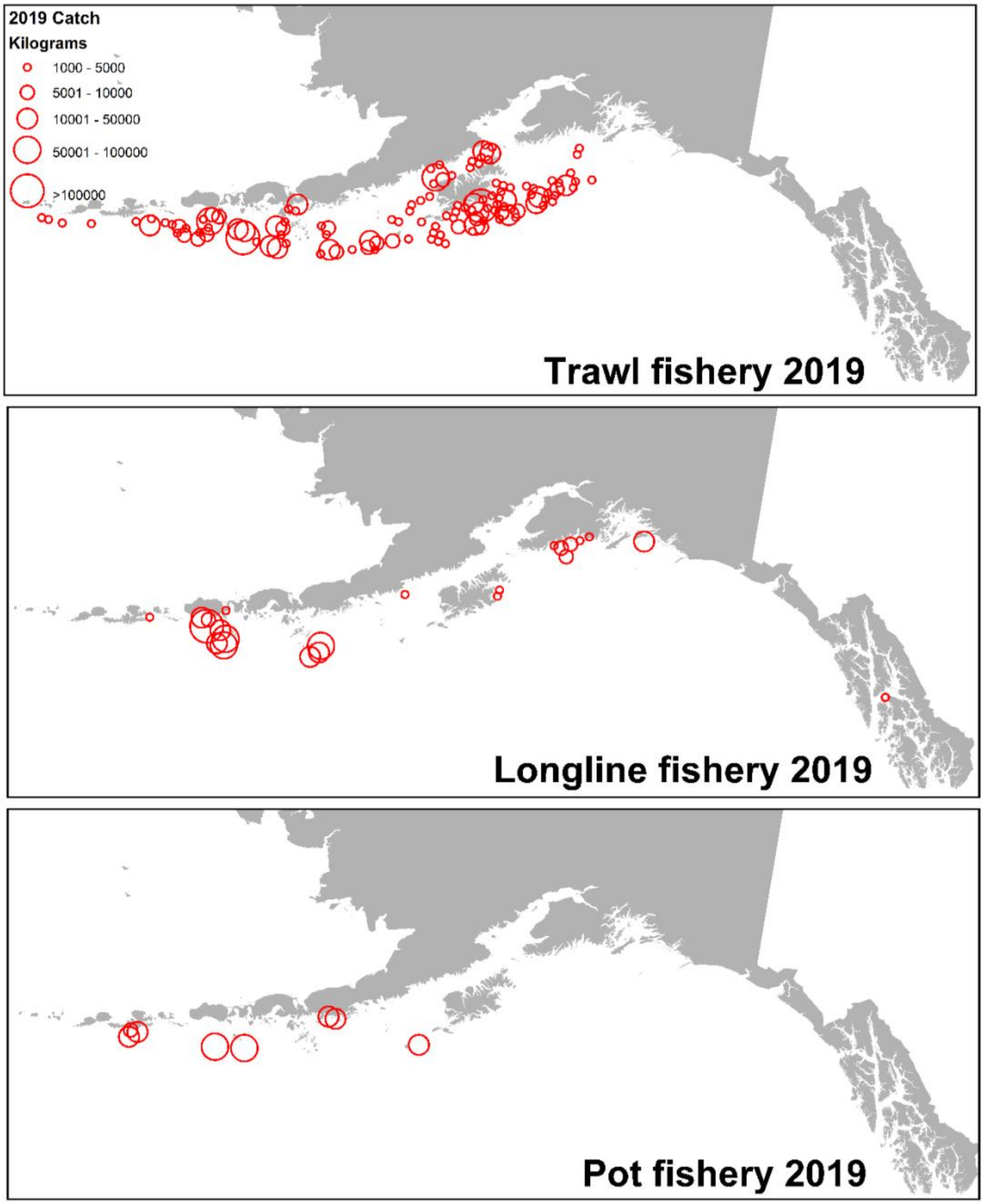


Figure 2.14 Commercial catch of Pacific cod in the Gulf of Alaska by 20km2 grid for 2019 as of October 28, 2019 for catch greater than 1000 kg.

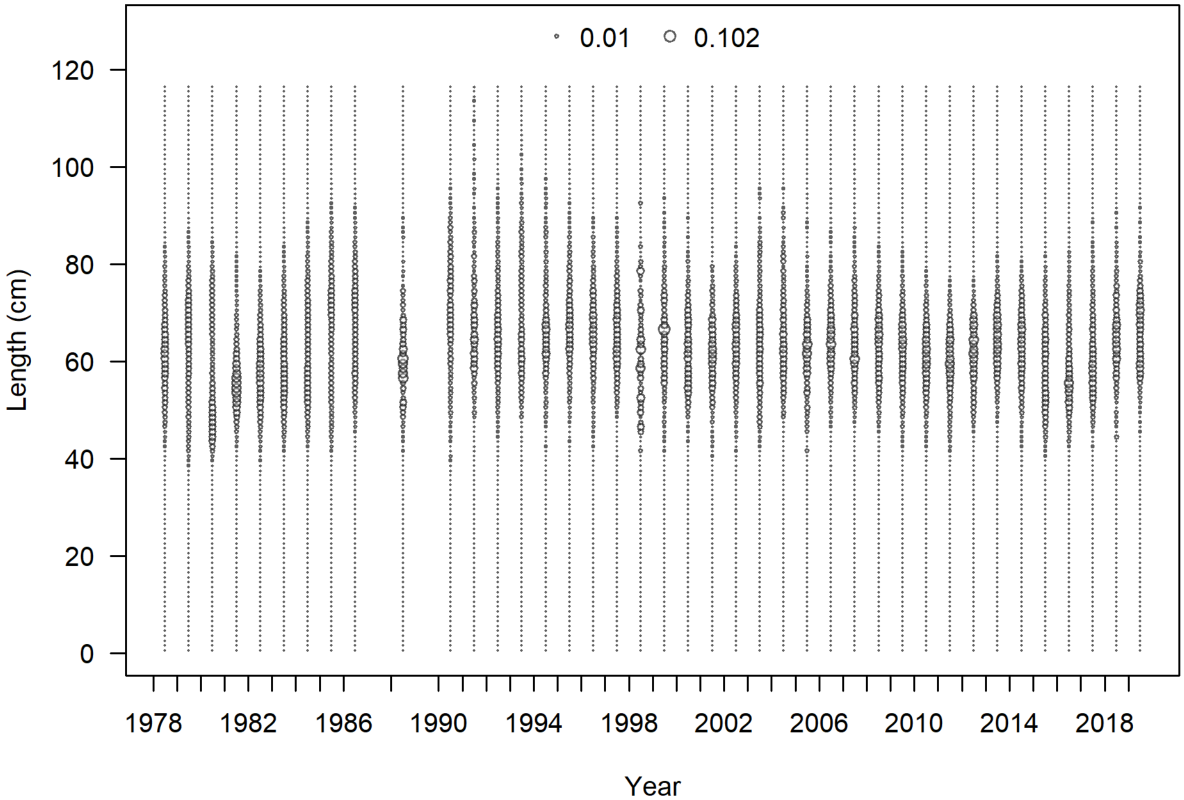


Figure 2.15 Pacific cod length composition by annual proportion from the Gulf of Alaska longline fishery (max=0.102).

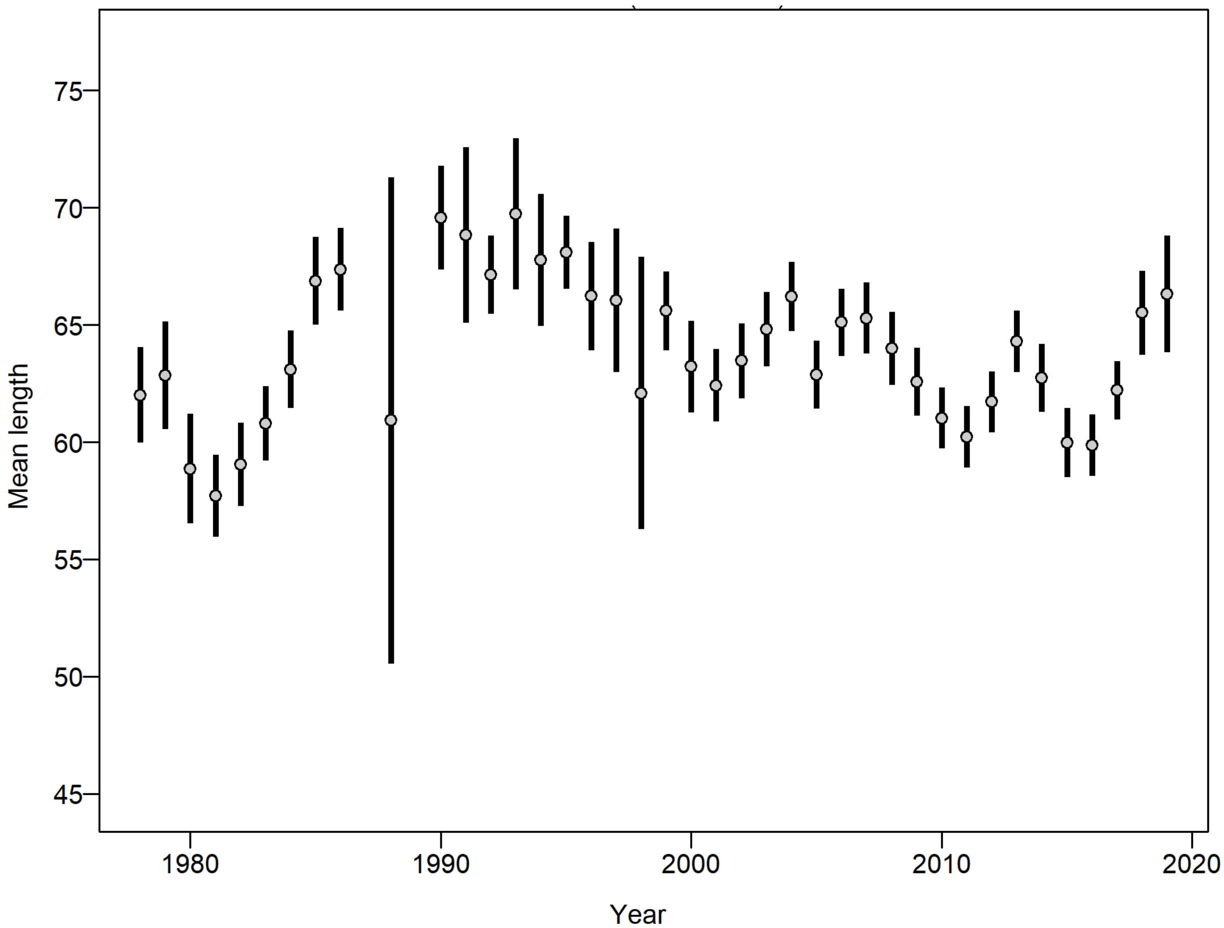


Figure 2.16 Mean length (cm) of Pacific cod from the Gulf of Alaska longline fishery.

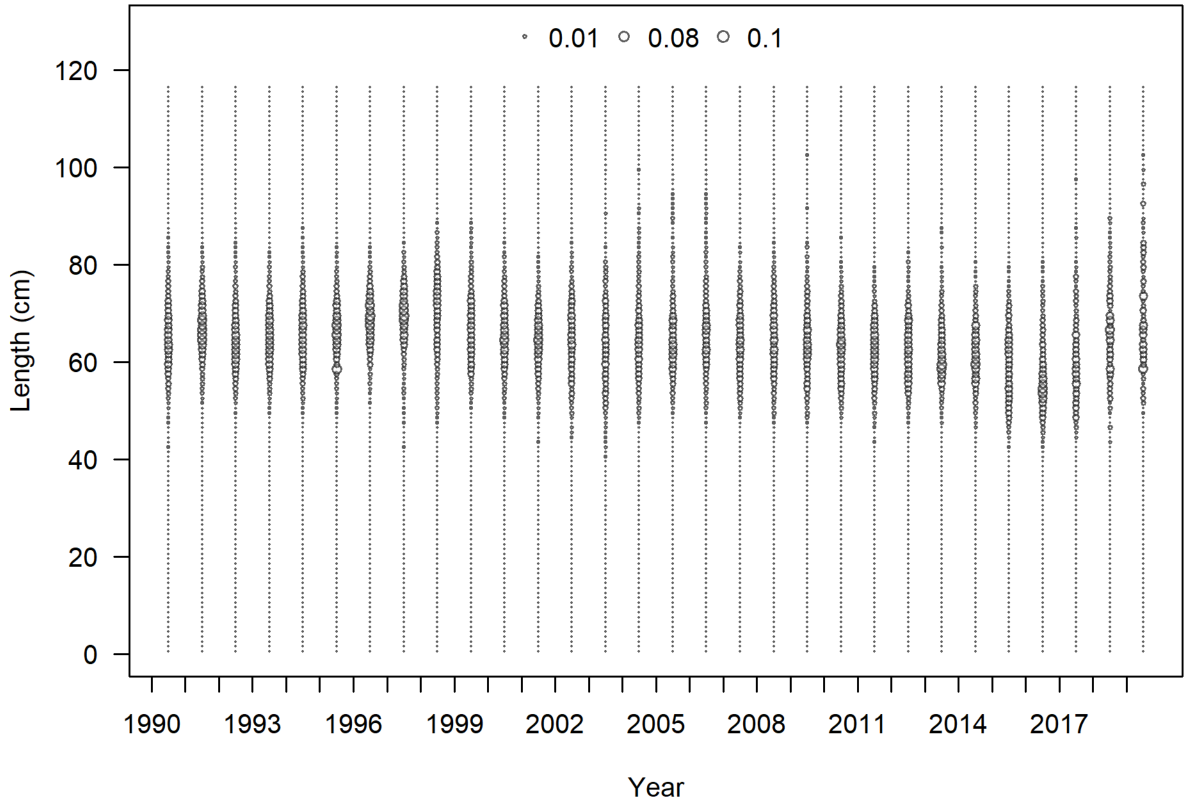


Figure 2.17 Pacific cod length composition by annual proportion from the Gulf of Alaska pot fishery (max=0.1).

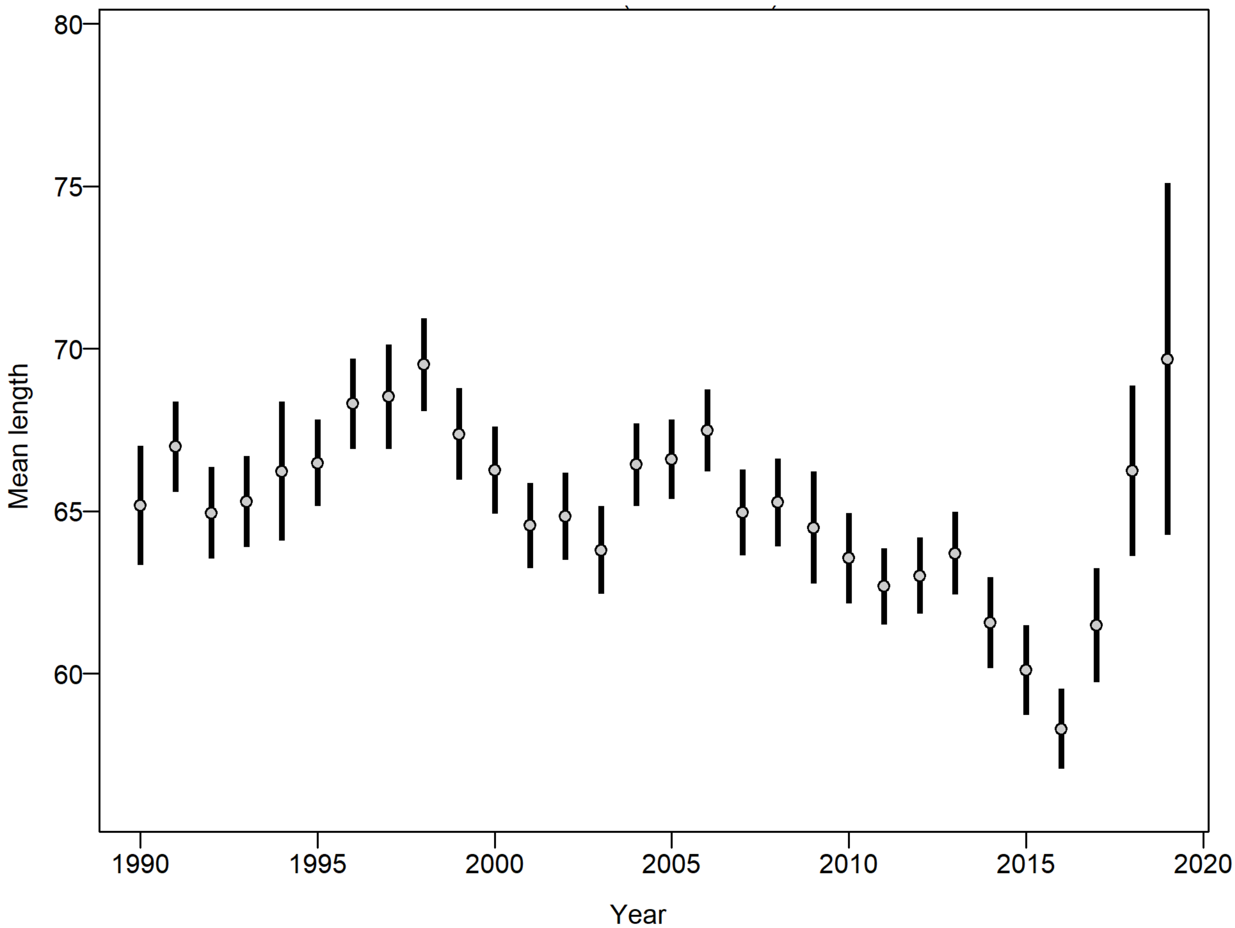


Figure 2.18 Mean length (cm) of Pacific cod from the Gulf of Alaska pot fishery.

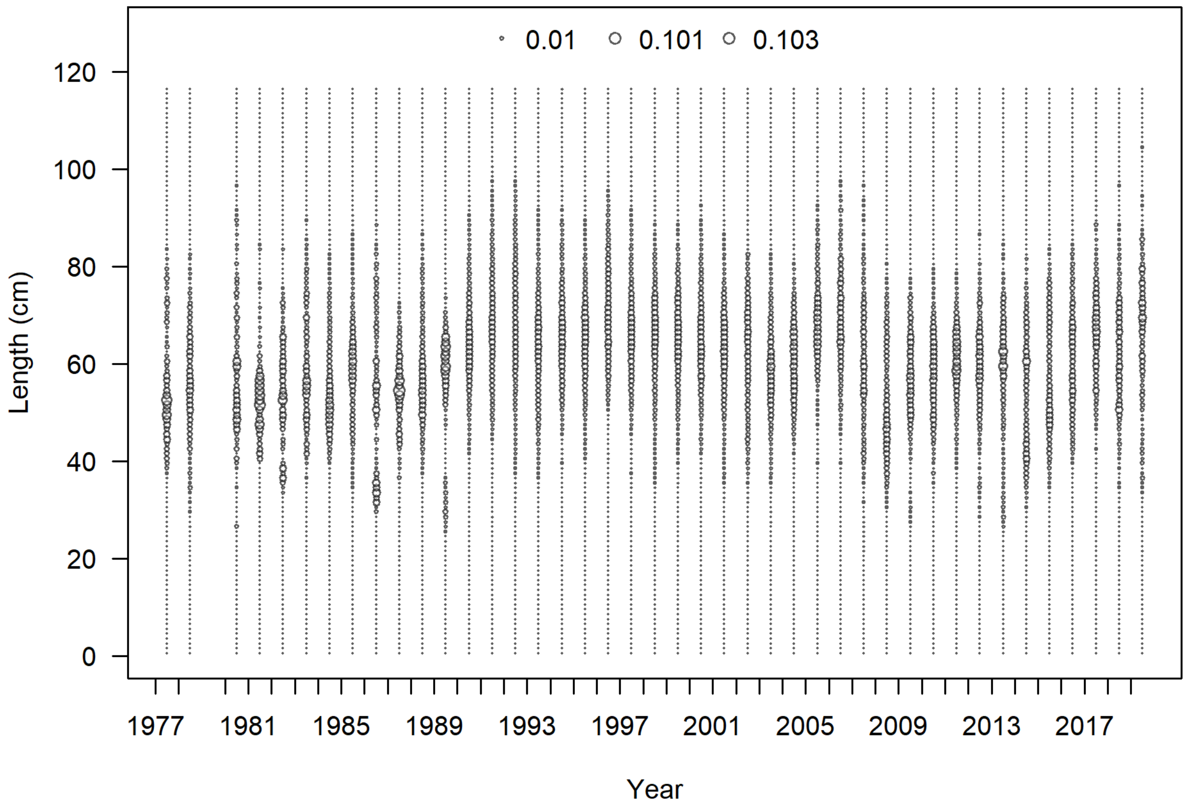


Figure 2.19 Pacific cod length composition by annual proportion from the Gulf of Alaska trawl fishery (max=0.103).

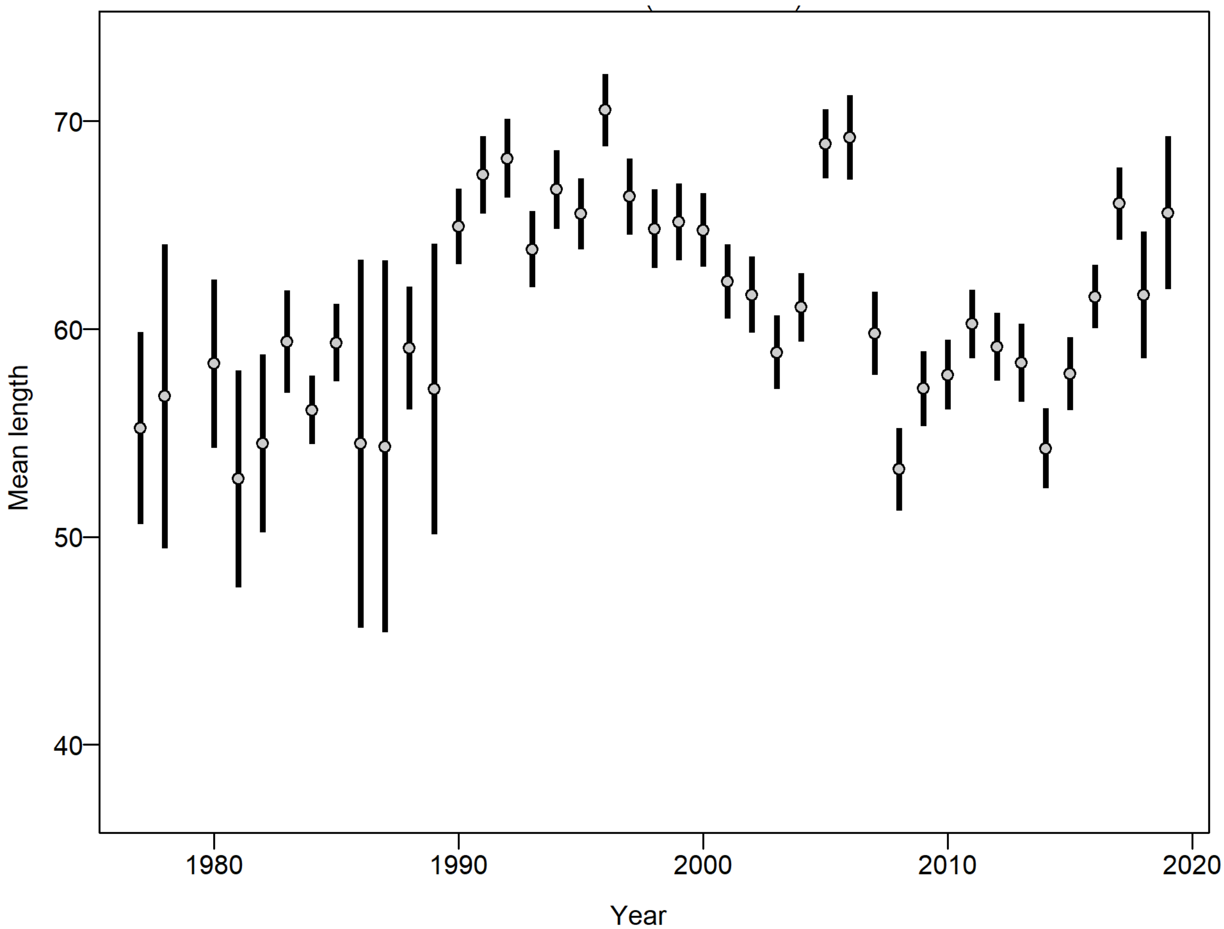


Figure 2.20 Mean length (cm) of Pacific cod from the Gulf of Alaska trawl fishery.

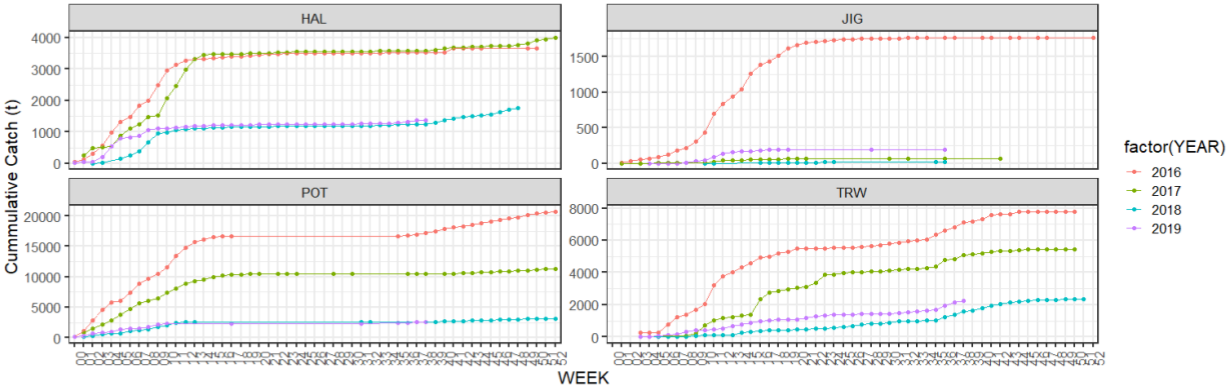


Figure 2.21 Cumulative catch by week of the year and gear for 2015-2019 in the Central regulatory area. 2019 data are through October 10, 2019.

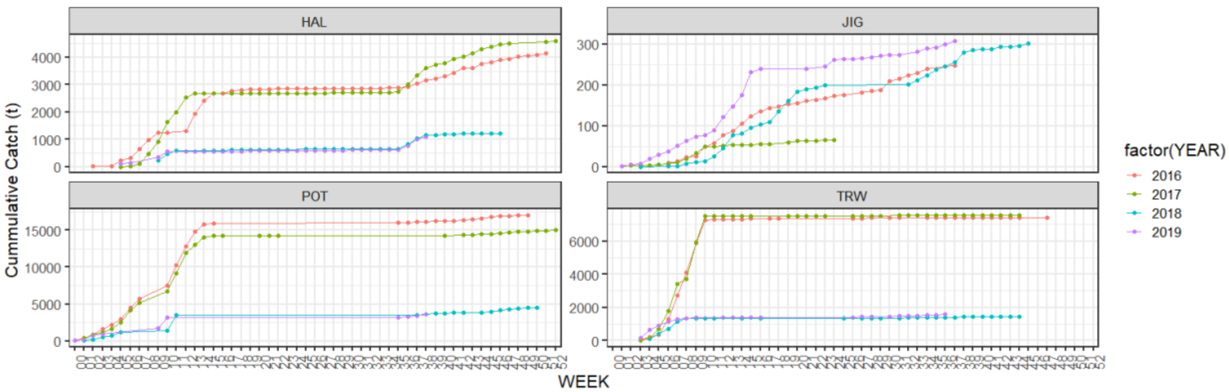


Figure 2.22 Cumulative catch by week of the year and gear for 2015-2019 in the Western regulatory area. The 2019 data are through October 10, 2019.

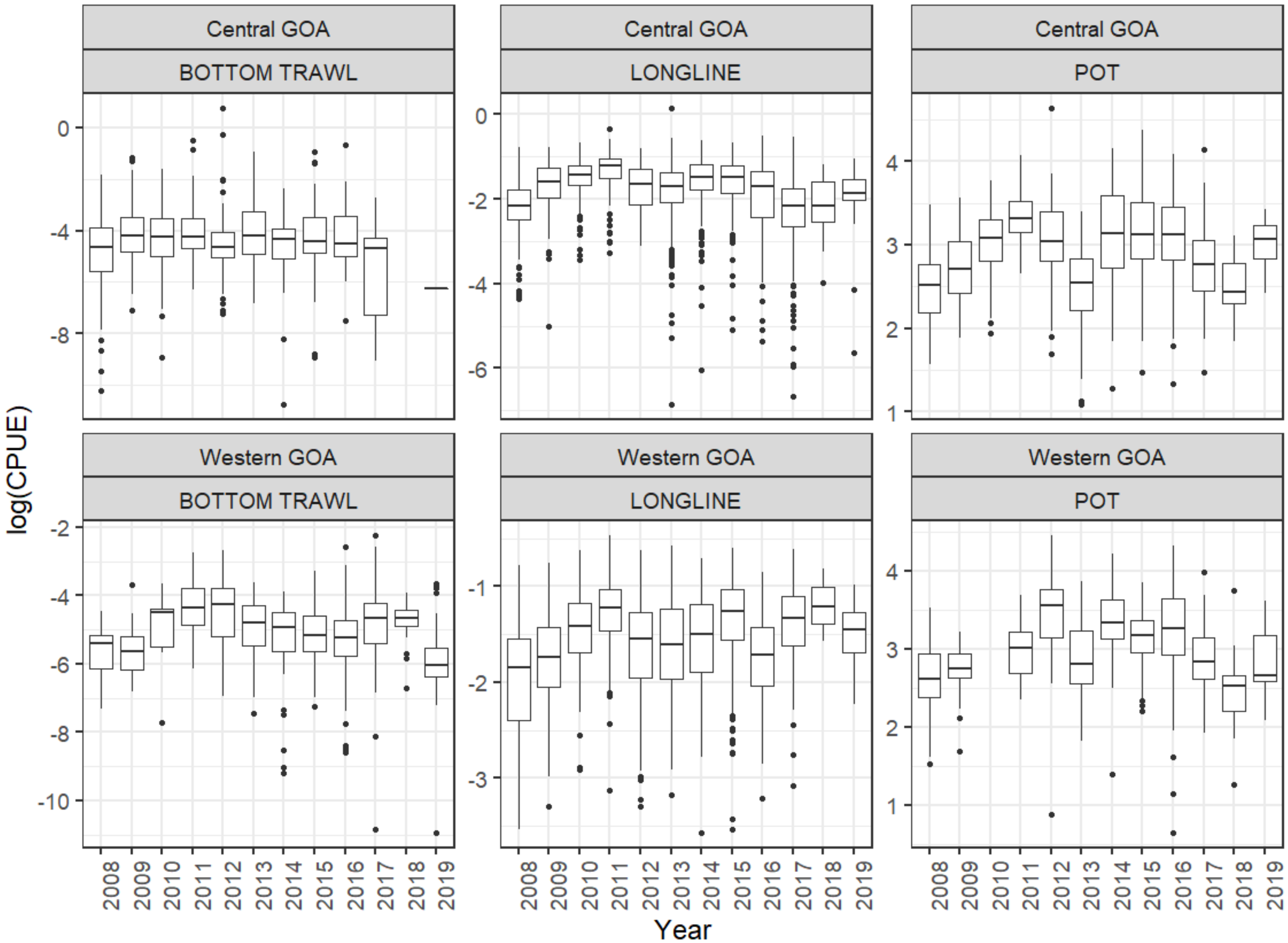


Figure 2.23 Boxplot of CPUE by number from the 2008-2019 Pacific cod CPUE for January-April for the Central (top) and Western (bottom) regulatory areas. Note that the data in these figures are not controlled for vessel or gear differences within a gear type across time, but shows the raw CPUE data distribution. These represent all catches and is limited to the directed cod fishery.

