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

Steven Barbeaux, Bridget Ferriss, Wayne Palsson, Kalei

Shotwell, Ingrid Spies, Muyin Wang, and Stephani Zador

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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 2019 were updated and preliminary federal and state catch data for 2020 were included;
2. Commercial federal and state fishery size composition data for 2019 were updated, and preliminary commercial federal and state fishery size composition data for 2020 were included;
3. AFSC bottom trawl survey Pacific cod conditional length-at-age data for the GOA for 2019 were included;
4. AFSC longline survey Pacific cod abundance index and length composition data for the GOA for 2020 were included;
5. All length composition samples with less than 30 fish for a particular area, year, quarter, and gear type were excluded from the dataset. This made up 2% of the data representing < 1% of the overall catch.

Changes in the methodology

Model 19.1 is last year's accepted model (Model 19.14.48c) with the addition of the new data described above. There is one new exploratory research model described this year, Model 20.1, which has temperature dependent growth and a parameter which scales R_0 with the spawning marine heatwave cumulative index.

Both models presented in this document are 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 are available for all three fisheries and both indices. In both models growth is parameterized using the standard three parameter von Bertalanffy growth curve. In Model 20.1 the von Bertalanffy growth curve has additional parameters on L_∞ and K which scale growth to the CFSR temperature at depth for 0-20cm fish and a parameter on L_0 which scales this size to an index of growth for larval Pacific cod based on the relationship of larval growth to temperatures published by Laurel et al. (2016). Recruitment is parameterized as a standard Beverton-Holt with Sigma R is fixed at 0.44 for both models and steepness fixed at 1.0 for Model 19.1 and fit in Model 20.1 with an uninformative prior. All selectivity estimates are fit using six parameter double-normal selectivity curves.

Model 19.1 and Model 20.1 performed well, however with the added parameters Model 20.1 outperforms Model 19.1 with the lowest negative log-likelihood and similar results to Model 19.1. Model 19.1 provides a marginally better in the retrospective analysis. The authors conclude that the relationships between recruitment and the marine heatwave index and growth and temperature are not well enough established to be relied on for management at this time. Therefore Model 19.1 is the Authors' preferred model. Parameter estimates and model results are little changed from 2019 model runs.

Summary of results

The data as interpreted through Model 19.1indicates that the stock remains at low levels, but is increasing with a better 2018 recruitment and reduction in fishing mortality. Model 19.1 indicates the stock was likely below $B_{20\%}$ from 2018 through 2020, but will be above $B_{20\%}$ in 2021. For 2021 the stock is estimated to be at $B_{22.2\%}$, above the overfished determination level. The beginning of the year 2020 spawning biomass level was the lowest of the time series. A stronger 2018 year class and lower fishing mortality is projected to increase the spawning stock biomass above $B_{20\%}$ at the start of 2021 and continue to increase to the beginning of 2022 to $B_{28.2\%}$. Although 2018 was stronger than the 2014-2017 year classes, the cohort is still well below average, the apparent recent increase in biomass is likely due to substantially lower fishing mortality since 2018.

Key results are tabulated below:

Quantity	As estimated or *specified last* year for:		As estimated or *specified this* year for:	
	2020	2021	2021	2022
M (natural mortality rate)	0.49	0.49	0.47	0.47
Tier	3b	3b	3b	3b
Projected total (age 0+) biomass (t)	203,373	261,484	265,661	312,783
Female spawning biomass (t)				
Projected	32,958	42,026	39,977	50,813
$B_{100\%}$	187,780	187,780	180,111	180,111
$B_{40\%}$	75,112	75,112	72,045	72,045
$B_{35\%}$	65,723	65,723	63,039	63,039
F_{OFL}	0.27	0.36	0.41	0.54
$maxF_{ABC}$	0.22	0.29	0.33	0.43
F_{ABC}	0.22	0.29	0.33	0.43
OFL (t)	17,794	30,099	28,977	46,587
maxABC (t)	14,621	24,820	23,627	38,141
ABC (t)	*14,621	*24,820	23,627	38,141
Status	2018	2019	2019	2020
Overfishing	No	n/a	No	n/a
Overfished	n/a	No	n/a	No
Approaching overfished	n/a	No	n/a	No

** Assumed 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 would be:

	Western	Central	Eastern	Total
Random effects area apportionment	22.7%	70.6%	6.7%	100%
2021 ABC	5,363	16,681	1,583	23,627
2022 ABC	8,658	26,928	2,555	38,141

Due to the large shift in distribution in the 2019 bottom trawl survey the SSC chose a 'stair-step' approach to the allocation of Pacific cod among regions (Table 2.4). The approach used the halfway point between the 2017 and 2019 random effects allocation. For this method the ABCs would be:

	Western	Central	Eastern	Total
Stair-step area apportionment	33.8%	57.8%	8.4%	100%
2021 ABC	7,986	13,656	1,985	23,627
2022 ABC	12,892	22,045	3,204	38,141

Responses to SSC and Plan Team Comments Specific to this Assessment

Plan Team Comments - November 2019

The Team recommended that the author coordinate with IPHC to obtain and evaluate length compositions so that the IPHC RPN index can be investigated within the assessment model.

The author coordinated with the IPHC on the collection of Pacific cod lengths, however due to changes in IPHC policy and the COVID-19 pandemic Pacific cod lengths were not collected during the 2020 survey. In addition the IPHC reduced the survey footprint in 2020 to not include western GOA strata. This reduction in survey area will make it difficult to calculate a comparable RPN for the entire GOA region. However to date the Pacific cod catch data has not been made available for analysis and changes to the IPHC data sharing routine have made it more difficult to obtain these data.

The Team recommended that the author work with the AFSC FMA Division (Observer Program) to identify alternative ways to collect information on cod for 2019 and beyond given the likelihood of a reduced fishery and expanding displacement of observers with EM and that these efforts should complement ADFG data collection efforts.

The authors have coordinated with the FMA division and data are being collected in non-target fisheries. As there wasn't a directed federal fishery in 2020, there was not opportunity to increases sampling effort for EM fisheries. However lack of biological data from the EM fleet will be a continuing issue in the future when the fishery reopens. Currently ADFG port sampling data are being used to support the assessment model when at-sea federal observer data are not available for a specific time, gear, and area.

The Team proposed apportionment percentages that are an average between the apportionments estimated in 2017 and 2019 as an alternative to the 2019 random effects model results. The Team also recommended that the author investigate alternatives of the random effects model that integrates multiple population indices.

The authors were planning on using IPHC survey results to inform apportionment. Since these data became unavailable for the western GOA, this method will not be considered for this year. We did investigate using the AFSC longline survey results. However using the RPNs from this survey for allocation would result in a substantial shift of ABC to the eastern GOA as 47% and 49% of the total RPN were estimated to be in eastern GOA strata in 2019 and 2020. On average over the full time series, the eastern GOA accounts for 30% of the total Pacific cod RPN for the AFSC longline survey.

Science and Statistical Committee comments – December 2019

The SSC encourages the authors to evaluate ways to effectively deal with the lack of observer data, including working directly with FMA (the observer program) or ADF&G to obtain biological samples from incidental catch or state harvest.

See above comment to Plan Team recommendations.

SSC agrees with the GPT that the authors should explore a model that includes the IPHC survey.

See above comment to Plan Team recommendations.

The SSC requests the authors compare results from the standard projection model with results from projections generated within the SS model under different assumptions about natural mortality (perhaps time or age-varying) and recruitment.

Projections using the stock synthesis were conducted and presented here. Model 20.1 is presented as an experimental model with growth modeled as a function of temperature and recruitment as a function of the spawning marine heatwave cumulative index. Other models were explored with natural mortality impacted by the MHWI, however relationships between temperature and natural mortality appeared to be largely driven by the 2014-2016 heatwave event. These models were judged to not provide adequate mechanisms for explaining natural mortality during less extreme conditions.

The SSC recommends the authors consider a two-survey random effects model, a VAST apportionment method, or other options to stabilize apportionments.

See above comment to Plan Team recommendations.

The SSC recommends that the authors in 2020 choose a model nomenclature of their new models that is more in line with SAFE guidelines, such as Model 19.3, if the base model from 2019 is chosen.

The authors changed to a simpler model naming convention in line with SAFE guidelines. Model 19.14.48c is now named Model 19.1, this year's experimental model is names Model 20.1 as it has substantial changes from Model 19.1 and is new in 2020.

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 6000 years) of exploitation. Over this period, the archeological record reveals fluctuations in Pacific cod size distribution which Betts et al. (2011) tie to changes in abundance due to climate variability (Fig. 2.1). Over this long period colder climate conditions appear to have consistently led to higher abundance with more small/young cod in the population and warmer conditions to lower abundance with fewer small/young cod in the population. Recent comparisons of Pacific cod length distributions extrapolated from bones retrieved from middens and those from the modern domestic fishery show a cline in size from larger fish in the west to smaller fish in the southeastern GOA that has been consistent for over 6000 years (West *et al.* 2020) (Fig 2.2).

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. 2.3). 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 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. 2.4; 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. Pooled whole genome sequence data is currently being analyzed, and individual whole genome sequencing is planned. This work is designed to enhance our understanding of mechanisms causing observed levels of differentiation among cod stocks.

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.

A detailed account of Pacific cod life history, environmental drivers, economic and social indicators can be found in the GOA Pacific cod ecosystem and social processes (ESP) Appendix 2.1.

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. Figure 2.5 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 Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA, 1977), the catch limit for GOA Pacific cod was established at slightly less than the 1976 total reported landings. During the period 1978-1981, catch limits varied between 34,800 and 70,000 t, settling at 60,000 t in 1982. Prior to 1981 these limits were assigned for "fishing years" rather than calendar years. In 1981 the catch limit was raised temporarily to 70,000 t and the fishing year was extended until December 31 to allow for a smooth transition to management based on calendar years, after which the catch limit returned to 60,000 t until 1986, when ABC began to be set on an annual basis. From 1986 (the first year in which an ABC was set) through 1996, TAC averaged about 83% of ABC and catch averaged about 81% of TAC. In 8 of those 11 years, TAC equaled ABC exactly. In 2 of those 11 years (1992 and 1996), catch exceeded TAC.

To understand the relationships between ABC, TAC, and catch for the period since 1997, it is important to understand that a substantial fishery for Pacific cod has been conducted during these years inside State of Alaska waters (Table 2.2), mostly in the Western and Central Regulatory Areas. To accommodate the State-managed fishery, the Federal TAC was set well below ABC (15-25% lower) in each of those years. Thus, although total (Federal plus State) catch has exceeded the Federal TAC in 16 of the 23 years since 1997, this is basically an artifact of the bi-jurisdictional nature of the fishery and is not evidence of overfishing as this would require exceeding OFL. At no time since the separate State waters fishery began in 1997 has total catch exceeded ABC, and total catch has never exceeded OFL.

Historically, the majority of the GOA catch has come from the Central regulatory area. To some extent the distribution of effort within the GOA is driven by regulation, as catch limits within this region have been apportioned by area throughout the history of management under the MFCMA. Changes in area-specific allocation between years have usually been traceable to changes in biomass distributions estimated by Alaska Fisheries Science Center (AFSC) trawl surveys or management responses to local concerns. Currently the area-specific ABC allocation is derived from the random effects model (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 2.6 shows the distribution of catch from 1990-2015 for the three major gear types. Figure 2.7 and Figure 2.8 show the distribution of observed catch for 2019 and 2020 through October 13, 2020 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. 2.5). 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 79,489t (23%) below the ABC while in 2016 combined catch was 64,087 t (35% below the ABC) and in 2017 catch was 48,734 t (45% below the ABC) (Table 2.3). The ABC was substantially reduced for 2018 to 18,000 t from 88,342 t in 2017, an 81% reduction. This was a 65% reduction from the realized 2017 catch. In 2018 the total catch was 15,247 t. For 2019 the ABC was set below the maximum ABC at 17,000t and combined fishery caught 15,411 t which was 91% of the ABC.

In 2020 the spawning stock biomass dropped below 20% of the unfished spawning biomass ($B_{20\%}$) and the federal Pacific cod fishery in the GOA was closed by regulation to directed Pacific cod fishing. $B_{20\%}$ is a minimum spawning stock size threshold instituted to help ensure adequate forage for the endangered western stock of Steller sea lions. The Alaska State directed Pacific cod fishery remained open and Pacific cod bycatch in other federally managed groundfish fisheries was allowed. The Pacific cod ABC for 2020 was set to 14,621 t, but the combined TAC and Alaska State groundfish harvest level (GHL) was reduced to account for additional uncertainty. The Alaska State managed fisheries are allocated 26.7% of the GOA Pacific cod ABC. The federal Pacific cod TAC was reduced by 40% from the maximum of 10,719t as a further level of precaution to 6,431 t. ADF&G also reduced their maximum prescribed harvest limit of 3,902 t by 35% to 2,537 t. This resulted in a total combined federal TAC and Alaska State GHL of 8,968 t or 61% of the maximum ABC. As of October 14, 2020 a total combined catch of 5,742 t have been harvested (Table 2.2), the state having taken 2,235 t (88% of the GHL) and federal fisheries have taken 3,507 t (55% of the federal TAC).

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. 2.6). 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. 2.7). In 2020 there was no directed Pacific cod longline fishery in federal waters (Fig. 2.8). In years with a fishery the longline fishery tends to catch larger fish on average than the other fisheries (Fig. 2.9). 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. 2.10). 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. 2.15). In 2018 and 2019 fewer boats participated in the fishery and catch was substantially slower and lower than previous years and in 2020 as stated earlier there was no directed federal fishery. The A season CPUE in the Central GOA longline fishery in 2018 was substantially lower than the previous years (Fig. 2.17) 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. 2.15, Fig. 2.16, and Fig. 2.17). It should be noted that CPUE is not available from the EM monitored vessels as number of hooks retrieved and soak time are not recorded

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 removed using pots. Pot fishing occurs close to the major ports of Kodiak, Sand Point and on either side of the Seward Peninsula (Fig. 2.6). 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 due to the lower TAC and low fishing levels, and in 2020 the directed federal fishery was closed (Fig. 2.7 and Fig. 2.8). 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. 2.17) from 2016 and 2018 declined even further, however 2019 showed a marked increase in CPUE in both the Central and Western GOA (Fig. 2.17).

The pot fishery generally catches fish greater than 40 cm (Fig. 2.11), but like the longline fishery there was a declining trend in Pacific cod mean length in the fishery from 1998 through 2016 with the smallest fish at less than 60cm on average caught during the 2016 fishery (Fig. 2.12). 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. 2.16). In 2018 and 2019, the Pot fisheries 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. 2.17), on par with CPUE during 2013 and 2008-2010 (Fig. 2.17). 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. 2.6) 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 Bank to the southeast of Kodiak. There was substantially less catch and observed effort in 2018 and 2019 (Fig. 2.7) than previous years. Although the 2020 directed federal Pacific cod fishery was closed there was observations of Pacific cod catch in other fisheries (Fig. 2.8), these observations are primarily surrounding Kodiak from the pollock and shallow water flatfish fisheries.

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. 2.13). The average size of Pacific cod caught by trawl in the 1980's was on average smaller than those caught later (Fig. 2.14). 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 2020. The change to deeper depth and a larger proportion of the catch coming from the Western GOA might partially explain this recent increase as well as lower recruitment in recent years leading to a larger overall population on average as older fish make up higher percentage of the population age structure.

The 2018-2019, directed A-season trawl fishery in the Central GOA started much later than previous years, catch rates were lower and the fishery did not take the full TAC (Fig. 2.15). 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. 2.17). 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 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, 3,434 t in 2019, and as of October 14th 3,535 t in 2020. 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 2019 (Table 2.9). The largest component of this catch comes from the recreational fishery, generally taking approximately one-third to one-half of the accounted for non-commercial catch and the IPHC Annual Longline survey also taking between one-third and one half of the accounted for non-commercial catch.

Other fishery related indices for stock health

There is a long history of evaluating the health of a stock by its condition which examines changes in the weight to length relationship (Nash *et al.* 2006). Condition is measured in this document as the deviance from a log linear regression on weight by length for all Pacific cod 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. 2.18 - 2.21). 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. 2.20), 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 2.19), 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. 2.20), 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. 2.21), 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. 2.22). In the shallow water flatfish fishery, catch rates in tons of Pacific cod per ton of all species catch were examined (Fig. 2.23). For the pollock fishery the 2017 value was the lowest in the series (2008-2020) with a slight increase in 2018 and continued increase through 2020 in areas 610. For the shallow water flatfish fishery, 2017 was the lowest value with an increasing trend through 2020. It should be noted that none of these indices are controlled for gear, vessel, effort, or fishing practice changes.

Surveys

Bottom trawl survey

The AFSC has been conducting standardized bottom trawl surveys for groundfish and crab in the Gulf of Alaska since 1984. From 1984-1997 surveys were conducted every third year, and every two years thereafter. Two or three commercial fishing vessels are contracted to conduct the surveys with fishermen working alongside AFSC scientists. Survey design is stratified random with the strata based on depth and distance along the shelf, with some concentrated strata in troughs and canyons (Raring *et al.* 2016). There are generally between 500 and 825 stations completed during each survey conducted between June and August starting in the western and ending in the southeastern Gulf of Alaska. Some changes in methods have occurred over the years with the addition of electronics to monitor how well the net is tending on-bottom, also to measure differences in net and trawl door dynamics and detect when general problems with the trawl gear occur. Surveys conducted prior to 1996 are considered to have more uncertainty given changes in gear mensuration. Also, the trawl duration was changed in 1996 to be 15 minutes instead of 30. Since 1996, methods have been consistent but in some years the extent of the survey has varied. In 2001 the Southeastern portion of the survey was omitted and in 2011, 2013, 2017, 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. 2.24). 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. 2.25). The mean length in the trawl survey generally increased from 1984-2005 excepting the 1997 and 2001 surveys (Fig. 2.26). 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. 2.27) 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 AFSC has conducted annual longline surveys of the upper continental slope, referred to as domestic longline surveys, designed to continue the time series of the Japan-U.S. cooperative survey (Sigler and Zenger 1989). The domestic longline survey began annual sampling of the GOA in 1987, biennial sampling of the AI in 1996, and biennial sampling of the eastern BS in 1997 (Rutecki *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 2.28). 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. The 2020 RPN shows a 30% increase from 2019, but the 2020 RPN remains the second lowest estimate of the time series.

Unlike the bottom trawl survey, the longline survey encounters few small fish (Fig. 2.29). The size composition data show consistent and steep unimodal distributions with a stepped decreasing trend in mean size between 1990 and 2015 (Fig. 2.30) and then increasing mean size from 2015-2018 and a leveling off in 2019 and 2020. This matches the trend observed in all three fisheries. Changes in mean size appear consistent with changing availability in the survey due to bottom temperatures and changes in the overall population with large year classes. A larger number of smaller fish are encountered during this survey in warm years vs. cold years. There is a sharp decline in mean size in 2009 when the large 2005 year-class would be becoming available to this survey. The even steeper decline in average length in 2015 was encountered in the second warmest year on record for the time series. In 2019 a more severe drop in average length was anticipated due to the increased temperatures on the shelf and an increase in abundance due to increased availability. That we observed neither of these anticipated outcomes portends that either very few small fish were available in the population, or a change in behavior. Given the high abundance of sablefish in recent years, there could potentially be an issue with hook competition. This has not been adequately examined and should be a priority in future examination of these data.

International Pacific halibut Commission (IPHC) longline survey

This survey differs from the AFSC longline survey in gear configuration and sampling design, but catches substantial numbers of Pacific cod. More information on this survey can be found in Soderlund *et al.* (2009). A major difference between the two longline surveys is that the IPHC survey samples the shelf consistently from ~ 10-500 meters, whereas the AFSC longline survey samples the slope and select gullies from 150-1000 meters. Because the majority of effort occurs on the shelf in shallower depths, the IPHC survey may catch smaller and younger Pacific cod than the AFSC longline survey. On the other hand, the IPHC uses larger hooks (16/0) than the AFSC longline survey (13/0) which may prevent very small Pacific cod from getting hooked. To compare these two surveys, IPHC relative population number's (RPN) were calculated using the same methods used to estimate the AFSC longline survey RPNs (but using different depth strata). Stratum areas (km^2) from the RACE trawl surveys were used for IPHC RPN calculations.

The IPHC survey estimates of Pacific cod tracks well with both the AFSC longline and AFSC bottom trawl surveys (Table 2.12 and Fig. 2.31). There was an apparent drop in abundance from 1997-1999 followed by a stable but low population through to 2006. The population increases sharply starting in 2007, likely with the incoming large 2005 year class and continues to increase through 2009 as the large 2005-2008 year classes matured. The population then remained relatively stable through to 2014. The RPN index shows a steep decline in 2015 and 2017 consistent with the two AFSC surveys. The 2017 RPN was the lowest on record for the 20-year time series. This index showed a slight increase of the population abundance in 2018 (28% from 2017) to values slightly higher than 2016, but remain the fourth lowest estimate on record after 2001, 2016, and 2017. The 2019 survey estimated a slight decrease (3.5%), however the uncertainty in the estimate is high. The length composition data available from 2018 and 2019 (Fig. 2.32) show the IPHC survey encounters fish greater than 40 cm. The length data in 2018 have a mode at approximately 60 cm in the western GOA. The other management areas have modes slightly higher between 65 and 75 cm. 2019 shows a slight increase in these modes for all three areas.

Due to COVID-19 restrictions the 2020 IPHC survey did not survey the western GOA and did not collect length composition data for Pacific cod. The IPHC survey Pacific cod catch data for the other GOA regions has not yet been made available for this analysis.

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 1988-2020. 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= 2097.37). 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. 2.33). 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, but 2020 showed a sharp increase of 41% from 2019 and a 64% increase from the 2016 record low, but still below the time series average. Length composition data (Fig. 2.34) 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 and 2020 surveys have no fish smaller than 22cm. The 2018 year class is apparent as a mode at between 40 cm and 55 cm and the 2017 year class at between 55 and 65cm.

Environmental indices

CFSR bottom temperature indices

The Climate Forecast System Reanalysis (CFSR) is the latest version of the National Centers for Environmental Prediction (NCEP) climate reanalysis. The oceanic component of CFSR includes the Geophysical Fluid Dynamics Laboratory Modular Ocean Model version 4 (MOM4) with iterative sea-ice (Saha *et al.* 2010). It uses 40 levels in the vertical with a 10-meter resolution from surface down to about

262 meters. The zonal resolution is 0.5° and a meridional resolution of 0.25° between 10°S and 10°N, gradually increasing through the tropics until becoming fixed at 0.5° poleward of 30°S and 30°N.

To make the index, the CFSR reanalysis grid points were co-located with the AFSC bottom trawl survey stations. The co-located CFSR oceanic temperature profiles were then linearly interpolated to obtain the temperatures at the depths centers of gravity for 10 cm and 40 cm Pacific cod as determined from the AFSC bottom trawl survey. All co-located grid points were then averaged to get the time series of CFSR temperatures over the period of 1979-2020 (Fig. 2.35 and Table 2.14).

The mean depth of Pacific cod at 0-20 cm and 20-40cm 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 ($R^2 = 0.89$) 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 ($CV_{0\text{-}20\ cm}$ 0.12 vs. $CV_{20\text{-}40cm}$=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 0-20 cm index was in 2009 and in the 20-40 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 October 2020 were retrieved from the NOAA High-resolution Blended Analysis Data database (NOAA 2017) and filtered to only include data from the central Gulf of Alaska between 145°W and 160°W longitude for waters less than 300m in depth. The overall daily mean sea surface temperature was then calculated for the entire region. These daily mean sea surface temperatures data were processed through the R package heatwaveR (Schlegel and Smit 2018) to obtain the marine heatwave cumulative intensity (MHCI; Hobday *et al.* 2016) value where we defined a heat wave as 5 days or more with daily mean sea surface temperatures greater than the 90th percentile of the 1 January 1982 through 31 December 2012 time series. The MHCI were then summed for each year to create an annual index ($MHCI_{AN}$), summed for each year for the months of January through March, November, and December to create an annual winter index ($MHCI_{W}$), and the months of February and March to create an annual spawning season index ($MHCI_{SP}$).

The marine heatwave analysis using the daily mean Central GOA sea surface temperatures indicated a prolonged period of increased temperatures in the Central GOA from 2 May 2014 to 13 January 2017 with heatwave conditions persisting for 815 of the 917 days in 14 events of greater than 5 days (Fig. 2.36). The longest stretch of uninterrupted heatwave conditions occurred between 14 December 2015 and 13 January 2017 (397 days). By the criteria developed by Hobday et al. (2018) for marine heatwave classification the event in the Central GOA reached a Category III (Severe) on 16 May 2016 with a peak intensity (I_{max}) of 3.02°C. The heatwave had a summed cumulative intensity (I_{cum}) for 2016 of 635.26°C days, more than 25% of the sum of the I_{cum} for the entire time series (1981-2018). The 14 events of this prolonged heatwave period summed to 1291.91°C days or 52% of the summed I_{cum} for the time series.

There have been 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 2018-2020. Short winter marine heatwaves (Category I to II) occurred every winter between 1983 and 1986, however none of these exceeded 17 days and the total winter I_{cum} for this period was 84.23°C days over a total of 86 days. In the winter of 1997 there were two short (7 and 12 days) winter heatwave events with a total cumulative intensity of 17.19 °C days. In 1998 there was a strong heatwave from 3 March to the 14 June (102 days) with an I_{max} of 2.36°C and cumulative intensity of 146.01°C days. From 2001 through 2006 there were 6 winter heatwave events, most were minor and less than two weeks in length, however between 6 November 2002 and 4 March 2003 there were two that lasted in sum 141 days with a cumulative intensity of 165.94°C days and an I_{max} of 2.04°C. The 2014-2016 series of marine heatwave as described above was substantially longer lasting and more intense than anything experience previously in the region reaching a maximum SST anomaly of 3.12°C on 5 May 2016 and having a cumulative intensity of 1369.24 °C days across the three years. The most recent heatwave began 9 September 2018 to 23 December 2019. There are six distinct events making up the 2018-2019 heatwave with a maximum SST anomaly of 3.03 °C and a cumulative intensity of 625.23 °C days. For 2020 the sea surface temperatures dropped below the long-term mean in March but then increased in April (Fig. 2.36). After April the SST remained above the 1982-2012 mean oscillating into and out of heatwave conditions through October 2020 with four heatwave events occurring between 8 June and mid-October for a cumulative intensity of 131.24 °C days. The highest seasonal anomaly for 2020 was on 22 August at 2.68°C. The longest heatwave event in 2020 has lasted 33 days starting 13 September and continuing to at least 16 October. This heatwave was ongoing as of the writing of this section.

Data

This section describes data used in the current assessment (Fig. 2.37). It does not attempt to summarize all available data pertaining to Pacific cod in the GOA. All data used are provided in Appendix 2.2 in the Stock Synthesis data file (https://archive.fisheries.noaa.gov/afsc/refm/stocks/plan_team/2020/GOA_PCOD_2020_Appendix_2.2_Model_19.1.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 – 2020
Federal fishery catch-at-length, by gear type	AKFIN / FMA	number, by cm bin	1977 – 2020
State fishery catch-at-length, by gear type	ADF&G	number, by cm bin	1997 – 2020
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 – 2020
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 – 2019
GOA NMFS bottom trawl survey mean length-at-age and conditional age-at-length	AFSC	mean value and number	1990 – 2019
AFSC Sablefish Longline survey Pacific Cod length composition	AFSC	Number, by cm bin	1990 – 2020
CFSR bottom temperature indices	National Center for Atmospheric Research	Temperature anomaly at mean depth for P. cod size bins 10 cm and 40 cm.	1979-2020

Fishery

Catch Biomass

Catches for the period 1991-2020 are shown for the three main gear types in Table 2.2, with the catches for 2020 presented through October 14, 2020. For the assessment model the Oct-Dec catch was assumed to reach the full TAC and state GHL. Three gear type categories were modeled; 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 2020 are shown in Table 2.6, and incidental catch of non-commercial species for 2016 – 2020 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 fishery length composition data are in Figures 2.9 – 2.14 and provided in Appendix 2.3 in an Excel spreadsheet.

(https://archive.fisheries.noaa.gov/afsc/refm/stocks/plan_team/2020/GOA_PCOD_2020_Appendix_2.3_Model 19.1.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 2020 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*. In 2020 we have added the additional condition that there be more than 30 lengths measured for a gear type, trimester, and area or else the data for that gear type/trimester/area are not included. This has resulted in a loss of approximately 2% of the length data representing less than 1% of the overall catch.

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

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

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

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

Age composition

Otoliths for fishery age composition have been collected since 1982. In 2017, the Age and Growth laboratory made a concerted effort to begin aging these data. These data have been processed in two ways, the first was to develop an age and gear specific age-length key which was then used in conjunction with the length composition data described above to create age composition distributions (Fig. 2.38). The age data was also used to develop an annual conditional length-at-age matrix for each fishery (Fig. 2.39-2.41).

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. 2.24, together with their respective coefficients of variation.

Length Composition

The relative length compositions used in the assessment models examined this year from 1984-2020 are shown in Figure 2.42 and provided in Appendix 2.3 in an Excel spreadsheet (https://archive.fisheries.noaa.gov/afsc/refm/stocks/plan_team/2020/GOA_PCOD_2020_Appendix_2.3_Model 19.1.xlsx).

Age Composition

Age compositions (Fig. 2.42) and conditional length at age (Fig. 2.43) from 1990-2019 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 2.3 in an Excel spreadsheet. (https://archive.fisheries.noaa.gov/afsc/refm/stocks/plan_team/2020/GOA_PCOD_2020_Appendix_2.3_Model 19.1.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. 2.44). Plotting all of the GOA AFSC bottom trawl survey age at length data for 1996-2017 as pre- and post-2007 shows the bias is most apparent from ages 3 onward with at least one year between length categories. Upon further investigation the apparent change in growth observed post-2007 with fish becoming larger at age may have been due to a change in reading criteria and predominant age readers. As in last year's management model aging bias for the pre-2007 ages were explored in this year's 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. 2.28.

Length Composition

The length composition data for the AFSC longline survey data are shown in Figure 2.32 and provided in Appendix 2.3 in an Excel spreadsheet.

(https://archive.fisheries.noaa.gov/afsc/refm/stocks/plan_team/2020/GOA_PCOD_2020_Appendix_2.3_Model 19.1.xlsx)

Environmental indices

CFSR bottom temperature indices

The CFSR bottom temperature indices for 0-20 cm Pacific cod were used in this assessment (see description above; Table 2.14).

Analytic Approach

Model Structure

This year's proposed management model (Model 19.1) is the same as last year's model (Model 19.14.48C) with updated data. We also include a description of an experimental ecosystem-linked model (Model 20.1) based on last year's model configuration for comparison. To see the history of models used in this assessment refer to A'mar and Palsson (2015). All models for this year were run in Stock Synthesis version 3.30.16 (Methot and Wetzell 2013).

Both 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.

For Model 19.1 length at age, L_a, was modeled as a three parameter von Bertalanffy growth model with length in June, L_0, maximum asymptotic length, L_∞, and growth rate, k, as:

$L_a = L_\infty - (L_\infty - L_0)e^{-ak}$, where *a* is age.

For the ecosystem-linked model (Model 20.1) length at age for each year, L_{ay}, was modeled as a six parameter von Bertalanffy growth model with annual water temperature covariates on L_0, L_∞, and k as:

$$L_{ay} = L_{\infty y} - (L_{\infty y} - L_{0y})e^{-ak_y}$$

$$L_{0y} = \bar{L}_0 + \alpha\left(\frac{e^{(0.294+0.3216(\bar{t}+f_y)-0.0069(\bar{t}+f_y)^2-0.0004(\bar{t}+f_y)^3)}}{e^{(0.294+0.3216(\bar{t})-0.0069(\bar{t})^2-0.0004(\bar{t})^3)}}\right),$$

$$k_y = k(e^{\beta f_y}), \text{ and } L_{\infty y} = L_\infty(e^{\gamma f_y}).$$

where f_y is the 0-20 cm June CFSR bottom temperature anomaly in the Central GOA in year y, α is the temperature anomaly covariate for L_0 and an index of the ratio of the annual June temperature, $\bar{t} + f_y$, dependent juvenile growth (Laurel *et al.* 2015) for a given year over the growth in June for the mean temperature for 1982-2012, $\bar{t}$, β the parameter scaling *k* to the temperature anomaly, and γ the parameter scaling L_∞ to the temperature anomaly.

All selectivity curves were fit using six parameter double-normal curves.

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 for Model 19.1 are provided in a zip file in Appendix 2.2 (https://archive.fisheries.noaa.gov/afsc/refm/stocks/plan_team/2020/GOA_PCOD_2020_Appendix_2.2_Model_19.1.zip) and for Model 20.1 in a zip file in Appendix 2.4 (https://archive.fisheries.noaa.gov/afsc/refm/stocks/plan_team/2020/GOA_PCOD_2020_Appendix_2.4_Model_20.1.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 σ of either 0.1 or 0.41. The σ of 0.41 was based on a reevaluation of the data presented by Dr. Thompson described above and in Table 2.1, but limited to not include data from the Gulf of Alaska used in the current model. This configuration was used in the 2019 reference model and 2020 proposed models as well. The use of special mortality periods have been proposed and approved for use in several Bering Sea crab assessments.

Growth

For Model 19.1 length at age, L_a, was modeled as a three parameter von Bertalanffy growth model with length in June, L_0, maximum asymptotic length, L_∞, and growth rate, k, as:

$L_a = L_\infty - (L_\infty - L_0)e^{-ak}$, where *a* is age.

For the ecosystem-linked model (Model 20.1) length at age for each year, L_{ay}, was modeled as a six parameter von Bertalanffy growth model with annual water temperature covariates on L_0, L_∞, and k as:

$$L_{ay} = L_{\infty y} - (L_{\infty y} - L_{0y})e^{-ak_y}$$

$$L_{0y} = \bar{L}_0 + \alpha\left(\frac{e^{\left(0.294+0.3216(\bar{t}+f_y)-0.0069(\bar{t}+f_y)^2-0.0004(\bar{t}+f_y)^3\right)}}{e^{\left(0.294+0.3216(\bar{t})-0.0069(\bar{t})^2-0.0004(\bar{t})^3\right)}}\right),$$

$$k_y = k\left(e^{\beta f_y}\right), \text{ and } L_{\infty y} = L_\infty\left(e^{\gamma f_y}\right).$$

where f_y is the June CFSR bottom temperature anomaly in the Central GOA in year y, α is the temperature anomaly covariate for L_0 and an index of the ratio of the annual June temperature, $\bar{t} + f_y$, dependent juvenile growth (Laurel *et al.* 2015) for a given year over the growth in June for the mean temperature for 1982-2012, $\bar{t}$, β the parameter scaling *k* to the temperature anomaly, and γ the parameter scaling L_∞ to the temperature anomaly. For Model 20.1 the α, β, and γ parameters were fit with non-informative uniform priors.

The initial growth parameters L_0, k, and L_∞ initial values and 'priors' based on a nonlinear least squares regression of the 2007-2015 AFSC GOA bottom trawl survey length at age data (Fig. 2.45). The *nls* function from the **nlstools** library (Baty *et al.* 2015) in R was used to fit the basic model. Variance of the parameters were determined through bootstrap of the model with 1,000 iterations. L_{inf} was estimated at μ=99.46 CV=0.015, K was μ = 0.1966 CV=0.03, L_0 was -0.11 CV=0.25. We recognized that these 'priors' are not true priors as they are drawn from the data used in the model, but were necessary in setting structure within the model while allowing some flexibility in the model fitting which we think is a compromise to fixing parameters. Previous modeling effort using uninformative priors on these three parameters has led to model convergence at unreasonable values or non-convergence.

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

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. 2.46).

Aging Error

Aging error matrices were included in Models 19.1. 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 and Appendix 2.3). (https://archive.fisheries.noaa.gov/afsc/refm/stocks/plan_team/2020/GOA_PCOD_2020_Appendix_2.3_Model_19.1.xlsx)

Recruitment

In Model 19.1 recruitment by year, R_y, was modeled as:

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

R_0 is the unfished equilibrium recruitment, $\tilde{R}_y$ is the lognormal recruitment deviation for year y, σ_R^2 is the standard deviation among recruitment deviations in log space and was fixed at 0.44, and b_y is a bias adjustment fraction applied during year y (Methot and Taylor 2011). To account for the regime change in 1977 the parameter ϑ was fit for recruitment allowing for a change in R_0 prior to the regime change in 1977. Projections in the base model post-2017 assumed average recruitment for 1977-2017 for R_y.

In the ecosystem-linked model recruitment (R_y) was modeled as a Beverton-Holt relationship with a parameter (ω) which scales the unfished equilibrium recruitment, R_0, using the annual central GOA marine heatwave cumulative index (I_y; described below) as:

$$R_y = \frac{4h(R_0 e^{\vartheta})(e^{\omega I_y})SB_y}{SB_0(1-h)+SB_y(5h-1)} e^{-0.5 b_y \sigma_R^2 + \tilde{R}_y}\text{, if } y \geq 1977 \rightarrow \vartheta = 0\text{, where } \tilde{R}_Y = N(0;\ \sigma_R^2),$$

h is the steepness parameter, SB_0 is the unfished equilibrium spawning biomass (corresponding to R_0), and SB_y is the spawning biomass at the start of the spawning season during year y.

Selectivity

The same functional form (pattern 24 for length-based selectivity) used in Stock Synthesis to define the fishery selectivity schedules in previous year's assessments was used this year for both the fishery and survey in both models described. 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 19.1 and Model 20.1 aging bias was estimated for ages 3+ with two parameters, bias at age 3 and bias at age 10, with a linear interpolation between the two, applied to all age data collected prior to 2007 (aged prior to 2008). Age data from post-2007 were assumed to be aged without bias.

Catchability

For both models the catchability for the AFSC bottom trawl survey was fit with a non-informative prior. All prior. In all models presented this year, the AFSC longline survey catchability included a parameter, P, which was used to additively adjust annual catchability values based on an annual temperature index, Iy, as $\log(Q_y) = (\bar{Q} + PI_y)$ where Q_y is catchability for a given year, and Q is the expected catchability across all time. We used an index of mean annual temperature at depth for cod developed from the Climate Forecast System Reanalysis (CFSR) as our temperature index (see description above). An analysis introducing this methodology was presented 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. Bottom trawl survey data show a centroid of distribution for Pacific cod greater than 34 cm shifts to deeper water in years with warmer shelf temperatures (Barbeaux *et al.* 2019). This relationship was verified in Yang *et al.* (2019) with a shift to deeper depths in all size classes examined during warm years and shift to shallower waters in cold years. This shift would make Pacific cod more available to the AFSC longline survey which starts at 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 both models presented there were no parameters near bounds and the likelihoods appear well defined with the gradient of the objective function at less than $10e^{-4}$. Both 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. As was done last year, we set initial sample sizes for the fishery at the number of hauls sampled or 200 whichever is least, for the surveys both size and age composition sample sizes were initially set at 100.

Results

Model Evaluation

Two models are presented, Model 19.1, which is the 2019 base model (Model 19.14.48c) with updates to the data, and Model 20.1, which is a climate enhanced model based on Model 19.1 with the addition of temperature dependent growth and recruitment. Model evaluation criteria included AIC, 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. Both models 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. Retrospective results, index RMSE and composition mean effective sample sizes are provided in Table 2.18.

Comparing and Contrasting Model Configurations

For this year the authors are presenting only a single model for consideration for management, Model 19.1, which has the same configuration as last year's author's preferred model with the addition of 2020 data. Description of this model configuration compared with other model configurations and its evolution from previous model configurations can be found in Barbeaux *et al.* (2019). The authors are also presenting an experimental ecosystem-linked model, Model 20.1, which was based on Model 19.1 with the addition of temperature dependent growth and recruitment. Model 20.1 is experimental and only presented to contrast with the author's preferred model and not for consideration for use in management as this model requires further validation, particularly the choice of climate indices. It should be noted that the results from the GOA Pacific cod stock assessment have been particularly volatile with a wide-array of models presented over the past 18 years (A'mar and Palsson 2015). The models presented this year are well within the bounds of models presented in previous years for the spawning stock biomass time series (Fig. 2.47). The female spawning biomass and age-0 recruitment for both models presented this year are provided in Figure 2.48 along with the reference model from last year without updated data. Both models show a similar fit, and similar recruitment and biomass trends. The size based selectivity curves (Fig. 2.49 and Fig. 2.51) are nearly indistinguishable between the two models. The difference in model fit to the indices (Fig. 2.50) between Model 19.1 and Model 20.1 are difficult to discern by eye. Model 20.1 provides a slightly better fit (ΔAIC 16.6; Table 2.16 and Table 2.17) with an overall better fit to the composition data and slightly degraded fit to the survey indices. There was also a slight increase in the parameter prior penalties (+0.14) from Model 19.1 to Model 20.1. The largest improvements in Model 20.1 were to the longline survey length composition (-4.39) and the conditional length at age data (-8.91 over all data components). Model 20.1 had worse fits to the length composition for the trawl (+1.77), trawl survey length composition (+1.89), and the longline survey index (+1.00).

Effective N calculations (Table 2.18) have a pattern similar to the likelihood metric with Model 20.1 showing marginal improvements in the fits to the conditional length at age data and a mix in the length composition data where Model 19.1 provided a marginally better fit to the trawl and longline fishery and longline survey length composition data. The difference in RMSE for the survey indices were negligible.

The improvements to fit in Model 20.1 were accomplished by allowing time varying growth and recruitment. Figure 2.52 provides an illustration of the ecosystem-linked changes allowed in Model 20.1 with increased growth with increasing June temperature anomalies. The three ecosystem-linked scaling parameters on growth, α, β, and γ, were well fit with CVs of 0.22, 0.36, and 0.27 and low final gradients in the fit (Appendix 2.5; https://archive.fisheries.noaa.gov/afsc/refm/stocks/plan_team/2020/GOA_PCOD_2020_Appendix_2.5_Model_20.1.xlsx). Because maturity is size based Model 20.1 exhibits a decrease in age at 50% maturity (Fig. 2.53) as growth increases with temperature. Figure 2.54 illustrates the results of the ecosystem-linked recruitment model where recruitment decreases with increasing $MHCI_{SP}$ and a steepness of 0.89. The decrease in recruitment in years with spawning heatwave values allows the model to fit a slightly lower natural mortality. Model 19.1 estimated natural mortality at 0.466 (σ = 0.02) during the standard years, while Model 20.1 natural mortality was estimated at 0.458 (σ = 0.02) during the standard years. However Model 20.1 fits a higher natural mortality during the 2014-2016 heatwave block at 0.850 (σ = 0.05) versus 0.823 (σ = 0.06) in Model 19.1. The most impactful difference between the two models is a lower recruitment estimate for 2019 (193 vs 399 million fish) being driven by the high 2019 $MHCI_{SP}$ value (Table 2.21). There is little data informing this estimate in Model 19.1 and therefore the value tends towards the mean.

Both models exhibit low retrospective bias (Table 2.18 and Fig. 2.55) however in both spawning biomass and recruitment at age-0 across all three metrics (Mohn's ρ, Woods hole ρ, and RMSE) Model 19.1 performed marginally better.

Selection of Final Model

The authors do not consider Model 20.1 fully validated and therefore not ready for management at this time. The authors would prefer to have a much more rigorous review of the possible advancements in this model through a peer-reviewed journal or CIE review prior to using it for management. That said, Model 20.1 does provide a marginally better fit to the available data, however Model 19.1 provides a marginally better retrospective pattern. The authors recommend continue using Model 19.1.

All Stock Synthesis files for Model 19.1 are provided in a linked zip file Appendix 2.2:

(https://archive.fisheries.noaa.gov/afsc/refm/stocks/plan_team/2020/GOA_PCOD_2020_Appendix_2.2_Model_19.1.zip).

All data, results, and parameter estimates for Model 19.1 are provided in an excel sheet in Appendix 2.3:

(https://archive.fisheries.noaa.gov/afsc/refm/stocks/plan_team/2020/GOA_PCOD_2020_Appendix_2.3_Model_19.1.xlsx).

All Stock Synthesis files for Model 20.1 are provided in a linked zip file Appendix 2.4:

(https://archive.fisheries.noaa.gov/afsc/refm/stocks/plan_team/2020/GOA_PCOD_2020_Appendix_2.4_Model_20.1.zip).

All data, results, and parameter estimates for Model 20.1 are provided in an excel sheet in Appendix 2.5:

(https://archive.fisheries.noaa.gov/afsc/refm/stocks/plan_team/2020/GOA_PCOD_2020_Appendix_2.5_Model_20.1.xlsx).

Model 19.1 diagnostics and Suggestions for Future Improvement

Survey Indices

Model 19.1 fit to the NMFS bottom trawl survey was similar to previous base model fits (Fig. 2.50), 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. Comparison of total biomass predictions and AFSC bottom trawl survey abundance estimates are relatively closely matched for the 1996-2017 values with predictions at 1.06 times the survey estimates (Fig. 2.56), an effective “catchability” of 0.94.

Model 19.1 fits the AFSC longline survey index well (Fig. 2.50). 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

Selectivity curves in Model 19.1 were allowed to be dome-shaped for the pot fishery, the longline survey and the bottom trawl survey prior to 1996 (Fig. 2.51 and Fig. 2.57). Overall model predictions of the length compositions closely match the data for all components (Fig. 2.58). For the trawl fishery the model predictions (Fig. 2.59 and Fig. 2.60) 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. 2.61 and Fig. 2.62) 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. The increase in mean length for 2019 and 2020 are not well fit in the model and the model underestimated the mean length. Predictions of the pot fishery length composition (Fig. 2.63) were generally well fit, again, like the trawl and longline fisheries the high peaks of the distributions tended to be underestimated. The drop in mean length for 2013-2017 were not fit well and may indicate a change in selectivity not accounted for in this model. In addition the 2020 length composition is not well fit, although the mode is modeled correctly the model predicts much smaller fish than what was observed. This is may be due to the fishery data changing substantially with the closure of the federal fishery and inclusion of only ADFG port sampling data for this year or potentially a less likely change in growth. 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 19.1 matched the NMFS bottom trawl survey length composition data mean lengths well (Fig. 2.64), 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 19.1 AFSC longline survey length composition data (Fig. 2.65) 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, could 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. 2.66). The aging bias adjustment made in the 2019 model 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 19.1 has time-invariant growth (Fig. 2.67). Fits to the conditional length-at-age data are within the error bounds for most ages (Fig. 2.68, Fig. 2.69, Fig. 2.70, and Fig. 2.71), 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 19.1 to be larger at age than the data shown for the oldest fish, while for 2005 and 2013 the opposite was true. The fishery data appear more consistent, except for 2007 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 19.1 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 selectivity curves as estimated (noting that there are no indices involving age-0 Pacific cod). All results presented are from Model 19.1.

Biomass

Estimates of total biomass were on average 106% higher than the NMFS bottom trawl survey total biomass estimates. Total biomass estimates show a long decline from their peak of 794,280 t in 1988 (Table 2.20 and Fig. 2.72) to 266,500 t in 2006 and then an increase to another peak in 2014 of 553,456 t then decrease continuously through 2018. With improved recruitment in 2018 and decrease in fishing mortality in 2018 through 2020 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 243,230 t to a low in 2008 of 58,345 t. There was then a short increase in spawning biomass coincident with the maturation of the 2005-2008 year classes through 2014 to 106,775 t, after which the decline continued to lowest level of

34,631 t in 2020. The spawning biomass is projected to increase in 2021, Projections of Model 19.1 indicate that the stock was below $B_{20\%}$ between 2018 and 2020 but is projected to be above $B_{20\%}$ at the start of the year 2021 and continue to increase in 2022.

Numbers at age and length are shown in Figure 2.73 and given in Appendix 2.3 available online at (https://archive.fisheries.noaa.gov/afsc/refm/stocks/plan_team/2020/GOA_PCOD_2020_Appendix_2.3_Model_19.1.xlsx) .

Recruitment and Numbers at Age

The recruitment predictions in Model 19.1 (Table 2.21, Fig. 2.74 and Fig. 2.75) show large 1977, 1980-1985, 1987-1990, 2006, 2008, and 2010-2013 year-classes with more than 0.5 billion (at age-0) fish for each, although uncertainty on the 1977 and 1984 year-class estimates were large (σ_{1977} = 0.34 and $\sigma_{1984-1990}$ > 0.13). Between 1991 and 2010 the average recruitment was estimated at 0.385 billion, 40% lower than the 1977-1989 mean recruitment of 0.652 billion and 22% lower than the 1977-2017 mean recruitment of 0.493 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). 2017 had the highest total exploitation rate of the time series at 0.353. The period between 1990 and 2008 saw both a decline in recruitment paired with increases in catch. The period of increasing fishing mortality was mainly attributed to the rise in the pot fishery, which also shows the largest increase in continuous F (Fig. 2.76). There is a steep rise in F in 2016 and 2017 following the sharp population drop during the 2014-2016 marine heatwave. In 2018 through 2020 there was a sharp decrease in fishing mortality coincident with the drastic cuts in ABC and closure of the federal directed fishery in 2020. In retrospect the phase plane plot (Fig. 2.77) shows that F was estimated to have been above the ABC control rule advised levels for 2005 through 2011 and 2014 through 2017 and biomass was below $B_{35\%}$ in 2007 through 2009 and again 2016 through 2020, and projected to continue to be below through 2022. The spawning biomass in 2018 through 2020 was 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 19.1 with an ending year of 2011 through 2020 are not consistently biased in either direction (Fig. 2.55). The Mohn's ρ for SSB was at 0.08, Woods Hole ρ at 0.083 and an RMSE of 0.152 (Table 2.18). Both models examined this year had retrospective patterns within reasonable bounds.

MCMC results

MCMC were conducted with 1,000,000 iterations with 10,000 burn-in and thinned to every 1000th iteration leaving 990 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. 2.78). Posterior distributions of key parameters appear well defined and bracket the MLE estimates (Table 2.23). Using the projection model estimate for unfished biomass of 180,111 t there is a 74.2% probability that the stock was below $B_{20\%}$ in 2020 and a 29.7% probability the stock was below $B_{17.5\%}$. For 2021 there is a 7.1% probability of the stock being below $B_{20\%}$ and 0.3% probability of it being below $B_{17.5\%}$. Using the MCMC estimates of unfished spawning biomass from the Stock Synthesis projection there is a 96.2% probability that the stock was below $B_{20\%}$ in 2020 and a 74.2% probability the stock was below $B_{17.5\%}$ (Fig 2.79 and Fig. 2.80). For 2021 there is a 37.1% probability of the stock being below $B_{20\%}$ and 5.8% probability of it being below $B_{17.5\%}$. For 2022 there is a < 0.1% probability of the stock being below $B_{20\%}$ using the projection model estimate of unfished spawning biomass and a 0.5% probability using the MCMC derived unfished spawning biomass from Stock Synthesis.

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 19.1:

Reference point:	$B_{35\%}$	$B_{40\%}$	$B_{100\%}$
Spawning biomass:	63,039t	72,045 t	180,111 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 (2014-2019). 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 0.78 and 0.62 in aggregate.

Specification of OFL and Maximum Permissible ABC

Spawning biomass for 2021 is estimated by this year’s model to be 39,997 t at spawning. This is below the $B_{40\%}$ value of 72,045 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 2021 and 2022 as follows (2022 values are predicated on the assumption of 5,239 t catch in 2020 and that the 2021 catch will be at maximum ABC):

Units	Year	Overfishing Level (OFL)	Maximum Permissible ABC
Harvest amount	2021	28,977	23,627
Harvest amount	2022	46,587	38,141
Fishing mortality rate	2021	0.41	0.33
Fishing mortality rate	2022	0.54	0.43

The age 0+ biomass projections for 2021 and 2022 from this year's model are 265,662 t and 312,783 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 through 2019 an ABC was recommended below the maximum ABC in an attempt to ensure the 2019 and 2020 SSB would remain above $B_{20\%}$. For 2020 although the ABC was set at the maximum the stock was below $B_{20\%}$ and because of the rules in place to protect forage for Steller sea lions the directed federal fishery was be required to remain closed. However for added precaution both the federal TAC and state GHL were reduced. For Biological reference points from GOA Pacific cod SAFE documents for years 2001 – 2020 are provided in Table 2.24.

For 2021 the spawning stock biomass is projected to be above $B_{20\%}$ and is projected to continue rising through 2022. Here we recommend a maximum ABC of 23,627 t for 2021 and 38,141 t in 2022.

Risk Table and ABC Recommendation

The following template is used to complete the risk table:

	Assessment-related considerations	*Population dynamics considerations*	*Environmental/ecosystem considerations*	*Fishery Performance*
Level 1: Normal	Typical to moderately increased uncertainty/minor unresolved issues in assessment.	Stock trends are typical for the stock; recent recruitment is within normal range.	No apparent environmental/ecosystem concerns	No apparent fishery/resource-use performance and/or behavior concerns
Level 2: Substantially increased concerns	Substantially increased assessment uncertainty/ unresolved issues.	Stock trends are unusual; abundance increasing or decreasing faster than has been seen recently, or recruitment pattern is atypical.	Some indicators showing adverse signals relevant to the stock but the pattern is not consistent across all indicators.	Some indicators showing adverse signals but the pattern is not consistent across all indicators
Level 3: Major Concern	Major problems with the stock assessment; very poor fits to data; high level of	Stock trends are highly unusual; very rapid changes in stock abundance, or highly atypical	Multiple indicators showing consistent adverse signals a) across the same trophic level as the stock, and/or b) up or down trophic levels (i.e.,	Multiple indicators showing consistent adverse signals a) across different

	uncertainty; strong retrospective bias.	recruitment patterns.	predators and prey of the stock)	sectors, and/or b) different gear types
Level 4: Extreme concern	Severe problems with the stock assessment; severe retrospective bias. Assessment considered unreliable.	Stock trends are unprecedented; More rapid changes in stock abundance than have ever been seen previously, or a very long stretch of poor recruitment compared to previous patterns.	Extreme anomalies in multiple ecosystem indicators that are highly likely to impact the stock; Potential for cascading effects on other ecosystem components	Extreme anomalies in multiple performance indicators that are highly likely to impact the stock

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

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

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

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

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

Assessment considerations. The GOA Pacific cod assessment does not show a strong retrospective bias, 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 2016-2020 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 remain at a low level but climbing. This following three years of poor recruitment in 2014-2017 and increased natural mortality during the 2014-2016 GOA marine heat wave. There are little data in the assessment to estimate recruitment post-2018 and therefore recruitment for these years is estimated at or near average in Model 19.1. 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 an increase in the 2018 recruitment over the record lows during the heatwave, however information from spring ichthyoplankton and beach seine surveys suggest a very weak 2019 year class at age-0. How these indices relate to overall recruitment into the fishery is currently unknown. However in response to heatwave conditions during the spawning months the experimental ecosystem-linked Model 20.1 shows low recruitment in 2019. Currently for the projection model the 2019 year class is assumes it 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 9 September 2018 to 23 December 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 the groundfish predators of juvenile cod. Sea surface temperature during spawning in 2020 was below the 1982-2012 mean suggesting good conditions for hatch success, and the beach seine surveys recorded high densities of age-0 Pacific cod in the summer of 2020. The summer of 2020 showed temperature conditions in the western GOA oscillating above and below the heatwave threshold. It is unknown whether the higher temperatures will persist, however the NMME forecast projects warm conditions in the western GOA going into the upcoming winter.

Both juvenile and adult Pacific cod eat euphausiids, polychaetes, forage fish (including walleye pollock), amphipods and crangonid shrimp. Euphausiid biomass was slightly above average during the May 2020 Seward Line sampling. Summer 2020 euphausiid densities in Icy Strait, SEAK, were below average and lower than 2019. Taken together, these euphausiid indicators suggest moderate euphausiid abundance during 2020. Forage fish indicators suggest mixed signals for abundance during 2020. Forage-fish eating seabirds at Middleton Island had strong reproductive success, although observations indicated that diets were dominated by *hexagrammidae* (primarily greenlings) and moderate amounts of sand lance relative to other years where typical forage fish such as age-0 gadids, capelin, and sand lance predominate. Winter 2020 acoustic surveys found very low biomass of age-2 (and age-3) pollock. However, a relatively small increase of age-0 pollock and a large increase in age-0 cod were observed by summer beach seine sampling in Kodiak and western GOA. Taken together these indicators suggest moderate to poor forage fish prey abundance in 2020. 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. The most recent data available suggest that 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 1 - some indicators showing adverse signals relevant to the stock but the pattern is not consistent across all indicators and there are indicators that environmental conditions for Pacific cod were near average or better.

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 for 2019 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 1: Normal	Level 1: Normal	Level 2: Substantially increased

The overall score of level 2 suggests that setting the ABC below the maximum permissible is not warranted at this time.

Area Allocation of Harvests

In 2012, the ABC for GOA Pacific cod was apportioned among regulatory areas using a Kalman filter approach based on trawl survey biomass estimates. In the 2013 assessment, the random effects model (which is similar to the Kalman filter approach, and was recommended in the Survey Average working group report which was presented to the Plan Team in September 2013) was used; this method was used for the ABC apportionment for 2014. The SSC concurred with this method in December 2013. Using this method with the trawl survey biomass estimates through 2019 (Fig. 2.83), the area-apportioned ABCs would be:

	Western	Central	Eastern	Total
Random effects area apportionment	22.7%	70.6%	6.7%	100%
2021 ABC	5,363	16,681	1,583	23,627
2022 ABC	8,658	26,928	2,555	38,141

Due to the large shift in distribution in the 2019 bottom trawl survey the SSC chose a 'stair-step' approach to the allocation of Pacific cod among regions (Table 2.4). The approach used the halfway point between the 2017 and 2019 random effects allocation which resulted in the following area allocation:

	Western	Central	Eastern	Total
Random effects area apportionment	33.8%	57.8%	8.4%	100%
2021 ABC	7,986	13,656	1,985	23,627
2022 ABC	12,892	22,045	3,204	38,141

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 2020 numbers at age estimated in the assessment. This vector is then projected forward to the beginning of 2033 using the schedules of natural mortality and selectivity described in the assessment and the best available estimate of total (year-end) catch for 2020 (here assumed to be 6,431 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 19.1 with the 2014-2016 natural mortality block was set at the standard M value (Fig. 2.81 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 2015-2019 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 2020 and above its B_{MSY} level in 2030 under this scenario, then the stock is not overfished.)

Scenario 7: In 2021 and 2022, 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 2022 or 2) above 1/2 of its MSY level in 2022 and expected to be above its MSY level in 2032 under this scenario, then the stock is not approaching an overfished condition.)

Scenarios 1 through 7 were projected 13 years from 2020 in Model 19.1 (Table 2.26). Scenarios 3 and 5 (no fishing) project the stock to be below $B_{35\%}$ until 2023, scenarios 1, 2, 6, and 7 have the stock below $B_{35\%}$ until 2024. Fishing at the maximum permissible rate indicate that the spawning stock (Fig. 2.82) will be below $B_{35\%}$ in 2021 through 2023 due to poor recruitment and high mortality in 2014-2017. Under an assumption of mean recruitment, the stock recovers above $B_{35\%}$ by 2024.

Our projection model run under these conditions indicates that for Scenario 6, the GOA Pacific cod stock although below $B_{35\%}$ in 2021 at 39,977 t will be above its MSY value in 2030 at 68,127 t and therefore is not overfished.

Projections 7 with fishing at the OFL after 2022 results in an expected spawning biomass of 67,988 t by 2032.

Under Scenarios 6 (Fig. 2.82) and 7 of the 2020 Model 19.1 the projected spawning biomass for Gulf of Alaska Pacific cod is not currently overfished, nor is it approaching an overfished status. However the stock was below $B_{20\%}$ in 2020 which triggered a closure of the directed Pacific cod fisheries managed under the GOA FMP. In 2021 the stock is expected to be above $B_{20\%}$ potentially allowing for an open federal directed fishery.

The 2020 OFL given this year's model would have produced a sum of apical F of 0.3180.

Alternative Projections for Model 20.1

Stock synthesis has the ability to conduct projections that, unlike the bootstrap method described above, propagates the full range of model uncertainty forward into the projections and use projections of environmental covariates to drive assessment model projections. For Model 20.1 we conducted exploratory projections using this feature to examine potential impacts of climate change and the increase of heatwaves on the GOA Pacific cod stock. We conducted an initial projection to 2033 assuming future conditions to be at the 1982-2012 mean conditions (Table 2.27, Fig. 2.84 and Fig. 2.85). This model reveals a similar trajectory to Model 19.1 with slightly higher ABC and OFL values until 2023 when projections of spawning biomass and catch for Model 20.1 drop below those from Model 19.1. The difference in these projections is the low estimate of recruitment for 2019 in Model 20.1. The Model 20.1 projections in this scenario after 2025 exceeds those of Model 19.1 as the assumed recruitment and growth conditions mirroring 1982-2012 were more favorable to growth and recruitment than those observed over the full time series.

For projections 2021-2099 the surface temperature anomaly for the central Gulf of Alaska for five climate models (HadGEM2-ES, MIROC-ESM, MIROC5, IMPI-ESM-LR, and IMPI-ESM-MR) under RCP 2.6 and RCP 4.5 IPCC carbon emission scenarios were used to simulate temperature and heatwave conditions. We selected these specific five models because they had both RCP 4.5 and RCP 2.6 output available to 2099 for the Gulf of Alaska. We retrieved these modeled projections from the Physical Sciences Laboratory Coupled Model Inter-comparison Project (CMIP5; Hermann et al., 2016, 2019) webserver (https://psl.noaa.gov/ipcc/ocn/timeseries.html). Please note that RCP 2.6 and RCP 4.5 are the two most optimistic of the four possible IPCC scenarios. RCP 2.6 is the best-case scenario in limiting anthropogenic climate change. It assumes a major turnaround in climate policies and a start to concerted action in the next few years in all countries, both developing and developed. RCP 4.5 is a moderate carbon emissions scenario where emissions peak around mid-century at around 50% higher than 2000 levels and then decline rapidly over 30 years, stabilizing at half of 2000 emission levels. In RCP 4.5 CO^2 concentration in the atmosphere continues on trend upward from current condition to about 520 ppm in 2070 and then continues to increase more slowly afterwards. Future runs of the ecosystem-linked model could include the less optimistic scenarios.

