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

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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 2020 were updated and preliminary federal and state catch data for 2021 were included;
2. Commercial federal and state fishery size composition data for 2020 were updated, and preliminary commercial federal and state fishery size composition data for 2021 were included;
3. AFSC bottom trawl survey Pacific cod abundance and length composition data for 2021 were included;
4. AFSC longline survey Pacific cod abundance index and length composition data for the GOA for 2021 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.
6. Age-0 beach seine survey index was included in one alternative model.

Changes in the methodology

Model 19.1 is last year's accepted model (Model 19.1) with the addition of the new data described above. There are two new models described this year, Model 21.1, which is Model 19.1 but with a changed mortality block to 2015-2017 from 2014-2016 in Model 19.1 fit with the same prior for the base natural mortality (Table 2.1), and Model 21.2 which has temperature dependent growth, heatwave dependent recruitment, and heatwave dependent natural mortality instead of the 2014-2016 block used in Model 19.1. In addition 21.2 includes an age-0 beach seine survey index (Litzow *et al.* In review).

All three 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 21.2 the von Bertalanffy growth curve has additional link parameters on L_2 and K which scale growth to the CFSR temperature at depth for 0-20 cm fish, and a link parameter on L_1 which scales this parameter to an index of growth for larval Pacific cod based on the relationship of larval growth with temperatures published by Laurel et al. (2016). In Model 19.1 and 21.1 recruitment is parameterized as a standard Beverton-Holt with Sigma R is fixed at 0.44 and steepness is fixed at 1.0 for all three models. For model 21.2 there is a parameter on R_0 which scales it based on the spawning heatwave index. All scaling parameters are fit with non-informative priors. All selectivity estimates are fit using six parameter double-normal selectivity curves. For Model 21.2 the age-0 beach seine survey index is fit with an additional parameter which estimates variance of the index internally.

Summary of results

All three models performed well, and all three models produce similar results. Model 21.1 provided an overall better fit than Model 19.1; however, the fit made a tradeoff in providing an improved fit to the longline survey, length composition, and recruitment while degrading the fit to the bottom trawl survey. Because of the addition of the beach seine survey index data Model 21.2 could not be directly compared to the other two models using overall likelihoods. Model 21.2 provided a better fit to all of the conditional age at length data. However the seine data index was in conflict with the longline and trawl surveys resulting in a worse fit for these two. While all three models performed well in the retrospective analyses, Model 19.1 performed marginally better in the spawning stock biomass retrospective analysis and Model 21.2 performed marginally better in the recruitment retrospective analysis. A leave-one-out analysis was performed where all data for a single year were removed back to 11 years and changes in the variance of parameters and derived quantities evaluated. In this analysis all three models performed similarly with rather low bias. However Model 21.2 showed the least bias in the unfished spawning biomass, 2022 spawning stock biomass, and 2022 ABC. In particular, the removal of the 2021 data from Models 19.1 and 21.1 resulted in a substantial change in unfished spawning biomass, 2022 spawning stock biomass, and 2022 ABC, while the change in results from Model 21.2 were substantially lower. The largest differences among models were in the projections. Model 19.1 and 21.1 assume average 1977-2019 recruitment, growth, and natural mortality after 2020. For Model 21.2 the authors present two different assumptions; Projection A assumes environmental conditions after 2021 will match the 1977-2021 average, Projection B assumes that the environmental conditions after 2021 will match the 2012-2021 average. Projection B was provided because conditions for 2012-2021 in the GOA have been decidedly warmer than previous decades in the time series and projections by the IPCC suggests the warming trend will continue and worsen in the coming decades.

The data as interpreted through Model 21.2 indicates that the stock remains at low levels with poor recruitment since 2014. Although the 2017 and 2018 beach seine survey indicated higher densities of age-0 cod in those years, these fish failed to materialize at higher abundance in the 2019 - 2021 surveys or fisheries. Given selectivity in the fisheries and surveys, the high density of age-0 cod in the 2020 beach seine survey would not yet be collaborated by other data. Despite recent low recruitment, the stock was projected to either increase slowly (Projection A) or remain relatively stable (Projection B) due to low fishing levels in 2020 and 2021. Both projections have the stock at $B_{24.5\%}$ in 2022, however they differ in 2023 with Projections A at $B_{23.8\%}$ and Projection B at $B_{21.6\%}$. For setting ABC and OFL in 2022 and 2023 the authors present results for both Projection A and Projection B and seek guidance from the Plan Team and SSC on which future conditions should be considered for setting management advice.

Key results for both projections are tabulated below:

M21.2 Projection A **(Mean 1977-2021 conditions projected)** **Quantity**	As estimated or *specified last* year for: 2021	2022	As estimated or *specified this* year for: 2022	2023
M (natural mortality rate)	0.47	0.47	0.48*	0.48*
Tier	3b	3b	3b	3b
Projected total (age 0+) biomass (t)	265,661	312,783	159,837	185,745
Female spawning biomass (t)				
Projected	39,977	50,813	39,873	38,594
$B_{100\%}$	180,111	180,111	162,426	162,426
$B_{40\%}$	72,045	72,045	64,970	64,970
$B_{35\%}$	63,039	63,039	56,849	56,849
F_{OFL}	0.41	0.54	0.54	0.52
$maxF_{ABC}$	0.33	0.43	0.44	0.42
F_{ABC}	0.33	0.43	0.44	0.42
OFL (t)	28,977	46,587	29,131	27,715
maxABC (t)	23,627	38,141	24,043	22,882
ABC (t)	23,627	38,141	24,043	22,882
Status	2019	2020	2020	2021
Overfishing	No	n/a	No	n/a
Overfished	n/a	No	n/a	No
Approaching overfished	n/a	No	n/a	No

**Base natural mortality M varies between 0.48 and 1.07*
*** Assumed 2021 catch at the ABC, 23,627 t . For 2023 projections the 2022 catch was assumed to be at the projected ABC.*

M21.2 Projection B (Mean 2010-2021 conditions projected) Quantity	As estimated or *specified last* year for: 2021	2022	As estimated or *specified this* year for: 2022	2023
M (natural mortality rate)	0.47	0.47	0.48*	0.48*
Tier	3b	3b	3b	3b
Projected total (age 0+) biomass (t)	265,661	312,783	160,755	169,832
Female spawning biomass (t)				
Projected	39,977	50,813	39,873	35,050
$B_{100\%}$	180,111	180,111	162,426	162,426
$B_{40\%}$	72,045	72,045	64,970	64,970
$B_{35\%}$	63,039	63,039	56,849	56,849
F_{OFL}	0.41	0.54	0.54	0.47
$maxF_{ABC}$	0.33	0.43	0.44	0.38
F_{ABC}	0.33	0.43	0.44	0.38
OFL (t)	28,977	46,587	28,000	22,072
maxABC (t)	23,627	38,141	23,099	18,170
ABC (t)	23,627	38,141	23,099	18,170
Status	2019	2020	2020	2021
Overfishing	No	n/a	No	n/a
Overfished	n/a	No	n/a	Yes
Approaching overfished	n/a	No	n/a	Yes

**Base natural mortality M varies between 0.48 and 1.07*
*** Assumed 2021 catch at the ABC, 23,627t . For 2023 projections the 2022 catch was assumed to be at the projected ABC.*

Area apportionment

In 2012 the ABC for GOA Pacific cod was apportioned among regulatory areas using a Kalman filter approach based on summer trawl survey biomass estimates. In the 2013 assessment, the random effects model (which is similar to the Kalman filter approach, and was recommended in the Survey Average working group report which was presented to the Plan Team in September 2013) was used; this method was used for the ABC apportionment for 2014. The SSC concurred with this method in December 2013. Using this method with the trawl survey biomass estimates through 2021, the area-apportioned ABCs would be:

Projection A:

	Western	Central	Eastern	Total
Random effects area apportionment	30.3%	60.2%	9.5%	100%
2022 ABC	7,285	14,474	2,284	24,043
2023 ABC	6,933	13,775	2,174	22,882

Projection B:

	Western	Central	Eastern	Total
Random effects area apportionment	30.3%	60.2%	9.5%	100%
2022 ABC	6,999	13,905	2,194	23,099
2023 ABC	5,505	10,938	1,726	18,170

Responses to SSC and Plan Team Comments Specific to this Assessment

Plan Team Comments – September 2021

The Team recommended that the rationale for increases in the bottom trawl catchability parameter, particularly when re-weighting, should be noted; specifically, compare values with earlier experimental results.

Under the newest version of Stock Synthesis the Dirichlet multinomial option has been updated and now appears to function. There was a bug in the programing prior to August that was identified and has since been fixed.This configuration suggested no reweighting of the composition data and therefore these models were not brought forward for this assessment. Models presented for consideration have survey catchabilities within historic norms (1.0 to 1.15)

Science and Statistical Committee comments – October 2021

The SSC supports the authors' recommendation to bring forward Model 19.1 for the November assessment, and encourages the authors to explore a tuned version of this model that does not fit to the age-0 beach seine index. The SSC further supports the authors presenting several additional research models at their discretion:

- Model 21.1e that includes the age-0 beach seine index and environmentally-linked growth, mortality, and recruitment.
- Model 21.1g a tuned version of 21.1e.
- Model 21.5c which includes environmentally-linked growth and recruitment, the updated natural mortality time block, and is tuned.
- A possible model variant described in the GOA GPT presentation as 21.6 which includes the age-0 beach seine index and is tuned.