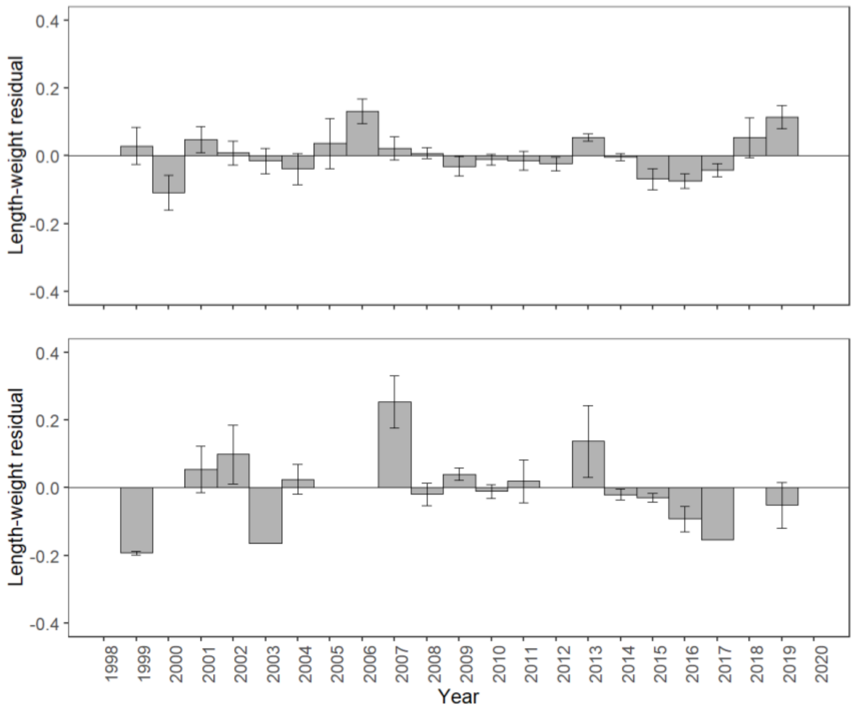


Figure 2.24 Condition of Pacific cod by year in the Central GOA for the longline January-April (top) and May-September (bottom).

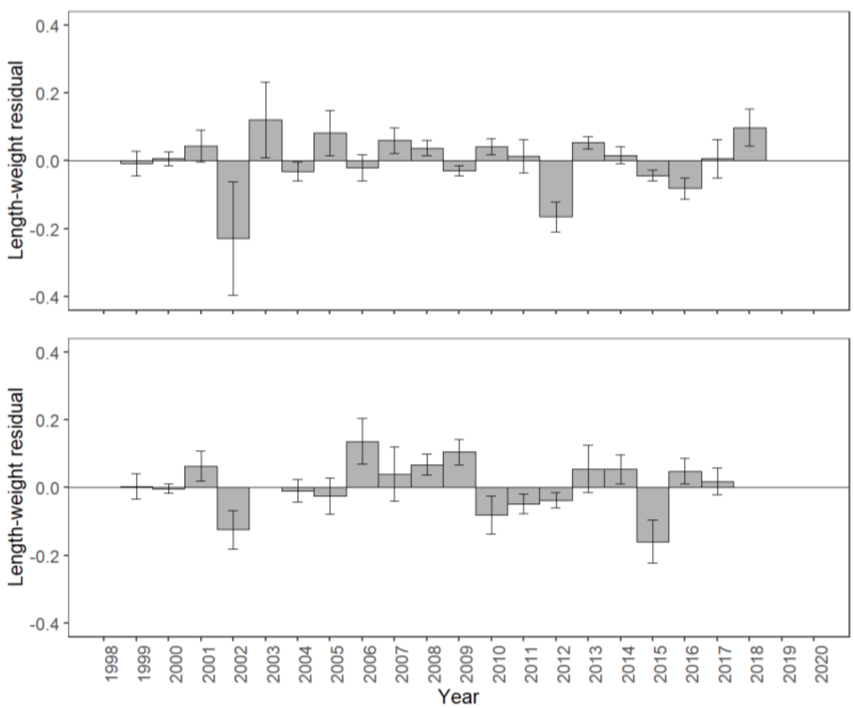


Figure 2.25 Condition of Pacific cod by length category and year in the Central GOA for the pot January-April (top) and May-September (bottom). Note that there are no pot fishery data for Central GOA in 2019 for either season and no data for 2018 May-September .

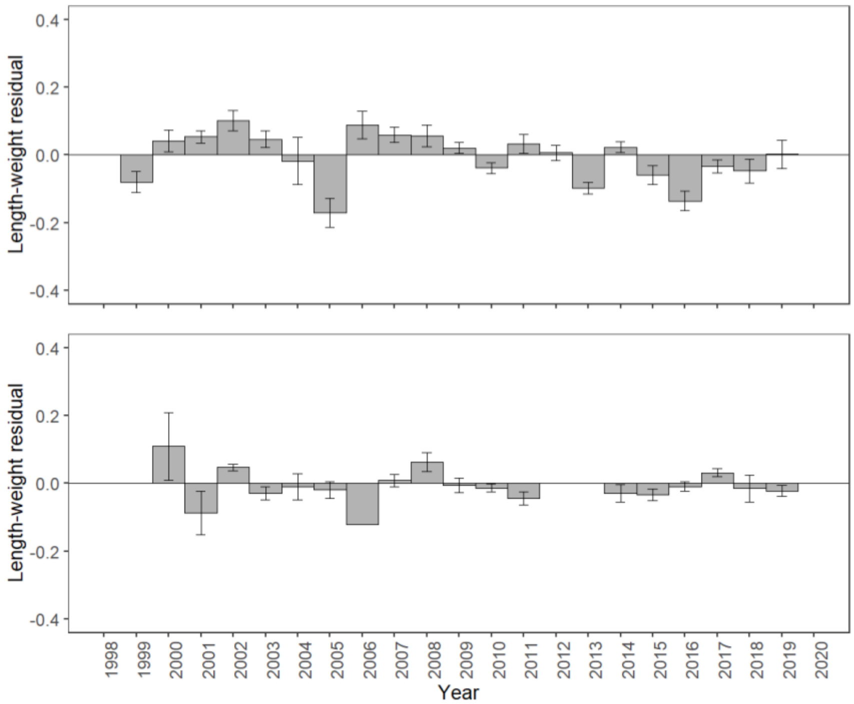


Figure 2.26 Condition of Pacific cod by year in the Western GOA for the longline January-April (top) and May-September (bottom).

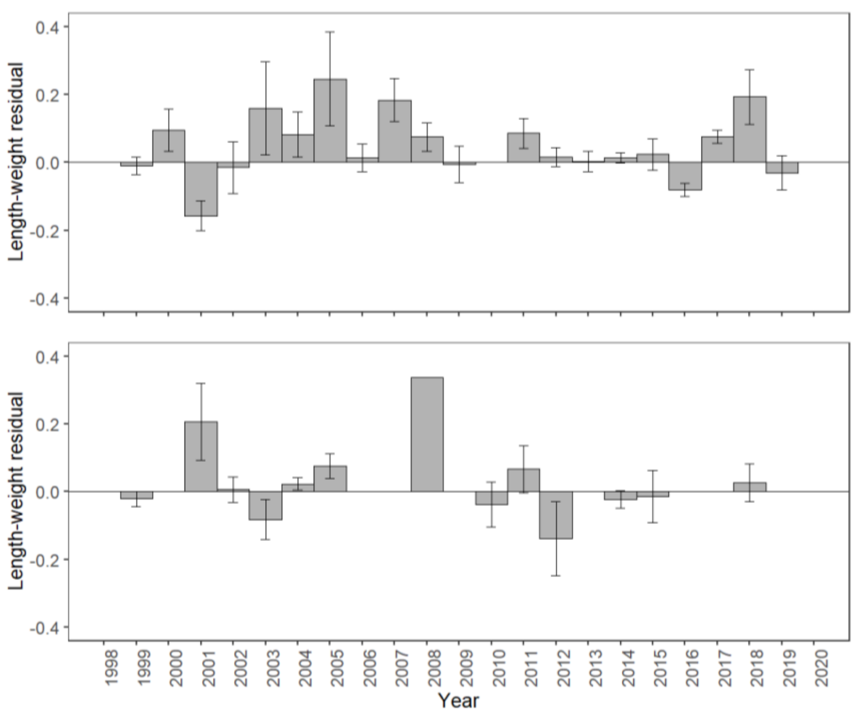


Figure 2.27 Condition of Pacific cod by year in the Western GOA for pot January-April (top) and May-September (bottom).

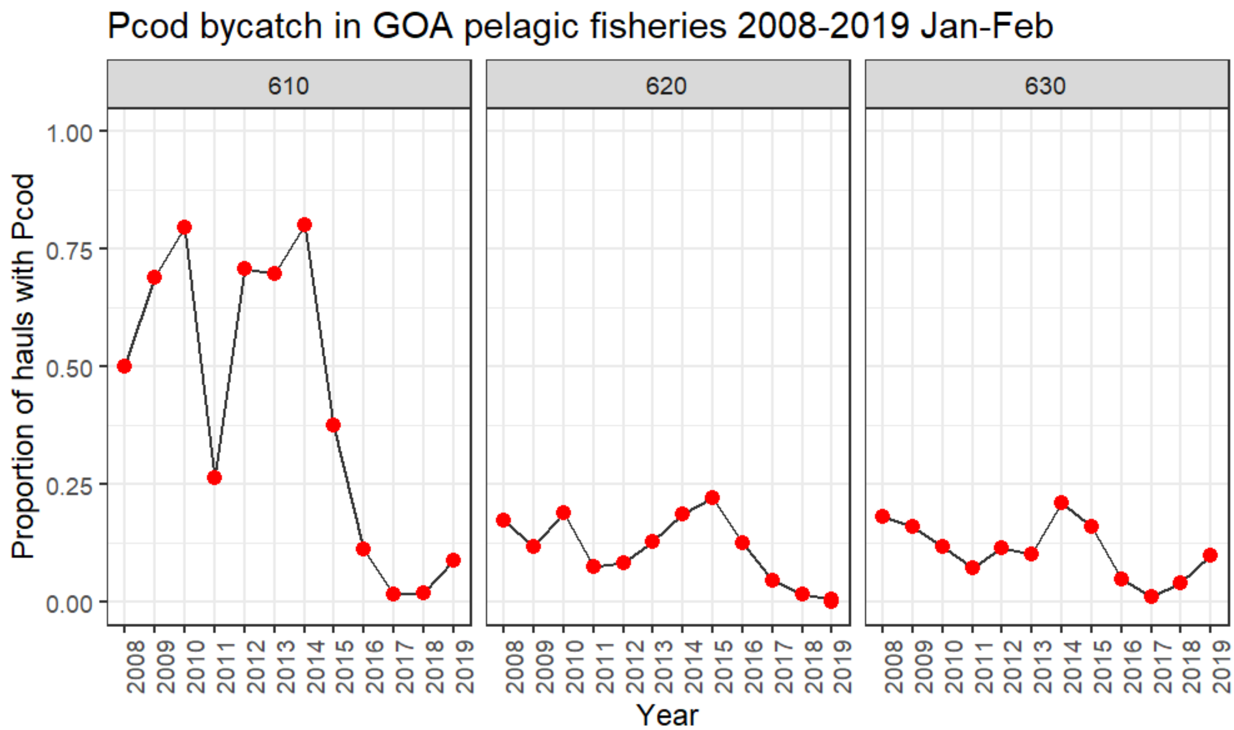


Figure 2.28 Proportion of pelagic trawls in the A Season (January-April) walleye pollock fishery with Pacific cod present by region.

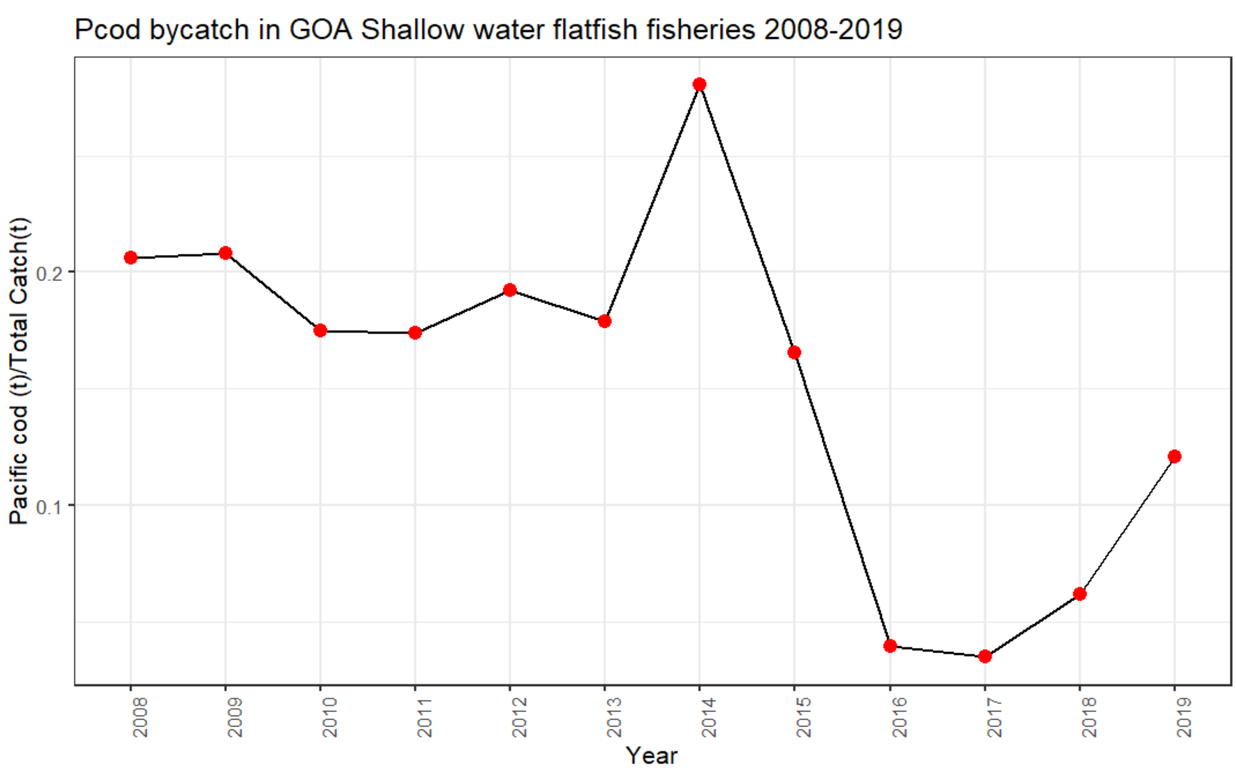


Figure 2.29 Pacific cod bycatch in the Gulf of Alaska shallow water flatfish fishery as tons of Pacific cod per tons of total catch in the fishery by year.

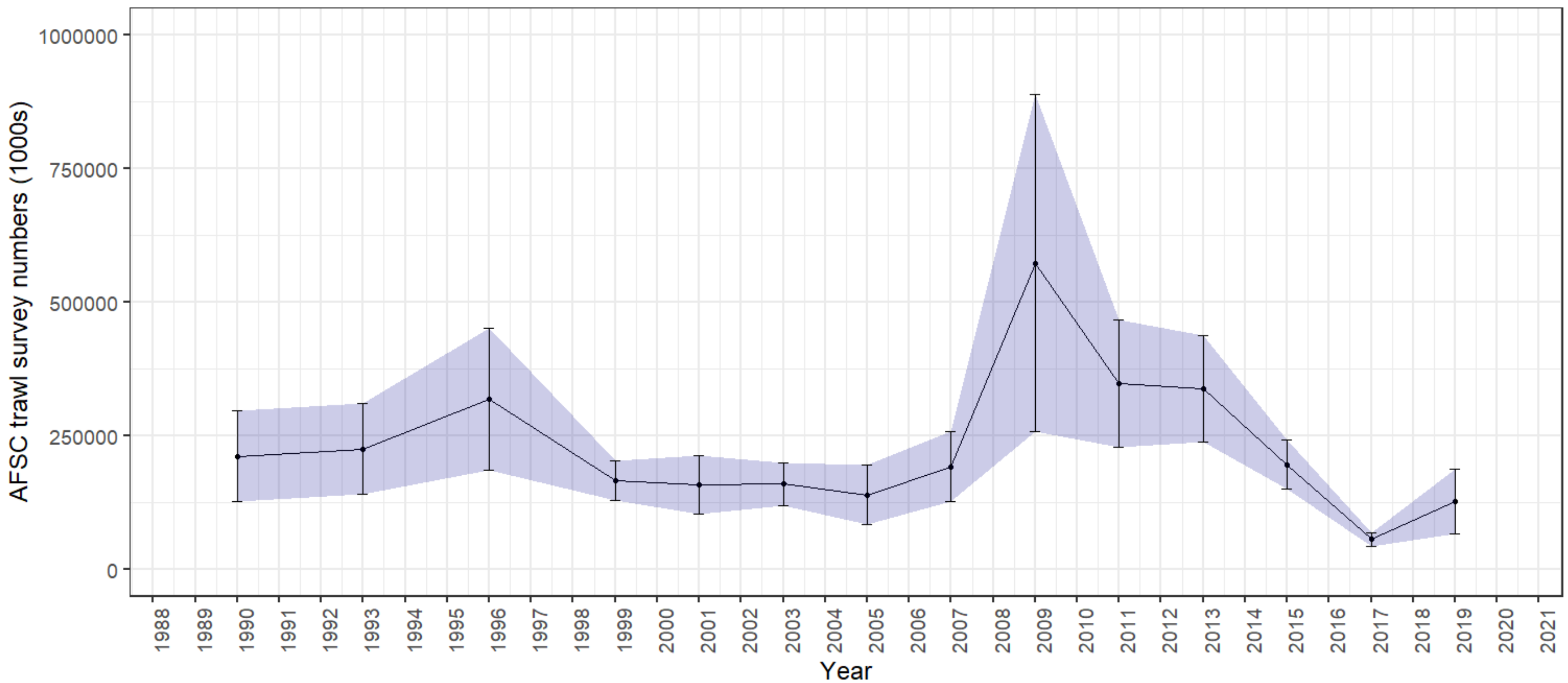


Figure 2.30 GOA bottom trawl survey abundance (numbers) estimate. Bars and shading indicate the 95th percentile confidence intervals.

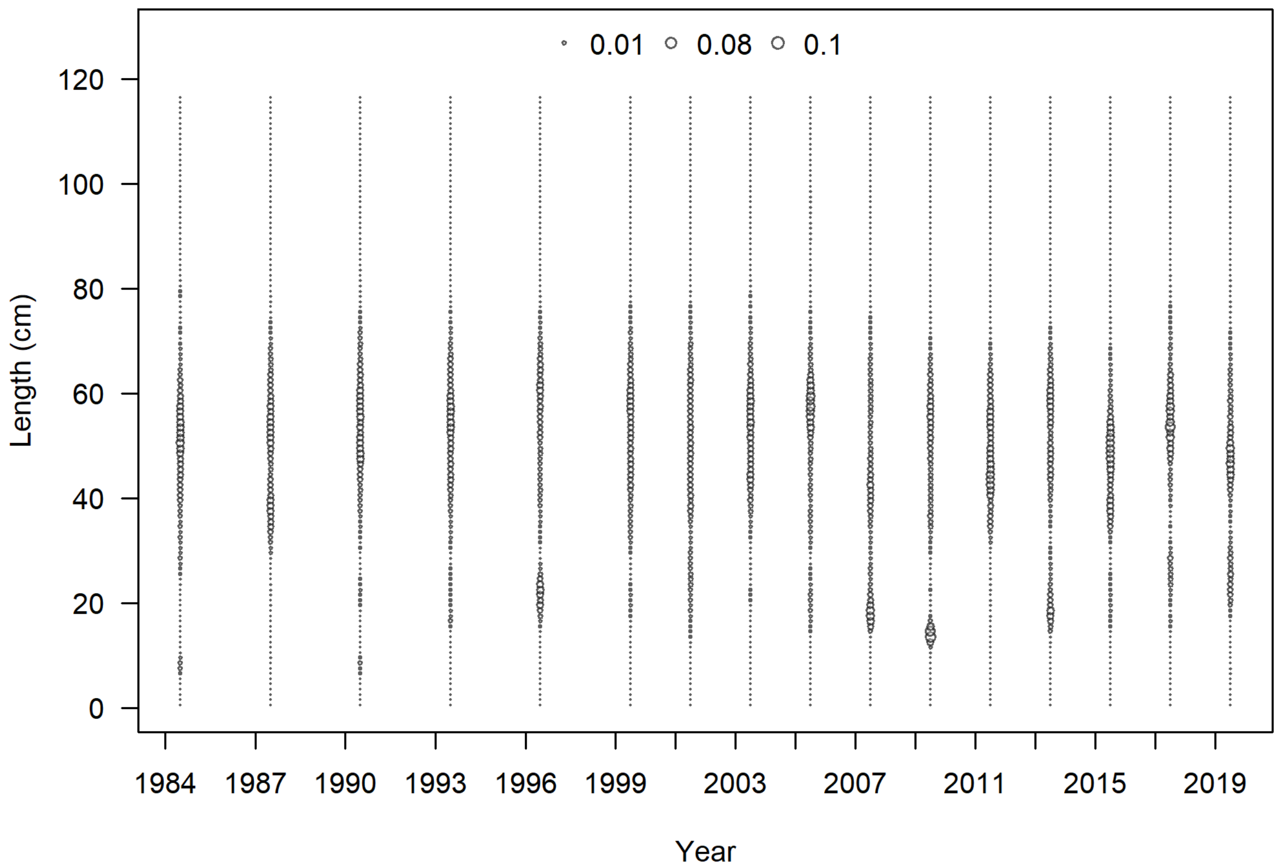


Figure 2.31 GOA bottom trawl survey Pacific cod population numbers at length estimates (max = 0.07).

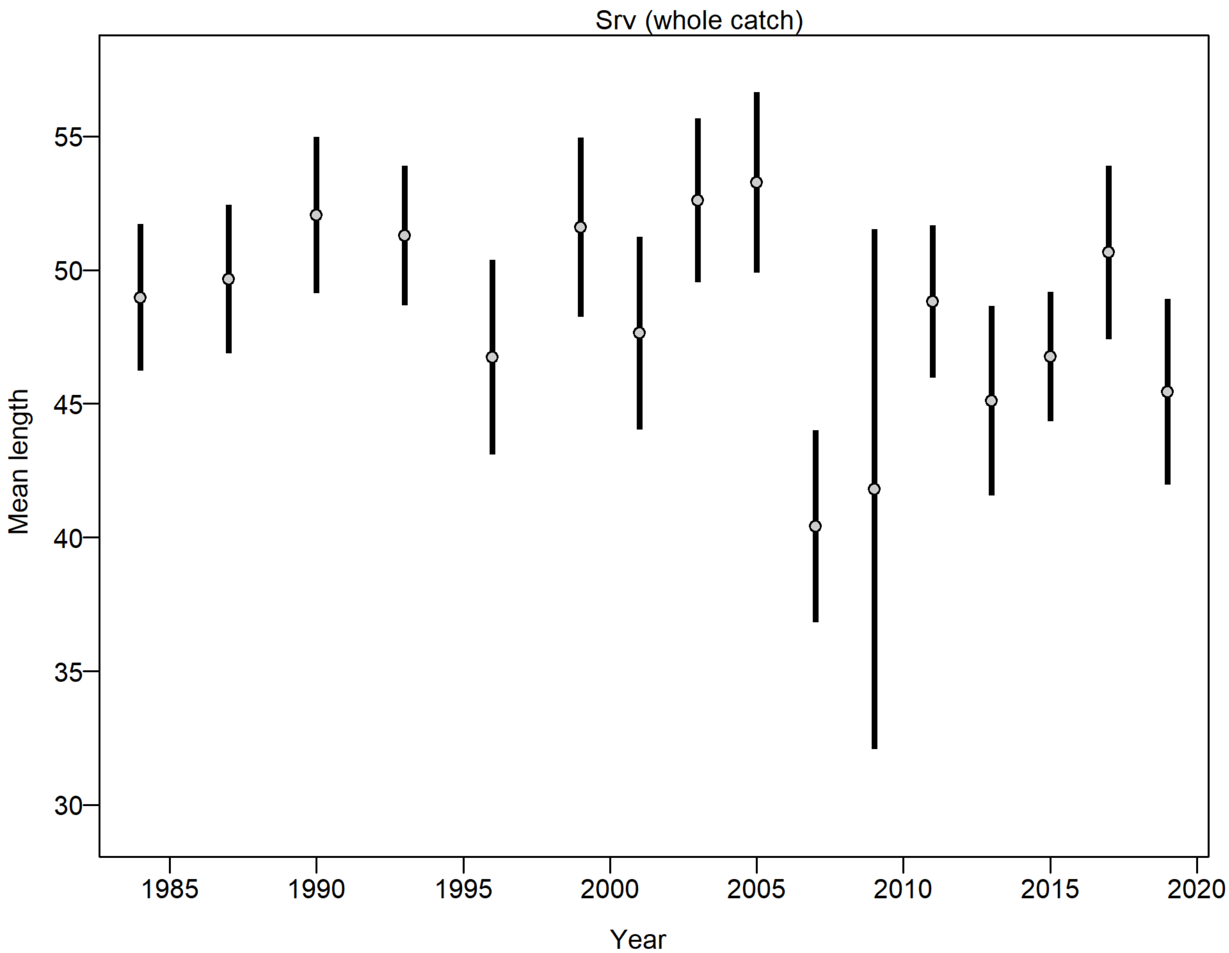


Figure 2.32 Mean length (cm) of Pacific cod in the GOA bottom trawl survey.

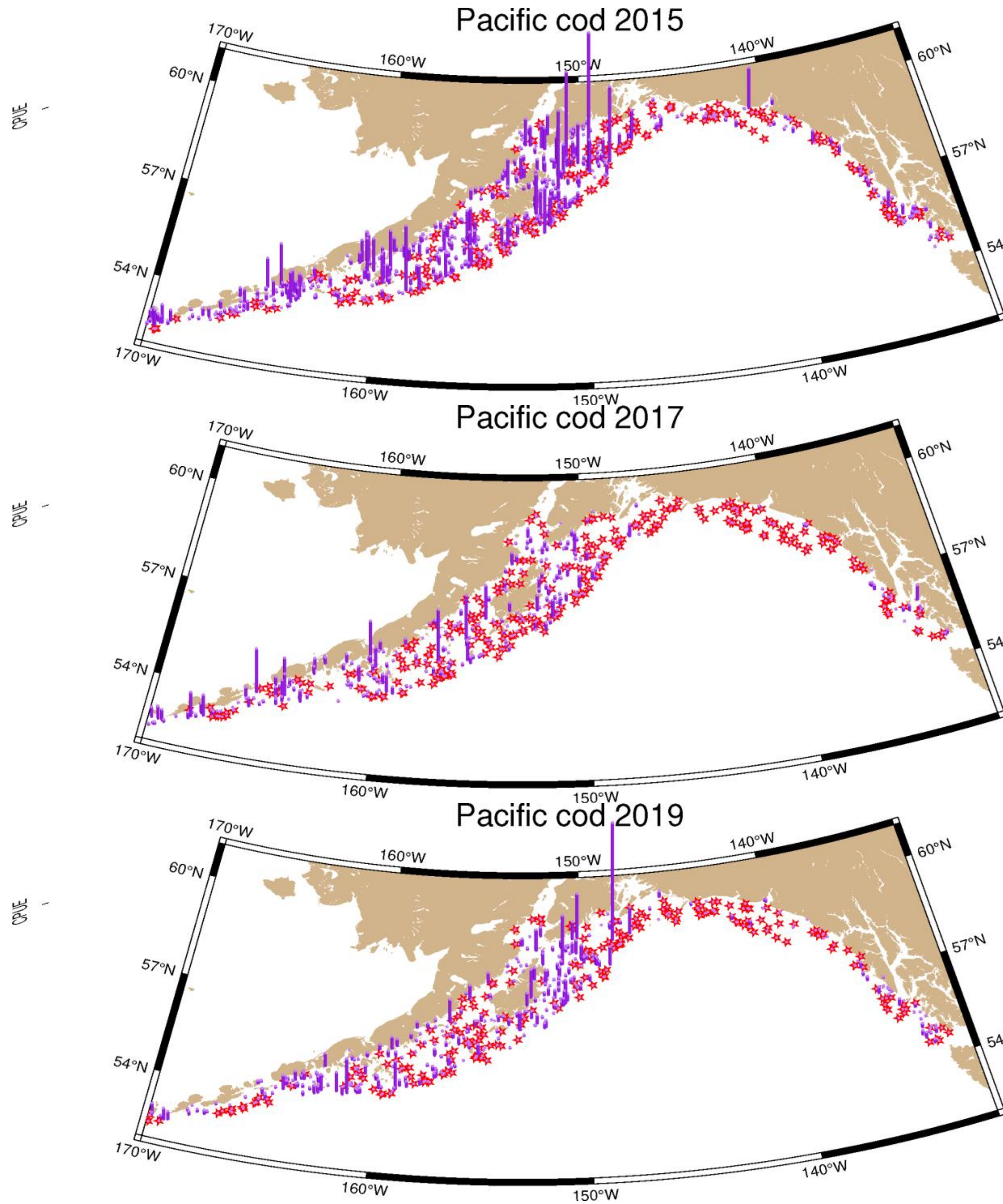


Figure 2.33 Distribution of AFSC bottom trawl survey CPUE of Pacific cod for 2015-2019.