The spawning marine heatwave cumulative intensity index, $\hat{I}_y$, was modeled as a function of the June temperature anomaly, t_y, for the central GOA. We used a delta linear model where the probability of a spawning heatwave for all years 1981-2020 was fit as a binomial process and the cumulative intensity of the heatwave given the mean June temperature for the years with a heatwave modeled as a Gaussian process.

$$\hat{I}_y = \left(\frac{e^{\beta_1 t_y + \beta_0}}{1 + e^{\beta_1 t_y + \beta_0}}\right)(\beta_3 t_y + \beta_2)$$

The model was fit using *glm* function in the **stats** R library. Table 2.28 contains the covariate values and standard errors of the parameters. This allowed us to project Model 20.1 to 2099 under each of the five models and two carbon emission scenarios. We also projected each of the scenarios under no catch and under F_{maxABC} for each of the projections. Changes in spawning biomass under no fishing and with fishing under the current groundfish control rules and catch compared to projections using static 1982-2012 conditions are provided in Table 2.29. Figure 2.86 illustrates the projection of spawning biomass under a no fishing and provides an estimate stock productivity under RCP 2.6 and RCP 4.5. These models show a counterintuitive result, with a higher unfished spawning biomass under the higher carbon emission scenario. This is an estimate with no fishing and in this case increases in growth with increasing temperatures in the RCP 4.5 models outweigh the decreases in abundance observed in recruitment compared to RCP 2.6 when no fishing is present. Figure 2.87 illustrates the projection of spawning biomass under the standard North Pacific groundfish control rule. Under these conditions there is a larger drop in the expected spawning biomass with RCP 4.5 compared to the 1982-2012 base conditions than with RCP 2.6. As shown in Figure 2.88 and Table 2.28 these drops in average spawning biomass also result in a drop in the average maximum ABC. In all of the projections there is an apparent shift in productivity that occurs between 2050 and 2060, this is not an artifact of the ecosystem-linked assessment model but rather a feature in the CMIP5 climate models.

It should be noted that Model 20.1 does not take into account any changes in natural mortality. We assume a constant natural mortality of 0.46 for all model runs and projections. During the 2014-2016 marine heatwave we did see an increase in natural mortality that had a substantial impact on the stock, we have not been able to determine a consistent mechanism for this increase in natural mortality. Future work will concentrate on improving our understanding of this phenomenon.

Ecosystem and Economic Considerations

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

Data Gaps and Research Priorities

Research is needed around three linked themes:

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

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

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

Specific project to support these research themes:

Growth and survival of young cod

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

Tagging to determine cod movement

Pop-up satellite tags in GOA recording temperature and depth (modeled location) combined with bioenergetics models could be used to ascertain movement, growth, and spawn timing. Tagging is also useful for improving age estimation for cod, which is critical for successful stock assessment models.

Improved stock assessment modeling

In connection with the pop-up tag study, there is a need to develop a multi-area assessment model for the BSAI and GOA. The development of an ecosystem-linked GOA model is also needed to test potential reactions to climate change.

Survey

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

Genetics

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

Maturity

The stock assessment critically needs better estimates of size and age at maturity and how these parameters are affected by temperature.

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Tables

Table 2.1. 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 2020 by jurisdiction and gear type (as of 2020-10-14)

	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	3,817	2,964	4,014	121	10,916	36	3,660	194	3,889	14,805
2019	4,537	2,737	3,732	178	11,184	78	3,820	329	4,227	15,411
*2020	3,040	455	11	0	3,507	50	1,717	468	2,235	5,742

Table 2.3 History of Pacific cod catch (t, includes catch from State waters), Federal TAC (does not include State guideline harvest level), ABC, OFL and Alaska State GHL (1997-Present). ABC was not used in management of GOA groundfish prior to 1986. Catch for 2020 is current through 2020-10-14 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	GHL
1980	35,345	60,000	-	-	-
1981	36,131	70,000	-	-	-
1982	29,465	60,000	-	-	-
1983	36,540	60,000	-	-	-
1984	23,898	60,000	-	-	-
1985	14,428	60,000		-	-
1986	25,012	75,000	136,000	-	-
1987	32,939	50,000	125,000	-	-
1988	33,802	80,000	99,000	-	-
1989	43,293	71,200	71,200	-	-
1990	72,517	90,000	90,000	-	-
1991	76,328	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	12,385
1998	62,121	66,060	77,900	141,000	11,840
1999	68,614	67,835	84,400	134,000	16,565
2000	54,508	59,800	76,400	102,000	17,685
2001	41,619	52,110	67,800	91,200	15,690
2002	42,345	44,230	57,600	77,100	13,370
2003	52,582	40,540	52,800	70,100	12,260
2004	56,624	48,033	62,810	102,000	14,777
2005	47,584	44,433	58,100	86,200	13,667
2006	47,897	52,264	68,859	95,500	16,595
2007	52,261	52,264	68,859	97,600	16,595
2008	59,014	50,269	64,493	88,660	16,224
2009	53,196	41,807	55,300	66,000	13,493
2010	78,325	59,563	79,100	94,100	19,537
2011	85,412	65,100	86,800	102,600	21,700
2012	77,918	65,700	87,600	104,000	21,900
2013	68,600	60,600	80,800	97,200	20,200
2014	84,840	64,738	88,500	107,300	23,762
2015	79,489	75,202	102,850	140,300	27,648
2016	64,087	71,925	98,600	116,700	26,675
2017	48,734	64,442	88,342	105,378	23,900
2018	15,247	13,096	18,000	23,565	4,904
2019	15,411	12,368	17,000	23,669	4,632
2020	5,742	6,431	14,621	17,794	2,537

*As of 10/14/2020

Table 2.4. History of GOA Pacific cod allocations by regulatory area (in percent) for 1991-2020 and proposed for 2021. See Barbeaux et al. (2018) for 1977-1990.

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

Table 2.5 Estimated retained-and discarded GOA Pacific cod (*as of 2020-10-14)

Year	Discarded	Retained	Grand Total
1991	1,429	74,899	76,328
1992	3,873	76,199	80,073
1993	5,844	49,865	55,709
1994	3,109	43,540	46,649
1995	3,546	64,560	68,085
1996	7,555	60,530	68,064
1997	4,783	63,057	67,840
1998	1,709	59,811	61,520
1999	1,617	66,311	67,928
2000	1,362	52,904	54,266
2001	1,901	39,632	41,533
2002	3,713	38,594	42,307
2003	2,414	50,047	52,461
2004	1,265	55,304	56,569
2005	1,039	46,499	47,538
2006	1,835	45,986	47,822
2007	1,438	50,456	51,895
2008	3,299	55,367	58,666
2009	3,877	48,756	52,633
2010	2,881	74,821	77,703
2011	2,116	82,439	84,556
2012	938	76,273	77,211
2013	4,436	62,963	67,398
2014	5,248	78,572	83,820
2015	1,637	76,149	77,786
2016	831	62,133	62,963
2017	679	47,587	48,266
2018	583	14,222	14,805
2019	1,141	14,270	15,411
*2020	1,218	4,524	5,742

Table 2.6 – Weight of groundfish bycatch (t), discarded (D) and retained (R), for 2016 – 2020 for GOA Pacific cod as target species (AKFIN; as of 2020-10-14). For 2018 and 2019 the discard of halibut bycatch is no longer reported in the AKFIN tables.

	2016		2017		2018		2019		2020		Grand Total
	D	R	D	R	D	R	D	R	D	R	
Bering flounder									0.01		0.01
flounder, Alaska plaice		0.01	0.03		0.06		0.06				0.15
flounder, arrowtooth	551.85	802.36	226.87	262.27	89.91	5.11	220.24	17.13	39.01		2,214.74
flounder, general				1.46	0.11						1.57
flounder, starry	3.99	3.25	3.55	2.66	0.17		0.06				13.68
greenling, atka mackerel	30.95	10.73	351.62	31.80	3.01	0.24	32.79	0.24			461.38
groundfish, general	2.23		5.85		3.63		2.96		3.14		17.81
halibut, Pacific	5.57	15.58	11.04	24.67	1.81	11.35	1.40	4.31		0.21	75.94
Kamchatka flounder	1.06		11.77	0.04	0.03	0.00	0.15	0.01	0.00		13.06
octopus, North Pacific	154.08	207.41	26.58	196.91	10.25	142.35	39.70	192.28	0.03	12.00	981.58
Pacific sleeper shark	8.92		1.79		6.27		10.19		0.22		27.39
perch, Pacific ocean	687.31	10.72	46.27	30.56	0.07	0.01	0.16	19.37	0.00		794.48
pollock, walleye	58.56	402.19	316.62	485.93	24.59	71.58	71.50	31.05	0.00	1.25	1,463.25
rockfish, bocaccio		0.01									0.01
rockfish, canary		0.29		0.06		0.15	0.11	0.05	0.00	0.03	0.70
rockfish, china		0.00		0.02		0.00		0.01	0.00		0.03
rockfish, copper	0.02	0.05		0.01		0.00		0.01			0.09
rockfish, dusky	59.94	19.00	77.72	17.34	3.45	3.94	2.34	5.44		0.71	189.90
rockfish, harlequin	2.52		0.64		0.02						3.18
rockfish, northern	57.23	16.91	44.34	9.22	3.57	1.40	3.33	0.25			136.24
rockfish, other	14.82	0.49	15.88	0.04	3.84		0.74		0.01		35.82
rockfish, quillback	3.55	15.34	1.54	7.67	0.07	2.10	0.90	2.98	0.01	0.33	34.51
rockfish, redbanded	0.43	0.02	1.38	0.53	0.61	0.02	0.07	0.02	0.02	0.01	3.11
rockfish, redstripe	0.06	0.01	0.25	0.13		0.00		0.00			0.45
rockfish, rosethorn	0.01	0.02		0.01	0.01	0.00	0.04				0.10
rockfish, rougheye	1.39	1.60	8.16	2.46	5.95	1.72	0.62	1.22	0.03	0.12	23.27
rockfish, sharpchin	0.31										0.31
rockfish, shortraker	0.95	1.03	5.25	2.60	7.61	0.31	1.17	0.18	0.04	0.03	19.18
rockfish, silvergray	0.76	1.34	0.08	0.36	0.06	0.10	0.01	0.04		0.03	2.78
rockfish, thornyhead (idiots)	2.96	6.64	11.27	24.59	0.52	1.99	0.61	1.16	0.01		49.75
rockfish, tiger	0.47	0.37	0.16	0.22	0.03	0.03	0.16	0.05			1.49
rockfish, widow	0.06						0.15				0.21
rockfish, yelloweye (red snapper)	16.19	17.13	44.57	34.44	1.55	15.88	3.34	13.45	0.11	0.23	146.91
rockfish, yellowtail		0.02				0.01				0.00	0.02
sablefish (blackcod)	98.88	28.56	84.53	22.55	55.95	2.88	36.44	53.04	5.36		388.18
sculpin, bigmouth	19.52		16.51		0.36		1.18				37.57
sculpin, general	0.09	11.81	0.52	2.76	0.05	0.32		0.24		0.20	16.00
sculpin, great	157.55		324.91		18.62		4.28		0.02		505.38
sculpin, other large	163.36		226.33		42.93		79.41		0.38		512.40
sculpin, plain	3.23		0.07				0.12				3.42
sculpin, warty	0.07										0.07
sculpin, yellow irish lord	503.96	0.03	407.76		21.33		15.90		0.25		949.22
shark, other							0.61	0.45			1.06
shark, salmon		0.01			0.45						0.46
shark, spiny dogfish	329.23	0.18	242.25		104.24	0.00	104.22	0.00	11.96		792.08
skate, Alaskan		1.57		1.14		0.07		0.08			2.87
skate, Aleutian		8.00		18.18		2.11		1.13			29.42
skate, big	381.78	244.64	459.55	148.88	54.26	20.65	133.55	29.95	3.68	0.17	1,477.11
skate, longnose	335.42	152.89	321.56	91.79	30.54	39.74	50.28	35.96	4.68	1.46	1,064.31
skate, other	911.79	62.97	943.29	85.13	170.91	12.66	202.34	32.58	3.88		2,425.53
skate, Whiteblotched		0.18		0.74		0.01					0.93
sole, butter	1.89	44.58	1.87	9.29	2.79		0.17	0.05			60.63
sole, dover	14.51	3.55	0.41	0.50	0.02	0.01	0.02		0.00		19.03
sole, English	13.96	2.49	2.46	0.98	0.54		3.50	0.46			24.40
sole, flathead	77.81	241.55	51.79	93.20	22.12	0.68	92.54	8.53	0.00		588.21
sole, rex	23.00	145.61	2.75	14.93	4.51	0.01	27.68	2.00			220.48
sole, rock	150.96	511.58	263.62	547.33	19.51	0.37	36.27	37.47		0.00	1,567.11
sole, yellowfin	5.76	0.03	1.57	0.02	4.56	0.00	0.90		0.00		12.85
squid, majestic	0.03	0.13	0.02	0.11							0.29
turbot, Greenland	0.48		6.56		0.00		0.47				7.51
Grand Total	4859.48	2992.87	4571.54	2173.52	720.91	337.81	1182.67	491.19	72.85	16.79	17,419.63

Table 2.7 - Incidental catch (t or *birds by number*) of non-target species groups by GOA Pacific cod fisheries, 2016-2020 (as of 2020-10-14). 0.0 indicates less and 0.005 tons, a blank indicates no catch.

	2016	2017	2018	2019	2020
Benthic urochordata	1.37	0.01	0.23		1.62
Birds	*158*	*379*	*334*	*23*	*895*
Bivalves	0.60	0.92	2.72	0.23	
Brittle star unidentified	0.04	0.04	0.00		
Corals Bryozoans - Corals Bryozoans Unidentified	0.31	1.89	1.46	1.55	0.30
Eelpouts	0.05	0.11	0.01	0.19	
Eulachon		0.00			
Giant Grenadier	84.77	13.79	0.12	0.12	
Greenlings	4.47	5.46	0.77	0.77	
Grenadier - Rattail Grenadier Unidentified	1.17	0.03	0.59	0.15	
Hermit crab unidentified	0.57	0.14	0.09	0.92	
Invertebrate unidentified	0.19	0.63	0.08	0.08	0.19
Misc crabs	1.03	0.80	0.43	0.14	
Misc crustaceans		0.01		0.00	
Misc fish	152.51	177.92	31.38	15.35	
Other osmerids	0.01				
Pacific Hake	0.04				
Pacific Sand lance		0.01			
Pandalid shrimp	0.03				
Polychaete unidentified	0.00				
Scypho jellies	21.02	0.89		2.65	0.03
Sea anemone unidentified	20.93	12.57	2.63	1.31	
Sea pens whips	0.61	0.80	0.33	0.46	
Sea star	872.29	385.73	37.64	37.48	2.79
Snails	14.57	9.46	6.78	4.74	0.11
Sponge unidentified	1.29	2.34	2.08	5.36	
State-managed Rockfish	46.33	68.57	2.89	3.45	
Stichaeidae		0.27			
urchins dollars cucumbers	1.93	4.56	0.39	0.31	

Table 2.8 – Pacific cod catch (t) by trip target in Gulf of Alaska groundfish fisheries. *Data for 2020 is as of 10/14/2020.

Trip Target	2016	2017	2018	2019	2020
Arrowtooth Flounder	1,337	1,256	880	1,439	1,231
Atka Mackerel	-	5	2	-	-
Flathead Sole	39	2	2	18	-
Halibut	279	342	300	301	450
Other Species	-	2	-	-	-
Pacific Cod	***59,506***	***45,319***	***12,010***	***11,977***	***2,207***
Pollock - bottom	855	819	782	711	774
Pollock - midwater	230	68	65	100	152
Rex Sole - GOA	25	6	76	83	14
Rockfish	364	253	401	322	126
Sablefish	102	72	37	52	19
Shallow Water Flatfish - GOA	225	124	251	408	771
Grand Total	62,963	48,266	14,805	15,411	5,742
Non Pacific cod trip target total	3,458	2,947	2,795	3,434	3,535

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 2020-10-14)

Source	2016	2017	2018	2019
AFSC Annual Longline Survey	24,203	15,597	10,242	5,530
Bait for Crab Fishery	498	-	-	-
GOA Shelf and Slope Walleye Pollock Acoustic-Trawl Survey	-	53	-	-
Gulf of Alaska Bottom Trawl Survey	-	5,197	-	7,796
IPHC Annual Longline Survey	46,273	38,927	89,231	104,968
IPHC Research	-	-	34	-
Kachemak Bay Large Mesh Trawl Survey	-	1,254	-	-
Kenai/Prince William Sound Walleye Pollock Acoustic-Trawl Survey	-	15	-	-
Kodiak Scallop Dredge	-	1	-	-
Large-Mesh Trawl Survey	6,076	6,597	6,361	7,317
Prince William Sound Large Mesh Trawl Survey	-	164	-	-
Shumagin Islands Walleye Pollock Acoustic-Trawl Survey	-	11	23	-
Small-Mesh Trawl Survey	160	161	151	341
Sport Fishery	122,501	56,994	42,446	-
Spot Shrimp Survey	2	-	1	4
Summer Acoustic-Trawl Survey of Walleye Pollock in the Gulf of Alaska	-	-	-	70
Total	199,713	124,971	148,489	126,026

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	2020	19,459	0.218
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	29,431.30	0.24	2009	30,159.79	0.16
1998	16,367.53	0.21	2010	27,815.33	0.16
1999	12,373.39	0.22	2011	31,746.63	0.17
2000	14,641.58	0.22	2012	23,509.36	0.18
2001	12,169.30	0.24	2013	26,432.41	0.19
2002	16,494.80	0.22	2014	27,750.79	0.16
2003	15,404.35	0.24	2015	16,722.46	0.20
2004	16,046.61	0.20	2016	11,917.64	0.22
2005	16,301.24	0.23	2017	10,355.52	0.24
2006	15,804.85	0.21	2018	13,909.87	0.22
2007	18,205.76	0.20	2019	13,412.09	0.20
2008	22,217.52	0.18			

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

Year	Index	CV	Year	Index	CV
1988	2.782	0.093	2005	1.051	0.092
1989	3.686	0.086	2006	0.904	0.088
1990	2.755	0.080	2007	1.078	0.080
1991	1.878	0.138	2008	1.246	0.066
1992	2.855	0.084	2009	1.253	0.070
1993	2.310	0.086	2010	1.062	0.072
1994	2.074	0.082	2011	1.364	0.070
1995	2.293	0.109	2012	2.582	0.090
1996	2.325	0.085	2013	1.948	0.098
1997	2.504	0.079	2014	1.337	0.098
1998	2.257	0.085	2015	1.207	0.096
1999	1.251	0.071	2016	0.832	0.112
2000	0.973	0.077	2017	0.879	0.106
2001	0.856	0.075	2018	1.147	0.097
2002	1.082	0.069	2019	0.966	0.092
2003	0.868	0.079	2020	1.365	0.090
2004	1.330	0.073			

Table 2.14 – CFSR bottom temperature index for 10 cm and 40 cm Pacific cod and marine heatwave cumulative intensity index (MHCI) in °C days for full year, Winter (Jan-Mar & Oct - Dec), and spawning (Feb-Mar) for 1979-2020. Note that the MHCI for 2020 are only through October 16.

Year	10cm	40cm	Annual MHCI	Winter MHC1	Spawn MHCI	Year	10cm	40cm	Annual MHCI	Winter MHCI	Spawn MHCI
1979	4.91	5.08	0	0	0	2000	4.51	4.79	0	0	0
1980	5.03	4.92	0	0	0	2001	4.98	5.02	46.91	23.35	11.33
1981	5.71	5.36	0	0	0	2002	4.20	4.36	51.27	51.27	0
1982	4.00	4.52	0	0	0	2003	5.30	5.39	207.85	151.48	108.12
1983	5.11	5.25	31.88	15.20	4.73	2004	4.60	4.98	117.64	0	0
1984	4.73	5.23	88.21	43.10	0.00	2005	4.91	5.27	284.60	3.78	0
1985	4.57	5.17	24.61	24.61	19.68	2006	4.63	4.97	35.14	5.81	0
1986	4.73	5.00	16.35	16.35	0	2007	4.13	4.29	0	0	0
1987	5.30	5.31	5.58	0	0	2008	4.33	4.56	0	0	0
1988	4.70	4.95	0	0	0	2009	3.66	4.31	0	0	0
1989	4.05	4.40	0	0	0	2010	5.21	5.08	6.52	0	0
1990	4.12	4.53	8.72	0	0	2011	4.55	4.66	0	0	0
1991	4.38	4.62	0	0	0	2012	4.00	4.08	0	0	0
1992	4.89	4.89	0	0	0	2013	4.18	4.64	0	0	0
1993	4.52	4.70	19.10	0	0	2014	4.73	4.96	283.02	105.44	0.00
1994	4.47	4.82	0	0	0	2015	5.88	5.59	402.32	202.38	133.28
1995	4.04	4.62	0	0	0	2016	5.71	5.10	630.87	314.57	155.56
1996	4.50	4.77	0	0	0	2017	4.75	4.58	53.03	38.78	0
1997	4.56	4.85	142.05	23.24	0	2018	5.10	5.02	128.50	99.89	0
1998	5.73	5.52	150.85	87.05	80.81	2019	5.94	5.63	496.74	199.48	100.45
1999	4.43	4.86	0	0	0	2020	4.30	4.70	131.24	16.18	0

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

	M19.1	M20.1
Recruitment		
Early Init Ages	10	10
Early Rec. Devs (1977)	1	1
Main Rec. Devs (1978-2018)	37	37
Late Rec. Devs (2018-2020)	3	3
Future Rec. Devs. (2021-2035)	15	15
R_0	1	2
1976 R reg.	1	1
Steepness (H)	0	1
Natural mortality	2	2
Growth	5	8
Aging Bias	2	2
Catchability		
Q_{trawl}	1	1
$Q_{longline}$	1	1
$Q_{longline}$ env. offset	1	1
Initial F	2	2
Selectivity		
Trawl Survey	16	16
Longline survey	5	5
Trawl Fishery	59(39 dev)	59(39 dev)
Longline Fishery	40(24 dev)	40 (24 dev)
Pot Fishery	8	8
Total	211	216

Table 2.16 – Model fit statistics and results. Note that likelihoods between model series are not completely comparable. Note for Model 19.1Proj the 2020 SSB is beginning of year from Stock Synthesis, 2021 and 2022 SSB are beginning of the year from the 'proj' program. All projections in M19.1SS and Model 20.1SS are from stock synthesis. Authors' preferred model in green.

	M19.1Proj	M19.1SS	M20.1SS
Likelihoods Total	3190.02		3176.72
Survey	-16.12		-15.91
Length Comp.	1568.22		1564.99
Age Comp.	1633.74		1624.83
Recruitment	-5.50		-7.32
Parameter priors	1.59		1.73
Parameter Devs.	6.54		6.36
Parameters			
R_0 billions	0.464		*0.513
Steepness	1.0		0.82
Natural Mortality	0.47		0.46
M_{14-16}	0.82		0.85
q_{Shelf}	1.16		1.19
$q_{longline}$	*1.18		*1.19
L_{min}	12.09		*12.25
L_{max}	99.46		*99.46
Von Bert K	0.17		*0.17
Results			
SSB_{1978} (t)	119,849	119,849	130,820
$SSB_{100\%}$ (t)	180,111	206,773	181,522
SSB_{2020} (t)	34,631	34,361	35,235
$SSB_{2020\%}$	19.2	16.6	19.4
SSB_{2021}(t)	39,977	44,559	41,943
$SSB_{2021\%}$	22.2	21.5	23.1
SSB_{2022}(t)	50,813	56,796	50,761
$SSB_{2022\%}$	28.2	27.5	28.0
$F_{35\%}$	0.778	0.778	0.715
$F_{40\%}$	0.621	0.621	0.669
2021 ABC (t)	23,627	24,612	26,533
F_{ABC}	0.330	0.344	0.372
OFL (t)	28,977	30,307	32,438
F_{OFL}	0.414	0.433	0.467
2022 ABC (t)	38,141	39,561	38,266
F_{ABC}	0.428	0.448	0.457
OFL (t)	46,587	48,505	46,300
F_{OFL}	0.537	0.564	0.571

*Indicates parameters that were time varying based on environmental covariates.

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

Model	Label	ALL	FshTrawl	FshLL	FshPot	Srv	LLSrv
19.1	Age_like	1633.74	302.58	362.41	288.45	680.30	
20.1	Age_like	1624.83	302.10	359.50	286.47	676.77	
19.1	Catch_like	8.05E-12	2.50E-12	2.77E-12	2.77E-12		
20.1	Catch_like	1.39E-11	4.41E-12	4.74E-12	4.76E-12		
19.1	Init_equ_like	1.44E-04	2.74E-05	1.17E-04			
20.1	Init_equ_like	1.40E-04	2.68E-05	1.13E-04			
19.1	Length_like	1568.22	467.69	316.81	362.55	170.06	251.10
20.1	Length_like	1564.99	469.46	317.16	359.71	171.95	246.71
19.1	Surv_like	-16.12				-10.64	-5.48
20.1	Surv_like	-15.91				-11.43	-4.48

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

		M19.1	M20.1
Retrospective			
Spawning biomass	Mohn's ρ	0.080	0.109
	Woods Hole ρ	0.083	0.091
	RMSE	0.152	0.195
Recruit. (age -0)	Mohn's ρ	-0.061	-0.124
	Woods Hole ρ	0.039	0.018
	RMSE	0.217	0.256
	Index RMSE		
	AFSC Trawl	0.295	0.296
	AFSC Longline	0.302	0.305
Size Comp			
Har. Mean EffN	Trawl	297.101	297.014
	Longline	467.044	463.548
	Pot	369.869	371.498
	AFSC Trawl	293.466	296.061
	AFSC Longline	264.347	263.801
Mean input N	Trawl	149.140	149.140
	Longline	154.024	154.024
	Pot	170.613	170.613
	AFSC Trawl	94.375	94.375
	AFSC Longline	100.000	100.000
Age Data			
Har. Mean EffN	Trawl	1.714	1.721
	Longline	2.438	2.479
	Pot	2.329	2.367
	AFSC Trawl	3.025	3.047
Mean input N	Trawl	0.401	0.401
	Longline	1.179	1.179
	Pot	0.824	0.824
	AFSC Trawl	1.124	1.124
Rec. Var. (1977-2018)			
	Std.dev(ln(No. Age 1))	0.524	0.571

Table 2.19 – Estimated beginning year weight and length at age from Model 19.1.

Age	Weight (kg)	Length (cm)
0	1.23E-04	0.500
1	0.063	19.130
2	0.292	31.556
3	0.711	42.059
4	1.290	50.938
5	1.978	58.444
6	2.726	64.788
7	3.493	70.152
8	4.246	74.685
9	4.963	78.518
10	6.960	87.327

Table 2.20 – Estimated female spawning biomass (t) from the last year's assessment and this year's assessment from Models 19.14.48c and the author's recommended Model 19.1. For 2021 the Sp.Bio. and Tot. Bio. in **bold** is from the Projection model Proj, the non-bolded from Stock Synthesis.

	Last Year's Model			Model 19.1		
	Sp.Bio	St.dev	Tot. Bio. 0+	Sp.Bio	St.dev	Tot. Bio. 0+
1977	104,750	23,105	340,687	110,410	24,581	364,209
1978	117,115	24,505	353,530	119,850	25,067	405,023
1979	114,285	23,198	401,961	117,990	23,590	471,526
1980	110,135	21,309	465,619	120,265	22,926	530,446
1981	125,320	23,684	496,767	143,780	27,033	556,366
1982	153,290	28,367	524,234	166,785	30,771	579,603
1983	162,280	29,274	565,329	172,375	30,733	618,424
1984	164,770	28,964	612,364	173,590	29,945	651,063
1985	182,455	29,559	664,827	188,540	30,012	690,522
1986	210,695	29,955	715,967	211,100	29,897	742,523
1987	232,910	29,421	764,445	227,490	28,914	787,267
1988	236,290	26,653	778,122	233,010	26,573	794,280
1989	245,590	24,537	777,175	243,170	24,688	787,561
1990	248,915	22,288	759,213	243,230	22,323	769,439
1991	228,490	19,601	717,933	223,300	19,714	736,250
1992	210,315	17,628	689,490	205,080	17,718	707,463
1993	193,725	16,084	654,597	191,450	16,417	665,035
1994	196,020	15,306	627,867	194,485	15,679	628,624
1995	199,155	14,210	588,782	194,410	14,283	585,143
1996	179,380	12,250	518,686	172,765	12,123	519,793
1997	153,285	10,210	461,210	146,845	10,039	465,313
1998	127,445	8,561	413,127	123,625	8,519	416,933
1999	112,615	7,674	375,787	110,480	7,689	377,406
2000	100,450	7,173	335,702	97,345	7,072	338,761
2001	91,975	6,585	318,708	87,890	6,394	324,757
2002	87,065	5,971	324,404	83,510	5,809	328,461
2003	85,975	5,663	325,922	82,880	5,531	323,780
2004	87,350	5,736	307,850	83,425	5,551	300,952
2005	84,680	5,590	280,816	79,040	5,302	274,389
2006	77,450	4,995	264,538	70,960	4,687	266,500
2007	68,365	4,420	268,873	62,375	4,190	284,405
2008	61,215	4,161	299,342	58,345	4,129	321,322
2009	62,835	4,557	342,596	63,025	4,683	365,206
2010	81,485	5,743	401,264	82,160	5,914	412,065
2011	94,895	7,039	425,866	93,315	7,026	425,550
2012	105,105	8,484	428,225	99,360	8,160	431,913
2013	113,350	9,743	445,224	102,620	9,141	475,139
2014	113,830	10,614	498,565	106,775	10,451	553,456
2015	80,020	6,587	381,875	78,265	6,746	408,888
2016	62,215	4,811	257,969	62,895	4,957	266,608
2017	46,080	3,787	155,394	44,961	3,601	157,240
2018	37,369	3,837	127,165	35,940	3,578	131,650
2019	35,231	3,711	141,458	34,794	3,513	149,969
2020	**33,274**		170,124	34,631	3,762	186,666
2021				**39,977**/44,559	5,019	**265,662**/247,415

Table 2.21 – Age-0 recruitment and standard deviation of age-0 recruits by year for last year's model and Model19.1 and Model 20.1. Highlighted are the 1977 and 2012 year classes.

	M19.14.48c		M19.1		M20.1	
Year	Age-0 x 10^9	Stdev	Age-0 x 10^9	Stdev	Age-0 x 10^9	Stdev
1977	1.363	0.367	1.208	0.335	1.273	0.389
1978	0.441	0.144	0.378	0.132	0.470	0.171
1979	0.476	0.142	0.370	0.118	0.421	0.144
1980	0.880	0.235	0.624	0.180	0.578	0.184
1981	0.801	0.214	0.690	0.185	0.783	0.214
1982	1.105	0.282	0.756	0.205	0.822	0.236
1983	0.618	0.190	0.539	0.167	0.437	0.150
1984	0.875	0.228	0.709	0.196	0.759	0.212
1985	1.158	0.255	0.887	0.211	0.847	0.209
1986	0.543	0.140	0.499	0.135	0.443	0.132
1987	0.865	0.176	0.588	0.133	0.551	0.128
1988	0.668	0.144	0.598	0.132	0.610	0.136
1989	0.842	0.169	0.632	0.137	0.664	0.147
1990	0.882	0.173	0.749	0.152	0.701	0.150
1991	0.600	0.124	0.445	0.100	0.383	0.092
1992	0.467	0.097	0.385	0.083	0.343	0.076
1993	0.392	0.081	0.310	0.068	0.283	0.063
1994	0.440	0.086	0.348	0.072	0.339	0.070
1995	0.541	0.098	0.438	0.082	0.414	0.080
1996	0.416	0.077	0.309	0.061	0.278	0.057
1997	0.353	0.067	0.294	0.057	0.263	0.054
1998	0.356	0.065	0.272	0.052	0.226	0.044
1999	0.514	0.089	0.367	0.066	0.379	0.069
2000	0.530	0.090	0.439	0.076	0.391	0.071
2001	0.301	0.057	0.251	0.048	0.257	0.049
2002	0.284	0.052	0.193	0.037	0.187	0.038
2003	0.323	0.055	0.244	0.043	0.222	0.040
2004	0.330	0.057	0.308	0.053	0.317	0.055
2005	0.646	0.103	0.420	0.070	0.395	0.068
2006	0.777	0.126	0.687	0.112	0.681	0.114
2007	0.636	0.109	0.443	0.079	0.433	0.079
2008	0.893	0.152	0.652	0.112	0.648	0.114
2009	0.483	0.093	0.392	0.076	0.348	0.073
2010	0.558	0.105	0.507	0.097	0.430	0.085
2011	0.907	0.177	0.655	0.132	0.670	0.137
2012	1.250	0.266	1.215	0.261	1.205	0.267
2013	0.688	0.166	0.638	0.159	0.658	0.167
2014	0.200	0.057	0.211	0.060	0.214	0.063
2015	0.302	0.077	0.260	0.064	0.174	0.047
2016	0.269	0.069	0.168	0.042	0.175	0.041
2017	0.395	0.122	0.246	0.058	0.192	0.046
2018	0.297	0.095	0.390	0.108	0.352	0.094
2019	0.579	0.278	0.399	0.160	0.193	0.080
2020			0.464	0.223	0.375	0.195
Mean 1977-2018	0.611		0.493		0.481	
Stdev(Ln(x))		0.468		0.471		0.513

Table 2.22 – Estimated fishing mortality in Apical F and Total exploitation for Model 19.1.

	Sum Apical F		Total		Sum Apical F		Total
Year	F	σ	**Exploitation**	**Year**	F	σ	**Exploitation**
1977	0.010	0.003	0.007	2001	0.348	0.031	0.157
1978	0.046	0.010	0.037	2002	0.367	0.030	0.158
1979	0.062	0.014	0.047	2003	0.479	0.037	0.183
1980	0.146	0.033	0.075	2004	0.523	0.039	0.210
1981	0.089	0.017	0.074	2005	0.653	0.104	0.203
1982	0.072	0.013	0.061	2006	0.698	0.103	0.223
1983	0.094	0.017	0.072	2007	0.664	0.060	0.250
1984	0.063	0.011	0.044	2008	0.812	0.082	0.262
1985	0.059	0.013	0.024	2009	0.640	0.063	0.184
1986	0.086	0.017	0.040	2010	0.757	0.074	0.244
1987	0.064	0.015	0.049	2011	0.719	0.069	0.237
1988	0.063	0.008	0.047	2012	0.609	0.063	0.224
1989	0.080	0.012	0.062	2013	0.509	0.056	0.195
1990	0.213	0.023	0.107	2014	0.729	0.080	0.219
1991	0.246	0.025	0.120	2015	0.960	0.097	0.226
1992	0.283	0.029	0.134	2016	0.988	0.094	0.259
1993	0.209	0.020	0.094	2017	0.792	0.102	0.353
1994	0.174	0.016	0.083	2018	0.270	0.034	0.140
1995	0.259	0.022	0.129	2019	0.286	0.034	0.148
1996	0.289	0.024	0.148	2020	0.088	0.010	0.042
1997	0.343	0.029	0.170				
1998	0.371	0.032	0.168				
1999	0.478	0.041	0.206				
2000	0.424	0.037	0.186				

Table 2.23 – Model 19.1 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 1977-2018 as reference.

	MLE estimates		**MCMC posterior distribution**		
	MLE	**σ**	**50%**	**2.5%**	**97.5%**
$M_{Standard}$	0.4665	0.0217	0.4608	0.4169	0.4992
$M_{2014-2016}$	0.8231	0.0540	0.8134	0.6982	0.9252
Von Bert K	0.1686	0.0002	0.1675	0.1638	0.1713
Lmin	12.0887	0.3670	12.1361	11.3935	12.8171
Lmax	99.4614	0.0150	99.4617	99.4304	99.4897
$Ln(Q_{Trawl\ survey})$	0.1471	0.0879	0.1736	0.0120	0.3362
$Ln(Q_{ll\ survey})$	0.1631	0.0755	0.1879	0.0693	0.3393
$Ln(Q_{ll\ survey\ envir.})$	0.9406	0.3051	0.8196	0.4433	1.4110
$FSSB_{1978}$	119,850	25,067	119,272	81,632	173,754
$FSSB_{2020}$	34,361	3,762	33,491	26,752	40,606
Recr_1977	1,207,600	334,850	1,139,030	660,373	1,851,030
Recr_2012	1,215,100	261,200	1,158,660	763,190	1,793,680
$FSSB_{100\%}$	173,492	13,381	172,309	147,198	206,042
$FSSB_{2020}/FSSB_{100\%}$	0.1981	0.2811	0.1935	0.1550	0.2399

Table 2.24 – Biological reference points from GOA Pacific cod SAFE documents for years 2001 – 2020

Year	$SB_{100\%}$	$SB_{40\%}$	$F_{40\%}$	SB_{y+1}	ABC_{y+1}
2001	212,000	85,000	0.41	82,000	57,600
2002	226,000	90,300	0.35	88,300	52,800
2003	222,000	88,900	0.34	103,000	62,810
2004	211,000	84,400	0.31	91,700	58,100
2005	329,000	132,000	0.56	165,000	68,859
2006	259,000	103,000	0.46	136,000	68,859
2007	302,000	121,000	0.49	108,000	66,493
2008	255,500	102,200	0.52	88,000	55,300
2009	291,500	116,600	0.49	117,600	79,100
2010	256,300	102,500	0.42	124,100	86,800
2011	261,000	104,000	0.44	121,000	87,600
2012	234,800	93,900	0.49	111,000	80,800
2013	227,800	91,100	0.54	120,100	88,500
2014	316,500	126,600	0.50	155,400	102,850
2015	325,200	130,000	0.41	116,600	98,600
2016	196,776	78,711	0.53	105,378	88,342
2017	168,583	67,433	0.80	35,973	18,972
2018	172,240	68,896	0.76	34,515	19,665
2019	187,780	75,112	0.67	32,957	14,621
2020	180,111	72,045	0.62	39,977	23,627

Table 2.25 – Number of fish at age-1 from Model 19.1 with the M 2014-2016 block fixed at the standard M value used in projection model.

Year	Age-1	Year	Age-1
1977	157,493	2000	237,532
1978	805,621	2001	244,546
1979	297,345	2002	159,225
1980	266,423	2003	116,050
1981	365,814	2004	135,601
1982	495,194	2005	191,349
1983	520,273	2006	232,722
1984	276,676	2007	385,937
1985	479,970	2008	230,020
1986	536,082	2009	315,332
1987	280,501	2010	143,940
1988	348,285	2011	165,940
1989	385,913	2012	192,089
1990	419,836	2013	287,778
1991	443,279	2014	136,398
1992	242,064	2015	50,699
1993	217,034	2016	58,033
1994	178,720	2017	88,964
1995	213,928	2018	145,547
1996	261,174		
1997	175,191		
1998	165,797		
1999	142,272		

Table 2.26 – Results for the projection scenarios from Model 19.1. 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
2020	31,974	31,974	31,974	31,974	31,974	31,974	31,974
2021	39,977	39,977	39,977	39,977	39,977	39,977	39,977
2022	50,813	50,813	53,969	52,127	58,663	49,088	50,813
2023	62,363	62,363	71,363	67,542	81,808	59,100	62,363
2024	68,786	68,786	86,858	80,900	104,075	64,189	65,046
2025	71,569	71,569	99,000	90,896	123,688	65,908	65,999
2026	73,252	73,252	107,653	97,718	139,430	66,858	66,813
2027	74,667	74,667	114,208	102,730	152,639	67,835	67,804
2028	75,544	75,544	118,881	106,169	163,151	68,415	68,403
2029	75,626	75,626	121,338	107,795	169,949	68,279	68,276
2030	75,517	75,517	122,628	108,548	174,375	68,127	68,127
2031	75,507	75,507	123,329	108,933	177,226	68,130	68,130
2032	75,332	75,332	123,511	108,923	178,882	67,988	67,988
2033	75,058	75,058	123,363	108,672	179,713	67,731	67,731
F							
2020	0.11	0.11	0.11	0.11	0.11	0.11	0.11
2021	0.33	0.33	0.19	0.27	0.00	0.41	0.33
2022	0.43	0.43	0.19	0.27	0.00	0.52	0.43
2023	0.53	0.53	0.19	0.27	0.00	0.63	0.67
2024	0.57	0.57	0.19	0.27	0.00	0.68	0.68
2025	0.57	0.57	0.19	0.27	0.00	0.67	0.67
2026	0.57	0.57	0.19	0.27	0.00	0.67	0.67
2027	0.57	0.57	0.19	0.27	0.00	0.68	0.68
2028	0.57	0.57	0.19	0.27	0.00	0.68	0.68
2029	0.57	0.57	0.19	0.27	0.00	0.68	0.68
2030	0.57	0.57	0.19	0.27	0.00	0.68	0.68
2031	0.57	0.57	0.19	0.27	0.00	0.68	0.68
2032	0.57	0.57	0.19	0.27	0.00	0.68	0.68
2033	0.57	0.57	0.19	0.27	0.00	0.68	0.68
Catch							
2020	6,431	6,431	6,431	6,431	6,431	6,431	6,431
2021	23,627	23,627	13,997	19,592	0	28,977	23,627
2022	38,141	38,141	18,759	25,491	0	43,781	38,141
2023	56,009	56,009	24,300	32,382	0	61,863	67,978
2024	65,404	65,404	29,135	38,195	0	71,218	72,657
2025	67,669	67,669	32,864	42,469	0	73,169	73,269
2026	69,455	69,455	35,512	45,384	0	74,572	74,489
2027	71,093	71,093	37,470	47,473	0	76,135	76,084
2028	71,717	71,717	38,812	48,837	0	76,734	76,717
2029	71,772	71,772	39,521	49,481	0	76,424	76,419
2030	71,655	71,655	39,892	49,781	0	76,239	76,238
2031	71,475	71,475	40,073	49,906	0	75,974	75,975
2032	71,209	71,209	40,105	49,872	0	75,739	75,739
2033	71,010	71,010	40,062	49,772	0	75,409	75,410

Table 2.27 – Results for the projection scenarios from Model 20.1 from Stock Sythesis projection model. 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
2020	6,431	6,431	6,431	6,431	6,431	6,431	6,431
2021	26,533	26,533	26,024	6,180	-	32,438	27,079
2022	38,266	38,266	37,777	11,628	-	43,370	38,597
2023	46,064	46,064	45,673	17,681	-	49,893	55,361
2024	52,228	52,228	51,883	20,880	-	55,647	57,082
2025	64,771	64,771	64,338	24,297	-	69,196	69,379
2026	75,591	75,591	75,166	27,892	-	79,755	80,074
2027	78,792	78,792	77,927	31,143	-	83,948	84,715
2028	80,601	80,601	79,910	33,829	-	85,537	86,196
2029	82,178	82,178	81,579	35,948	-	87,164	87,426
2030	83,638	83,638	83,078	37,606	-	88,948	88,999
2031	84,820	84,820	84,279	38,894	-	90,168	90,201
2032	85,650	85,650	85,128	39,879	-	90,723	90,776
2033	86,196	86,196	85,695	40,618	-	90,941	90,982
F							
2020	0.10	0.10	0.10	0.10	0.10	0.10	0.10
2021	0.37	0.37	0.36	0.08	0.00	0.47	0.38
2022	0.46	0.46	0.45	0.11	0.00	0.55	0.46
2023	0.51	0.51	0.50	0.14	0.00	0.60	0.63
2024	0.54	0.54	0.53	0.14	0.00	0.63	0.64
2025	0.61	0.61	0.60	0.14	0.00	0.71	0.71
2026	0.66	0.66	0.65	0.14	0.00	0.77	0.77
2027	0.67	0.67	0.65	0.14	0.00	0.79	0.80
2028	0.67	0.67	0.65	0.14	0.00	0.80	0.80
2029	0.67	0.67	0.65	0.14	0.00	0.81	0.81
2030	0.67	0.67	0.65	0.14	0.00	0.82	0.82
2031	0.67	0.67	0.65	0.14	0.00	0.82	0.82
2032	0.67	0.67	0.65	0.14	0.00	0.83	0.83
2033	0.67	0.67	0.65	0.14	0.00	0.83	0.83
Catch							
2020	6,431	6,431	6,431	6,431	6,431	6,431	6431
2021	26,533	26,533	26,024	6,180	-	32,438	27078.5
2022	38,266	38,266	37,777	11,628	-	43,370	38597.1
2023	46,064	46,064	45,673	17,681	-	49,893	55361.3
2024	52,228	52,228	51,883	20,880	-	55,647	57082.3
2025	64,771	64,771	64,338	24,297	-	69,196	69379.2
2026	75,591	75,591	75,166	27,892	-	79,755	80074.2
2027	78,792	78,792	77,927	31,143	-	83,948	84715.2
2028	80,601	80,601	79,910	33,829	-	85,537	86195.8
2029	82,178	82,178	81,579	35,948	-	87,164	87,426
2030	83,638	83,638	83,078	37,606	-	88,948	88,999
2031	84,820	84,820	84,279	38,894	-	90,168	90,201
2032	85,650	85,650	85,128	39,879	-	90,723	90,776
2033	86,196	86,196	85,695	40,618	-	90,941	90,982

Table 2.28 – Delta-LM covariate fits and standard errors for converting the annual Gulf of Alaska June sea surface temperature anomaly to a spawning marine heatwave cumulative index value.

Covariate	Value	Std. Error
β_0	-2.8593	0.8117
β_1	3.6810	1.2133
β_2	-21.48	11.96
β_3	89.60	17.50

Table 2.29– Percent change in simple model averaged spawning biomass and catch from Model 20.1 for RCP 2.6 and RCP 4.5 projection scenarios for the 5 climate models as a difference from projections generated for the same time period assuming constant 1982-2012 climate conditions.

	Time period	RCP 2.6	RCP 4.5
Δ unfished spawning biomass	2022-2049	3.32%	0.50%
	2050-2099	20.37%	17.67%
Δ spawning biomass with fishing	2022-2049	9.98%	12.92%
	2050-2099	23.26%	27.38%
Δ projected catch	2022-2049	11.53%	14.99%
	2050-2099	30.29%	36.47%

Figures

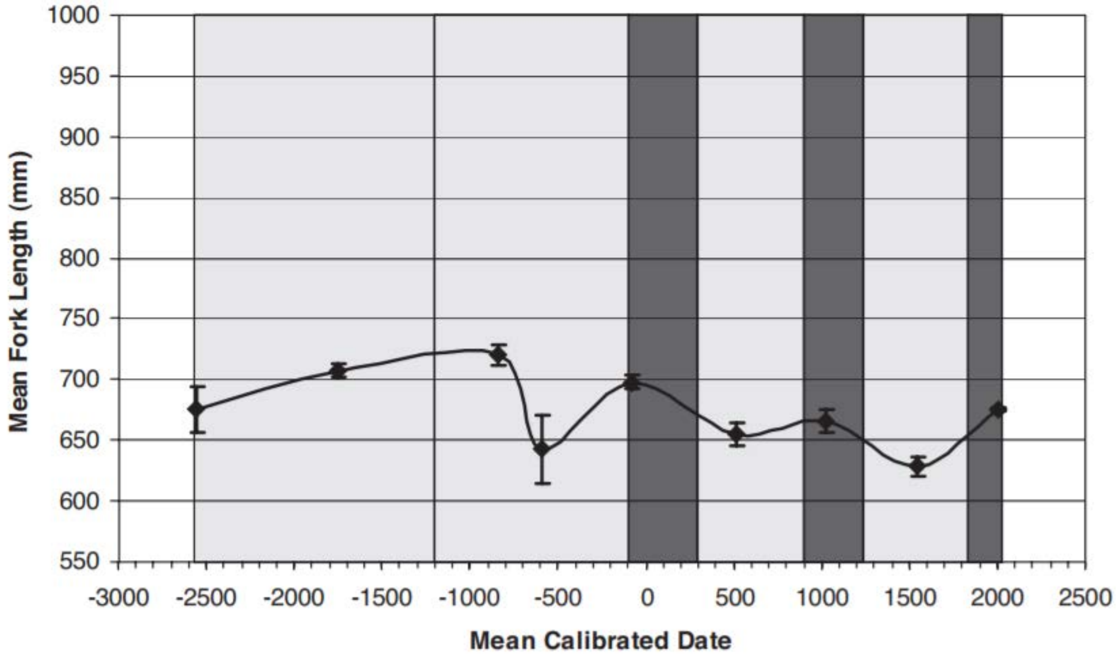


Figure 2.1 Gulf of Alaska mean lengths with climate reconstruction. The shaded boxes represent periods of significant changes in air temperature, sea surface temperature, storminess, and ocean circulation that drive ocean productivity. The lightly shaded boxes represent periods of cooler and stormier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

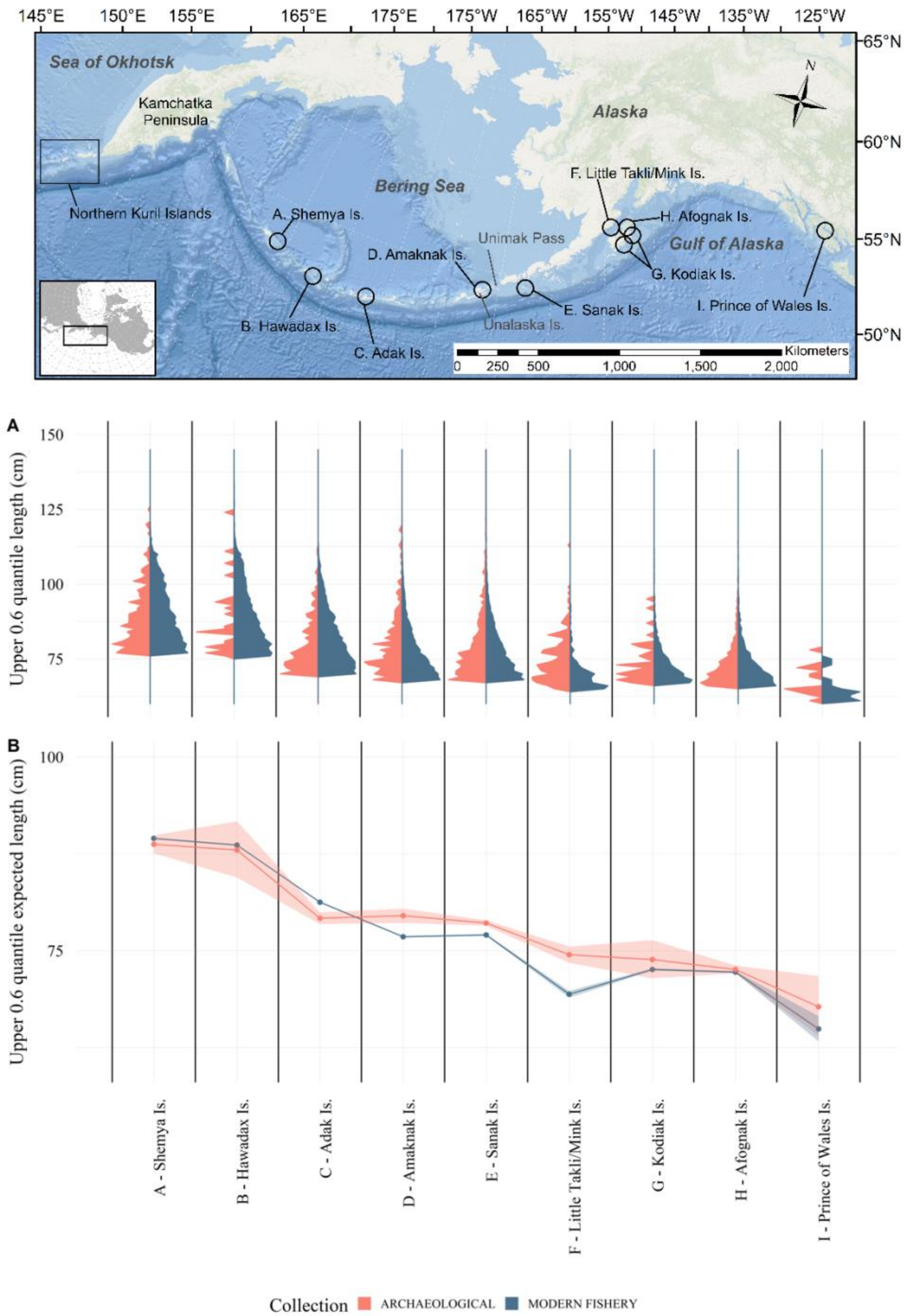


Figure 2.2 (A) The 0.6 quantile of the length distribution of Pacific cod from the Alaska archaeological collections (red) and modern longline and jig commercial fishery data (blue) within 50 km of the archaeological sites; and (B) log-linked gamma generalized linear regression results of Alaska modern fishery and archaeological collections by site showing expected lengths and 95% confidence intervals (From West *et al.* 2020; Figure 1 and Figure 5).

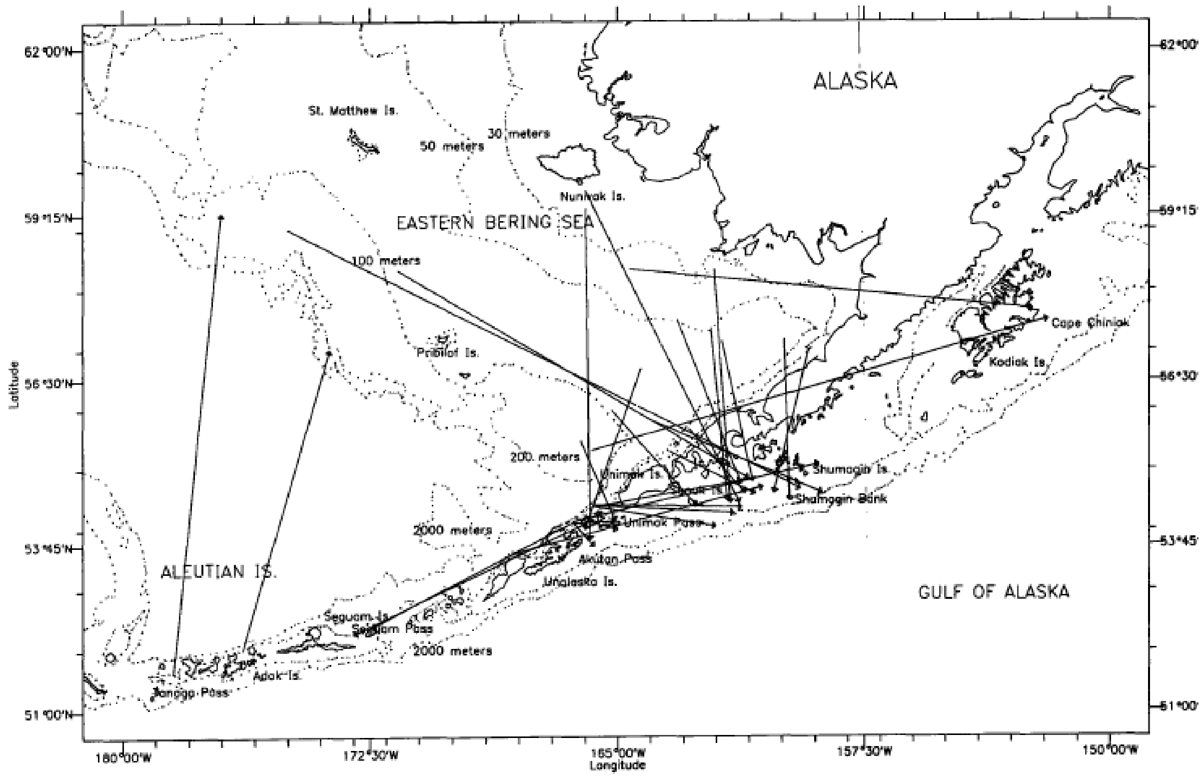


Figure 2.3 Tag recoveries from Shimada and Kimura 1994 (Figure 8), showing movement of individual tagged Pacific cod from eastern Bering Sea into the Gulf of Alaska and other interregional migrations.

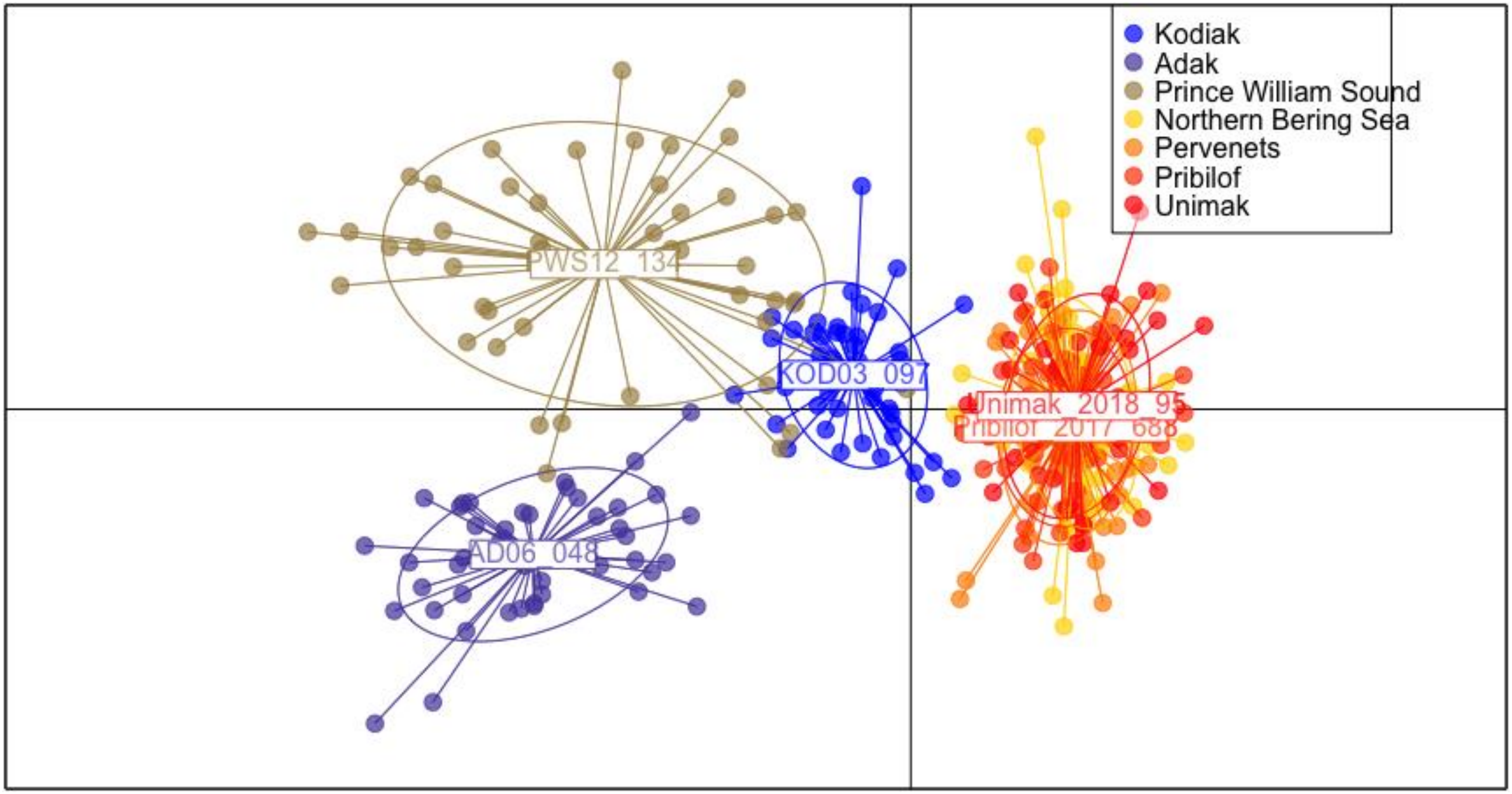


Figure 2.4 Discriminant analysis of principal components (DAPC) scatterplot with the following populations represented: Adak (2006), Prince William Sound, PWS (2012), Kodiak (2003), Unimak (2018), Pervenets (2016), Pribilof (2017), and Norton Sound, NBS (2017). All populations represent spawning groups 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.

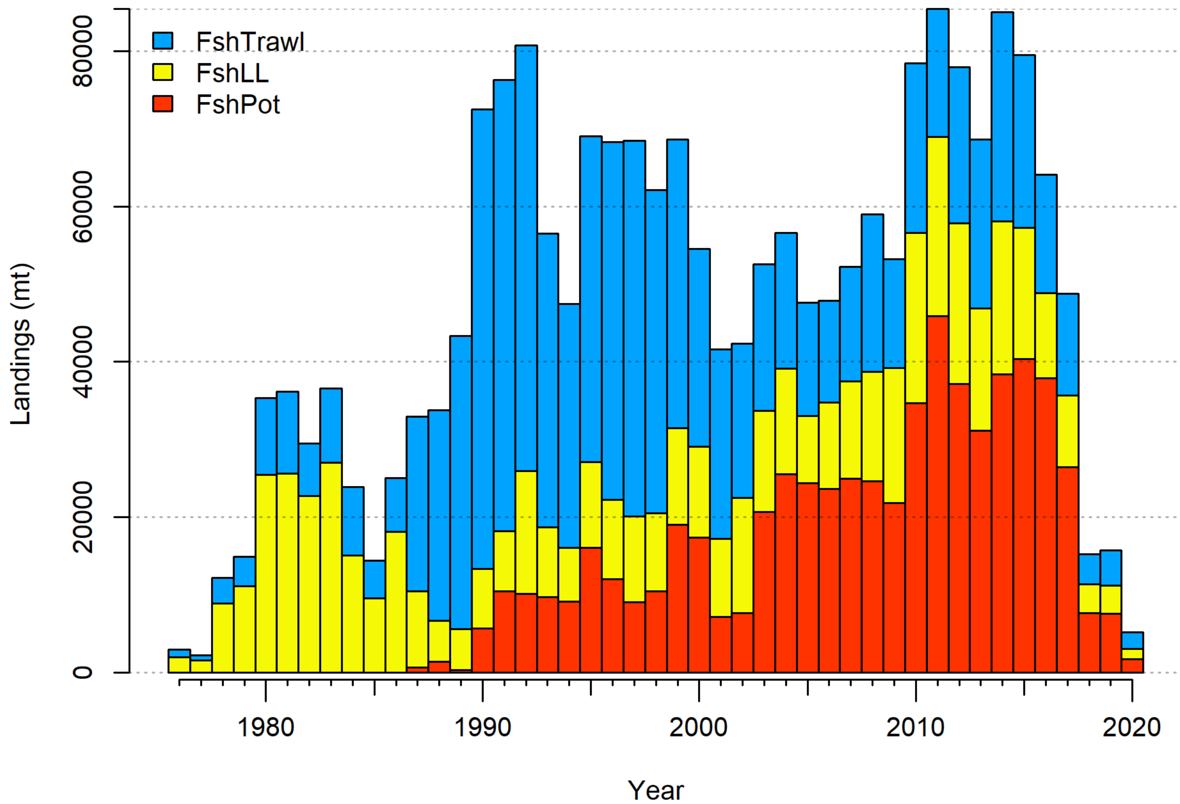


Figure 2.5 Gulf of Alaska Pacific cod catch from 1977-2020. Note that 2020 catch was through October 2.