The authors presented three models for consideration which don't include any additional tuning. The Dirichlet multinomial option was explored and results indicated that the model would not require changes in data weighting. Given continued issues with convergence when the Dirichlet multinomial was used the authors chose to return to the base weighting used in prior year's assessments and described below. Model 21.1 includes an updated time block for natural mortality as described in model 21.5c and Model 21.2 includes all of the environmental links demonstrated in the September exploratory models along with the age-0 beach seine index.

With respect to the age-0 beach seine index, the SSC encourages the authors to consider whether the model-based estimates of uncertainty are accurately reflecting the true uncertainty in juvenile Pacific cod abundance, given the spatial extent of sampling relative to the distribution of juvenile Pacific cod in the GOA.

To address this issue the authors chose to fit an additional parameter which internally estimates the scale of the variance of the beach seine index in Model 21.2. This parameter in effect inflated the variance by 138% on average substantially reducing the indices weight within the model.

Introduction

Pacific cod (*Gadus macrocephalus*) is a transoceanic species, occurring at depths from shoreline to 500 m. The southern limit of the species' distribution is about 34° N latitude, with a northern limit of about 63° N latitude. Pacific cod is distributed widely over Gulf of Alaska (GOA), as well as the eastern Bering Sea (EBS) and the Aleutian Islands (AI) area. The Aleut word for Pacific cod, *atxidax*, literally translates to "the fish that stops" (Betts *et al.* 2011). Recoveries from archeological middens on Sanak Island in the Western GOA show a long history (at least 6,000 years) of exploitation. Over this period, the archeological record reveals fluctuations in Pacific cod size distribution which Betts et al. (2011) tie to changes in abundance due to climate variability (Fig. 2.1). Over this long period colder climate conditions appear to have consistently led to higher abundance with more small/young cod in the population and warmer conditions to lower abundance with fewer small/young cod in the population. Recent comparisons of Pacific cod length distributions extrapolated from bones retrieved from middens and those from the modern domestic fishery show a cline in size from larger fish in the west to smaller fish in the southeastern GOA that has been consistent for over 6,000 years (West *et al.* 2020) (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. In March 2021, a cooperative tagging study between the Alaska Fisheries Science Center (AFSC) and the Aleutian East Borough (AEB) was initiated to examine the seasonal movements of Pacific cod captured in the western GOA during the spawning season (P.I.s McDermott, Palsson, and Barbeaux, AFSC, and Levy, AEB). The goal of this study is to better understand the relationship of these fish to Pacific cod in the wider GOA and eastern Bering Sea (EBS) during the summer when the AFSC bottom trawl surveys are conducted. Twenty-five satellite-tagged and 957 conventionally-tagged Pacific cod were released in 8 subareas of the Western GOA near the Shumagin and Sanak Islands (Fig. 2.4). Satellite tags were programmed to pop-up and transmit data after 90, 180, or 365 days. Early pop-ups were likely due to predation instead of tagging mortality. Locations of tags recovered in March, April, and May were largely in the vicinity of release area but fish with tags recovered June through September had moved west toward the Aleutian Islands region and north into the EBS, Northern Bering Sea (NBS), Russia, and the Chukchi Sea. More than half of the tag recoveries (10 of 17) between the beginning of June and the end of September had moved northward out of the GOA, indicating substantial seasonal connectivity between the GOA and other management regions. Work is in progress to reconstruct movement paths of fish tagged with satellite tags which will provide valuable information on migration timing and pathways. Additional satellite and conventional tag releases are planned for March 2022.

Two genetics studies using Restriction-site Associated DNA sequencing have indicated significant genetic differentiation among spawning stocks of Pacific cod in the GOA and the EBS (Drinan et al. 2018; Spies et al. 2019). High assignment success (>80%) was demonstrated among five spawning populations of Pacific cod throughout their range off Alaska using 6,425 single-nucleotide polymorphism (SNP) loci (Drinan et al. 2018). 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 GOA, 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. 2.5; Drinan et al. 2018). 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 (Drinan et al. 2018). This locus had the level of differentiation of any locus examined (FST=0.071). ZP3 a reproductive protein that is known to undergo rapid selection, and it has been shown to neofunctionalize as an antifreeze protein in Antarctic icefishes (Spies et al. 2021). At the putative ZP3 locus in Pacific cod, a distinct set of haplotypes have been observed in spawning cod from Kodiak Island westward vs. Prince William Sound and samples to the east. Results were consistent with directional selection in the Bering Sea (Bering Sea, Aleutian Islands, Shumagin Islands, and Kodiak Island), and large regional differences among ZP3 haplotype frequencies between the Bering Sea group and other spawning locations in the Gulf of Alaska and further south, including Prince William Sound and Hecate Strait (Fig. 2.6). Results were also indicative of selection currently acting on northern collections, as may indicate local adaptation driven by differences in ZP3.

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

A detailed account of Pacific cod life history, environmental drivers, economic and social indicators can be found in the GOA Pacific cod ecosystem and social processes (ESP) 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 2.7 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 2.8 shows the distribution of catch from 1990-2015 for the three major gear types. Figure 2.9 and Figure 2.10 show the distribution of observed catch for 2020 and 2021 through October 13, 2021 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 for 2003 through 2021 the pot sector caught on average 58% of the total catch of Pacific cod in the Gulf of Alaska annually.

In 2015 combined state and federal catch was 79,489 t (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 17,000 t and combined fishery caught 15,411 t which was 91% of the ABC.

In 2020 the spawning stock biomass was projected to have dropped below 20% of the unfished spawning biomass ($B_{20\%}$) and the federal Pacific cod fishery in the GOA was closed by regulation to directed Pacific cod fishing. $B_{20\%}$ is a minimum spawning stock size threshold instituted to help ensure adequate forage for the endangered western stock of Steller sea lions. The 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 10,719 t as a further level of precaution to 6,431 t. ADF&G also reduced their maximum prescribed harvest limit of 3,902 t by 35% to 2,537 t. This resulted in a total combined federal TAC and Alaska State GHL of 8,968 t or 61% of the maximum ABC. In 2020 a total combined catch of 6,233 t was harvested (Table 2.2), the state having taken 2,318 t (91% of the GHL) and federal fisheries haven taken 3,916 t (61% of the federal TAC). The catch in the federal fisheries were split primarily between the arrowtooth flounder (1,237 t), walleye pollock (1,040 t), and shallow water flatfish fisheries (938 t).

In 2021 the stock was projected to be above $B_{20\%}$ and the federal fishery was once again allowed to open. The federal TAC was set at 17,321 t and state GHL set at 5,864 t (Table 2.3). As of October 4, 2021 a total of 16,502 t (69% of the ABC) have been harvested (Table 2.2). State fisheries have harvested 5,573 t (95% of the GHL) and federal fisheries 10,930 t (63% of the TAC). In 2021 43% of the Pacific cod catch was by pot gear (Table 2.2), 32% by trawl, 1and 8% by longline, while jig and other gear harvested less than 7%.

The largest component of incidental catch of other targeted groundfish species in the GOA Pacific cod fisheries by weight are skate species in combination followed by walleye pollock, shark species, rock sole, arrowtooth flounder, and octopus (Table 2.6). Rockfish 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. 2.8). 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. In 2020 there was no directed Pacific cod longline fishery in federal waters (Fig. 2.9). In 2021 observers and electronic monitoring show a large portion of the longline catch coming from near the Shumagin Islands in the Western GOA, and the southern edge of Kodiak Island and the southern edge of the Seward Peninsula in the Central GOA (Fig. 2.10). In years with a fishery, the longline fishery tends to catch larger fish on average than the other fisheries (Fig. 2.11). 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. 2.12). In 2018 and 2019 fewer boats participated in the fishery and catch was substantially slower and lower than previous years, this trend continued in 2020 when the federal fishery was closed (Fig. 2.20). In 2021 there was an increase in vessels participating in the Pacific cod longline fishery in the Central GOA from 3 in 2020 to 37 in 2021 exceeding the 33 that participated in 2019. There was only a single longline vessel fishing Pacific cod in the Western GOA, up from 2020, but fewer than the 3 that participated in 2019 (Fig. 2.20). In both the Central and Western GOA catch in 2021 was earlier than in 2018 or 2019, but like those years the A-season was completed by week 10 (Fig. 2.18 and Fig. 2.19). Although CPUE figures were produced for the longline fisheries in the GOA (Fig. 2.21), the consistency of the data are in question in the last three years, first because of the electronic monitoring reducing the available data and second because of changes in observer coverage due to COVID-19. It should be noted that CPUE is not available from the EM monitored vessels as number of hooks retrieved and soak time are not recorded.

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. 2.8). In 2017, the observer coverage rate of pot fishing vessels was greatly reduced from 14% to ~4% this impacted our ability to adequately identify the spatial distribution of the pot fishery. From the data collected there appears to have been less fishing to the southwest of Kodiak in 2017, however this may be due to low observer coverage. In 2018 - 2020, there were few observed hauls throughout the GOA due to the lower TAC, low fishing levels, and 2020 directed federal fishery closure (Fig. 2.9 and Fig. 2.10). The pot fishery in the Central GOA moved to deeper water in 2017 through 2019 than previous years. Like the longline fishery CPUE figures were produced for the pot fisheries in the GOA and similarly the consistency of the data are in question in the last three years for the same reasons. It should be noted that there were no data available for CPUE calculations in 2020 nor any CPUE data available for the Western GOA in 2021.