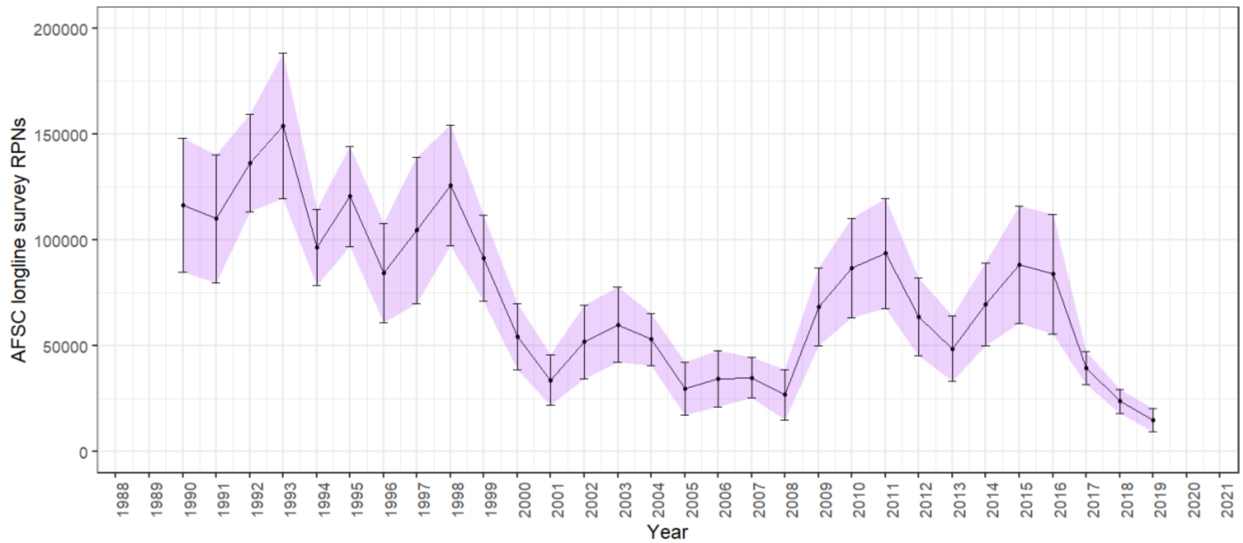


Figure 2.34 AFSC longline survey Pacific cod relative population numbers (RPN) time series. Bars and shading indicate the 95th percentile confidence intervals.

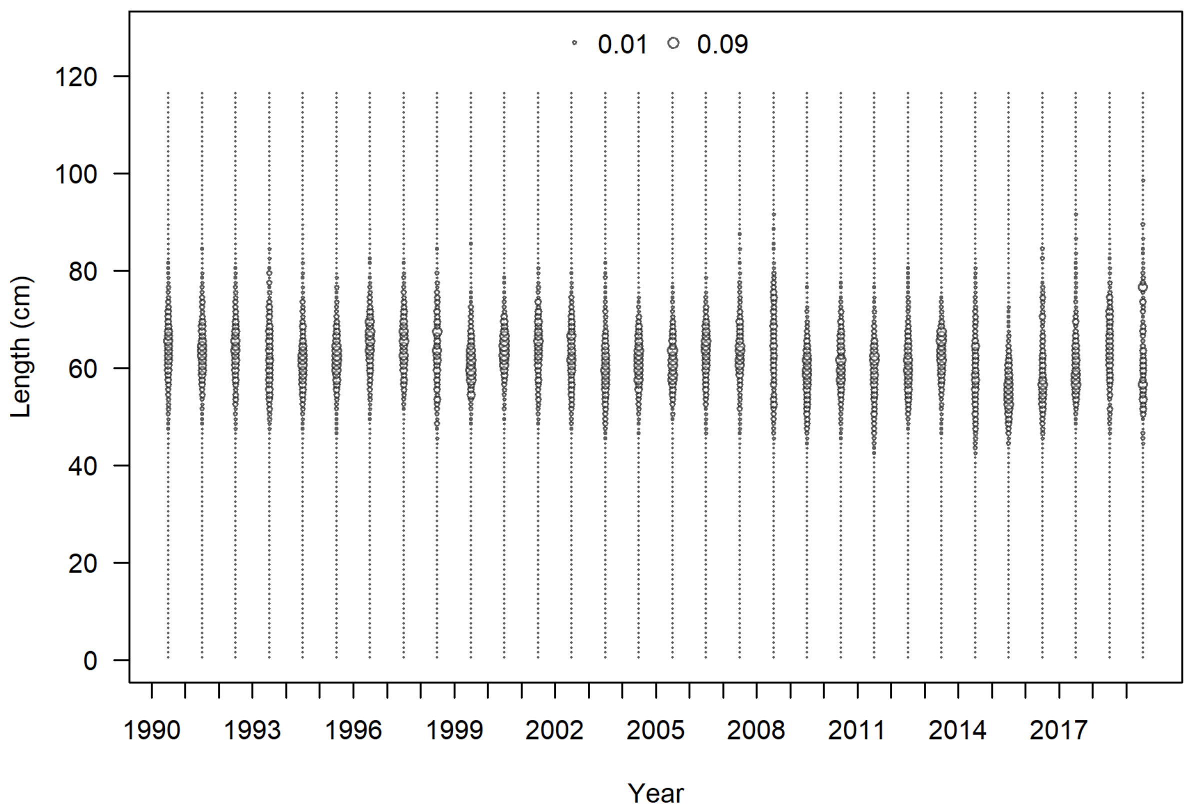


Figure 2.35 AFSC longline survey Pacific cod size composition (max=0.09).

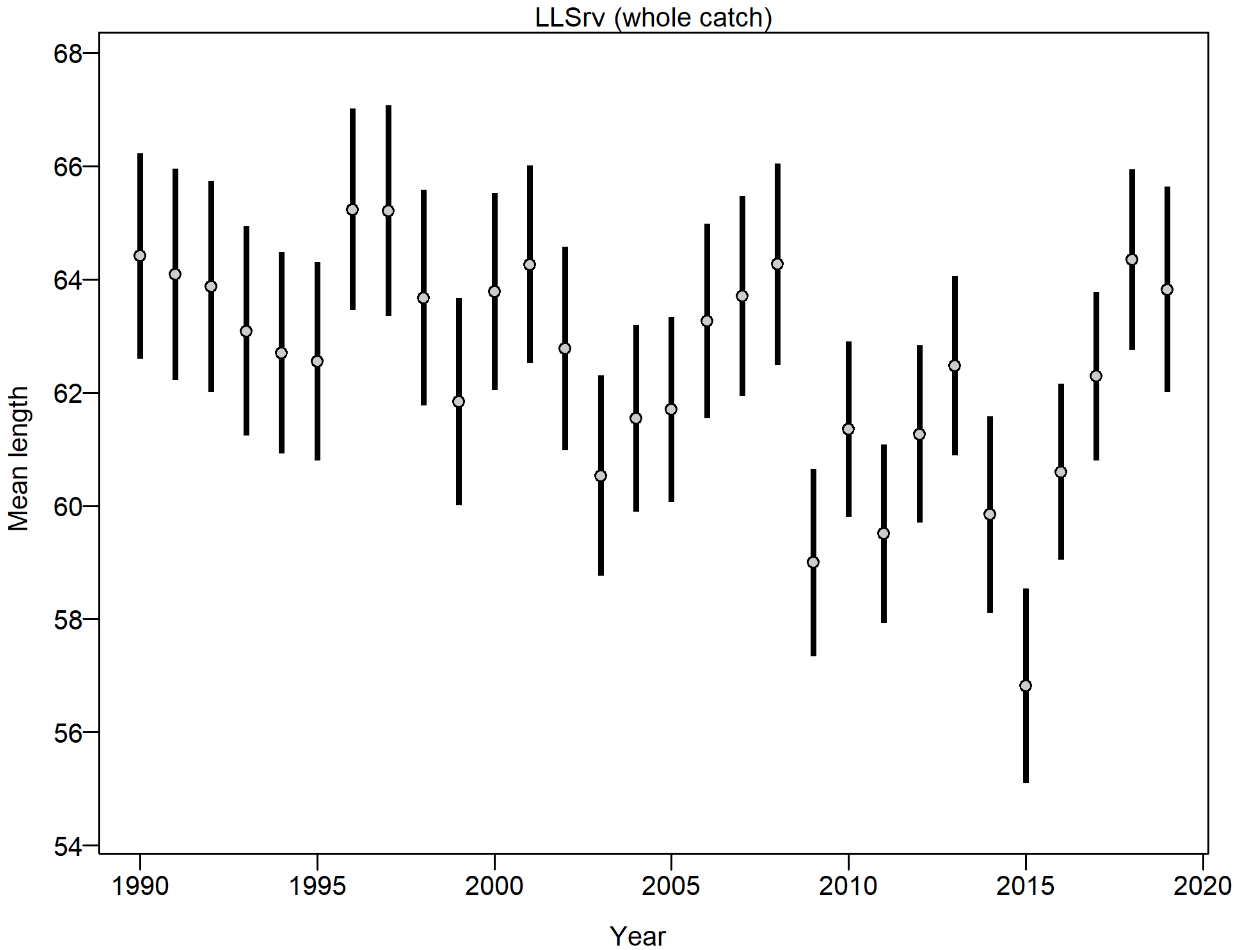


Figure 2.36 Mean length (cm) of Pacific cod from the AFSC longline survey.

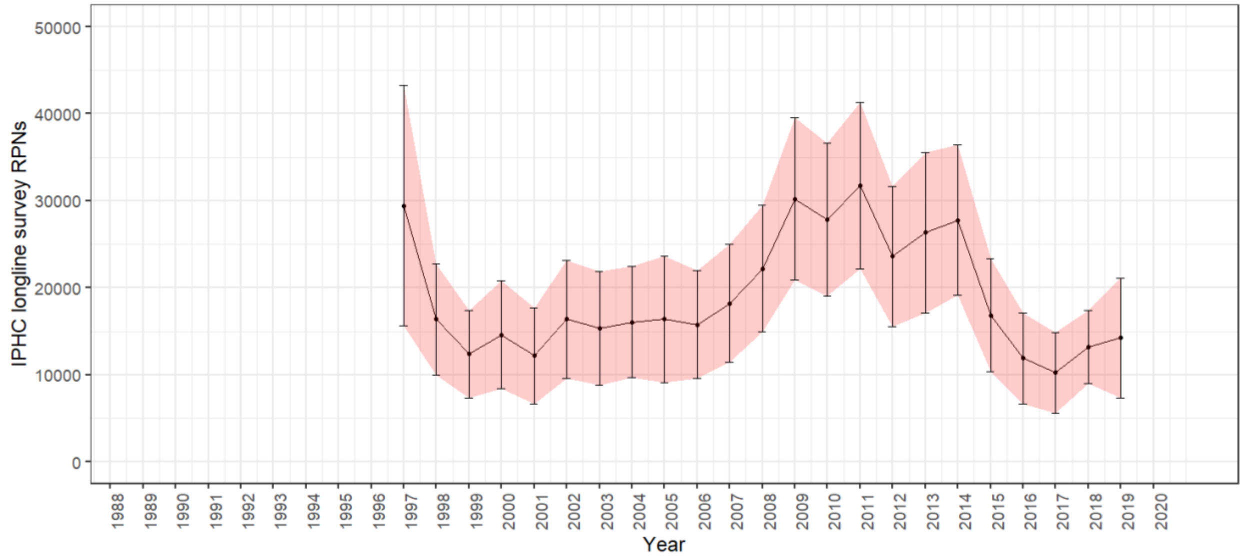


Figure 2.37 IPHC halibut longline survey Pacific cod RPN time series. Bars and shading indicate the 95th percentile confidence intervals.

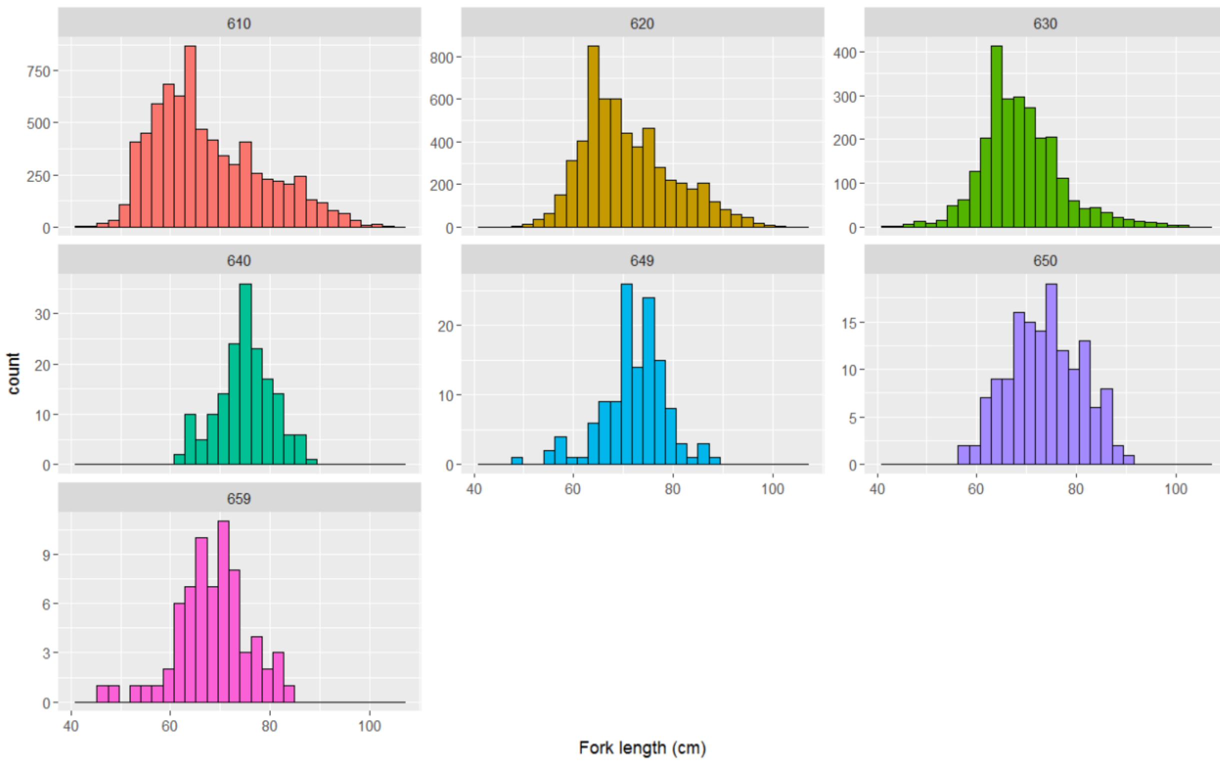


Figure 2.38 IPHC halibut longline survey Pacific cod RPN length composition collection for 2018 by NMFS management area.

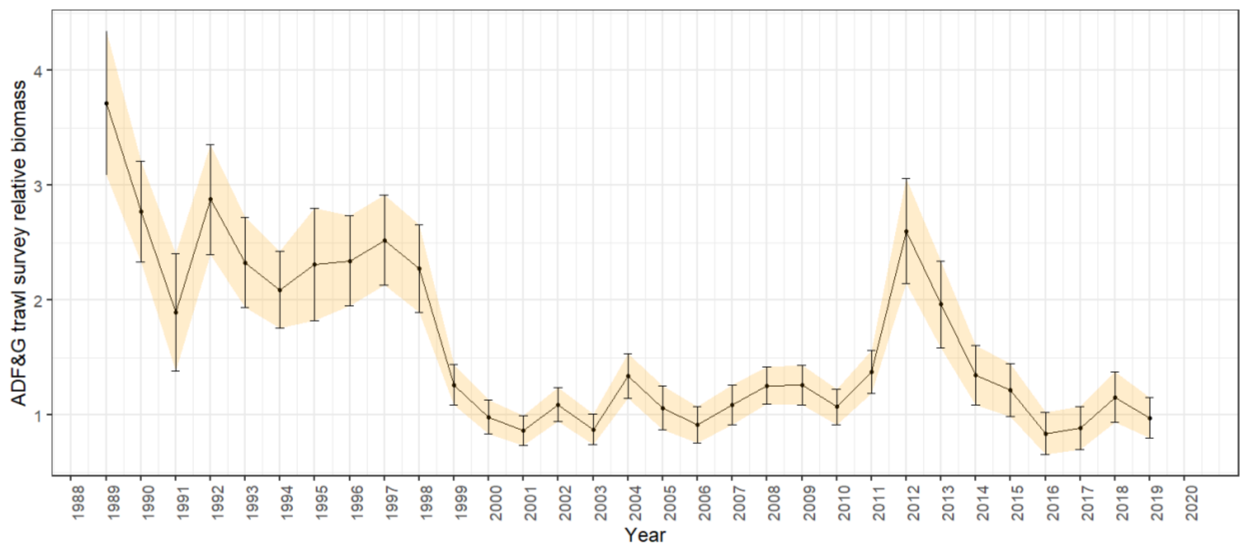


Figure 2.39 ADFG bottom trawl survey delta-glm Pacific cod density index time series. Bars and shading indicate the 95th percentile confidence intervals.

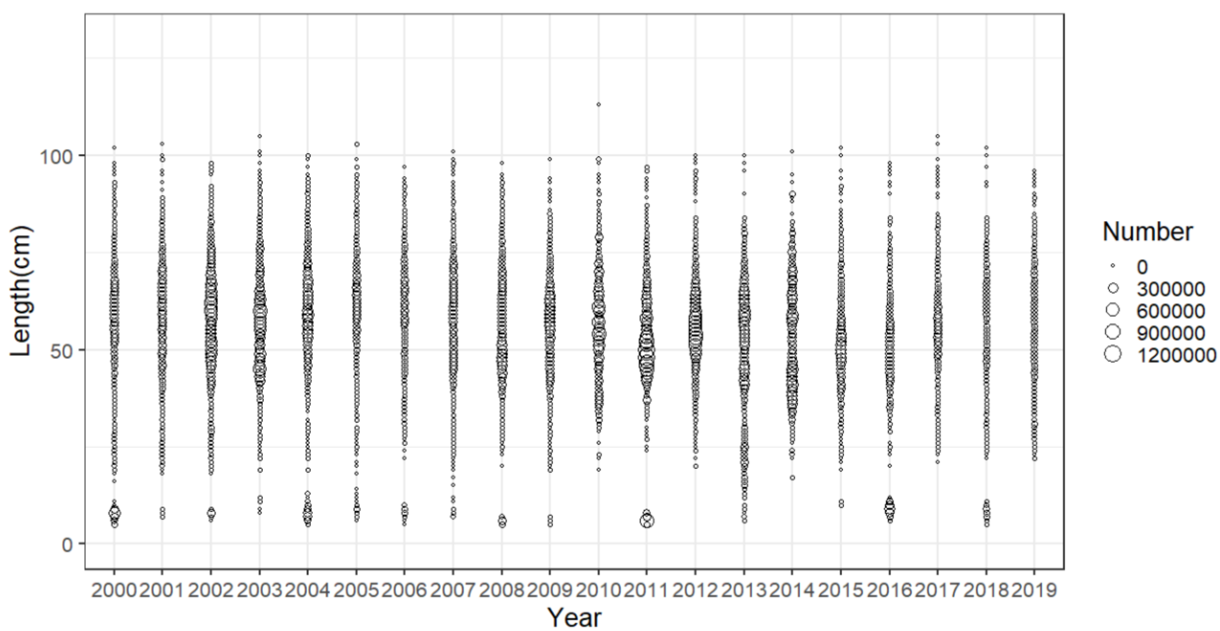


Figure 2.40 ADFG large-mesh trawl survey Pacific cod population numbers at length estimates.

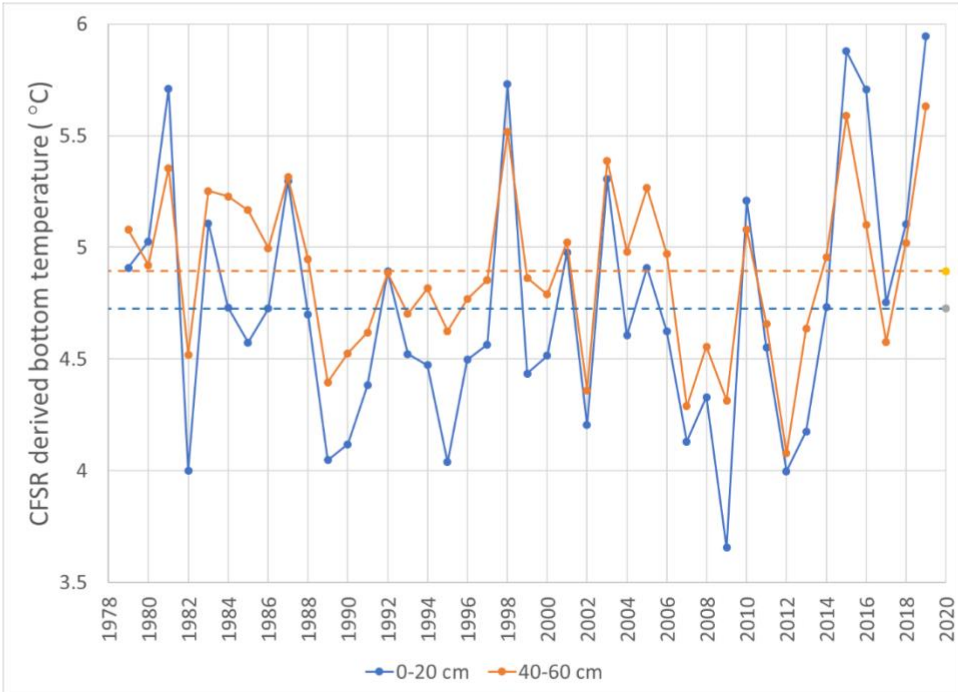


Figure 2.41 Climate Forcast System Reanalysis (CFSR) Central Gulf of Alaska bottom temperatures at the AFSC bottom trawl survey mean depths for 0-20 cm and 40-60 cm Pacific cod in June.

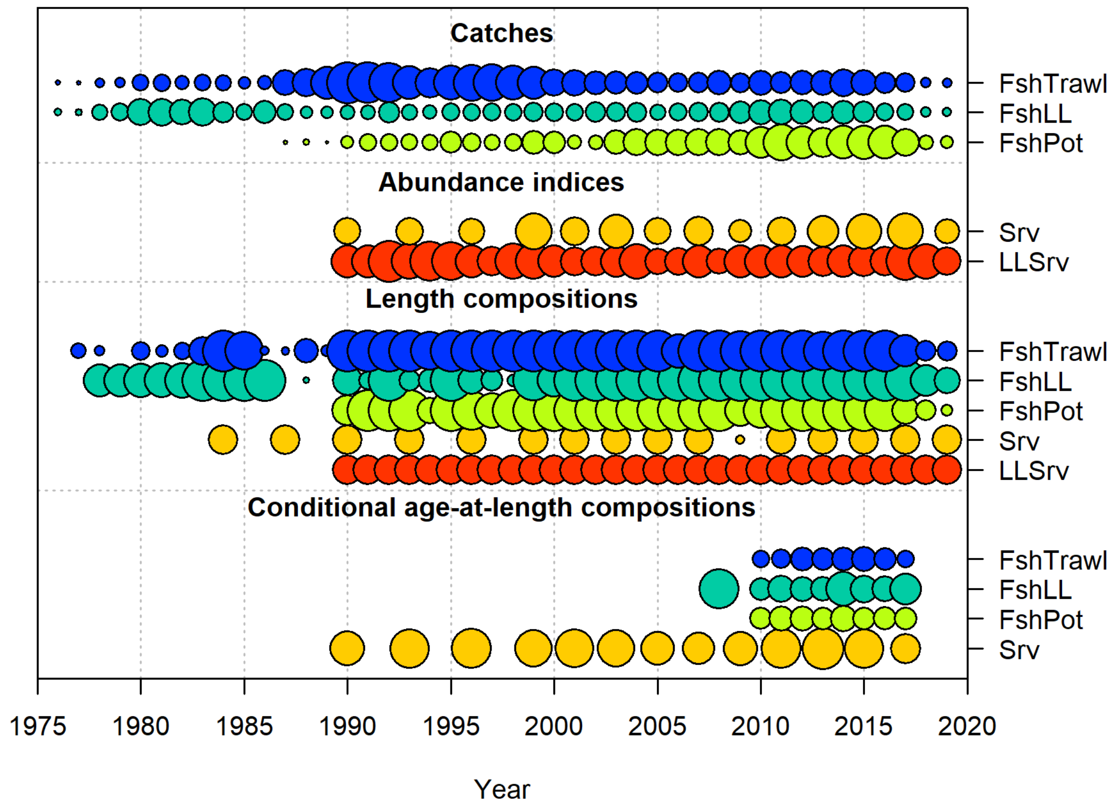


Figure 2.42 Data used in the 2019 models, circle area is relative to initial precision within data type.

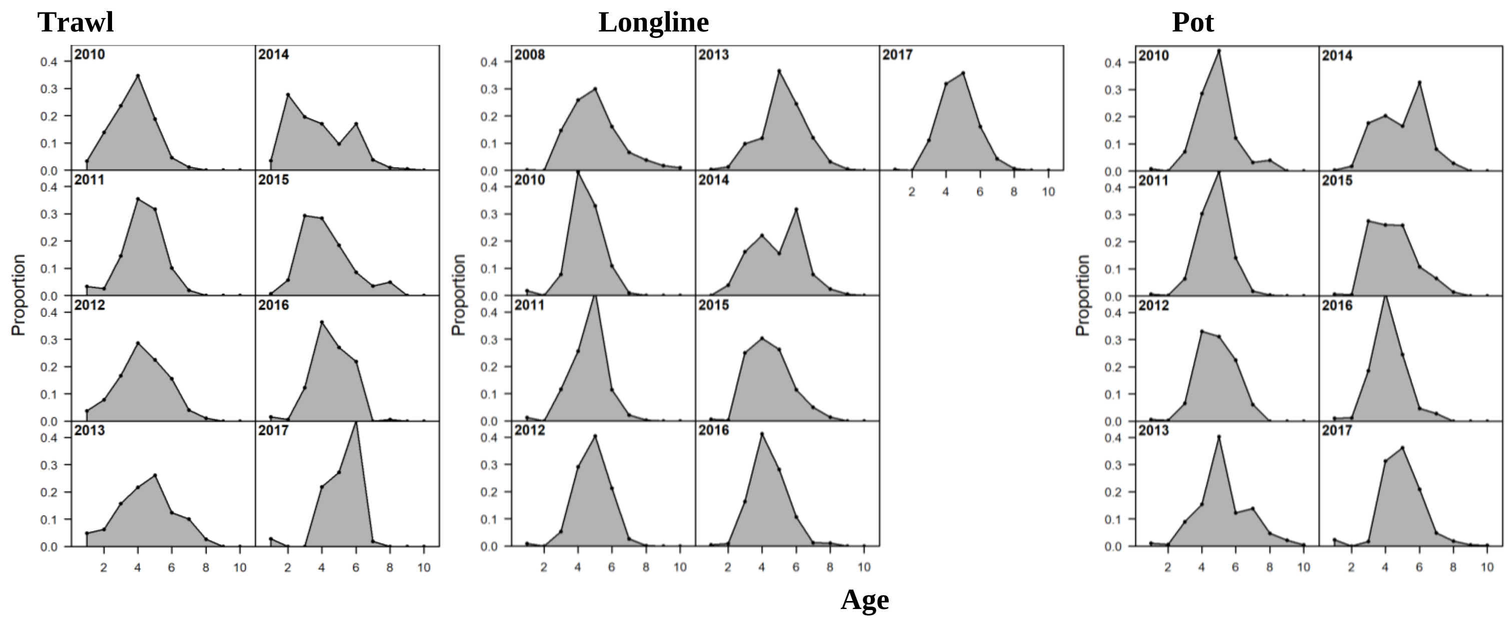


Figure 2.43 Pacific cod age composition data from the Gulf of Alaska fisheries by gear type.

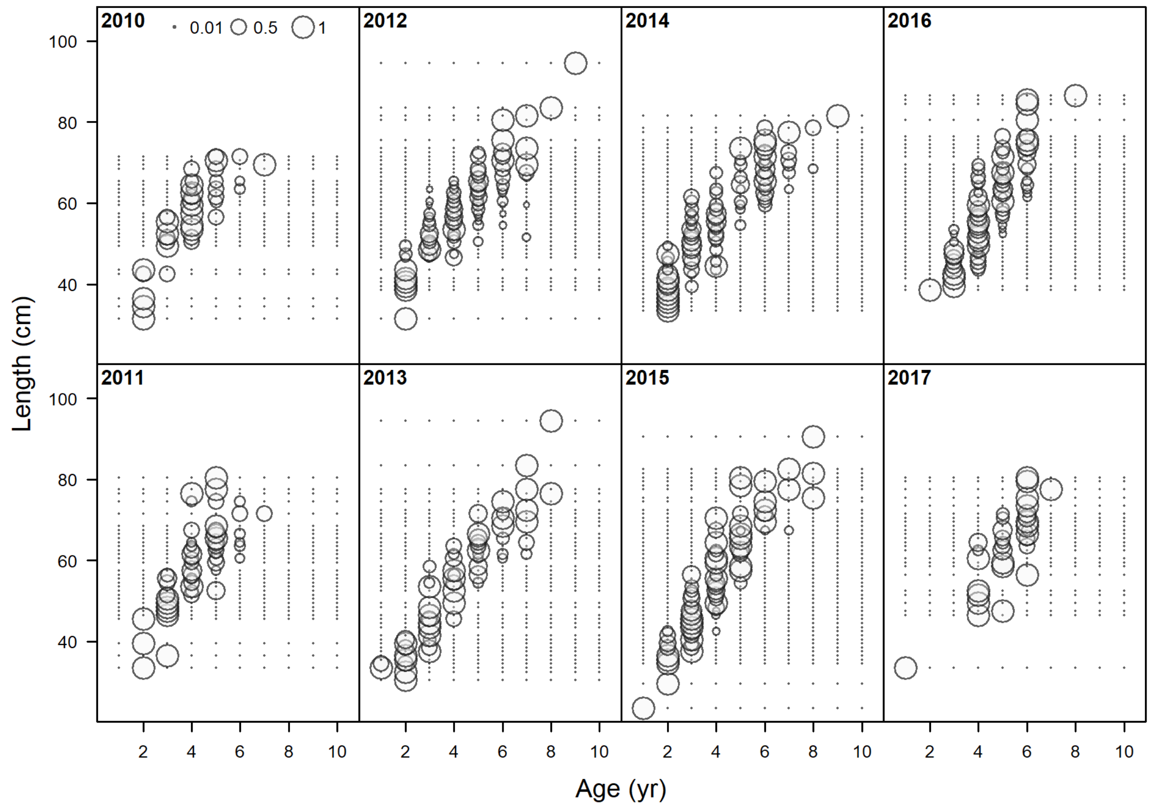


Figure 2.44 Pacific cod conditional length at age from the Gulf of Alaska trawl fishery.