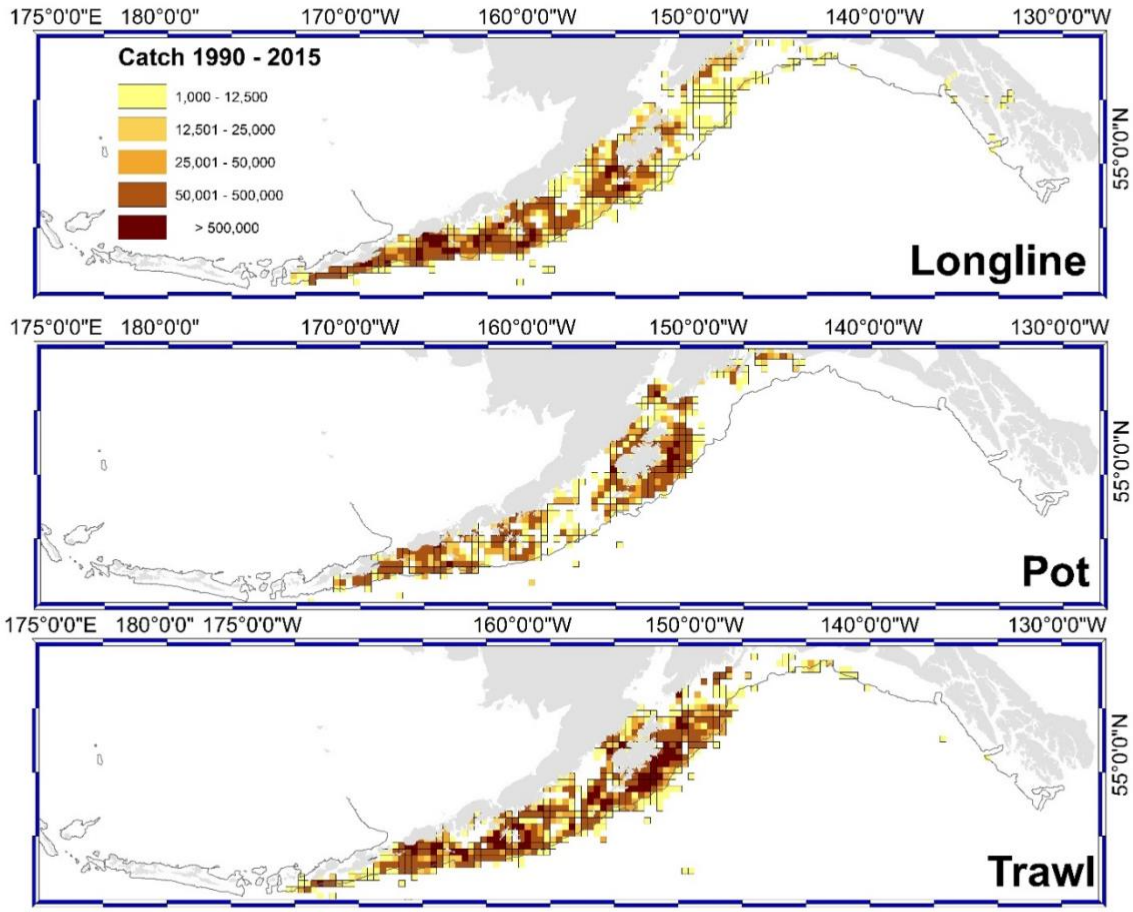


Figure 2.6 Commercial catch of Pacific cod in the Gulf of Alaska by 20km^2 grid for 1990-2015.

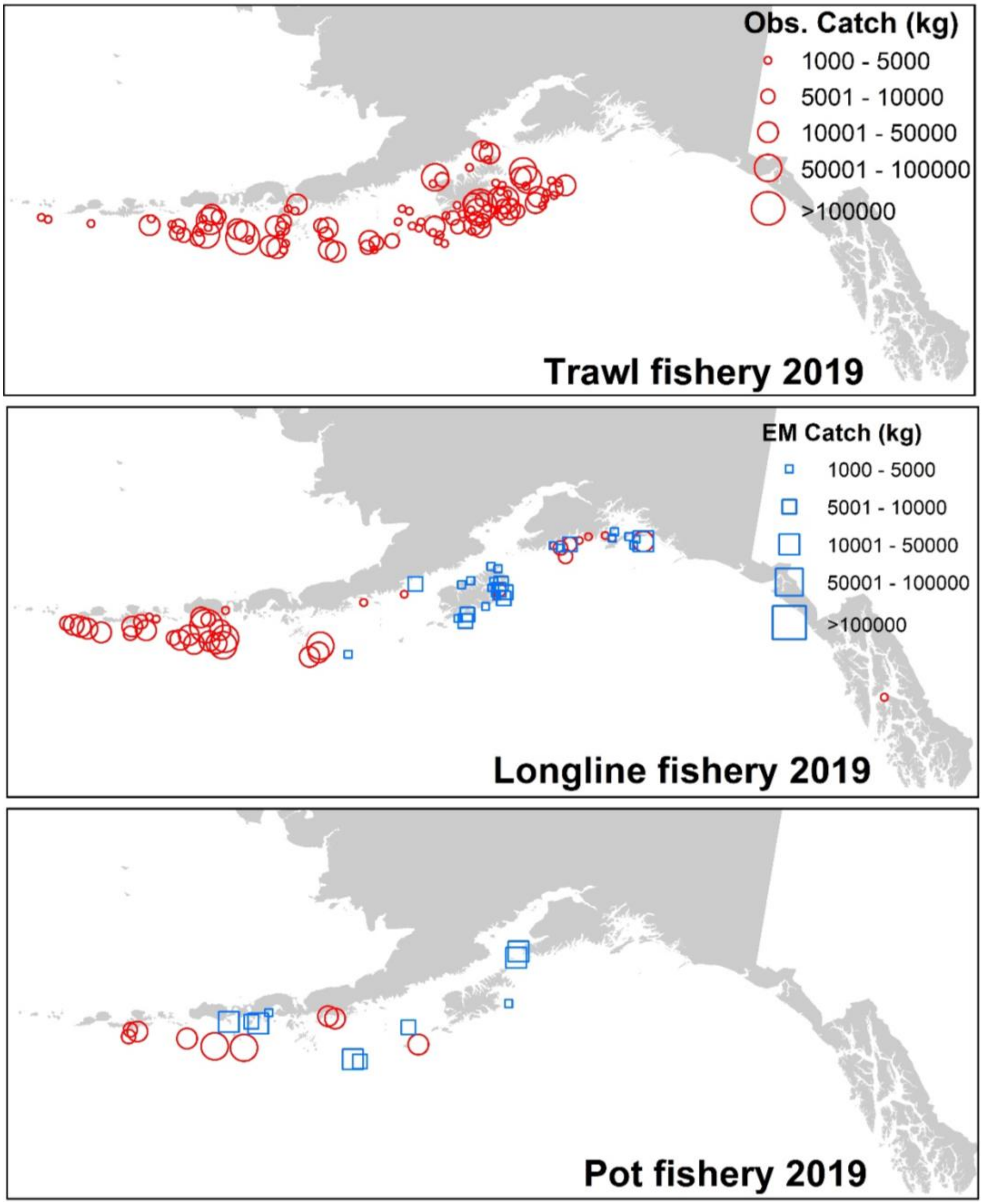


Figure 2.7 Commercial catch of Pacific cod in the Gulf of Alaska by 20km^2 grid for 2019 for catch greater than 1000 kg. Observed catch in red circles and EM catch for longline and pot in blue squares. These data include bycatch Pacific cod.

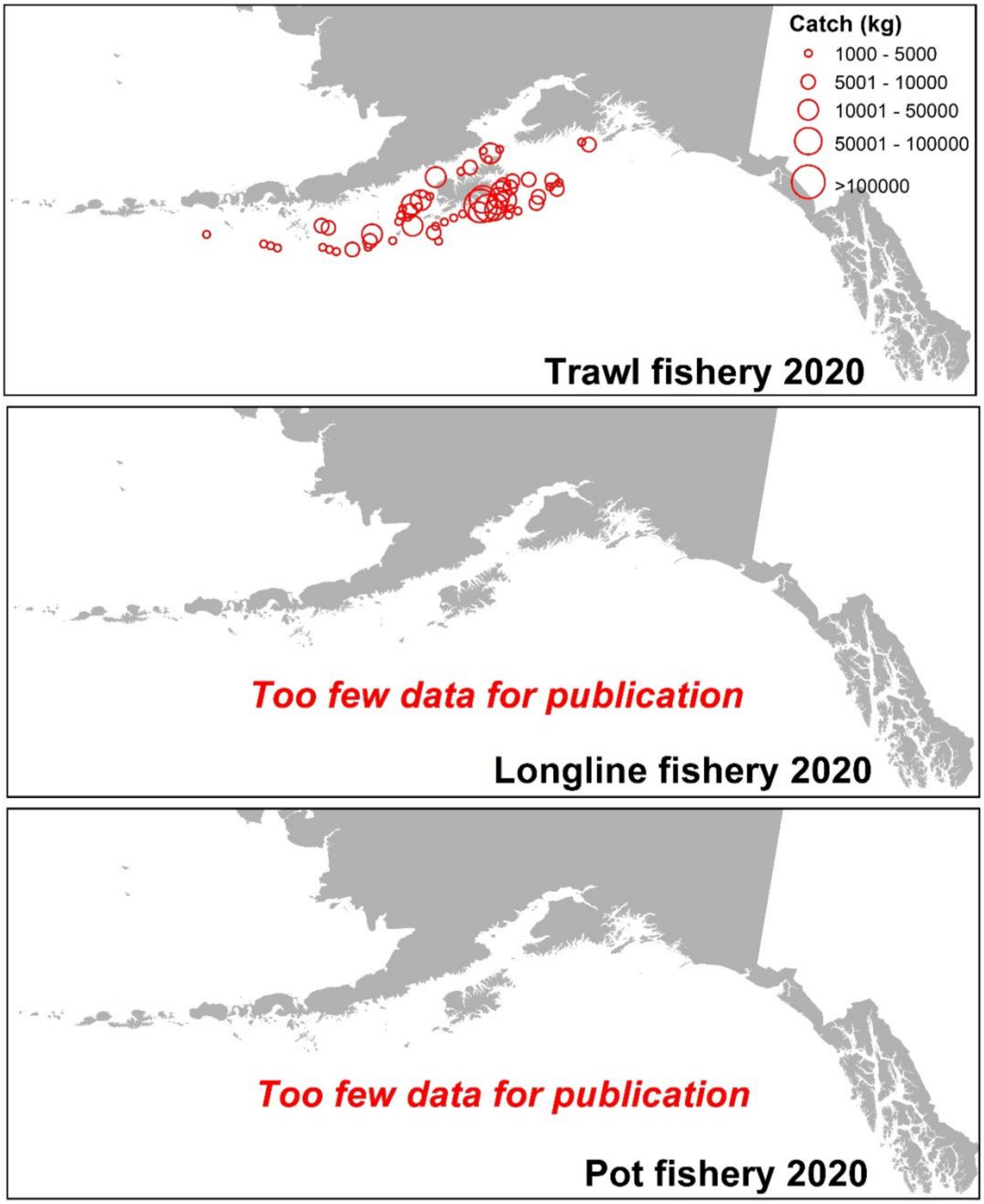


Figure 2.8 Observed commercial catch of Pacific cod in the Gulf of Alaska by 20km^2 grid for 2020 as of October 7, 2020 for catch greater than 1000 kg. These data include bycatch Pacific cod.

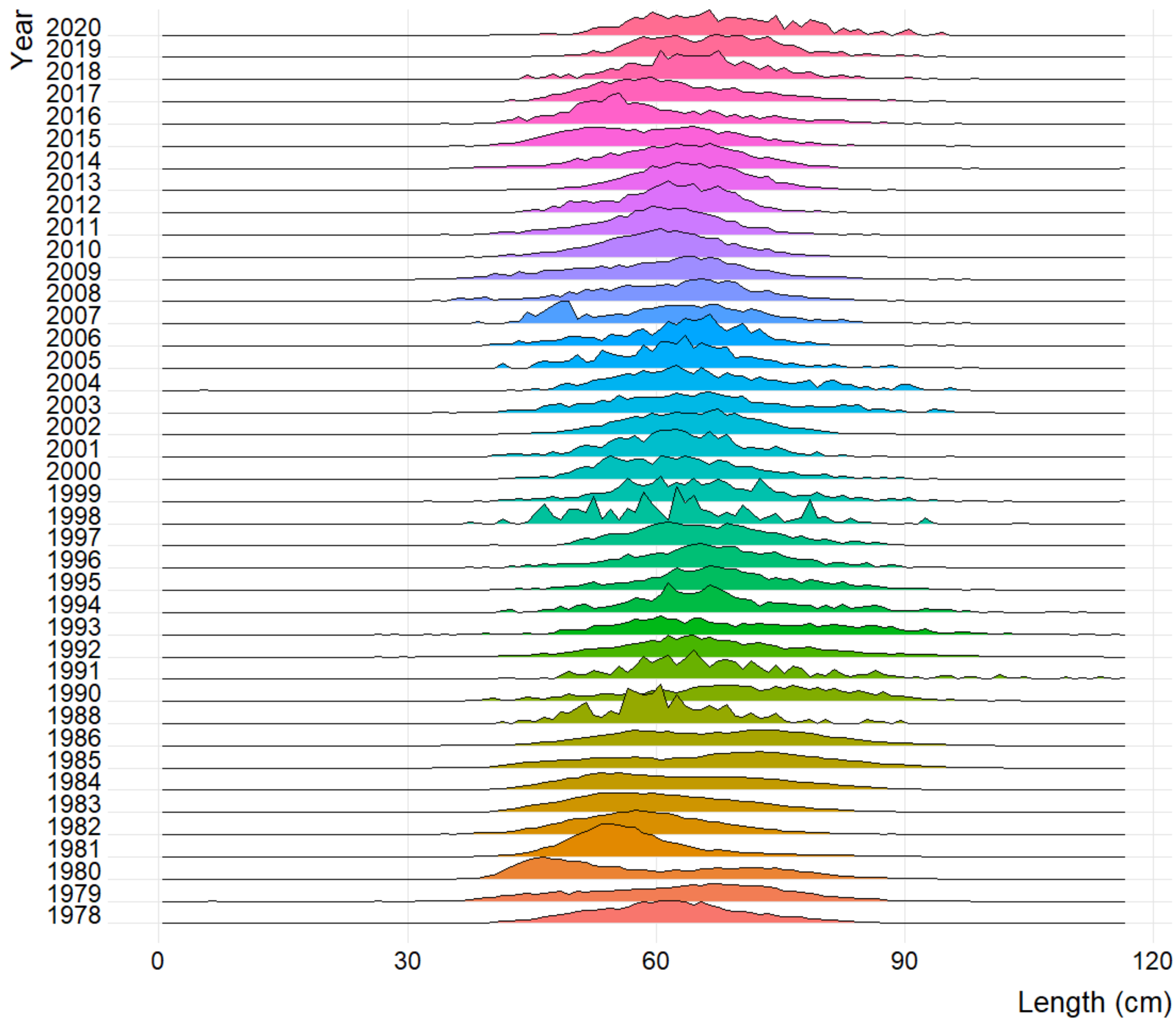


Figure 2.9 Pacific cod length composition by annual proportion from the Gulf of Alaska longline fishery.

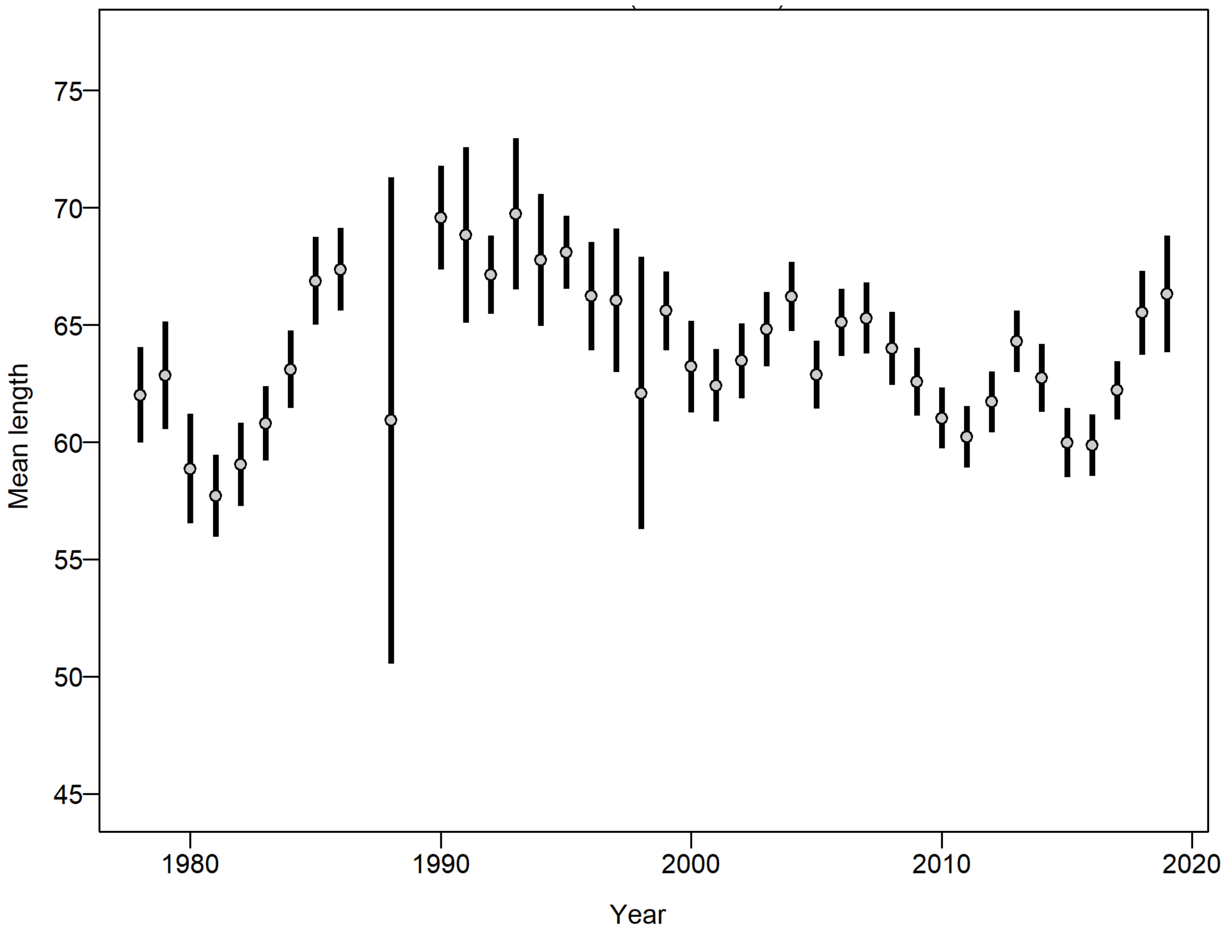


Figure 2.10 Mean length (cm) of Pacific cod from the Gulf of Alaska longline fishery.

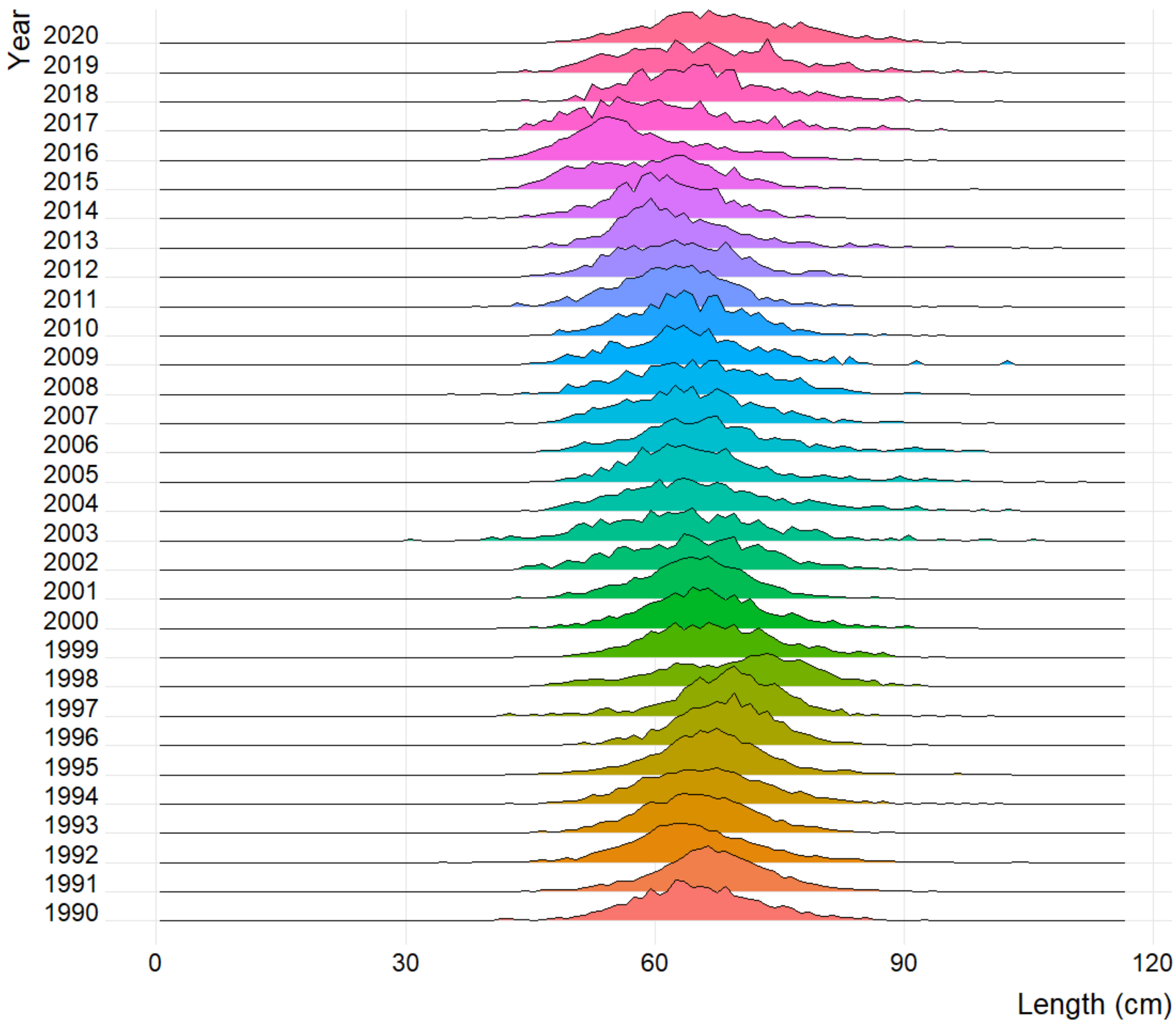


Figure 2.11 Pacific cod length composition by annual proportion from the Gulf of Alaska pot fishery.

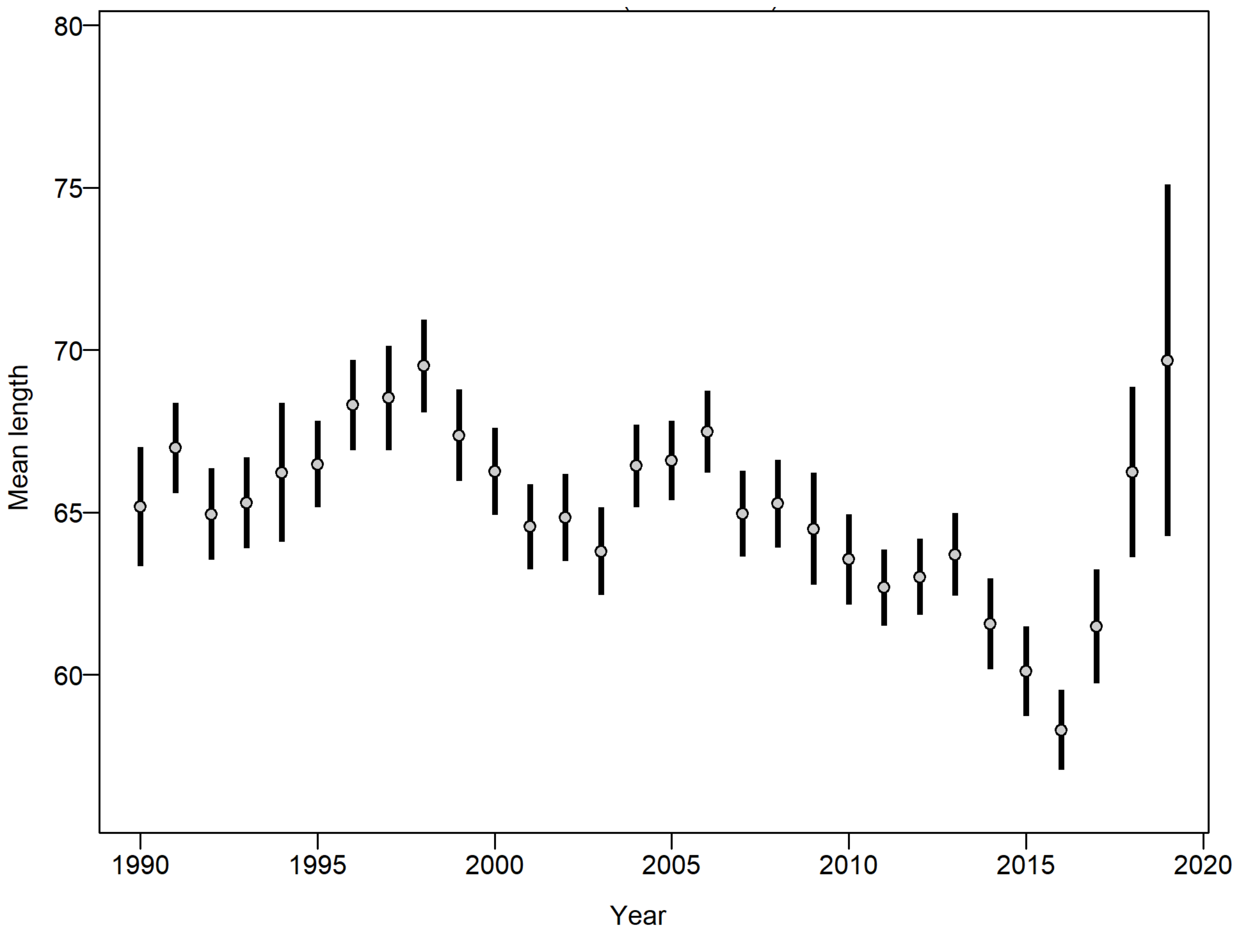


Figure 2.12 Mean length (cm) of Pacific cod from the Gulf of Alaska pot fishery.

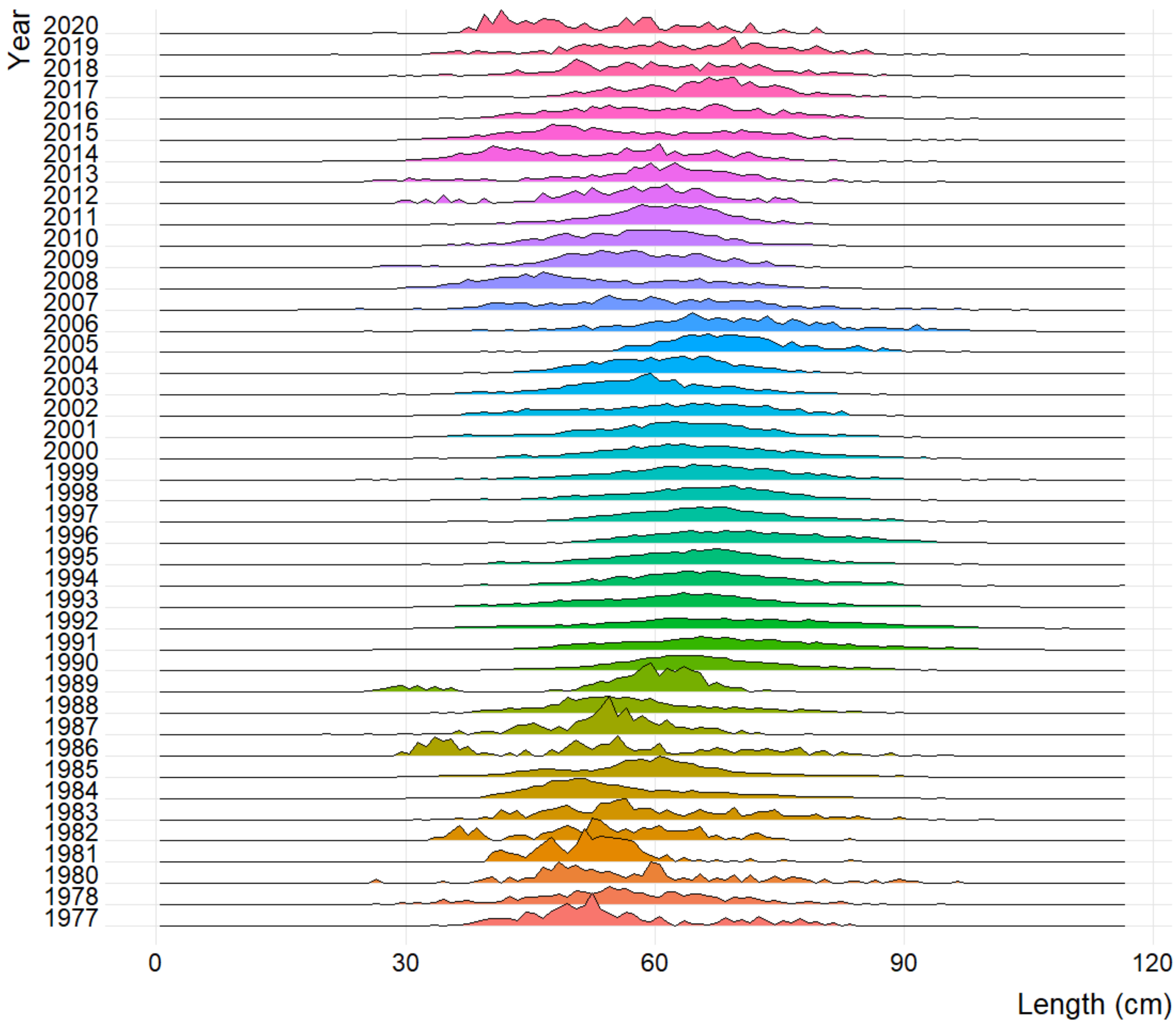


Figure 2.13 Pacific cod length composition by annual proportion from the Gulf of Alaska trawl fishery.

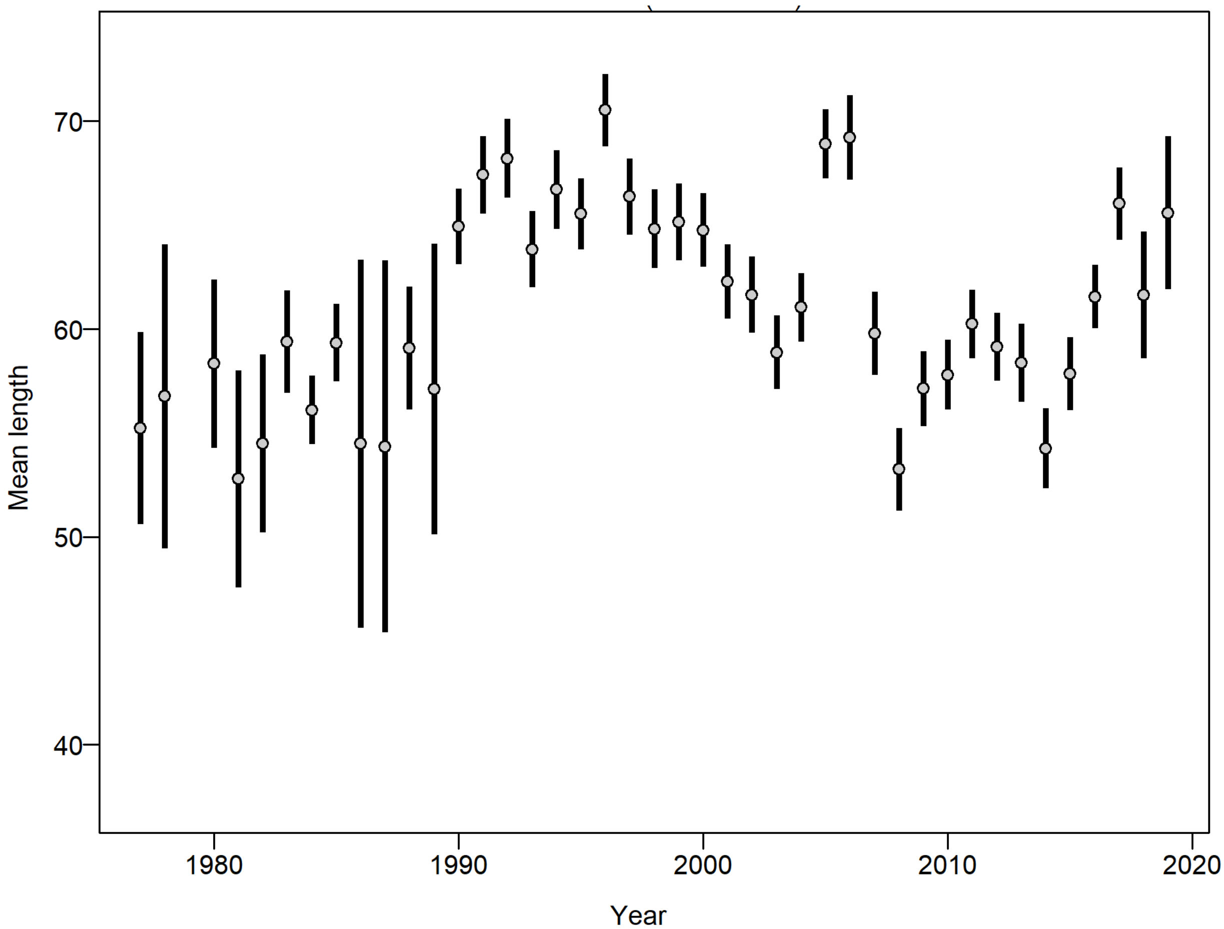


Figure 2.14 Mean length (cm) of Pacific cod from the Gulf of Alaska trawl fishery.

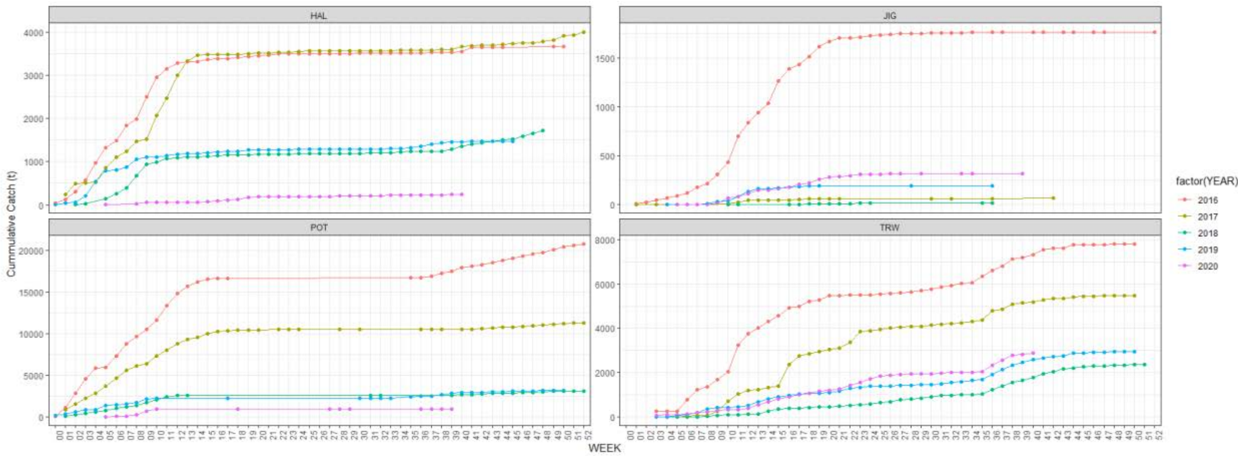


Figure 2.15 Cumulative catch by week of the year and gear for 2016-2020 in the Central regulatory area. 2020 data are through October 19, 2020.

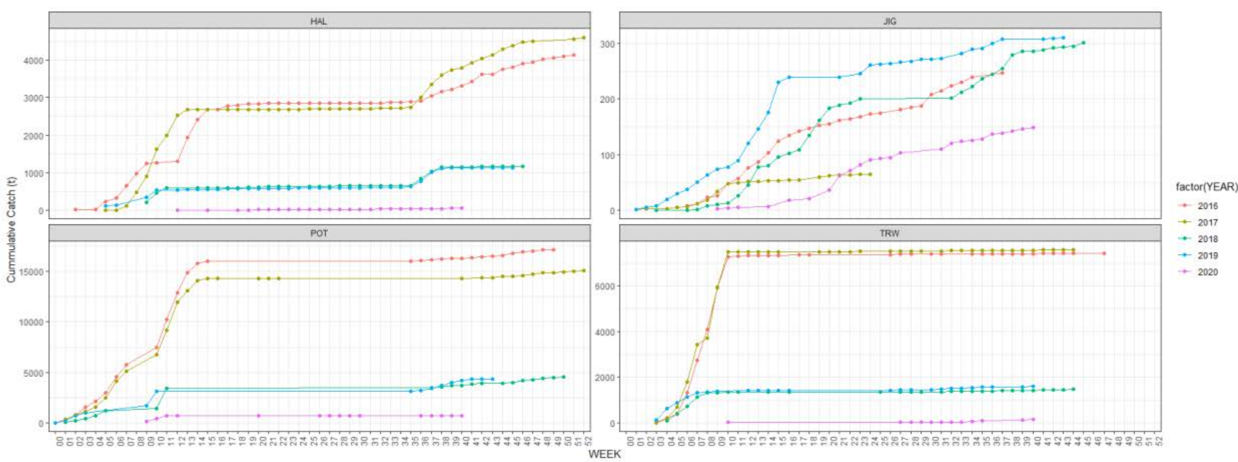


Figure 2.16 Cumulative catch by week of the year and gear for 2016-2020 in the Western regulatory area. The 2019 data are through October 19, 2020.

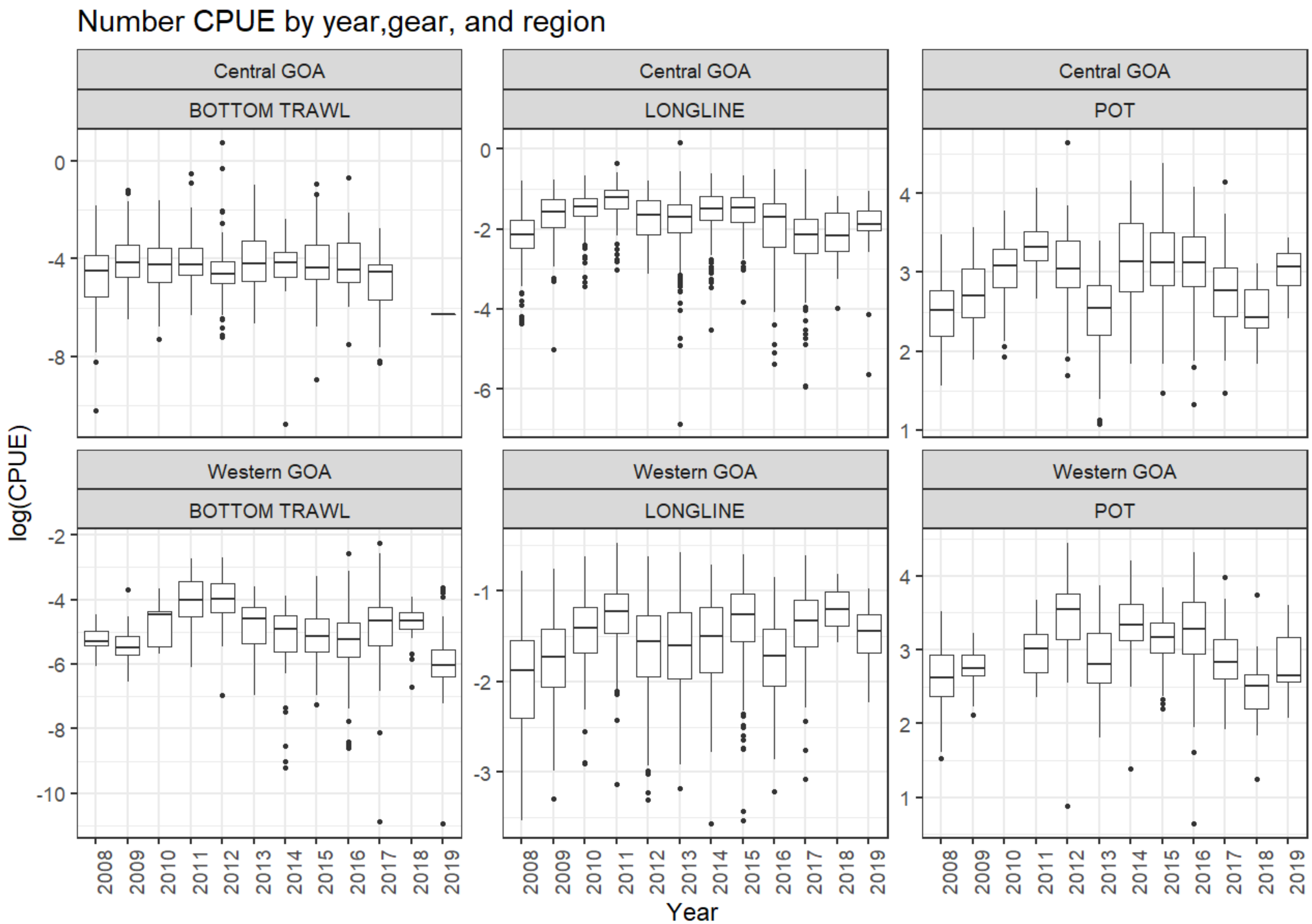


Figure 2.17 Boxplot of CPUE by number from the 2008-2019 Pacific cod CPUE for January-April for the Central (top) and Western (bottom) regulatory areas in the Pacific cod target fishery. Note that the data in these figures are not controlled for vessel or gear differences within a gear type across time, but shows the raw CPUE data distribution. These represent all observed catches and is limited to the directed cod fishery.

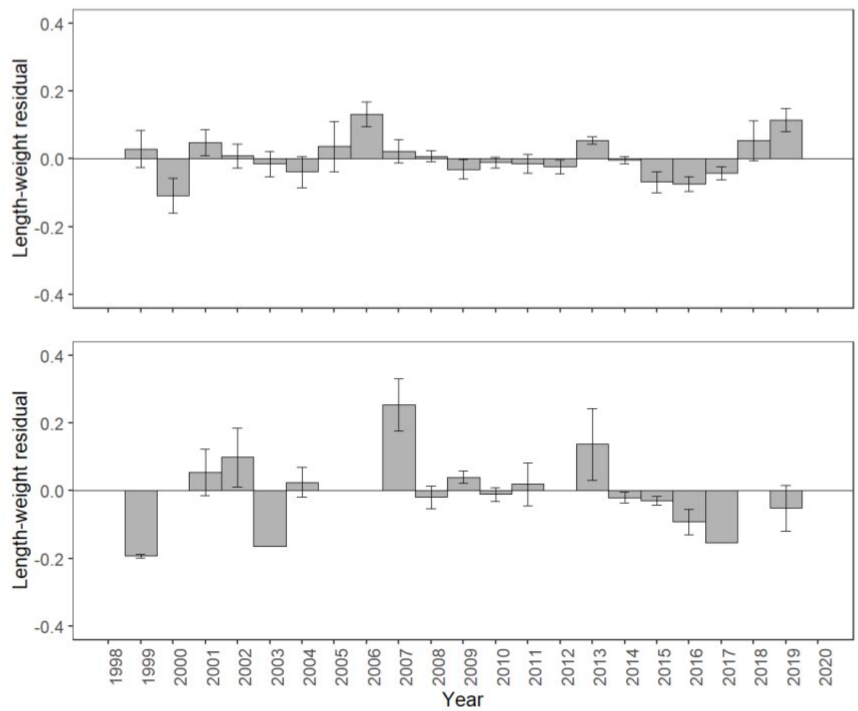


Figure 2.18 Condition of Pacific cod by year in the Central GOA for the longline January-April (top) and May-September (bottom).

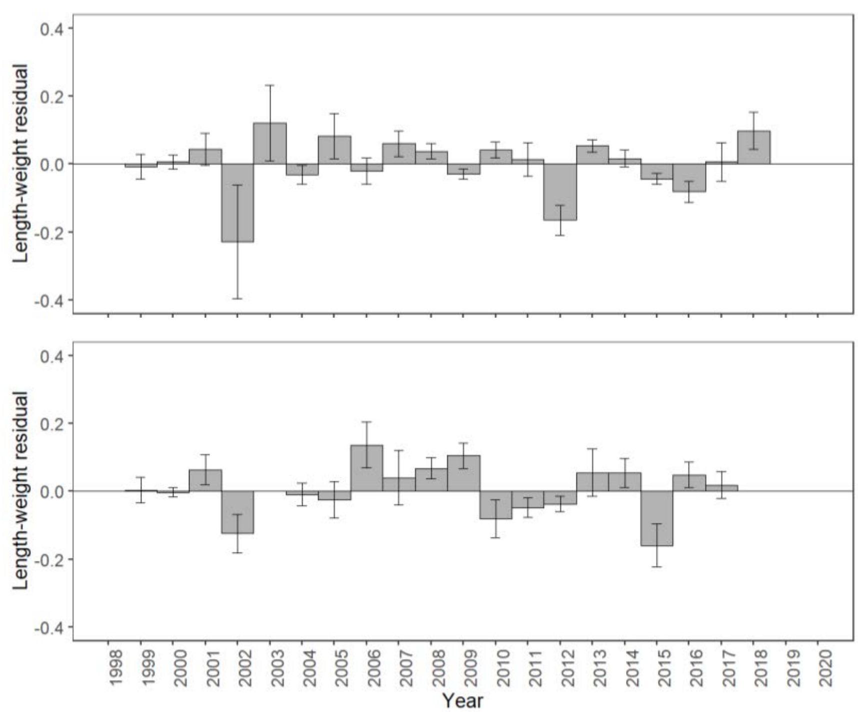


Figure 2.19 Condition of Pacific cod by length category and year in the Central GOA for the pot January-April (top) and May-September (bottom). Note that there are no pot fishery data for Central GOA in 2019 for either season and no data for 2018 May-September.

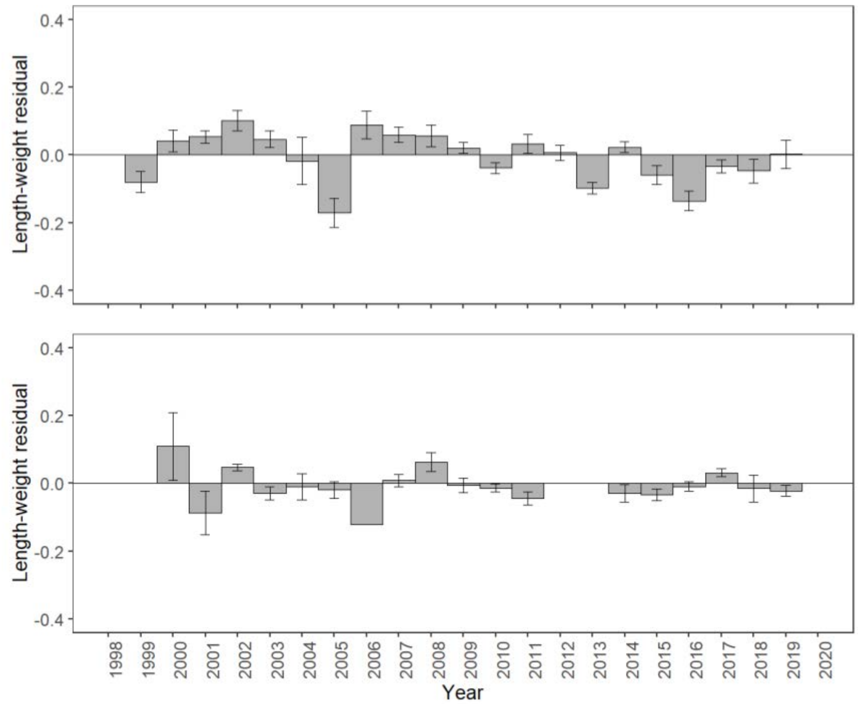


Figure 2.20 Condition of Pacific cod by year in the Western GOA for the longline January-April (top) and May-September (bottom).

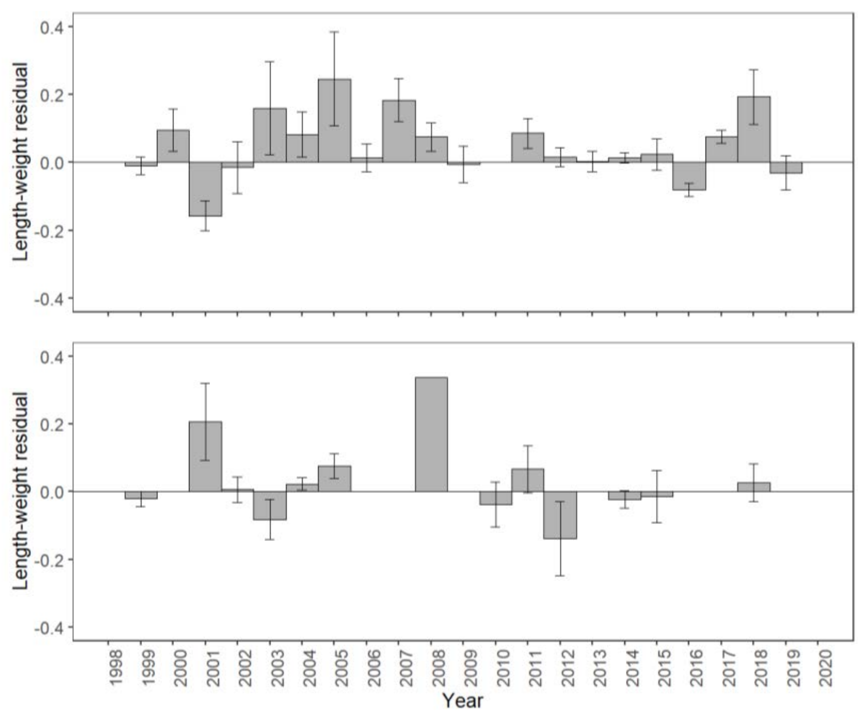


Figure 2.21 Condition of Pacific cod by year in the Western GOA for pot January-April (top) and May-September (bottom).

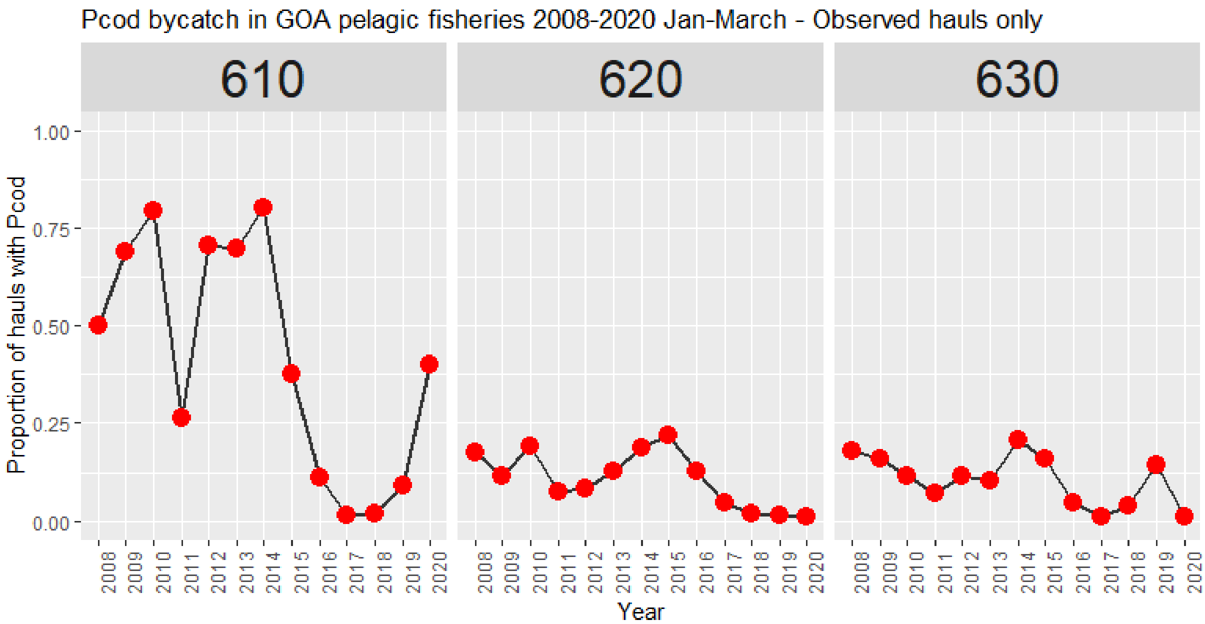


Figure 2.22 Proportion of pelagic trawls in the A Season (January-April) walleye pollock fishery with Pacific cod present by region.

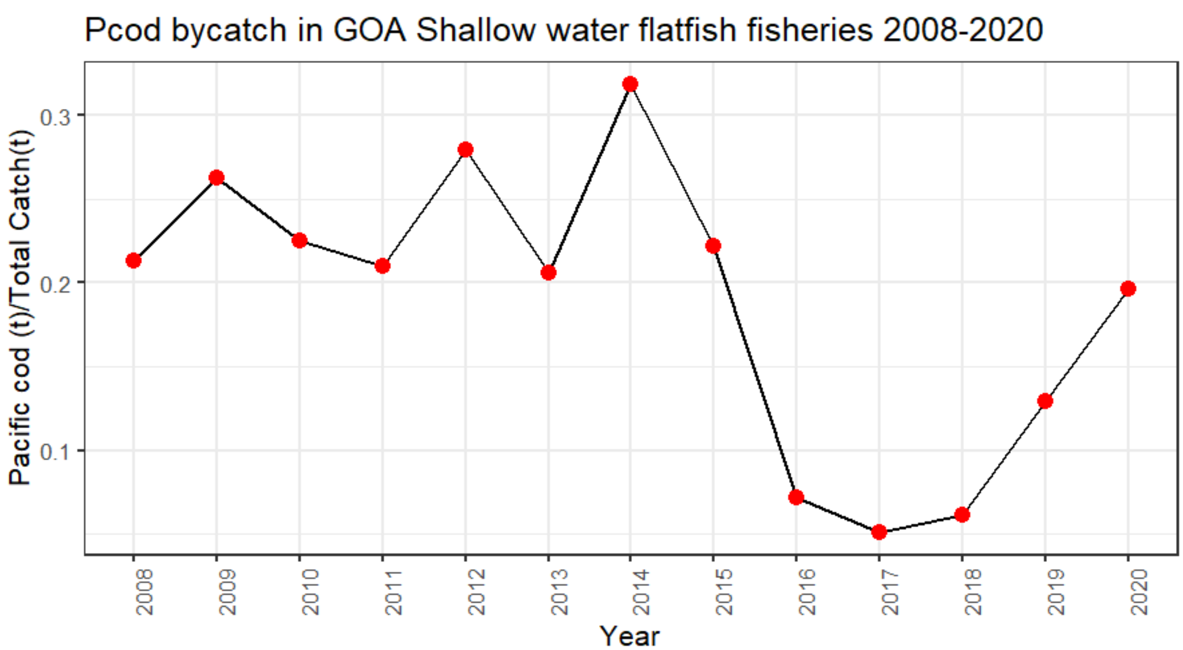


Figure 2.23 Pacific cod bycatch in the Gulf of Alaska shallow water flatfish fishery as tons of Pacific cod per tons of total catch in the fishery by year.

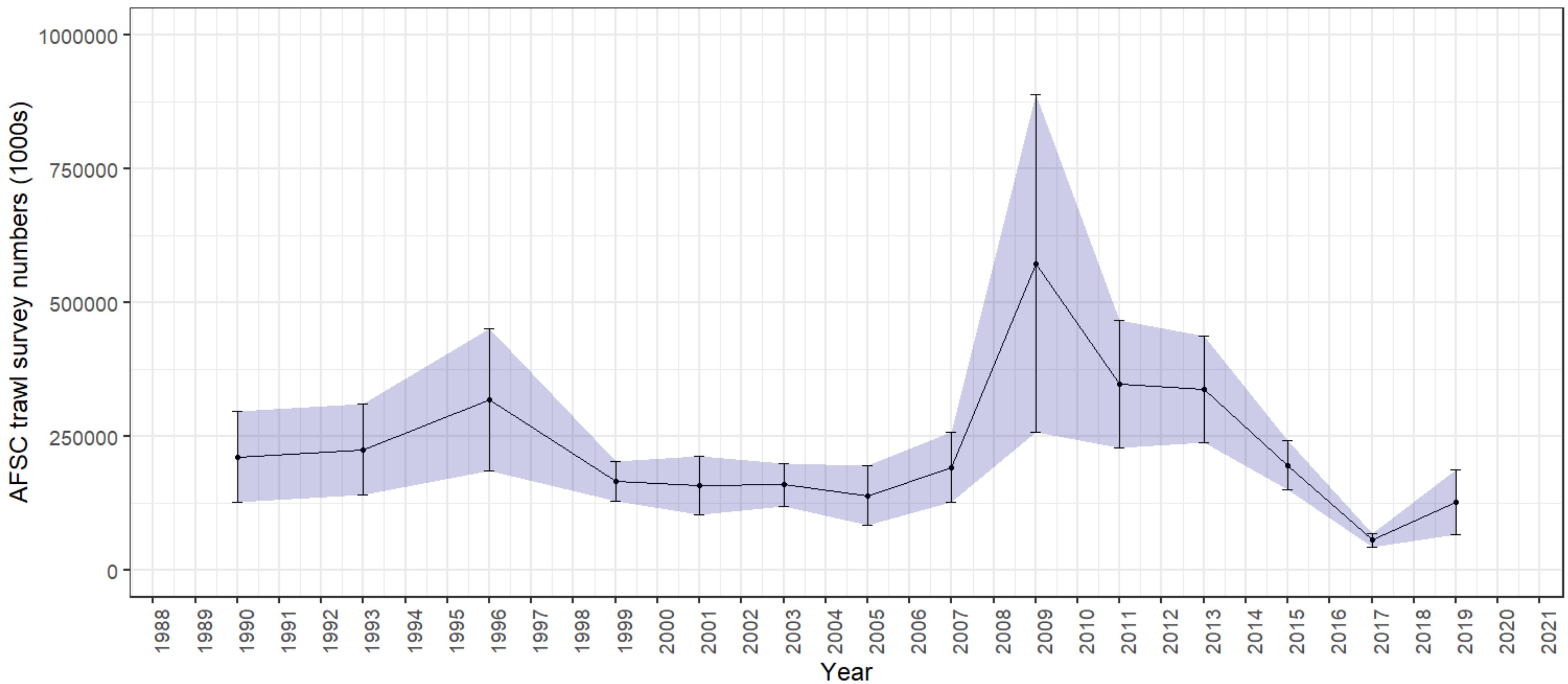


Figure 2.24 GOA bottom trawl survey abundance (numbers) estimate. Bars and shading indicate the 95th percentile confidence intervals.

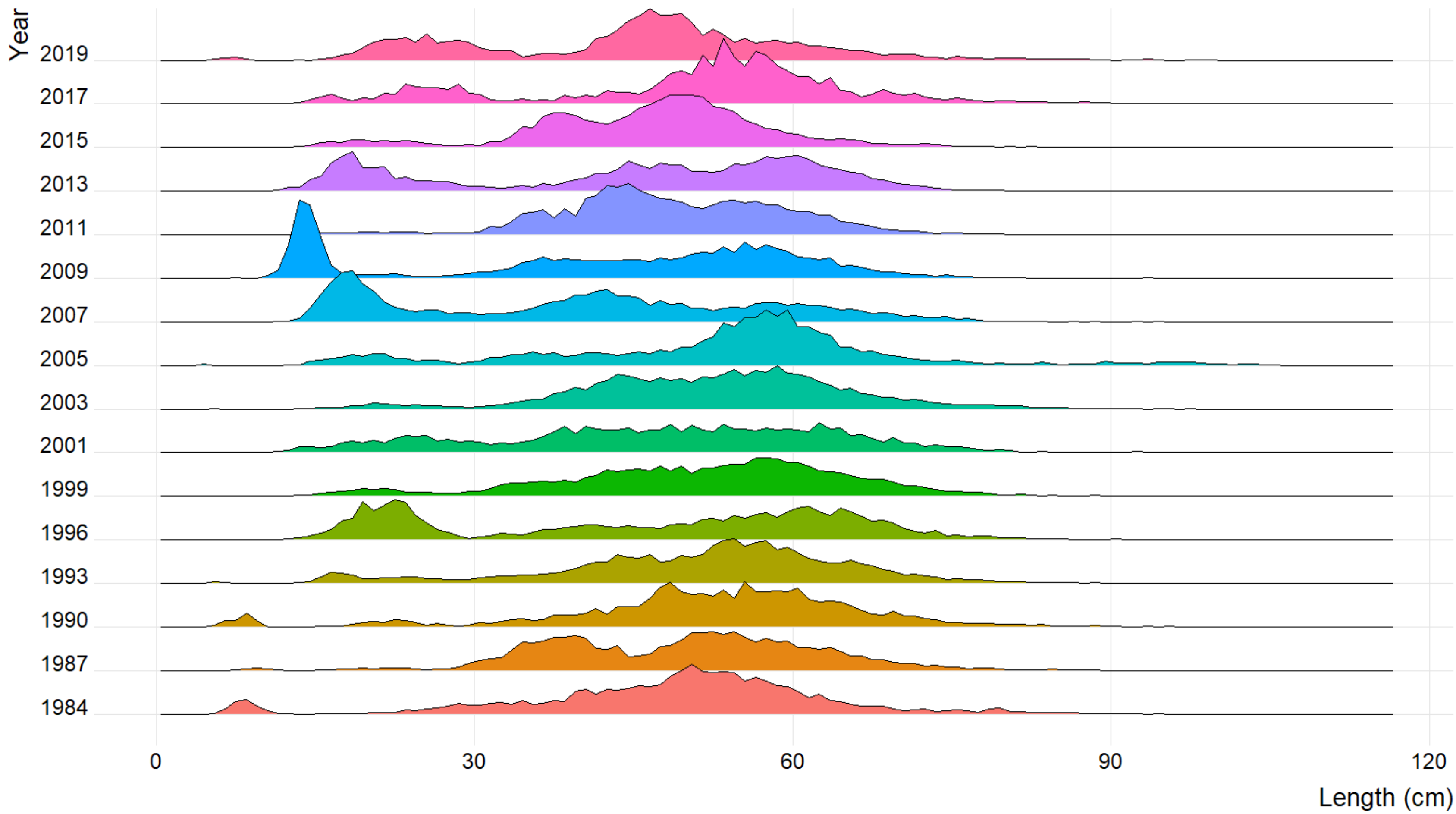


Figure 2.25 GOA bottom trawl survey Pacific cod population numbers at length estimates (max = 0.07).