The pot fishery generally catches fish greater than 40 cm (Fig. 2.13), 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. 2.14). 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. In 2018 and 2019, the Pot fisheries in both regions were slower than the previous three years. In the Western GOA in 2018 and 2019, approximately half the catch was caught in a single week in March (Fig.18). In 2020 pot fishing was greatly reduced with 15 vessels in the Central GOA and 19 in the Western GOA compared to 27 and 33 the year previously (Fig. 2.20). In 2021 the number of participating vessels increased again to pre-closure levels with 24 vessels in the Central GOA and 37 in the Western GOA. In 2020 and 2021 there was no observer coverage of the pot fishery in the Western GOA despite substantial participation (37 vessels) and catch of 3,073 t (19% of the total GOA cod catch). There was however biological data collected from the Western GOA region by the ADF&G port samplers which were incorporated into the stock assessment.

Trawl

The Gulf of Alaska Pacific cod trawl fishery rapidly developed starting in 1987, surpassing the catch from the foreign longline fishery pursued in the 1970's to mid-1980s in 1987. The trawl fishery dominated the catch into the early-2000s, but was then replaced by increases in pot fishing in the mid-2000's. This transition to pot fishing was partially due to Steller sea lion regulations, halibut bycatch caps, and development of an 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. 2.8) with the highest concentration of catch coming from southeast of Kodiak Island in the Central GOA and around the Shumigan Islands in the Western GOA. In 2016 trawl fishing in the Western GOA shifted away from the Shumigan Islands further to the west around Sanak Island and near the Alaska Peninsula, this shift continued through 2017. Trawl fishing in 2018 for the A-season had a similar pattern as 2017 with large catches from around Sanak Island, but some increased effort on Portlock Bank to the southeast of Kodiak. There was substantially less catch and observed effort in 2018 and 2019 (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. 2.9), these observations primarily surrounded Kodiak from the pollock and shallow water flatfish fisheries. In 2021with the reopening of the directed Federal Pacific cod fishery there were observed catches in the Western GOA (Fig. 2.10). Trawl catch in the Western GOA was 1,780 t as of October 24, exceeding the 2018 and 2019 catches for the region (1,464 t and 1,589 t). Trawl catch of Pacific cod in the Central GOA so far in 2021 (3,767 t) have exceeded the catch over the previous 3 years. Due to bycatch in other fisheries trawl catch of Pacific cod in 2020 remained above 3,000 t despite the closure of the federal directed fishery.

The trawl fishery catches smaller fish than the other two gear types with fish as small as 10 cm appearing in the observed length composition samples (Fig. 2.15). The average size of Pacific cod caught by trawl in the 1980's was on average smaller than those caught later (Fig. 2.16). 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. 2.17). In 2018, 2019, and 2021 despite there being vessels 14 to 18 vessels participating in the Western GOA trawl fishery, there was no observed effort. There were no vessels participating in the directed Pacific cod fishery in the Central GOA for 2018-2020 and only 2 vessels in 2021 (Fig. 2.20).

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 2020 the jig fishery remained low with catch at less than 500 t for all regions (Table 2.2 and Fig. 2.19). In 2017 there were 35 Jig vessels participating in the GOA Pacific cod fishery, 27 in 2018, 61 vessels in 2019, 41 vessels in 2020, then a sharp increase in 2021 to 65 vessels (Fig. 2.20). Catch in 2021 also increased to 1,125 t, with 808 t of that from the Central GOA.

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 2,803 in 2017, 2,770 in 2018, 3,400 t in 2019, 3,903 t in 2020, and in 2021 as of October 4 a total of 4,071 t. 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-March) data for 1998-2021. 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. 2.22 - 2.25). In 2018 and 2019, where data are available the condition of fish in both the Central and Western GOA are mixed with differences in condition by gear and season. The Central GOA longline fishery shows improving condition in January through March (Fig. 2.22) in 2018 through 2021. The Central GOA pot fishery shows improvement in 2018 and 2021 as well (Fig 2.23), but there were no data available for 2019 and 2020. In the Western GOA, longline fishery cod condition in

2019 returned to average (Fig. 2.24). The Western GOA pot fishery shows improved cod condition in 2017 and 2018 following the heatwave (Fig. 2.25), but then again in 2019, cod condition once again drops to below average. There were no data for 2019-2021 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. 2.26). There were no haul data available from the pollock fishery in the Western GOA for 2020 and 2021 due to electronic monitoring and COVID-19 restriction on observer deployment. In the shallow water flatfish fishery, catch rates in tons of Pacific cod per ton of all species catch were examined (Fig. 2.27). For the pollock fishery in areas 620 and 630 the 2021 value was the lowest in the series (2008-2021). There were no data available in area 610 in 2021 to conduct this analysis. The catch of Pacific cod in the shallow water flatfish fisheries was the lowest in 2017 with an increasing trend through 2020, however 2021 shows a drop to the 2019 level. 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, 2019, and 2021 deeper strata had fewer stations sampled than in other years due to budget and/or vessel constraints.

The 2021 survey was conducted with two chartered vessels that accomplished 529 stations following the protocols of Stauffer (2004) and von Szalay and Raring (2018). While the GOA Bottom Trawl Survey optimally employs three chartered vessels and targets 825 stations, the reduced 2021 survey likely captured the trend and magnitude of the cod abundance in the GOA. The 2021 survey covered all strata; regions; and shelf, gully, and upper slope habitats to 700 m. The percent standard error of the biomass estimate was 8.7% and was lower than the historic average of 17.2%. The 2021 survey design was comparable to the 2013, 2017, and 2019 surveys that were also conducted with two vessels and achieved 547, 534, and 541 stations, respectively.

The Pacific cod biomass estimates from the bottom trawl survey are highly variable between survey years (Table 2.10 and Fig. 2.28). For example, the estimates dropped by 48% between the 1996 and 1999 estimates, but subsequent estimates were similar through 2005. The 2009 survey estimate spiked at 2 times the 2006 estimate, but was highly uncertain (CV = 0.185). Subsequent surveys showed a decline through 2017 with a slight uptick in 2019 and drop in 2021. The 2017 estimates for abundance and biomass estimates were the lowest in the time series (a 71% drop in abundance and 58% drop in biomass compared to the 2015 estimate). Although the 2019 survey resulted in a 126% increase in abundance over 2017, the estimate remained historically low at 58% of the time series mean. The 2021 survey abundance estimate (90,914,000) was the second lowest in the time series (41% of the time series mean), next only to the 2017 estimate. The 2021 abundance estimate was 73% lower than the 2013 estimate (337,992,000) and 28% lower than the 2019 estimate (127,118,000). The 2021 biomass estimate was only 4% lower than the 2019 biomass estimate and 62% higher than the 2017 biomass estimate. The 2021 biomass and abundance estimate were within the 95% confidence intervals of the 2019 survey estimates.

The bottom trawl survey encounters fish as small as 5 cm and generally tracks large year-classes as they grow (e.g., the 1996, 2005-2008, and 2012 year-classes; Fig. 2.29). The mean length in the trawl survey generally increased from 1984-2005 excepting the 1997 and 2001 surveys (Fig. 2.30). The decline in mean length in 2007 and 2009 were apparently due to the large incoming 2005-2008 year-classes. The mean length in the survey increased in the 2011-2017 survey then dropped again in 2019, but then increased again in 2021. The average length of fish for 2007-2021 remains below the 1984-2005 overall average.

The spatial distribution of Pacific cod in the survey has been highly variable (Fig. 2.31) with inconsistent peaks in CPUE. In 2017 the survey had the lowest average density of the time series, but also no high density peaks in CPUE were observed in any survey station. There were some higher than average densities for the 2017 survey located along the Alaska Peninsula and south of Unimak island, but for the most part CPUE was universally low throughout the Gulf of Alaska. The 2019 survey showed an increase in cod in the area of the Central GOA east of Kodiak Island on Portlock Bank and South of Marmot Island, but fewer cod in the Eastern and Western GOA. The distribution of cod in the 2021 survey is comparable to the 2019 survey except the peaks in CPUE east of Kodiak were not observed and more cod were encountered to the west of Kodiak Island and in the Western GOA near the Shumagin Islands.

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 2021 is available from this survey (Table 2.11 and Fig 2.32). 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 showed a sharp drop (53%) in abundance from 2016 to 2017, again (40%) from 2017 to 2018, and yet again (37%) from 2018 to 2019. The 2019 estimate was 83% lower than the 2015 abundance estimate. The 2020 RPN showed a 30% increase from 2019, but the 2020 RPN remains the second lowest estimate of the time series. The increasing trend observed in 2020 continues in 2021 with a 58% increase, however the index remains rather low at 43% of the 1990-2021 average.

Unlike the bottom trawl survey, the longline survey encounters few small fish (Fig. 2.33). The size composition data show consistent and steep unimodal distributions with a stepped decreasing trend in mean size between 1990 and 2015 (Fig. 2.34) and then increasing mean size from 2015-2021. 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.