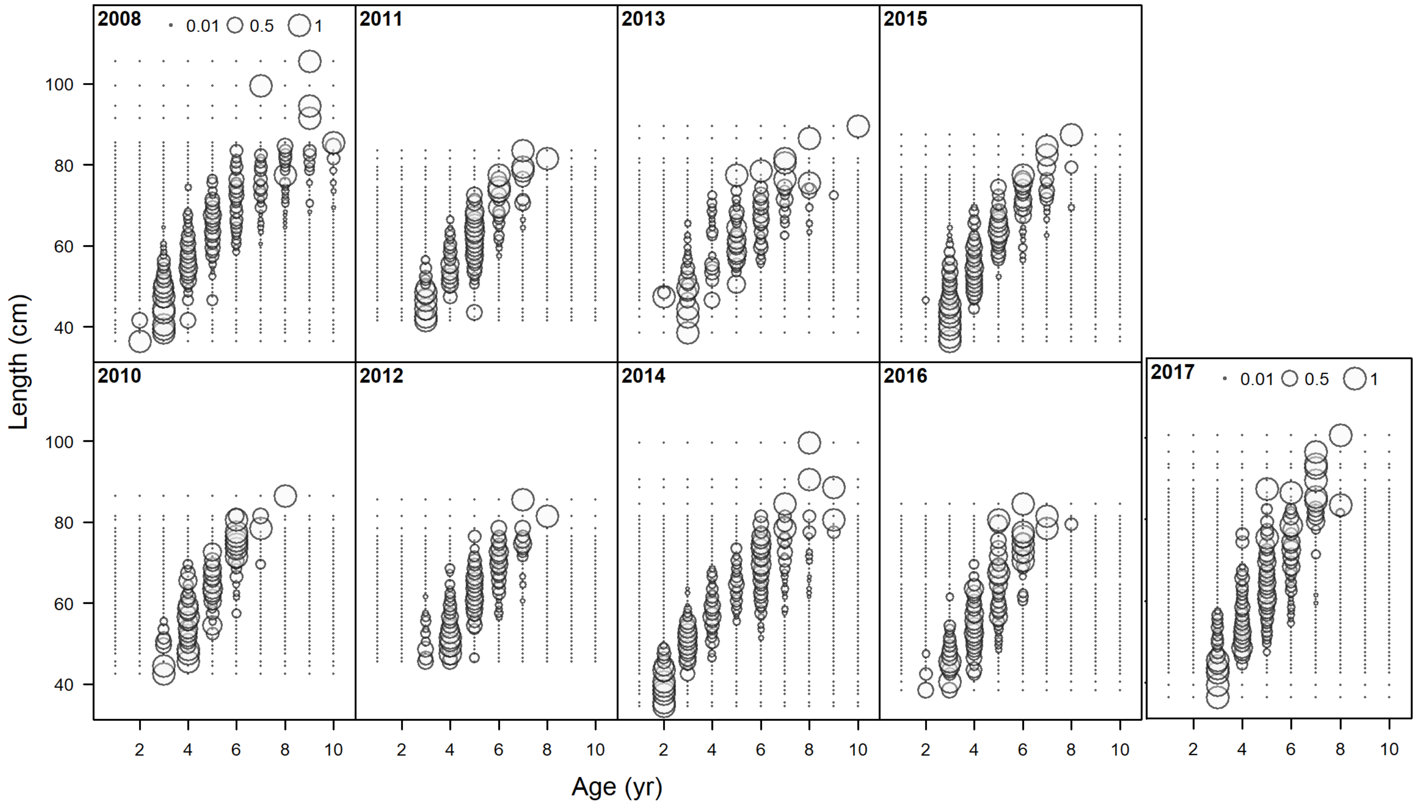


Figure 2.45 Pacific cod conditional length at age from the Gulf of Alaska bottom longline fishery.

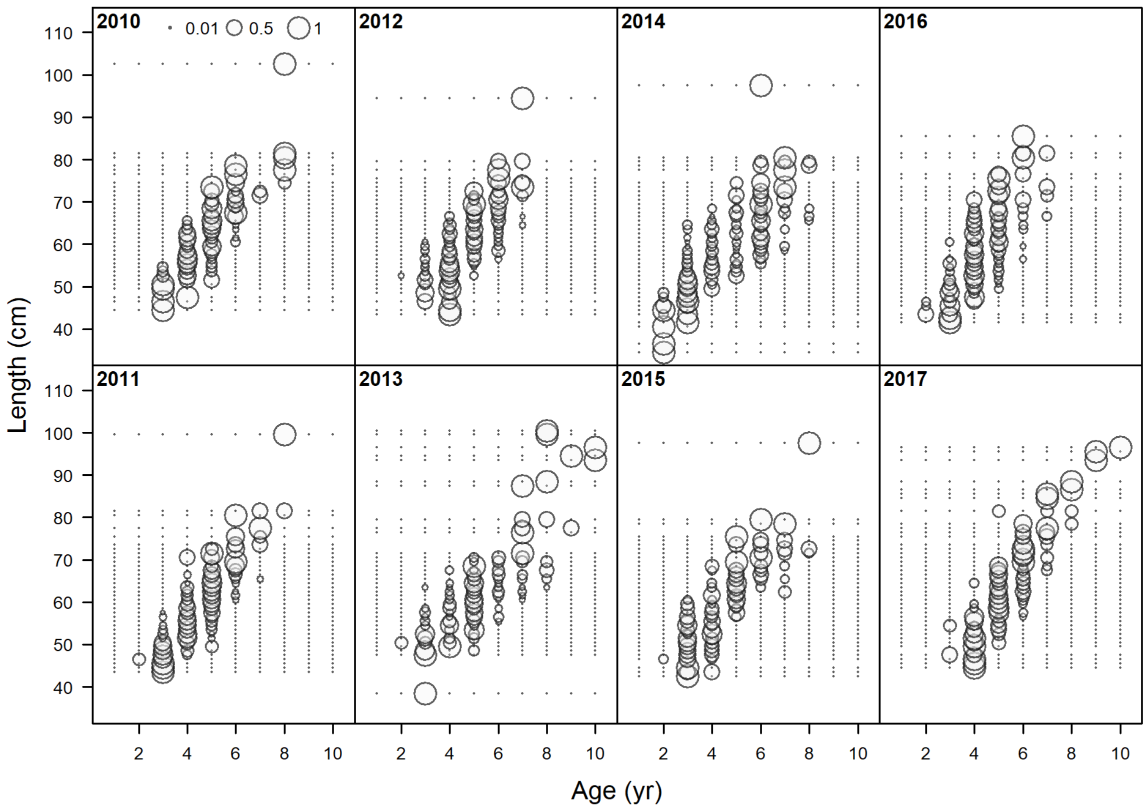


Figure 2.46 Pacific cod conditional length at age from the Gulf of Alaska pot fishery.

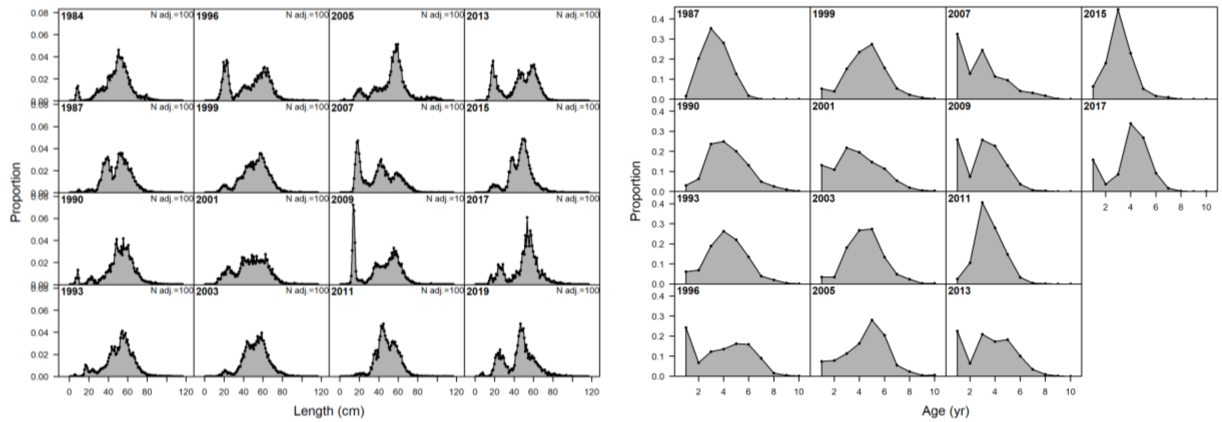


Figure 2.47 Pacific cod length (left) and age (right) composition data from the Gulf of Alaska bottom trawl survey 1984-2019.

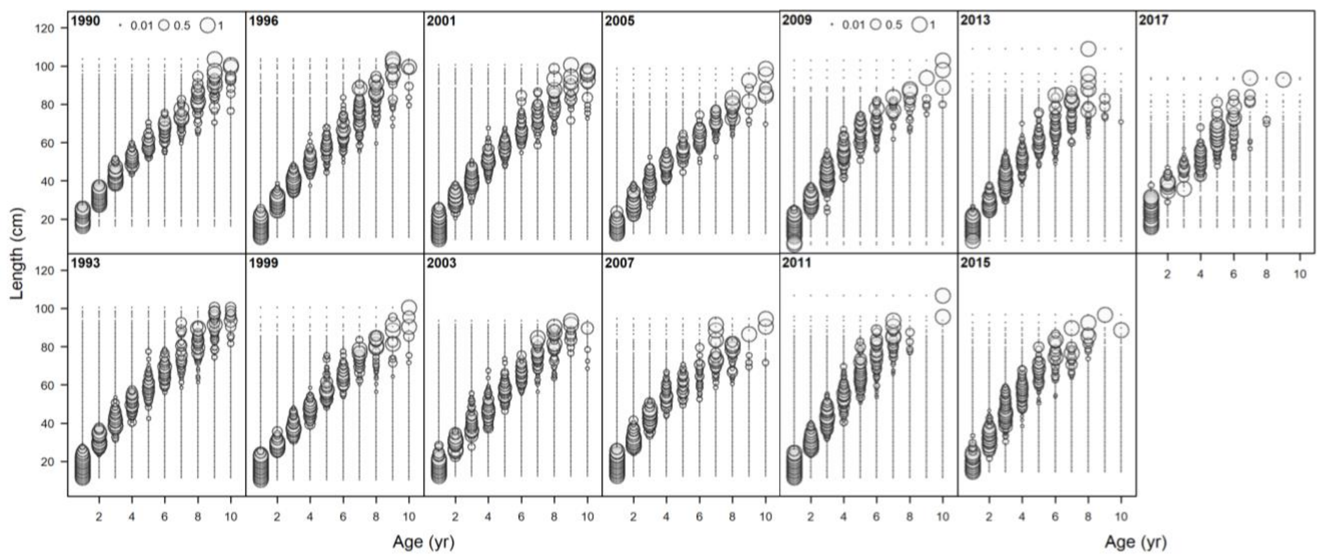


Figure 2.48 Pacific cod conditional length at age from the Gulf of Alaska bottom trawl survey 1990-2017.

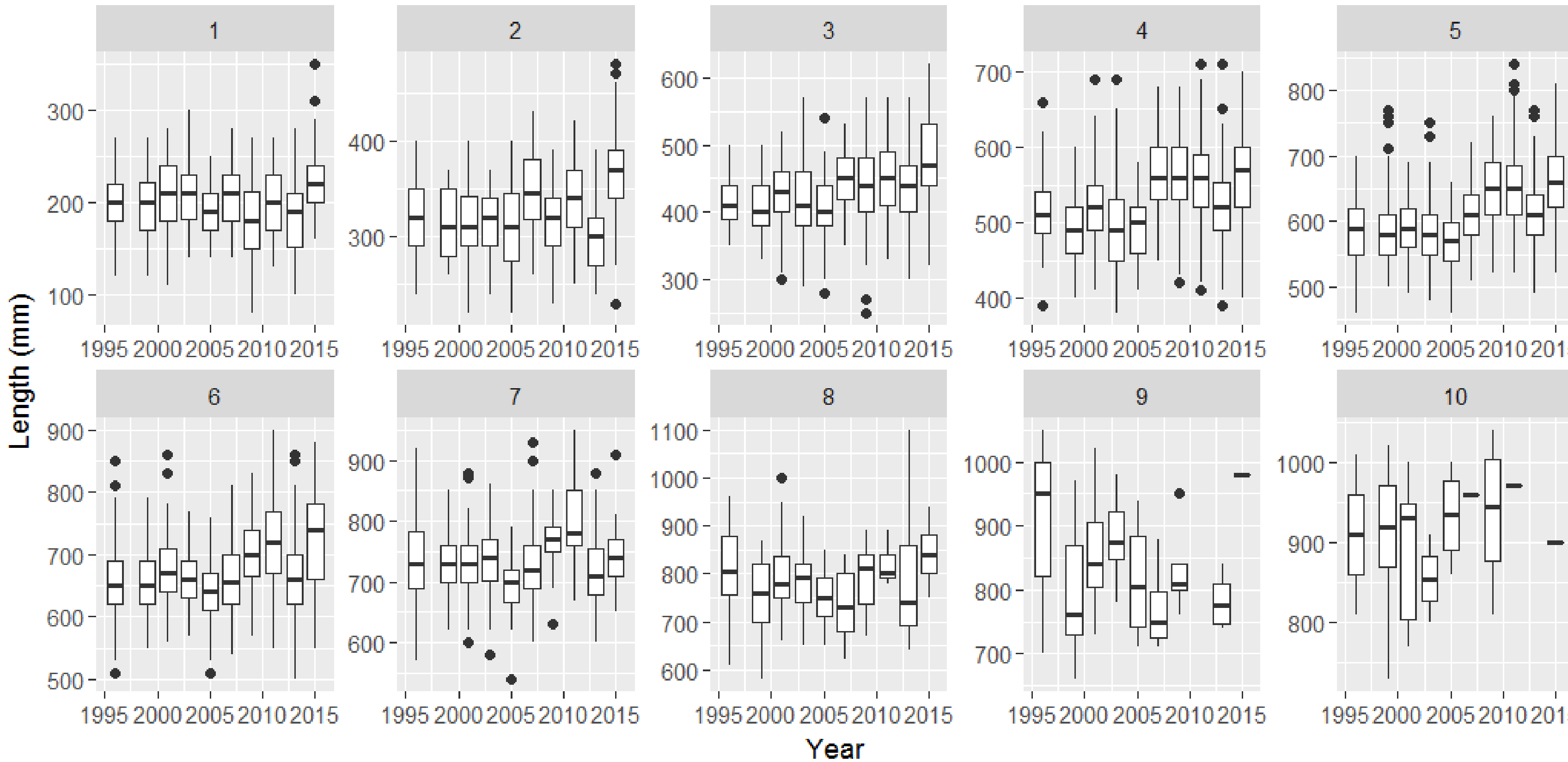


Figure 2.49 Length-at-age by year for each age 1 through 10 for Pacific cod otoliths collected during the summer bottom trawl surveys showing an increase in median length in 2007 for ages 2 through 6.

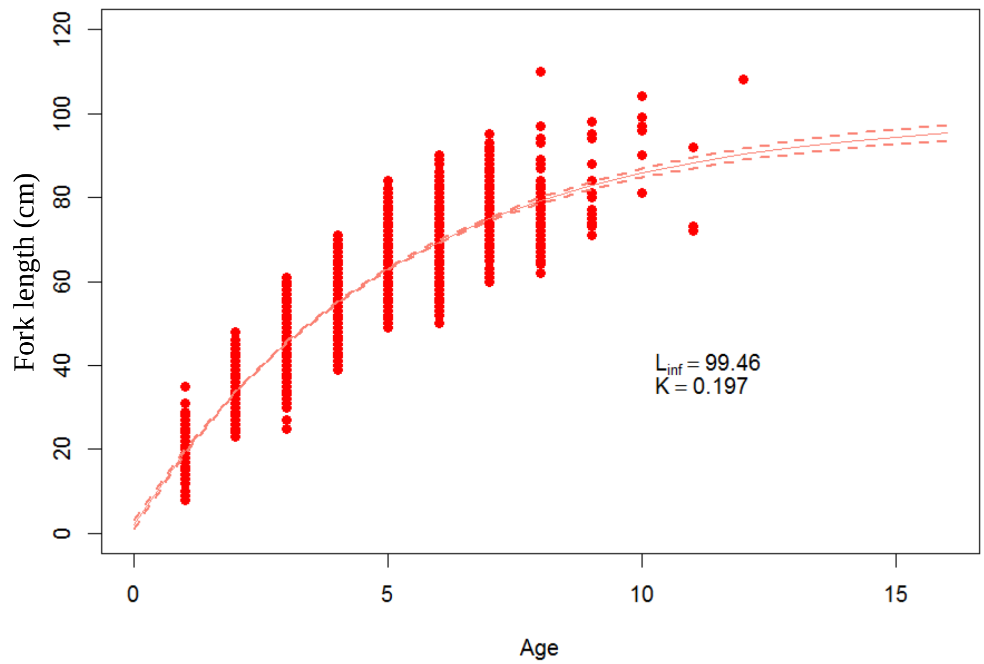


Figure 2.50 Fit to von Bertalanffy growth model for 2007-2015 length at age data from the AFSC bottom trawl surveys.

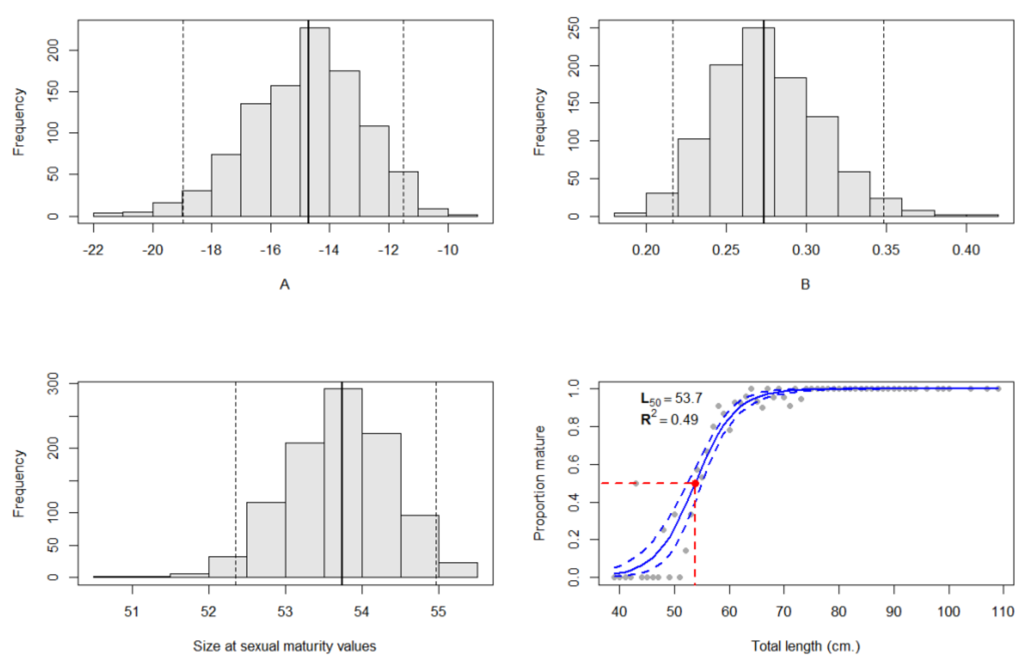


Figure 2.51 Bootstrapped (n=1000) parameters and results for the logistic length-based maturity using Stark (2007) reread otolith and maturity data. Proportion mature $P = {}^{1}/_{1+e^{-(A+BL)}}$ and L_{50} = A/-B

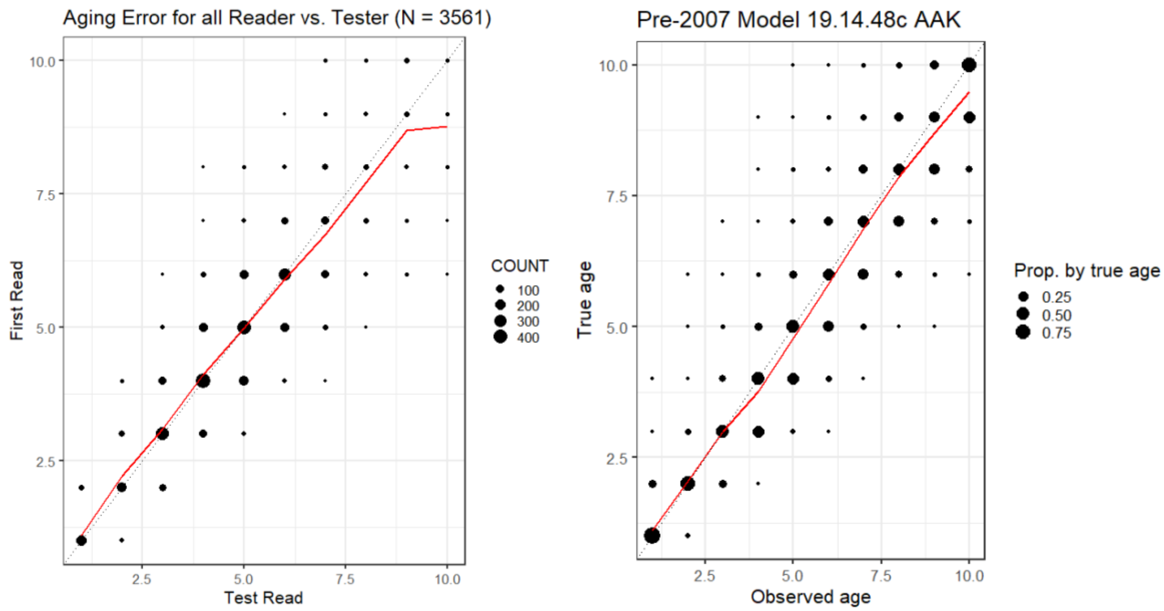


Figure 2.52 (Left top) Aging error matrix from reader-tester validation with red line showing mean first read by test read, (top right) as implemented in Model 19.14.48c with aging bias for pre-2007 age data. The red line in this figure indicates the mean true age by observed age.

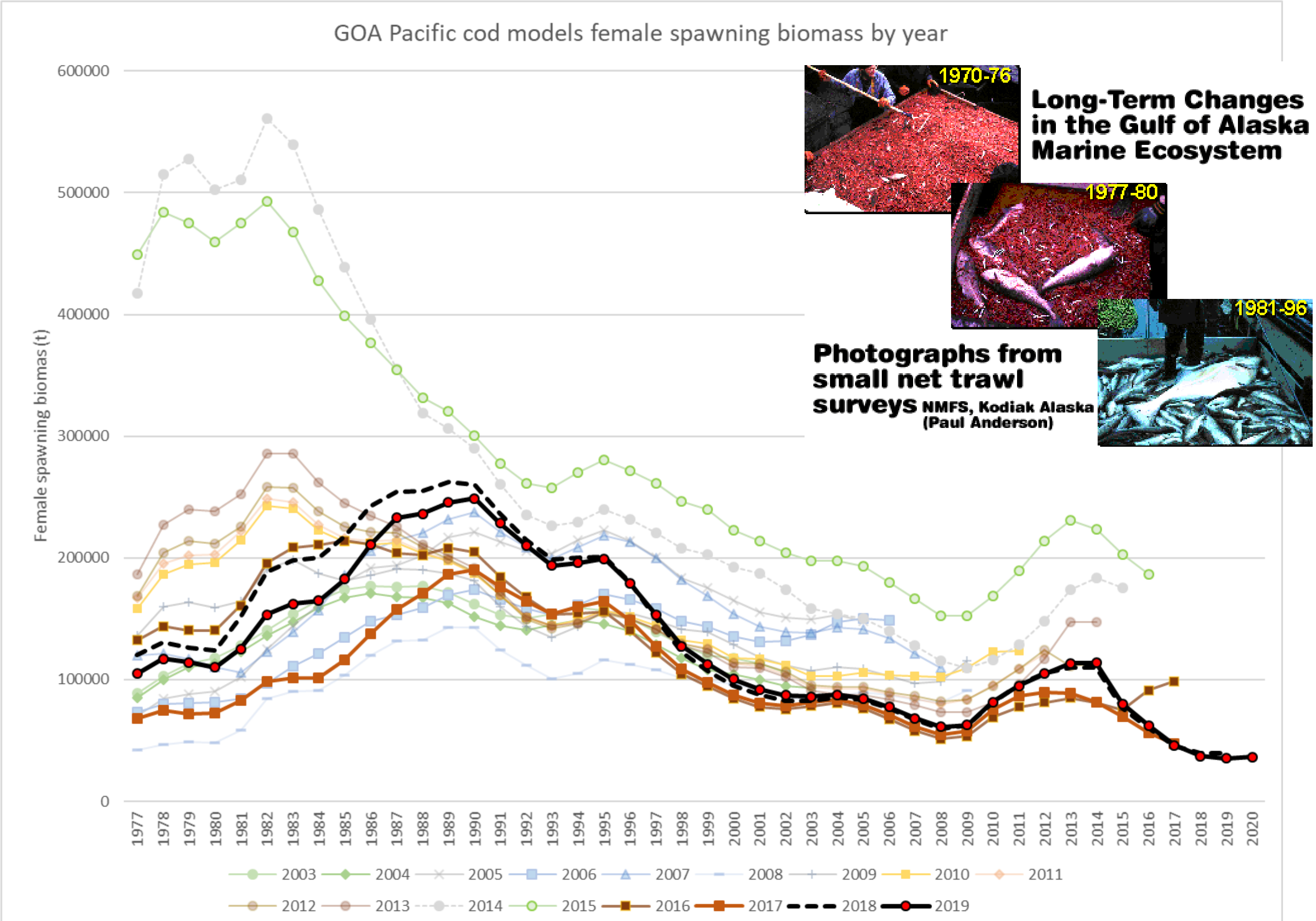


Figure 2.53 1977-2019 Gulf of Alaska Pacific cod female spawning biomass from the 2003 through 2019 stock assessments with the author's preferred Model 19.14.48c as the 2019 estimate and (inset) images from the NMFS small net surveys off Kodiak Alaska showing change in species composition over time from: http://www.thexxnakedscientists.com/HTML/articles/article/brucewrightcolumn1.htm/

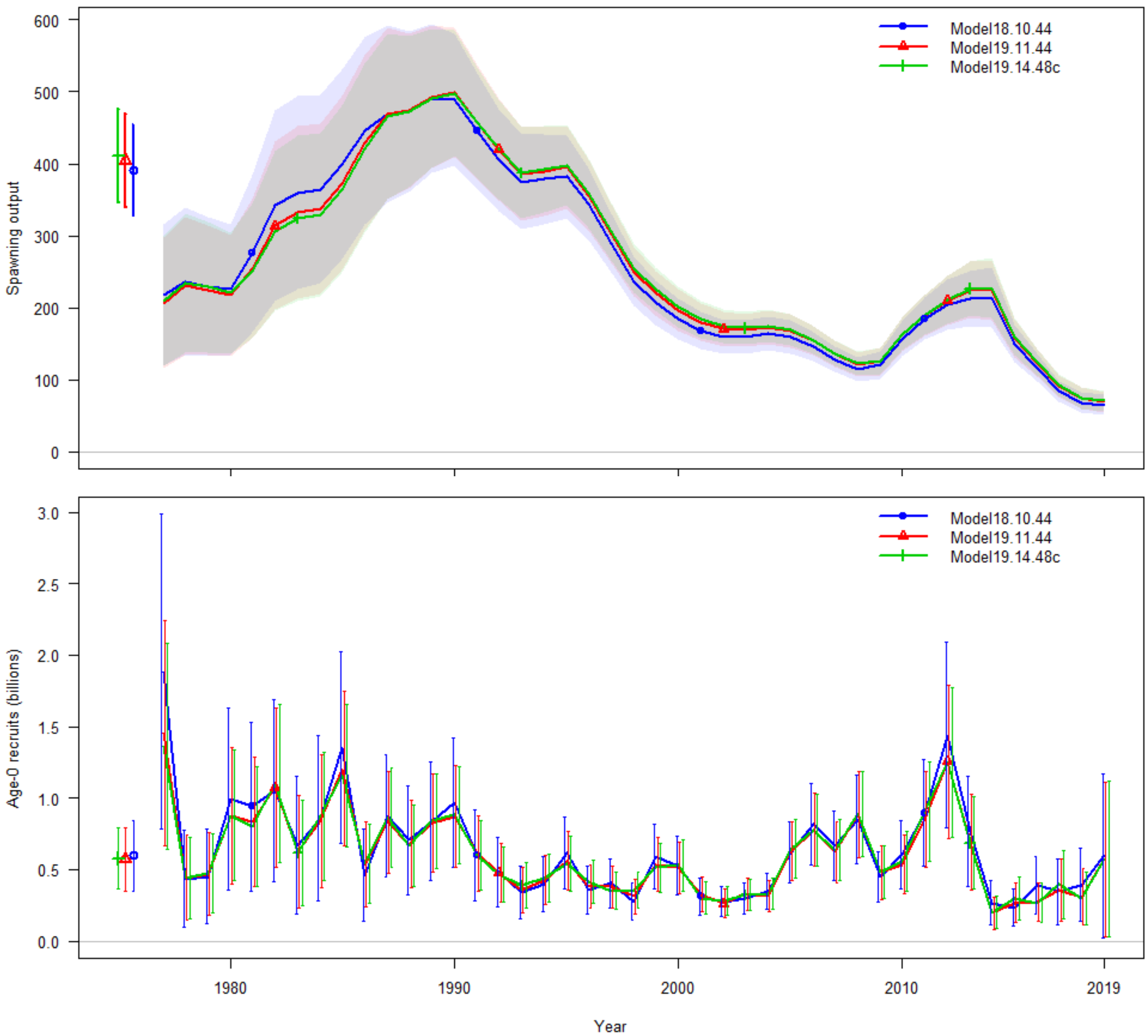


Figure 2.54 Estimates of female spawning biomass (t; top) and age-0 recruits (billions; bottom) for 2018 reference model without (Model 18.10.44), with 2019 data and change in plus age group to 10+ and aging error (Model 19.11.44), and the proposed alternative 2019 model (Model19.14.48c) with pre-2007 age data and aging bias.