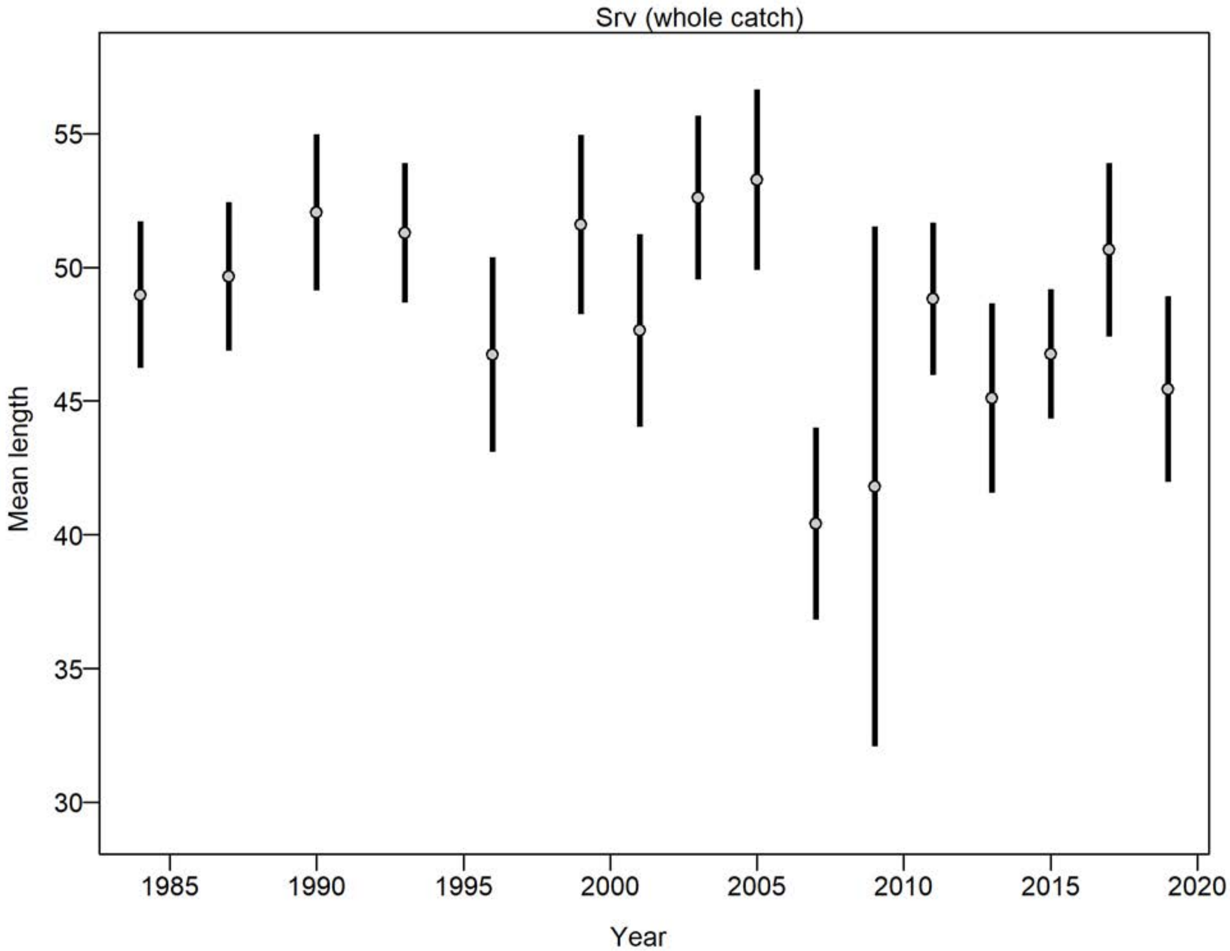


Figure 2.26 Mean length (cm) of Pacific cod in the GOA bottom trawl survey.

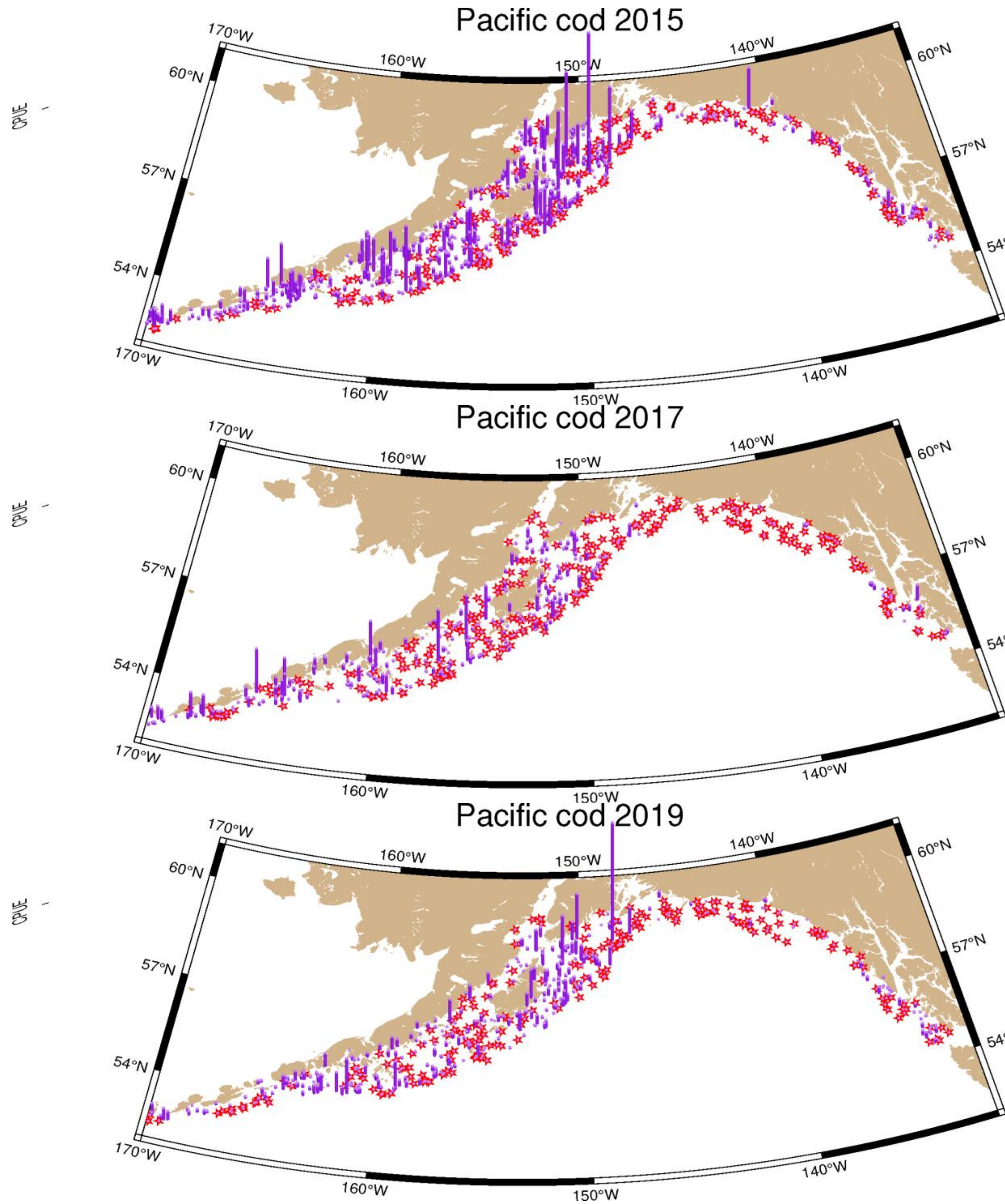


Figure 2.27 Distribution of AFSC bottom trawl survey CPUE of Pacific cod for 2015-2019.

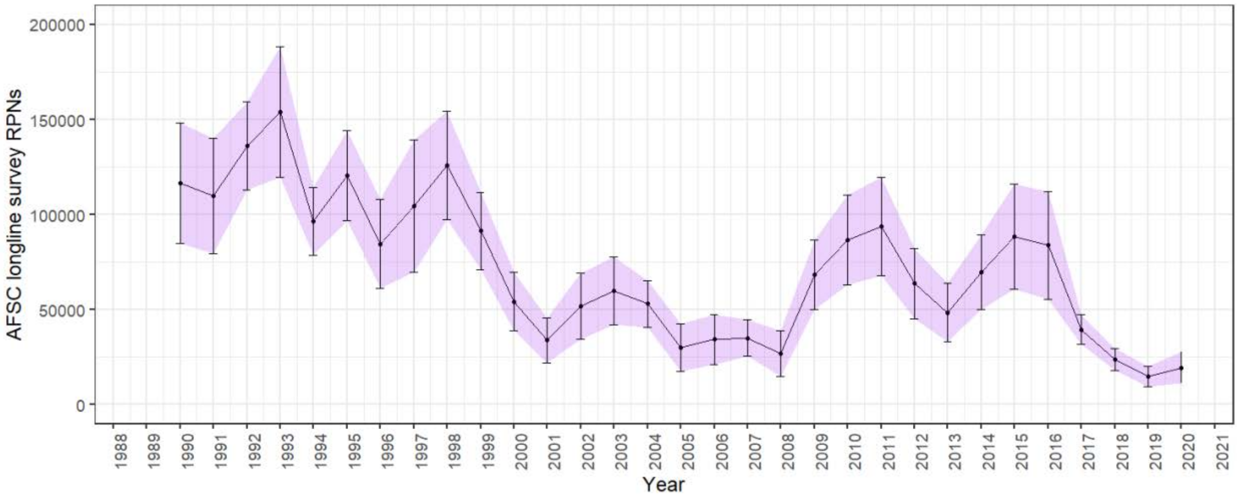


Figure 2.28 AFSC longline survey Pacific cod relative population numbers (RPN) time series. Bars and shading indicate the 95th percentile confidence intervals.

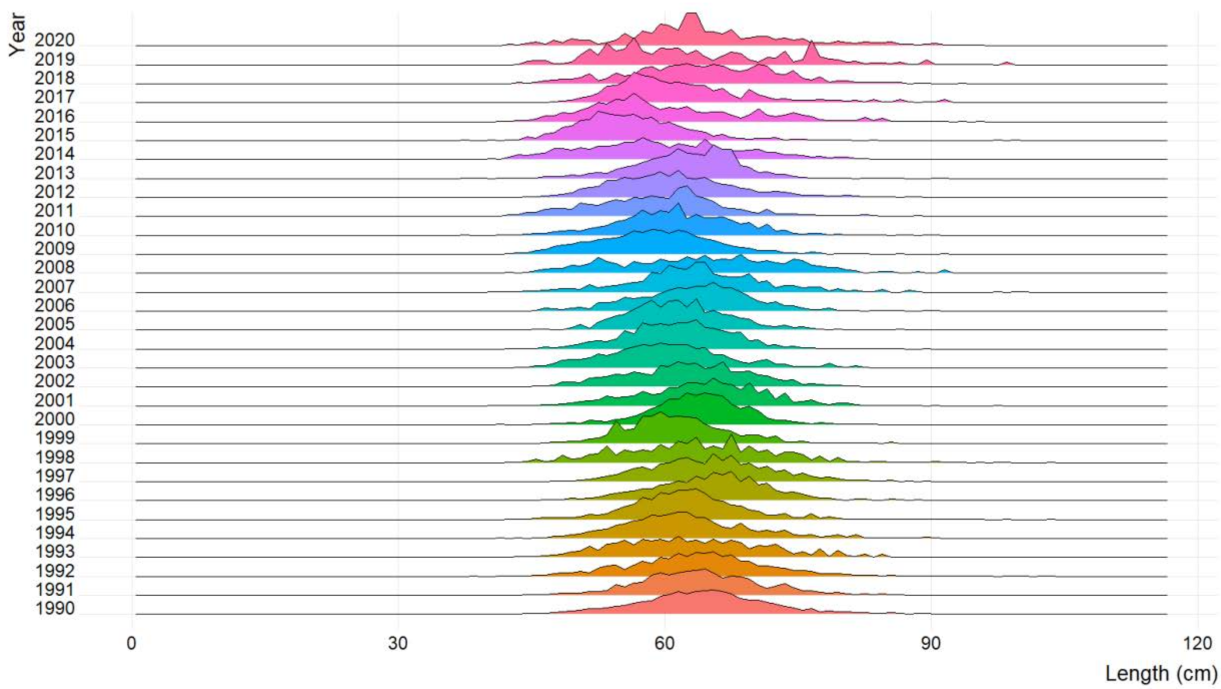


Figure 2.29 AFSC longline survey Pacific cod size composition (max=0.09).

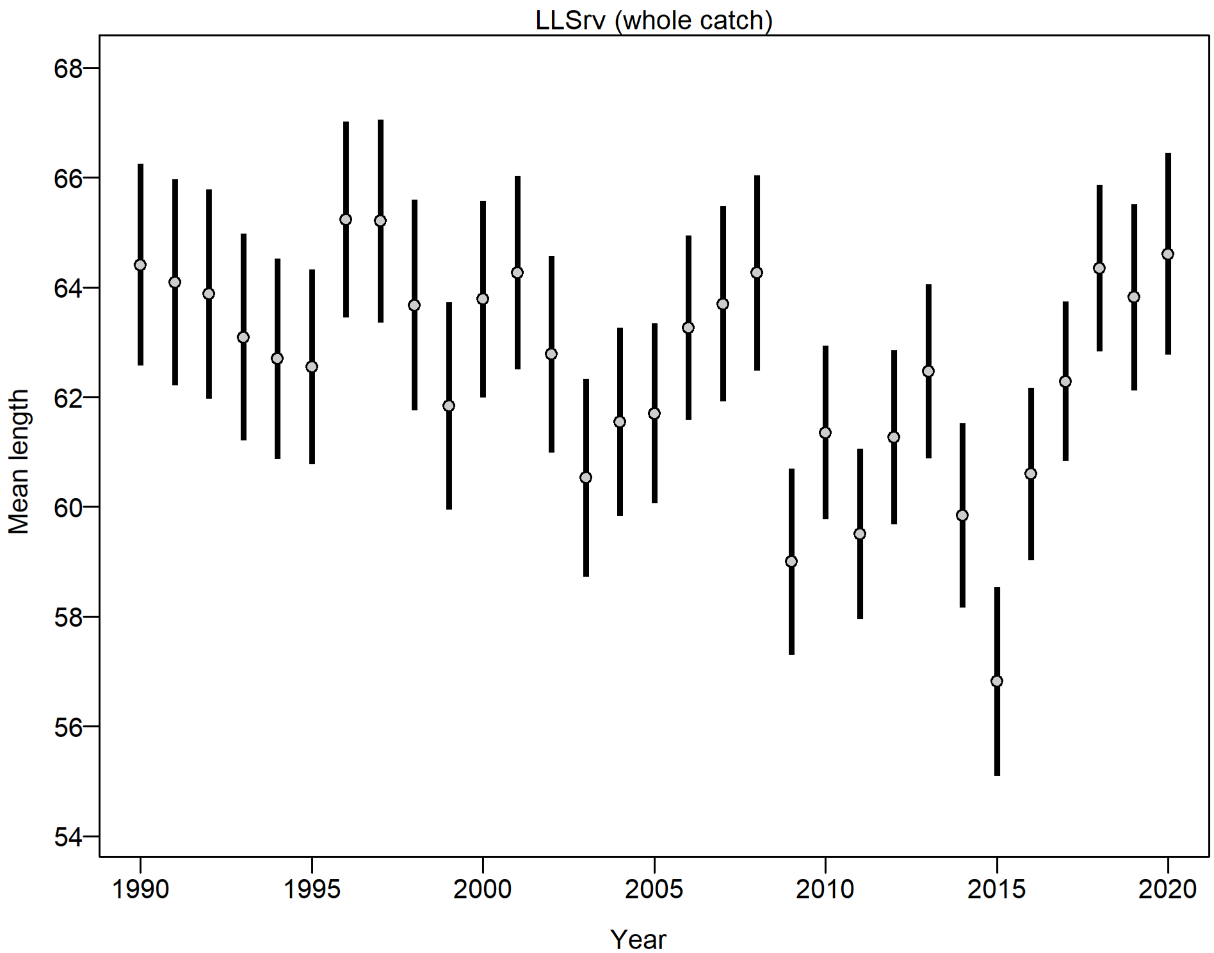


Figure 2.30 Mean length (cm) of Pacific cod from the AFSC longline survey.

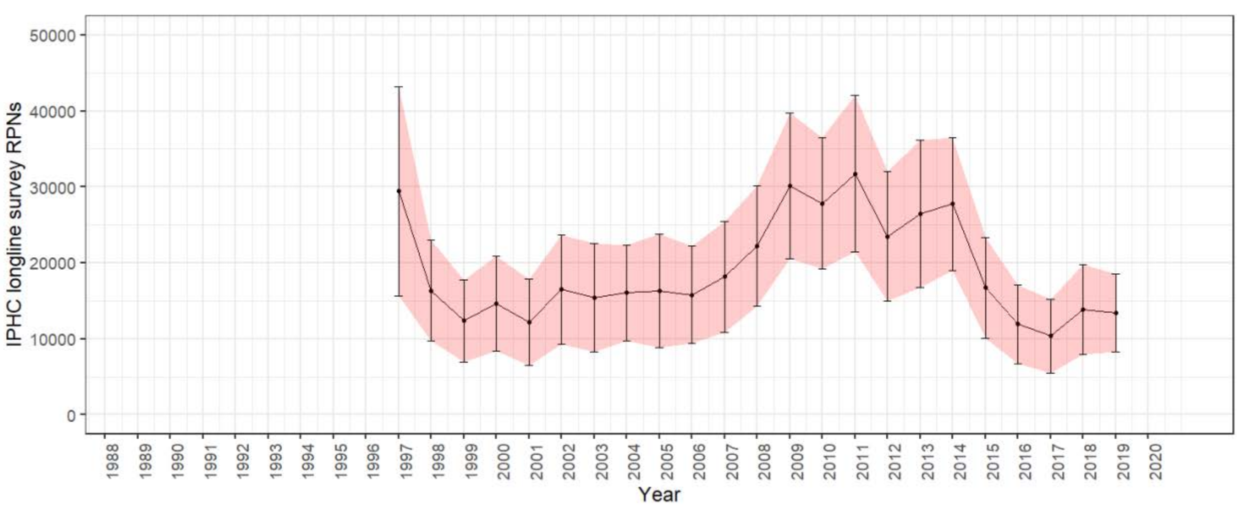


Figure 2.31 IPHC halibut longline survey Pacific cod RPN time series. Bars and shading indicate the 95th percentile confidence intervals.

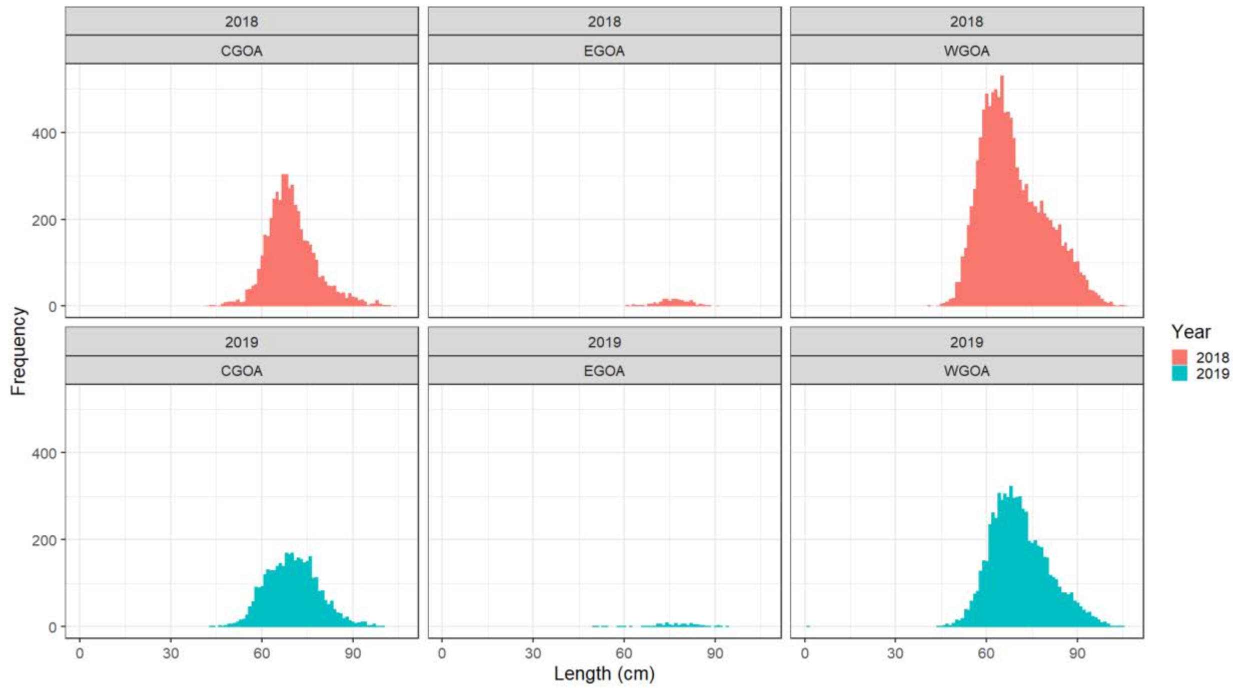


Figure 2.32 IPHC halibut longline survey Pacific cod RPN length composition collection for 2018 by GOA Regions for 2018 and 2019.

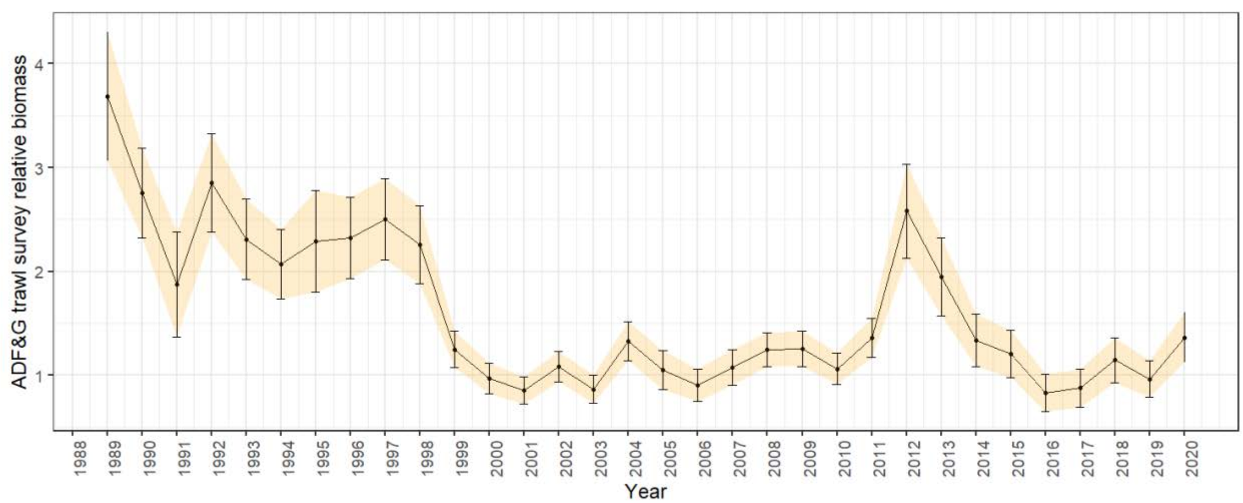


Figure 2.33 ADFG bottom trawl survey delta-glm Pacific cod density index time series. Bars and shading indicate the 95th percentile confidence intervals.

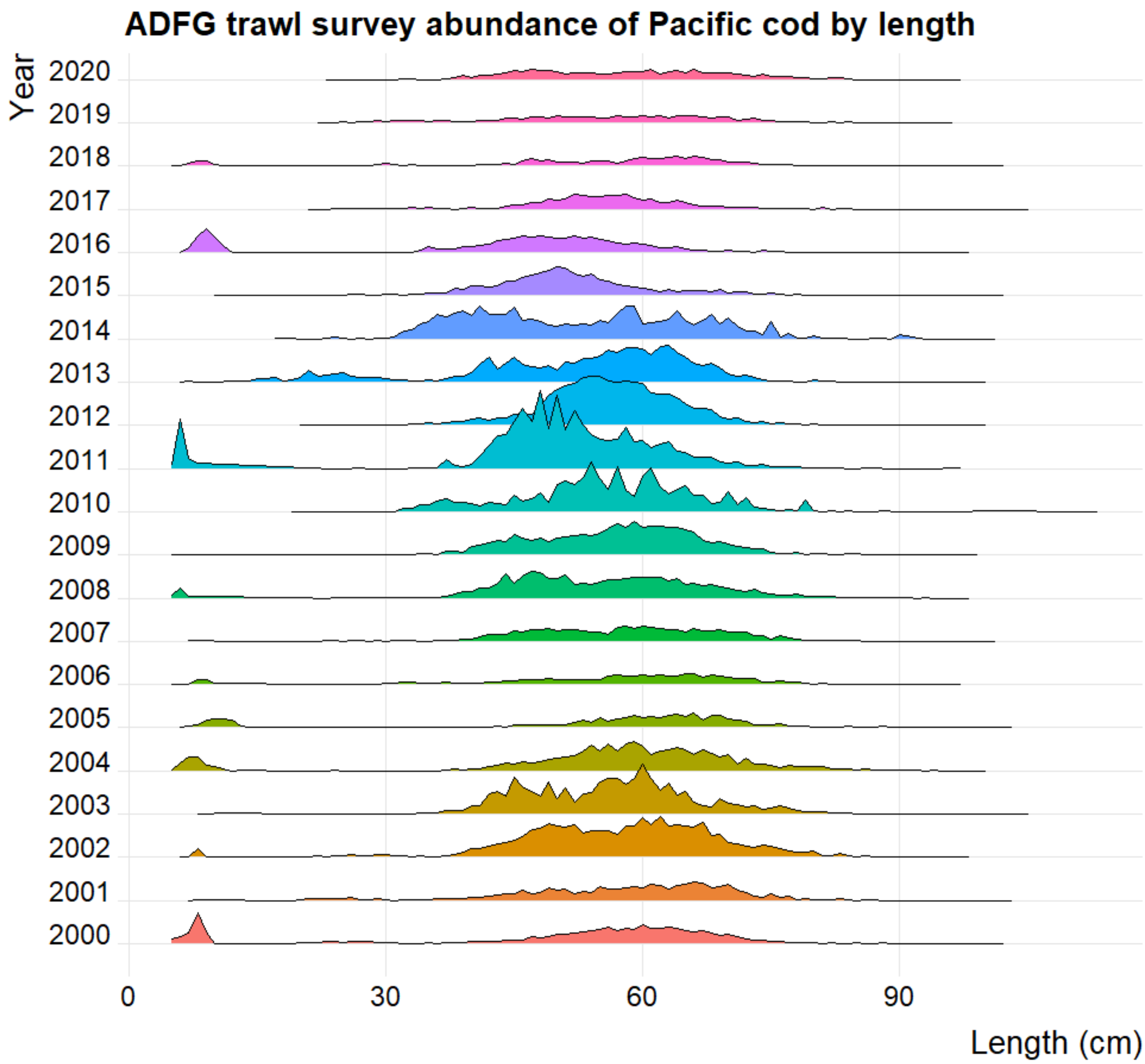


Figure 2.34 ADFG large-mesh trawl survey Pacific cod population numbers at length estimates.

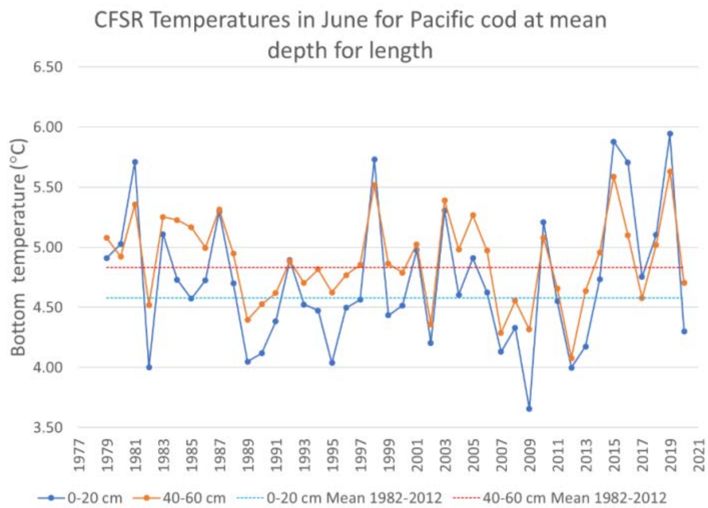


Figure 2.35 Climate Forcast System Reanalysis (CFSR) Central Gulf of Alaska bottom temperatures at the AFSC bottom trawl survey mean depths for 0-20 cm and 40-60 cm Pacific cod in June.

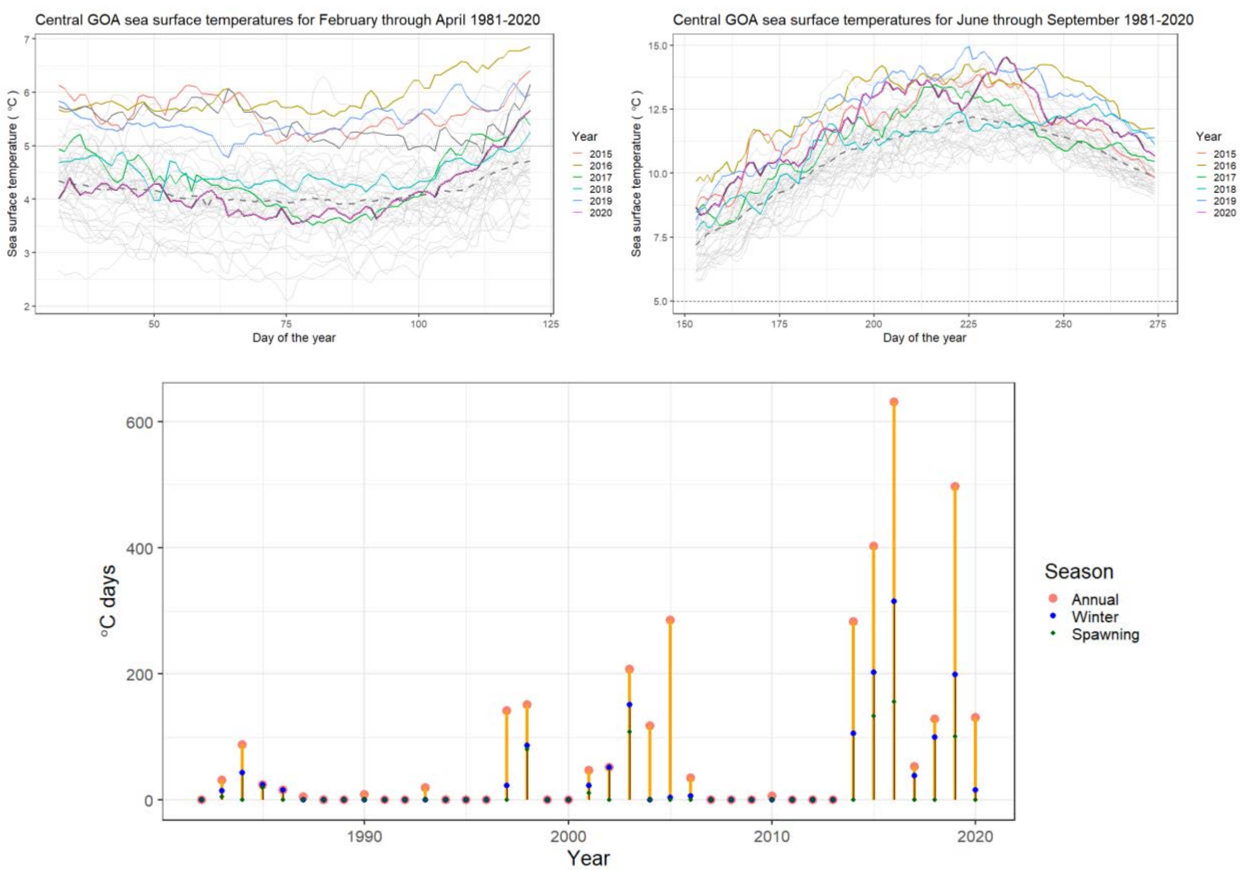


Figure 2.36 Sea surface temperatures (top left) February to March, (top right) June through September, and (bottom) index of the sum of the annual marine heatwave cumulative intensity (°C days) for 1981-2020 (larger yellow points) and index of the sum of the annual winter marine heatwave cumulative intensity for 1981-2020 (smaller blue points) from the daily mean sea surface temperatures NOAA high resolution blended analysis data for the Central Gulf of Alaska. The 2020 index value is the sum through 16 October 2020.

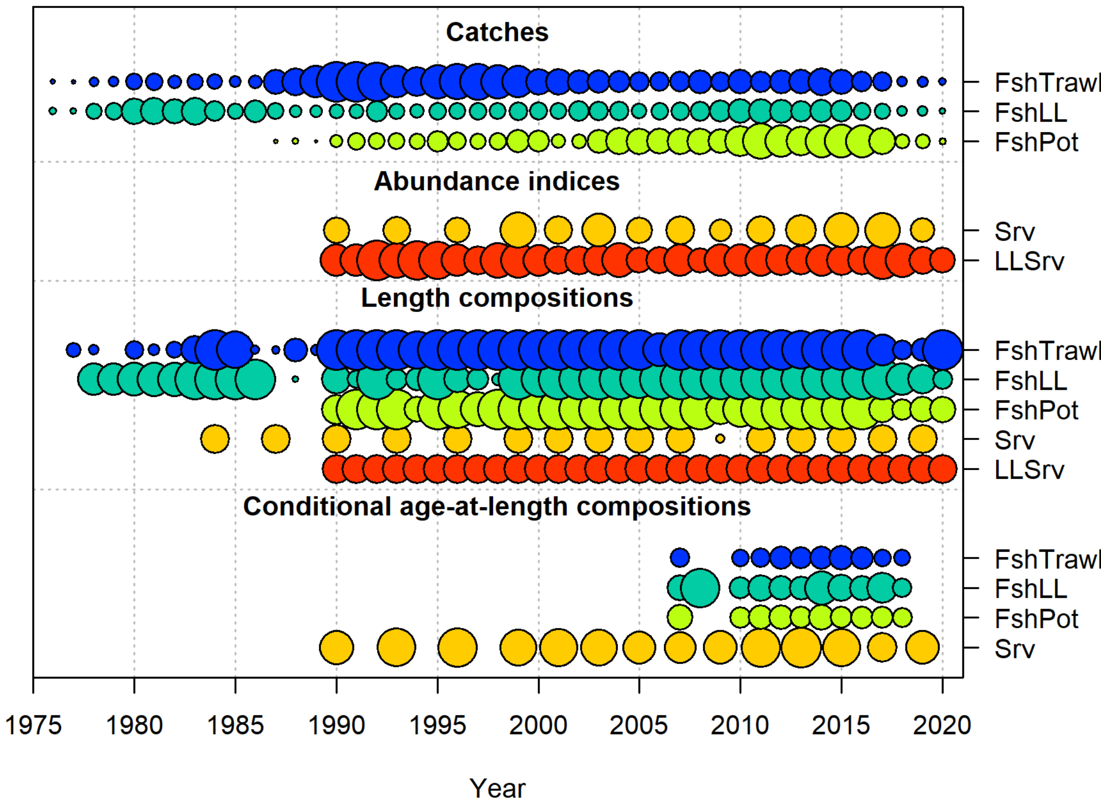


Figure 2.37 Data used in the 2020 models, circle area is relative to initial precision within data type.

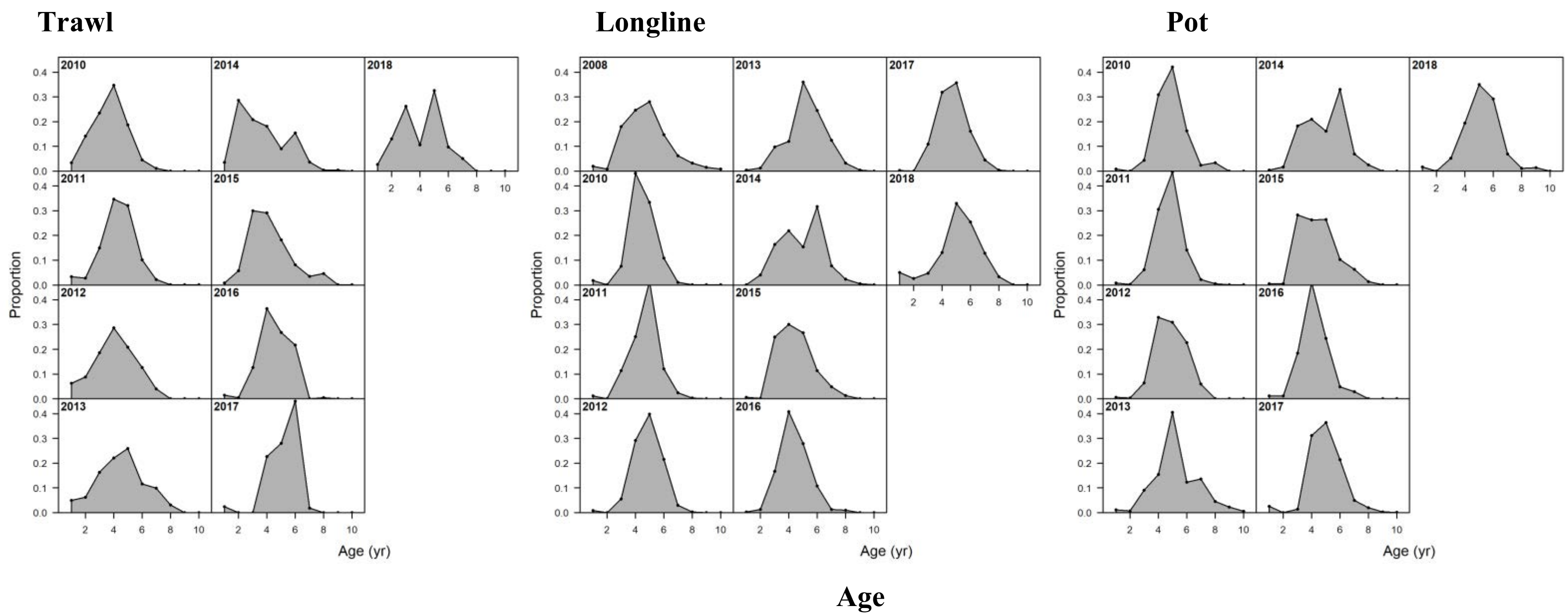


Figure 2.38 Pacific cod age composition data from the Gulf of Alaska fisheries by gear type.

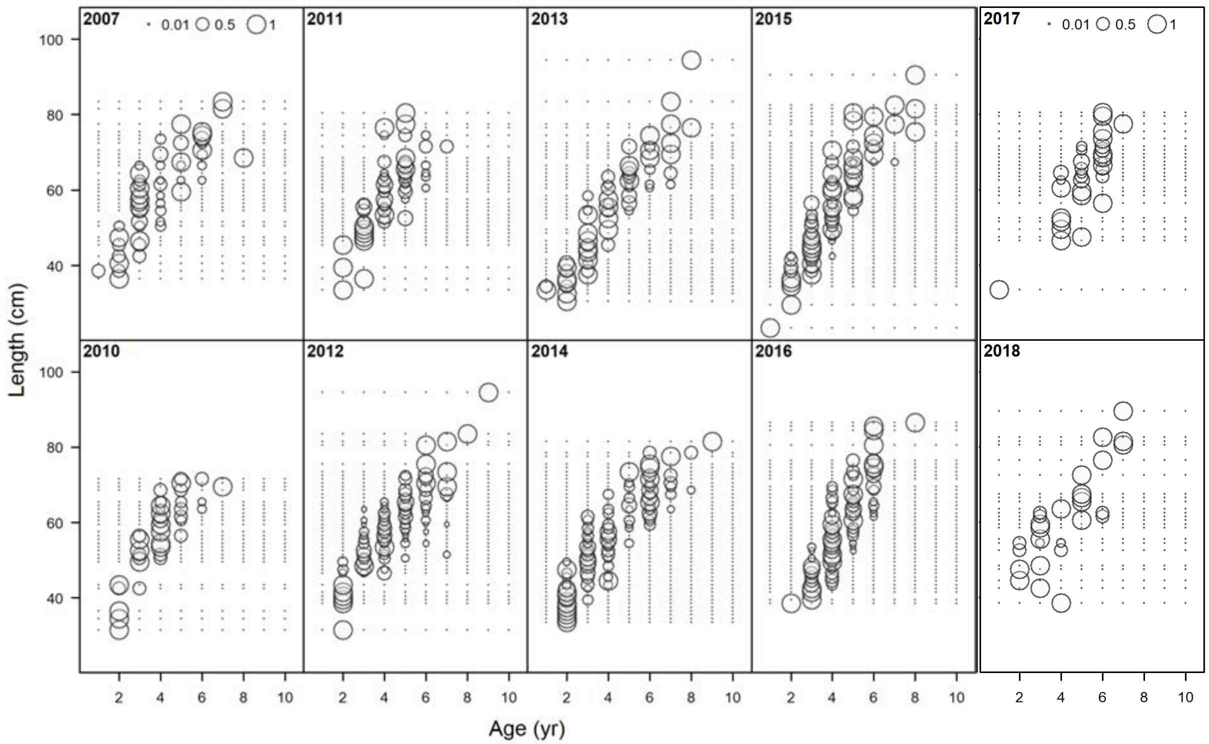


Figure 2.39 Pacific cod conditional length at age from the Gulf of Alaska trawl fishery.

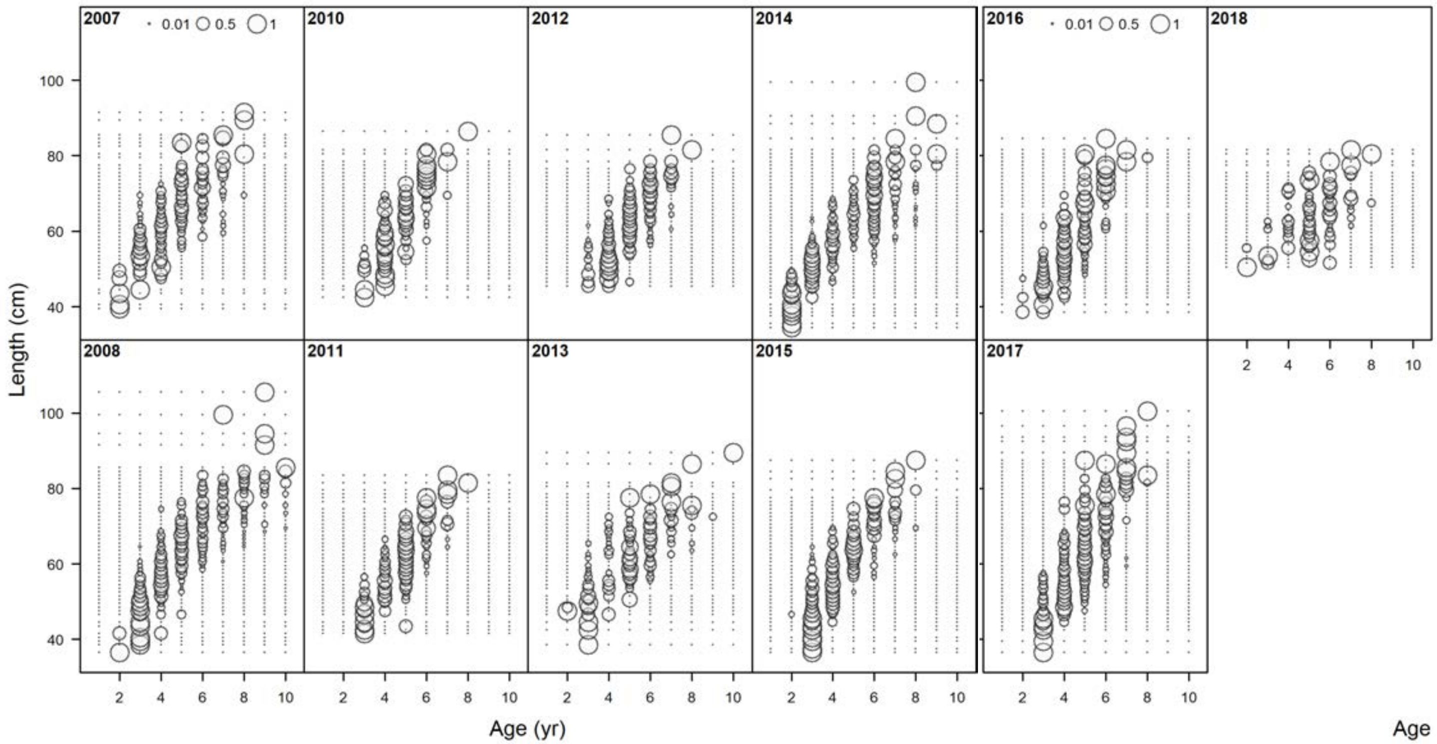


Figure 2.40 Pacific cod conditional length at age from the Gulf of Alaska bottom longline fishery.

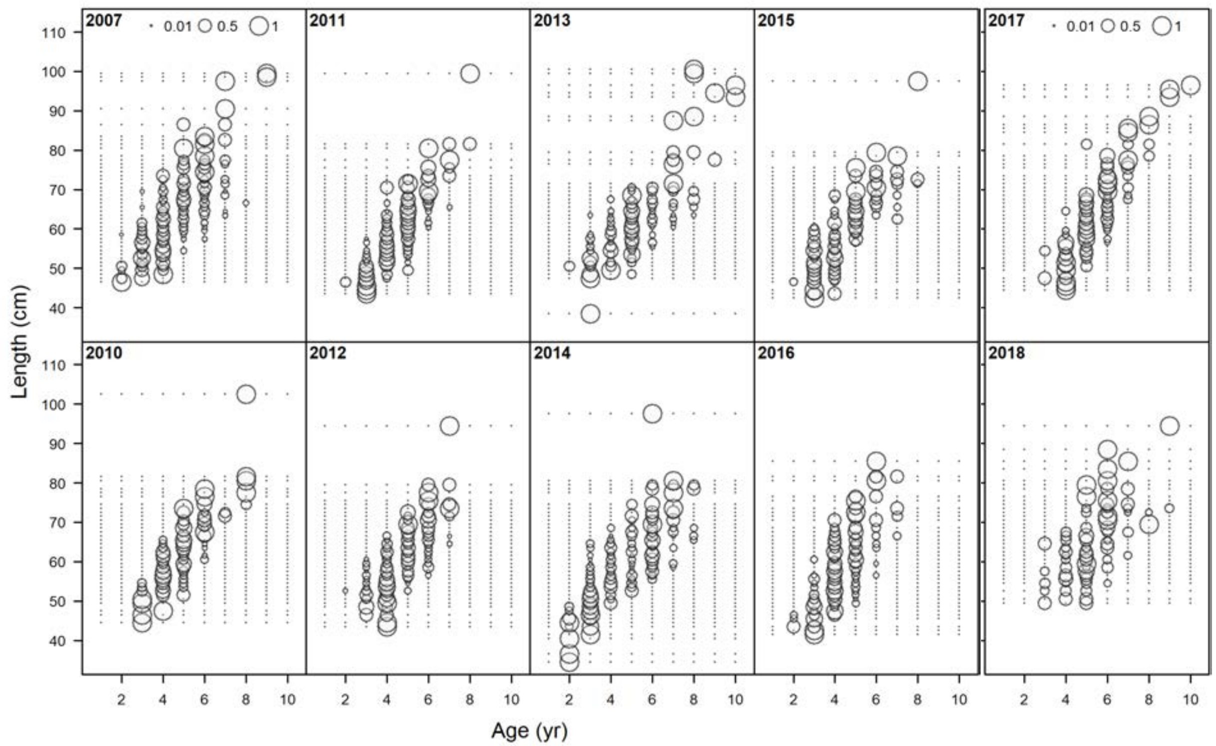


Figure 2.41 Pacific cod conditional length at age from the Gulf of Alaska pot fishery.

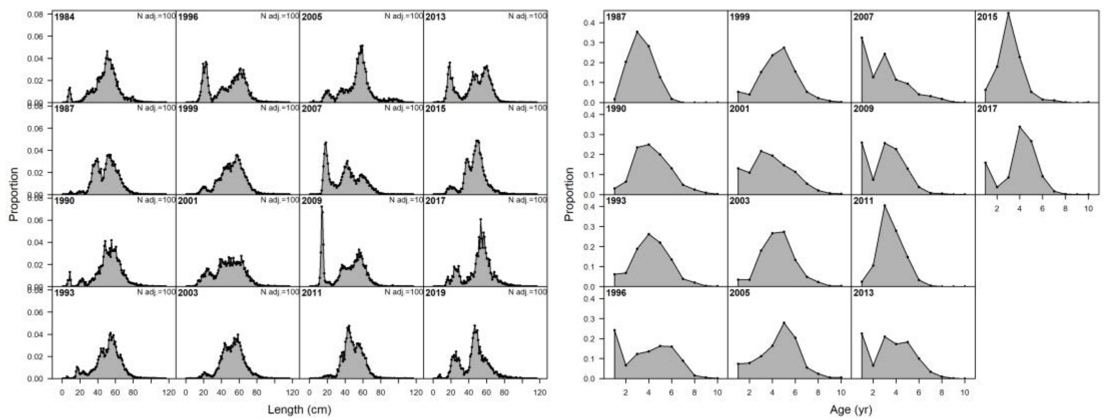


Figure 2.42 Pacific cod length (left) and age (right) composition data from the Gulf of Alaska bottom trawl survey 1984-2019.

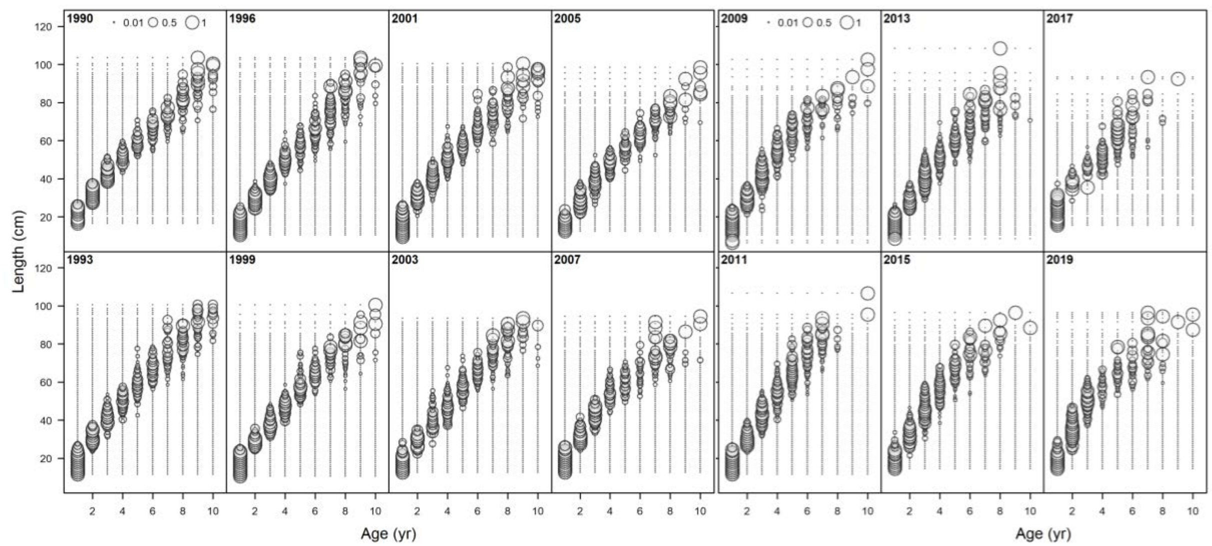


Figure 2.43 Pacific cod conditional length at age from the Gulf of Alaska bottom trawl survey 1990-2019.

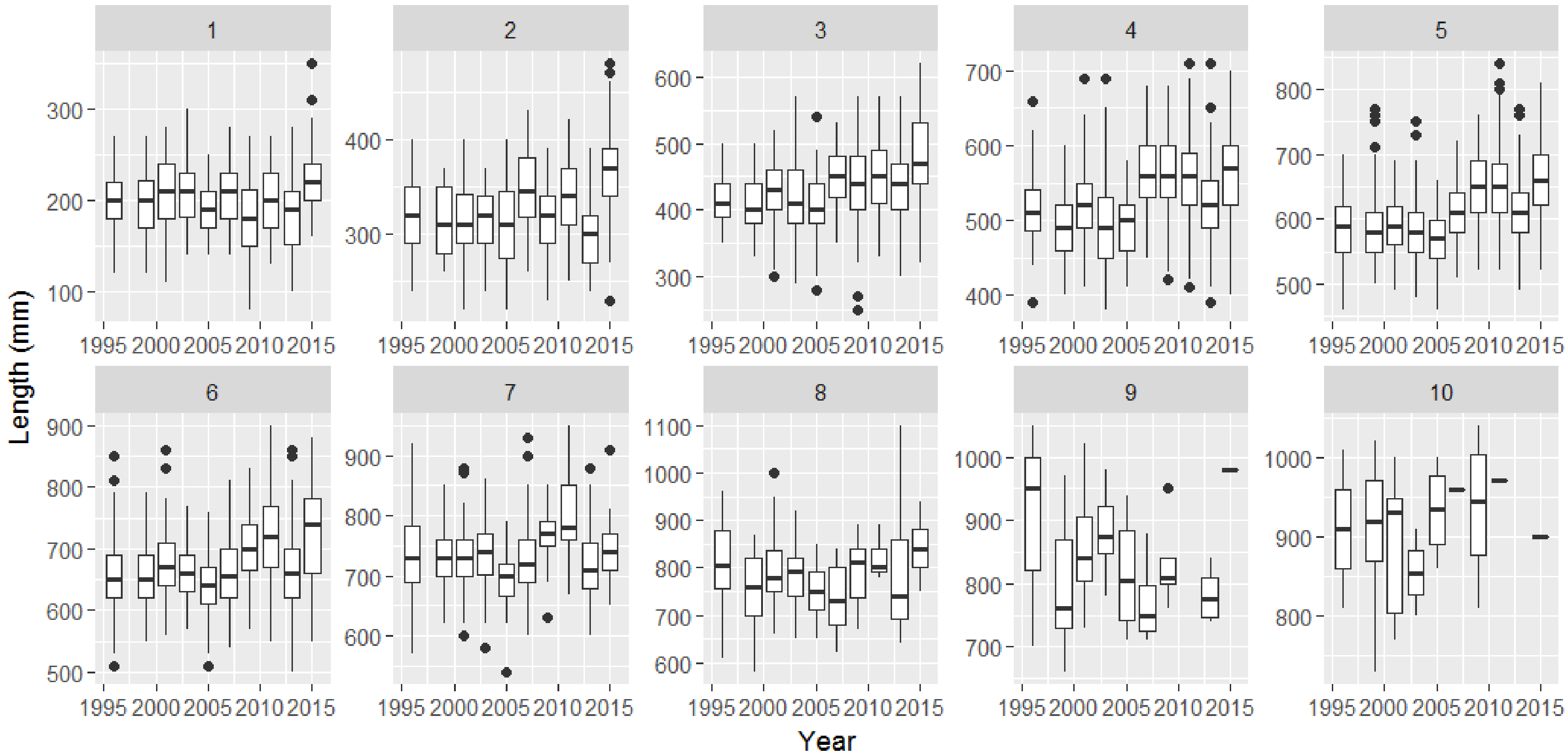


Figure 2.44 Length-at-age by year for each age 1 through 10 for Pacific cod otoliths collected during the summer bottom trawl surveys showing an increase in median length in 2007 for ages 2 through 6.

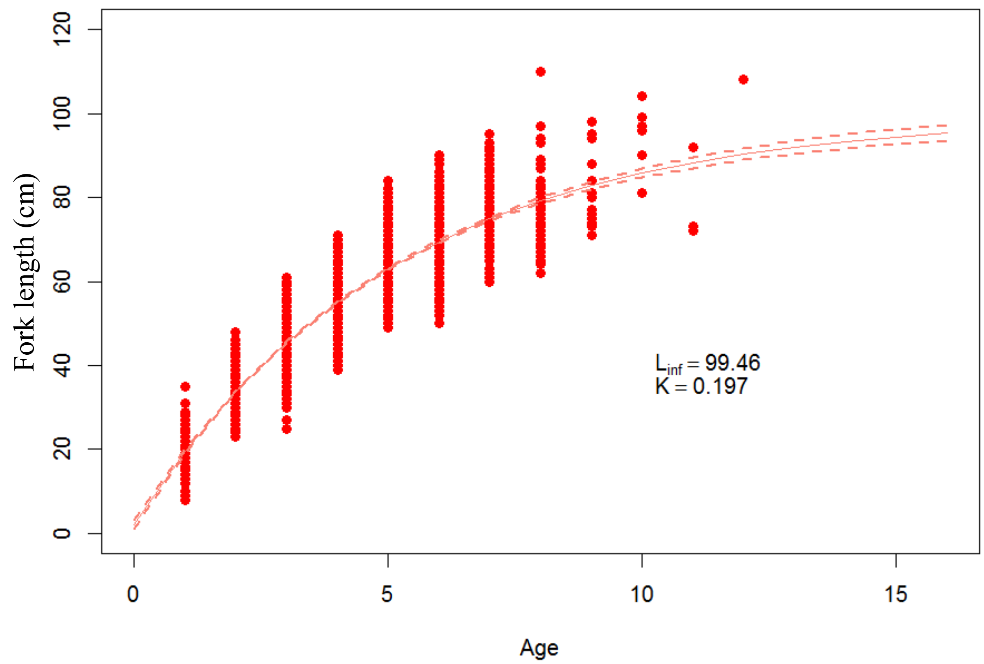


Figure 2.45 Fit to von Bertalanffy growth model for 2007-2015 length at age data from the AFSC bottom trawl surveys.

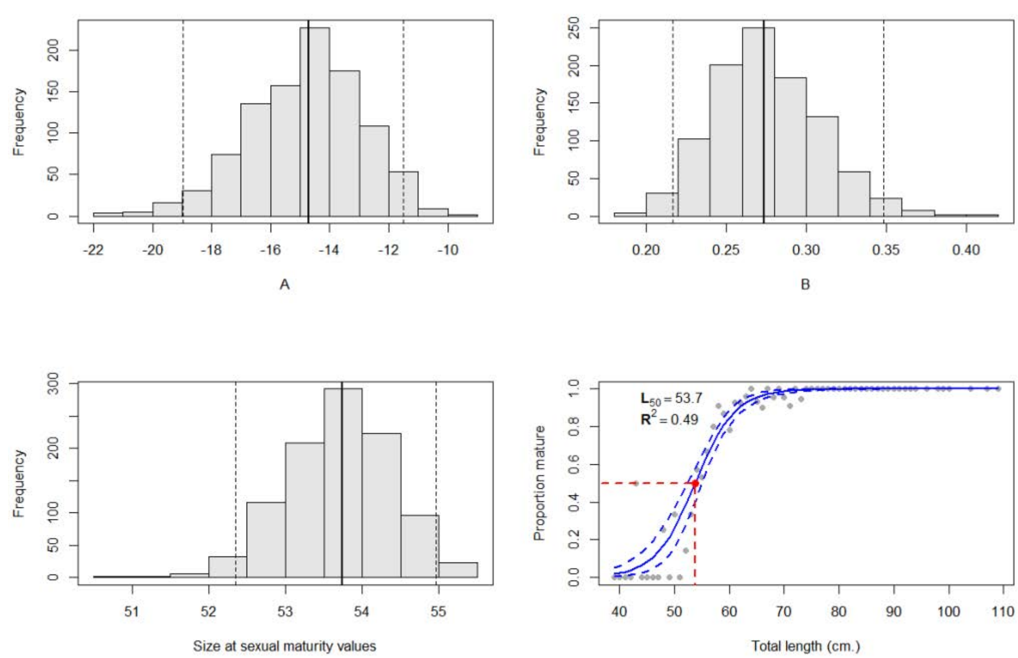


Figure 2.46 Bootstrapped (n=1000) parameters and results for the logistic length-based maturity using Stark (2007) reread otolith and maturity data. Proportion mature $P = {}^{1}/_{1+e^{-(A+BL)}}$ and L_{50} = A/-B

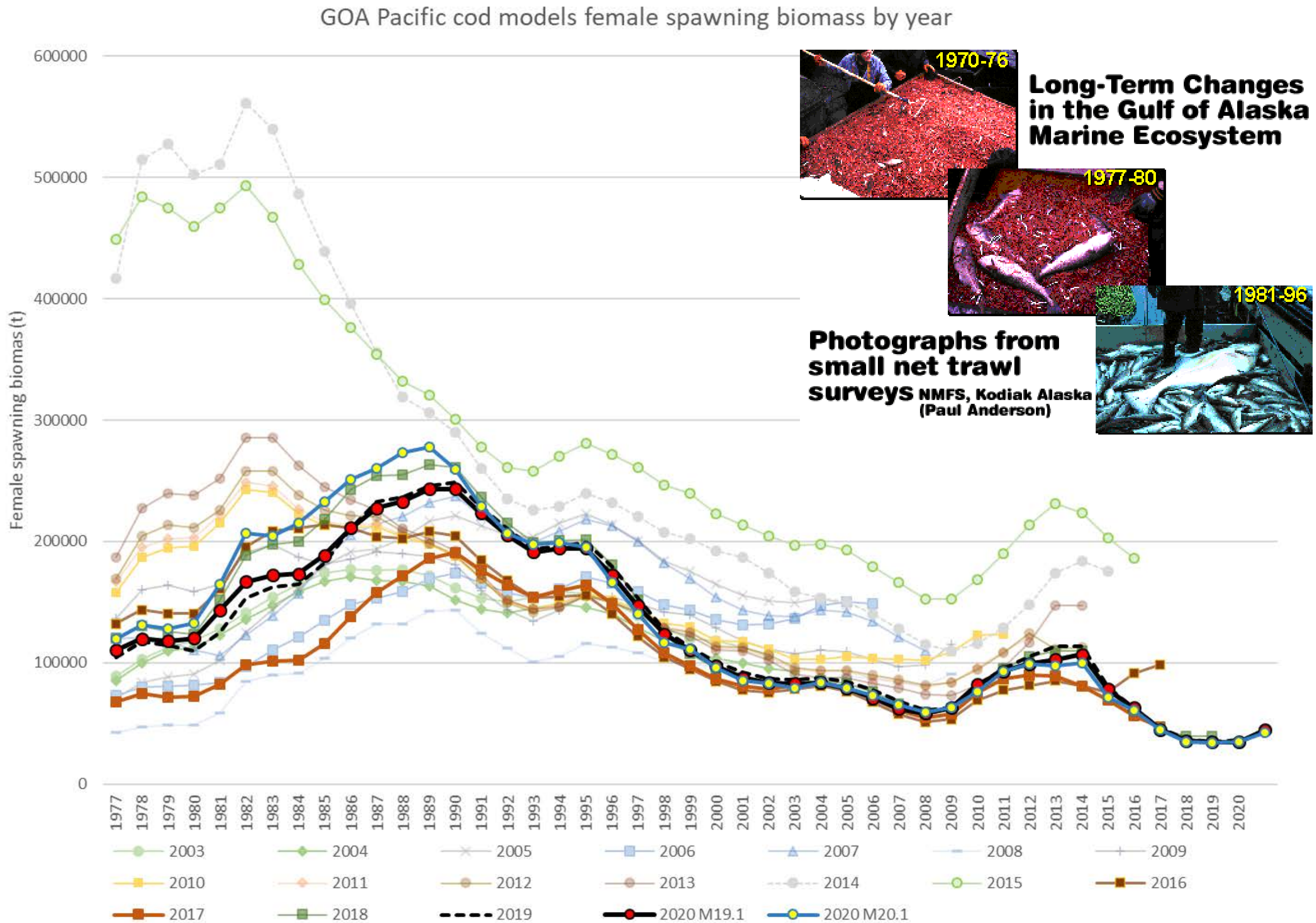


Figure 2.47 1977-2021 Gulf of Alaska Pacific cod female spawning biomass from the 2003 through 2020 stock assessments with estimates from both the author's preferred (Model 19.1) and research (Model 20.1) model results and (inset) images from the NMFS small net surveys off Kodiak Alaska showing change in species composition over time from: http://www.thexxnakedscientists.com/HTML/articles/article/brucewrightcolumn1.htm/

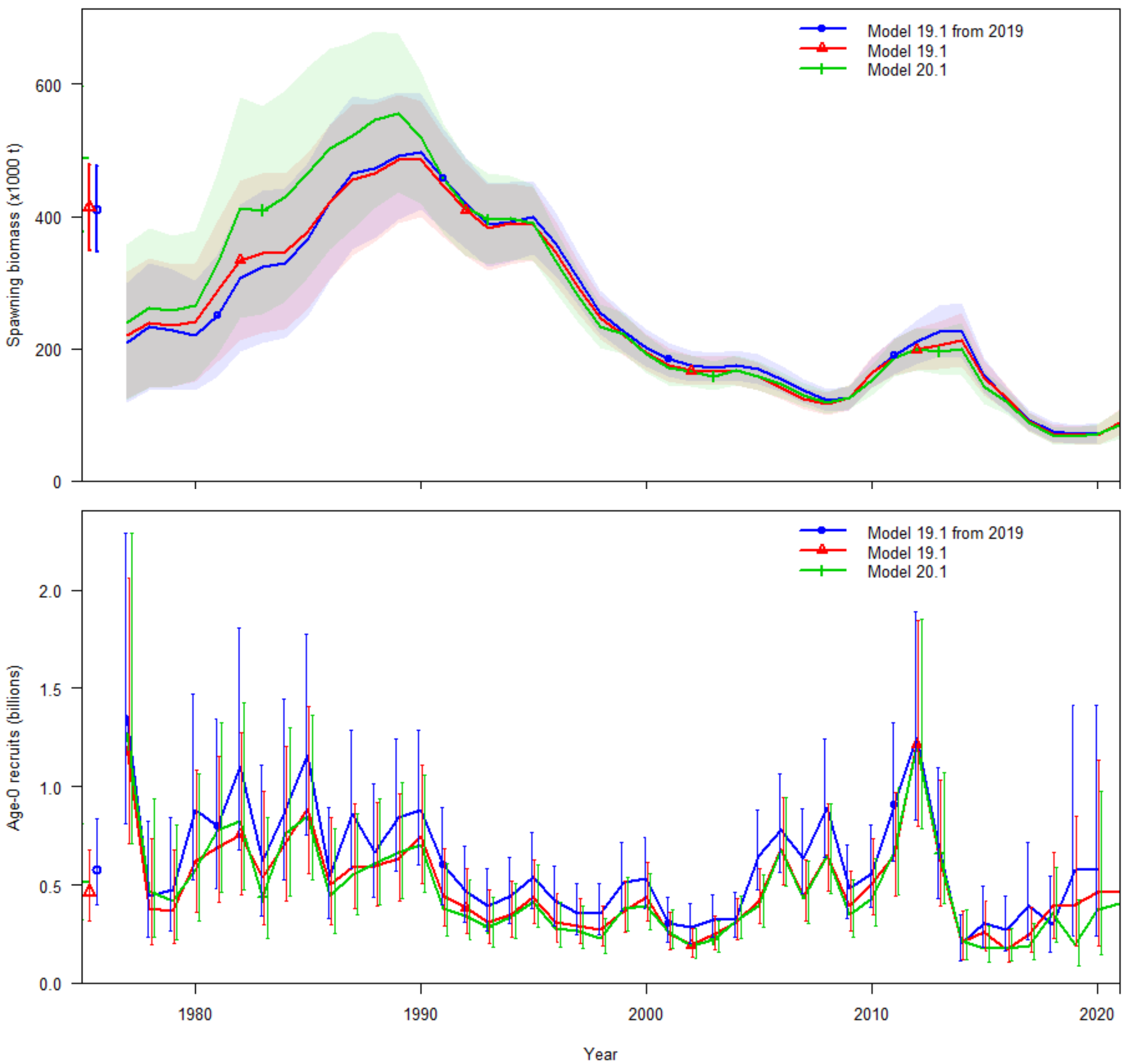


Figure 2.48 Estimates of female spawning biomass (t; top) and age-0 recruits (billions; bottom) for 2020 reference model (Model 19.14.48c), the proposed alternate Model 19.1, and the experimental environmentally enhanced Model 20.1.