Laurel and Litzow age-0 index

Beach seine sampling of age-0 cod was conducted at two Kodiak Island bays during 2006-2021 and an expanded survey was conducted during 2018-21 at 13 additional bays on Kodiak Island, the Alaska Peninsula, and the Shumagin Islands (n = 3 - 9 fixed stations per bay, 95 total stations). Sampling occurred during July and August (days of year 184-240), within two hours of a minus tide at the long-term Kodiak sites, and within three hours of a low tide at the expanded survey sites. At all sites, a 36 m long, negatively buoyant beach seine was deployed from a boat and pulled to shore by two people standing a fixed distance apart on shore. Wings on the seine (13 mm mesh) were 1 m deep at the ends and 2.25 m in the middle with a 5 mm delta mesh cod end bag. The seine wings were attached to 25 m ropes for deployment and retrieval from shore. The seine was set parallel to and ~ 25 m, making the effective sampling area ~ 900 m^2 of bottom habitat.

A model-based index of annual catch per unit effort (CPUE) for age-0 cod was used to resolve inter-annual differences in sampling across different bays and different days of the year. Specifically, a Bayesian zero-inflated negative binomial (ZINB) model was used invoking year as a categorical variable, day of year as a continuous variable, and site nested within bay as a group-level (random) effect. The day of year effect was modeled with thin plate regression splines to account for non-linear changes in abundance through the season and the number of basis functions was limited to 3 to avoid over-fitting data. This model was fit using Stan 2.21.0, R 4.0.2 and the *brms* package (Carpenter et al. 2017, Buerkner 2017, R Core Team 2021). The beach seine age-0 CPUE index showed the large 2012 year class and subsequent drop in CPUE for 2013-2016, larger recruitment in 2017 and 2018, a drop again in 2019, and a large 2020 year class, and then low 2021 value (Table 2.12 and Fig. 2.35).

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 2.13 and Fig. 2.36). 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.

The 2021 IPHC survey observed a 28% increase from 2019 (Table 2.13), but remained 7.8% below the timeseries average. The RPN weighted length composition data were not available at the time this document was written, however the raw length data were. The raw length composition data collected during the IPHC survey was comparable to the 2018 length distribution with a similar mean and variance, both these years were smaller on average than the 2019 data (Fig. 2.37).

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 1988-2021. 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= 2092.89). 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 2.14 and Fig. 2.37). This survey differs from other indices as the estimates only increased in 2012 (an 89% increase from 2011), and then dropped off steadily afterwards to a record low in 2016. The 2017 survey index was 6% higher than the 2016 survey index. 2018 increased by 31% from 2017. The 2019 survey showed a slight decline (15.8%) from 2018, but 2020 showed a sharp increase of 41% from 2019 and a 64% increase from the 2016 record low, but still below the time series average. 2021 showed a 19.8% decrease from 2020 with a biomass estimate 67% lower than the time series average. Length composition data (Fig. 2.38) from this survey show wide multi-modal length distributions are common with modes of age-0 fish at times available at near 10cm, however the 2019 through 2021 surveys have no fish smaller than 22 cm.

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. 2.40 and Table 2.15).

The mean depth of Pacific cod at 0-20 cm and 40-60 cm was found to be 47.9 m and 103.4 m in the Central GOA and 41.9 m and 64.07 m in the Western GOA. The temperatures of the 0-20 cm and 40-60 cm Pacific cod in the CFSR indices are highly correlated ($R^2 = 0.89$). The shallower index is more variable ($CV_{0\text{-}20\text{ cm}} = 0.12$ vs. $CV_{40\text{-}60\text{cm}}= 0.08$). There are high peaks in water temperature in 1981, 1987, 1998, 2015, 2016 and 2019 with 2019 being the highest in both the 0-10 cm and 40-60 cm indices. There are low valleys in temperature in 1982, 1989, 1995, 2002, 2009, 2012, and 2013. The coldest temperature in the 0-20 cm index was in 2009 and in the 40-60 cm index in 2012. The trend is insignificant for both indices. In 2020 and 2021 the temperatures at both the 0-20 and 40-60 are below the time series mean with 2021 being within 1% of the 2020 temperatures.

Sum of annual marine heatwave cumulative intensity index (MHWCI)

The daily sea surface temperatures for 1981 through October 2021 were retrieved from the NOAA High-resolution Blended Analysis Data database (NOAA 2017) and filtered to only include data from the central Gulf of Alaska between 145°W and 160°W longitude for waters less than 300m in depth. The overall daily mean sea surface temperature was then calculated for the entire region. These daily mean sea surface temperatures data were processed through the R package heatwaveR (Schlegel and Smit 2018) to obtain the marine heatwave cumulative intensity (MHCI; Hobday *et al.* 2016) value where we defined a heat wave as 5 days or more with daily mean sea surface temperatures greater than the 90th percentile of the 1 January 1982 through 31 December 2012 time series. The MHCI were then summed for each year to create an annual index ($MHCI_{AN}$), summed for each year for the months of January through March, November, and December to create an annual winter index ($MHCI_{W}$), and the months of February and March to create an annual spawning season index ($MHCI_{SP}$).

The marine heatwave analysis using the daily mean Central GOA sea surface temperatures indicated a prolonged period of increased temperatures in the Central GOA from 2 May 2014 to 13 January 2017 with heatwave conditions persisting for 815 of the 917 days in 14 events of greater than 5 days (Fig. 2.36). 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 (Table 2.15), 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. 2.41). After April the SST remained above the 1982-2012 mean oscillating into and out of heatwave conditions through October 2020 with four heatwave events occurring between 8 June and mid-October for a cumulative intensity of 131.24 °C days. The highest seasonal anomaly for 2020 was on 22 August at 2.68°C. The longest heatwave event in 2020 has lasted 48 days starting 13 September and continuing to 31 October. In 2021 there were three short heatwaves in January through March, two of 4 days and one of five days with a maximum temperature of 1.79 °C above the seasonal mean. For the most part 2021 remained cool or near average for the remainder of the year through October 24.

Data

This section describes data used in the current assessment (Fig. 2.42). It does not attempt to summarize all available data pertaining to Pacific cod in the GOA. All data used for all models presented are provided in Stock Synthesis data files in Appendix 2.2:

https://apps-afsc.fisheries.noaa.gov/Plan_Team/2021/GOAPCOD2021Appendix2.2.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 – 2021
Federal fishery catch-at-length, by gear type	AKFIN / FMA	number, by cm bin	1977 – 2021
State fishery catch-at-length, by gear type	ADF&G	number, by cm bin	1997 – 2021
GOA NMFS bottom trawl survey biomass and abundance estimates	AFSC	number	1984 – 2021
AFSC Sablefish Longline survey Pacific cod RPN	AFSC	RPN	1990 – 2021
GOA NMFS bottom trawl survey length composition	AFSC	number, by cm bin	1984 – 2021
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 – 2021
Federal fishery conditional age-at-length	ASC	proportion age at length	2007 – 2020
Age-0 beach seine index	AFSC	age-0 numbers per haul	2006-2021
CFSR bottom temperature indices	National Center for Atmospheric Research	temperature anomaly at mean depth for P. cod size bins 10 cm and 40 cm.	1979-2021

Fishery

Catch Biomass

Catches for the period 1991-2021 are shown for the three main gear types in Table 2.2, with the catches for 2021 presented through October 4, 2021. 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 2021 are shown in Table 2.6, and incidental catch of non-commercial species for 2017 – 2021 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 2021. 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 2.11 – 2.16 and provided in Appendix 2.3 - 2.6 in Excel spreadsheets:

Model 19.1

https://apps-afsc.fisheries.noaa.gov/Plan_Team/2021/GOAPCOD2021Appendix2.3.xlsx

Model 21.1

https://apps-afsc.fisheries.noaa.gov/Plan_Team/2021/GOAPCOD2021Appendix2.4.xlsx

Model 21.2

Projection A

https://apps-afsc.fisheries.noaa.gov/Plan_Team/2021/GOAPCOD2021Appendix2.5.xlsx

Projection B

https://apps-afsc.fisheries.noaa.gov/Plan_Team/2021/GOAPCOD2021Appendix2.6.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 2021 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. 2.43). The age data was also used to develop an annual conditional length-at-age matrix for each fishery (Fig. 2.44 - 2.46).

Surveys

NMFS Gulf of Alaska Bottom Trawl Survey

Abundance Estimates

Bottom trawl survey estimates of total abundance used in the assessment models examined this year are shown in Table 2.10 and Fig. 2.28, together with their respective coefficients of variation.

Length Composition

The relative length compositions used in the assessment models examined this year from 1984-2021 are shown in Figure 2.47 and provided in Appendices 2.2-2.4 in Stock Synthesis data files and in Appendices 2.3-2.6 in Excel spreadsheets (see links above).

Age Composition

Age compositions (Fig. 2.47) and conditional length at age (Fig. 2.48) 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 Stock Synthesis data files in Appendix 2.2 and in Excel spreadsheets in Appendices 2.3-2.6 (see links above).

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

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

AFSC Longline Survey for the Gulf of Alaska

<u>Relative Population Numbers Index and Length Composition</u>

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 2.11 and Fig. 2.32.