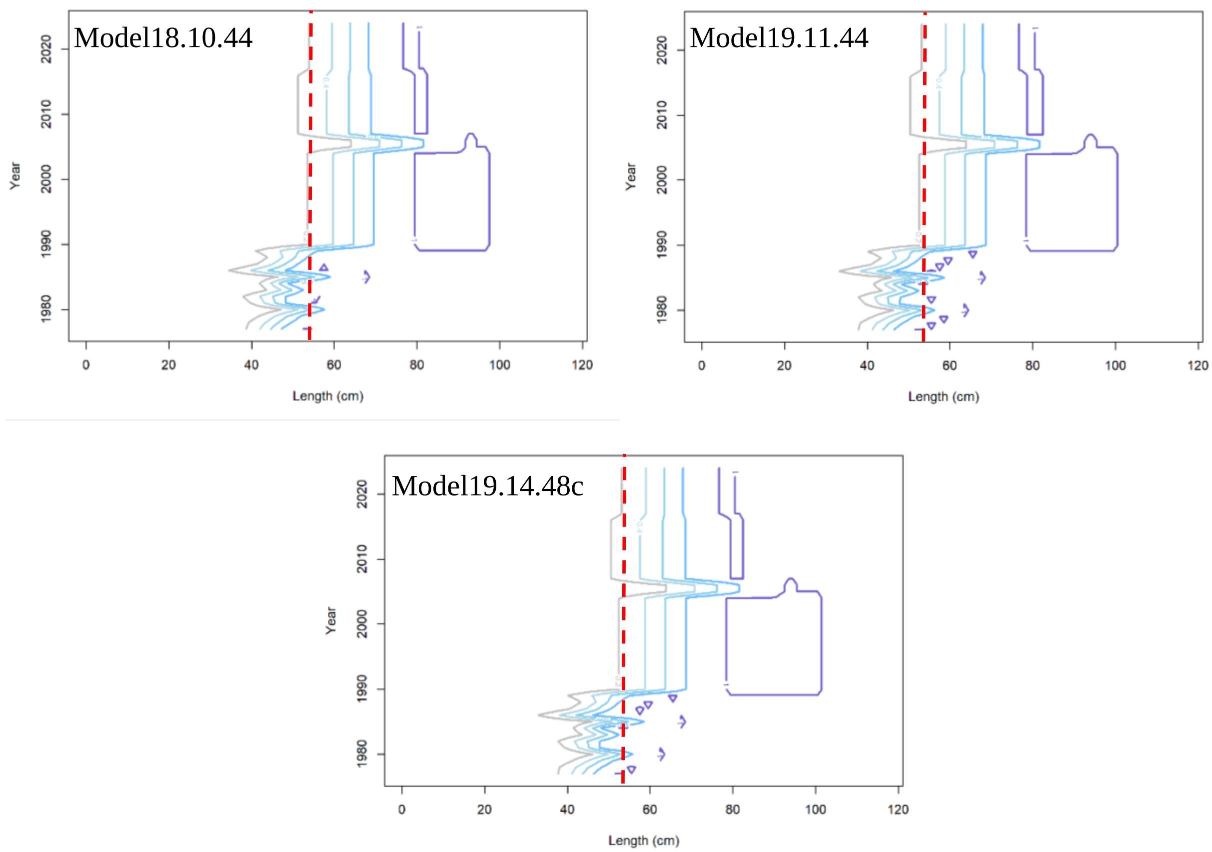


Figure 2.55 Estimates of trawl fishery selectivity for Model 18.10.44, Model 19.11.44, and Model 19.14.48c. Red dashed line is the size at 50% mature

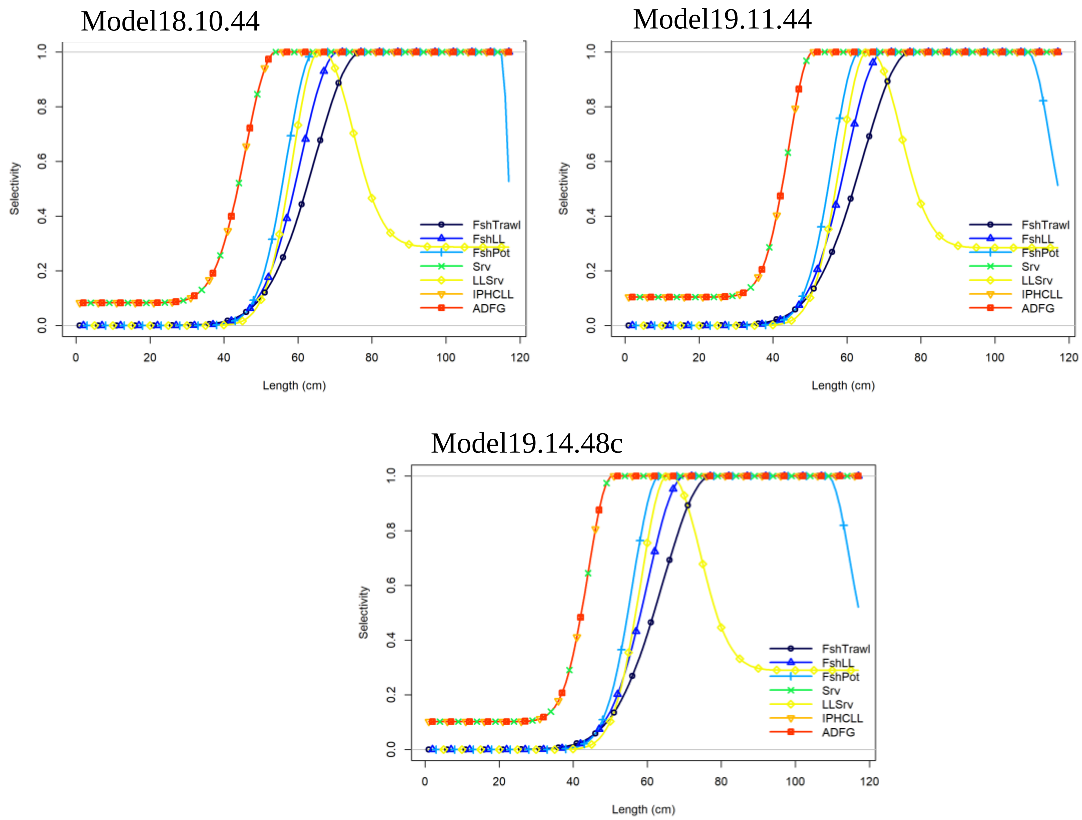


Figure 2.56 Model18.10.44, Model19.11.44, and Model19.14.48c selectivity for all size composition components for 2019.

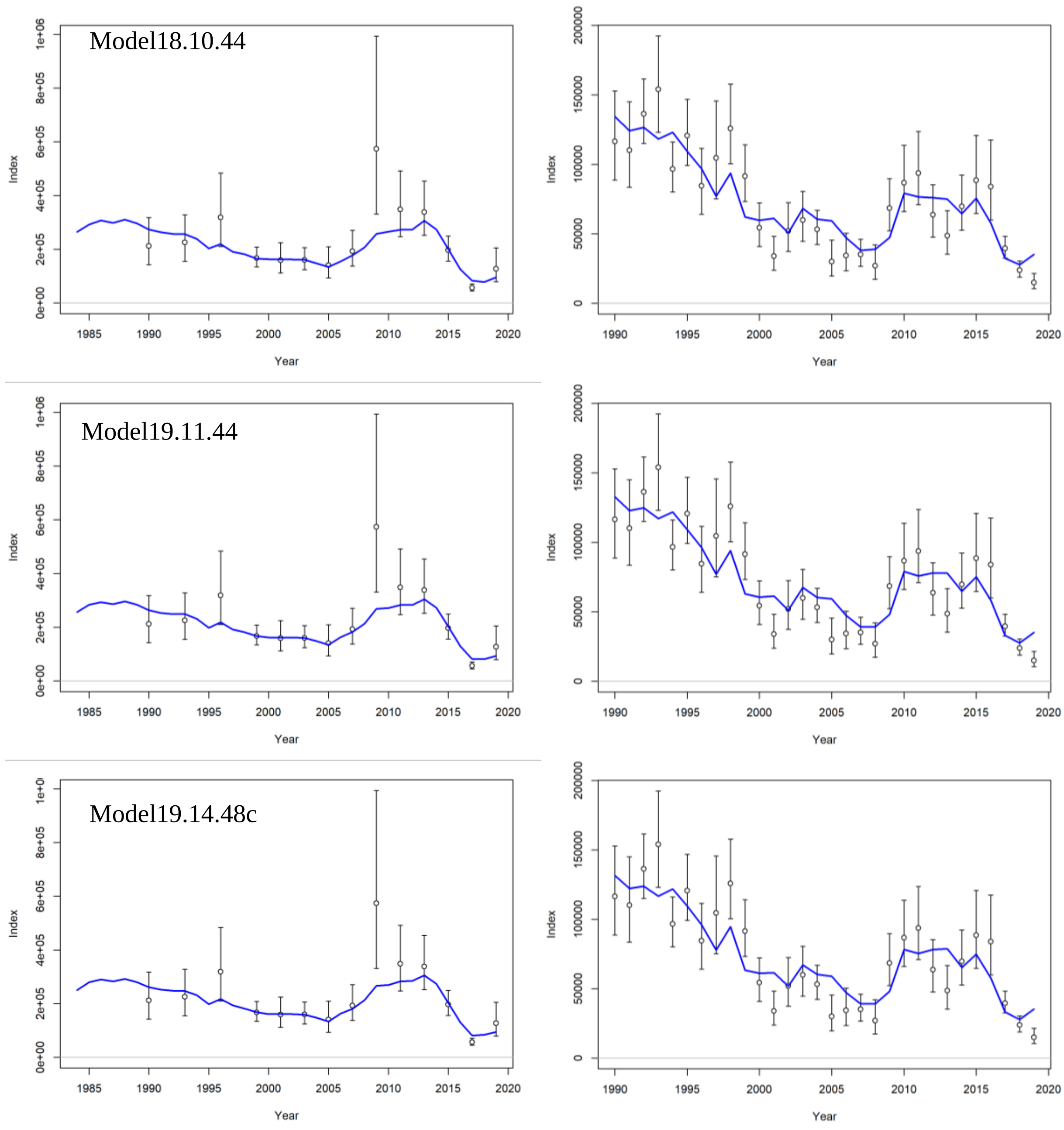


Figure 2.57 Model fits to AFSC bottom trawl (left) and AFSC longline (right) survey indices.

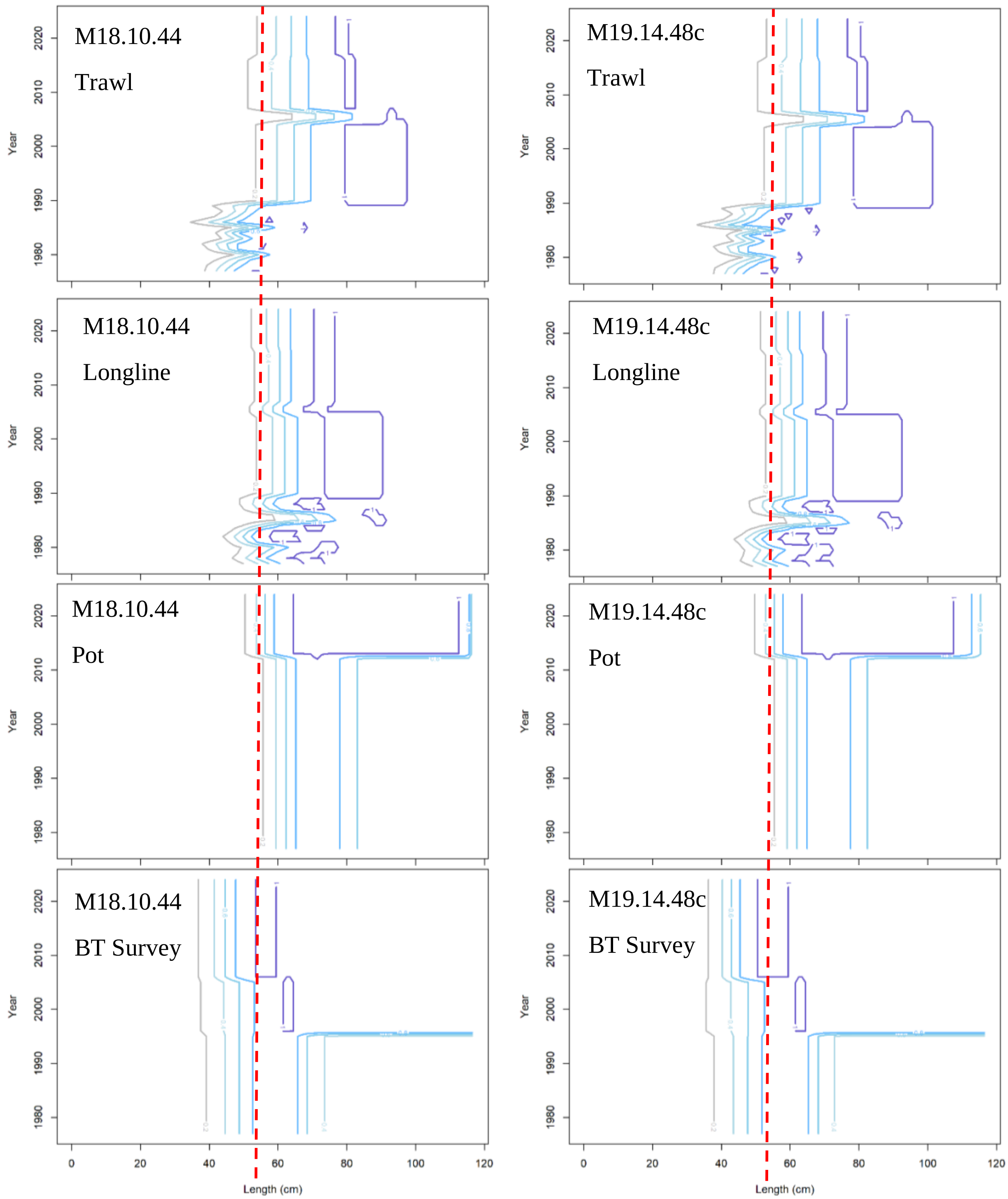


Figure 2.58 Estimates of fishery and AFSC bottom trawl survey selectivities for Model 18.10.44 (left) and Model 19.14.48c (right). Red dashed line is the size at 50% mature.

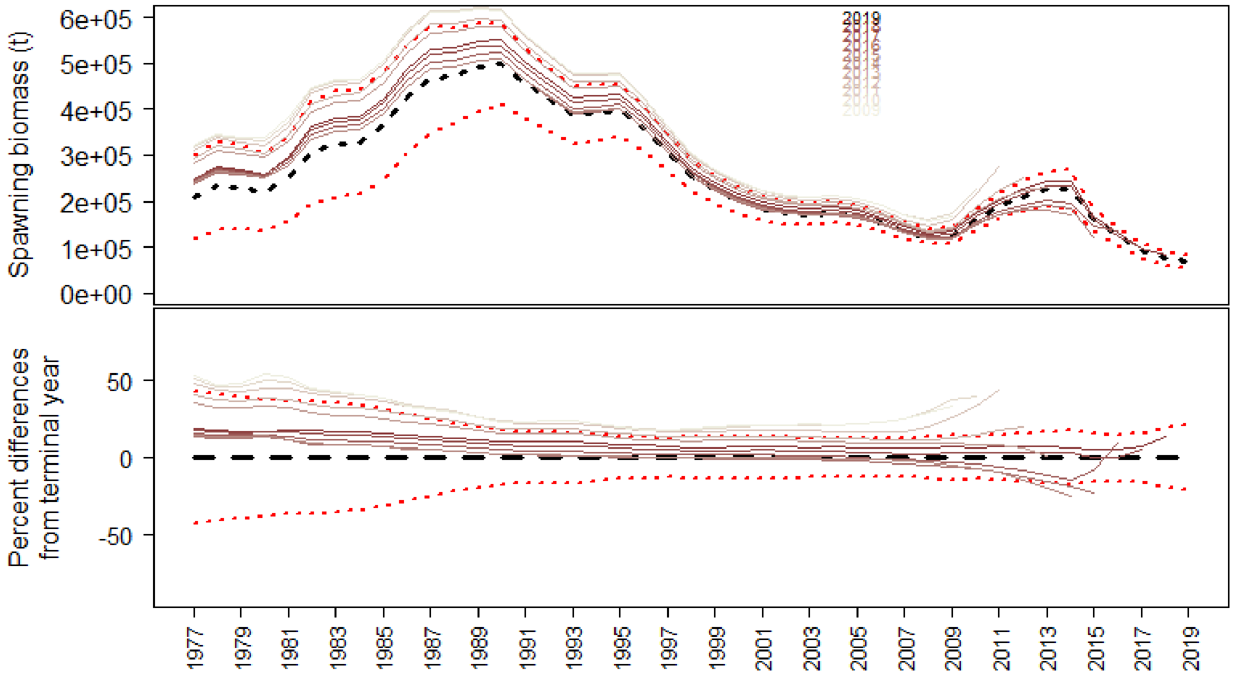


Figure 2.59 Retrospective analysis for Model 18.14.48c for Female spawning biomass.

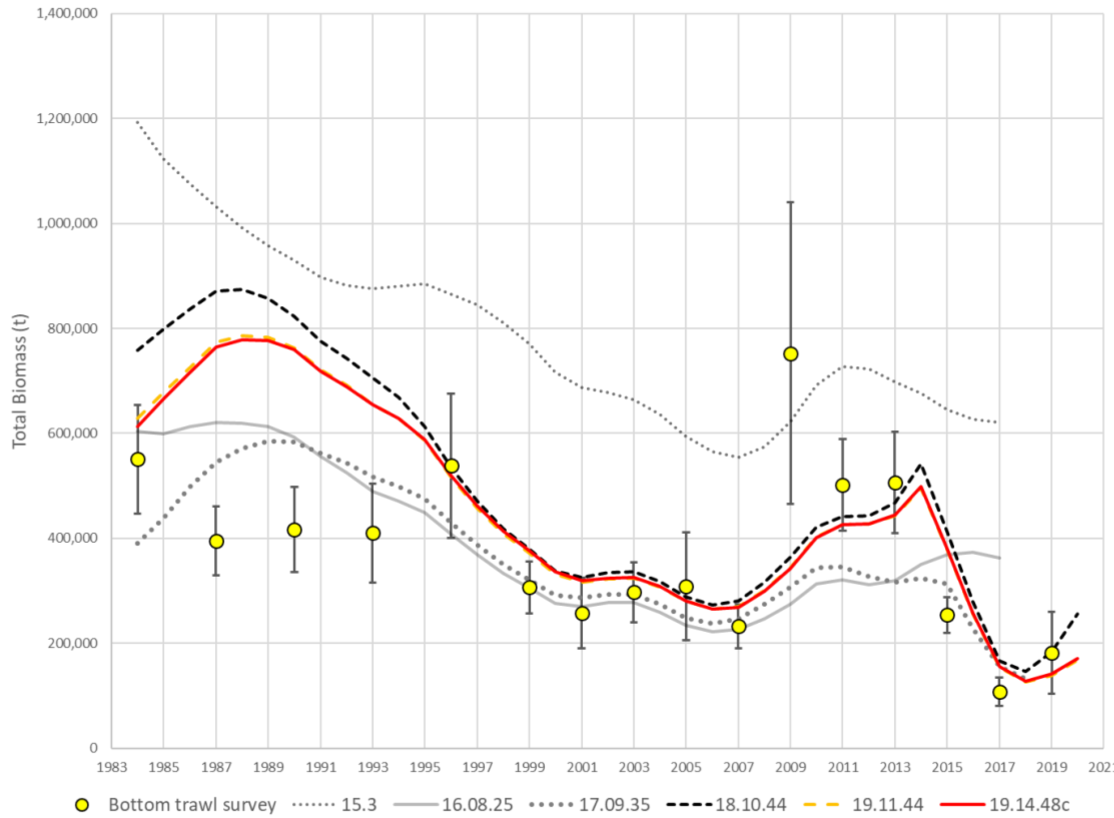


Figure 2.60 Total biomass estimates from reviewed models and NMFS bottom trawl survey biomass estimates with 95% confidence bounds.

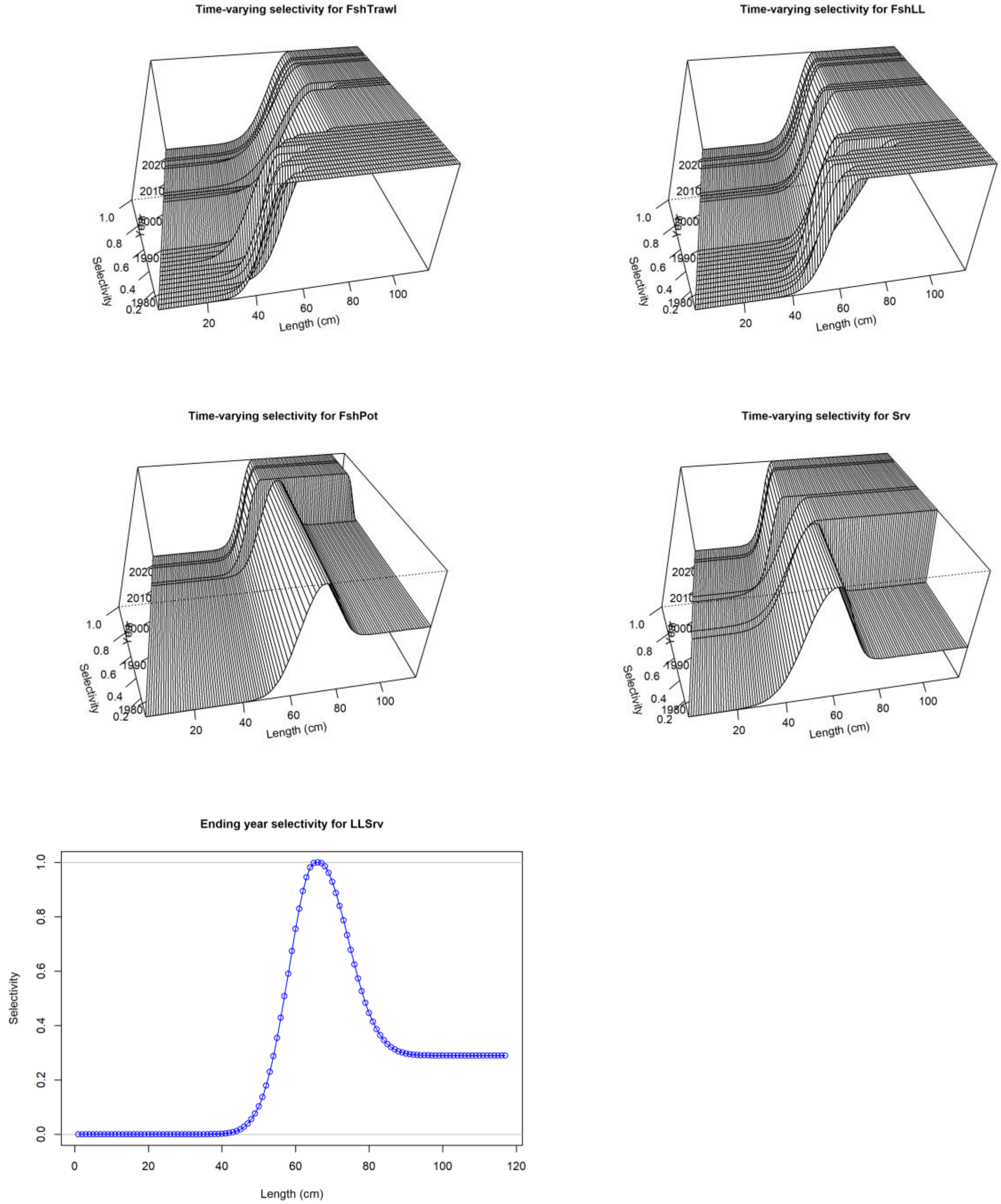


Figure 2.61 Selectivity curves for Model 19.14.48c Trawl fishery (FshTrawl), longline fishery (FshLL), pot fishery (FshPot), NMFS bottom trawl survey (Srv), and AFSC Longline survey (LLSrv) length composition data.

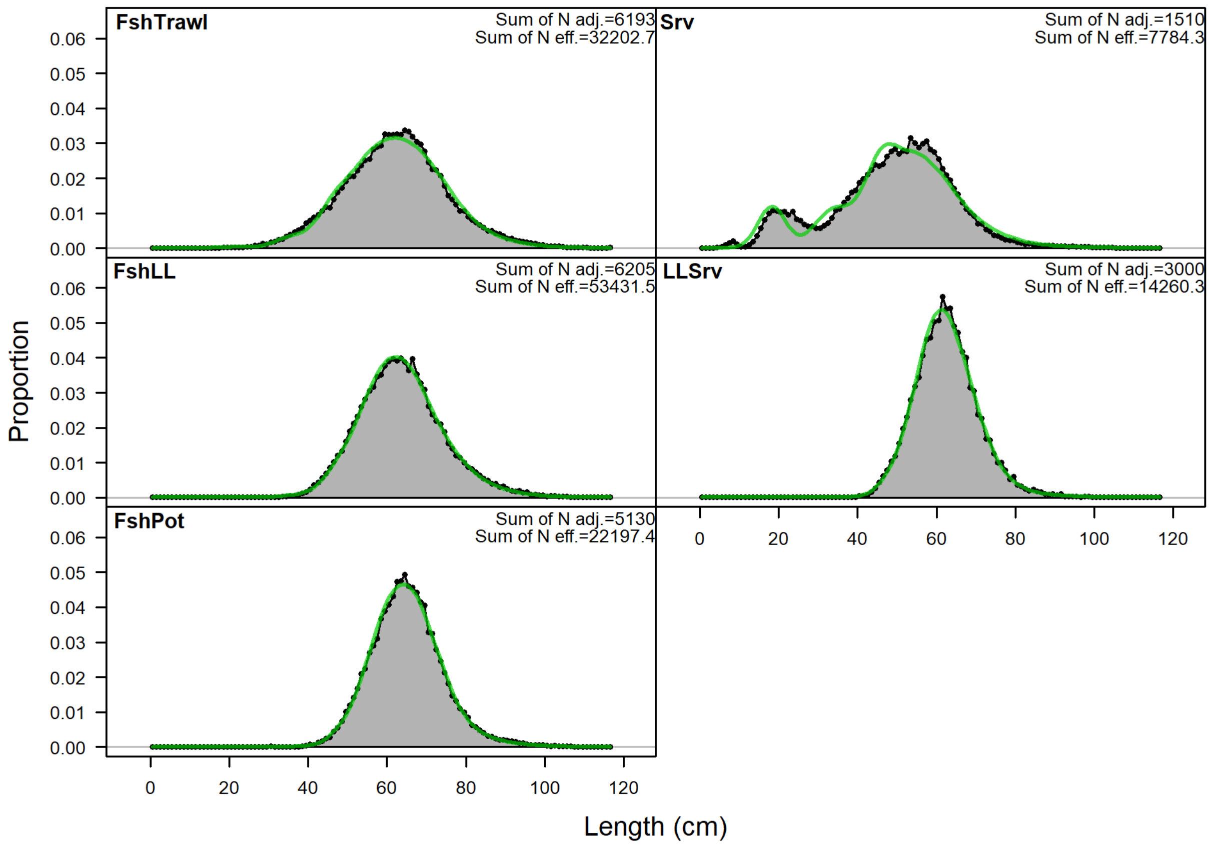


Figure 2.62 Overall Model 19.14.48c fits to Trawl fishery (FshTrawl), longline fishery (FshLL), pot fishery (FshPot), NMFS bottom trawl survey (Srv), and AFSC Longline survey (LLSrv) length composition data.

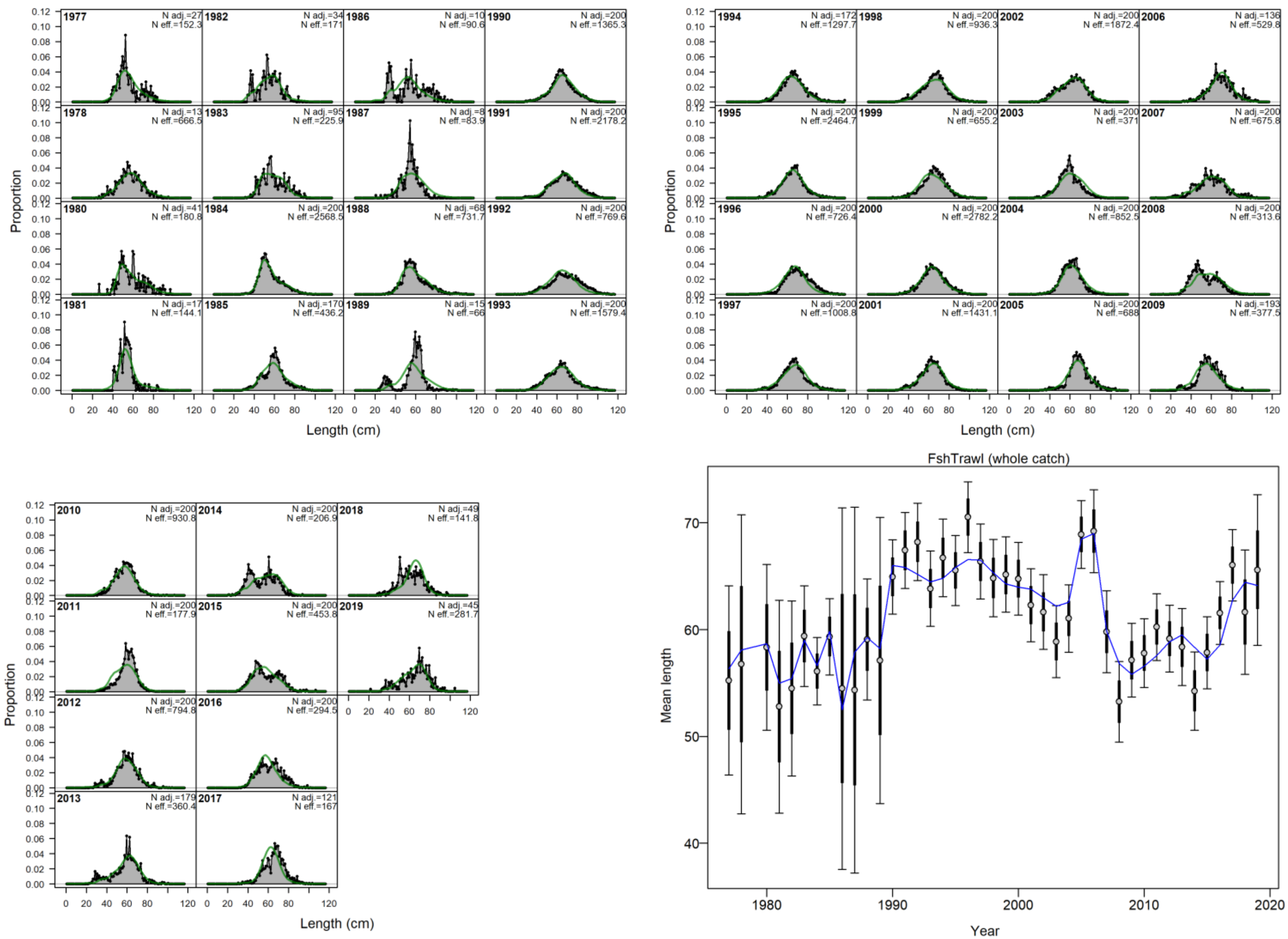


Figure 2.63 Trawl fishery length composition and Model 19.14.48c fit (top and left) and mean length (cm; right bottom).