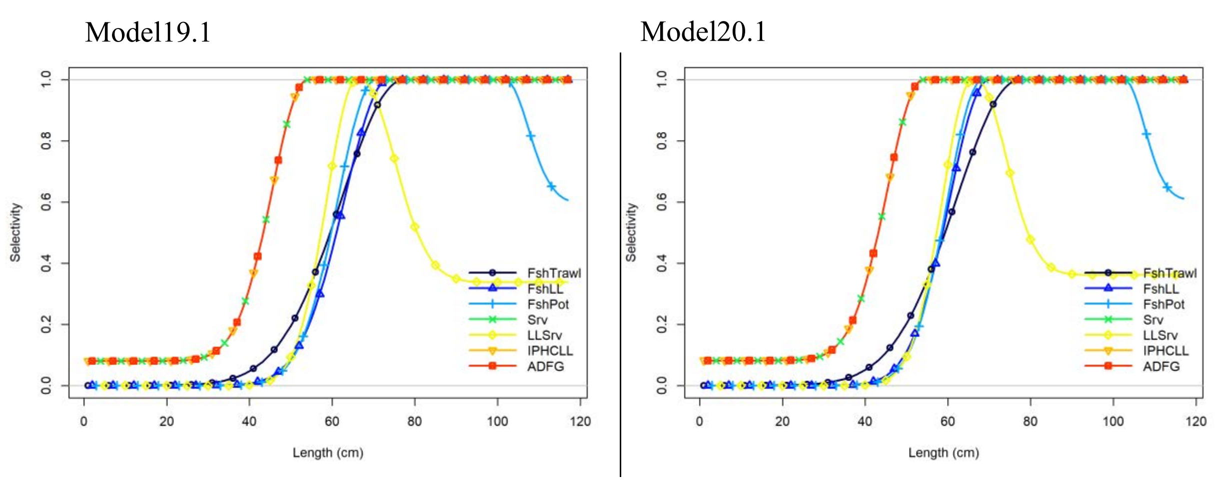


Figure 2.49 Model19.1 and Model 20.1 selectivity for all size composition components for 2020.

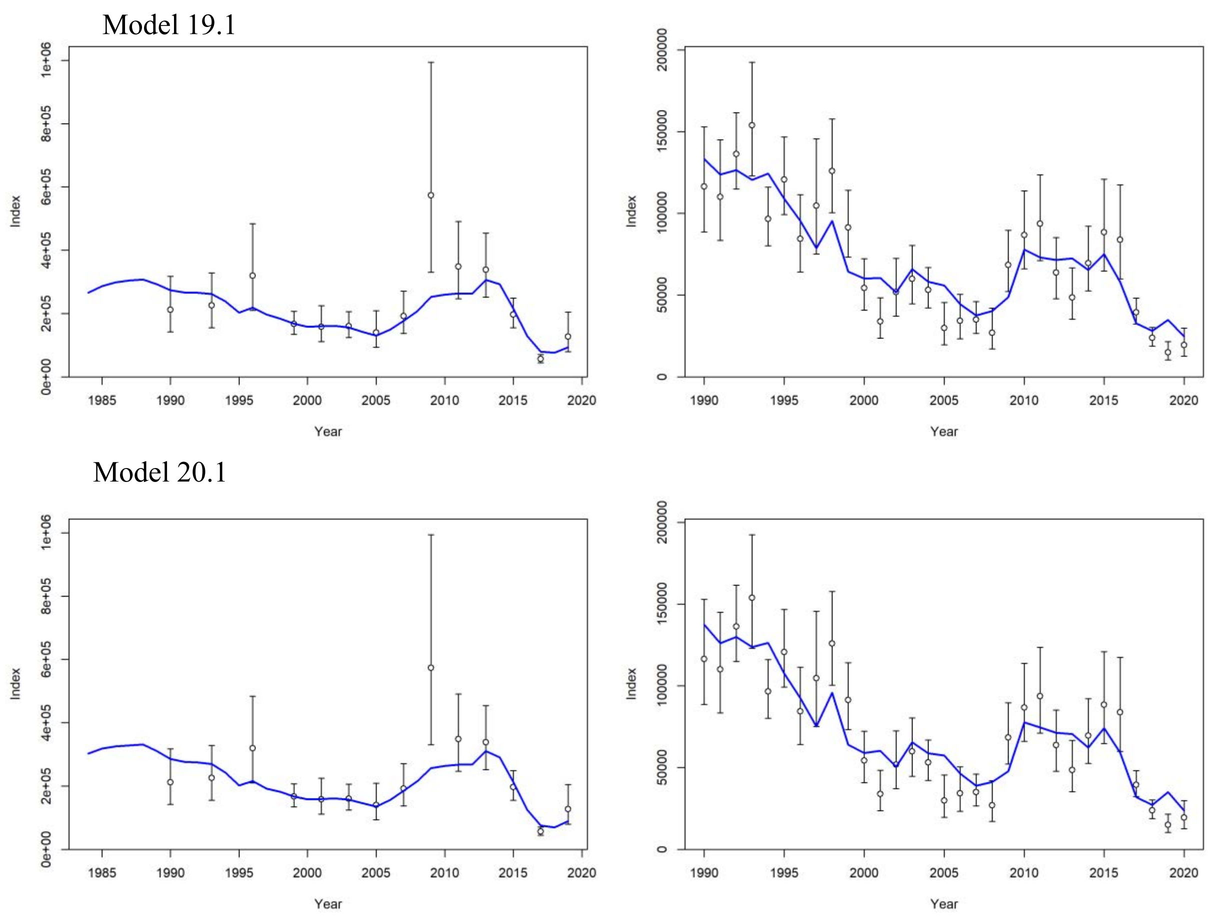


Figure 2.50 Model fits to AFSC bottom trawl (left) and AFSC longline (right) survey indices.

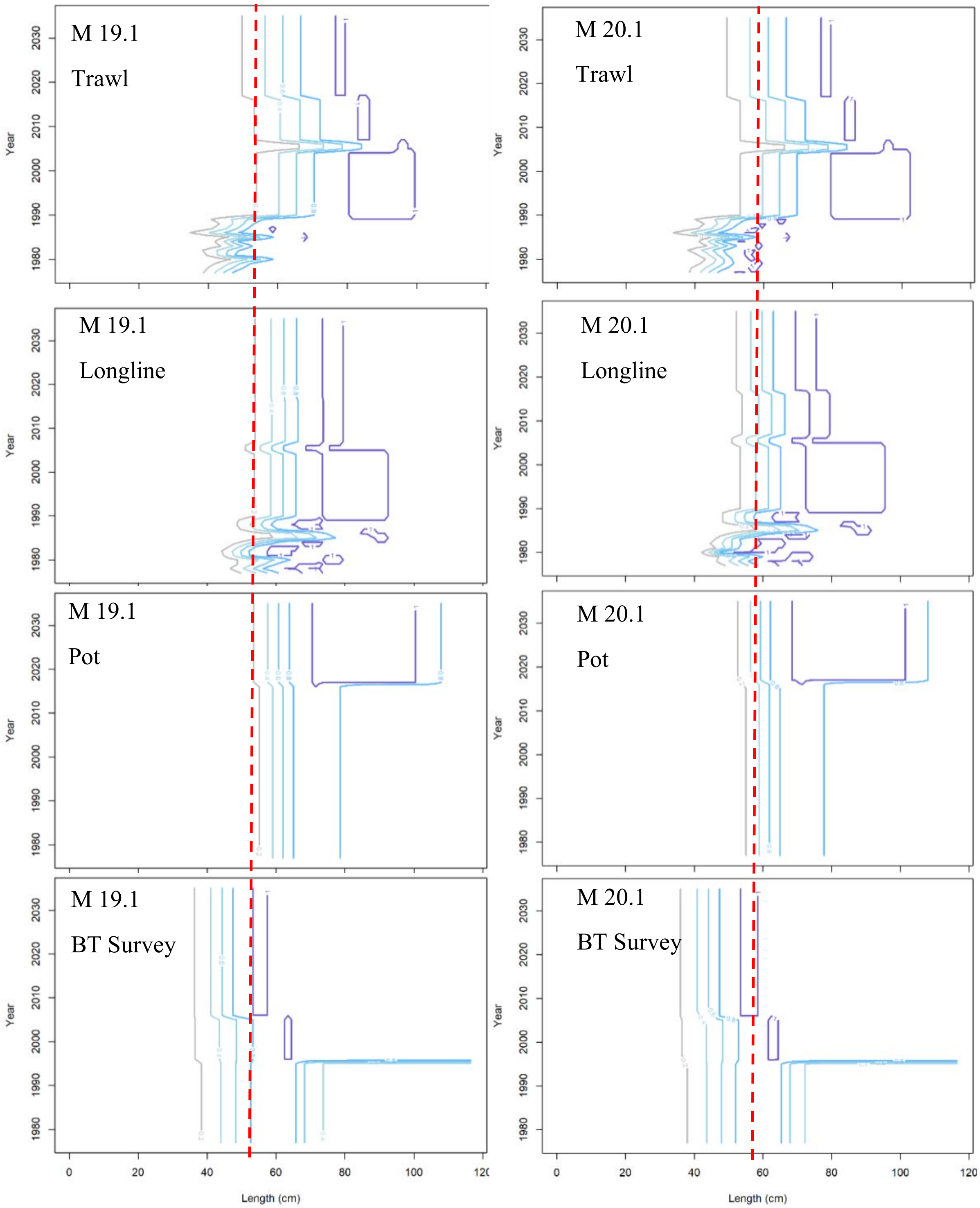


Figure 2.51 Estimates of fishery and AFSC bottom trawl survey selectivities for Model 19.1 (left) and Model 20.1 (right). Red dashed line is the size at 50% mature.

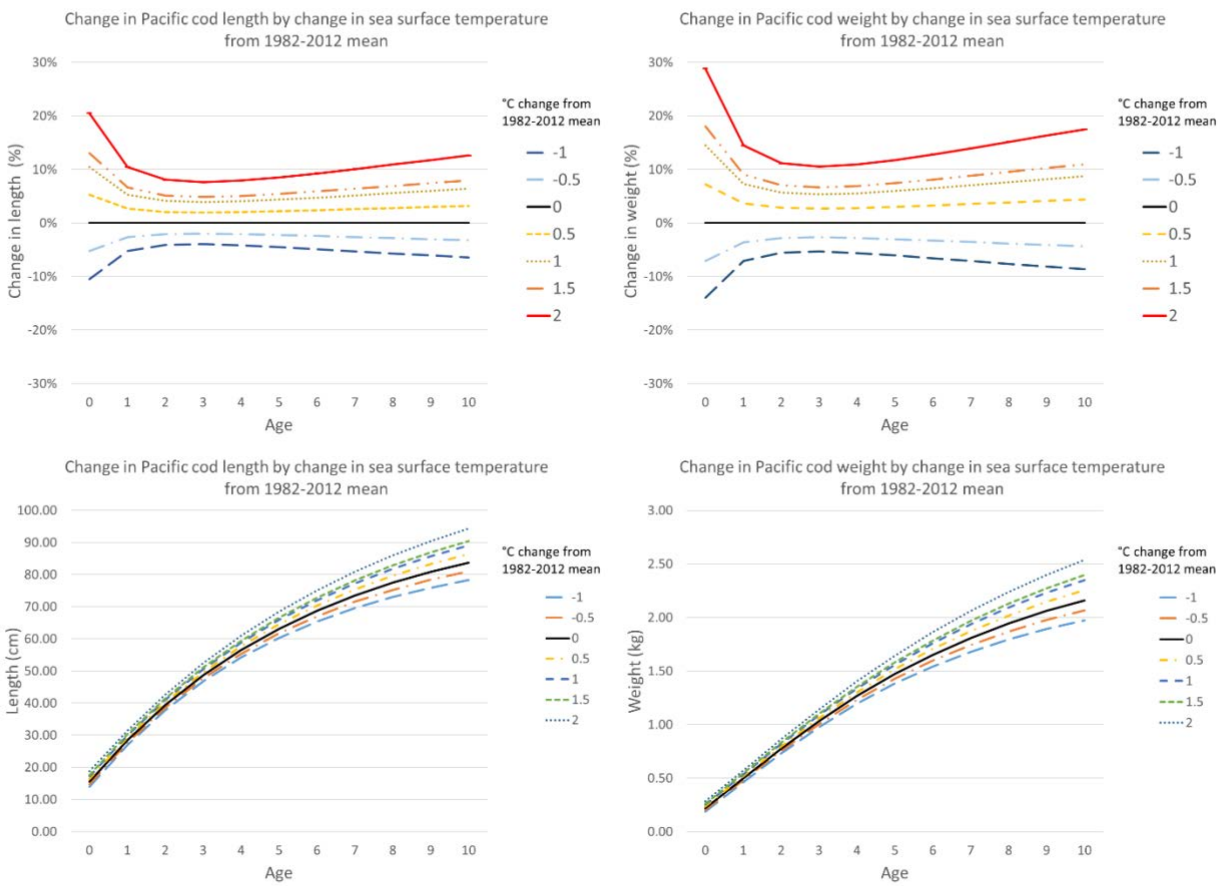


Figure 2.52 Model 20.1 change in length by age (left) and change in weight by age (right) by temperature anomaly from the 1982-2012 mean.

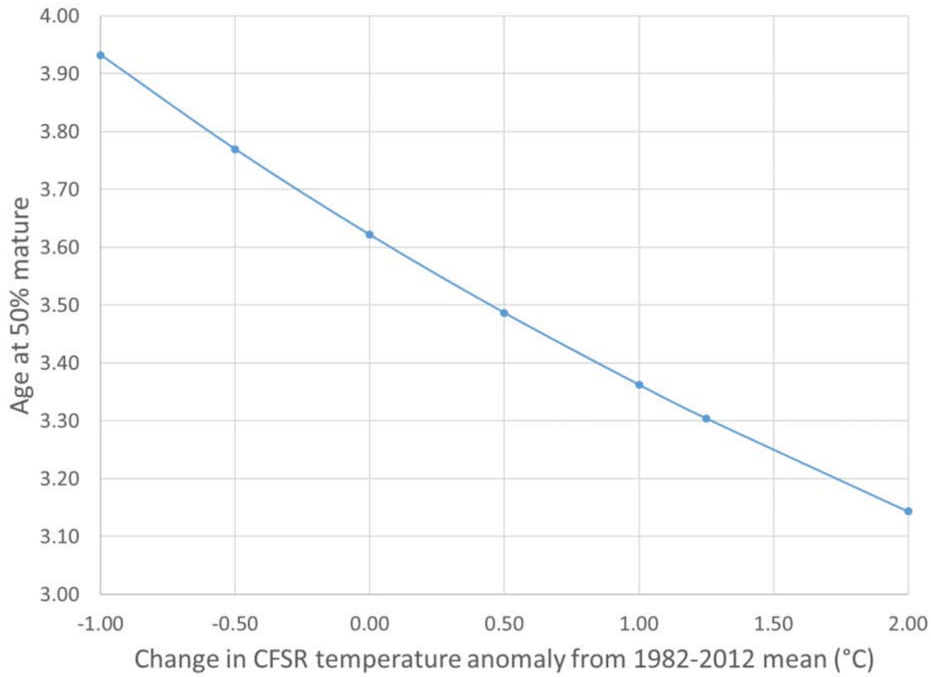


Figure 2.53 Relationship of maturity to temperature anomaly from the 1982-2012 mean for Model 20.1.

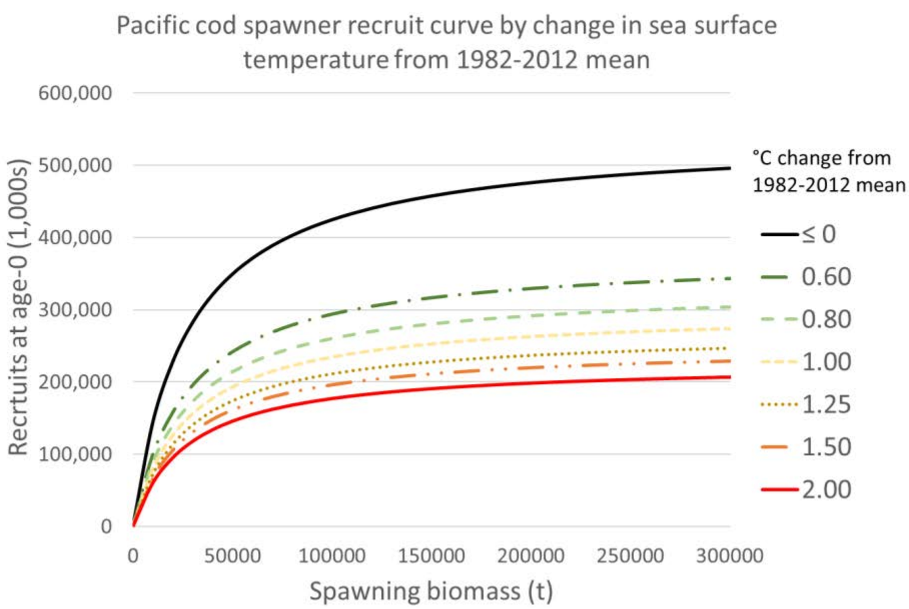


Figure 2.54 Recruits by spawning biomass in Model 20.1 related to temperature anomaly as interpreted through the modeled relationship with the spawning marine heatwave index ($MHWI_{SP}$).

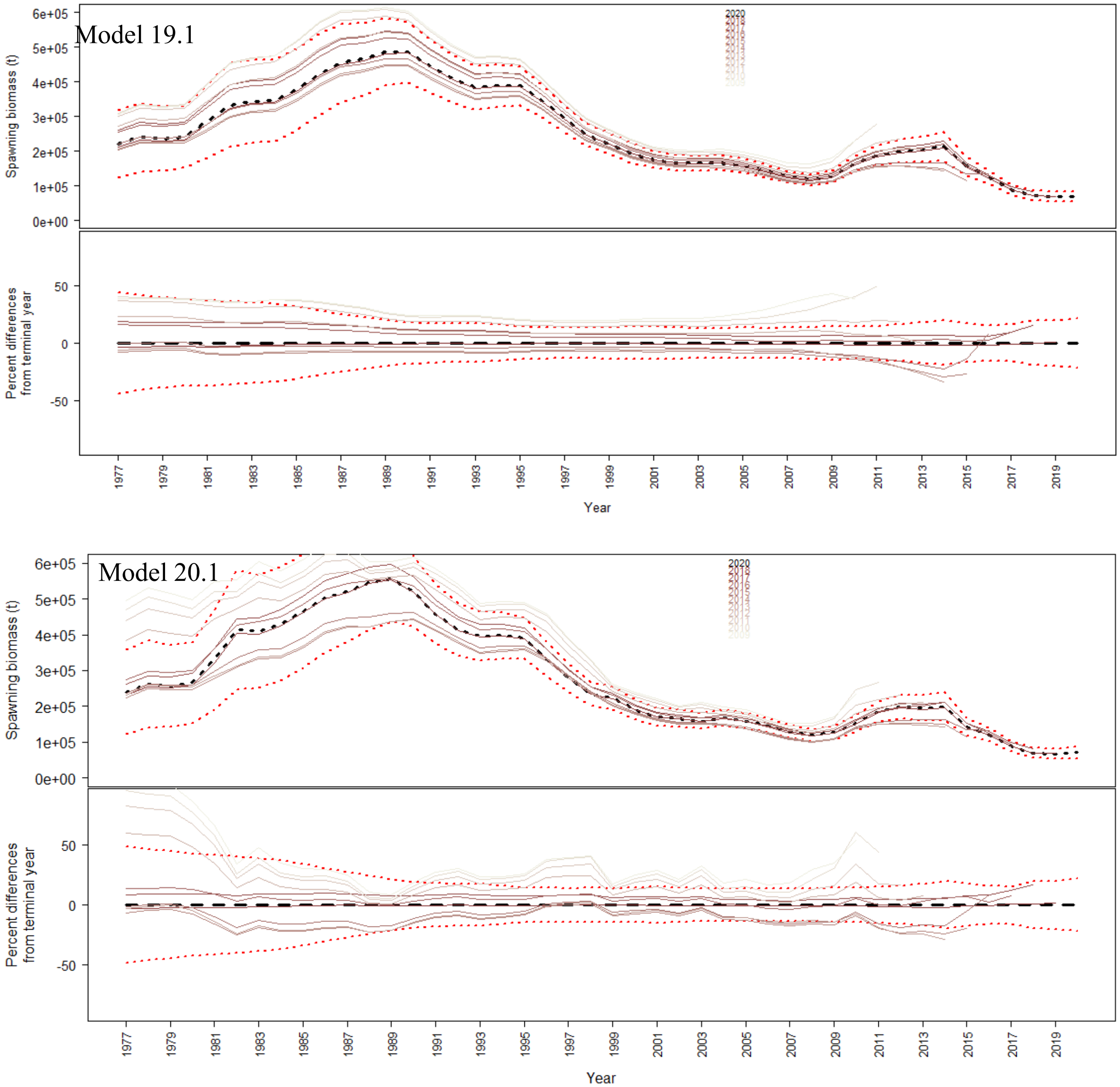


Figure 2.55 Retrospective analysis for (top) Model 19.1 and (bottom) Model 20.1 for Female spawning biomass.

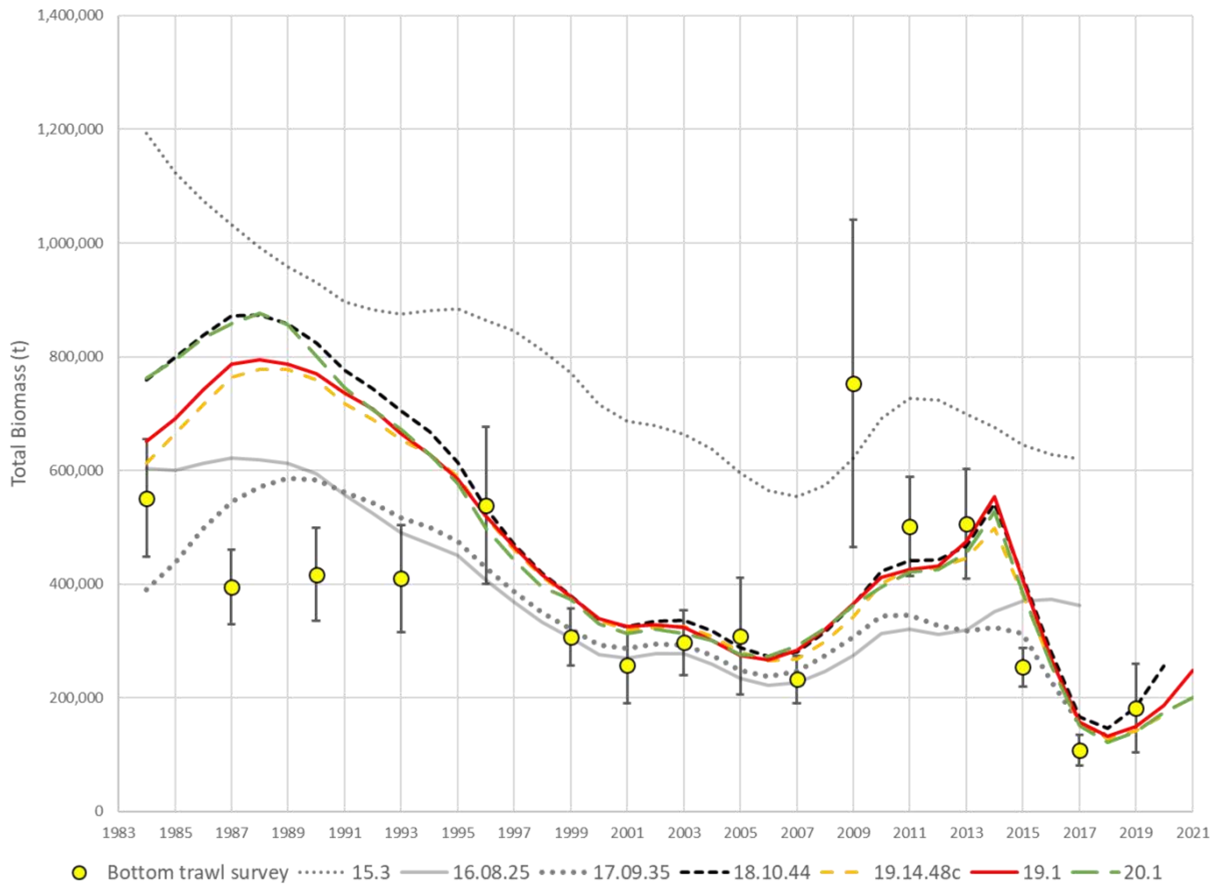


Figure 2.56 Total biomass estimates from reviewed models and NMFS bottom trawl survey biomass estimates with 95% confidence bounds.

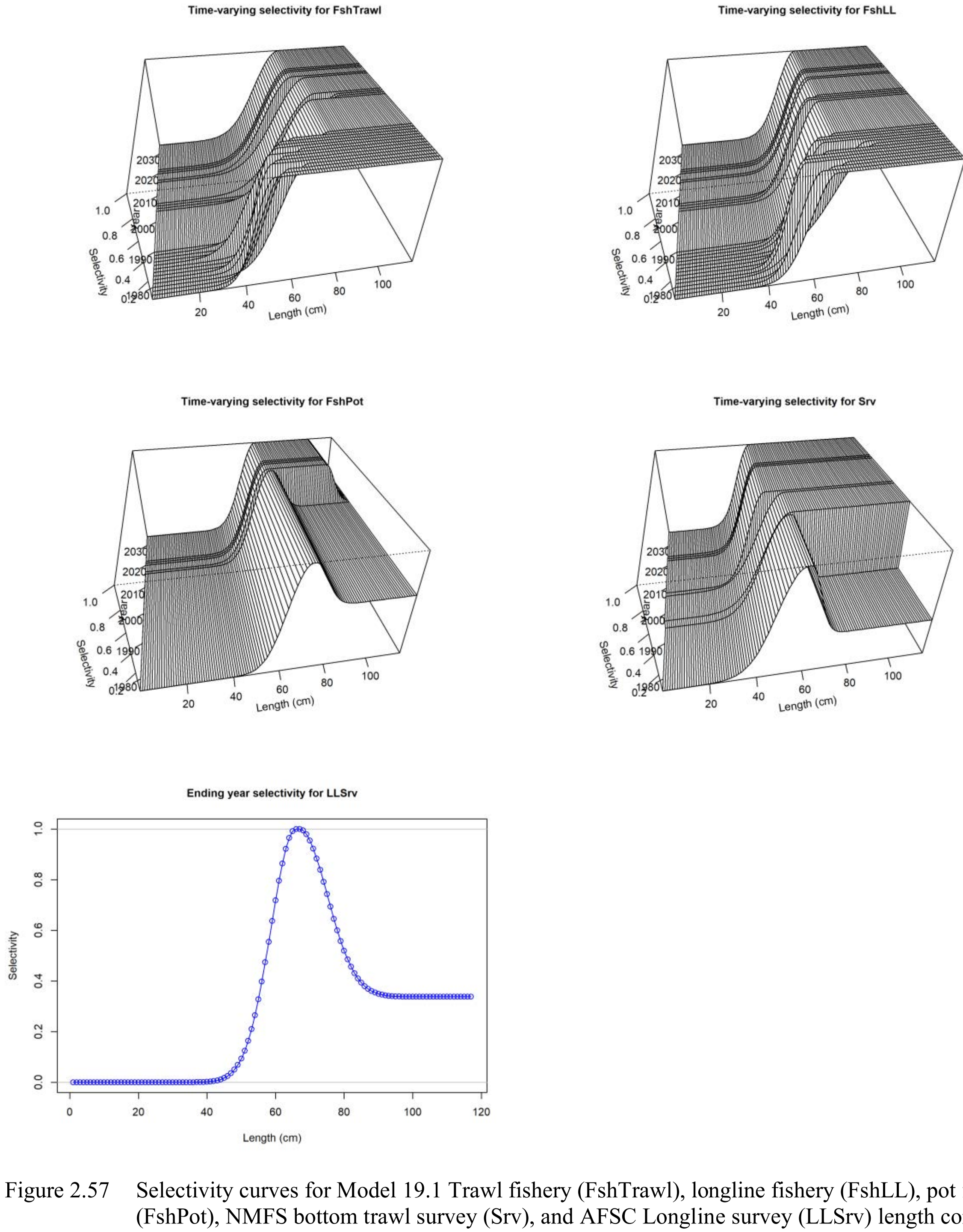


Figure 2.57 Selectivity curves for Model 19.1 Trawl fishery (FshTrawl), longline fishery (FshLL), pot fishery (FshPot), NMFS bottom trawl survey (Srv), and AFSC Longline survey (LLSrv) length composition data.

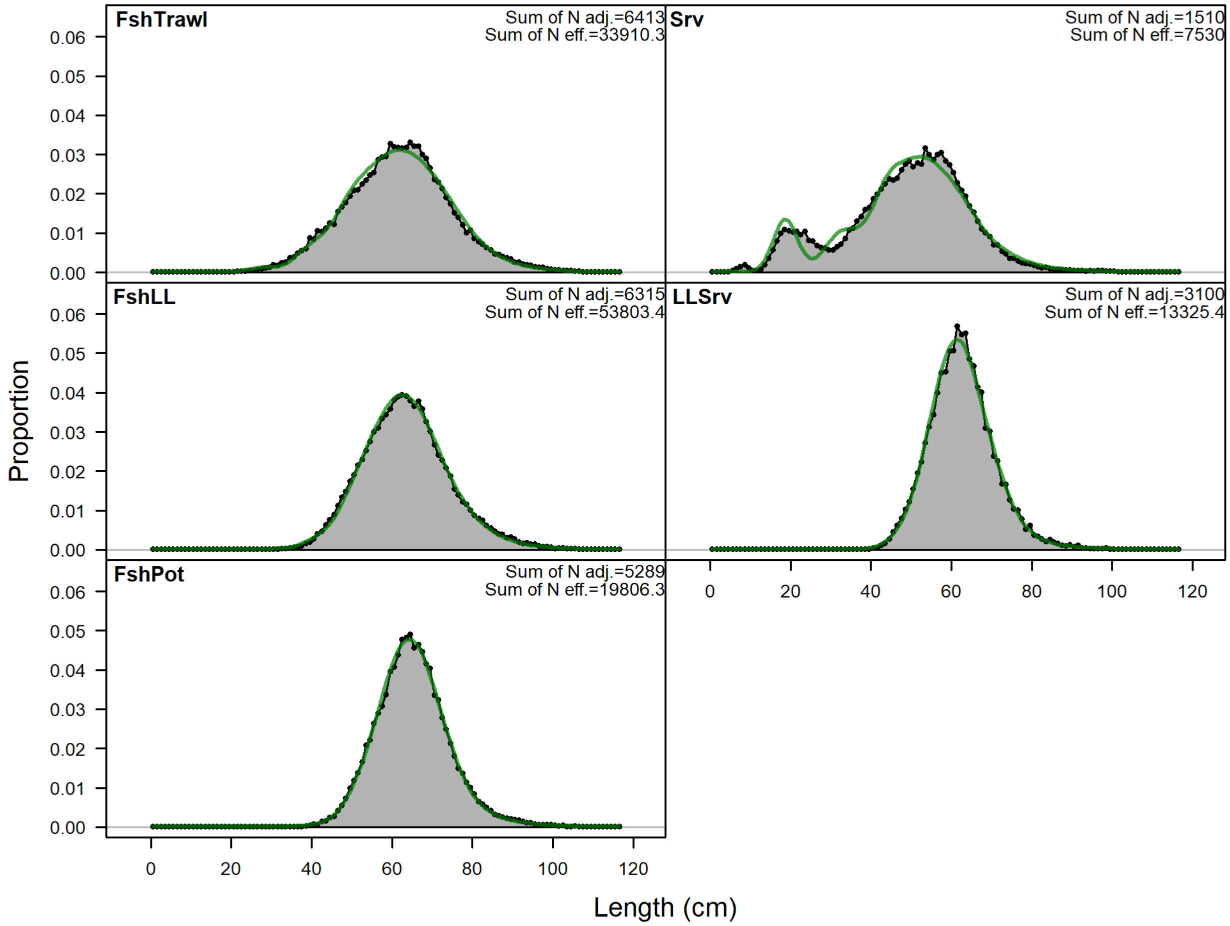


Figure 2.58 Overall Model 19.1 fits to Trawl fishery (FshTrawl), longline fishery (FshLL), pot fishery (FshPot), NMFS bottom trawl survey (Srv), and AFSC Longline survey (LLSrv) length composition data.

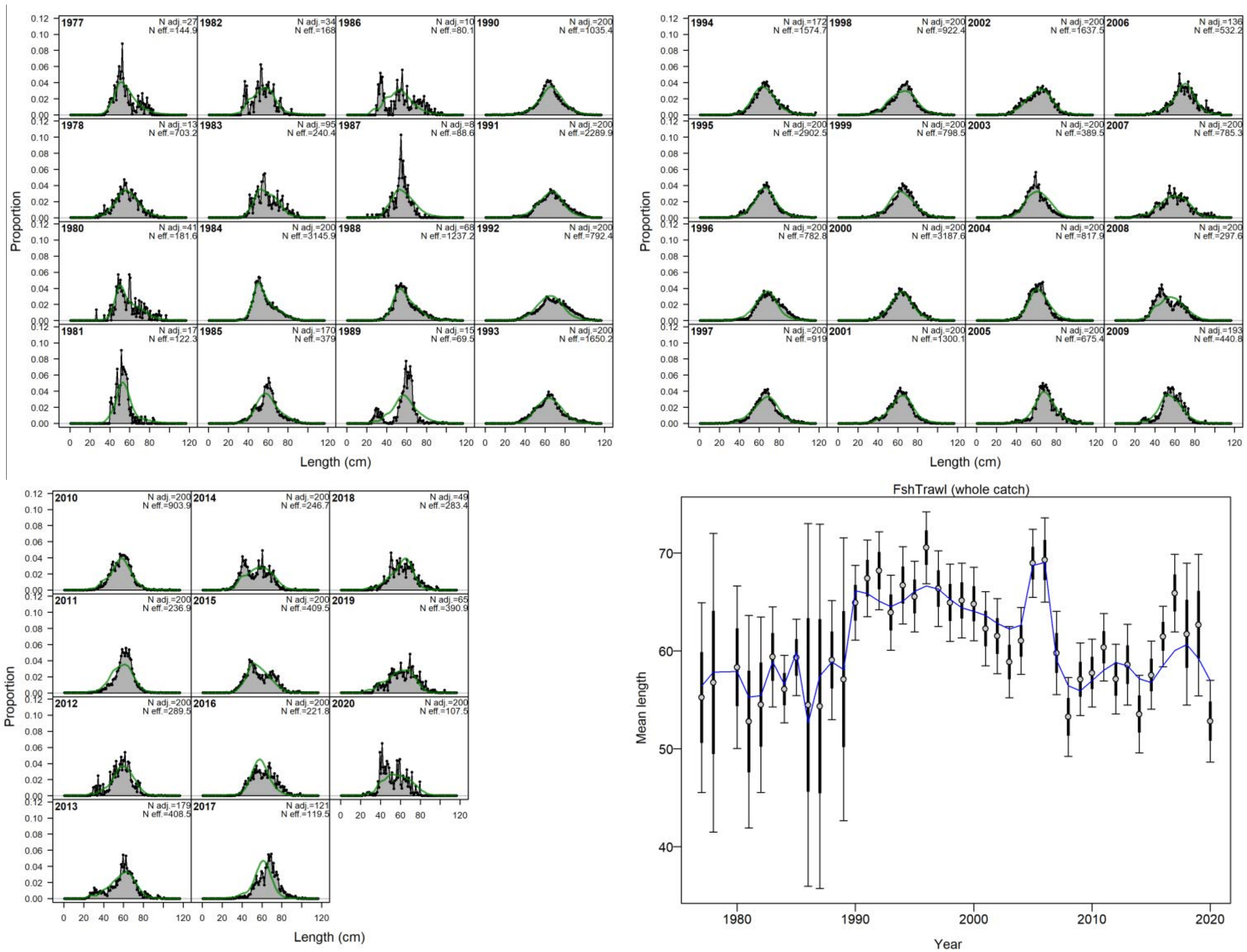


Figure 2.59 Trawl fishery length composition and Model 19.1 fit (top and left) and mean length (cm; right bottom).

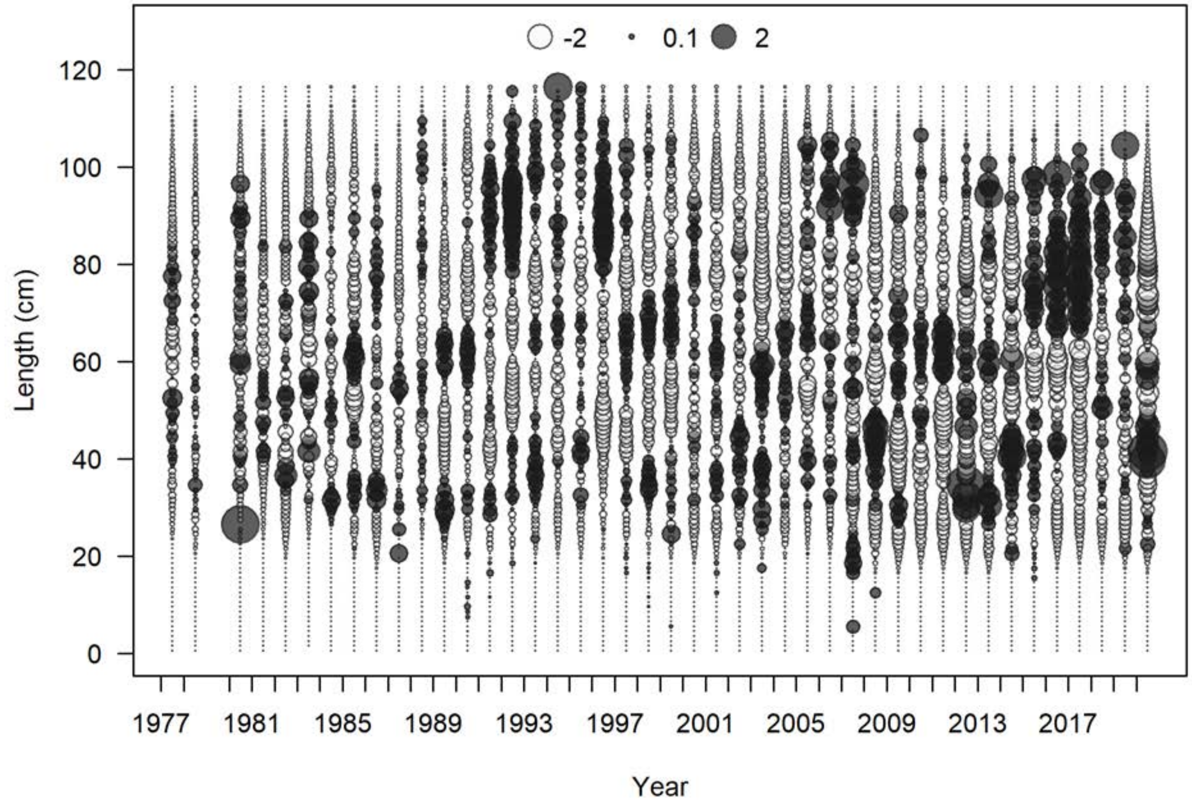


Figure 2.60 Trawl fishery length composition Pearson residuals (max = 8.01) for Model 19.1.

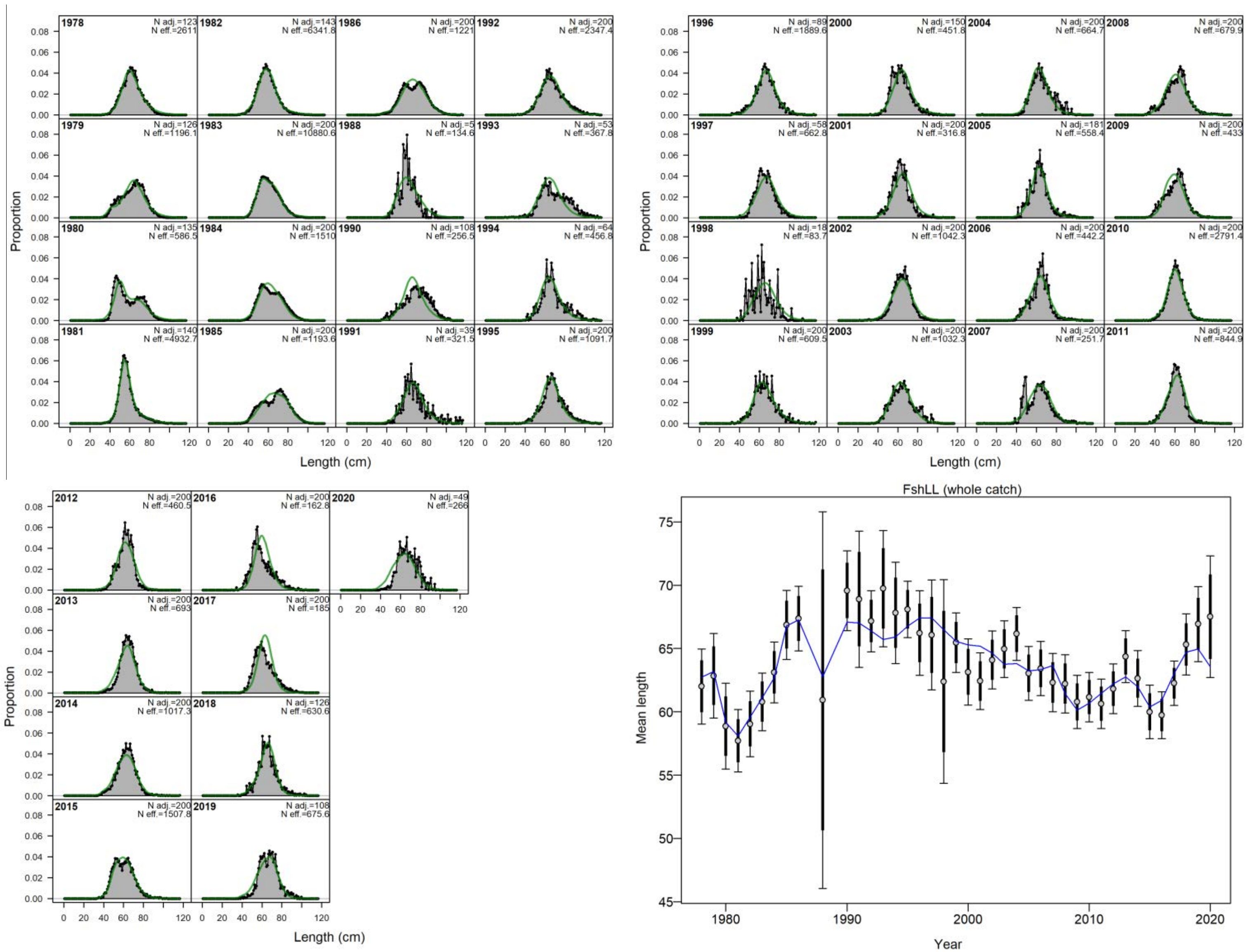


Figure 2.61 Longline fishery length composition and Model 19.1 fit (top and left) and mean length (cm; right bottom).

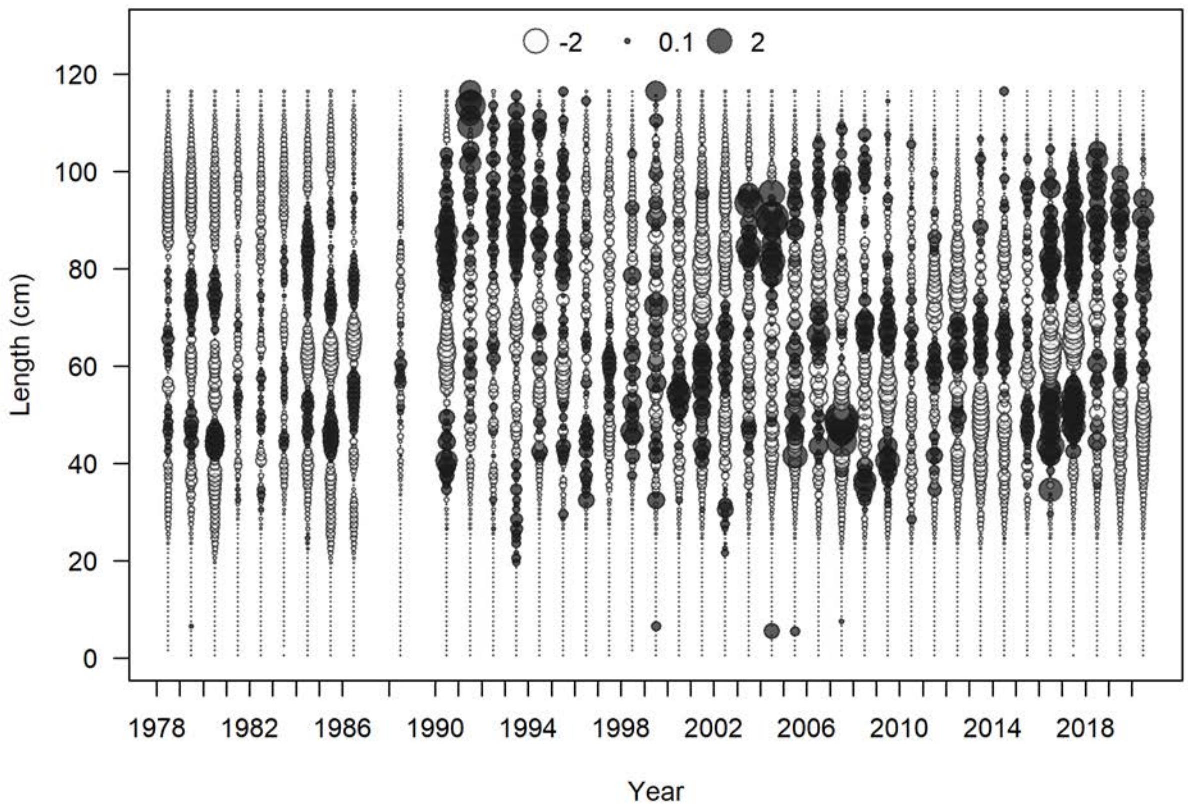


Figure 2.62 Longline fishery length composition and Model 19.1 fit (top and left) and Pearson residuals.

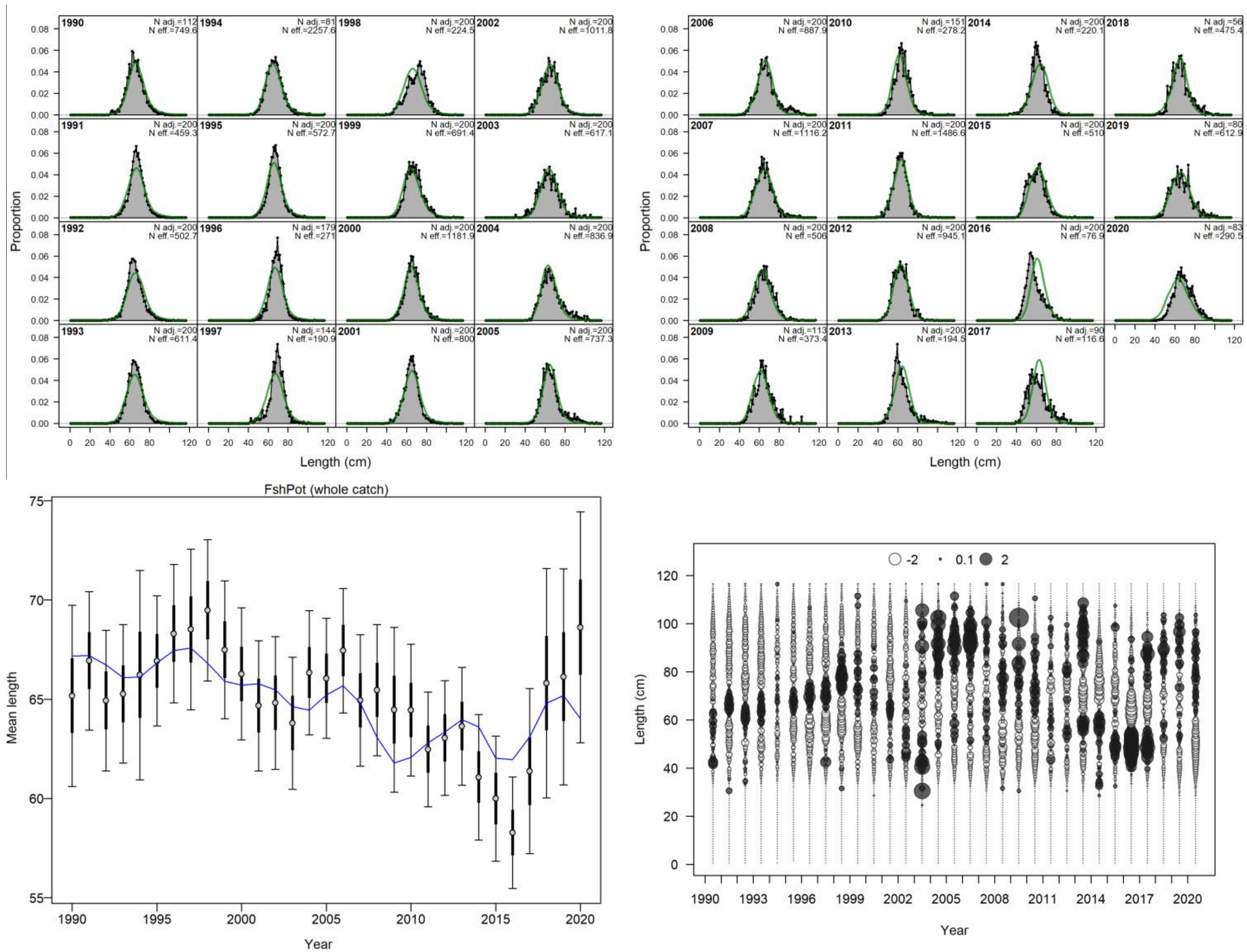


Figure 2.63 Pot fishery length composition and Model 19.1 fit (top), mean length (bottom left), and Pearson residuals (max=4.61; bottom right).

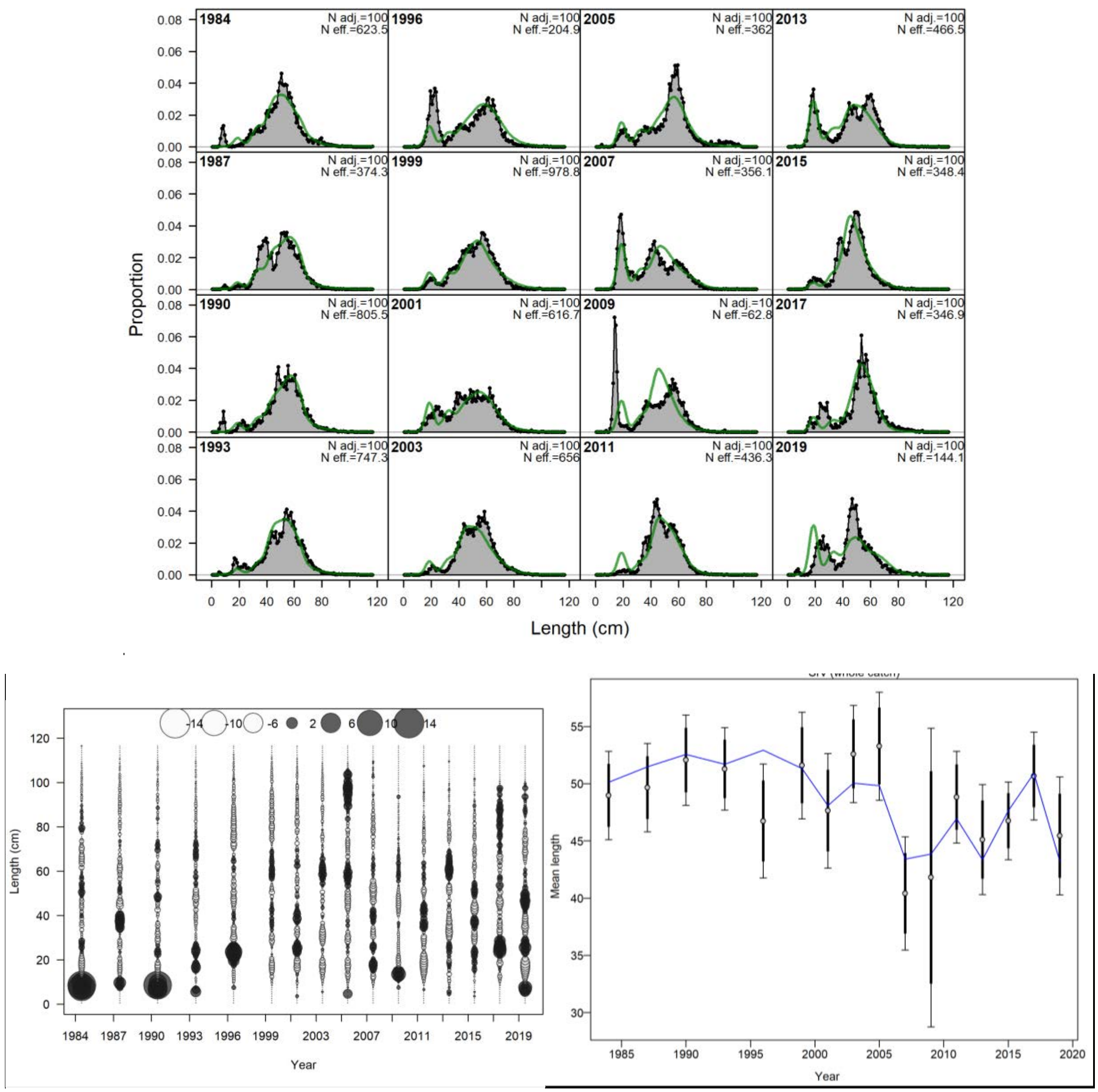


Figure 2.64 NMFS bottom trawl survey length composition and Model 19.1 fit (top), Pearson residuals (left bottom; max = 9.66), and mean length (cm; right bottom).

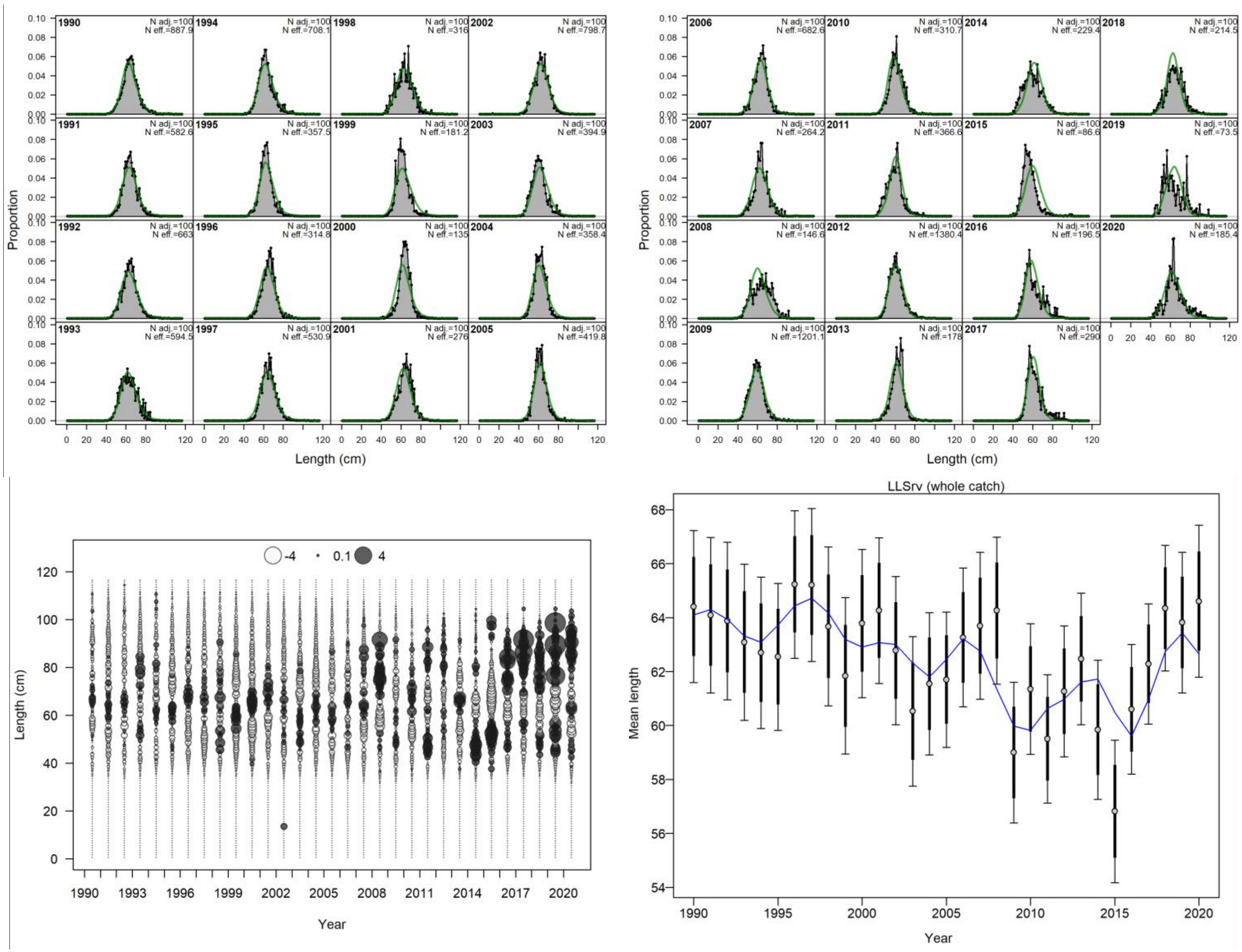


Figure 2.65 AFSC Longline survey length composition and Model 19.1 fit (top), Pearson residuals (left bottom; max=5.19), and mean length (cm; right bottom).