<u>Length Composition</u>

The length composition data for the AFSC longline survey data are shown in Figure 2.33 and provided in Stock Synthesis data files in Appendices 2.2 and in Excel spreadsheets in Appendices 2.3- 2.6 (see links above).

Laurel and Litzow age-0 index

Beach seine sampling of age-0 Pacific cod number per haul index values together with their respective coefficients of variation used in the assessment models examined this year are shown in Table 2.12 and Fig. 2.35.

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 2.15 and Fig. 2.40).

Heatwave indices

The annual and spawning heatwave indices were used in this assessment (see description above; Table 2.15 and Fig. 2.41).

Analytic Approach

Model Structure

This year we present three models; Model 19.1 is the same as last year's model with updated data, Model 21.1 is the same except for a change to the natural mortality block from 2014-2016 to 2015-2017, and Model 21.2 which is an ecosystem-linked model with temperature or heatwave index links to recruitment, growth, and natural mortality. 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 3.30.18 (Methot and Wetzell 2013).

All three 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.

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

The Stock Synthesis control files for all three models evaluated are provided in a zip file in Appendix 2.2 (see links above).

Parameters Estimated Outside the Assessment Model

Variability in Estimated Age

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

Weight at Length

Parameters governing the weight-at-length were estimated outside the model using AFSC GOA bottom trawl survey data through 2015, giving the following values:

	Value
α:	5.631×10^{-6}
β:	3.1306
Samples:	7,366

Maturity

The length at 50% maturity was calculated using the *morp_mature* function in the sizeMat R package (Torrejon-Magallanes 2017) using all of the length at maturity data available from the Stark (2007) study for the Gulf of Alaska. This included some maturity data that was not available to Stark (2007) at the time of publication and some maturities from March and April not used in the calculation of $L_{50\%}$ published. This resulted in the following values: length at 50% maturity = 57.3 cm and slope of linearized logistic equation = -0.27365 (Fig. 2.46).

Aging Error

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

Parameters Estimated Inside the Assessment Model

Parameters estimated conditionally (i.e., within individual SS runs, based on the data and the parameters estimated independently) in the model include the growth parameters, annual recruitment deviations, gear-specific fishery selectivity parameters, aging bias adjustment parameters, survey catchability, and survey and fishery selectivity parameters (Table 2.16 and Appendices 2.3 - 2.6 see above).

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 marine heatwave. The 2017 reference model, Model 17.09.35 used a block for 2015-2016 where M could be fit separately from all other years. In consideration of the marine heatwave analysis, models in 2018 expanded the natural mortality block to 2014-2016. For this $M_{standard}$ is fit separate from $M_{2014\text{-}2016}$ with a lognormal prior of log(μ) = -0.81 and σ of either 0.1 or 0.41. The σ of 0.41 was based on a reevaluation of the data presented by Dr. Thompson described above and in Table 2.1, but limited to not include data from the Gulf of Alaska used in the current model.

Natural mortality in the Model 19.1 were fit for two time blocks, 2014-2016 and all other years, as a single non-varying parameter for all ages for each block. For Models 21.1 natural mortality were fit for two time blocks, 2015-2017 and all other years, as a single non-varying parameter for all ages for each block with uninformative priors. The new time block was determined through iterative fits of the model with different blocks specified with the 2015-2017 block resulting in the best objective function. Natural mortality in Model 21.2 was annually varying with a linear ecosystem-link parameter, η, which scaled the non-heatwave year natural mortality, $\widehat{M}$, using the annual central GOA marine heatwave cumulative index (I_{Ay}) as:

$$\mathrm{M_y} = \widehat{M} + \eta l_y$$

$$l_y = \lambda / \left(1 + e^{-\varsigma(I_{Ay} - \psi)}\right)$$

A logistic curve was used to convert the index forcing M to asymptote at higher index values (Table 3). Here the shape of the logistic curve including the asymptote, λ, slope, ς, and inflection point in °C days, ψ, was determined within the model iteratively and the parameters resulting in the lowest negative log-likelihood were selected for projections. The best fit model had λ at 0.65, ς = 0.005 and ψ = 400 resulting in increased natural mortality estimates for years with positive I_{Ay} values. Note the maximum annual marine heatwave index value in the time series was 631°C-days in 2016, well below future projected values.

Growth

For Model 19.1 and Model 21.1 length at age, $\mathrm{L_a}$, were modeled as three parameter von Bertalanffy growth models with length in June, $\mathrm{L_1}$, maximum asymptotic length, $\mathrm{L_2}$, and growth rate, k, as:

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

where a was age.

For the ecosystem-linked Model 21.2 length at age for each year, $\mathrm{L_{ay}}$, was modeled as six parameter von Bertalanffy growth modeled with annual water temperature covariates on $\mathrm{L_1}$, $\mathrm{L_2}$, and k as:

$$\mathrm{L_{ay} = L_{2y} - \left(L_{2y} - L_{1y}\right)e^{-ak\left(e^{\varphi f_{Jy}}\right)}}$$

$$L_{1y} = \bar{L}_1 e^{\left(\gamma \frac{e^{\left(0.2494+0.3216\left(\bar{t}+f_{Jy}\right)-0.0069\left(\bar{t}+f_{Jy}\right)^2-0.0004\left(\bar{t}+f_{Jy}\right)^3\right)}}{e^{\left(0.2494+0.3216(\bar{t})-0.0069(\bar{t})^2-0.0004(\bar{t})^3\right)}}\right)}$$

$$L_{2y} = \bar{L}_2 e^{\upsilon f_{Jy}}$$

where f_{Jy} was the June bottom temperature anomaly in the Central GOA (described above) in year y, γ was the temperature anomaly link parameters for L_1 and an index of the ratio of the annual June temperature, $\bar{t} + f_{Jy}$, dependent juvenile growth (Laurel *et al.* 2015) for a given year over the growth in June for the mean temperature for 1982-2012, $\bar{t}$, υ was the temperature anomaly link parameter for L_2, and φ the temperature anomaly link parameter for *k*.

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

Recruitment

In Model 19.1 and Model 21.1 recruitment by year, R_y, were modeled as:

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

R_0 was the unfished equilibrium recruitment, $\tilde{R}_y$ was the lognormal recruitment deviation for year y, σ_R^2 was the standard deviation among recruitment deviations in log space and was fixed at 0.44, and b_y was a bias adjustment fraction applied during year, y (Methot Jr and Taylor, 2011). To account for an environmental regime change in 1977 (Anderson and Piatt, 1999) the parameter ϑ was fit for recruitment allowing for a change in R_0 prior to the regime change in 1977. Projections in the base model post-2017 assumed average recruitment for 1977-2017 for R_y.

The ecosystem-linked recruitment (R_y) in Model 21.2 was modeled as Beverton-Holt relationships with parameter (ω) which scaled the unfished equilibrium recruitment, R_0, using the annual spawning Central GOA marine heatwave cumulative index (I_y; described below) as:

$$R_y = \frac{4h\left(e^{\vartheta + \ln\left(R_0 e^{\omega I_{Sy}^{\frac{1}{3}}}\right)}\right) SB_y}{SB_0(1-h) + SB_y(5h-1)} e^{-0.5 b_y \sigma_R^2 + \tilde{R}_y}, \text{ if } y \geq 1977 \rightarrow \vartheta = 0, \text{ where } \tilde{R}_Y = N\left(0;\ \sigma_R^2\right),$$

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

Where h=1, the formula reduces to $R_y = e^{\vartheta + \ln\left(R_0 e^{\omega I_{Sy}^{\frac{1}{3}}}\right)} e^{-0.5 b_y \sigma_R^2 + \tilde{R}_y}$.

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

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

where $\bar{Q}$ was the mean catchability for the AFSC longline survey for 1977 through 2020,τ was the ecosystem link parameter fit with an uninformative prior, and f_{Jy} was the June CFSR bottom temperature anomaly in the Central GOA in year y. An analysis introducing this methodology was presented in 2017 (Barbeaux *et al.* 2017) and a method validating this methodology was presented at the 2018 September Plan team meeting and provided in Barbeaux *et al.* (2018) Appendix 2.1. Bottom trawl survey data show a centroid of distribution for cod greater than 34 cm shifts to deeper water in years with warmer shelf temperatures (Barbeaux *et al.* 2019). This relationship was verified in Yang *et al.* (2019) with a shift to deeper depths in all size classes examined during warm years and shift to shallower waters in cold years. This shift would make cod more available to the AFSC longline survey which starts at 150 m.

Beach Seine survey extra variance

Model 21.2 estimated an additive constant parameter which was added to the input standard deviation of the age-0 beach seine index variability. There was concern during the October SSC meeting that because of the limited area covered by the beach seine survey that the estimated variance for this index was too conservative. This allows for the variance and thus the weight of the index to be estimated internally within the model in consideration of all other model data and model structure.

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 a factor of 0.05 over 50 runs to evaluate if models had converged to local minima.

Use of Size and Age Composition Data in Parameter Estimation

Although there were model explorations using the Dirichlet multinomial configuration, all fits resulted in a recommendation of no change to the input weighting. Therefore for all three models presented this year use the same weighting as previous years. Size and age composition data were assumed to be drawn from a multinomial distribution specific to a particular year and gear within the year. In the parameter estimation process, SS weights of a given size composition observation (i.e., the size frequency distribution observed in a given year and gear) according to the emphasis associated with the respective likelihood component and the sample size specified for the multinomial distribution from which the data were assumed to have been drawn. As was done last year, we set initial sample sizes for the fishery at the number of hauls sampled or 200 whichever is least, for the surveys both size and age composition sample sizes were initially set at 100.