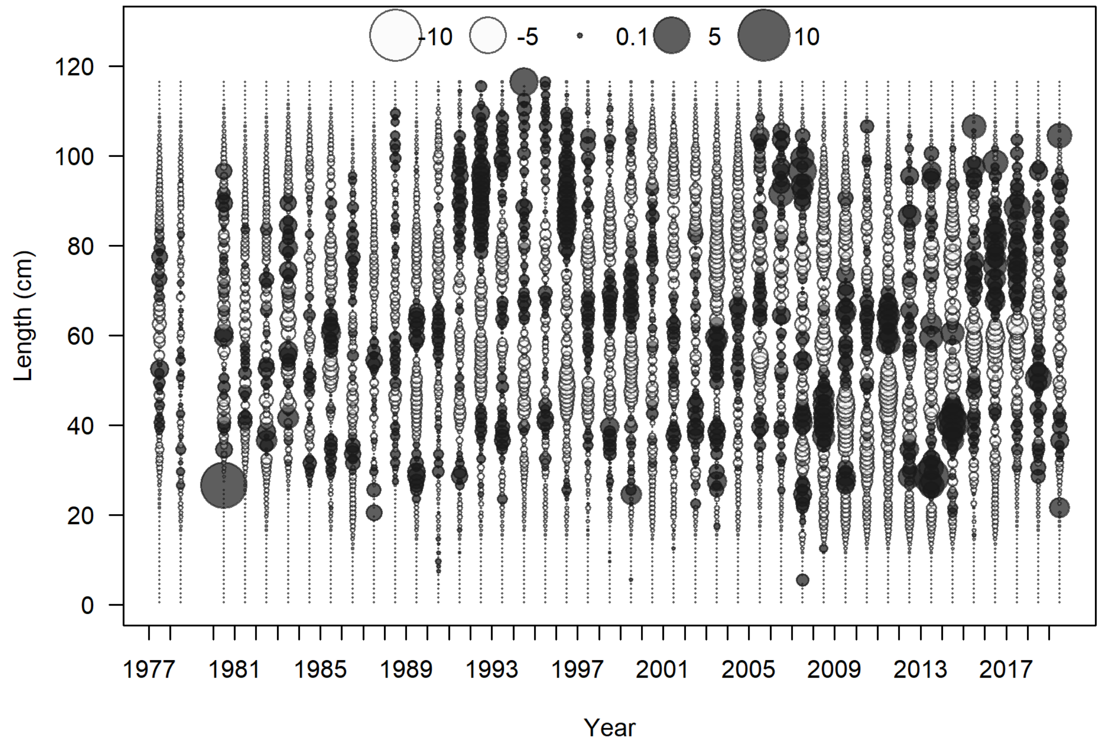


Figure 2.64 Trawl fishery length composition Pearson residuals (max = 8.01).

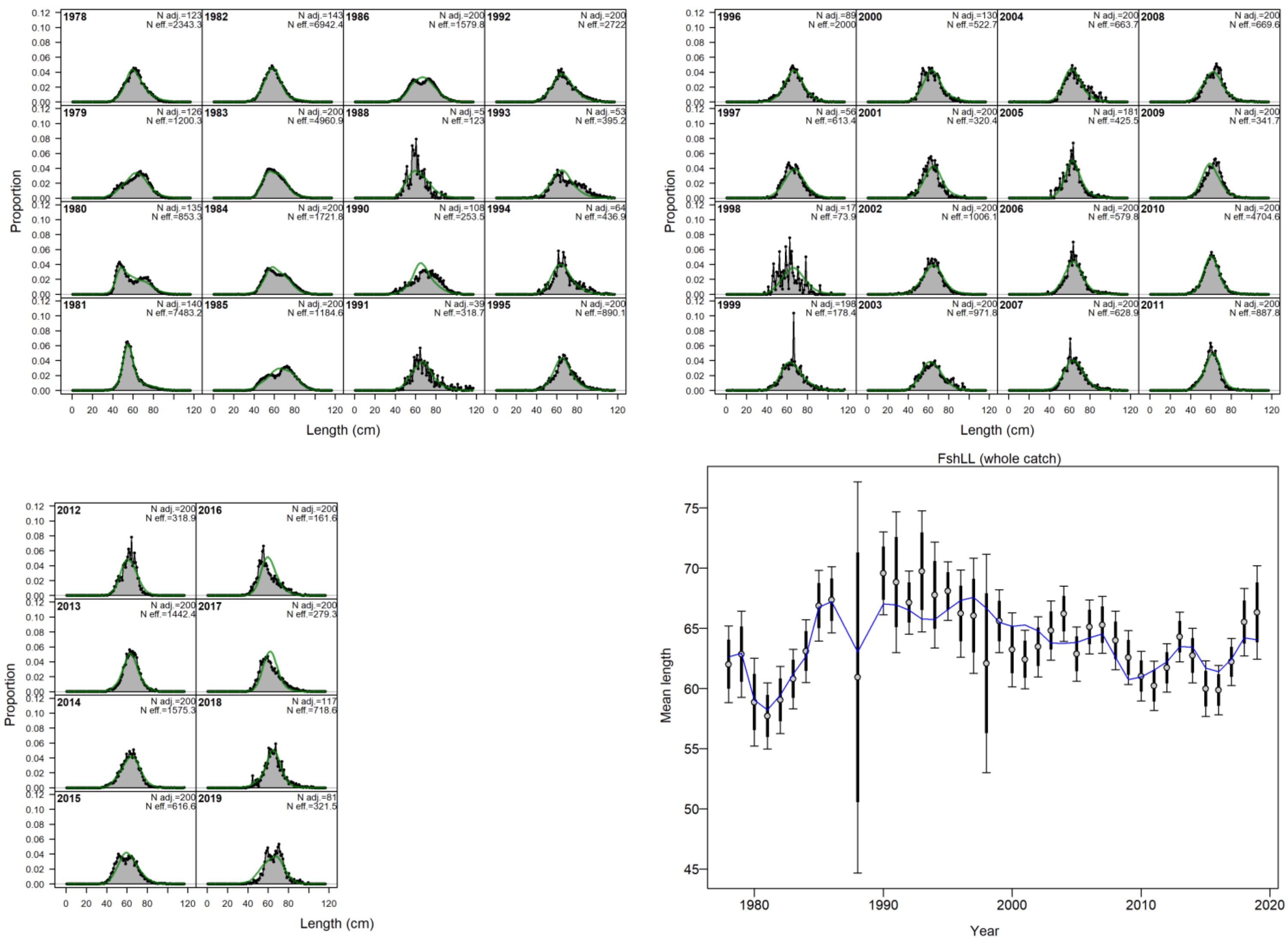


Figure 2.65 Longline fishery length composition and Model 19.14.48c fit (top and left) and mean length (cm; right bottom).

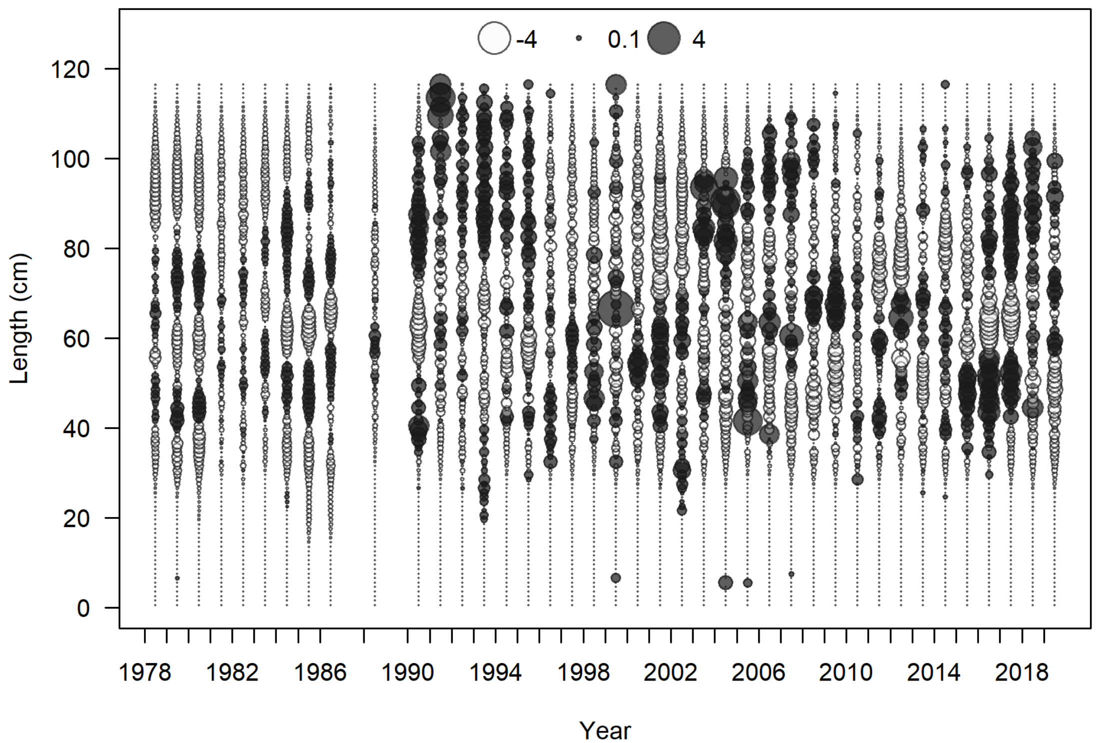


Figure 2.66 Longline fishery length composition and Model 19.14.48c fit (top and left) and Pearson residuals (max = 5.25).

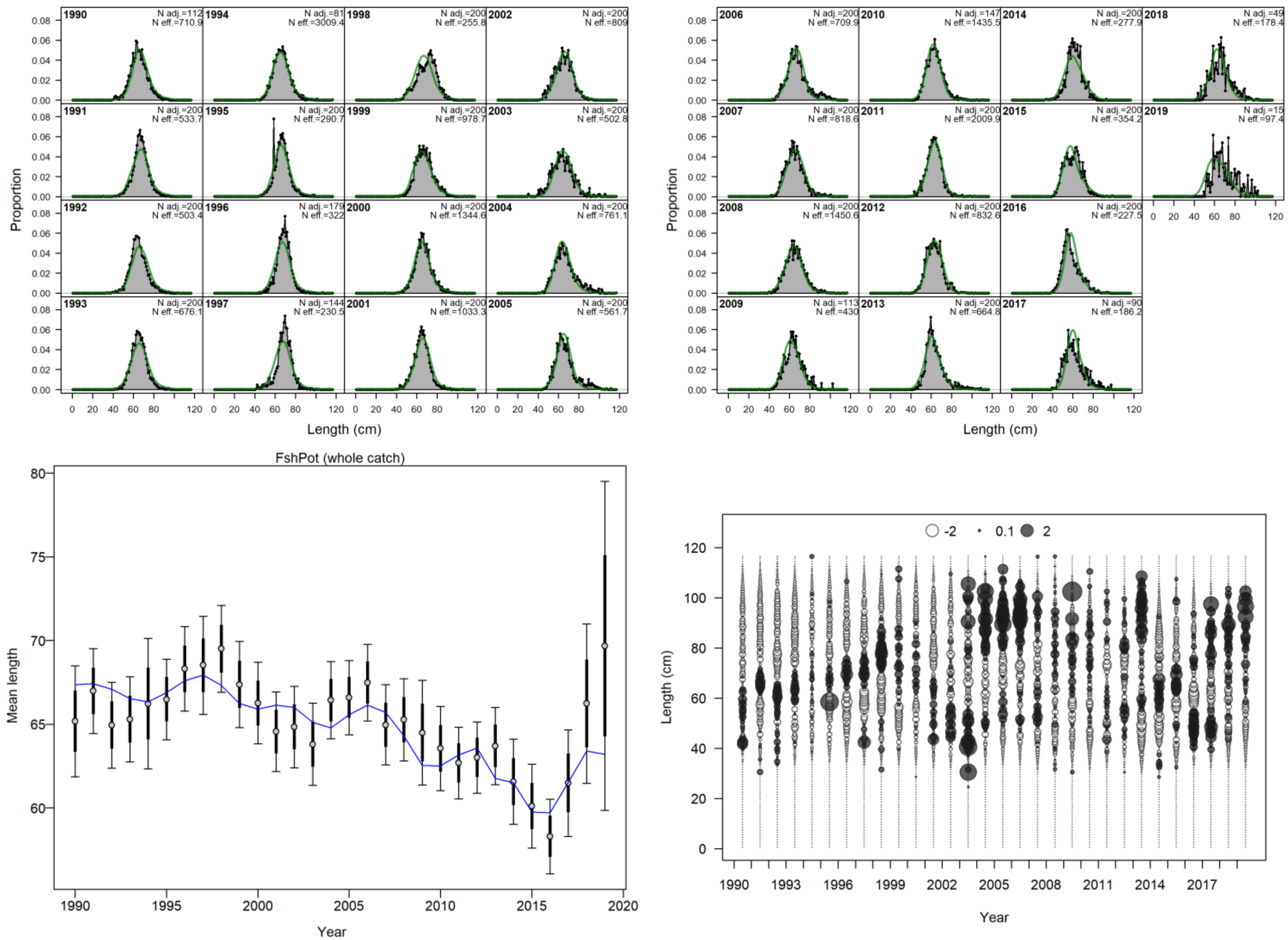


Figure 2.67 Pot fishery length composition and Model 19.14.48c fit (top), mean length (bottom left), and Pearson residuals (max=4.61; bottom right).

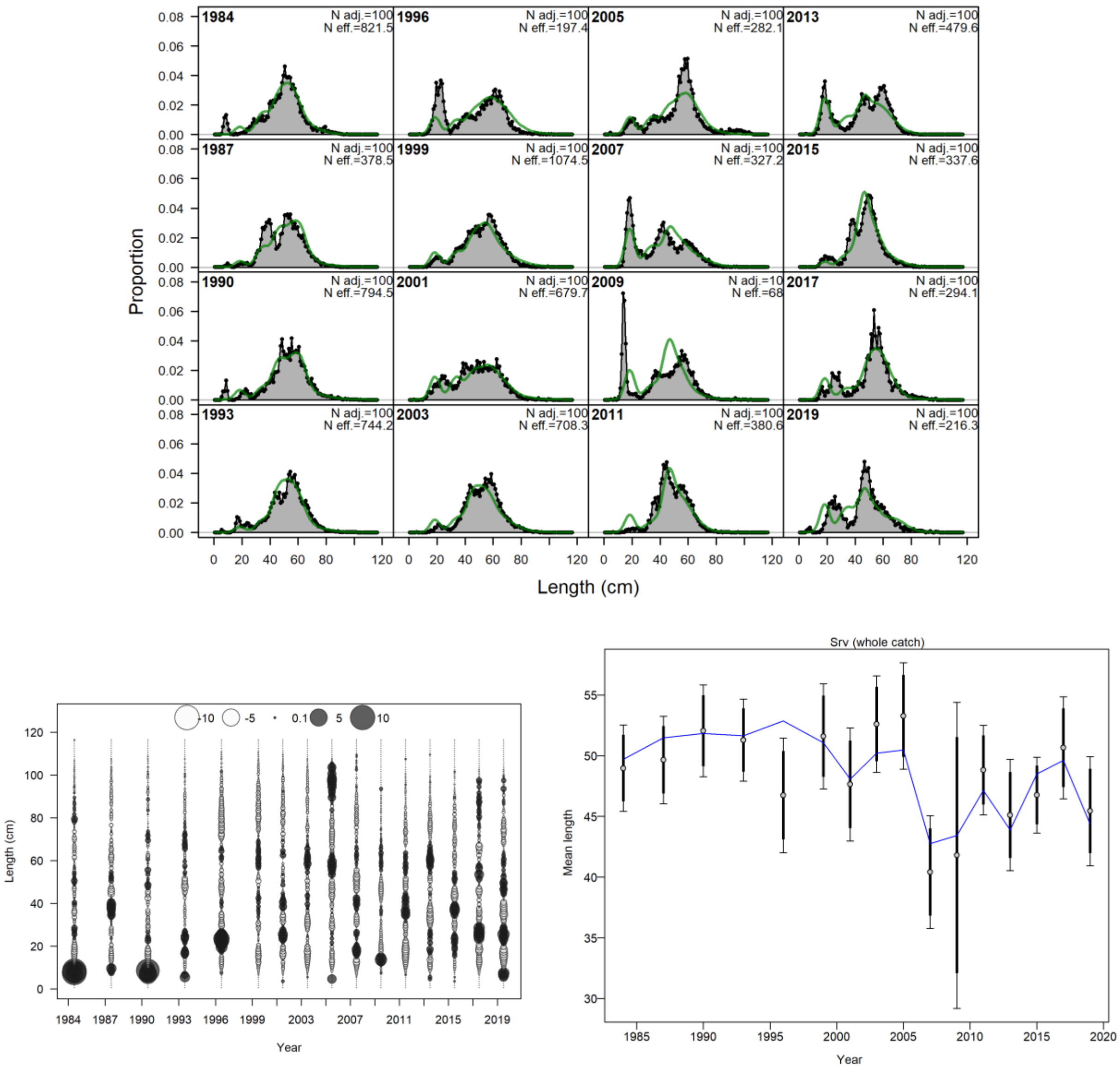


Figure 2.68 NMFS bottom trawl survey length composition and Model 19.14.48c fit (top), Pearson residuals (left bottom; max = 9.66), and mean length (cm; right bottom).

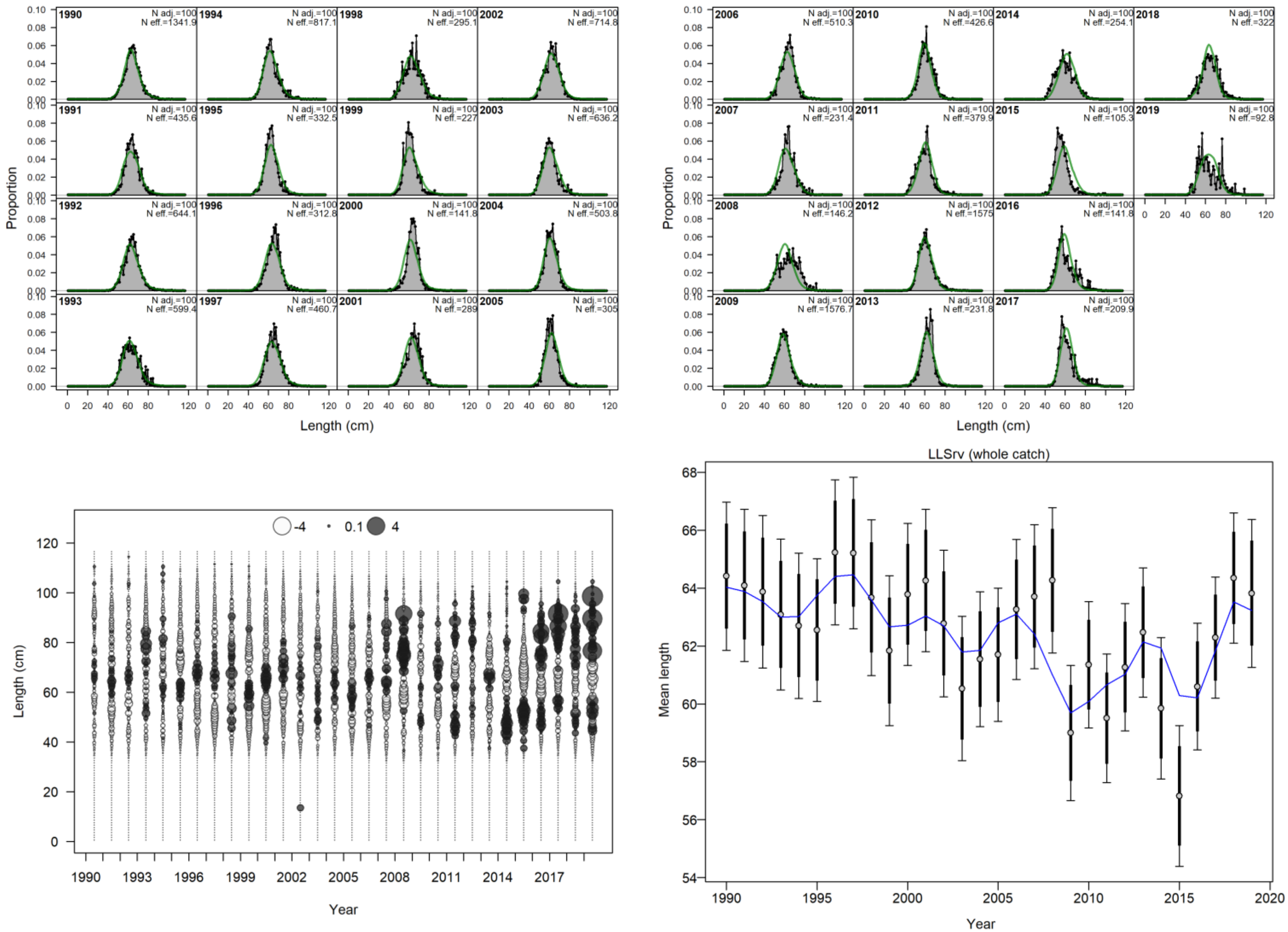


Figure 2.69 AFSC Longline survey length composition and Model 19.14.48c fit (top), Pearson residuals (left bottom; max=5.19), and mean length (cm; right bottom).

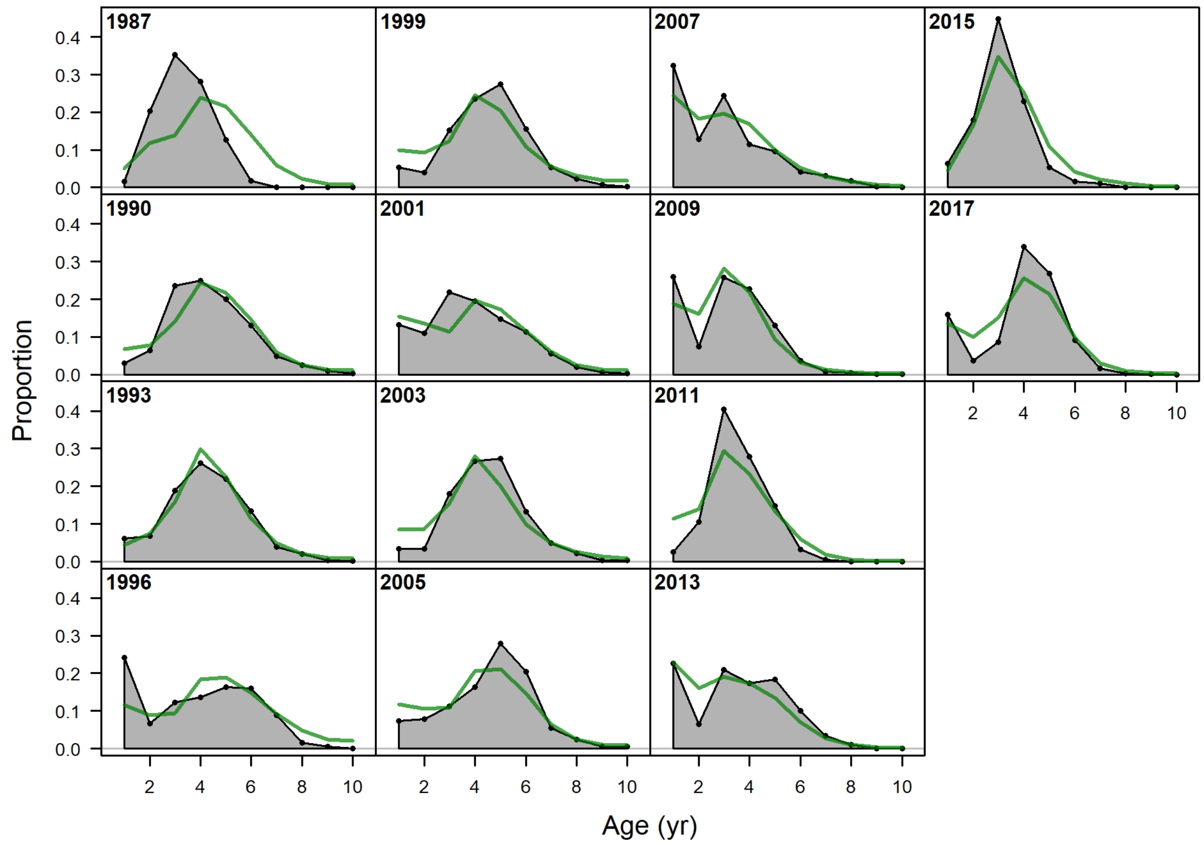


Figure 2.70 NMFS bottom trawl survey (Srv) age composition and Model 19.14.48c fit (left). Note the age data fits are not included in the objective function.

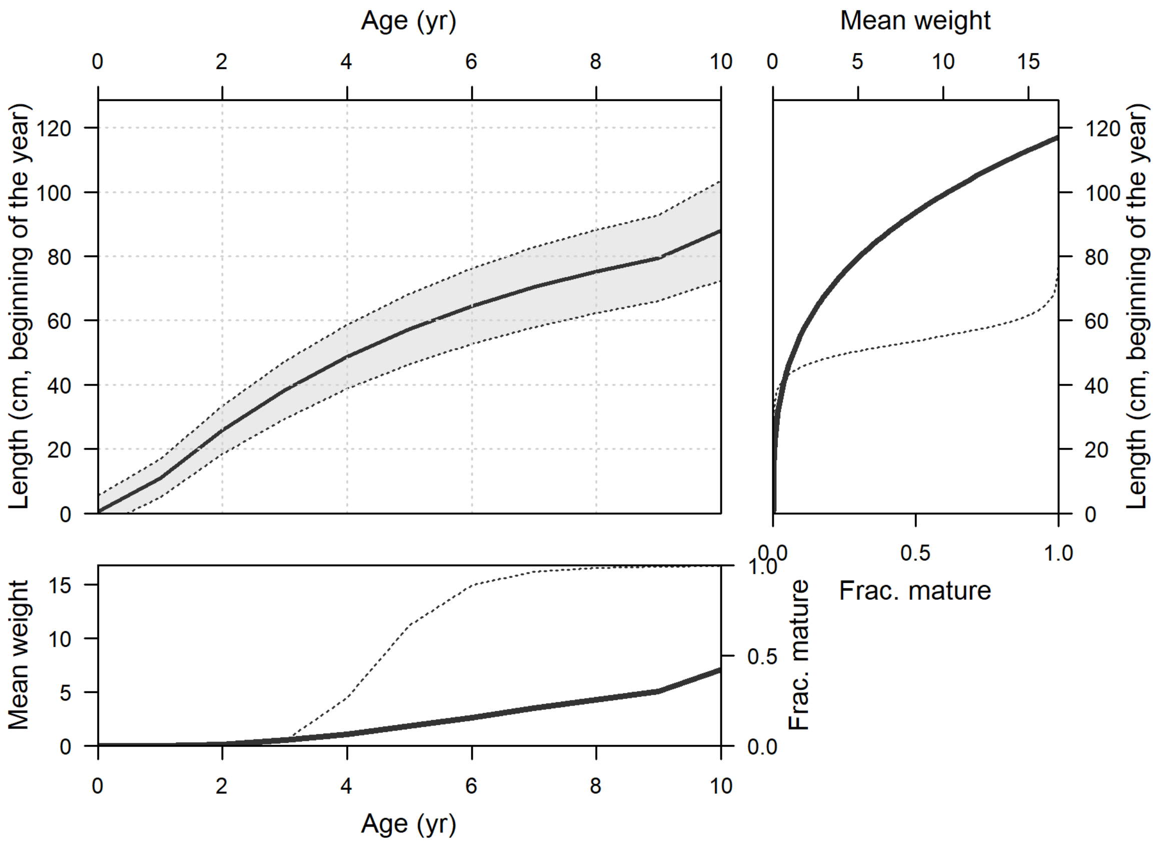


Figure 2.71 Model 19.14.48c length at age, weight at age, weight at length, and fraction mature at length, weight, and age.

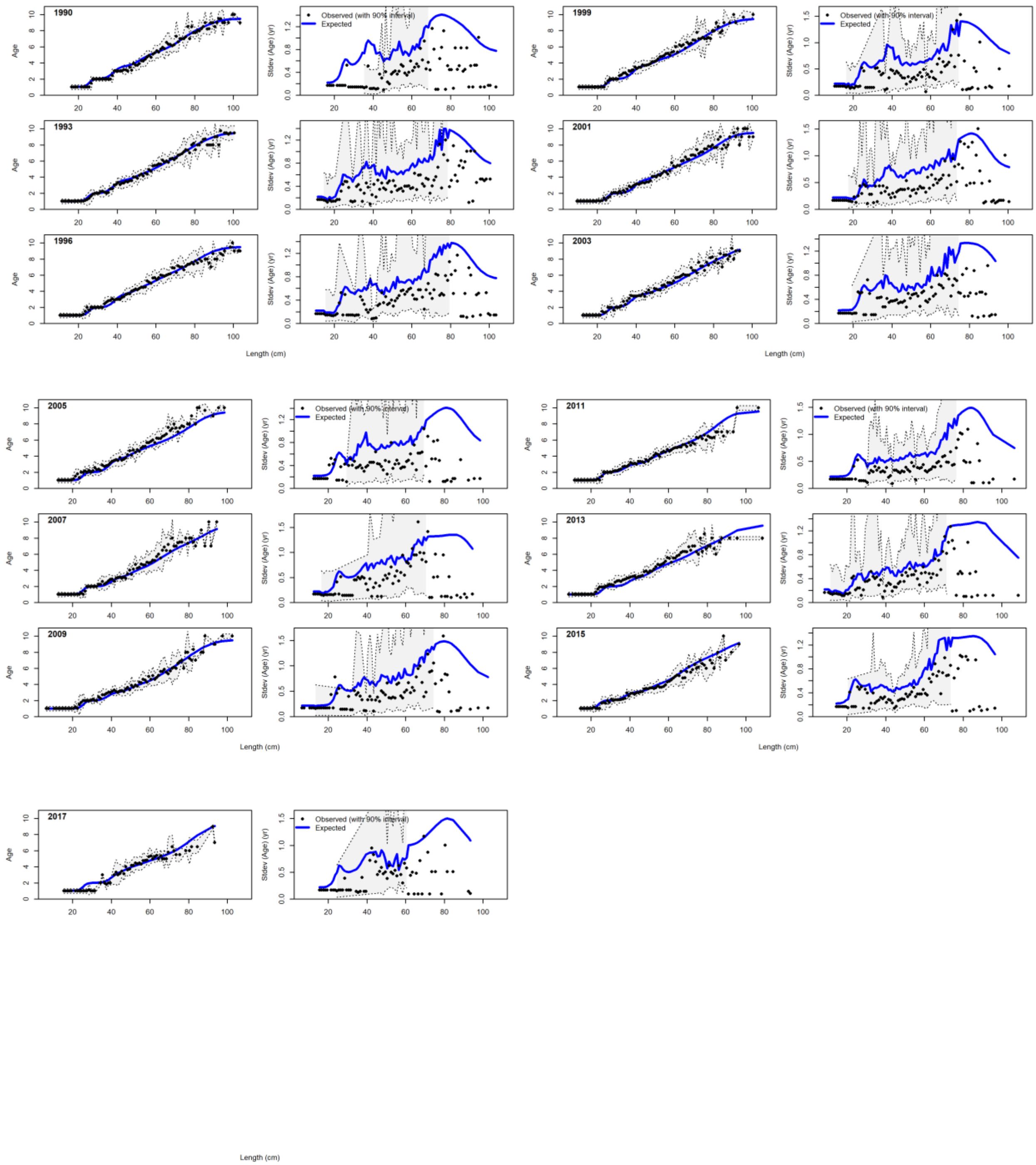


Figure 2.72 NMFS bottom trawl survey (Srv) conditional length-at-age data and Model 19.14.48c fit.