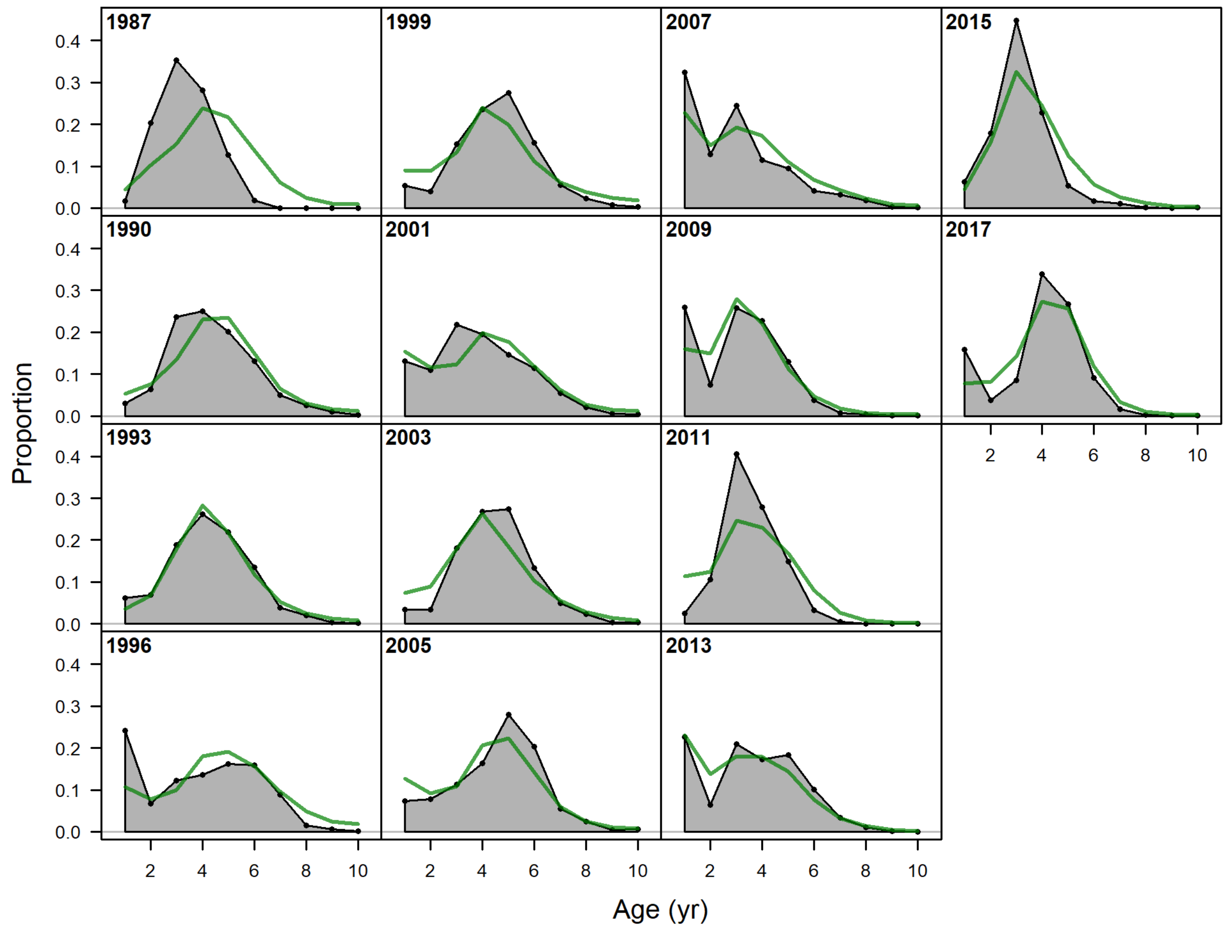


Figure 2.66 NMFS bottom trawl survey (Srv) age composition and Model 19.1 fit (left). Note the age data fits are not included in the objective function.

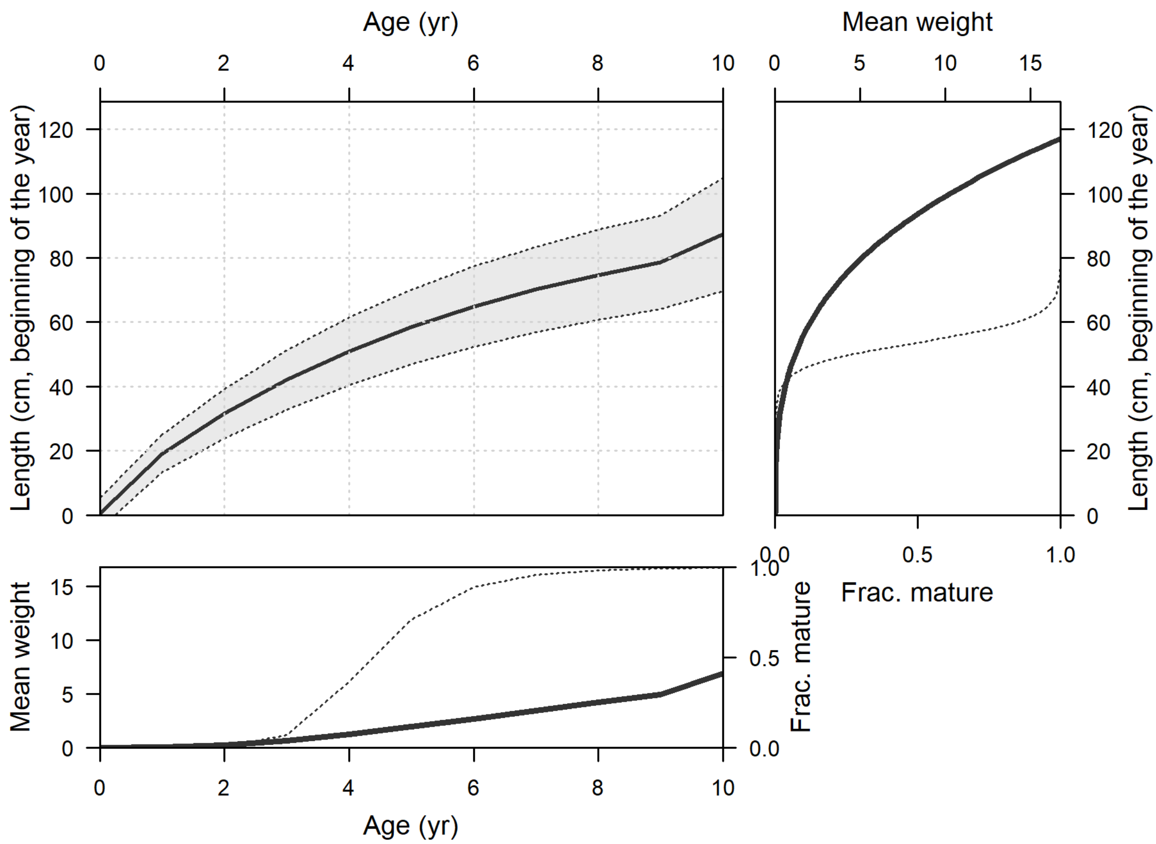


Figure 2.67 Model 19.1 length at age, weight at age, weight at length, and fraction mature at length, weight, and age.

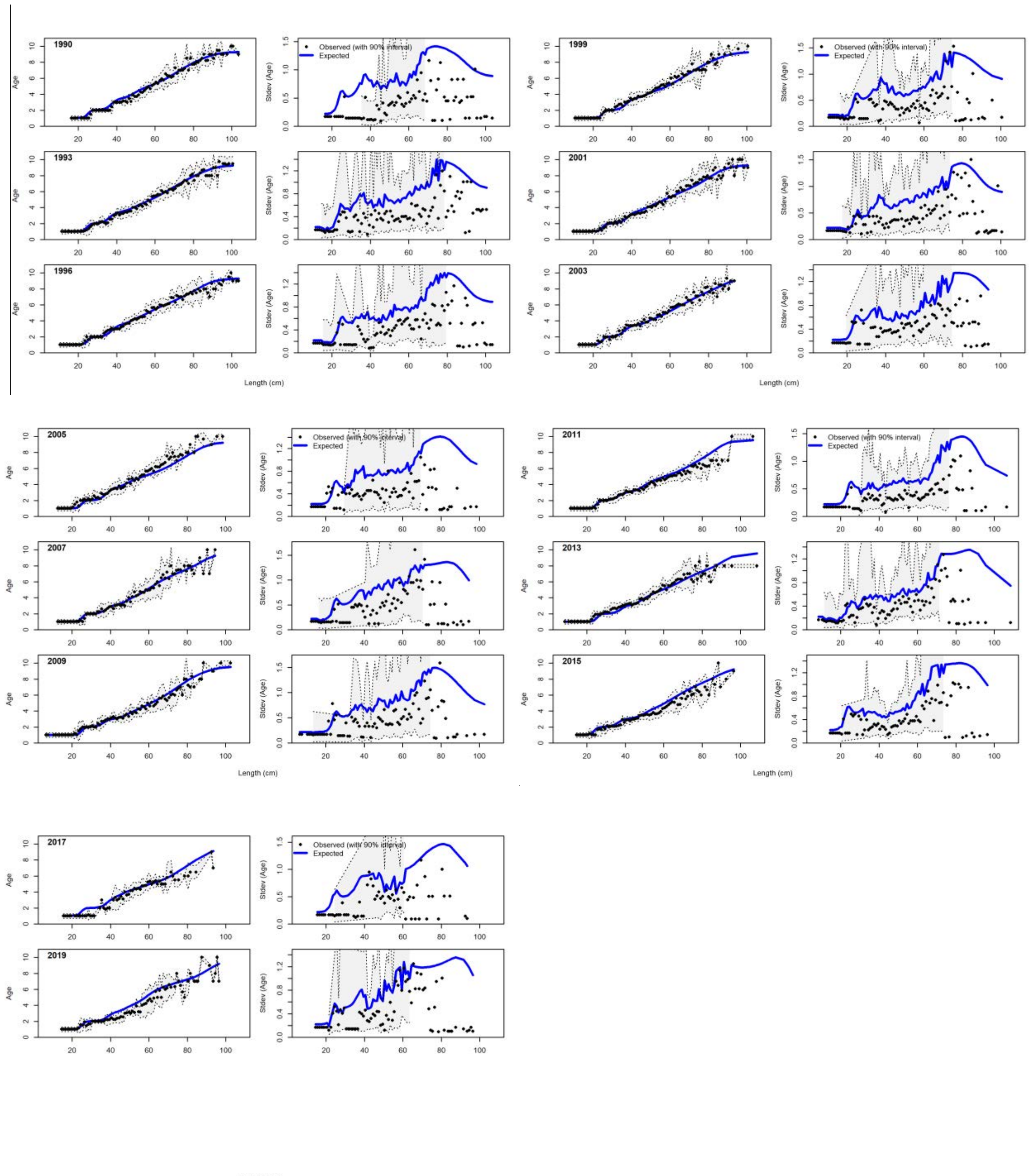


Figure 2.68 NMFS bottom trawl survey (Srv) conditional length-at-age data and Model 19.1 fit.

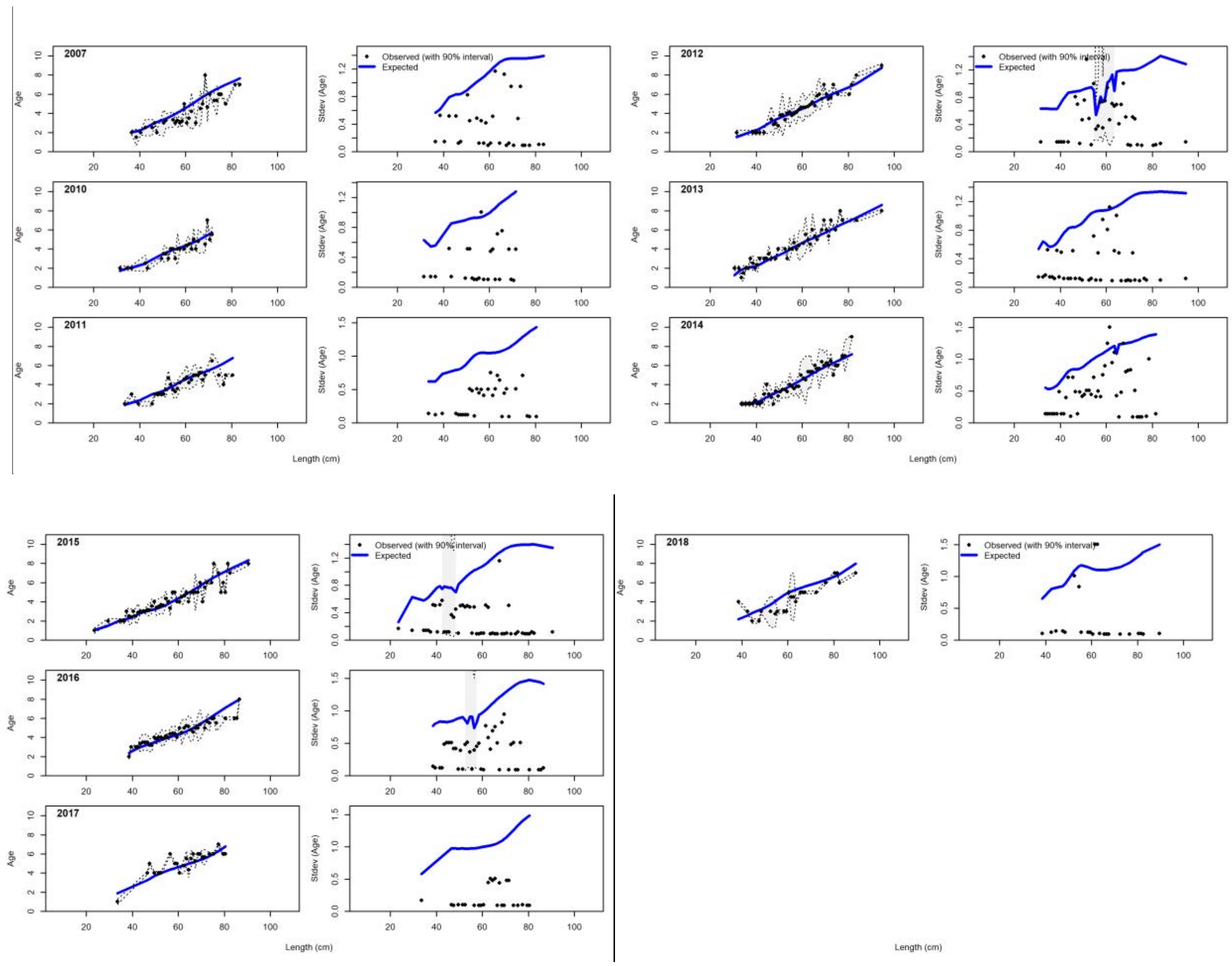


Figure 2.69 Trawl fishery conditional length-at-age data and Model 19.1 fit.

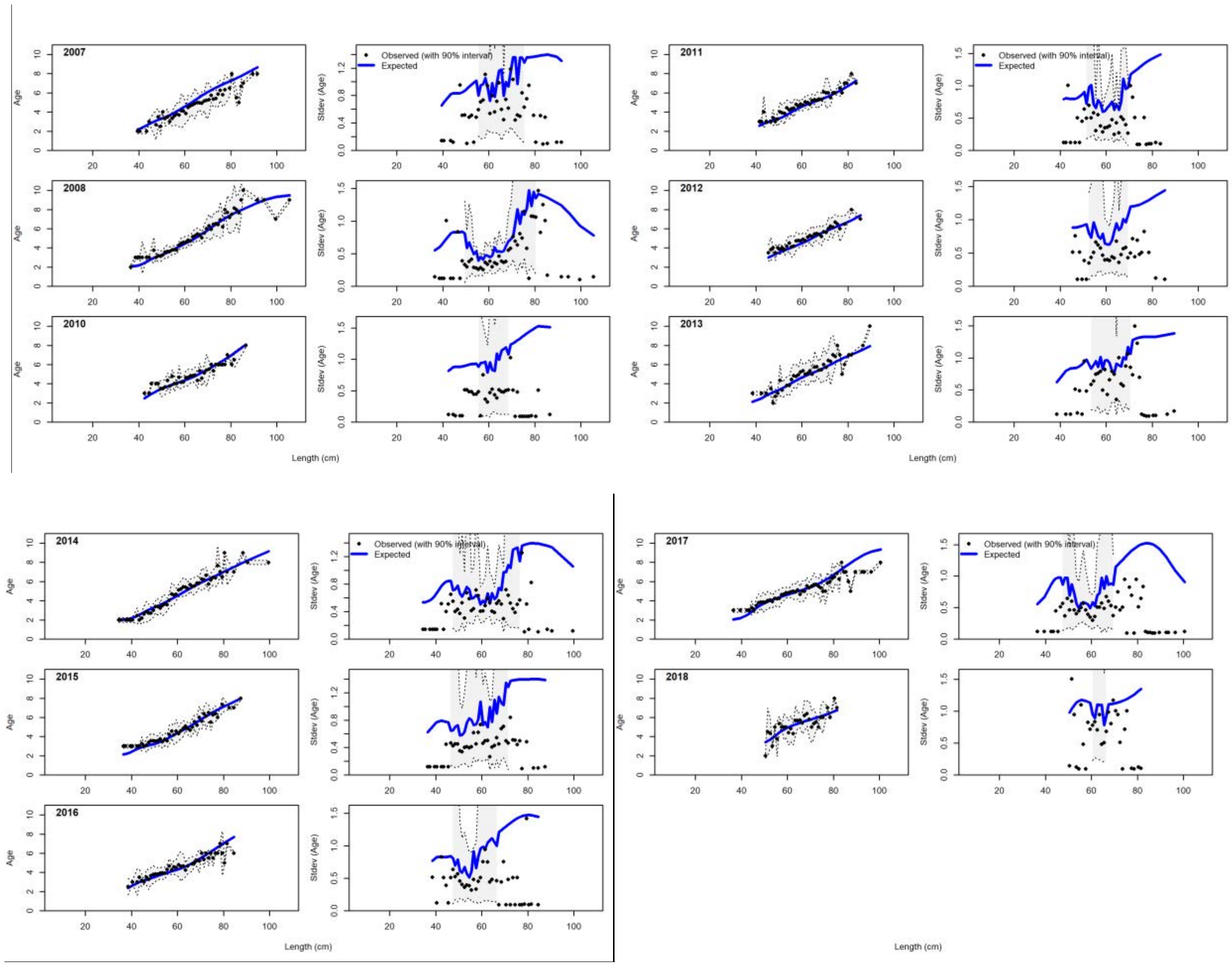


Figure 2.70 Longline fishery conditional length-at-age data and Model 19.1 fit.

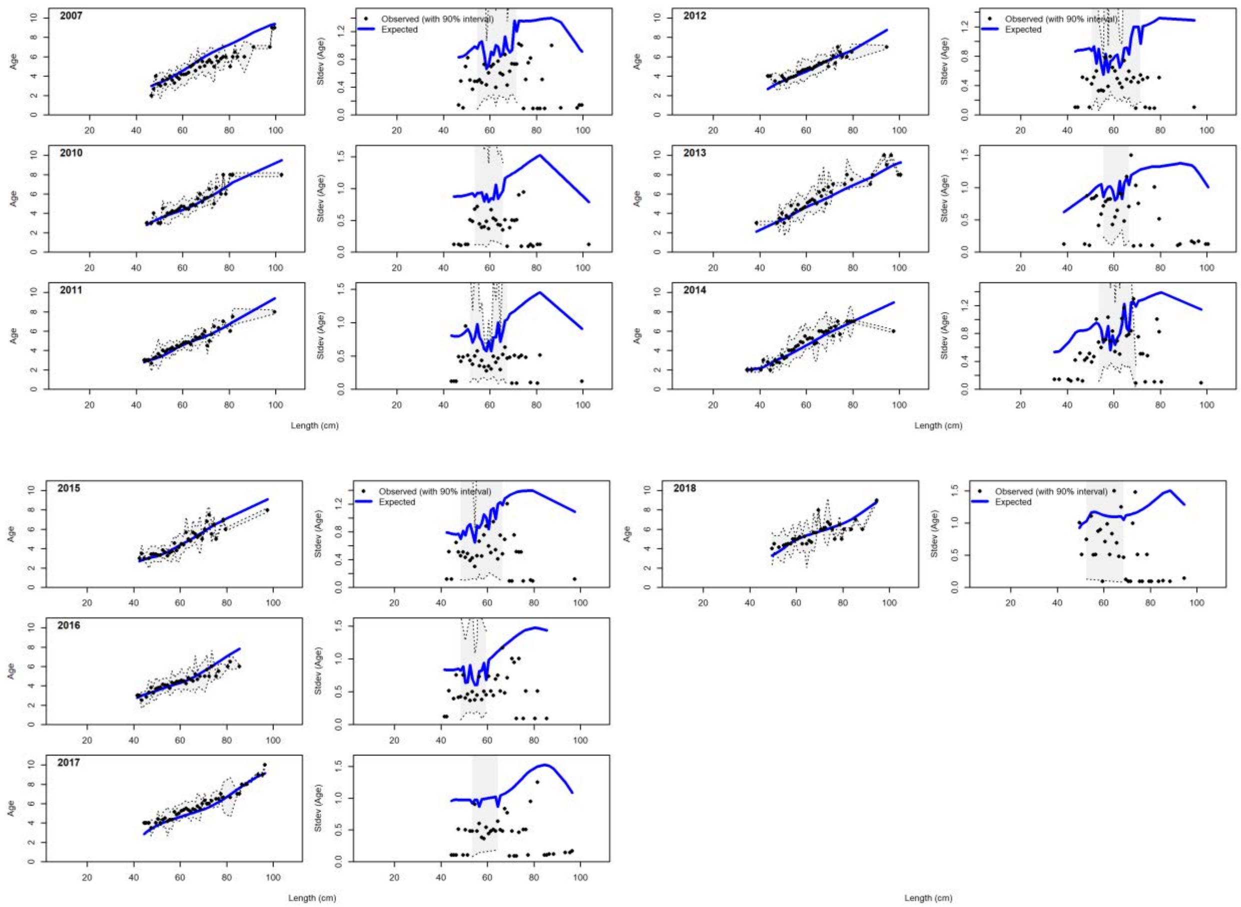


Figure 2.71 Pot fishery conditional length-at-age data and Model 19.1 fit.

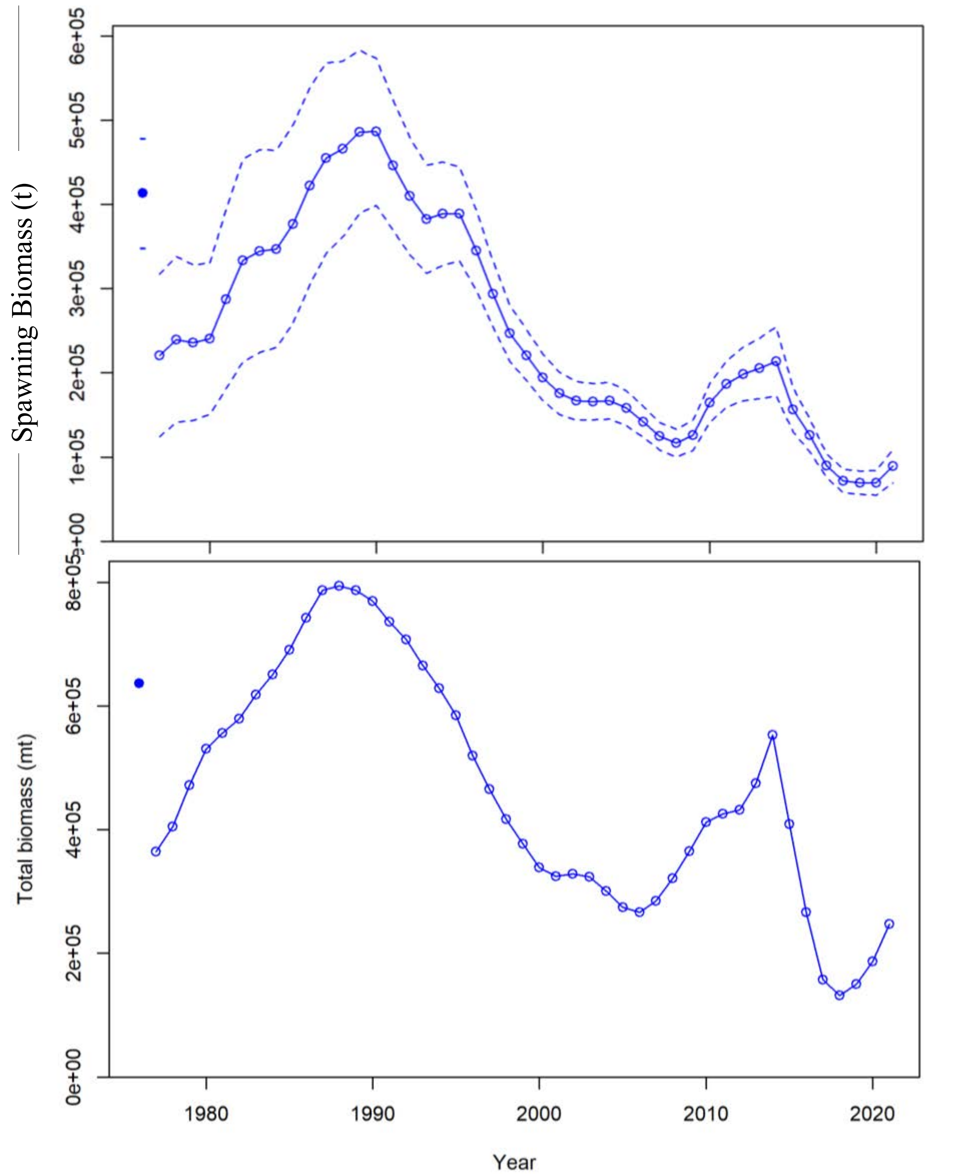


Figure 2.72 Model 19.1 predicted spawning output (femal spawning biomass; t) with 95% asymtotic error intervals (top) and total biomass (t).

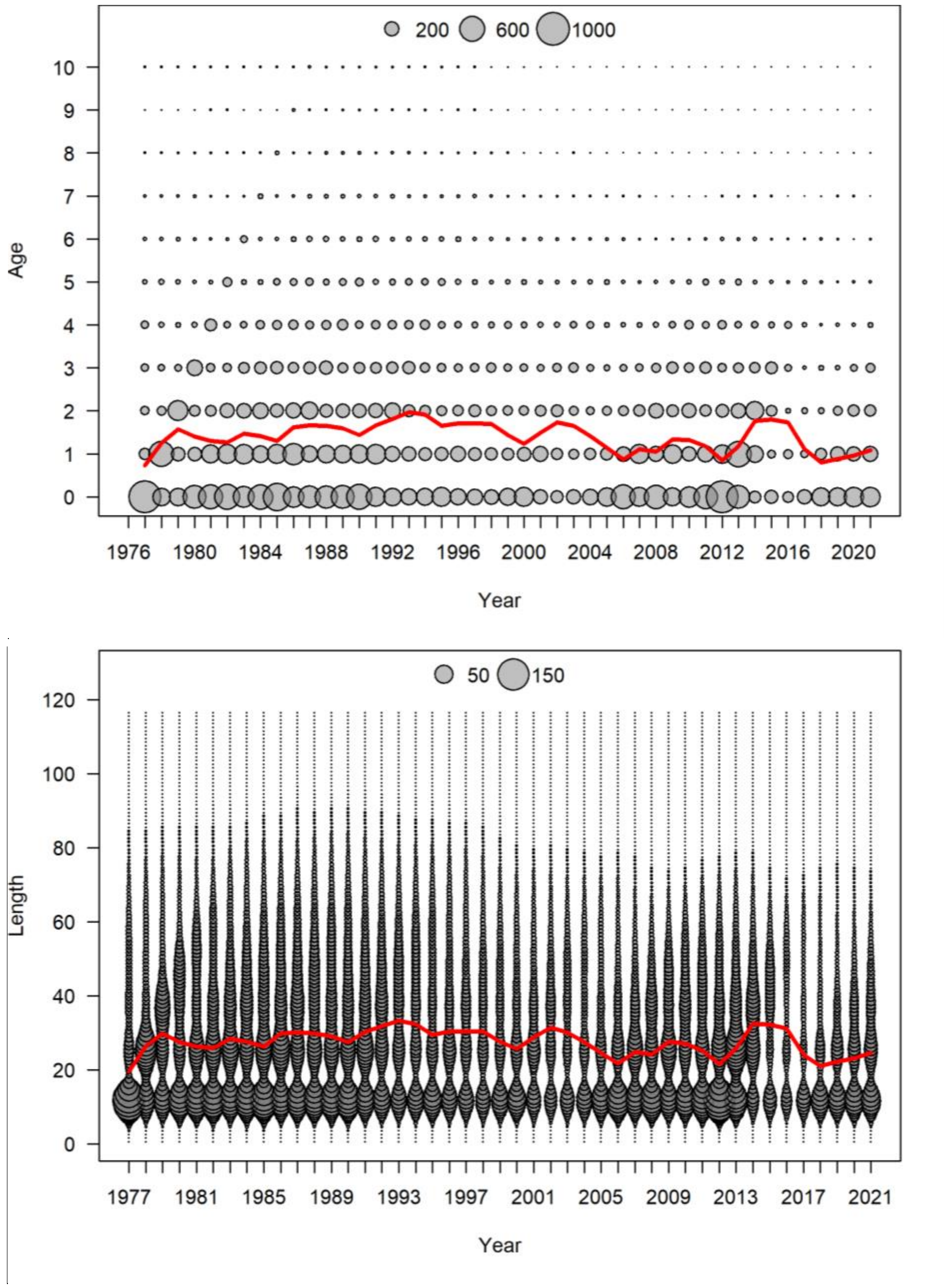


Figure 2.73 Model 19.1 predictions of middle of the year number at age (top) with mean age (red line) and numer at length (bottom)with mean length (red line).

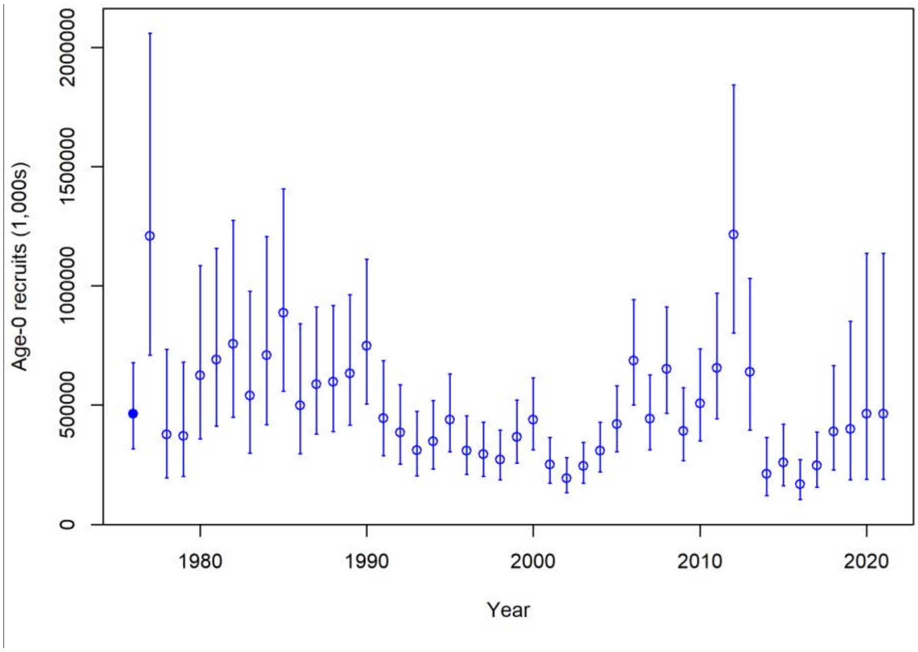


Figure 2.74 Model 19.1 age-0 recruitment (1000's) with 95% asymtotic error intervals.

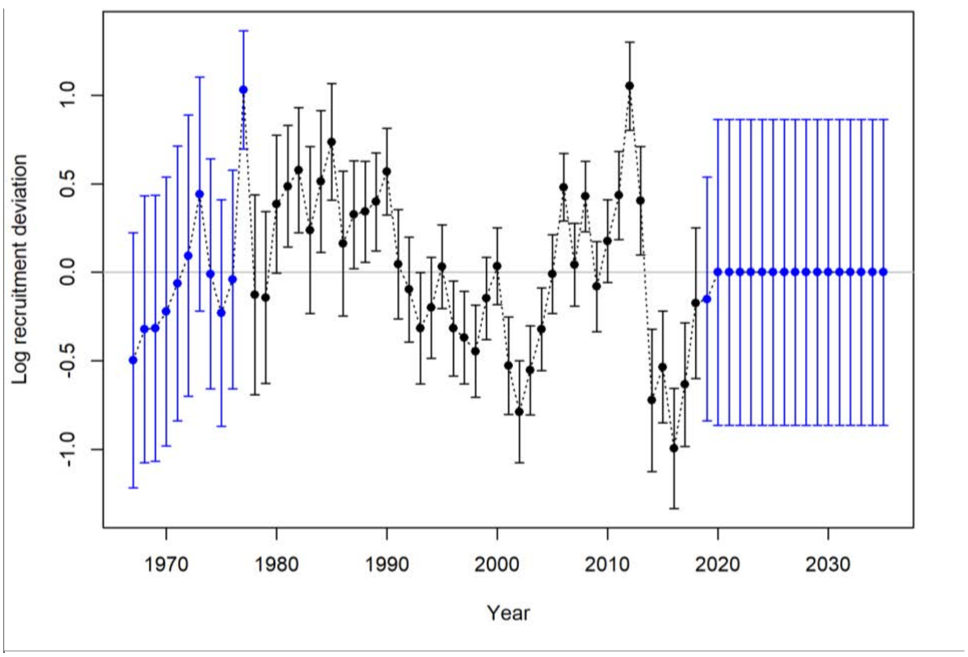


Figure 2.75 Model 19.1 log recruitment deviations with 95% asymtotic error intervals.

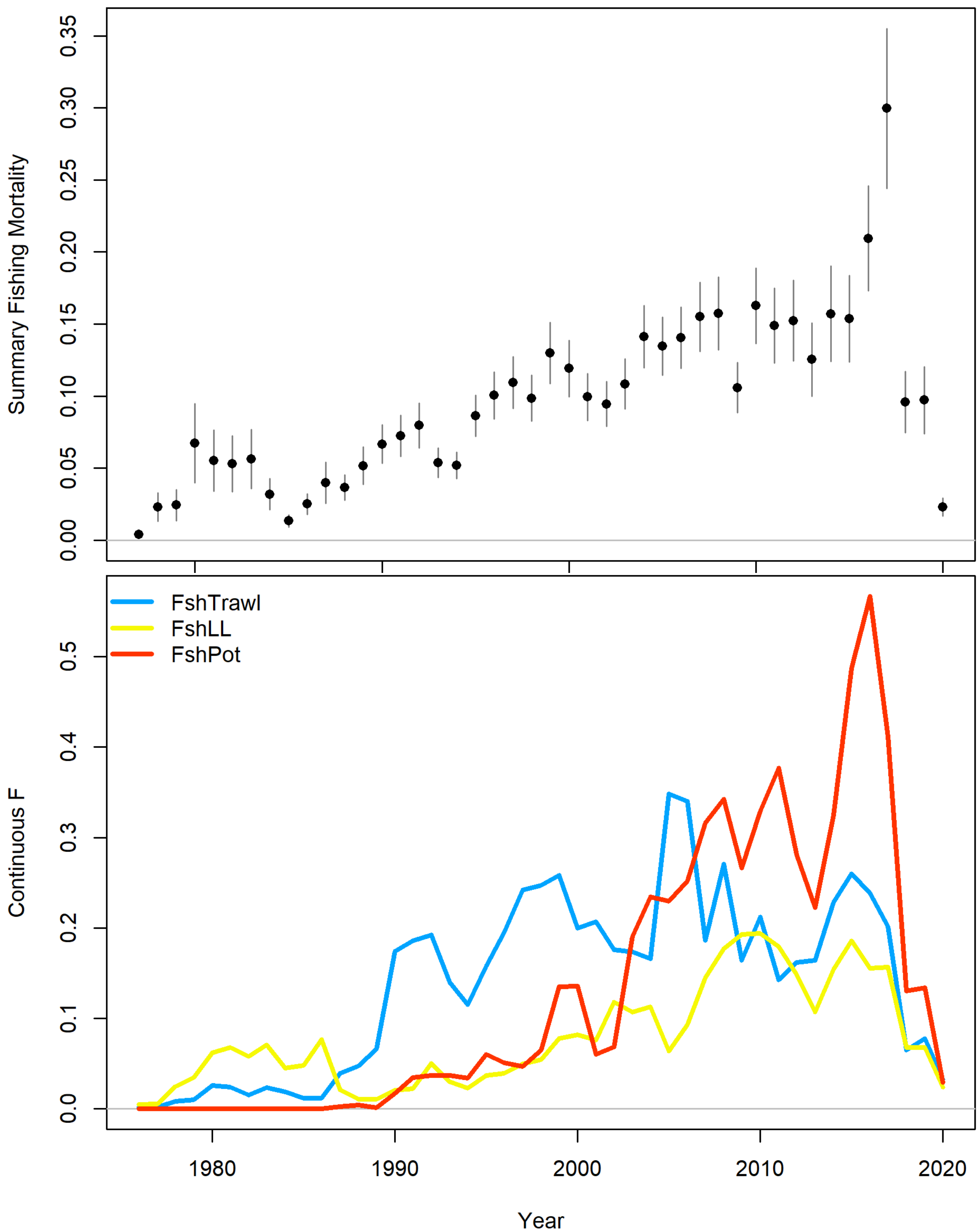


Figure 2.76 Model 19.1 age 3-8 true fishing mortality (top) and continuos fishing mortality by trawl (FshTrawl), longline (FshLL) and pot (FshPot) fisheries (bottom).

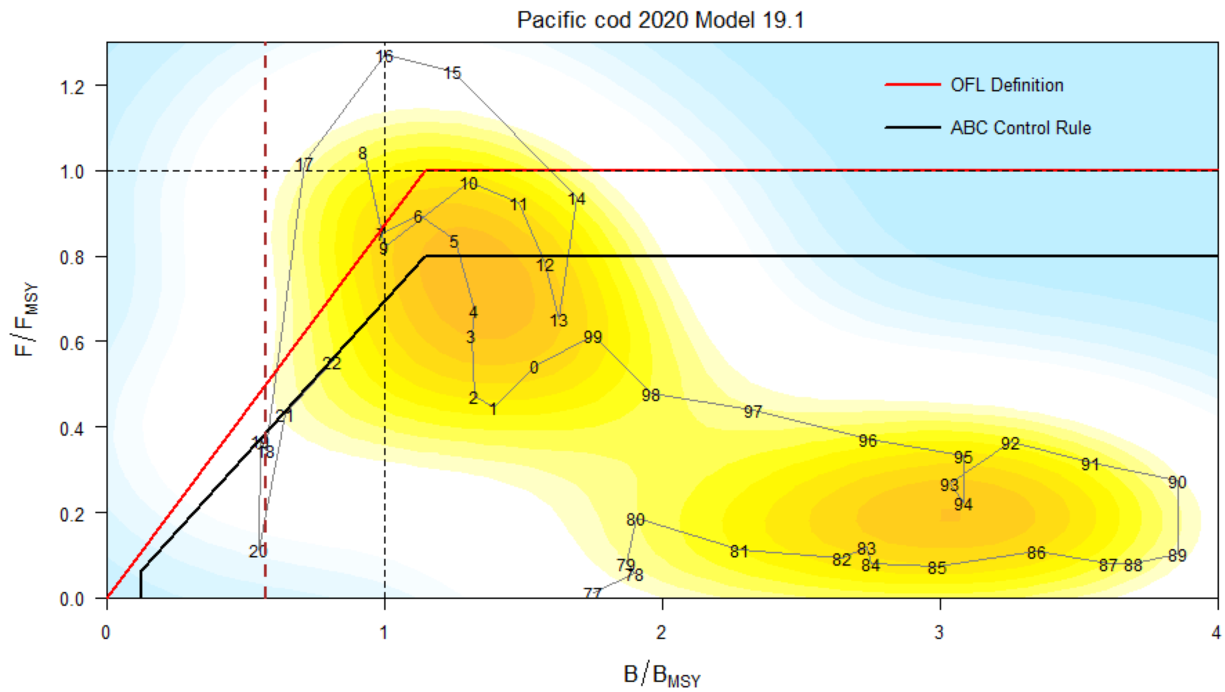


Figure 2.77 For Model 19.1 ratio of historical F/F_{msy} versus female spawning biomass relative to B_{msy} for GOA pacific cod, 1977-2022. Note that the proxies for *Fmsy* and *Bmsy* are $F_{35\%}$ and $B_{35\%}$, respectively. The Fs presented are the sum of the full Fs across fleets. Dashed line is at $B_{20\%}$, Steller sea lion closure rule for GOA Pacific cod.

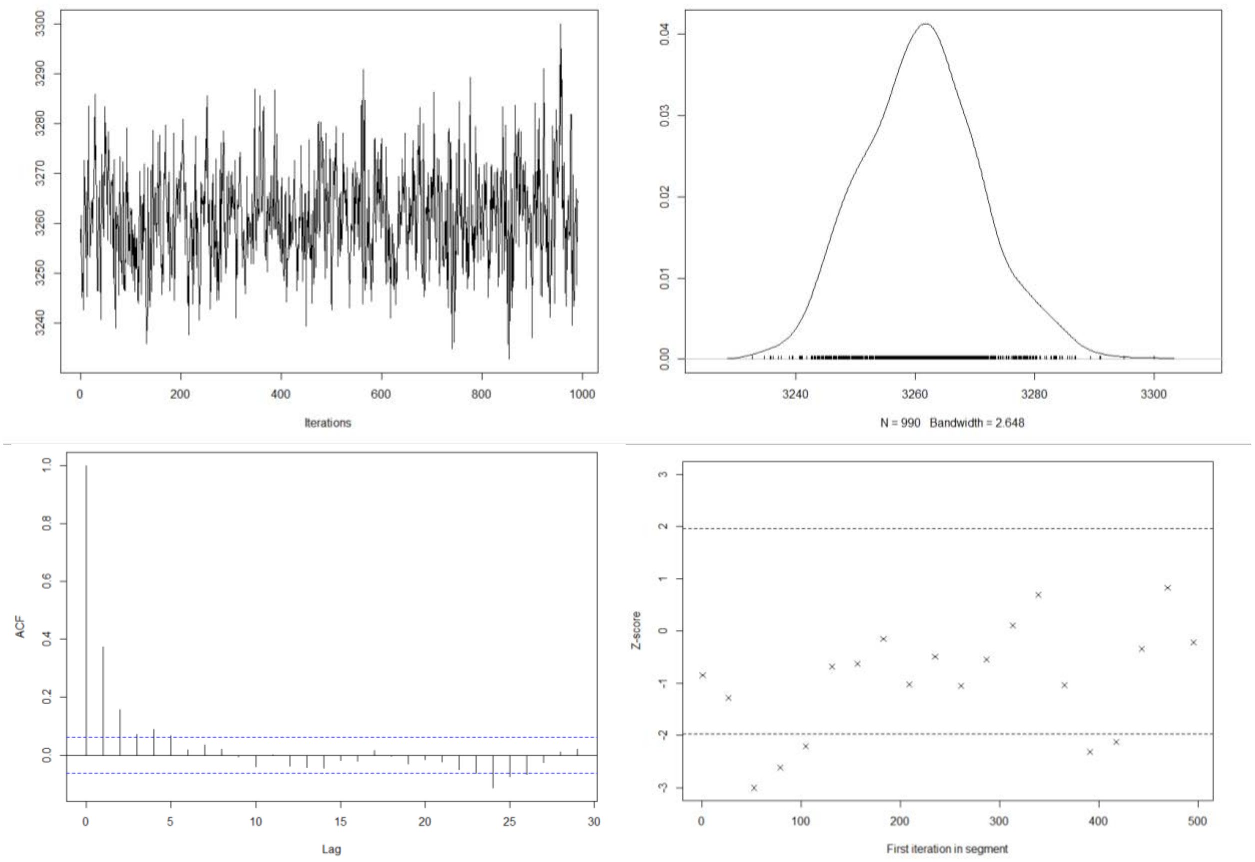


Figure 2.78 Model 19.1 MCMC trace (top left), density (top right), autocorrelation function plot (bottom left), and Geweke diagnostic plot (bottom right) for the objective function.

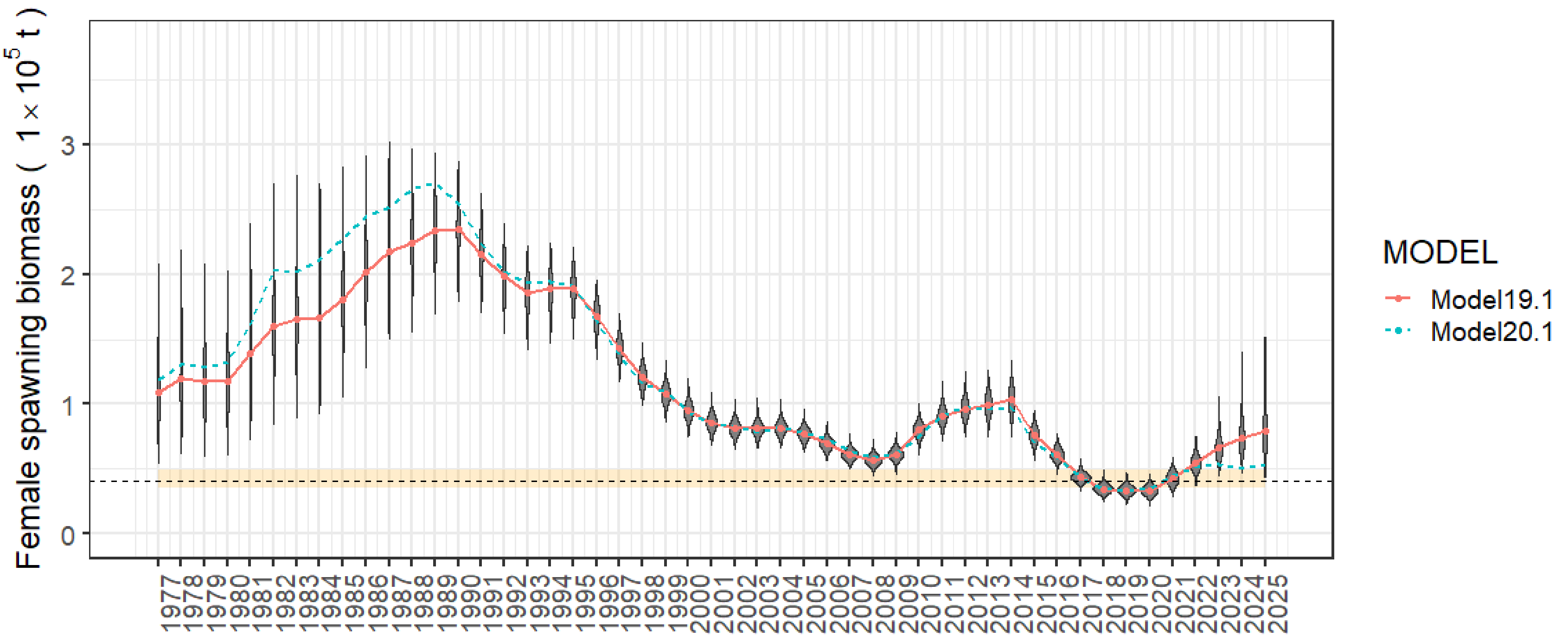


Figure 2.79 Model 19.1 MCMC posterior distribitions of beginning of the year female spawning biomass 1977-2025. Dotted line is the projected $SSB_{20\%}$ with 95% confidence interval in orange. The blue dashed line is the posterior median for Model 20.1.

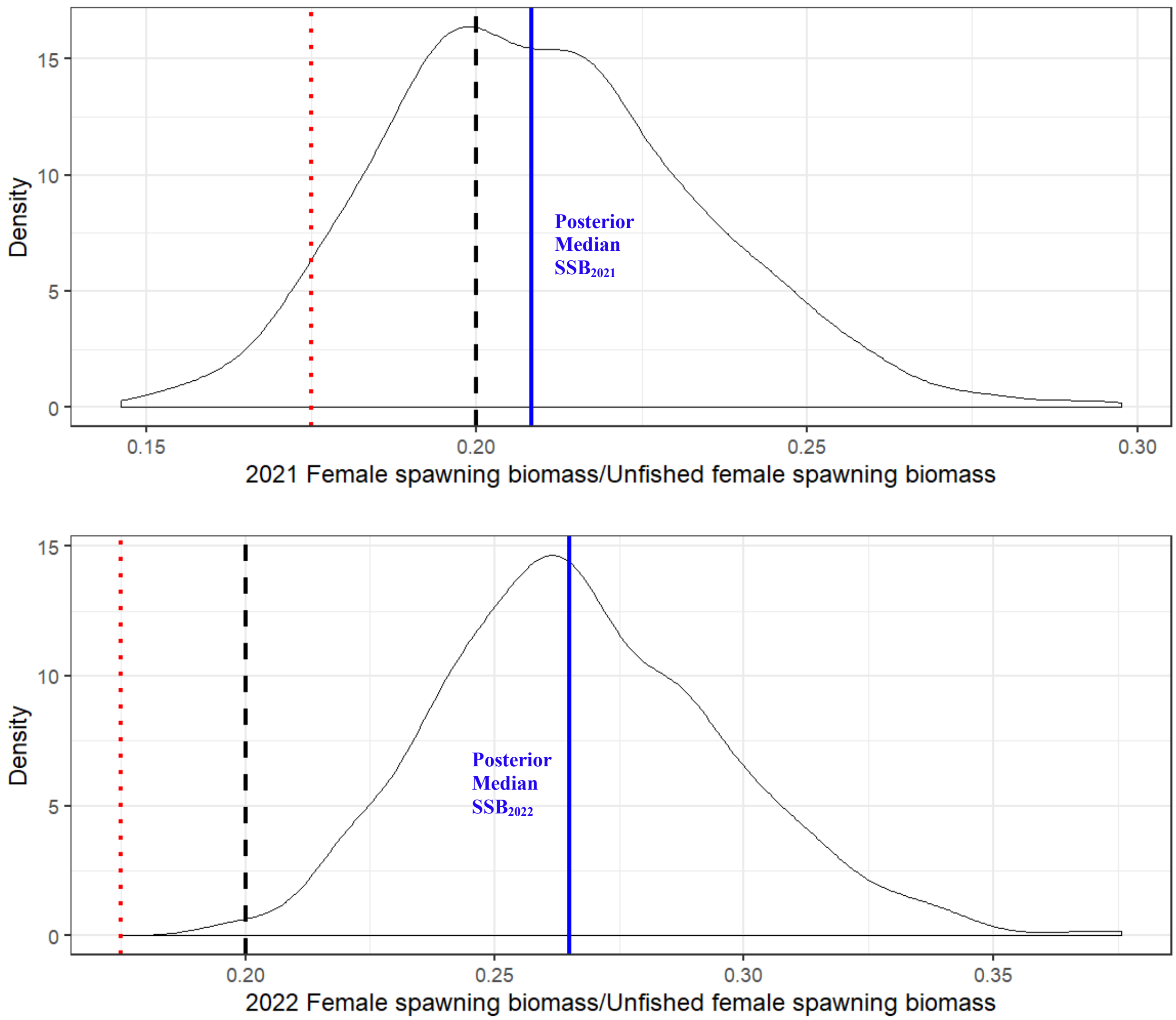


Figure 2.80 Model 19.1 MCMC posterior distribitions of the (top) 2021 and (bottom) 2022 spawning stock biomass ratio with estimates for $SSB_{20\%}$ (black dashed line) and $SSB_{17.5\%}$ (Red dotted line) from the projection model, and posterior median (blue solid line) for beginning year 2021 and 2022.

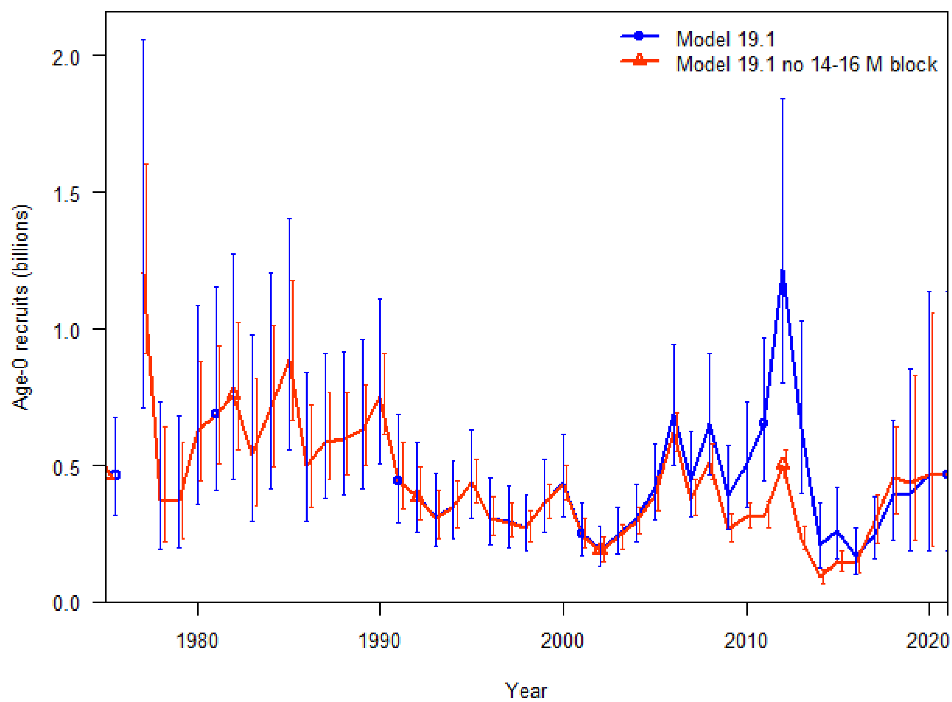


Figure 2.81 Model 19.1 Age-0 recruits with and without the 2014-2016 fitting block on natural mortality showing differences in estimated recruitment for 1977-2020.

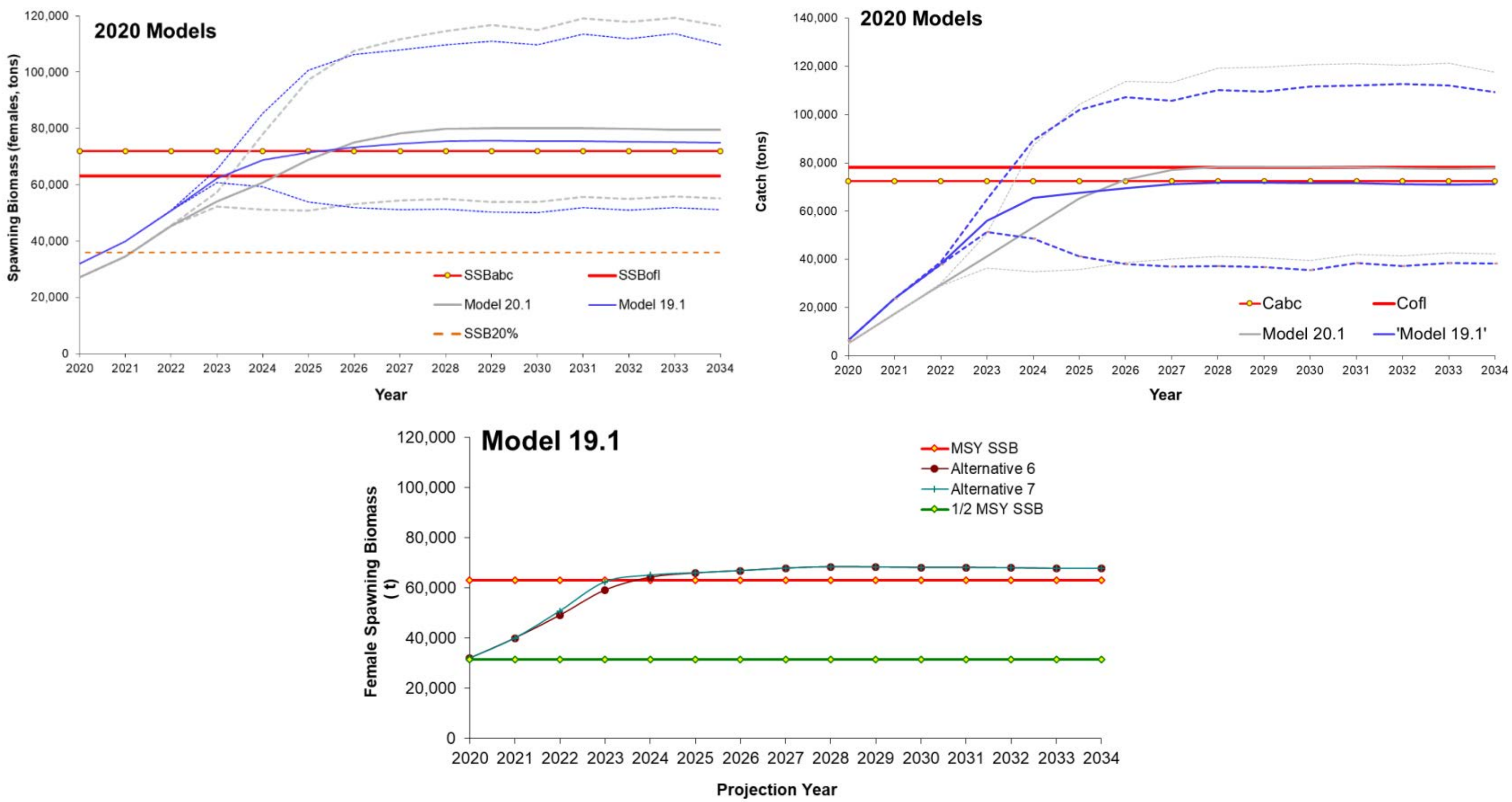


Figure 2.82 Model 19.1 projections of female spawning biomass (top), catch (bottom left), and female spawning biomass from scenarios 6 and 7 for status determination (bottom right). The projections shown are from the bootstrap ‘Proj’ projection model.

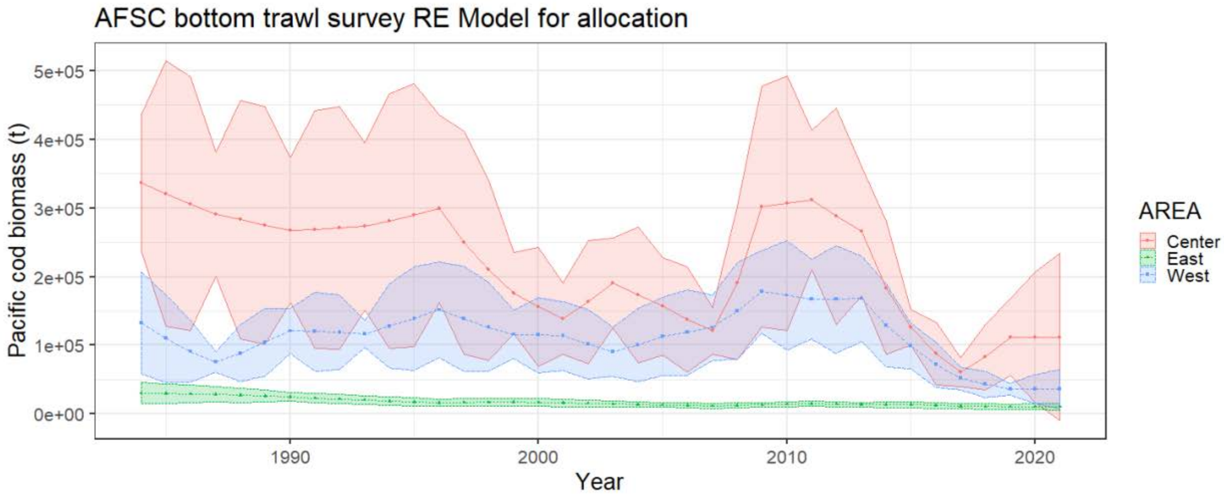


Figure 2.83 Random effects model results for the AFSC bottom trawl survey area used for area allocation.

Model 20.1

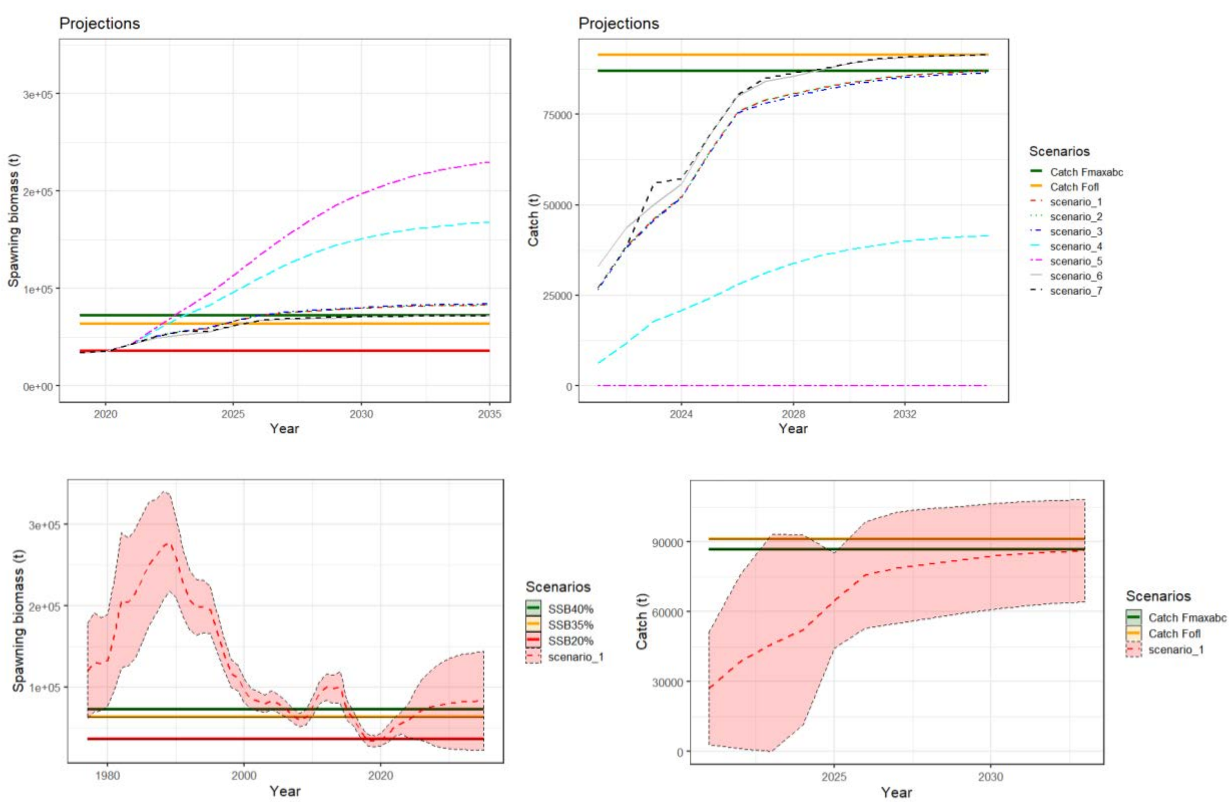


Figure 2.84 Stock Synthesis generated projections for Model 20.1 projections of (left) female spawning biomass and (right) catch for (top) the 7 North Pacific groundfish catch scenarios and (bottom) scenario 1 with 95% confidence intervals for 2019- 2035. Note that these are not currently used for management.