Results

Model Evaluation

Three models are presented, Model 19.1, which is the 2020 base model with updates to the data, Model 21.1 which has the same configuration and data as Model 19.1 except the heatwave natural mortality block is changed to 2015-2017 instead of 2014-2016, and Model 21.2 which is a climate-enhanced Model 19.1 with the addition of the age-0 beach seine index, temperature or heatwave index dependent growth, recruitment, and mortality. Model evaluation criteria included log likelihood, model adherence to biological principles and assumptions, the relative sizes of the likelihood components, and how well the model 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, retrospective pattern, and model behavior during leave-one-out analysis.

Model likelihoods and key parameter estimates and index RMSSR are provided in Table 2.17. Likelihoods by fleet and are provided in Table 2.18. Composition mean effective sample sizes are provided in Table 2.18. Retrospective results are presented in Table 2.19. Jitter analysis results are presented in Table 2.20 and leave-one-out in Table 2.21 and Table 2.22, as well as Figures 2.58- 2.60.

All parameter estimates and selected model results for all three models are provided in Excel spreadsheets in Appendices 2.3-2.6.

Comparing and Contrasting Model Configurations

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. 2.49). The female spawning biomass and age-0 recruitment for last year's base model and all three models presented this year are provided in Figure 2.50. All models show a similar overall fit, and similar recruitment and biomass trends. The size based selectivity curves (Fig. 2.51 and Fig. 2.52) are nearly indistinguishable between the three models.

Model 19.1 and Model 21.1

The only difference between Model 19.1 and Model 21.1 was a change in the natural mortality block to take into account increased mortality during the 2014-2016 heatwave. Model 19.1 has the block at 2014-2016 while Model 21.1 has a block for 2015-2017. Overall Model 21.1 with a negative log likelihood (LL) of 3549.61 shows an overall improvement in performance over Model 19.1 with a -LL of 3567.18. The difference in fit to the indices (Fig. 2.53) among the models reveals a changing balance between the fit to the bottom trawl and longline surveys. Model 19.1 demonstrated a closer fit to the 2015 bottom trawl survey index value than Model 21.1, however Model 21.1 fits the 2015 and 2016 longline survey indices better. The index likelihood components by fleet shown in Table 2.18 show that Model 19.1 has a superior fit to the bottom trawl survey while Model 21.1 has a superior fit to the longline survey. The change in overall fit to the indices only changes by -0.3 likelihood between the two models. The change in fit to the two survey indices is reflected in the root mean squared standardized residuals with Model 19.1 with a lower RMSSR for the bottom trawl survey and Model 21.1 with a lower RMSSR on the longline survey (Table 2.17). Model 21.1 has a lower objective function in all other likelihood components (Table 2.18), except for trawl fishery conditional age at length (increase of 0.36 LL). The largest improvement from Model 19.1 to Model 21.1 was in the length composition fit (-8.84 LL) and then recruitment devs (-5.06 LL). Although the fits to length composition and conditional age at length for these two models are quantifiably different, they are not readily differentiable by eye. Natural mortality (Table 2.27 and Fig. 2.54) in Model 19.1 for the base years was estimated at 0.5 which is slightly higher than that fit in Model 21.1 at 0.49. However natural mortality during the heatwave block years in Model 21.1 was estimated to be higher at 0.94 than in Model 19.1 at 0.87. Catchability in the bottom trawl survey for the two models remain within the range of previous years models with Model 19.1 catchability at 1.11 (mean (ln(total biomass estimate)/ln(index)) = 1.00) and Model 21.1 at 1.15 (mean (ln(total biomass estimate)/ln(index))= 1.00).

Both models had acceptable retrospective evaluation results from the 10-year peals (Fig. 2.55 and Fig. 2.56). The results however were mixed with Model 19.1 having lower Mohn's ρ for spawning biomass (Table 2.19) and Model 21.1 having a lower Mohn's ρ for age-0 recruitment. Mohn's ρ focuses on the end-year values in the peals. The Woods Hole ρ values, which uses the full time series values, was better behaved in Model 19.1 than Model 21.1 for both spawning biomass and recruitment.

Both models performed reasonably well in a jitter analysis with a CV of 0.05 and 50 runs (Table 2.20). For Model 19.1 a total of 49 of the 50 jitter runs converged with 65% of the converged models resulting in estimates at the lowest MLE from the accepted models. For Model 21.1 a total of 47 of the 50 model runs converged and 79% of the converged models resulted in estimates at the lowest MLE from the accepted model. There were no jitter runs from either model at a lower objective value than the final models presented here.

Leave-one-out analysis (LOO) is new to this assessment. For the LOO analysis data for a single year were pulled from the model sequentially and the model refit each time. We then examined the behavior of the model and the effects of removing the data on key parameter estimates (M, and Q), and derived quantities (F40%, unfished spawning biomass, 2022 spawning biomass, and 2022 ABC). Stability of the model estimates and estimates of variance while removing data provided insights on model performance and sensitivity to noise within the data. For this analysis we focused on bias, i.e. was there a direction of change when data were removed from the complete models, and the variability of the variance estimates as data were removed. Both models performed similarly with relatively low bias across all examined parameters and derived quantities (Table 2.21 and Table 2.22). The highest bias was observed in the 2022

ABC, which remained below 9% for both models. Examination of the variance estimates show the largest difference in the variance of the 2022 spawning biomass and ABC with Model 21.1 having the smallest variance of the variance estimates as data were removed. In both models the removal of the 2021 and 2016 data appear most impactful (Fig. 2.58 and Fig. 2.59). The 2016 dataset did not have a bottom trawl survey, but did include a longline survey. The 2016 longline survey remained high despite a dropping of abundance in the 2015 bottom trawl survey and subsequent drop in the 2017 longline survey. Taking the 2016 data out of the model allows it to more easily fit the lower abundances in the 2015 bottom trawl survey and lower 2017-2021 estimates in both surveys, causing reduced estimates of all of the later biomass estimates as well as reference points. In addition the removal of the 2016 data decreases the variability in all of the biomass estimates in both models. In contrast removing the 2021 data caused a sharp increase in spawning biomass for both of these models for 2022, as well as a sharp increase in the unfished spawning biomass. Without the 2021 data both models were expecting a higher abundance in 2021 than observed in the 2021 indices and thus higher biomass estimates for 2022.

<u>Model 21.2</u>

Model 21.2 differs from the other two models presented this year in having temperature dependent growth and heatwave dependent natural mortality and recruitment and the addition of the age-o beach seine index. Direct comparison of the overall likelihoods for this model versus the other two is not viable as we have additional data added to Model 21.2. However we can compare individual components. The changes to Model 21.2 deleteriously impact the fit to the bottom trawl and longline survey indices with an increase in negative log likelihoods compared to Model 19.1 for both indices (Table 2.17 and Table 2.18). The change in fit to the indices was most pronounced in the degradation of fit to the bottom trawl survey with an increase of 9.29 LL from Model 19.1 and 0.45 LL from Model 21.1. The fit to the longline survey in Model 21.2 was an increase of 2.63 LL from Model 19.1 and 11.77 LL from Model 21.1. The Model 21.2 fit to the bottom trawl survey was not visually distinguishable from the Model 21.1 fit (Fig. 2.53).

Model 21.2 with the inclusion of temperature dependent growth provides a superior fit to the conditional age-at-length data over both other models. This was an improvement of 30.65 LL from Model 19.1 and 28.83 from Model 21.1. The length composition data fits are comparable among models with Model 21.2 having a better fit to the index length composition data by 6.11 LL and Model 21.1 having a better fit to the fisheries length composition data by 12.03 LL. With heatwave dependent recruitment and natural mortality, as well as the addition of the age-0 beach seine index Model 21.2 has a lower recruitment deviance, an improvement of 8.66 LL from Model 19.1 and 3.6 LL from Model 21.1 (Table 2.17).

Model 21.2 had acceptable retrospective evaluation results from the 10-year peals (Fig. 2.57). Compared to the other two models presented the results were mixed with Model 19.1 and Model 21.1 having lower Mohn's ρs for spawning biomass (Table 2.19) and Model 21.2 having a lower Mohn's ρ for age-0 recruitment than the other two models. The Woods Hole ρ values for the spawning stock biomass was the nearly the same for Model 19.1 and Model 21.2 which had lower bias than Model 21.1, but Model 21.2 outperformed both other models in age-0 recruitment. All retrospective bias for all three models were positive for both spawning stock biomass and age-0 recruitment.

Model 21.2 performed reasonably well in a jitter analysis with a CV of 0.05 and 50 runs but not as well as the other two models (Table 2.20). Given the increased complexity of Model 21.2 this would be expected. For Model 21.2 a total of 38 of the 50 jitter runs converged with 61% of the converged models resulting in estimates at the lowest MLE from the accepted models. There were no jitter runs from Model 21.2 at a lower objective value than the final model.