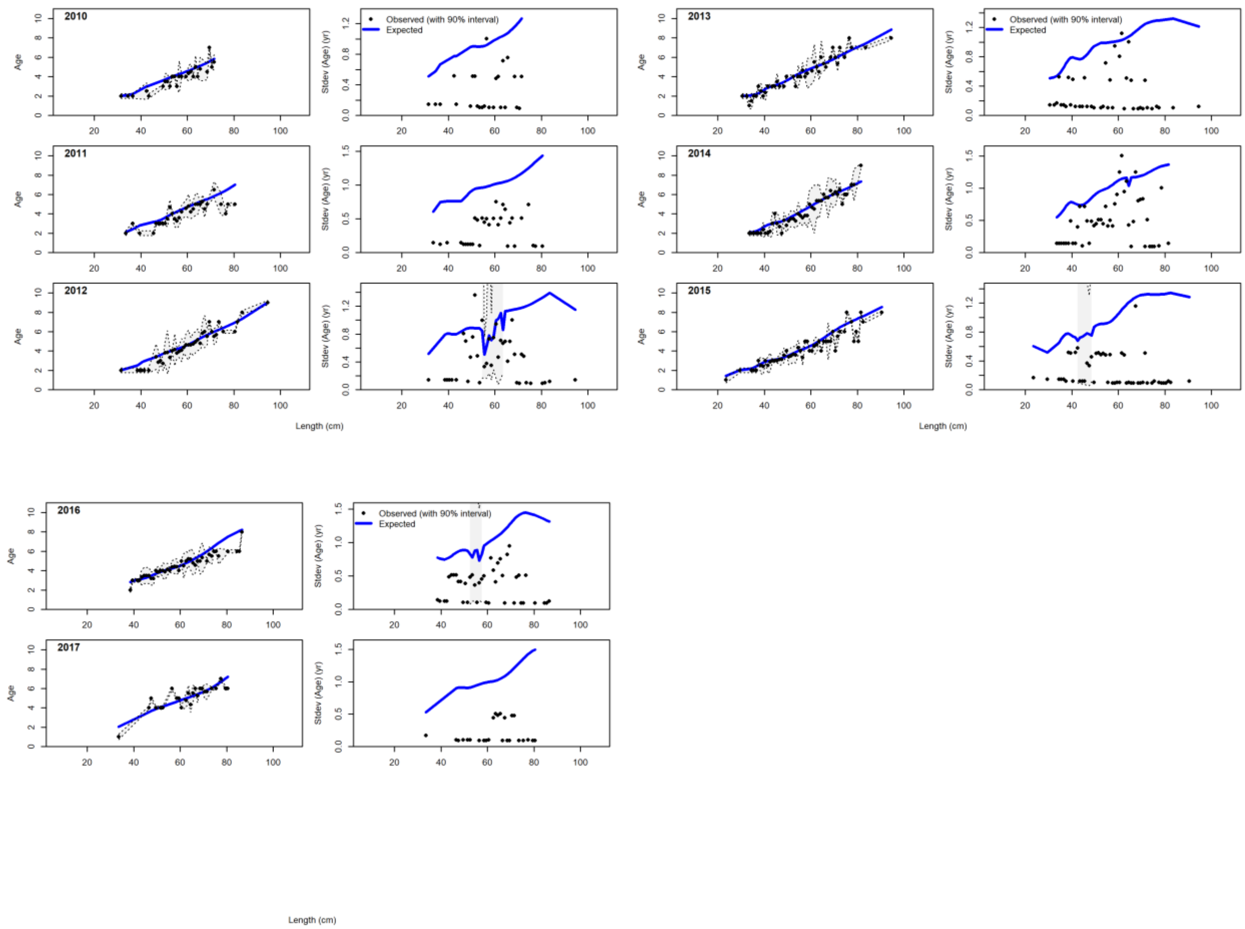
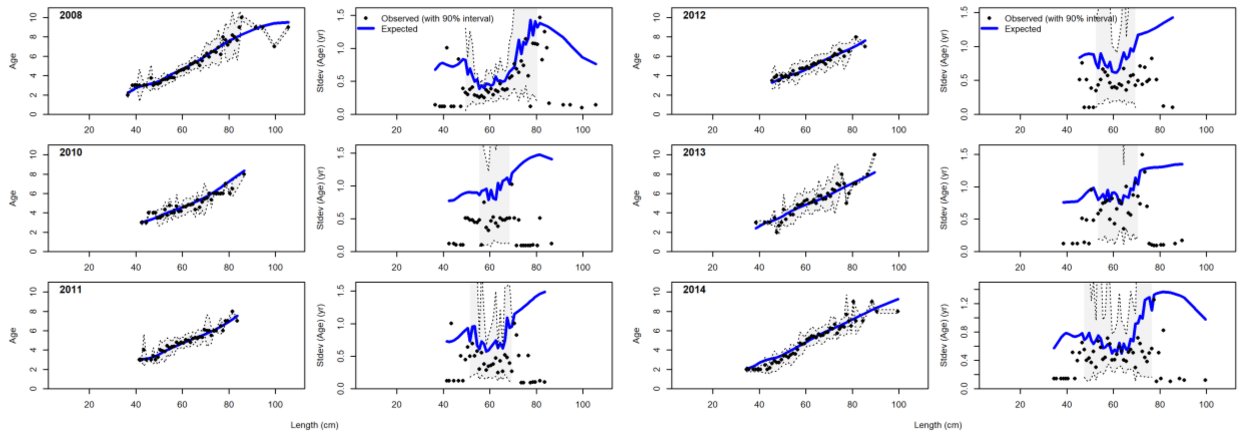


Figure 2.73 Trawl fishery conditional length-at-age data and Model 19.14.48c fit.



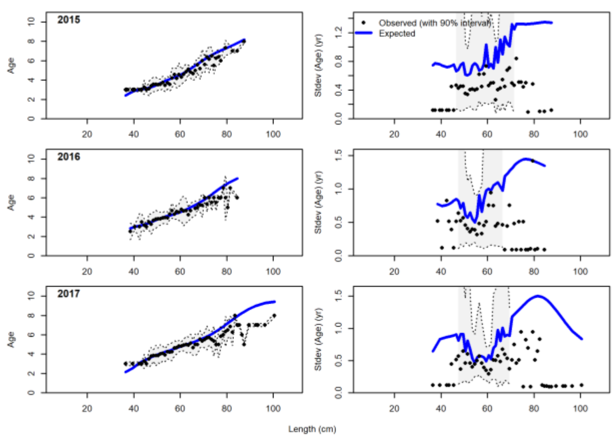


Figure 2.74 Longline fishery conditional length-at-age data and Model 19.14.48c fit.

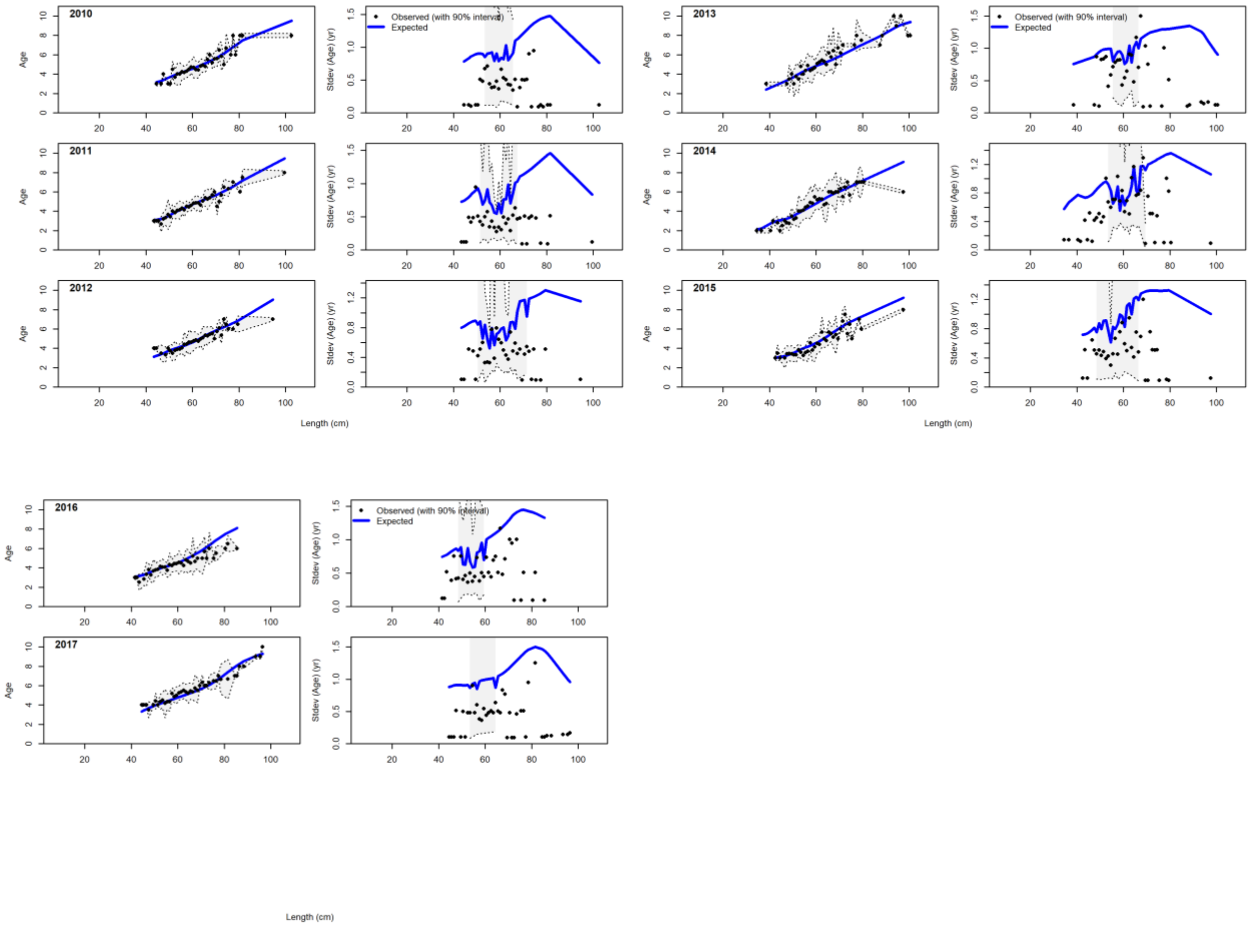


Figure 2.75 Pot fishery conditional length-at-age data and Model 19.14.48c fit.

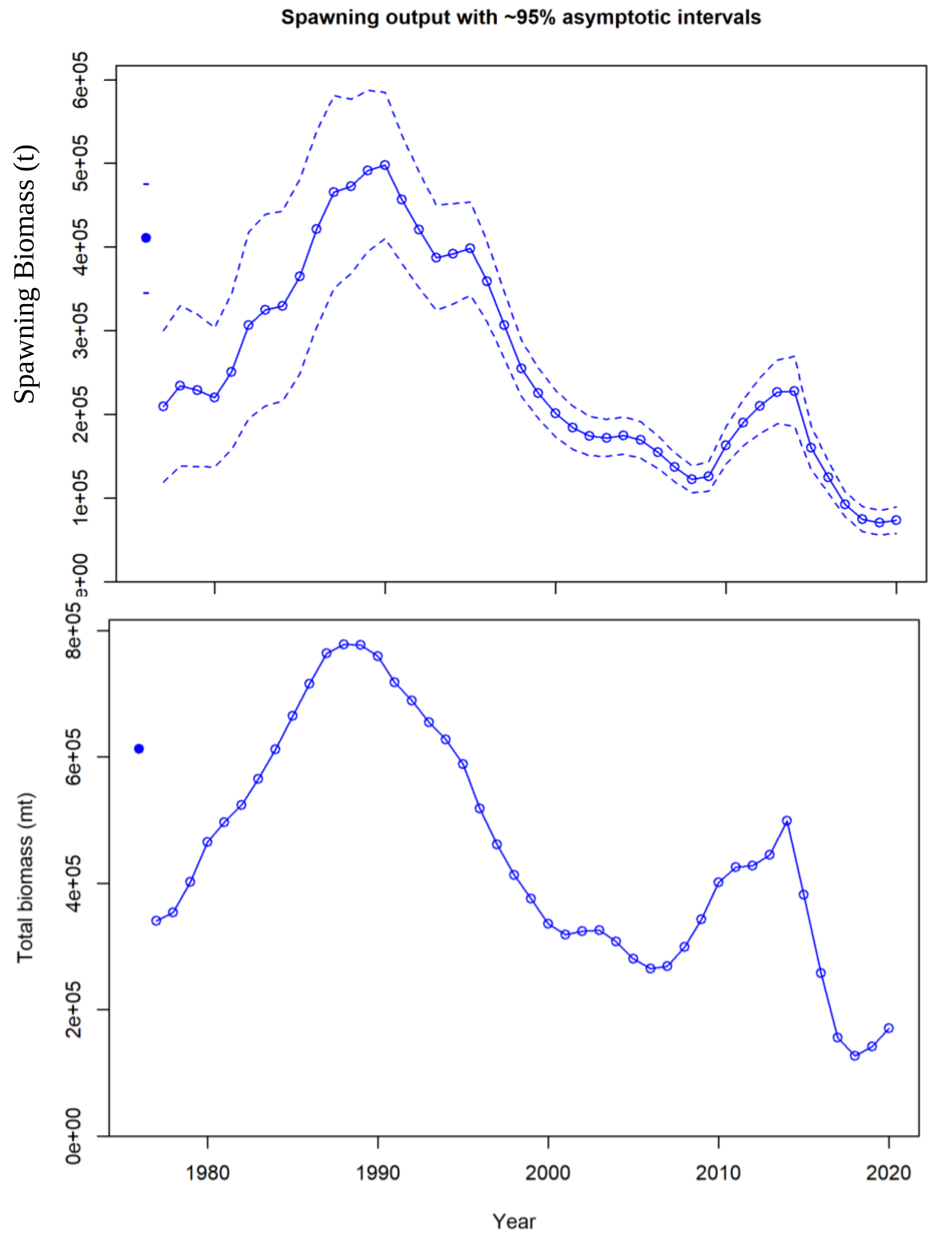
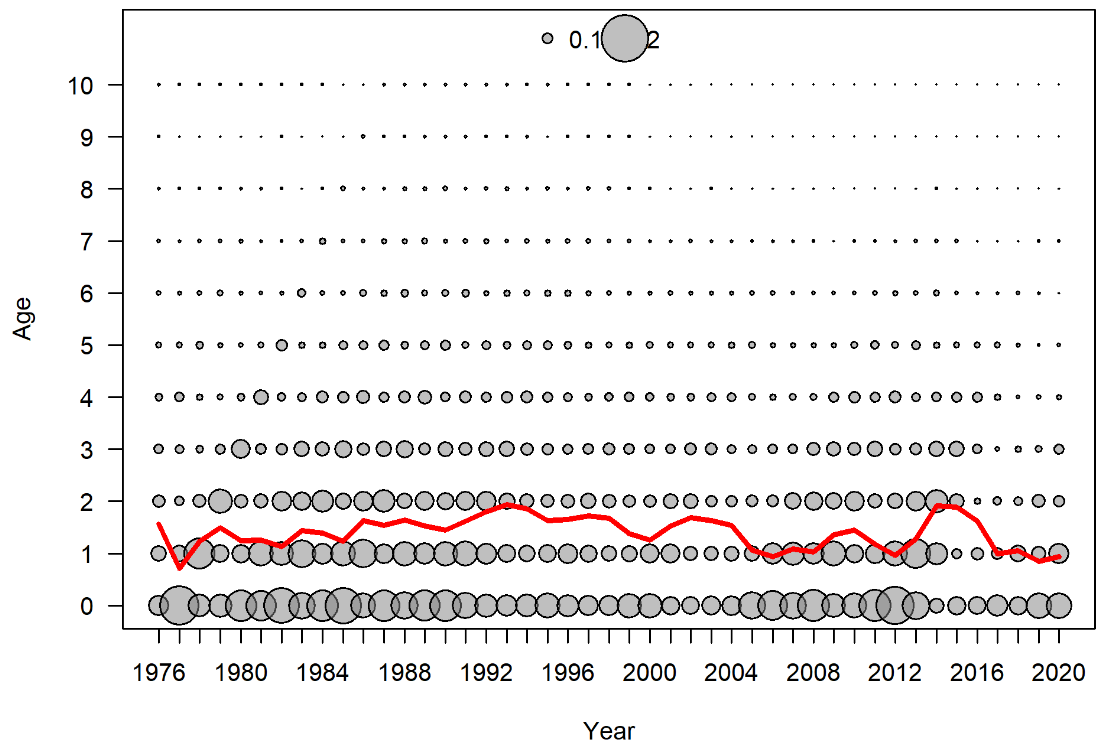


Figure 2.76 Model 19.14.48c predicted spawning output (femal spawning biomass; t) with 95% asymtotic error intervals (top) and total biomass (t).



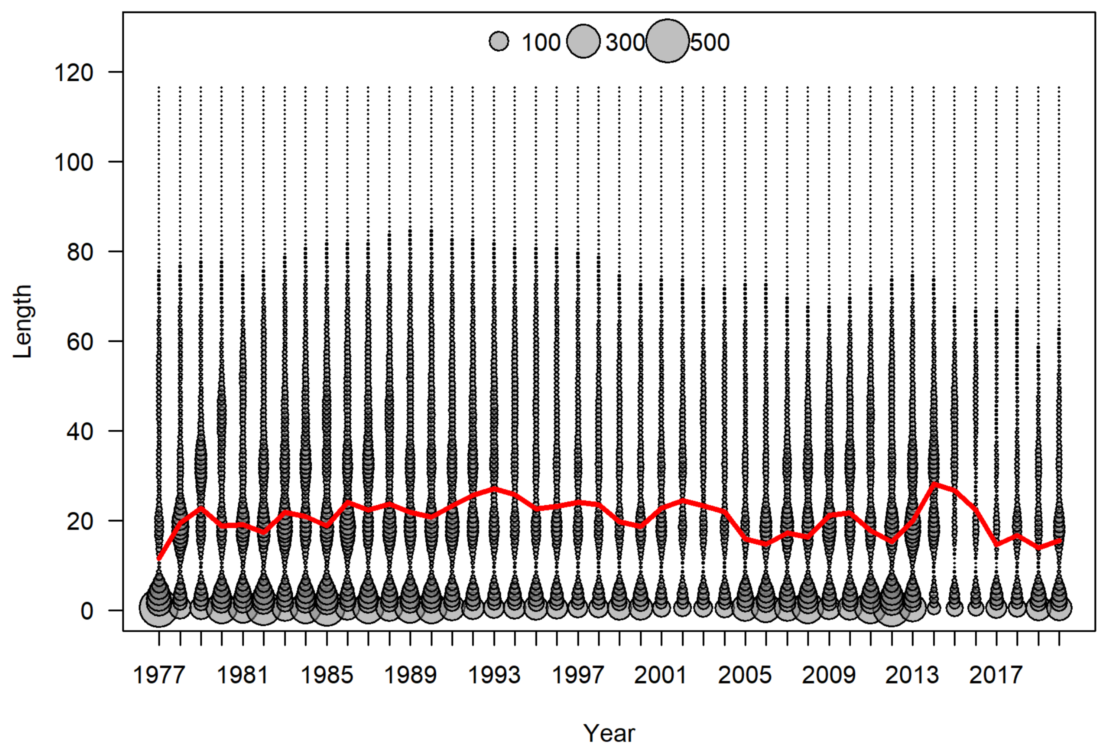


Figure 2.77 Model 19.14.48c predictions of middle of the year number at age (top) with mean age (red line) and numer at length (bottom)with mean length (red line).

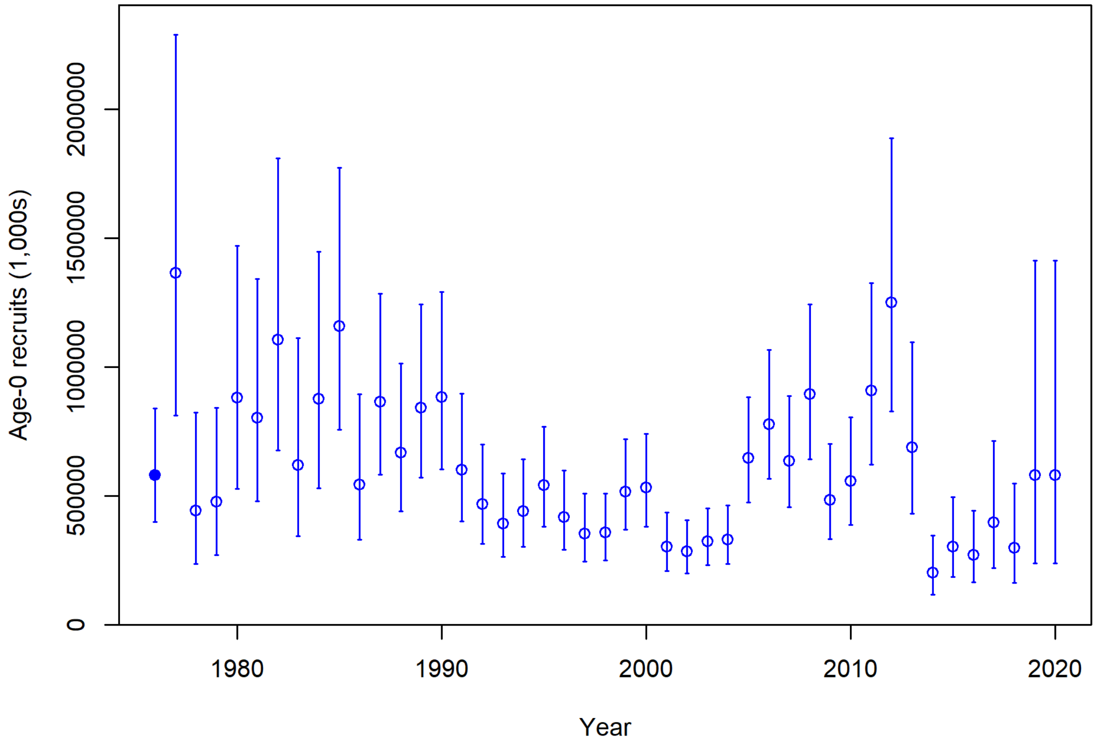


Figure 2.78 Model 19.14.48c age-0 recruitment (1000's) with 95% asymtotic error intervals.

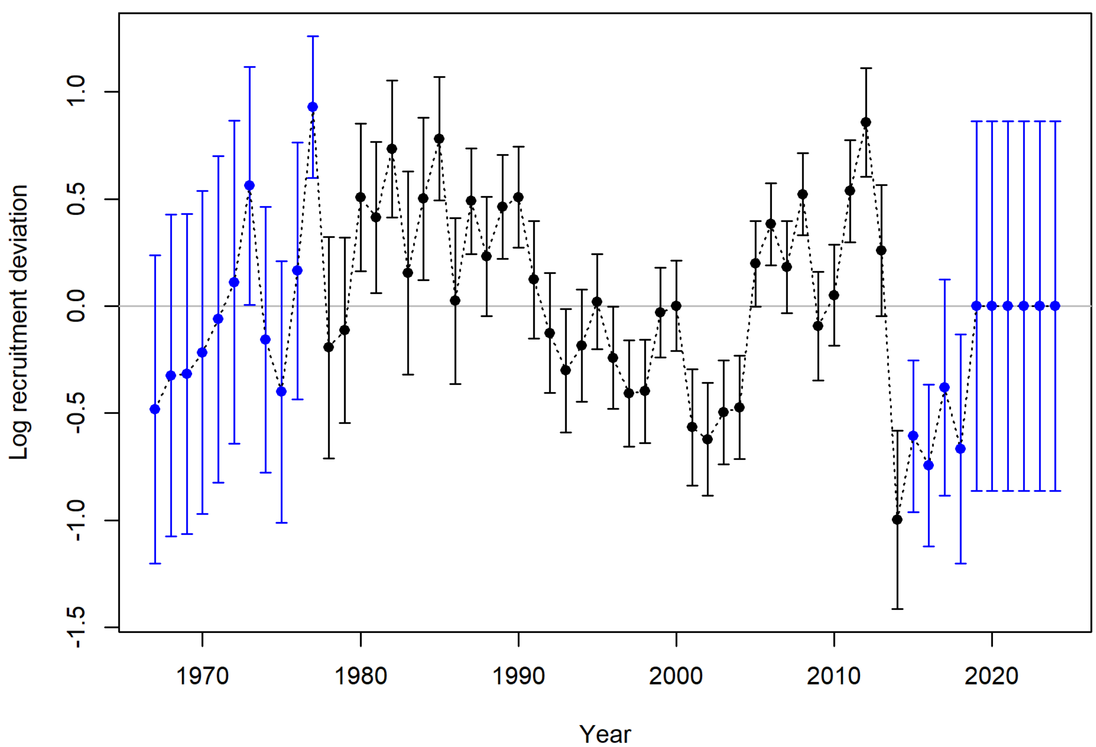


Figure 2.79 Model 19.14.48c log recruitment deviations with 95% asymtotic error intervals.

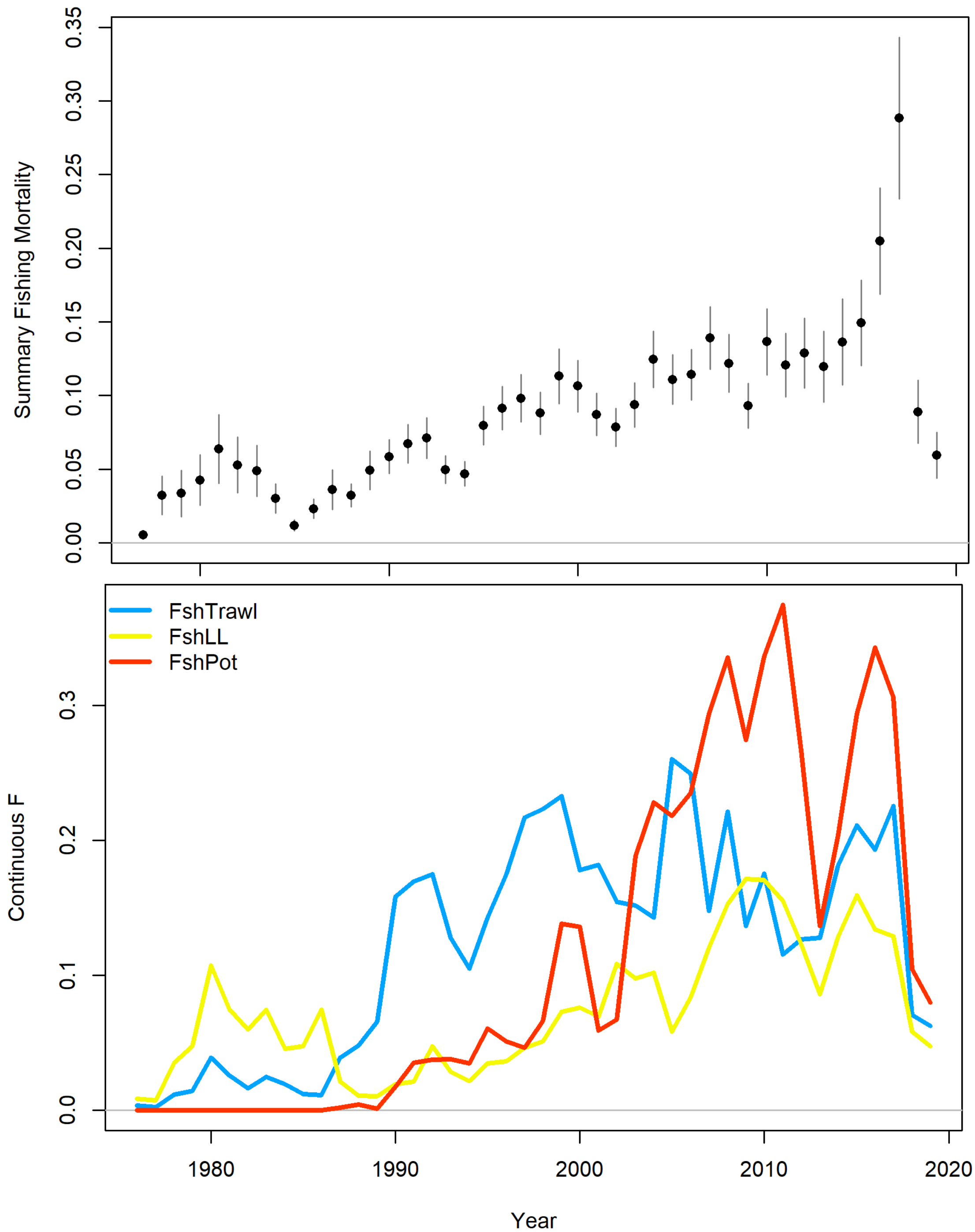


Figure 2.80 Model 19.14.48c age 3-8 true fishing mortality (top) and continuos fishing mortality by trawl (FshTrawl), longline (FshLL) and pot (FshPot) fisheries (bottom).