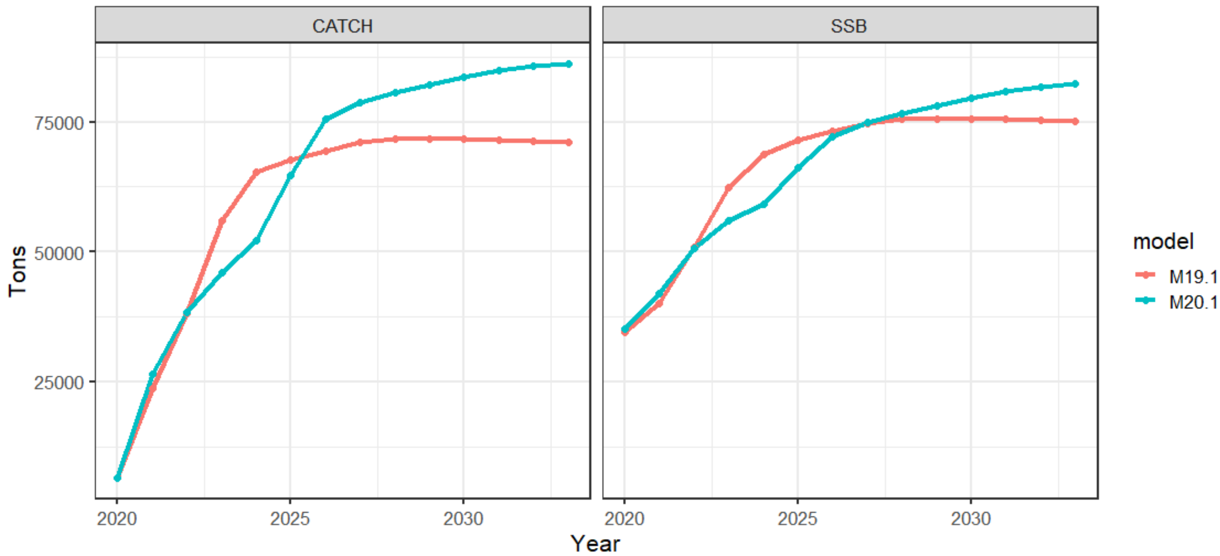


Figure 2.85 Comparison of projected (left) maximum ABC and (right) female spawning biomass from Model 19.1 bootstrap projections and Model 20.1 Stock Synthesis generated projection point estimates.

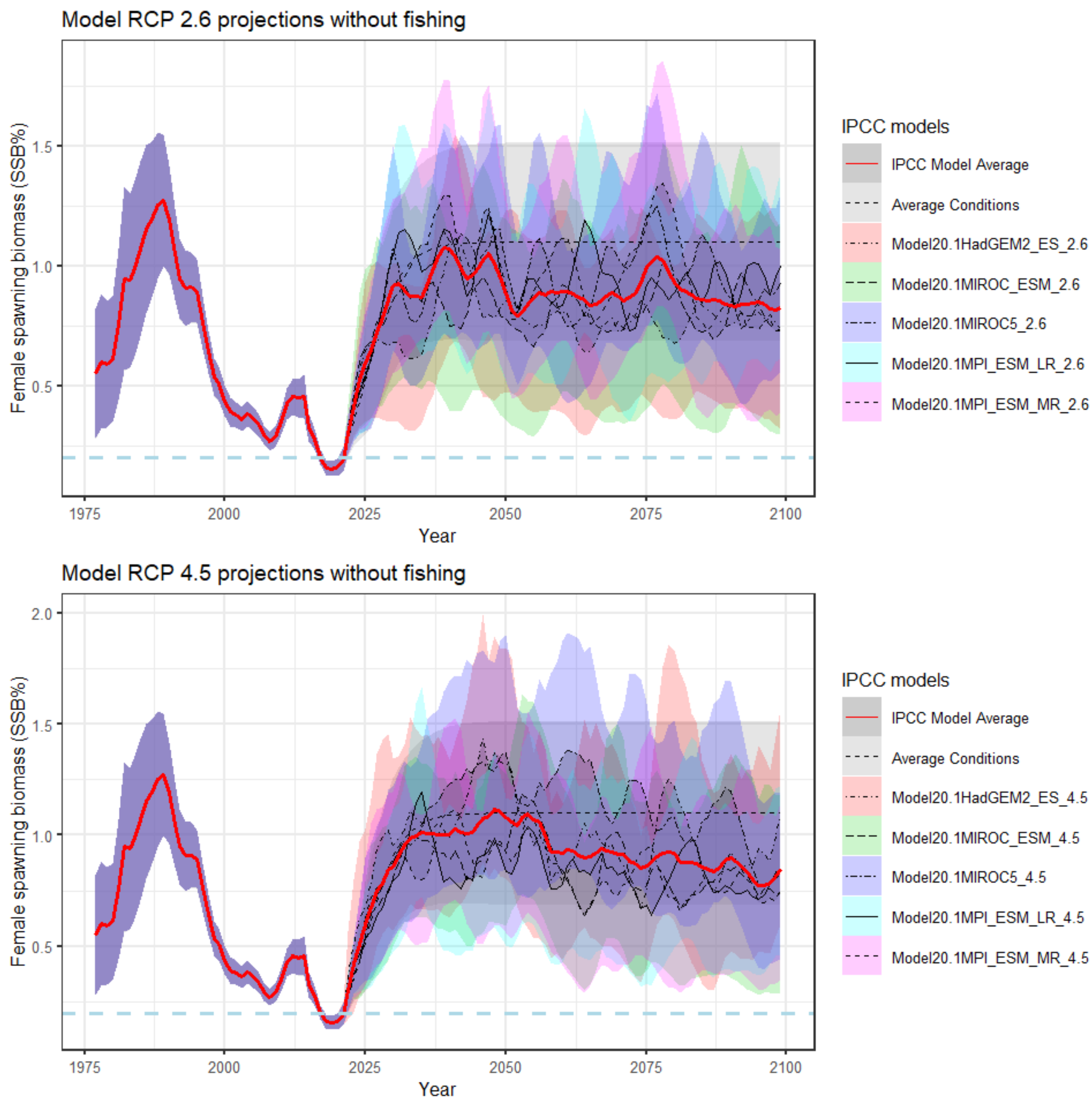
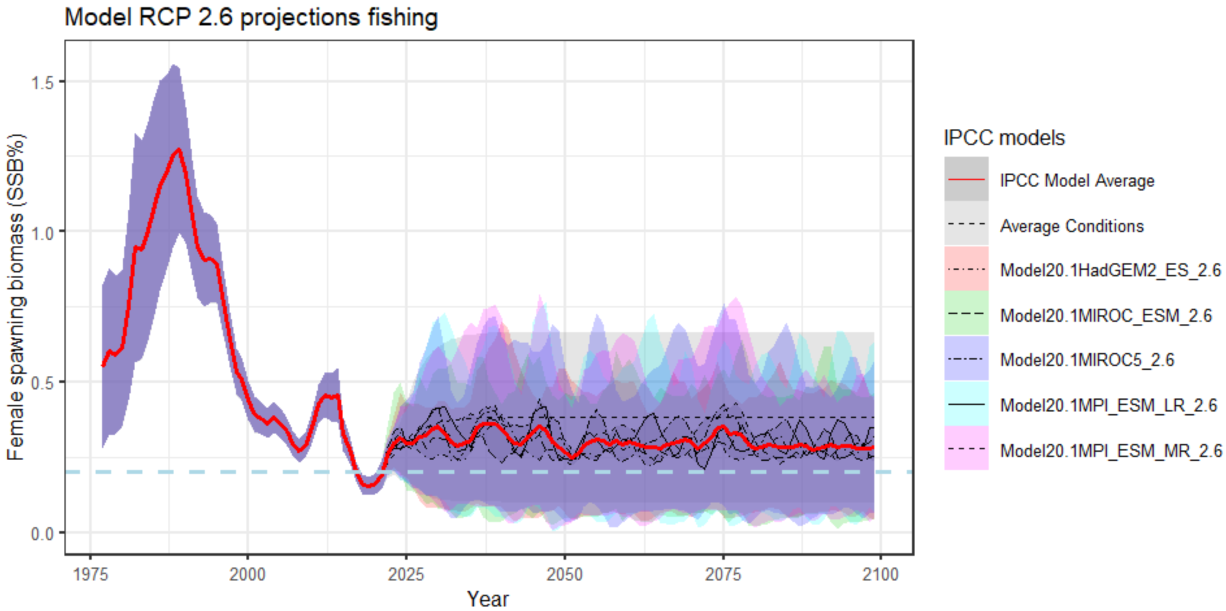


Figure 2.86 Model 20.1 Projections of spawning biomass under no fishing to 2099 using CMIP5 climate models for the Central Gulf of Alaska for (top) RCP 2.6 and (bottom) RCP 4.5. The blue dashed line is current $B_{20\%}$, the black dashed line is the projection under average 1982-2012 climate conditions, the red line is the model average across all five IPCC climate model projections.



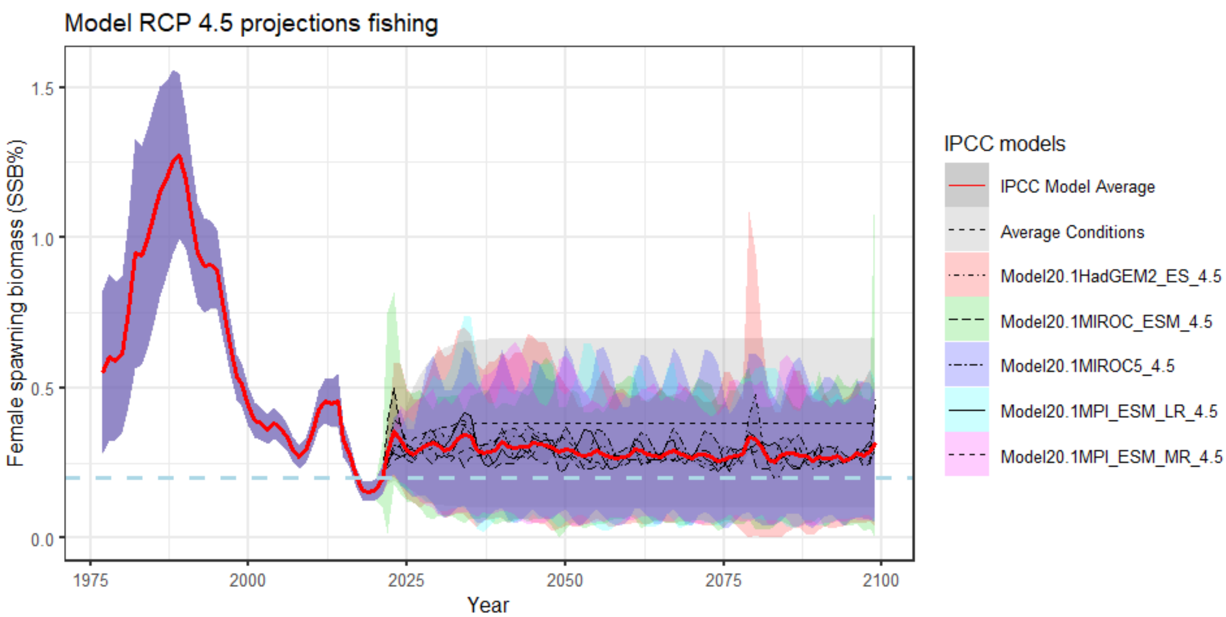
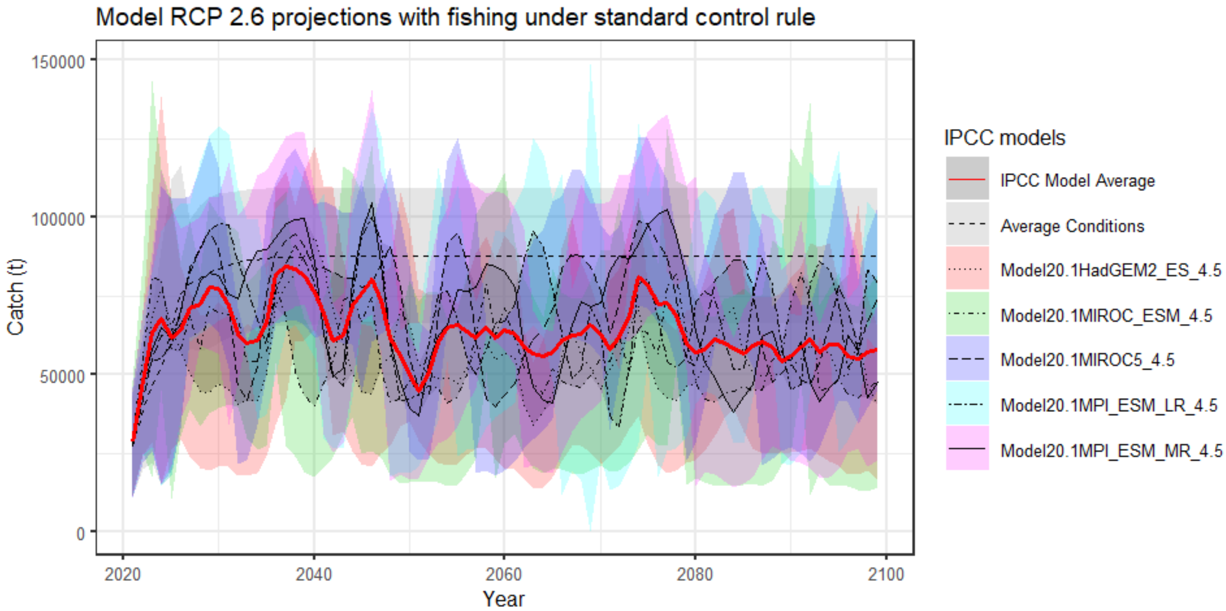


Figure 2.87 Model 20.1 Projections of spawning biomass under standard control rule fishing at $F_{Max\ ABC}$ for 2021 to 2099 using CMIP5 climate models for the Central Gulf of Alaska for (top) RCP 2.6 and (bottom) RCP 4.5. The blue dashed line is current $B_{20\%}$, the black dashed line is the projection under average 1982-2012 climate conditions, the red line is the model average across all five IPCC climate model projections.



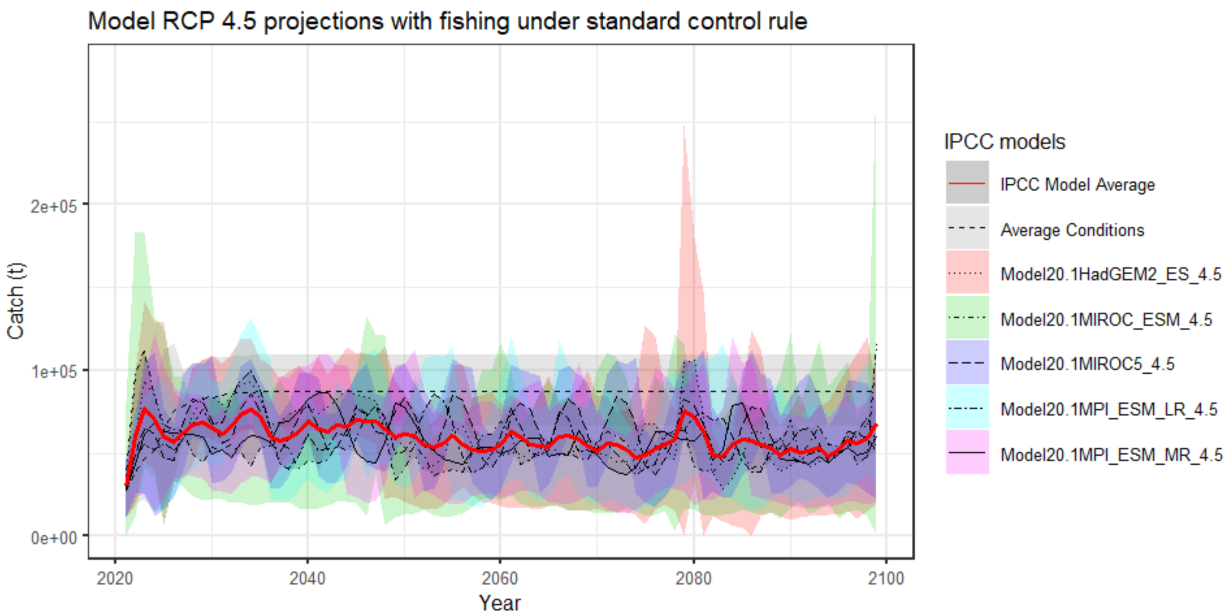
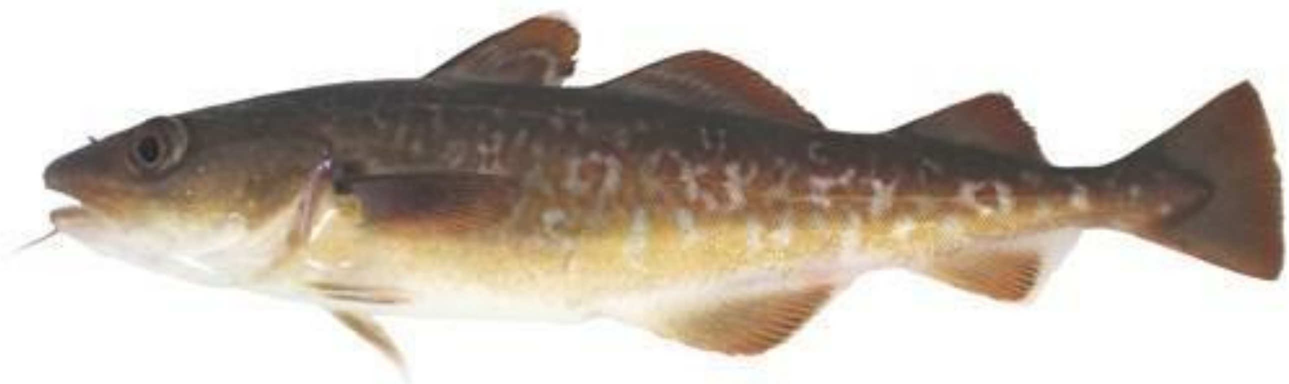


Figure 2.88 Model 20.1 Projections of catch (t) under standard control rule fishing at $F_{Max\ ABC}$ for 2021 to 2099 using CMIP5 climate models for the Central Gulf of Alaska for ICPP (top) RCP 2.6 and (bottom) RCP 4.5. The blue dashed line is current $B_{20\%}$, the black dashed line is the projection under average 1982-2012 climate conditions, the red line is the model average across all five IPCC climate model projections.

Appendix 2.1. Ecosystem and Socioeconomic Profile of the Pacific cod stock in Gulf of Alaska

S. Kalei Shotwell, Steven Barbeaux, Bridget Ferriss, Ben Fissel, Ben Laurel, Lauren Rogers

November 2020



With Contributions from:

Kerim Aydin, Curry Cunningham, Kirstin Holsman, Carol Ladd, Beth Matta, Sandi Neidetcher, Patrick Ressler, Heather Renner, Sean Rohan, Elizabeth Siddon, Ingrid Spies, Katie Sweeney, Grant Thompson, Muyin Wang, Jordan Watson, Sarah Wise, Stephani Zador

Executive Summary

National initiative scoring and AFSC research priorities suggest a high priority for conducting an ecosystem and socioeconomic profile (ESP) for Gulf of Alaska (GOA) Pacific cod. Annual guidelines for the AFSC support research that improves our understanding of environmental and climate forcing of ecosystem processes with a focus on variables that can provide direct input into or improve stock assessment and management. The GOA Pacific cod ESP follows the new standardized framework for evaluating ecosystem and socioeconomic considerations for GOA Pacific cod and may be considered a proving ground for potential use in the main stock assessment.

We use information from a variety of data streams available for the GOA Pacific cod stock and present results of applying the ESP process through a metric and subsequent indicator assessment. Analysis of the ecosystem and socioeconomic processes for GOA Pacific cod by life history stage along with information from the literature identified a suite of indicators for testing and continued monitoring within the ESP. Results of the metric and indicator assessment are summarized below as ecosystem and socioeconomic considerations that can be used for evaluating concerns in the main stock assessment.

Ecosystem Considerations

- Hatch timing and success is highly temperature dependent with optimal hatch occurring in waters between 4-6ºC and has implications for spawning habitat suitability and subsequent recruitment
- Warm temperatures can increase susceptibility of starvation for larval Pacific cod when mismatched to prey or reduce growth during shifts in the lipid/fatty acid composition of prey
- Cross-shelf transport may assist larvae and early juvniles to nearshore nurseries for settlement and eddies and gap winds may disrupt along-shore currents to increase growth and survival
- Copepods and euphausiids low since 2009 and returned to average in 2019, and condition of juvenile Pacific cod were poor for 2015 and 2017 surveys suggesting spatial shifts in prey base
- Annual eddy kinetic energy has shifted from high periods of eddy activity from 2003 to 2015 to a lower energy system in 2016 to 2019 and a strong, persistent eddy around Kodiak in 2020
- The overall spatial distribution of the stock has spread out substantially from 2009 to 2019 with a shift to the farthest northeast in 2019 from the farthest southwest in 2017
- Predators of Pacific cod have steadily decreased over the time series but have recently stabilized suggesting the primary pressure on the 2012 year-classes may be the lack of preferred prey
- Overall, ecosystem indicators have been decreasing since 2012 and have shown some modest recovery since 2017 when the heat in the system was reduced, similar to the GOA pollock
- Highest ranked predictor for recruitment regression model was spawning habitat suitability and the eddy kinetic energy temperature on the SEBS shelf (inclusion probability > 0.5)

Socioeconomic Considerations

- Kodiak and a combined group of small communities were selected as highly engaged communities when evaluating commercial processing and harvesting engagement
- Ex-vessel value has been decreasing since about 2011 with price per pound very low from 2013 to 2017 with a recent increase and revenue per unit effort has been increasing since 2016
- Processing and harvesting regional quotient (RQ) in Kodiak has been steadily decreasing since 2015 with small communities declining in both measures since 2014, a year earlier

Responses to SSC and Plan Team Comments on ESPs in General

"Regarding ESPs in general, the SSC recommends development of a method to aggregate indices into a score that could be estimated over time and compared to stock history. One potential pathway forward may be to normalize and use an unweighted sum of all the indicators where all time series overlap, or just assign +1 or -1 to each indicator so that a neutral environment would be zero." (SSC, February 2020)

"The Teams discussed concerns of over-emphasizing the 1:1 weighting on the first stage. In the absence of information to indicate an appropriate weighting strategy, it is recommended to not rely too heavily on the uninformed 1:1 weighting to select appropriate indicators. The Teams also requested that the ESP team/authors consider appropriately caveating the indicators to ensure they are interpreted species-specific and not over generalized. The Teams support continuing with the current 3-stage indicator analyses for now, and re-evaluate as the ESP process develops, recognizing that the actual value of the integrated index is yet to be clearly demonstrated although it is one high-level summary statistic that may be valuable to examine." (Joint Groundfish Plan Team, September 2020)

We provide a simple score following the SSC recommendation and compare the 1:1 weighting of indicators in this first stage score with the results of the second stage Bayesian Adaptive Sampling (BAS) method that produces inclusion probabilities for a subset of indicators with the most potential for informing a stock assessment parameter of interest (e.g., recruitment of GOA Pacific cod). This second stage may provide insight on how to weight the indicators in the first stage for a more informed score.

Responses to SSC and Plan Team Comments Specific to this ESP

"Given the results of the stock assessments and the vital historic economic, social, and community importance of Pacific cod, the SSC recommends that within the recognized constraints of available time and resources, Ecosystem and Socioeconomic Profiles (ESPs) of EBS Pacific cod (as well as AI and GOA Pacific cod) be prioritized as new ESPs are developed." (SSC, December 2019, pg. 24)

We have developed a first draft of the ESP for GOA Pacific cod, but some delays in production occurred due to the limitations under COVID-19. This is a near complete full ESP but certain element such as the life history tables and references therein may need more updating. Additionally, more information may become available for developing and evaluating indicators following the next ESP workshop. We recommend re-submitting this ESP with updates following those efforts for next year.

Introduction

Ecosystem-based science is becoming a component of effective marine conservation and resource management; however, the gap remains between conducting ecosystem research and integrating it with the stock assessment. A consistent approach has been lacking for deciding when and how to incorporate ecosystem and socioeconomic information into a stock assessment and how to test the reliability of this information for identifying future change. This new standardized framework termed the ecosystem and socioeconomic profile (ESP) has recently been developed to serve as a proving ground for testing ecosystem and socioeconomic linkages within the stock assessment process (Shotwell *et al., In Review*). The ESP uses data collected from a variety of national initiatives, literature, process studies, and laboratory analyses in a four-step process to generate a set of standardized products that culminate in a focused, succinct, and meaningful communication of potential drivers on a given stock. The ESP process and products are supported in several strategic documents (Sigler *et al.,* 2017; Dorn *et al.,* 2018; Lynch *et al.,* 2018) and recommended by the North Pacific Fishery Management Council's (NPFMC) groundfish and crab Plan Teams and the Scientific and Statistical Committee (SSC).

This ESP for Gulf of Alaska (GOA) Pacific cod (*Gadus macrocephalus*) follows the template for ESPs (Shotwell *et al., In Review*) and replaces the previous ecosystem considerations section in the main GOA Pacific cod stock assessment and fishery evaluation (SAFE) report. Information from the original ecosystem considerations section may be found in Barbeaux et al. (2019).

The ESP process consists of the following four steps:

1) Evaluate national initiative and stock assessment classification scores (Lynch *et al.,* 2018) along with regional research priorities to assess the priority and goals for conducting an ESP.
2) Perform a metric assessment to identify potential vulnerabilities and bottlenecks throughout the life history of the stock and provide mechanisms to refine indicator selection.
3) Select a suite of indicators that represent the critical processes identified in the metric assessment and monitor the indicators using statistical tests appropriate for the data availability of the stock.
4) Generate the standardized ESP report following the guideline template and report ecosystem and socioeconomic considerations, data gaps, caveats, and future research priorities.

Justification – Need to Update

The national initiative prioritization scores for GOA Pacific cod are overall high due to the high commercial importance of this stock and early life history habitat requirements (Hollowed *et al.,* 2016; McConnaughey *et al.,* 2017). The vulnerability scores were in the low to moderate of all groundfish scores based on productivity, susceptibility (Ormseth and Spencer, 2011), and sensitivity to future climate exposure (Spencer *et al.,* 2019). The new data classification scores for Pacific cod suggest a data-rich stock with high quality data for catch, size/age composition, abundance, life history categories, and ecosystem linkages (Lynch *et al.,* 2018). These initiative scores and data classification levels suggest a high priority for conducting an ESP for GOA Pacific cod particularly given the high level of life history information and current application of ecosystem linkages in the stock assessment model for natural mortality and catchability. Additionally, AFSC research priorities support studies that improve our understanding of environmental and climate forcing of ecosystem processes with focus on variables that provide direct input into stock assessment and management. Specifically, research that improves our understanding of Pacific cod dynamics in the Gulf of Alaska and the Bering Sea..

Data

Initial information on GOA Pacific cod was gathered through a variety of national initiatives that were conducted by AFSC personnel in 2015 and 2016. These include (but were not limited to) stock assessment prioritization, habitat assessment prioritization, climate vulnerability analysis, and stock assessment classification. Data from an earlier productivity susceptibility analysis conducted for all groundfish stocks in Alaska were also included (Ormseth and Spencer, 2011). Data derived from this effort served as the initial starting point for developing the ESP metrics for stocks in the Bering Sea and Aleutian Islands (BSAI) and Gulf of Alaska (GOA) groundfish fishery management plans (FMP). Please see Shotwell *et al., In Review*, for more details.

Supplementary data were also collected from the literature and a variety of process studies, surveys, laboratory analyses, accounting systems, and regional reports (Appendix Table 2.1.1). Information for the first year of life was derived from ecosystem surveys and laboratory analyses run by multiple programs and divisions at the AFSC (e.g., Ecosystems and Fisheries Oceanography Coordinated Investigations (EcoFOCI), Recruitment Processes Alliance (RPA), Resource Assessment and Conservation Engineering (RACE) Division, Resource Ecology and Fisheries Management (REFM) Division, Auke Bay Laboratory (ABL) Division, Marine Mammal Laboratory (MML) Division). Data for juveniles (less than 42 cm) through adult were consistently available from the AFSC bottom trawl surveys, and the North Pacific Observer Program administered by the Fisheries Monitoring and Analysis (FMA) division.

Data from Ecosystem Status Report (ESR) contributions were provided through personal communication with the contact author of the contribution (e.g., Ressler *et al.,* 2019). Essential fish habitat (EFH) model output and maps were provided by personal communication with the editors of the EFH update (e.g., Rooney *et al.,* 2018). Remote sensing data were collected through coordination with CoastWatch personnel at the Southwest Fisheries Science Center and initial development of an AFSC-specific ERDDAP (Simons, 2019). High resolution regional ocean modeling system (ROMS) and nutrient-phytoplankton-zooplankton (NPZ) data were provided through personal communication with authors of various publications (e.g., Kearney *et al.,* 2020) that develop these models.

The majority of GOA Pacific cod economic value data were compiled and provided by the Alaska Fisheries Information Network (AKFIN). GOA Pacific cod ex-vessel pricing data were derived from the NMFS Alaska Region Blend and Catch Accounting System, the NMFS Alaska Region At-sea Production Reports, and the ADFG Commercial Operators Annual Reports (COAR). GOA Pacific cod first-wholesale data were from NMFS Alaska Region At-sea and Shoreside Production Reports and ADFG Commercial Operators Annual Reports (COAR). Global catch statistics were found online at FAO Fisheries & Aquaculture Department of 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), and the U.S. Department of Agriculture (http://www.ers.usda.gov/data-products/agricultural-exchange-rate-data-set.aspx). Information regarding the community involvement and percent value was derived from reports of the Community Development Quota (CDQ) Program.

Metrics Assessment

We first provide the analysis of the national initiative data used to generate the baseline metrics for this second step of the ESP process and then provide more specific analyses on relevant ecosystem and/or socioeconomic processes. Metrics are quantitative stock-specific measures that identify vulnerability or resilience of the stock with respect to biological or socioeconomic processes. Over a century of process studies on cod stocks around the world, including research conducted by the FOCI program, revealed that evaluating ecosystem linkages by life history stage can highlight potential bottlenecks and improve mechanistic understanding of ecosystem or socioeconomic pressures on the stock ((Pepin, 1991; Bailey *et al.,* 1996; Megrey *et al.,* 1996; Bailey, 2000; Bailey, 2005; Ciannelli *et al.,* 2005; Sundby and Nakken, 2008; Reum *et al.,* 2020)).

National Metrics

The national initiative data were summarized into a metric panel (Appendix Figure 2.1.1) that acts as a first pass ecosystem and socioeconomic synthesis. Metrics range from estimated values to qualitative scores of population dynamics, life history, or economic data for a given stock (see Shotwell *et al., In Review* for more details). To simplify interpretation, the metrics are rescaled by using a percentile rank for GOA Pacific cod relative to all other stocks in the groundfish FMP. Additionally, some metrics are inverted so that all metrics can be compared on a low to high scale between all stocks in the FMP. These adjustments allow for initial identification of vulnerable (percentile rank value is high) and resilient (percentile rank value is low) traits for GOA Pacific cod. Data quality estimates are also provided from the lead stock assessment author (0 or green shaded means no data to support answer, 4 or purple shaded means complete data), and if there are no data available for a particular metric then an "NA" will appear in the panel. GOA Pacific cod did not have any data gaps for the metric panel and the data quality was rated as good to complete for nearly all metrics. The metric panel gives context for how GOA Pacific cod relate to other groundfish stocks in the FMP and highlights the potential vulnerabilities for the GOA Pacific cod stock.

The 80th and 90th percentile rank areas are provided to highlight metrics indicating a high level of vulnerability for GOA Pacific cod (Appendix Figure 2.1.1). Ecosystem value, depth range, and spawning duration fell within the 80th percentile rank when compared to other stocks in the groundfish FMP. For socioeconomic metrics, constituent demand and commercial demand fell within the 90th percentile rank. Additionally, GOA Pacific cod ecosystem value, commercial importance, and mean trophic level exceeded a threshold of highly vulnerable established in the national initiatives (e.g., Methot, 2015; Patrick et al., 2010). GOA Pacific cod were relatively resilient for habitat dependence, breeding strategy, geographic concentration, population growth rate, age 50% mature, age at 1st maturity, prey specificity, dispersal ELH, maximum age, temperature sensitivity, recruitment variability, reproductive strategy, mean age, habitat specificity, adult mobility, fecundity, and latitude range.

Ecosystem Processes

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, Ormseth and Norcross, 2007). Hatch timing/success is highly temperature-dependent (Laurel et al. 2008), with optimal hatch occurring in waters ranging between 4-6°C (Bian et al. 2016; Laurel and Rogers 2020) over a broad range of salinities (Alderdice and Forrester 1971). Eggs hatch into 4 mm larvae in ~2 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). Warm surface waters can accelerate larval growth when prey are abundant (Hurst et al. 2010), but field observations indicate a negative correlation between temperature and abundance of Pacific cod larvae in the Central and Western Gulf of Alaska (Doyle et al. 2009, Doyle and Mier 2016). Laboratory studies suggest warm temperatures can also indirectly impact Pacific cod larvae by way of two mechanisms: 1) increased susceptibility to starvation when the timing and biomass of prey is 'mis-matched' under warm spring conditions (Laurel et al. 2011), and 2) reduced growth by way of changes in the lipid/fatty acid composition of the zooplankton assemblage (Copeman and Laurel 2010).

The spatial-temporal distribution of Pacific cod larvae shifts with ontogeny and is dependent on a number of behavioral and oceanographic processes. In early April, Pacific cod larvae are most abundant around Kodiak Island before concentrations shift downstream to the SW in the Shumagin Islands in May and June (Doyle and Mier 2016). Newly hatched larvae are surface oriented and make extended diel vertical migrations with increased size and development (Hurst et al. 2009). Larvae reach a developmental milestone ('flexion') between 10-15 mm and gradually become more competent swimmers with increasing size (Voesenek et al. 2018). Very late stage larvae ('pelagic juveniles') eventually settle to the bottom in early summer around 30-40 mm and use nearshore nurseries through the summer and early fall in the Gulf of Alaska (Laurel et al. 2017). Cross-shelf transport may be an important process for assisting larvae and early juveniles to the nearshore nurseries for settlement. Sustained along shore currents may sweep eggs and larvae from the system before they can settle to the bottom as juveniles (Hinckley *et al.,* 2019). Mesoscale oceanographic features such as eddies or gap winds may assist in entraining eggs and larvae in the system to allow time for growth to a large enough size to settle in preferred nearshore habitat (Sinclair and Crawford, 2005). Eddies have also been shown to influence distribution of nutrients, phytoplankton, and ichthyoplankton in the GOA and areas near Kodiak are known to have high persistent mesoscale energy (Ladd 2020). Additionally frequent gap wind events can effect the regional oceanography resulting in disruption of the Alaska Coastal Current and decreased flow down Shelikof Strait. Correlative studies reveal that recruitment of Pacific cod in Hecate Strait, BC, Canada was negatively related to sea level pressure which is influenced by the Haida Eddy (Sinclair and Crawford, 2005) and GOA Pacific cod was positively related to gap wind events in the Kodiak region (Ladd *et al.,* 2016).

Shallow, coastal nursery areas provide age-0 juvenile Pacific cod ideal conditions for rapid growth and refuge from predators (Laurel et al. 2007). A benthic habitat suitability analysis for the most recent EFH update for Alaska groundfish (Appendix Figure 2.1.3) indicates depth as the top contributing habitat predictor for the early and late juvenile life stages (79% and 72%, respectively) (Pirtle *et al.,* 2016). A farily narrow and shallow depth range for the early juveniles suggesting the importance of these nearshore habitats for GOA Pacific cod. Tidal current also contributes to the spatial distribution in the early juvenile stage suggesting some influence of transport mechanisms in this stage as well. A preference for mixed mud, sand, and pebble sediments with some structural complexity was also noted (Pirtle *et al.,* 2016). Settled juvenile cod associate with bottom habitats and feed on small calanoid copepods, mysids, and gammarid amphipods during this period (Abookire et al. 2007). At the end of August, age-0 cod become less associated with structural habitats and transition into deeper water in the fall (Laurel et al. 2009). 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, first year assessments of Pacific cod in the Gulf of Alaska are better suited during the early larval or later post-settled juvenile period. There are two surveys that routinely survey early life stages of Pacific cod in the Gulf of Alaska during these phases: 1) the RACE EcoFOCI ichthyoplankton survey in the western GOA (1979 – present; https://access.afsc.noaa.gov/ichthyo/index.php), and 2) the RACE FBE nearshore seine survey in Kodiak (2006 – present). The EcoFOCI ichthyoplankton survey is focused in the vicinity of Kodiak Island, Shelikof Strait and Shelikof Sea Valley and captures Pacific cod larvae primarily in May when they are 5-8 mm in size (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 academic partners spatially extended the Kodiak seine survey to include 14 different bays on Kodiak Island, the Alaska Peninsula, and the Shumagin Islands (Fig 1; Litzow and Abookire 2018). This spatially extended survey is currently in its 3rd year and has thus far validated that the highly variable annual CPUEs observed in the small-scale surveys in Kodiak are largely mirrored across the Central and Western GOA.

The summer thermal conditions in the Central/Western GOA have historically been well-suited for high growth and survival potential for juvenile Pacific cod (Laurel et al. 2017), but may have been sub-optimal during the 2014-16 marine heatwave (Barbeaux *et al.,* 2020). However, the absence of age-0 fish arriving to nurseries in years with warm springs strongly suggests pre-settlement processes (egg/larval) are determining annual cohort strength in the GOA. Reductions in spawning habitat from subsurface warming appears to be an important mechanism limiting reproductive output in the GOA (Laurel and Rogers 2020), but it is likely one of several mechanisms driving recruitment dynamics. Post-settlement processes (e.g., overwintering processes) may also be important. For example, age-0 CPUEs returned to relatively high numbers in 2017 and 2018 after the heatwave (Fig 1; Fig. 3), but few age-1 fish from these cohorts were observed the following year in these surveys. It is unclear whether older juvenile stages have shifted to deeper water (beyond the survey) or if age-0 fish failed to successfully overwinter.

The direct impacts of temperature on life history processes in Pacific cod are stage- and size-dependent but these relationships generally are 'dome shaped' like other cod species (e.g., Hurst et al. 2010; Laurel et al. 2016a). In the earliest stages (eggs, yolk-sac larvae), individuals have less flexibility to behaviorally adapt and have finite energetic reserves (non-feeding). In later juvenile stages, individuals can move to more favorable thermal or food habitats that better suit their metabolic demands. Changes in seasonal temperatures also influence how energy is allocated. A recent laboratory study indicated age-0 juvenile Pacific cod shift more energy to lipid storage than to growth as temperatures drop, possibly as a strategy to offset limited food access during the winter (Copeman et al. 2017).

The AFSC continues 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 juvenile nursery areas will continue to be an important area of research as the Regional Oceanographic Model (ROMS) for the GOA is updated.

Pacific cod are opportunistic predators, eating a variety of zooplankton, crab, and fish species (Aydin *et al.,* 2007). Decreased prey availability and quality can lead to growth-dependent mortality (Gallego and Heath, 1997; Beaugrand *et al.,* 2004). In the absence of abundance estimates of prey resources, the reproductive success of piscivorous (e.g., Common Murre, *Uria aalge*) and planktivorous seabirds (e.g., planktivorous auklets, *Aethia* spp.) in the GOA can be used to inform prey quality and quantity (e.g., Piatt, 2002). Fish condition (length-weight residuals of Pacific cod) is another proxy for prey availability (Brodeur *et al.,* 2004).

Walleye pollock and halibut account for the greatest sources of predation mortality for Pacific cod in the GOA, followed by sperm whales (*Physeter microcephalus*), Steller sea lions (*Eumetopias jubatus*), and dogfish (*Squaliformes*) (Aydin *et al.,* 2007).

Socioeconomic Processes

Pacific cod has been a critical species in the catch portfolio of the Gulf of Alaska (GOA) fisheries (Fissel *et al.,* 2019). From 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 2019 these shares fell to approximately 7%. Catch of Pacific cod in the GOA was down 70% from 2017 with a total catch of 15.7 thousand t and retained catch 14.5 thousand t (Appendix Table 2.1.3a). Ex-vessel prices increased 9% to $0.49 per pound in 2019. Ex-vessel revenues in 2018 were up 9% to $15.7 million with the increase in prices (Appendix Table 2.1.3a). 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 (Appendix Table 2.1.3a). 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. The number of catcher processors has dropped from 11 in 2016 to 3 in 2019 and the number of catcher vessels has dropped from 360 in 2016 to 176 in 2019. Poor fishing conditions may have contributed to the significant reduction in jig fleet participation since 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 regions 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 (Appendix Table 2.1.3a). 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 $0.04 per pound in 2019.

The products made from GOA Pacific cod had a first-wholesale value of $35 million in 2019, which was up 10% from 2018 and below the 2010-2014 average of $112 million (Appendix Table 2.1.3b). The two primary product forms produced from cod in the GOA are fillets and head and gut (H&G), which comprised approximately 60% and 25% of the value in 2019, 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 2019 decreased 17% to $2.14 per pound as fillet prices decreased 5% to $4.13 per pound and H&G prices decreased 37% to $1.28 per pound (Appendix Table 2.1.3b). Since 2016 reductions in global supply have put upward pressure on prices resulting in significant year over year price increases in 2017 and 2018. In 2019 prices leveled off, decreasing slightly, as markets have adjusted. These price decreases were also reflected in Pacific cod export prices which fell 3%.

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 (Appendix Table 2.1.3c). China's rise as a 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 41% in 2019. The cod industry has largely avoided U.S. tariffs that would have a significant negative impact on them in the U.S.-China trade war. However, Chinese tariffs on U.S. products could be inhibiting growth in that market and putting downward pressure on Pacific cod export prices. Japan and Europe (mostly Germany and the Netherlands) are also important export destinations. Japan and Europe accounted for 12% and 22% of the export volume respectively. Approximately 35% of Alaska's cod production is estimated to remain in the U.S. Because U.S. cod production is approximately 15% of global production and the GOA is approximately 6% of U.S. production, the GOA Pacific cod is a relatively small component of the broader cod market. Strong demand and tight supply in 2017-2018 from the U.S. and globally contributed to increasing prices. The Barents Sea quota was reduced by 13% in 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. 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.

In order to examine participation trends for those communities substantially engaged in the commercial GOA Pacific cod fishery commercial processing and harvesting data were analyzed. This community engagement analysis has been conducted for several groundfish stocks in Alaska as part of the Annual Community Engagement and Participation Overview (ACEPO). This is a new summary document that focuses on providing an overview of harvesting and processing sectors of identified highly engaged communities for groundfish and crab fisheries in Alaska. The analysis presented here is similar to that conducted for the ACEPO report but on the stock level rather than the community level. The analysis separates variables into two categories of fisheries involvement: commercial processing and commercial harvesting. Processing engagement is represented by the amount of landings and associated revenues from landings in the community, the number of vessels delivering in the community, and the number of processors in the community. Harvesting engagement is represented by: the landings, revenues associated with vessels owned by community residents, the number of vessel landings owned by residents in the community, and the number of distinct resident vessel owners whose vessels made landings in any community. By separating commercial processing from commercial harvesting, the engagement indices highlight the importance of fisheries in communities that may not have a large amount of landings or processing in their community, but have a large number of fishers and/or vessel owners that participate in commercial fisheries who are based in the community. To examine the relative harvesting and processing engagement of each community, a separate principal components factor analysis (PCFA) was conducted each year for each category to determine a community's engagement relative to all other Alaska communities. Top communities were then selected for each sector based on the value and volume of GOA Pacific cod landed (for processing engagement) and value and volume harvested for harvesting engagement. To examine sustained participation in the commercial GOA Pacific cod fishery, engagement indices were calculated from 2000-2019. Within the processing sector four ports emerged as highly engaged: Akutan, King Cove, Kodiak, and Sand Point. Kodiak remained highly engaged for all years analyzed, and At Sea processing also registered as highly engaged. In the last five years, Kodiak accounted for an average of 47% of GOA Pacific cod landings revenue, with Sand Point, King Cove, and Akutan combined landed 53%

In 2019, the total volume of GOA Pacific cod processed in all communities was 27.8 million pounds, bringing in $12.7 million in associated value. One indication of community engagement in processing activities for the GOA Pacific cod fishery is calculating the portion of the total volume landed, as well as the percentage of the total revenue landed by vessels owned by residents of the specific community. Over the past two decades, the volume landed in these four communities showed a substantial dip in 2009 before peaking in 2011 and beginning to fall downward until 2017 (when volume decreased by 24%, and by an additional 78% in 2019. Kodiak). Akutan show a continued downward slope; however King Cove and Sand Point have slight upticks in 2018. The landed value in the processing sector has decreased, falling from 21.4% of revenue attributed to GOA Pacific cod in 2000 to 3.21% in 2019 (Appendix Figure 2.1.4a). Over the last two decades, at sea processors have accounted 10-20% of the GOA Pacific cod volume landed; however the amount has consistently diminished over time, and was not recorded for the past two years.

Within the GOA Pacific cod harvesting sector, four communities emerged as highly engaged: Kodiak and Sand Point again, Homer, and Seattle MSA (metropolitan statistical area). Kodiak has historically had the highest harvest engagement, bringing in an average of 50% of all the GOA Pacific cod harvested since 2015 The number of vessels owned by community residents has declined substantially from 2015 to 2019 in all four highly engaged communities: in Kodiak, the number of vessels has decreased by 73% (90 vessels); Seattle MSA by 44% (12 vessels); Homer and Sand Point combined has declined (12 vessels) (Appendix Figure 2.1.4b).

In order to explore community participation in harvesting activities for GOA Pacific cod, the associated harvest value by vessels owned by esidents from 2000 to 2019 was examined. Overall, there has been a decrease in the volume of GOA Pacific cod harvested since 2000 with the largest declines since 2015. Between 2015-2019, Kodiak is down 91% in harvested volume (86% since 2000); Seattle MSA down 82% since 2000 (66% compared to 2015); Homer and Sand Point are down since 2000. The value of Pacific cod harvested has also declined for all communities 2015-2019 Seattle were down 56% (82% since 2000); Kodiak is down 84% (79% since 2000); Homer is down and Sand Point is down 42% (72% since 2000). The number of vessels participating in the GOA Pacific cod fishery decreased across highly engaged communities by 70% (268 vessels) since 2000. These decreases depict an overall decline in sustained participation (Appendix Figure 2.1.4b).

Indicators Assessment

We first provide information on how we selected the indicators for the third step of the ESP process and then provide results on the indicators analysis. In this indicator assessment a time-series suite is first created that represent the critical processes identified by the metric assessment. These indicators must be useful for stock assessment in that they are regularly updated, reliable, consistent, and long-term. The indicator suite is then monitored in a series of stages that are statistical tests that gradually increase in complexity depending on the data availability of the stock (Shotwell *et al., In Review*).

Indicator Suite

GOA Pacific cod are vulnerable to changes in ocean temperature, relative to other groundfish, due to their short life spans and rapid growth rates. Temperature can influence recruitment due to a narrow temperature tolerance for egg development and larval survival (Alderdice and Forrester, 1971; Laurel *et al.,* 2008; Hurst *et al.,* 2009; Laurel *et al.,* 2011; Laurel and Rogers, 2020). The seasonality and duration of extended warm ocean conditions (e.g., marine heat waves) can influence productivity and prey availability (Barbeaux *et al.,* 2020). High larval abundance of Pacific cod is associated with years of cooler winters and stronger alongshore winds in the spring (Doyle *et al.,* 2009). Pacific cod can respond to warming shelf temperatures by moving to thermally optimal locations, including deeper depths (Li *et al.,* 2019; Yang *et al.,* 2019), presumably responding to metabolic demands (Paul *et al.,* 1988; Claireaux *et al.,* 1995; Holsman and Aydin, 2015) and prey availability (Nichol *et al.,* 2013).

The current GOA Pacific cod stock assessment includes an annual temperature index (mean temperature at depth) to increase AFSC longline survey catchability values (below 150m depth) in warmer years, as shown in Yang et al. (2019). The risk table considers sea surface temperature (including marine heat waves), indicators of prey quantity and quality (e.g., estimates of euphausiid abundance, seabird reproductive success, seabird diet composition, and Pacific cod condition), and predation mortality (e.g., population estimates of Walleye pollock and Steller sea lions).

We generated a suite of ecosystem and socioeconomic indicators using the mechanisms and tested relationships listed above from previous studies and the relevant ecosystem processes identified in the metric assessment (Appendix Table 2.1.2b, Appendix Figure 2.1.2). The following list of indicators for GOA Pacific cod is organized by categories, three for ecosystem indicators (physical, lower trophic, and upper trophic) and three for socioeconomic indicators (fishery performance, economic, and community) and provides information on whether the indicator was updated or new this year with references where possible. Time series of the ecosystem and socioeconomic indicators are provided in Appendix Figure 2.1.5a and Appendix Figure 2.1.5b, respectively

Ecosystem Indicators:

1. Physical Indicators (Appendix Figure 2.1.5a.a-f)
    - Spawning marine heatwave cumulative index over the central GOA, 1982 to present (contact: S. Barbeaux). The daily sea surface temperatures for 1 September 1981 through 13 October 2020 were retrieved from the NOAA High-resolution Blended Analysis Data database (National Oceanographic and Atmospheric Administration 2017) and filtered to only include data from the central GOA between 145°W and 160°W longitude for waters less than 300 m in depth. The overall daily mean sea surface temperature was then calculated for the entire region by averaging all points. The daily mean sea surface temperature data were processed through the R package heatwaveR (Schlegel and Smit 2018) to obtain the marine heatwave cumulative intensity (MHCI) value (Hobday, Alexander, et al. 2016) where we defined a heatwave 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. MHCI were then summed for each year to create an annual index of MHCI, summed for each year for the months of January through March, November, and December to create a winter marine heatwave cumulative index (WMHCI), and summed for February and March for the spawning marine heatwave cumulative index (SMHCI).
    - Spawning habitat suitability index, 1994 to present (contact: L. Rogers and B. Laurel). A temperature-dependent hatch success rate (derived from laboratory experiments) is applied to GAK-1 temperature-at-depth data and averaged over January to April for depths 100 to 250 m. While GAK-1 is located in the central GOA, it broadly represents interannual variation in thermal conditions across the central and western GOA shelf.

- Summer bottom temperature over the GOA shelf from the CFSR dataset across the depth ranges where 20 to 40 cm Pacific cod have been sampled on the AFSC bottom trawl survey (contact: S. Barbeaux, see SAFE for more details regarding the index creation). Data available from 1979 to present.
- Annual eddy kinetic energy (EKE) calculated from sea surface height in the Kodiak area (region D) as a measure of mesoscale energy in the ocean system. Suite of satellite altimeters provides sea surface height. The Ssalto/Duacs altimeter products were produced and distributed by the Copernicus Marine and Environment Monitoring Service (CMEMS) (http://www.marine.copernicus.eu). Data available from 1994 to 2019 (contact: C. Ladd)
- Peak timing of the spring bloom was calculated for the western and central GOA (WCGOA) region and derived from chlorophyll a concentration data obtained from MODIS satellite sensor at a 4x4 km resolution and aggregated 8-day composites. The data are served through the ERDDAP maintained by NOAA CoastWatch West Coast Regional Node and Southwest Fisheries Science Center's Environment Research Division. Data available from 2003 to present (contact: J. Watson).

2. Lower Trophic Indicators (Appendix Figure 2.1.5a.g-i)
    - Summer large copepods for young-of-the-year (YOY) GOA Pacific cod from the EcoFOCI summer surveys, 2000 to present, various years (contact: L. Rogers).
    - Summer euphausiid abundance is represented as the acoustic backscatter per unit area (sA at 120 kHz, m2 nmi-2) classified as euphausiids and integrated over the water column and then across the surveyed area to produce an annual estimate of acoustic abundance (sA * area, proportional to the total abundance of euphausiids). The index is for the Kodiak core survey area available for variable years historically and biennially since 2013 (Ressler *et al.,* 2019).
    - Spring Pacific cod larvae catch-per-unit-of-effort (CPUE) from the EcoFOCI spring surveys, 1981 to present, various years (contact: L. Rogers).
    - Summer Pacific cod CPUE of YOY from the AFSC Kodiak beach seine survey, 2006 to present (contact: B. Laurel).
    - Common murre reproductive success at Chowiet Island, 1979 to present, various years (contact: H. Renner).
3. Upper Trophic Indicators (Appendix Figure 2.1.5a.g-i)
    - Summer condition for juvenile (<42 cm) and adult (>=42 cm) Pacific cod. Body condition was estimated using a length-weight relationship (Rohan, 2020) from data collected randomly for otoliths in the GOA bottom trawl survey, 1984 to present, various years (contact: S. Rohan).
    - Spatio-temporal delta-generalized linear mixed model using standard settings for an "index standardization" model (Thorson 2019), implemented using the package VAST (Thorson and Barnett 2017) in the R statistical environment (R Core Team 2017). This configuration includes spatial and spatio-temporal variation in two linear predictors of a Poisson-link delta model (Thorson 2018), using a gamma distribution for residual variation in positive catch rates. We specified a model with 500 "knots" while using the "fine_scale=TRUE" feature to conduct bilinear interpolation from the location of knots to the location of extrapolation-grid cells. For the extrapolation-grid, we used the Gulf of Alaska grid that covers the spatial domain from which the bottom trawl survey randomizes sampling stations. We restricted this extrapolation-grid to exclude depths > 700 m and west of 140˚W. Knots were distributed proportional to the spatial distribution of extrapolation-grid cells within this spatial domain. We calculated center of gravity as the biomass-weighted average of the location of extrapolation-grid cells (Thorson et al. 2016a) with a northeast rotation when projecting Latitude/Longitude to UTM coordinates

within UTM zone 5. We also calculated effective area occupied as the area required to contain the population at its average biomass (Thorson et al. 2016b). We used epsilon bias-correction to correct for retransformation bias (Thorson and Kristensen, 2016).
- Arrowtooth flounder total biomass (metric tons) from the most recent stock assessment model (Spies *et al.,* 2017).
- Steller sea lion non-pup estimates for the GOA portion of the western Distinct Population Segment (known as the west, central and east GOA), 1978 to present (contact: K. Sweeney).

Socioeconomic Indicators:

1. Economic Indicators (Appendix Figure 2.1.5b.a-d)
    - Annual estimated real ex-vessel value measured in millions of dollars and inflation adjusted to 2019 USD (contact: B. Fissel).
    - Average real ex-vessel price per pound of GOA Pacific cod measured in millions of dollars and inflation adjusted to 2019 USD (contact: B. Fissel).
    - Annual estimated real revenue per unit effort measured in weeks fished and inflation adjusted to 2019 USD (contact: B. Fissel).
2. Community Indicators (Appendix Figure 2.1.5b.e-h)
    - The suite of community indicators are expressed as regional quotient (RQ) which is a measure of the importance of the community relative to all Alaska fisheries as calculated in pounds landed or revenue generated from specific fisheries. The RQ is calculated as the landings or revenue attributable to a community divided by the total landings or revenue from all communities and community groupings. Indicators of the annual RQ (expressed as percentage) for processing and harvesting revenue are evaluated for the highly engaged communities of Kodiak and a combined summary of three smaller highly engaged communities (Sand Point, King Cove, and Akutan). These three smaller communities were combined for confidentiality concerns. Data were available from 2000-2019 for processing engagement and 2008 to 2019 for harvesting engagement (contact: S. Wise).

Indicator Monitoring Analysis

We provide the list and time-series of indicators (Appendix Figure 2.1.5) and then monitor the indicators using three stages of statistical tests that gradually increase in complexity depending on the stability of the indicator for monitoring the ecosystem or socioeconomic process and the data availability for the stock (Shotwell *et al., In Review*). At this time, we report the initial results of the first and second stage statistical tests of the indicator monitoring analysis for GOA Pacific cod. The third stage will require more indicator development and review of the ESP modeling applications.

Stage 1, Traffic Light Test:

The first stage of the indicator analysis is a simple traffic-light style (Rupp *et al.,* 2.1.5) assessment of the time series values (log-transformed where applicable) relative to one standard deviation from the long-term mean of the time series. Following recommendations from the SSC in Febuary 2020, we include a scoring calculation to this test. The indicator values are evaluated if they are greater than (+), less than (-), or within (•) one standard deviation of the long-term mean for the time series. A value is then provided for the traffic-light based on whether the indicator creates conditions that are good (1), neutral (0), or poor (-1) for GOA Pacific cod (Caddy *et al.,* 2015). This is based on the conceptual model and associated processes tables (Appendix Figure 2.1.2, Appendix Table 2.1.2b. We then assign a qualitative score based on the value compare to the long term mean and the traffic light code. If a high value of an indicator generates good conditions for GOA Pacific cod and is also greater than one standard deviation from the mean, then that value receives a +1 score. If a high value generates poor conditions for GOA Pacific cod and is greater than one standard deviation from the mean, then that value receives a -1 score. All values less than or equal to one standard deviation from the long-term mean are average and receive a 0 score. The scores are summed by the three organizational categories within the ecosystem (physical, lower trophic, and upper trophic) or socioeconomic (fishery performance, economic, and community) indicators and divided by the total number of indicators available in that category for a given year. We also calculate the overall ecosystem and socioeconomic score and provide these aggregated scores for the past twenty years as the majority of indicators were available throughout this time period. The scores over time allow for comparison of the indicator performance and the history of stock productivity. Future iterations of this score could recognize that these qualitative indicators represent sequential events through the live history and therefore stopping rules should be considered where a mortality event in the early life history could govern a year class (see the "switch model proposed for GOA pollock in 1996 (Megrey *et al.,* 1996)).

We evaluate the list of ecosystem indicators to understand the pressures on the GOA Pacific cod stock regarding recruitment and stock productivity. We start with the physical indicators and proceed through the increasing trophic levels as the indicators are listed above. There has been increased sea surface warming in the GOA ecosystem and the presence of a series of major heatwaves from 2014-2016 and again in 2019 (Appendix Figure 2.1.5a.a) have had a large impact on the productivity of the GOA Pacific cod stock. The suitability of Pacific cod spawning habitat has fluctuated throughout the time series but showed a steep continuous decline from a time series high in 2012 to a time series low in 2016 basically responding to the increased heat in the system from the marine heatwave. The suitability rebounded to near average conditions in 2017 and 2018, concurrent with increases in GOA pollock recruitment (Dorn *et al.,* 2019) and dropped again during the 2019 marine heatwave and is back up to near average conditions in 2020 (Appendix Figure 2.1.5a.b). This suitability index mirrors the summer bottom temperatures on the shelf which suggests that the heat remains in the system well through the summer months (Appendix Figure 2.1.5a.c). This seems to have some impact on the timing of the spring bloom which appears to be somewhat delayed during years with a marine heatwave (Appendix Figure 2.1.5a.e). We also see a shift in the annual eddy kinetic energy from high periods of eddy activity from 2003 to 2015 to a lower energy system in 2016 to 2019 (Appendix Figure 2.1.5a.d). Preliminary estimates of near real-time 2020 eddy activity in this region suggest EKE was high in spring 2020 due to a strong persistent eddy in the region near Kodiak but had moved westward out of the region by summer (Ladd 2020).

For the lower trophic level indicators, the summer copepods decreased rather linearly from a high near the start of the time series in 2001 to a low in 2009 and only recovered to average in 2019. Similarly, euphausiid abundance has dropped from a high in 2011 to a low in 2017 and only moderate recovery in 2019 (Appendix Figure 2.1.5a.f-g). The CPUE of larvae in the spring EcoFOCI survey has been variable for the time series with peaks in 2007 and 2013 similar to GOA pollock. However, CPUE has remained low since 2013 consistent with the period of low recruitment estimates for this stock since the last large year class in 2012, and was particularly low in 2015 and 2019, during the heatwave years. The nearshore surveys in Kodiak showed above average CPUE in 2012 and high abundance in both 2017 and 2018, and very high abundance in 2020 (Appendix Figure 2.1.5a.h-i). It is possible that the diet of piscivorous seabirds in the Kodiak region may serve as a proxy for larval fish productivity in the region and this could be detected in the subsequent reproductive success of the seabirds. The common Murre reproductive success on Chowiet (Appendix Figure 2.1.5a.j) appears to be very high in 2015 consistent with the drop in spawning biomass for this stock, but has recovered to very high success from 2017 to 2019, suggesting there may be large spatial shifts in the available prey base.

Condition of juvneniles from the summer bottom trawl survey suggests poor condition for the 2015 and 2017 surveys and a return to average condition in 2019. Adult condition shows a slightly different pattern with only poor condition in 2015 and recovery to moderate to high condition in 2017 and 2019 (Appendix Figure 2.1.5a.k-l). The overall spatial distribution of the stock has spread out substantially from 2009 to 2019 with a shift to the farthest northeast in 2019 from the farthest southwest in 2017 (area occupied is trending high with increase then decrease in the northeast center of gravity, Appendix Figure 2.1.5a.m-n).

This suggests that some of the Pacific cod population may potentially be expanding out of preferred habitat. A historical analysis on pollock distribution in the GOA found dispersion of the pollock stock up until 1996, which may be consistent with increasing trend in effective area occupied (Shima *et al.,* 2002). Predator biomass of arrowtooth flounder and Steller sea lions has been decreasing and/or stable for the most recent years (Appendix Figure 2.1.5a.o-p), suggesting that the primary pressure on the 2012 and recent year-classes may be the lack of preferred prey. Pacific cod are generalist predators and so can switch to eating a variety of prey, so it may be a decrase in the overall prey base in the GOA causing recent declines rather than any particular prey item. We see that with decreases in many groundfish stocks and forage fish in recent years (Dorn *et al.,* 2019, Spies *et al.,* 2019, Ormseth *et al.,* 2019).

For the socioeconomic indicators (Appendix Figure 2.1.4b), there has been a decreasing trend in real ex-vessel value since 2011 to the projected lowest value in the time series in 2020. Conversely, there has been an increase in price since 2017 and since 2016 in revenue per unit effort. This is consistent with the large decreases in the spawning biomass of this stock during the marine heatwave years. (Appendix Figure 2.1.4a.a-c). Processing and harvesting regional quotient (RQ) in Kodiak has been on an decreasing trend since 2015 and is now at the lowest value for the time series. A more dramatic trend has occurred in the processing and harvesting RQ for small communities, decreasing rapidly from a time series high in 2014 to a low in 2018. There has been some recovery in 2019 but still well below the long term average of the time series. These trends may be due to the large decreases in the GOA Pacific cod stock at the onset of the marine heatwave.

Traffic light scores by category and overall are provided in Appendix Table 2.1.4. Overall, ecosystem indicators have been decreasing since 2013 and have shown some modest recovery since 2017 when the heat in the system was reduced (Figure 2.1.6). For the indicators available in the current year, the traffic light analysis shows improved condition in the physical and lower trophic indicators, and stable in the upper trophic indicators. This is consistent with last year except the lower trophic level indicators were trending down. It should be noted that only 6 of the potential 16 indicators were available this year for the ecosystem indicators (Appendix Table 2.1.4a). Socioeconomic indicators have also been trending down overall since 2014 with only slight recovery in 2019 and 2020. Also note only 2 of the potential 6 were available this year for the socioeconomic indicators (Appendix Table 2.1.4b). No community indicators were available this year as that information data lags the current year by at least one year. We also provide the direction of the current year score from the previous year score for these categories on the conceptual model graphic for quick reference (Appendix Figure 2.1.2). The historical traffic light score over all ecosystem and socioeconomic indicators is somewhat decoupled, with a lag in the socioeconomic indicators of about two years (Appendix Figure 2.1.6). This may reflect the delayed interaction between the decreases in Pacific cod revenue and community impacts and the recent large decreases of the stock during the marine heatwave years.