The leave-one-out analysis results for Model 21.2 although similar to the other two models was an improvement with lower bias in estimates of spawning biomass and ABC and lower variability of the variance for these derived quantities as well (Table 2.21 and Table 2.22). For the other parameters and derived quantities examined the difference was less than a 1% in relative bias among models. Although

2016 remained an influential data point as in the other two models presented, 2021 data were less influential on 2022 ABC, SSB, and unfished SSB (Fig. 2.60). With the removal of the 2021 data the variance of the 2022 ABC, 2022 SSB, and unfished biomass was increased with the removal of the 2021 data however the values remained stable compared to the other two models presented.

Model 21.2 is the only model being put forward this year with ecosystem links. The SSC requested a more thorough examination of these link parameters and the strength of the relationships. To that end we performed three related, but separate examinations. The first was to examine the MLE variance estimates obtained through the square root of the inverse Hessian, for the ecosystem-linked parameters. As they were parameterized a value which was not significantly different from 0.0 would indicate a weak relationship. All of the ecological link parameters for Model 21.2 except ϕ, the link parameter on the von Bertalanffy growth K parameter, were significantly different from 0.00 at an $\alpha = 0.05$ (Table 2.23). In addition an MCMC was run of Model 21.2 with 1 million draws, 10,000 burn in, and thinning at 2,000. The overall results (Table 2.23 and Fig. 2.61) were the same as those obtained from the square root of the inverse hessian approach with only the ϕ link parameter on K not being significantly different from 0 at α=0.05. The MCMC results show that the environmental link relationship to L_2 and R_0 were weaker than those for M, L_1 and Q_{BT}, but still measurably different from 0. The final examination was one suggested by the SSC. Here we placed normal priors (μ =0) with various levels of variance to test the strength of the relationships. We limited this examination to the new environmental link parameters, excluding the link on Q_{BT}. The results were the same as those obtained from the inverse hessian and MCMC approaches (Table 2.24). The strongest relationship held for the environmental links to M and L_1, followed by weaker relationships to L_2 and R_0, and finally a very weak relationship for the link to K with only a minor change in the objective function (+0.36 LL) from the uninformed prior even with the highly influential prior (CV=0.1).

Note that in running Model 21.2 without the K-link parameter ϕ we found very little difference in model results (Fig. 2.62) and given our limited time to conduct this assessment the ϕ parameter was retained in the final model.

Selection of Final Model

Model 21.1 was demonstrably better fit to the overall data than Model 19.1. This improvement was balanced on the change in fit between the bottom trawl survey and the longline survey as well as an improvement to the overall fit to the length composition, conditional age-at-length data, and recruitment deviations. The difference in retrospective bias shows that both models were within acceptable limits. The LOO analysis for these two models show they were comparable, with little difference, however both models show a substantial bias in unfished spawning biomass, 2022 spawning biomass and 2022 ABC estimates from the full model when the 2021 data were removed. Of the two models Model 21.1 provides a better fit overall to the data without a substantial change in other performance measures.

The choice between Model 21.1 and Model 21.2 was not as clear. The addition of the beach seine data make the fits to the indices not as straight forward. Model 21.2 has a worse fit to the indices which is expected with the addition of the new data, however the improvement of fit to the conditional age-at-length and recruitment data were substantially greater than the increase in LL due to the degradation of fit to the indices. The retrospective analysis shows that both models are within acceptable limits and therefore not very informative for choosing between models. The LOO analysis shows that Model 21.2 was more stable with the removal of the 2021 data and had less bias overall in the estimates of unfished spawning biomass and ABC.

All three models performed well and provide similar management advice, the authors chose Model 21.2 as this year's base model because of the strength of the relationships found for the environmental links. In addition Model 21.2 results were less sensitive to the end year data and appears to be less sensitive to removal of individual data points.

Model 21.2 Diagnostics

Survey indices

Model 21.2 fit to the NMFS bottom trawl survey was similar to previous base model fits (Fig. 2.53), 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. Model 21.2 differs from last year's model in delaying the peak abundance to 2016 instead of 2015. This was due to the 2016 longline survey RPN remaining high through 2016. Comparison of total biomass predictions and AFSC bottom trawl survey biomass estimates were closely matched for the 1996-2021 values with total biomass predictions at 1.01 times the survey biomass estimate (Fig. 2.63). The bottom trawl log catchability for survey abundance was well fit (Fig. 2.64) at 0.063 (ln(1.05)) with a standard deviation of 0.08.

Model 21.2 fits the AFSC longline survey index well (Fig. 2.53) with a base log catchability of 0.073 (ln(1.08)) and a standard deviation of 0.059. 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 continues to not be 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 expected 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 was at a lower abundance than modeled.

Growth and maturity

Model 21.2 has three environmental link parameters directing growth as a factor of June CFSR temperatures. The results suggest an increase in growth with warmer temperatures (Fig. 2.65 and Fig. 2.66). The largest association appears to be in the link from temperature to L_1 and L_2 (Fig. 2.67). This results in larger and heavier fish with warmer temperatures and smaller and lighter fish at cooler temperatures (Fig. 2.65 and 2.66). The model shows a cohort effect as cohorts that start in warmer years continuing to be larger on average throughout their life. The strength of this relationship was described in the improved fit to the conditional age at length data described above. 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 and with the temperature dependent growth, interannual variability in age at length appears to be well captured (Fig. 2.72). Mean length and weight at age from Model 21.2 are provided in Table 2.29. Because Model 21.2 treats maturity as a factor of length, increased growth of cohorts hatched in warm years also results in earlier maturity of these cohorts (Fig. 2.73).

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 were able to examine how consistent the model expectations were to the data (Fig. 2.74). The aging bias adjustment made in the 2019 model and carried forward last year's and this year's models 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.

<u>Length composition</u>

Selectivity curves in Model 21.2 do not differ substantially from previous year's selectivity. Selectivity was allowed to be dome-shaped for the pot fishery, the longline survey and the bottom trawl survey prior to 1996 (Fig. 2.51, Fig. 2.52, and Fig. 2.75). Overall model predictions of the length compositions closely match the data for all components (Fig. 2.76). For the trawl fishery the model predictions (Fig. 2.77 and Fig. 2.78) 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. The 2020 mean length was small, and not fit well. These data were dominated by lengths from the state and non-cod target fisheries. Predictions of the longline fishery length composition (Fig. 2.79 and Fig. 2.80) 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 through 2021 were not well fit in the model and the model underestimated the mean length. Predictions of the pot fishery length composition (Fig. 2.81) 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 2020-2021 length composition is not well fit, although the mode was modeled correctly the model predicts much smaller fish than what was observed. This 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 these years. 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.

Model 21.2 matched the NMFS bottom trawl survey length composition data mean lengths well (Fig. 2.82), 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. The 2021 length composition appears to underestimate the size of cod for this year with the predicted mode and mean approximately 5 cm below the observer mode and mean.

Although the selectivity for Model 21.2 AFSC longline survey length composition data (Fig. 2.83) 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.

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 21.2.

Biomass

Estimates of total biomass were on average 101% higher than the NMFS bottom trawl survey total biomass estimates. Total biomass estimates show a long decline from their peak of 845,182 t in 1988

(Table 2.30 and Fig. 2.84) to 249,486 t in 2006 and then an increase to another peak in 2014 of 486,477 t then decrease continuously through 2020 to a time series low of 141,337 t. With improved recruitment in 2016 and decrease in natural and fishing mortality in 2018 and 2020 total biomass is expected to have begun increasing again in 2021. Spawning biomass (Table 2.30 and Figure 2.85) shows a similar trend of decline since the late 1980s with a peak in 1989 at 275,204 t to a low in 2008 of 56,418 t. There was then a short increase in spawning biomass coincident with the maturation of the 2005-2008 year classes through 2014 to 102,241 t, after which the decline continued to lowest level of 34,006 t in 2020. The spawning biomass is projected to have increased in 2021 and continue to increase in 2022.

Numbers at age and length are shown in Figure 2.86 and given in Appendix 2.5 and Appendix 2.6 available online at:

Projection A

https://apps-afsc.fisheries.noaa.gov/Plan_Team/2021/GOAPCOD2021Appendix2.5.xlsx

Projection B

https://apps-afsc.fisheries.noaa.gov/Plan_Team/2021/GOAPCOD2021Appendix2.6.xlsx

Recruitment and Numbers at Age

Model 21.2 has R_0 linked to the spring heatwave index. The increase in heatwave °C days reduced R_0 such that recruitment drops with an increase in the index (Fig. 2.87). The recruitment predictions in Model 21.2 (Table 2.31, Fig. 2.88, and Fig. 2.89) show large 1977-1979,1981-1985,1987-1992, 2005-2006, 2008, and 2011-2013 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} = 0.32 and $\sigma_{1984\text{-}1990}$ > 0.12). Between 1991 and 2010 the average recruitment was estimated at 0.496 billion, 52% lower than the 1977-1989 mean recruitment of 0.758 billion and 15% lower than the 1977-2019 mean recruitment of 0.587 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 2.32). 2017 had the highest total exploitation rate of the time series at 0.291. 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. 2.90). In 2018 through 2020 there was a sharp decrease in fishing mortality coincident with the drastic cuts in ABC and closure of the federal directed fishery in 2020. In 2021 with the reopening of the federal fishery F once again increased, but remained lower than observed in the previous decade prior to 2017. In retrospect the phase plane plots (Fig. 2.91 and 2.92) show that F was estimated to have been above the ABC control rule advised levels for 2008 and 2017 and biomass was below $B_{35\%}$ in 2008 and again 2017 through 2021, and projected to continue to be below through 2023. 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.