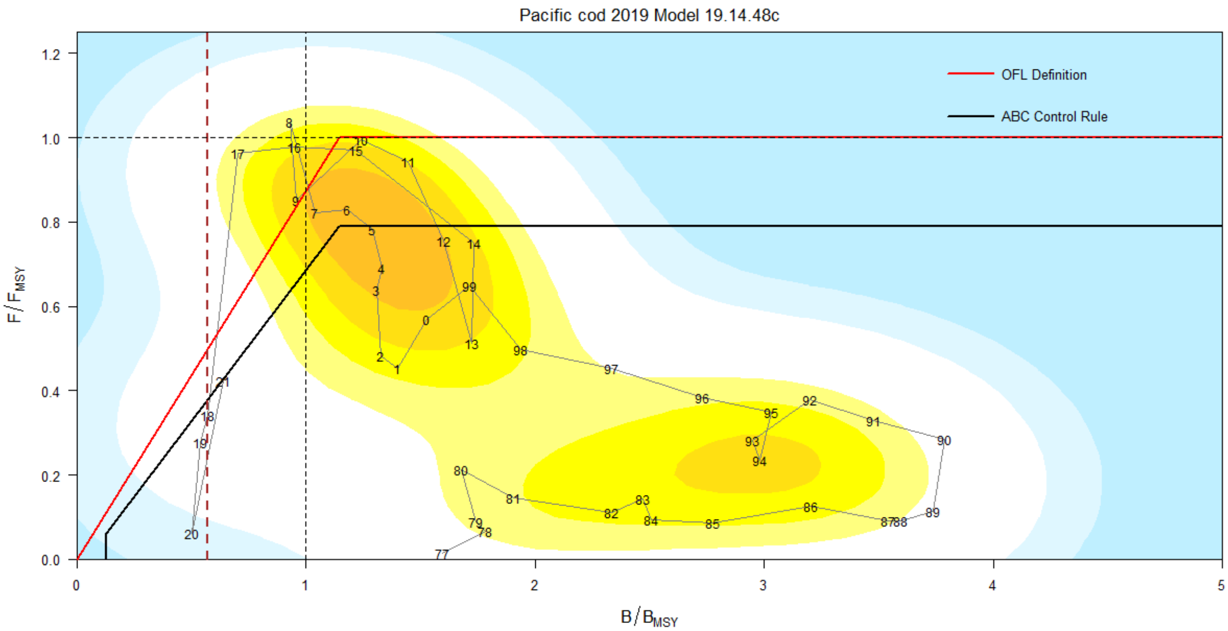


Figure 2.81 For Model 19.14.48c ratio of historical F/F_{msy} versus female spawning biomass relative to B_{msy} for GOA pacific cod, 1977-2021. Note that the proxies for *Fmsy* and *Bmsy* are $F_{35\%}$ and $B_{35\%}$, respectively. The Fs presented are the sum of the full Fs across fleets. Dashed line is at $B_{20\%}$, Steller sea lion closure rule for GOA Pacific cod.

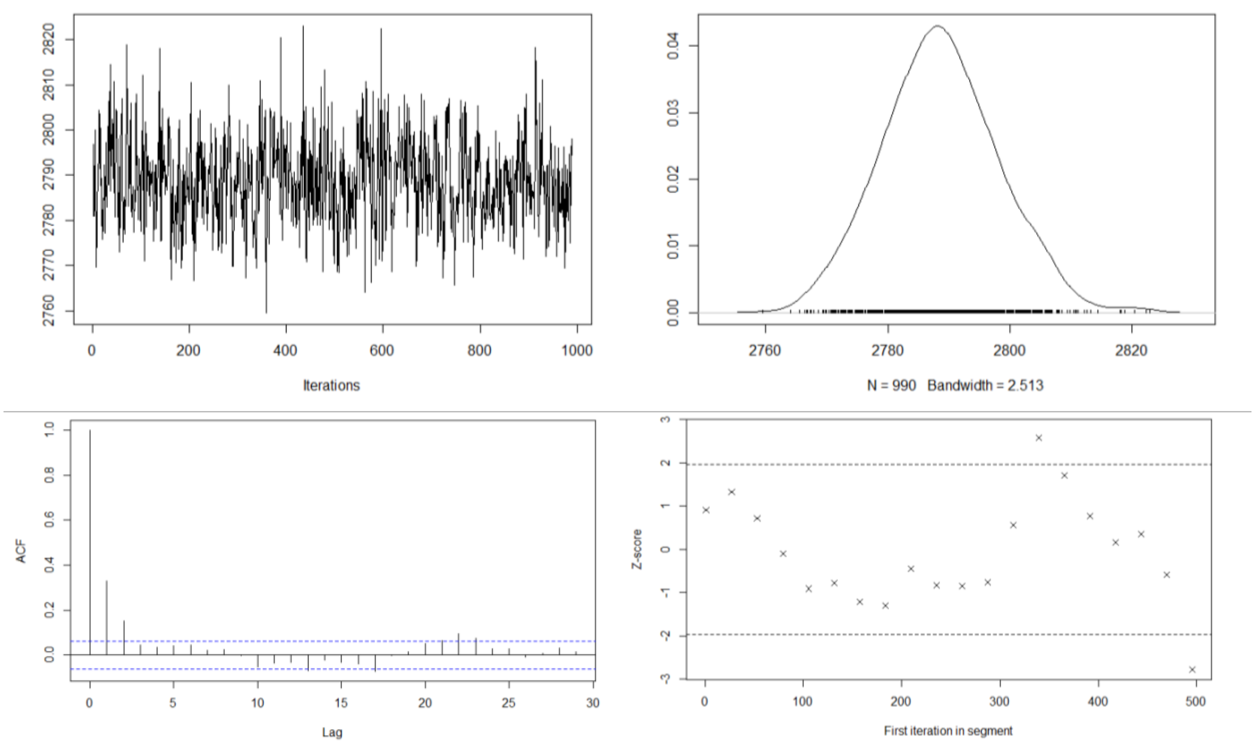


Figure 2.82 Model 19.14.48c MCMC trace (top left), density (top right), autocorrelation function plot (bottom left), and Geweke diagnostic plot (bottom right) for the objective function.

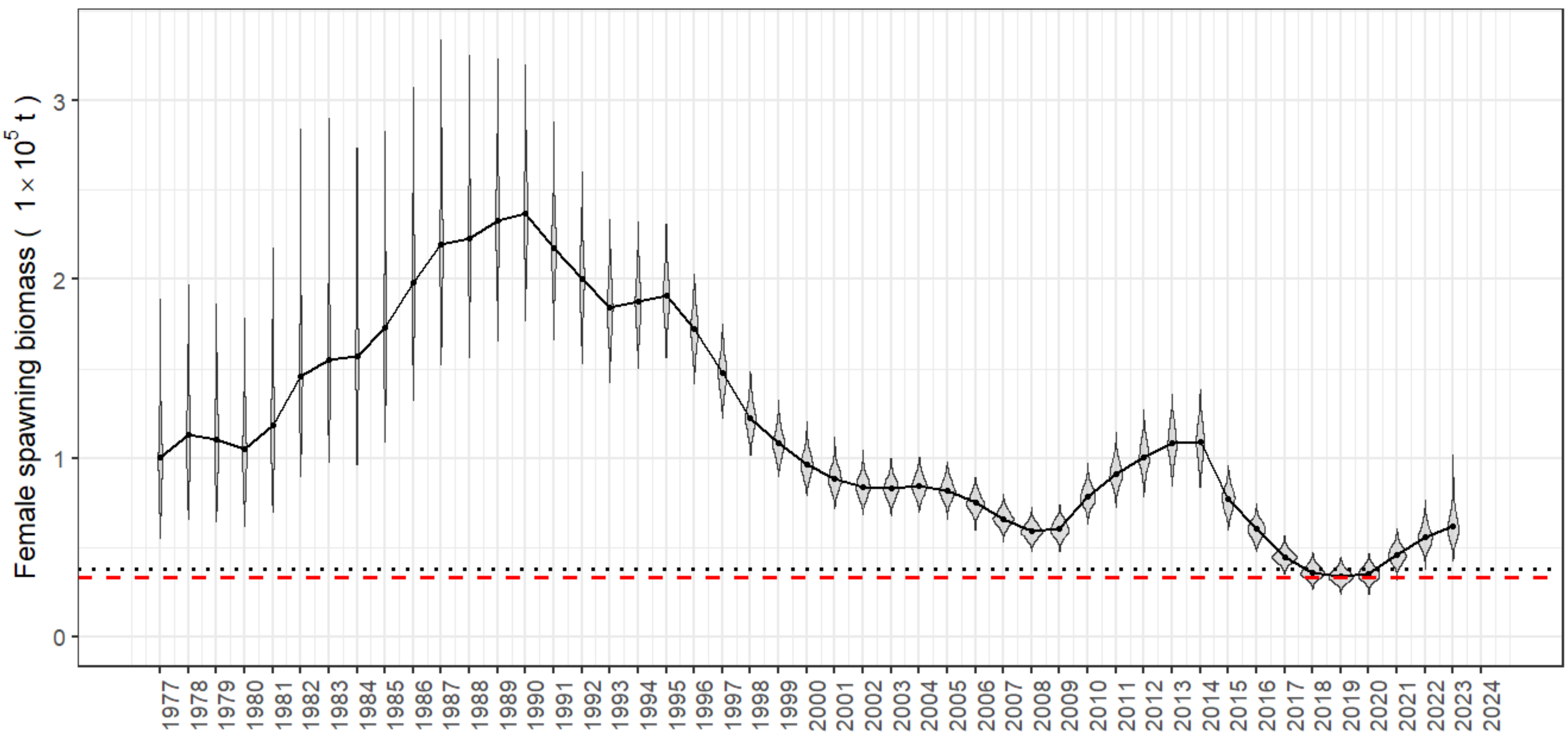


Figure 2.83 Model 19.14.48c MCMC posterior distribitions of beginning of the year female spawning biomass 1977-2023. Dotted line is the projected $SSB_{20\%}$, the red dashed line is the projected $SSB_{17.5\%}$.

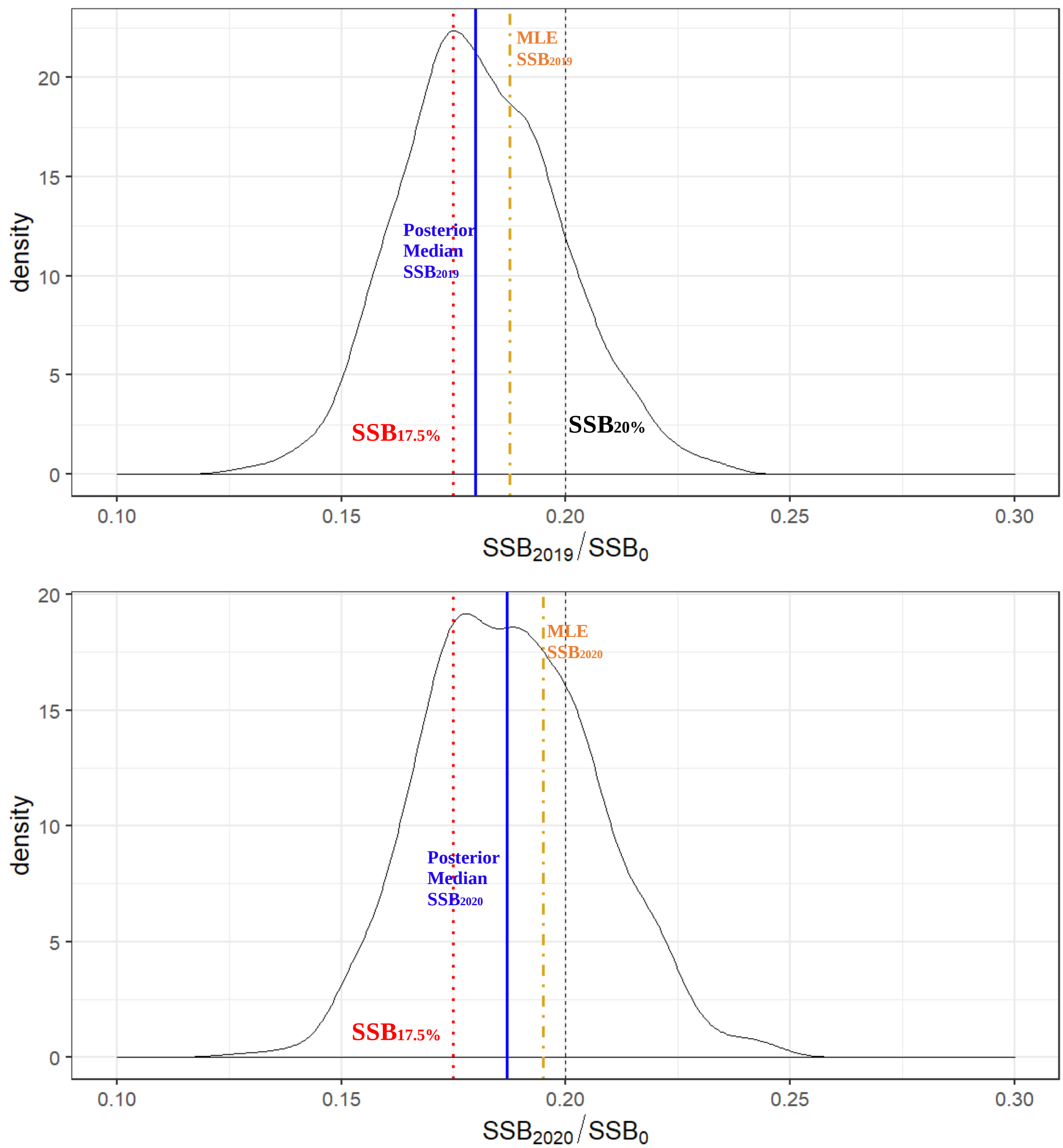


Figure 2.84 Model 18.14.48c MCMC posterior distribitions of the (top) 2019 and (bottom) 2020 spawning stock biomass ratio with estimates for $SSB_{20\%}$ (black dashed line) and $SSB_{17.5\%}$ (Red dotted line) from the projection model, MLE estimate (orange dashed-dot line) and posterior median (blue solid line) for beginning year 2019 and 2020.

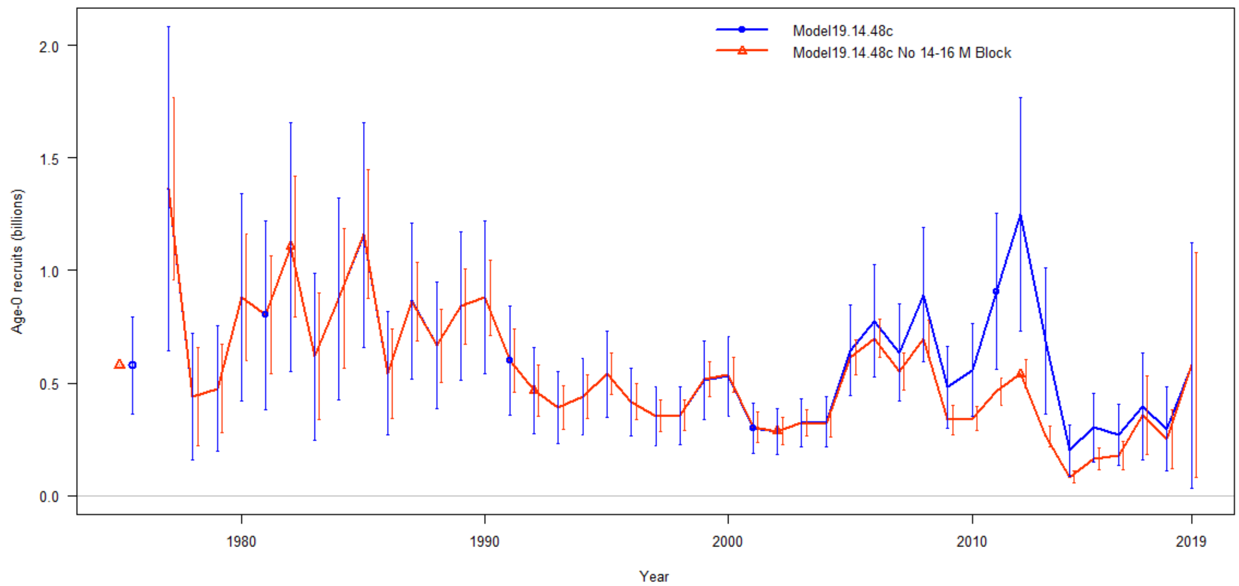


Figure 2.85 Model 19.14.48c Age-0 recruits with and without the 2014-2016 fitting block on natural mortality showing differences in estimated recruitment for 1977-2019.

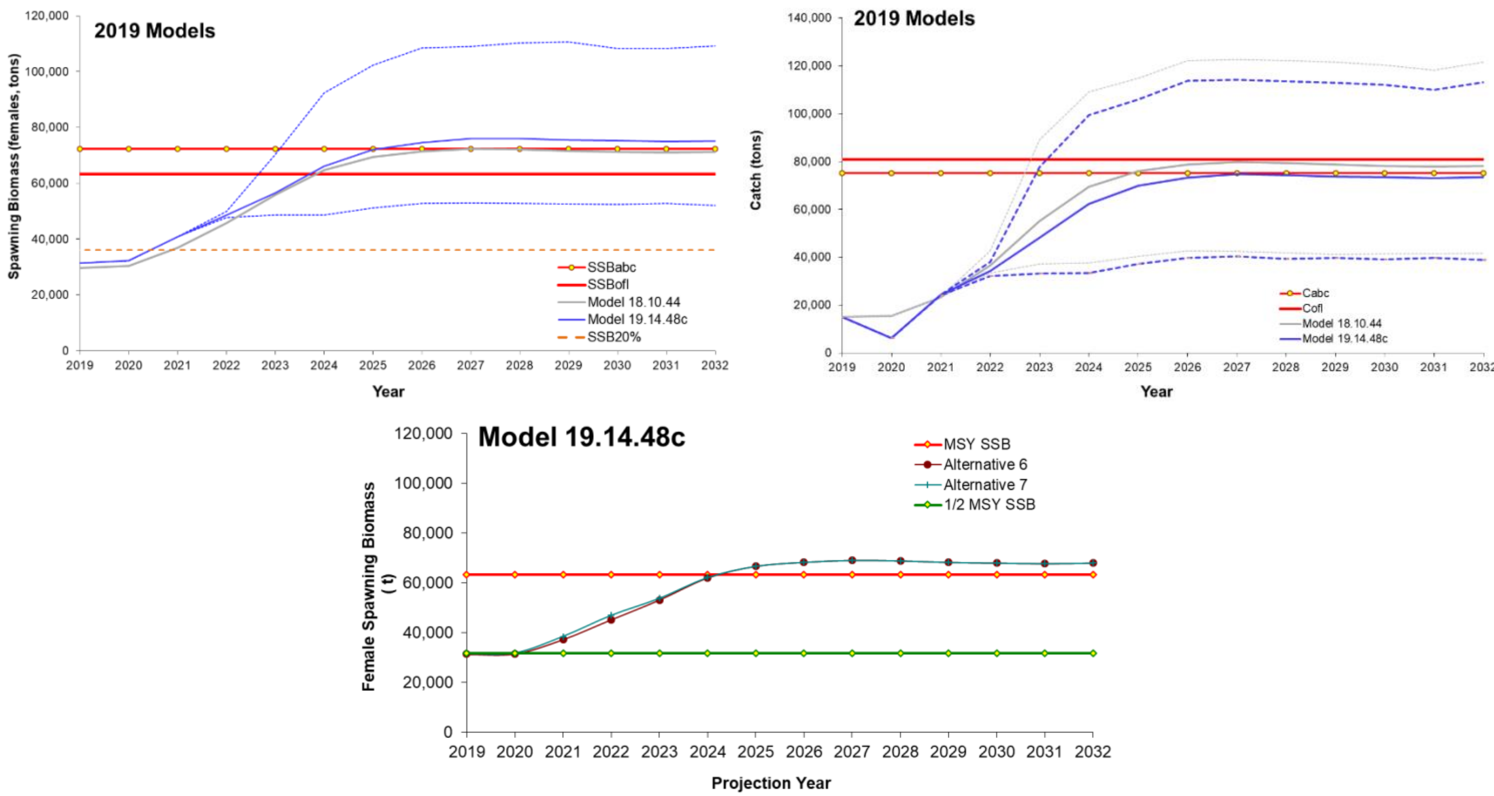


Figure 2.86 Model 19.14.48c projections of female spawning biomass (top), catch (bottom left), and female spawning biomass from scenarios 6 and 7 for status determination (bottom right).

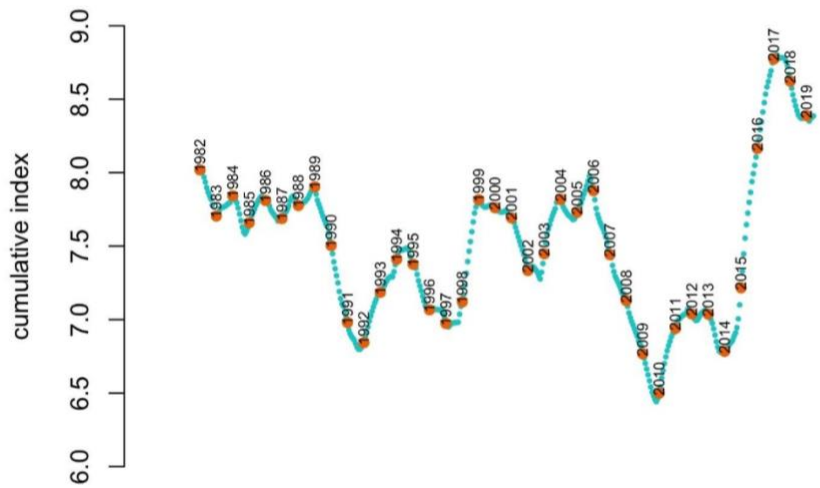


Figure 2.87 Cumulative f(T) function index based on 36 month moving window of thermal experience.

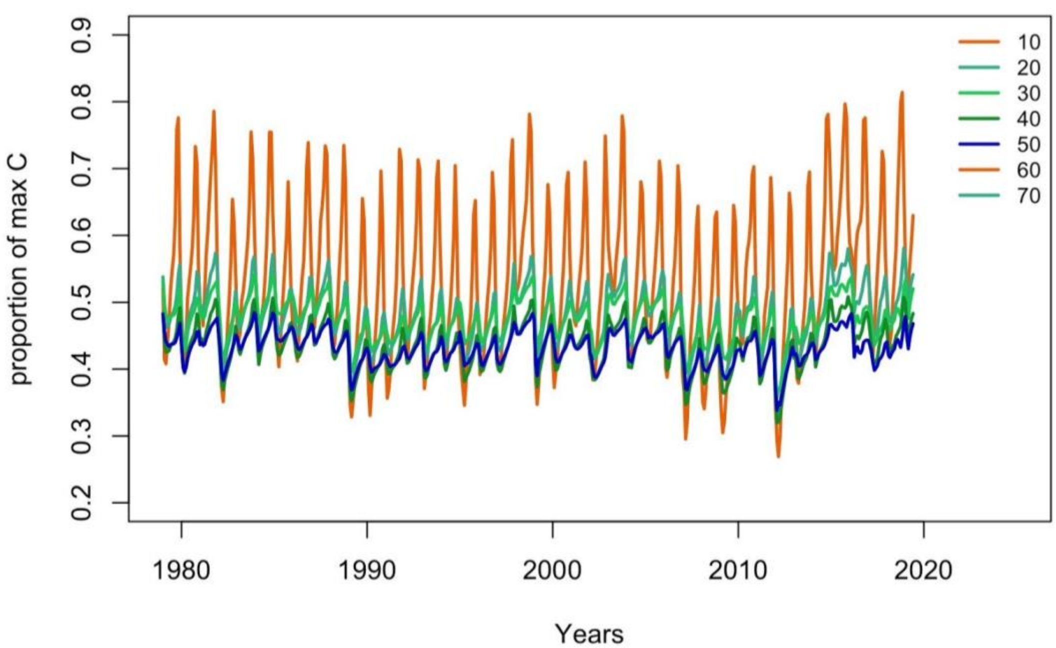


Figure 2.88 Pacific cod bioenergetic model (Holsman and Aydin, 2015; Holsman et al. in prep) estimates of foraging demand based on fish weight and CSFR age-specific depth-preference corrected water temperatures (Barbeaux, unpublished data).

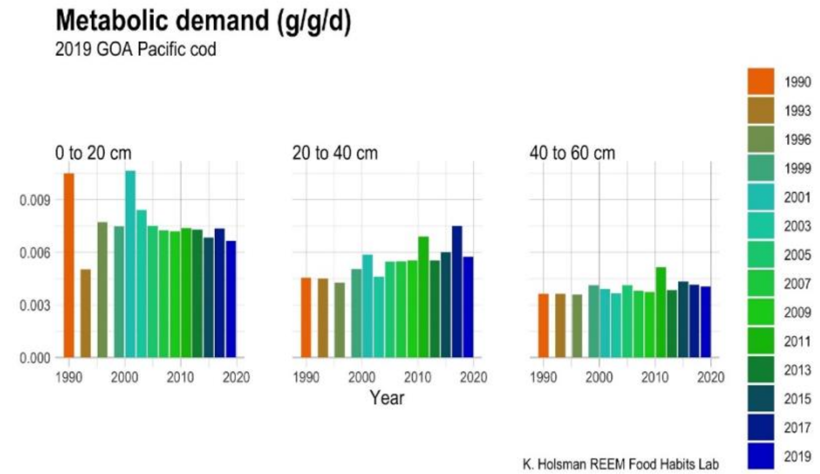


Figure 2.89 Pacific cod bioenergetic model (Holsman and Aydin, 2015; Holsman et al. in prep) estimates of metabolic demand based on fish weight, survey bottom temperature, annual indices of GOA prey energy density and ration (g/g/d; based on groundfish surveys), and an intermediate P. cod energy density of 3.62 kJ/g reported in Vollenweider et al. (2011).

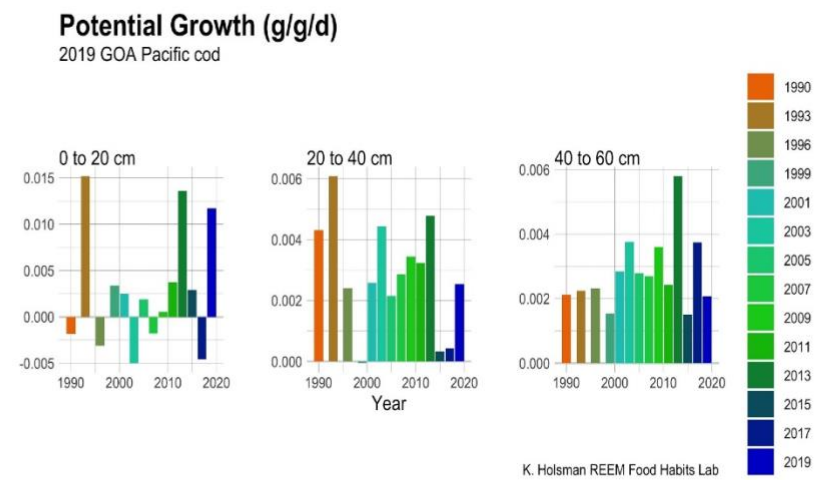


Figure 2.90 Pacific cod bioenergetic model (Holsman and Aydin, 2015; Holsman et al. in prep) estimates of growth potential based on fish weight, survey bottom temperature, annual indices of GOA prey energy density and ration (g/g/d; based on groundfish surveys), and an intermediate P. cod energy density of 3.62 kJ/g reported in Vollenweider et al. 2011.

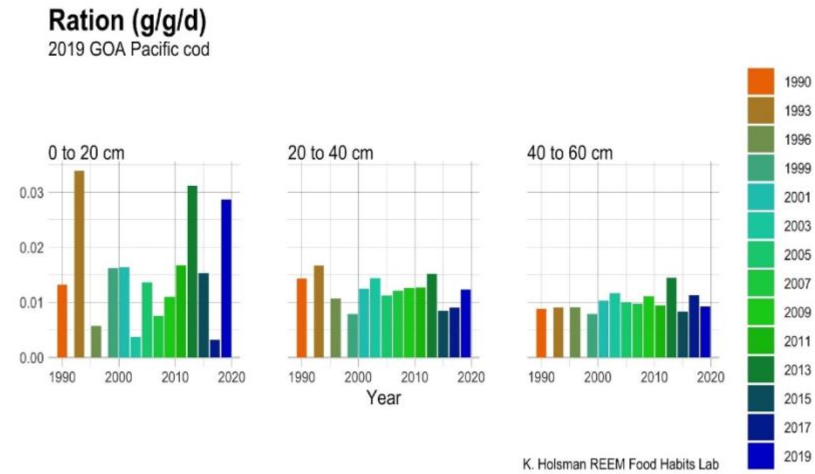


Figure 2.91 Specific weight (g prey/ g pred/ d) of prey in the diets of GOA Pacific cod, averaged across all survey diet samples and fish sizes. Diet data from NOAA REEM Food Habits database.

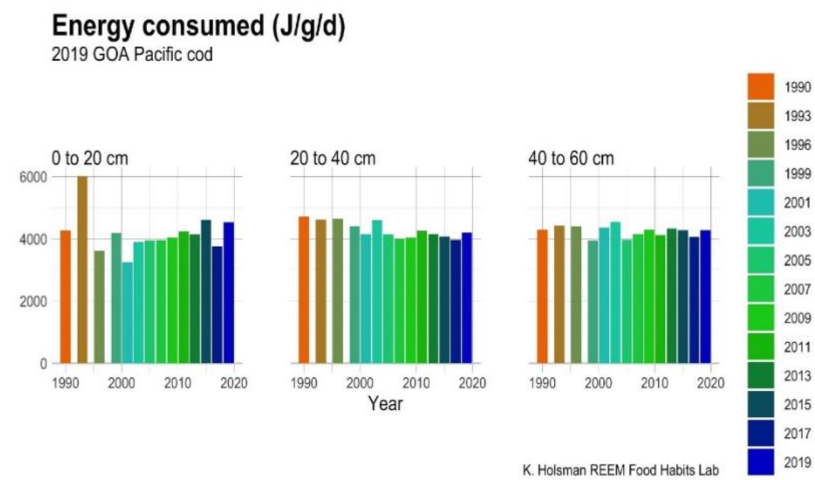


Figure 2.92 Average prey energy density based on mean energy density of prey items and diet composition from GOA Pacific cod stomach samples