Stage 2, Regression Test:

Bayesian adaptive sampling (BAS) was used for the second stage statistical test to quantify the association between hypothesized predictors and GOA Pacific cod recruitment and to assess the strength of support for each hypothesis. BAS explores model space, or the full range of candidate combinations of predictor variables, to calculate marginal inclusion probabilities for each predictor, model weights for each combination of predictors, and generate Bayesian model averaged predictions for outcomes (Clyde *et al.,* 2011). In this second test, the full set of indicators is first winnowed to the predictors that could directly relate to recruitment and highly correlated covariates are removed (Appendix Figure 2.1.7a). We further restrict potential covariates to those that can provide the longest model run and through the most recent estimate of recruitment that is well estimated in the current operational stock assessment model. This results in a model run from 1994 through the 2017 estimate of age 0 or the 2017 year-class. We then provide the mean relationship between each predictor variable and log GOA Pacific cod recruitment over time (Appendix Figure 2.1.7b, left side), with error bars describing the uncertainty (95% confidence intervals) in each estimated effect and the marginal inclusion probabilities for each predictor variable

(Appendix Figure 2.1.7b, right side). A higher probability indicates that the variable is a better candidate predictor of GOA Pacific cod recruitment. The highest ranked predictor variables (inclusion probability > 0.5) based on this process were the spawning habitat suitability index in the GOA and the eddy kinetic energy in Kodiak area D (Appendix Figure 2.1.7).

The BAS method requires observations of all predictor variables in order to fit a given data point. This method estimates the inclusion probability for each predictor, generally by looking at the relative likelihood of all model combinations (subsets of predictors). If the value of one predictor is missing in a given year, all likelihood comparisons cannot be computed. When the model is run, only the subset of observations with complete predictor and response time series are fit. It is possible to effectively "trick" the model into fitting all years by specifying a 0 (the long-term average in z-score space) for missing predictor values. However, this may bias inclusion probabilities for time series that have more zeros and result in those time series exhibiting low inclusion probability, independent of the strength of the true relationship. Due to this consideration of bias, we only fit years with complete observations for each covariate at the longest possible time frame. This resulted in a smaller final subset of covariates. We plan to explore alternate model runs (e.g., biennial) to potentially include more covariates in the future. As noted above, Megrey et al. (1996) found that a critical step in multi-variate statistical searches of processes governing recruitment required that the analysts considered the temporal sequence of mortality events. Temporal sequencing of mortality events will be considered future versions of this statististical approach. Efforts to include mortality switches could be informed by the planned Individual Based Models.

Stage 3, Modeling Test:

In the future, mortality switches could be evaluated in the third stage statistical test, which is a modeling application that analyzes predictor performance and estimates risk probabilities within the operational stock assessment model. Output of two new model developments could be used to generate or enhance an ecosystem-linked model for GOA Pacific cod. First, a new multi-species statistical catch-at-age assessment model (known as CEATTLE; Climate- Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics; Holsman *et al.,* 2015) has recently been developed for understanding trends in age 1 total mortality for Pacific cod, walley pollock, and arrowtooth flounder from the GOA (Adams *et al.,* 2020). Total mortality rates are based on residual mortality inputs (M1), model estimates of annual predation mortality (M2), and fishing mortality (F). CEATTLE has been modified for the GOA and implemented in Template Model Builder (Kristensen *et al.,* 2015) to allow for the fitting of multiple sources of data, time-varying selectivity, time-varying catchability, and random effects. The model is based, in part, on the parameterization and data used for the most recent stock assessment model of each species (Barbeaux *et al.,* 2019, Dorn *et al.,* 2019, and Spies & Palsson, 2019). The model is fit to data from five fisheries and seven surveys, including both age and length composition assumed to come from a multinomial distribution. Model estimates of M2 are empirically driven by bioenergetics-based consumption information and diet data from the GOA to inform predator-prey suitability. The model was fit to data from 1977 to 2020.

Second, a spatially-explicit individual-based model (IBM) for the early life stages of Pacific cod was developed as part of the GOA Integrated Ecosystem Research Program (GOAIERP) (Hinckley *et al.,* 2019) using the DisMELS (Dispersal Model for Early Life Stages) IBM framework. It has since been updated to include temperature-dependent egg development and a better characterization of juvenile nursery habitat based on a Habitat Suitability Model. The IBM tracks the 3-dimensional location, growth, and other characteristics of simulated individuals from the egg stage to the benthic juvenile stage using stored 4-dimensional (3-d space and time) ROMS model output to provide the spatiotemporally-varying environment (e.g., 3-dimensional temperature, NPZ, and current fields) in which the individuals "exist". Egg development and larval/juvenile growth rates depend on *in situ* temperature. Vertical movement in the water column is also stage-specific, but horizontal dispersion is currently assumed to be passive. Individual location and other characteristics are updated using Lagrangian particle tracking with a 20-

minute integration time step. It would be possible to derive several types of indices using the IBM and ROM model output for the current year, including: 1) changes in connectivity between presumed spawning and juvenile nursery habitats; 2) spatiotemporally-averaged, temperature-dependent egg development success; and 3) life stage-specific, spatiotemporally-averaged, temperature-dependent growth rates. Once the ROMS model output is available, it takes several hours on a laptop to run the IBM for a year simulating ~100,000 individuals. Additional time would be required to calculate the desired indices, but turn-around could be reasonably quick.

Once the GOA CEATTLE model is more developed and published, the age 1 mortality index could provide a gap free estimate of predation mortality that could be tested in the operational stock assessment model. Additionally, the spawning habitat suitability and the kinetic energy in Kodiak indicators could be used directly to help explain the variability in recruitment deviations and predict pending recruitment events for GOA Pacific cod. Indeed, an ecosystem-linked model is already in development for GOA Pacific cod (see main SAFE, Model 20.1) using the spawning marine heatwave cumulative index. If the spawning habitat suitability index could be expanded to the western/central GOA that may provide an additional index to be used within the context of the ecosystem-linked model.

Recommendations

The GOA Pacific cod ESP follows the standardized framework for evaluating the various ecosystem and socioeconomic considerations for this stock (Shotwell *et al., In Review*). Given the metric and indicator assessment we provide the following set of considerations:

Ecosystem Considerations

- Hatch timing and success is highly temperature dependent with optimal hatch occurring in waters between 4-6ºC and has implications for spawning habitat suitability and subsequent recruitment
- Warm temperatures can increase susceptibility of starvation for larval Pacific cod when mismatched to prey or reduce growth during shifts in the lipid/fatty acid composition of prey
- Cross-shelf transport may assist larvae and early juvniles to nearshore nurseries for settlement and eddies and gap winds may disrupt along-shore currents to increase growth and survival
- Copepods and euphausiids low since 2009 and returned to average in 2019, and condition of juvenile Pacific cod were poor for 2015 and 2017 surveys suggesting spatial shifts in prey base
- Annual eddy kinetic energy has shifted from high periods of eddy activity from 2003 to 2015 to a lower energy system in 2016 to 2019 and a strong, persistent eddy around Kodiak in 2020
- The overall spatial distribution of the stock has spread out substantially from 2009 to 2019 with a shift to the farthest northeast in 2019 from the farthest southwest in 2017
- Predators of Pacific cod have steadily decreased over the time series but have recently stabilized suggesting the primary pressure on the 2012 year-classes may be the lack of preferred prey
- Overall, ecosystem indicators have been decreasing since 2012 and have shown some modest recovery since 2017 when the heat in the system was reduced, similar to the GOA pollock
- Highest ranked predictor for recruitment regression model was spawning habitat suitability and the eddy kinetic energy temperature on the SEBS shelf (inclusion probability > 0.5)

Socioeconomic Considerations

- Kodiak and a combined group of small communities were selected as highly engaged communities when evaluating commercial processing and harvesting engagement
- Ex-vessel value has been decreasing since about 2011 with price per pound very low from 2013 to 2017 with a recent increase and revenue per unit effort has been increasing since 2016
- Processing and harvesting regional quotient (RQ) in Kodiak has been steadily decreasing since 2015 with small communities declining in both measures since 2014, a year earlier.

Data Gaps and Future Research Priorities

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

Additional refinement on the GOA CEATTLE model might also allow for a gap-free index of predation mortality for GOA Pacific cod. An updated set of indicators may then be used in the second and third stage modeling applications that provide direction of relationships, inclusion probabilities, and evaluation of performance and risk within the operational stock assessment model.

We currently lack an indicator of predation on YOY Pacific cod during their first autumn and winter, during a period when predation mortality is thought to be significant. Sampling of predator diets in fall and winter would help to fill this gap. Additionally, evaluating condition and energy density of juvenile and adult Pacific cod samples at the outer edge of the population may be useful for understanding the impacts of shifting spatial statistics such as center of gravity and area occupied. Information is available from the GulfWatch Alaska program that could be helpful for evaluating the eastern edge of the GOA Pacific cod population.

As indicators are improved or updated, they may replace those in the current set of indicators to allow for refinement of the BAS model and potential evaluation of performance and risk within the operational stock assessment model. This could be accomplished in the next full ESP assessment and the timing of that will depend on how the ESP process matures

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Tables

Appendix Table 2.1.1: List of data sources used in the ESP evaluation. Please see the main GOA Pacific cod SAFE document, the Ecosystem Considerations Report (Zador *et al.,* 2019) and the Economic Status Report (Fissel *et al.,* 2019) for more details.

Title	Description	Years	Extent
EcoFOCI Spring Survey	Shelf larval survey in spring on the eastern Bering Sea shelf using oblique 60 cm bongo tows, fixed-station grid, catch per unit effort in numbers per 10 m^2	1978 – present	Eastern Bering Sea annual, biennial
AFSC Summer Survey	Midwater trawl survey of groundfish and forage fish from August-September using Stauffer trawl and bongo tows in the eastern Bering Sea shelf, fixed-station grid	2000 – present	Eastern Bering Sea biennial
AFSC Bottom Trawl Survey	Bottom trawl survey of groundfish in June through August, eastern Bering Sea using Poly Nor'Eastern trawl on stratified random sample grid, catch per unit of effort in metric tons	1982 – present	Eastern Bering Sea annual
AFSC Acoustic Survey	Mid-water acoustic survey in March in Eastern Bering Sea for pre-spawning pollock and again in summer for age 1 pollock	1981 – present	Eastern Bering Sea annual, biennial
Seabird Surveys	Ecological monitoring for status and trend of suite of seabird species conducted by Institute for Seabird Research and Conservation	1978 – present	Bering Sea, Aleutian Islands
REEM Diet Database	Food habits data and associated analyses collected by the Resource Ecology and Ecosystem Modeling (REEM) Program, AFSC on multiple platforms	1990 – present	Eastern Bering Sea annual
Coral Reef Watch Program	NOAA Coral Reef Watch Program, Global 5km Satellite Coral Bleaching Heat Stress Monitoring Product Suite Version 3.1, derived from CoralTemp v1.0. product (NOAA Coral Reef Watch, 2018)	1985 – present	Global
MODIS	4 km MODIS ocean color data aggregated 8-day composites.	2003-present	Global
ROMS/NPZ Model Output	Coupled hydrographic Regional Ocean Modeling System and lower tropic Nutrient-Phytoplankton-Zooplankton dynamics model	1996 – 2013	Alaska variable

Appendix Table 2.1.1 (cont.): List of data sources used in the ESP evaluation. Please see the main GOA Pacific cod SAFE document, the Ecosystem Considerations Report (Zador *et al.,* 2019) and the Economic Status Report (Fissel *et al.,* 2019) for more details.

Title	Description	Years	Extent
Essential Fish Habitat Models	Habitat suitability MaxEnt models for describing essential fish habitat of groundfish and crab in Alaska, EFH 2016 Update	1970 – 2016	Alaska
FMA Observer Database	Observer sample database maintained by Fisheries Monitoring and Analysis Division	1988 – present	Alaska annual
NMFS Alaska Regional Office	Catch, economics, and social values for fishing industry, data processed and provided by Alaska Fisheries Information Network	1992 – 2018	Alaska annual
Reports & Online	ADFG Commercial Operators Annual Reports, AKRO At-sea Production Reports, Shoreside Production Reports, FAO Fisheries & Aquaculture Department of Statistics	2011 – 2018	Alaska, U.S., Global annual

Appendix Table 2.1.2a: Ecological information by life history stage for GOA Pacific cod. [NOTE: Updating references]

Stage	Habitat & Distribution	Phenology	Age, Length, Growth	Energetics	Diet	Predators/Competitors
Recruit	Shore to Shelf (0-500 m), depth varies by age then size(24), sublittoral-bathyal zone, move w/in, between LMEs(24)	Recruit to survey and fishery age-1, length 20-27 cm(24)	Max: 25 yrs, 147♀/134♂ cm L_inf=94 cm, K= 0.2 (24,AFSC)		Opportunistic, small on inverts, large on fish(20, 21, 24, AFSC)	Halibut, Steller sea lions, whales, tufted puffins, fisheries(24); shelf groundfish(24)
Spawning	Shelf (40-290 m)(13-16,24), semi-demersal in shelf areas(13,15,16), seasonal migrations variable duration(26)	Winter-spring, peak mid-March, 13 wks (1,20,25)	1st mature: 2 yr, 26♀/36♂cm, 50%: 4-5yr, 45-65cm (24,AFSC)	Oviparous, high fecundity (250-2220·10^3) eggs (13,15), range 4-6 °C(14,16)	Opportunistic (20,21)	Halibut, Steller sea lions, whales, tufted puffins, fisheries(24); shelf groundfish(24)
Egg	Shelf (20-200 m), demersal, adhesive eggs(13,15-17,24)	Incubation is ~20 days, 6 wks(14,22)	Egg size: 0.98-1.08 mm (Laurel et al 2008)	Optimal incubation 3-6°C, 13-23 ppt, 2-3ppm dO_2 (LR, 2020)	Yolk is dense and homogenous (AFSC)	
Yolk-sac Larvae	Epipelagic, nearshore shelf, coastal, upper 45 m, semi-demersal at hatching(13-15,18,24)	Spring, peak end April, 14 wks(22)	3-4.5 mm NL at hatch (13-15,24)	1-2 weeks before onset of feeding	Endogenous	Share larval period with pollock(13)
Feeding Larvae	Epipelagic, nearshore shelf(13-15,24), 0-45 m (24)	Late spring, April – June, (22	25-35 mm SL at transformation (3,13-15,24)		Copepod eggs, nauplii, and early copepodite stages (Strasburger et al. 2014)	Share larval period with pollock(13)
Juvenile	Nearshore (2-110 m), 15-30 m peak density, inside bays, coastal, mixed, structural complexity (1-6,11,21)	Nearshore settlement in June, deeper water migrations in October(3,13-15)	YOY: 35-110 mm FL(2), age 1+: 130-480 mm FL(1,3,4,6,10); growth sensitive to temp	Energy density ↑ with length, lower in pelagic stage,	Copepods, mysids, amphipods(2), small fish(10), crabs(19-21)	Pollock, halibut, arrowtooth flounder(19,20); macroalgae, eelgrass, structural inverts, king crab, skate egg case, juvenile pollock (1-5,7-9)
Pre-Recruit	Nearshore, shelf (10-216 m)(4), inside bays, coastal, mixed, mud, sand, gravel, rock pebble(1,2,4,6)	Age-2 may congregate more than age-1(25)	Begin to mature age 2-3, 480-490 mm FL (15)	Energy density and condition lower than in pelagic stage	Opportunistic, benthic invert, pollock, small fish, crabs(19-21)	Pacific cod, halibut, salmon, fur seal, sea lion, porpoise, whales, puffin(24); macroalgae, macroinvertebrate, king crab, skate egg case(4-5,7-9)

Appendix Table 2.1.2b. Key processes affecting survival by life history stage for GOA Pacific cod. [NOTE: Updating references]

Stage	Processes Affecting Survival	Relationship to GOA Pacific cod
Recruit	1. Competition 2. Predation 3. Temperature	Increases in main predator of Pacific cod would be negative but minor predators may indicate Pacific cod biomass increase. Increases in overall prey biomass would be positive for Pacific cod but generalists.
Spawning	1. Ice Dynamics 2. Spawning Habitat Suitability 3. Distribution	Temperatures outside the 3-6 C range contribute to poor hatching success and may impact physiological and behavioral aspects of spawning. Spring bottom temperatures outside this range are linked to observed pre-recruits and recruitment estimates (Laurel and Rogers 2020)
Egg	1. Temperature	Eggs are highly stenothermic (Laurel and Rogers 2020)
Yolk-sac Larvae	1. Temperature 2. Timing of spring bloom 3. Onshore shelf transport	Increases in temperature would increase metabolic rate and may result in rapid yolk-sac absorption that may lead to mismatch with prey. Current direction to preferred habitat would be positive for Pacific cod.
Feeding Larvae	1. Temperature 2. Prey availability 3. Onshore shelf transport	Increases in temperature would increase metabolic rate and may result in poor condition if feeding conditions are not optimal. Onshore transport to nursery habitat would be positive for Pacific cod while predation increases would be negative.
Juvenile	1. Competition 2. Predation 3. Temperature	Evidence of density-dependent growth in coastal nurseries (Laurel et al., 2016) would suggest that increases in competitors or predators would be negative for Pacific cod condition and therefore survival. Temperature increases may amplify risk of food availability and energy allocation (Laurel et al. 2017)
Pre-Recruit	1. Competition 2. Predation 3. Temperature	Evidence of density-dependent growth in coastal nurseries (Laurel et al., 2016) would suggest that increases in competitors or predators would be negative for Pacific cod condition and therefore survival. Temperature increases may amplify risk of food availability and energy allocation (Laurel et al. 2017)

Appendix Table 2.1.3a. 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; 2010-2014 average and 2015-2019.

	Avg 10-14	2015	2016	2017	2018	2019
Total catch K mt	79.06	79.5	64.1	48.7	15.2	15.7
Retained catch K mt	75.7	77.5	63.1	48.0	14.4	14.5
Ex-vessel value M $	$50.8	$50.3	$41.0	$35.3	$14.5	$15.7
Ex-vessel price lb $	$0.304	$0.293	$0.294	$0.334	$0.452	$0.492
Hook & line share of catch	25%	21%	17%	18%	23%	23%
Pot gear share of catch	49%	52%	60%	55%	53%	52%
Central Gulf share of catch	61%	60%	53%	43%	47%	47%
Shoreside share of catch	90%	92%	92%	87%	88%	89%
Vessels #	421.4	386	360	246	154	176

Appendix Table 2.1.3b. 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; 2010-2014 average and 2015-2019.

		Avg 10-14	2015	2016	2017	2018	2019
All Products	volume K mt	31.16	32.00	21.65	17.39	5.58	7.47
All Products	value M $	$111.5	$102.5	$91.8	$75.5	$31.9	$35.2
All Products	price lb $	$1.62	$1.45	$1.92	$1.97	$2.59	$2.14
Fillets	volume K mt	9.41	6.39	7.87	6.52	2.00	2.36
Fillets	value share	55.3%	36.3%	62.5%	60.0%	60.1%	61.0%
Fillets	price lb $	$2.97	$2.64	$3.30	$3.15	$4.35	$4.13
Head & Gut	volume K mt	13.43	19.05	8.43	6.11	1.92	3.02
Head & Gut	value share	32.2%	50.9%	24.7%	26.9%	27.0%	24.1%
Head & Gut	price lb $	$1.21	$1.24	$1.22	$1.51	$2.04	$1.28

Appendix Table 2.1.3c. GOA Pacific cod global catch (thousand metric tons), U.S. and AK shares of global catch; WA & AK export volume (thousand metric tons), value (million US$), price (US$ per pound) and the share of export value from trade with Japan and China, 2009-2013 average and 2014-2019.

		Avg 10-14	2015	2016	2017	2018	2019
Global cod catch K mt		1,631	1,762	1,789	1,761	1,633	-
U.S. P. cod share of global catch		18.5%	18.0%	18.0%	16.9%	14.2%	-
Europe share of global catch		74.7%	74.8%	74.9%	75.9%	78.3%	-
Pacific cod share of U.S. catch		97.8%	99.3%	99.5%	99.5%	99.7%	-
U.S. cod consumption K mt (est.)		97	108	114	118	114	106
Share of U.S. cod not exported		29%	26%	29%	32%	36%	37%
Export volume K mt		103.8	113.2	105.3	92.8	73.1	65.1
Export value M US$		$325.2	$335.0	$312.0	$295.5	$253.4	$218.1
Export price lb US$		$1.421	$1.342	$1.344	$1.445	$1.571	$1.519
Frozen (H&G)	volume Share	81%	91%	94%	94%	91%	92%
	value share	81%	90%	92%	92%	90%	91%
Fillets	volume Share	7%	3%	3%	4%	5%	5%
	value share	9%	4%	4%	5%	6%	6%
China	volume Share	44%	53%	55%	52%	48%	41%
	value share	41%	51%	52%	50%	46%	40%
Japan	volume Share	17%	13%	14%	16%	15%	12%
	value share	17%	14%	15%	18%	17%	13%
Europe*	volume Share	27%	19%	17%	17%	16%	22%
	value share	29%	19%	18%	18%	18%	23%

Note: 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: NMFS Alaska Region Blend and Catch-accounting System estimates; NMFS Alaska Region At-sea and Shoreside Production Reports; and ADF&G Commercial Operators Annual Reports (COAR). Data compiled and provided by the Alaska Fisheries Information Network (AKFIN). FAO Fisheries & Aquaculture Dept. Statistics http://www.fao.org/fishery/statistics/en. NMFS Alaska Region Blend and Catch-accounting System estimates. 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.

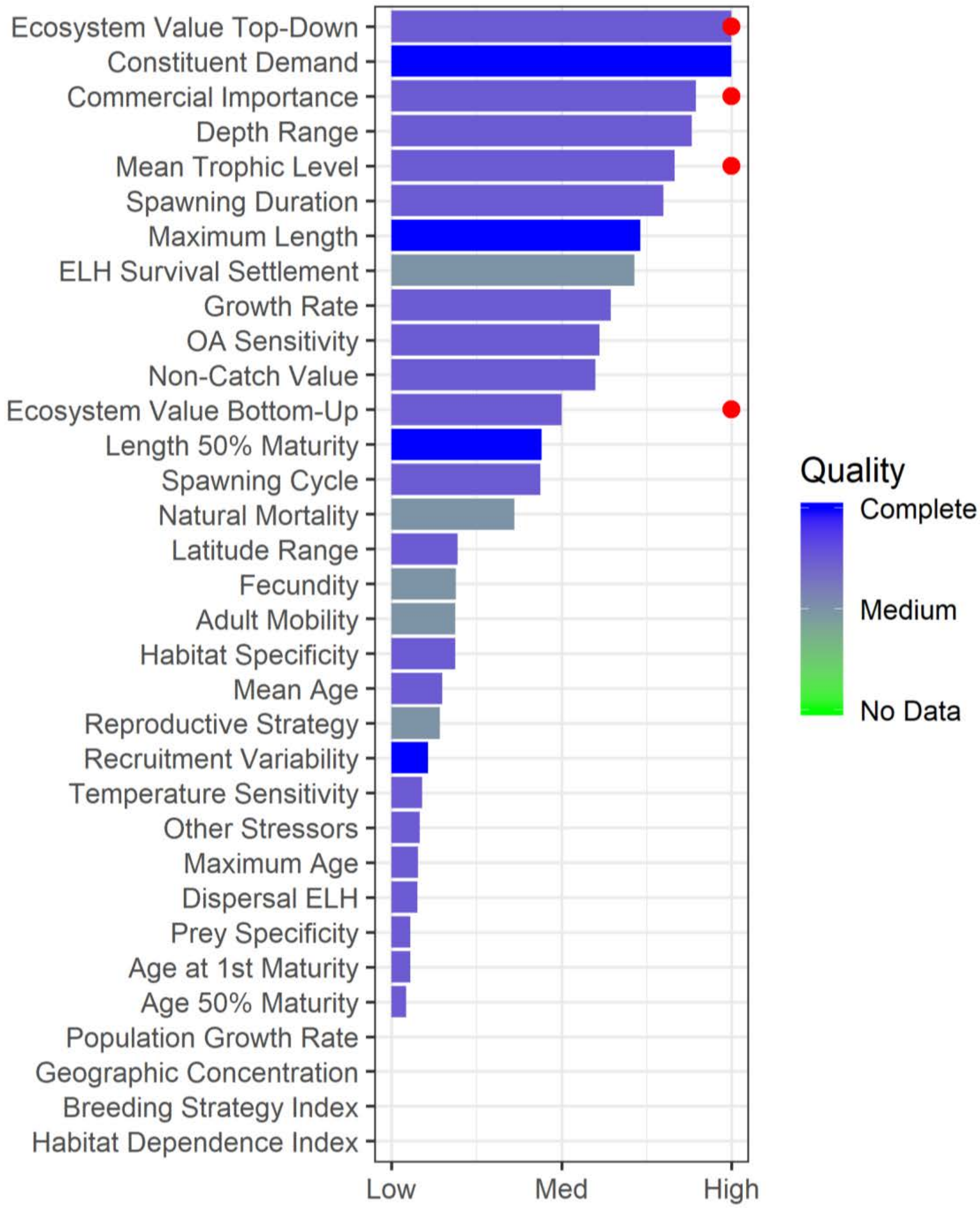
Appendix Table 2.1.4a. First stage ecosystem indicator score analysis for GOA Pacific cod by four main categories (physical, lower trophic, upper trophic, and overall ecosystem). Each indicator is scored based on the traffic light evaluation for that indicator (1 if a positive value increase creates good conditions for GOA Pacific cod, -1 if positive increase create poor conditions for GOA Pacific cod, 0 otherwise), multiplied by the value relative to the long-term mean of the time series (greater than, less than, or within 1 standard deviation). Those scores are summed by category and then divided by the total number of indicators for that category. Number of indicators for each category are also provided. NA = no indicators available. Color coding based on column, blue = 1 shading through white = 0 shading through red = -1.

	Physical		Lower Trophic		Upper Trophic		Total Ecosystem	
Year	Score	# Indicators	Score	# Indicators	Score	# Indicators	Score	# Indicators
2000	0.00	4	0.00	2	0.50	2	0.13	8
2001	-0.25	4	0.50	2	0.17	6	0.08	12
2002	0.25	4	0.00	2	-0.50	2	0.00	8
2003	-0.60	5	0.00	3	-0.50	6	-0.43	14
2004	0.20	5	0.00	2	-0.50	2	0.00	9
2005	0.00	5	-0.25	4	-0.50	6	-0.27	15
2006	0.00	5	0.00	3	-0.50	2	-0.10	10
2007	0.60	5	0.25	4	-0.17	6	0.20	15
2008	0.20	5	0.00	2	-0.50	2	0.00	9
2009	0.00	5	-0.25	4	-0.33	6	-0.20	15
2010	0.20	5	0.00	3	0.00	2	0.10	10
2011	0.00	5	0.00	4	-0.17	6	-0.07	15
2012	0.80	5	0.50	2	0.00	2	0.56	9
2013	0.00	5	0.25	4	0.00	6	0.07	15
2014	-0.20	5	0.00	2	0.00	2	-0.11	9
2015	-0.20	5	-0.60	5	-0.17	6	-0.31	16
2016	-0.20	5	-0.50	2	0.00	2	-0.22	9
2017	-0.20	5	-0.40	5	0.33	6	-0.06	16
2018	-0.40	5	0.00	2	0.00	2	-0.22	9
2019	-0.40	5	-0.20	5	0.00	6	-0.19	16
2020	-0.25	4	1.00	1	0.00	1	0.00	6

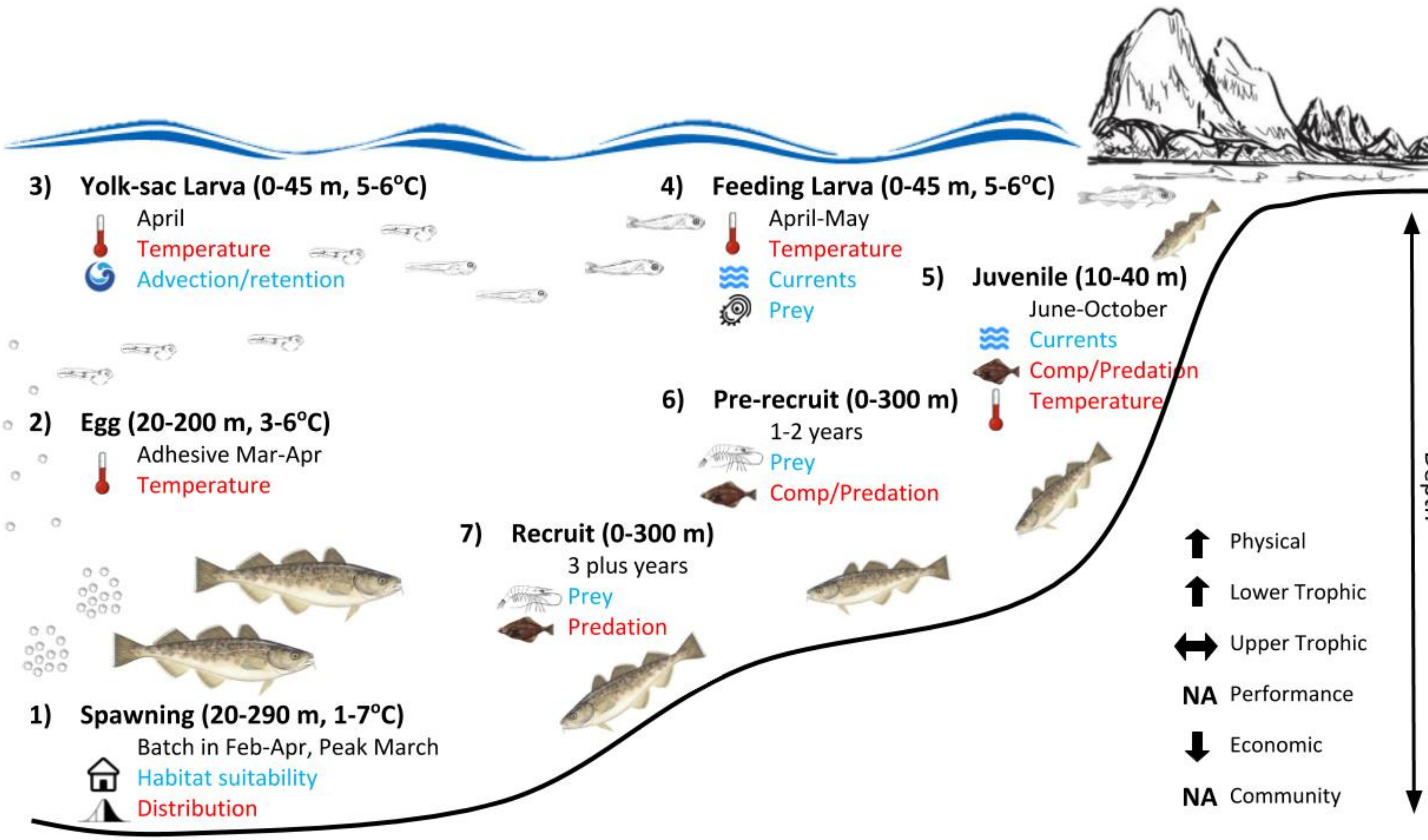
Appendix Table 2.1.4b. First stage socioeconomic indicator score analysis for GOA Pacific cod by four main categories (performance, economic, community, and overall socioeconomic). Each indicator is scored based on the traffic light evaluation for that indicator (1 if a positive value increase creates good socioeconomic environment for GOA Pacific cod, -1 if positive increase create poor conditions for GOA Pacific cod, 0 otherwise), multiplied by the value relative to the long-term mean of the time series (greater than, less than, or within 1 standard deviation). Those scores are summed by category and then divided by the total number of indicators for that category. Number of indicators for each category are also provided. NA = no indicators available. Color coding based on column, blue = 1 shading through white = 0 shading through red = -1.

	Fishery Performance		Economic		Community		Total Socioeconomic	
Year	Score	# Indicators	Score	# Indicators	Score	# Indicators	Score	# Indicators
2000	NA	NA	0.00	0	1.00	2	1.00	2
2001	NA	NA	0.00	0	0.00	2	0.00	2
2002	NA	NA	0.00	0	0.00	2	0.00	2
2003	NA	NA	0.00	3	0.00	2	0.00	5
2004	NA	NA	-0.33	3	0.00	2	-0.20	5
2005	NA	NA	-0.33	3	0.00	2	-0.20	5
2006	NA	NA	0.00	3	0.00	2	0.00	5
2007	NA	NA	1.00	3	0.00	2	0.60	5
2008	NA	NA	1.00	3	0.50	4	0.71	7
2009	NA	NA	-0.33	3	0.00	4	-0.14	7
2010	NA	NA	0.00	3	0.25	4	0.14	7
2011	NA	NA	0.67	3	0.00	4	0.29	7
2012	NA	NA	0.33	3	0.00	4	0.14	7
2013	NA	NA	-0.33	3	-0.25	4	-0.29	7
2014	NA	NA	0.00	3	0.50	4	0.29	7
2015	NA	NA	0.00	3	0.25	4	0.14	7
2016	NA	NA	-0.33	3	0.00	4	-0.14	7
2017	NA	NA	0.00	3	-0.50	4	-0.29	7
2018	NA	NA	-0.33	3	-1.00	4	-0.71	7
2019	NA	NA	0.33	3	-1.00	4	-0.43	7
2020	NA	NA	-0.50	2	0.00	0	-0.50	2

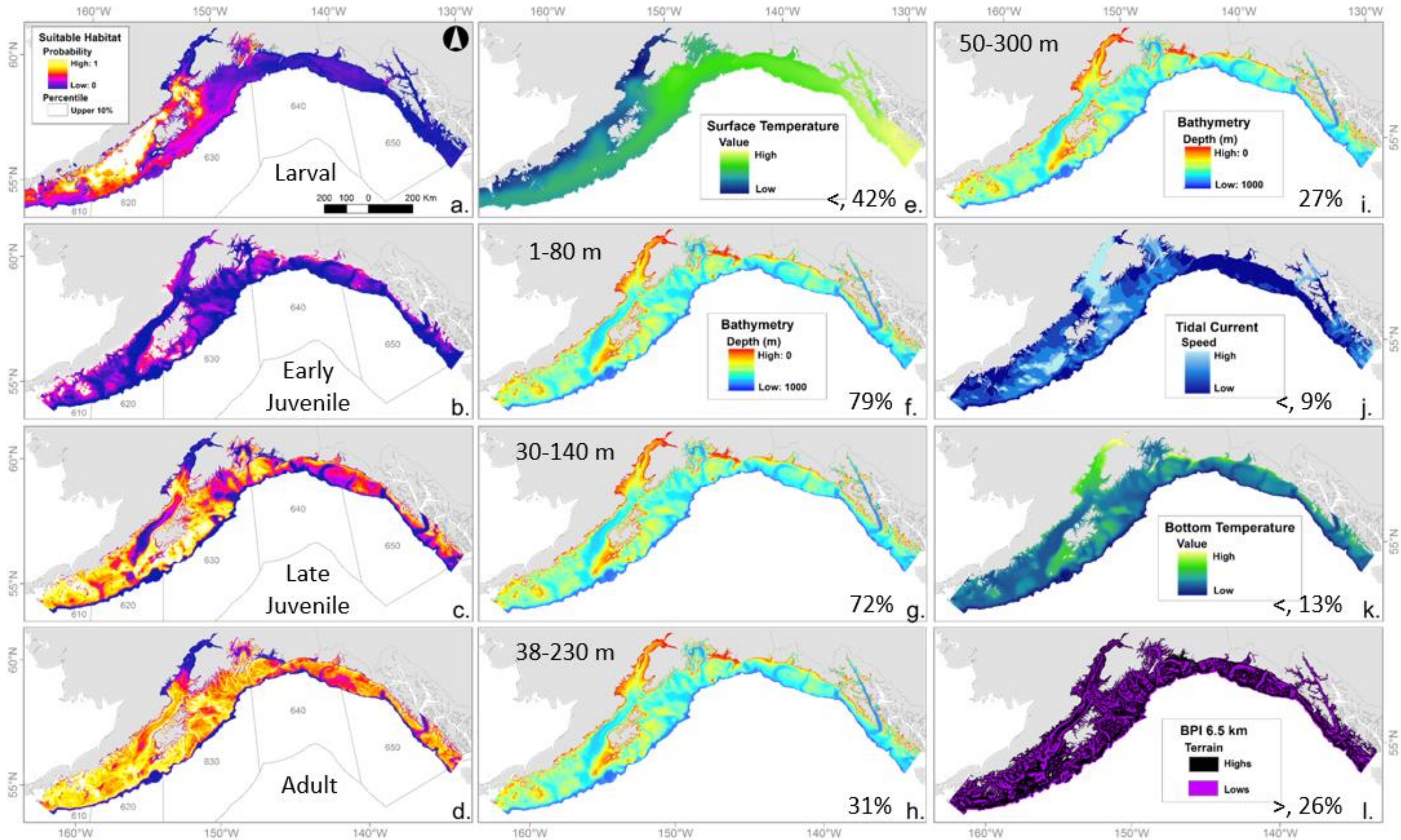
Figures



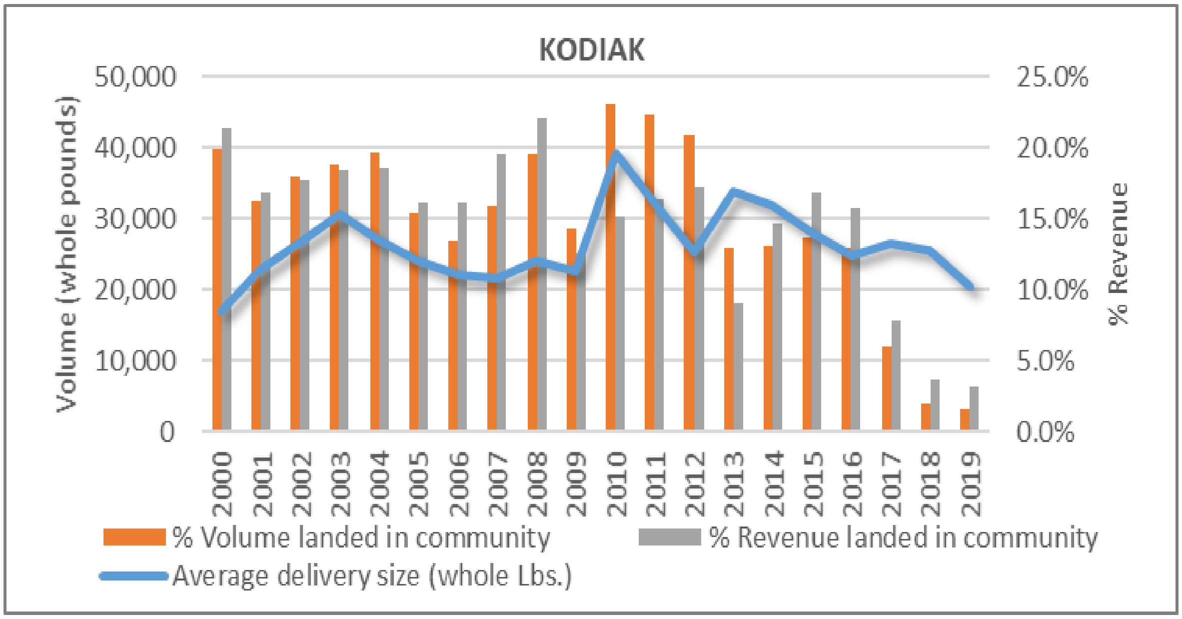
Appendix Figure 2.1.1. Baseline metrics for GOA Pacific cod graded as percentile rank over all groundfish in the FMP. Red dots indicates value passes a national threshold for vulnerability. Higher rank values indicate a vulnerability and color of the horizontal bar describes data quality of the metric (see Shotwell *et al., In Review*, for more details on the metric definitions and thresholds).



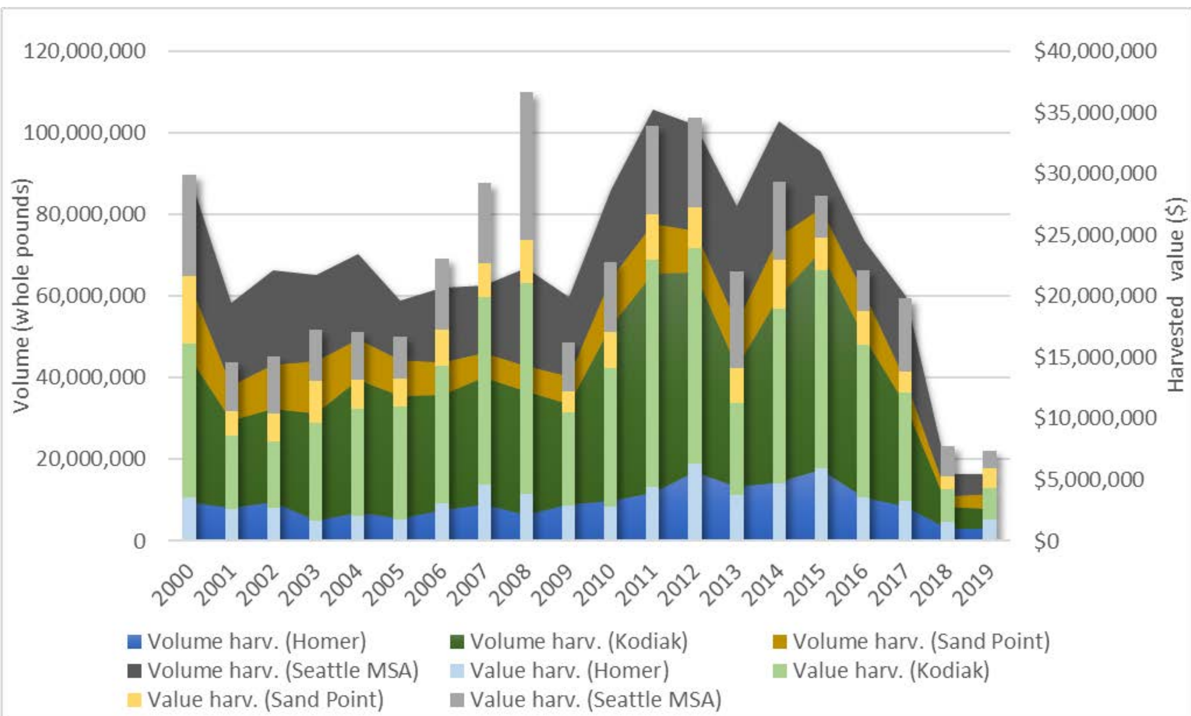
Appendix Figure 2.1.2: Life history conceptual model for GOA Pacific cod summarizing ecological information and key ecosystem processes affecting survival by life history stage. Red text means increases in process negatively affect survival, while blue text means increases in process positively affect survival.



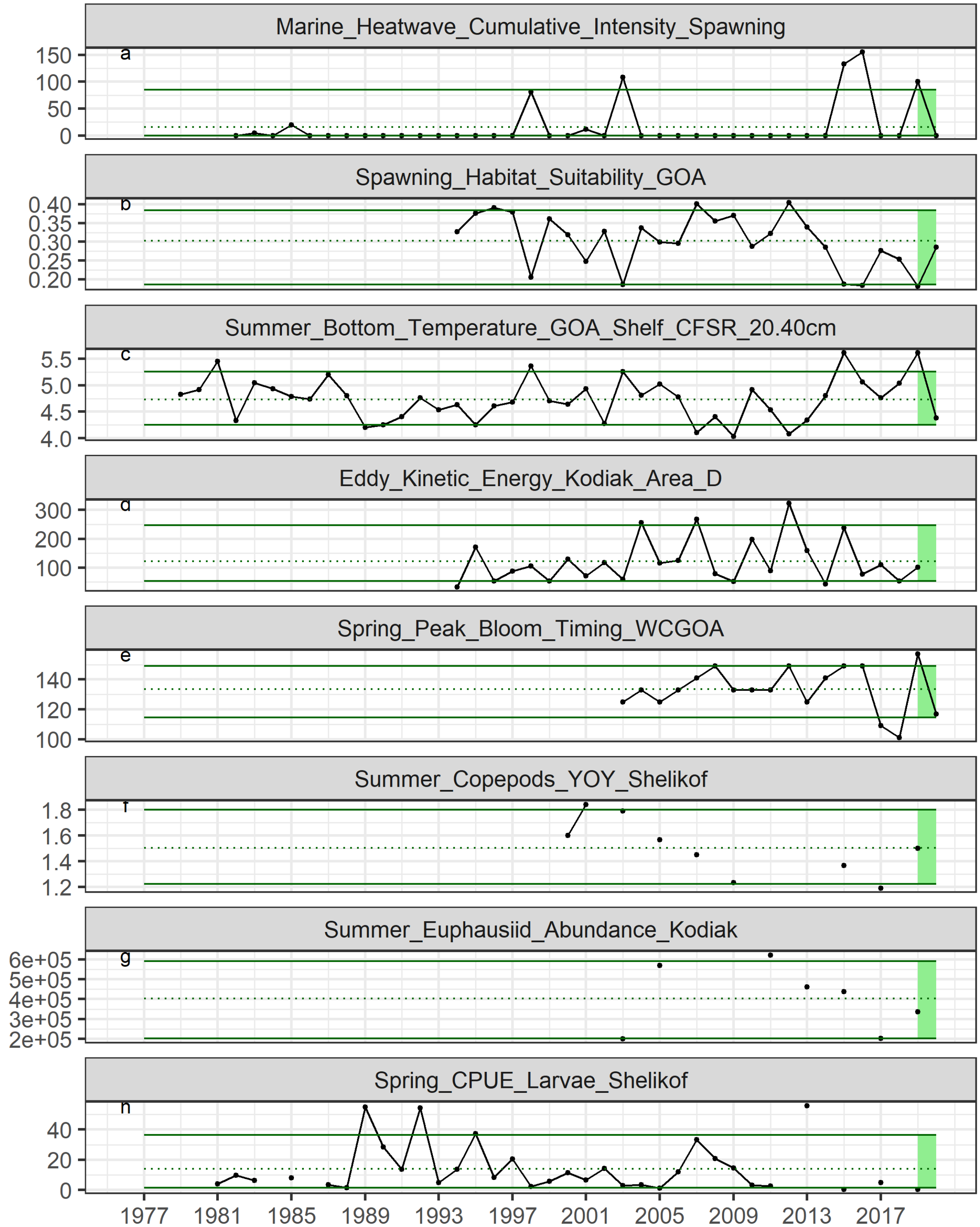
Appendix Figure 2.1.3. GOA Pacific cod probability of suitable habitat by life stage (a=larval, b=early juvenile, c=late juvenile, and d=adult) with predictor habitat variables representing the highest (e=depth, f=tidal current speed, g=depth, h=depth) and second highest contribution (i=surface temperature, j=bottom temperature, k=bottom temperature, and l=tidal current speed). Upper 10 %-ile of suitable habitat is shown in white within the probability of suitable habitat range (yellow to purple). Sign (<, >, <>) of the deviation from mean direction and the percent of contribution to predict suitability provided for each non-depth variable. Range provided for depth. See Shotwell *et al., In Review* for more details.



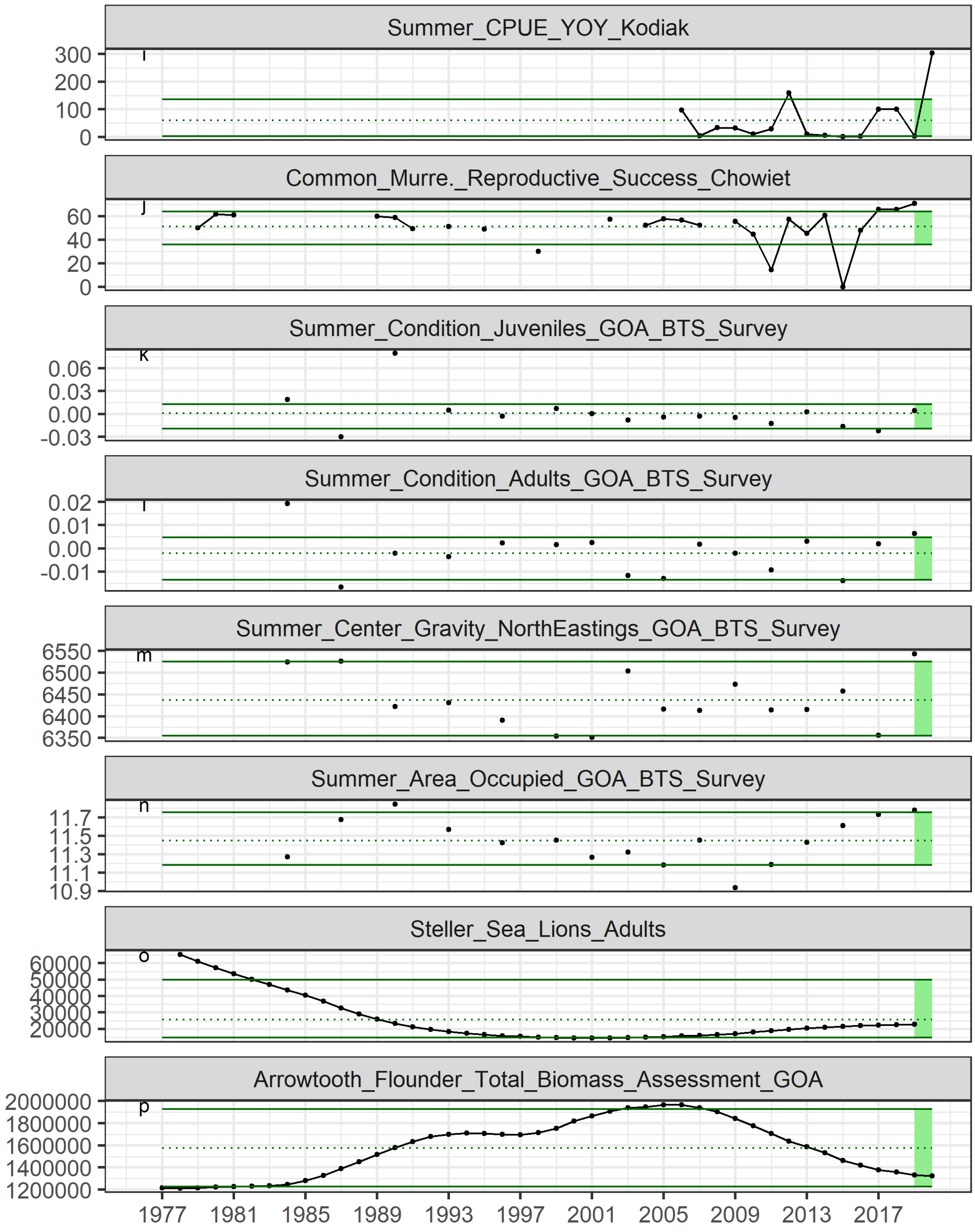
Appendix Figure 2.1.4a: Processing engagement for Kodiak: Average pounds delivered and percentage of value landed attributed to GOA Pacific cod for the highly engaged community of Kodiak (2000-2019).



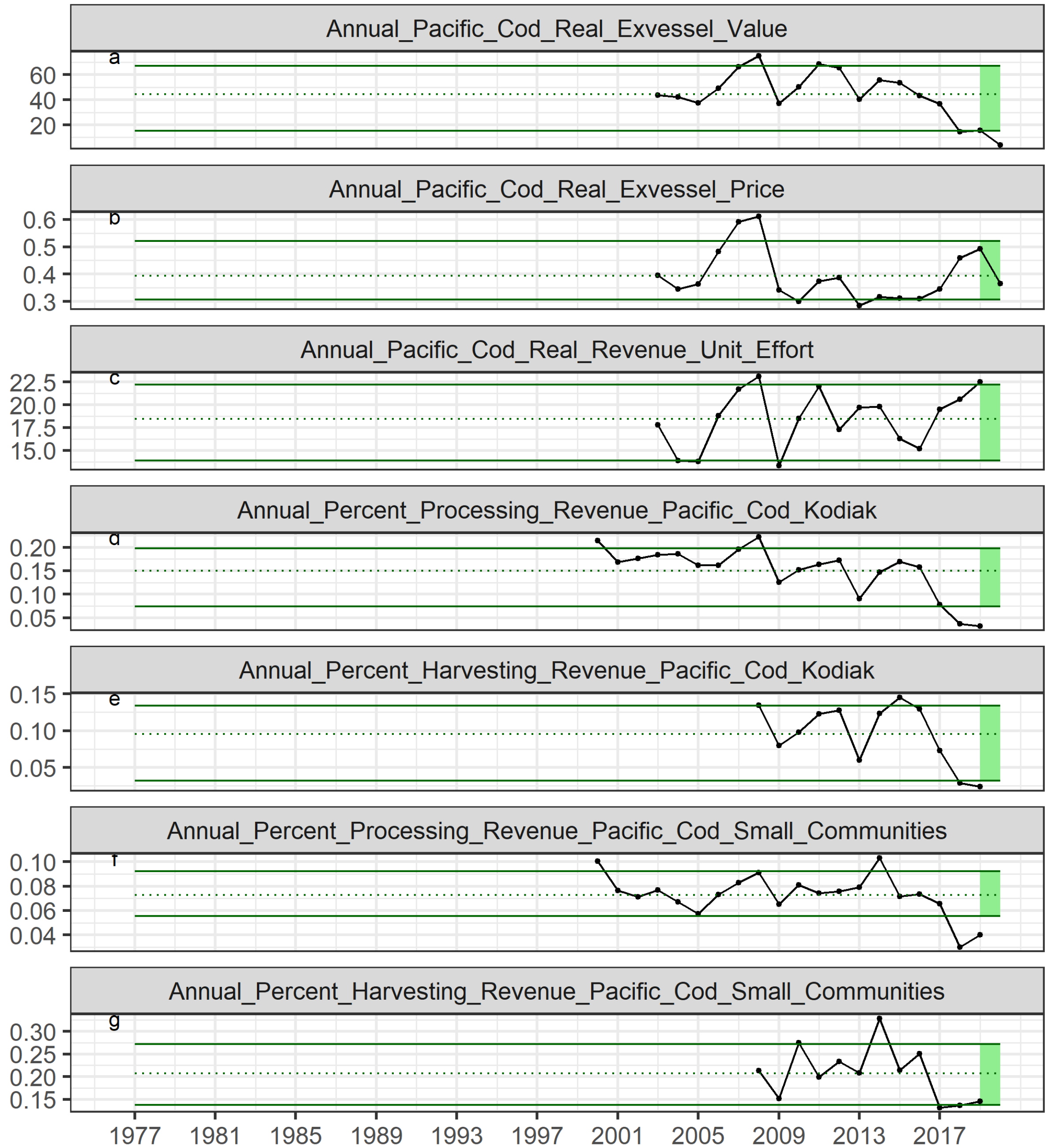
Appendix Figure 2.1.4b: Harvesting engagement: Average volume and value of GOA Pacific cod harvested by vessels owned by community residents (2000-2019).



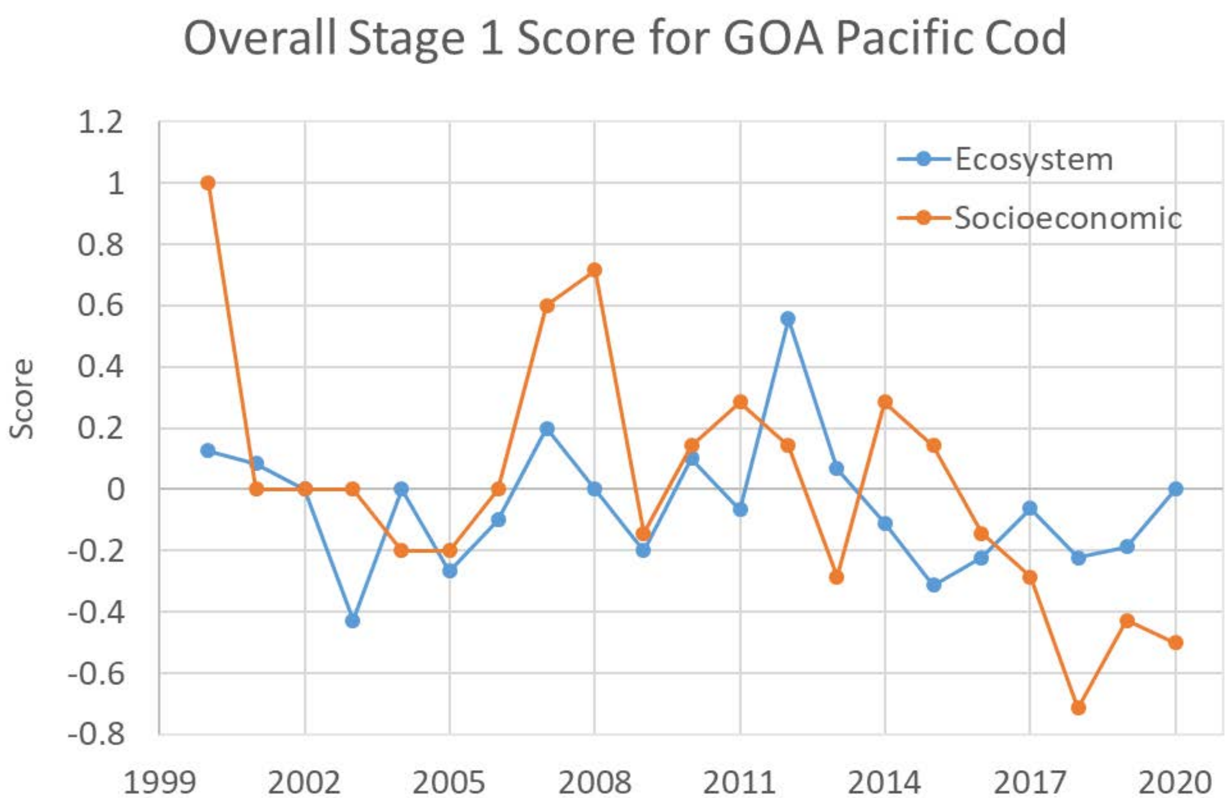
Appendix Figure 2.1.5a. Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines are 90th and 10th percentiles of time series. Dotted green horizontal line is mean of time series. Light green shaded area represents most recent year for traffic light analysis.



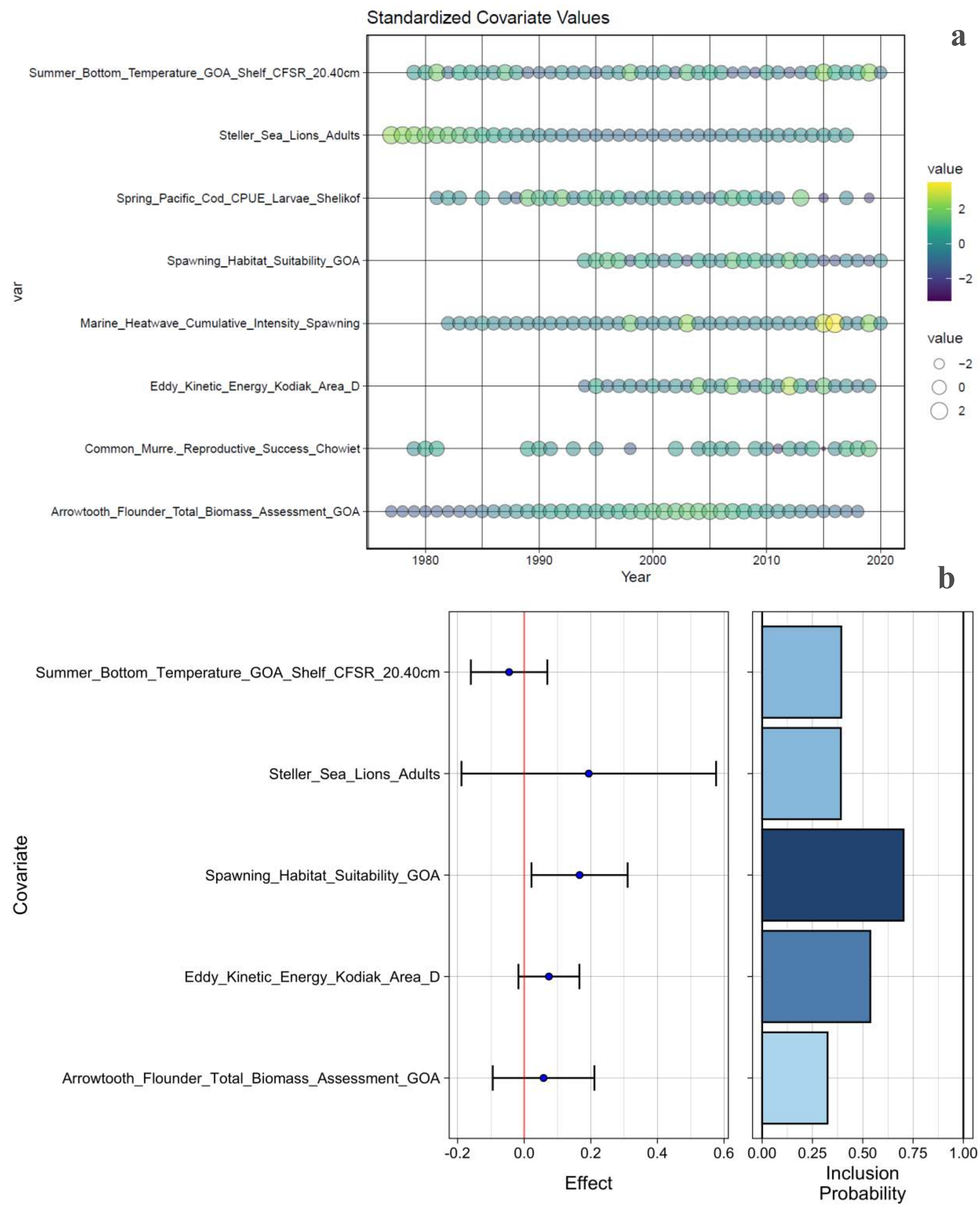
Appendix Figure 2.1.5a (cont.). Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines are 90th and 10th percentiles of time series. Dotted green horizontal line is mean of time series. Light green shaded area represents most recent year for traffic light analysis.



Appendix Figure 2.1.5b. Selected socioeconomic indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines are 90th and 10th percentiles of time series. Dotted green horizontal line is mean of time series. Light green shaded area represents most recent year for traffic light analysis.



Appendix Figure 2.1.6: Simple traffic light score for overall ecosystem and socioeconomic categories from 2000 to present.



Appendix Figure 2.1.7: Bayesian adaptive sampling output showing (a) standardized covariates prior to subsetting and (b) the mean relationship and uncertainty (95% confidence intervals) with log GOA Pacific cod recruitment, in each estimated effect (left bottom graph), and marginal inclusion probabilities (right bottom graph) for each predictor variable of the subsetted covariate set.