MCMC results

MCMC were conducted with 1,000,000 iterations with 10,000 burn-in and thinned to every 2000th iteration leaving 490 iterations for constructing the posterior distributions. Geweke (1992) and Heidelberger and Welch (1983) MCMC convergence tests, as implemented in the *coda* R library

(Plummer *et al.* 2006), concluded adequate convergence in the chain. Posterior distributions of key parameters appear well defined and bracket the MLE estimates and are provided in an Excel file here:

https://apps-afsc.fisheries.noaa.gov/Plan_Team/2021/GOAPCOD2021Appendix2.7.xlsx

Results from the MCMC are consistent with the MLE estimates (Fig. 2.93 and Fig. 2.94) Model 21.2 predicts an 8% probability that the stock was below $B_{20\%}$ in 2021 and a < 0.1% probability the stock was below $B_{17.5\%}$. For 2022 Model 21.2 Projection B (see below) predicts a 3% probability of the stock being below $B_{20\%}$ and < 0.1% probability of it being below $B_{17.5\%}$. For 2023 in Model 21.2 under projection B (see below) there is a 22% probability of the stock being below $B_{20\%}$ and 0.2% probability of it being below $B_{17.5\%}$ (Fig 2.95 and Fig. 2.96).

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 21.2:

Reference point:	$B_{35\%}$	$B_{40\%}$	$B_{100\%}$
Spawning biomass:	56,849 t	64,970 t	162,426 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 (2016-2020). This apportionment of catch given the projected selectivity for each gear results in estimates of $F_{35\%}$ and $F_{40\%}$ of 0.91 and 0.73 in aggregate.

Specification of OFL and Maximum Permissible ABC

The projections for Model 21.2 post 2021 are dependent on assumptions of future climate conditions. For projections and setting harvest specification for 2022 and 2023 we present two different climate scenarios. Projection A assumes temperature and heatwave conditions will be the average of the 1977-2021 conditions (mean CFSR temperature for 0-20cm cod anomaly at 0.127 °C) and Projection B assumes temperatures and heatwave conditions will be the average of the 2010-2021 conditions (mean CFSR temperature for 0-20cm cod anomaly at 0.278 °C).

For both projections spawning biomass for 2021 is estimated by this year's model to be 39,873 t at spawning. This is below the $B_{40\%}$ value of 64,970 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 2022 and 2023 as follows (2023 values are predicated on the assumption of the full TAC and GHL being taken 2021 and that the 2022 catch will be at maximum ABC for each projection):

Projection A:

Units	Year	Overfishing Level (OFL)	Maximum Permissible ABC
Harvest amount	2022	29,131	24,043
Harvest amount	2023	27,715	22,882
Fishing mortality rate	2022	0.54	0.44
Fishing mortality rate	2023	0.52	0.42

The age 0+ biomass projections for 2022 and 2023 from this year's model are 159,837 t and 185,745 t, respectively.

Projection B:

Units	Year	Overfishing Level (OFL)	Maximum Permissible ABC
Harvest amount	2022	28,000	23,066
Harvest amount	2023	22.072	18,170
Fishing mortality rate	2022	0.54	0.44
Fishing mortality rate	2023	0.57	0.38

The age 0+ biomass projections for 2022 and 2023 from this year's model are 160,755 t and 169,832 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 2002 – 2021 are provided in Table 2.33.

For 2022 the spawning stock biomass is projected to be above $B_{20\%}$, and despite a drop in spawning biomass in 2023 is projected to remain above B20% in 2023 in both Projection A and Projection B. The authors chose to show both Projection A and Projection B for determining the 2022 and 2023 management values. The standard operating rules for Tier 3 stocks under non-ecosystem linked models would be Projection A. However in light of the warming trend observed over the past decade and projections by the IPCC that this warming trend will continue and worsen in the next decade under all current projections (IPCC, 2021) Projection B would be more a more conservative approach. Under Projection A the maximum ABC for 2022 is 24,043 t and for 2023 is 22,882 t. Under Projection B the maximum ABC for 2022 is 23,066 t and for 2023 is 18,170 t.

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

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

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

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

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

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

Assessment considerations. The GOA Pacific cod assessment does not show a strong retrospective bias, 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 three surveys the AFSC bottom trawl survey, AFSC longline survey, and the age-0 beach seine survey. The two adult 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 2016-2021 shows substantial modeling uncertainty. We rated the assessment-related concern as level 1, normal, but still have concerns 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 or steady. This following several years of poor recruitment in 2014-2019 and increased natural mortality during the recent marine heatwaves 2014-2016 and 2019. Given the assumptions of 2010-2021 average conditions it is expected that recruitment will be at 87% of the 1977-2019 average. With this near average recruitment, it is expected that the stock status will improve, but will remain below $B_{40\%}$. There appears to be an increase in the 2020 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. Currently for the projection Model 21.2 the 2020 year class is assumed to be below average. Overall, we would rate our concern as level 1 normal. This is a reduction in concern from last year as environmental conditions are now being considered in estimation of recruitment, growth, and natural mortality within the model and Model 21.2 therefore should be adequately conservative.

Environmental/Ecosystem considerations. Appendix 2.1 provides a detailed look at environmental/ecosystem considerations specific to this stock within the ecosystem and socioeconomic profile (ESP). Broad-scale information on environmental and ecosystem considerations are provided by the Gulf of Alaska Ecosystem Status Report (GOA ESR; Ferriss et al., 2021). The text below summarizes ecosystem information related to GOA Pacific cod provided from both the ESP and GOA ESR.

We scored this category as level 1 (normal concern) for Pacific cod given moderate thermal conditions for adults and larvae, above average retention with mesoscale eddies, moderate to good adult cod prey base (with potential competition for planktivorous juveniles), and potentially unchanged, low levels of predation. The GOA population is still at low levels since the 2014-2016 marine heatwave and the 2021 age-0 cod appear low in abundance. However, the 2020 year class has been observed in high numbers as age-1s in 2021 surveys, and environmental conditions are cautiously favorable for them to persist into next year (cooler ocean temperatures, moderate to good prey base, average to below average predation and competition pressure).

Environmental Processes: It is reasonable to expect that 2021, and predicted 2022, average deeper ocean temperatures would provide good spawning habitat and the average to cooler surface temperatures would contribute to good pelagic conditions for cod during a time when they are growing to a size that promotes over winter survival. However, relatively low abundance of age-0 cod were observed in the EcoFOCI spring survey (Deary, 2021), potentially reflecting poor spring larval feeding conditions. Low abundance of larval cod, in addition to larval pollock and northern rock sole, has been observed in previous years that had warmer ocean temperatures and average to late phytoplankton bloom timing (e.g., 2019, 2016). While 2021 was not characterized as a ‘warm year’, the WGOA spring surface temperatures were above average and WGOA bloom timing was average with relatively low chlorophyll-a abundance (Watson 2021). Ocean temperatures at the surface and at depth on the shelf were around the long-term average in 2021 (not a marine heatwave year, Watson 2021; AFSC Bottom Trawl Survey, Laman 2021; AFSC EcoFOCI survey, Rogers 2021; Seward Line Survey, Danielson 2021), although Western GOA started the year with warmer surface waters (satellite data; Watson 2021) and there was above average warmth (5.2°C) at 200m depth along the outer edge of the shelf during the summer (AFSC Longline Survey; Siwicke 2021). Numerous temperature time series showed signs of cooling from previous surveys (returning to average from recent marine heatwave years 2014-2016, 2019) at the surface and at depth and 2022 surface temperatures are predicted to continue cooling, in alignment with La Niña conditions and a negative Pacific Decadal Oscillation. Mesoscale eddy kinetic energy in the Kodiak region remained above average, down from 2020, implying sustained retention in the area and enhanced cross-shelf transport to suitable nearshore nursery environments. The center of gravity in the northeast direction for the GOA Pacific cod population has decreased from 2019, while the area occupied estimate remains consistent and high, implying a shift in distribution toward the southwest and a fairly large population spread. These trends may also reflect a shift in the spatial clustering of the stock concurrent with the change in biomass.

Prey: Planktivorous foraging conditions were moderate and forage fish abundance was moderate to good, but regionally variable across the GOA in 2021. Both juvenile and adult Pacific cod eat euphausiids, polychaetes, forage fish (including walleye pollock), amphipods and crangonid shrimp. The average condition (weight at a given length) of cod was at the long-term average in 2021, a decrease from 2019 that occurred primarily in Eastern GOA (Kodiak was the one region that had positive condition) (Bottom Trawl Survey, O’Leary 2021). When split into juveniles and adults, condition was still above average for adults but below average for juveniles. Most other groundfish continued to have negative condition, a trend persisting since 2015. This difference potentially indicates that Pacific cod were more successful at meeting energetic demands via foraging than the other species. During 2021, euphausiid densities were above average in Icy Strait the Eastern GOA and of lower densities around Kodiak in May (Hopcroft and Coyle 2021, Kimmel 2021, Fergusson. 2021). Forage fish had mixed to positive trends, including a continued increase in herring spawning stock biomass (Southeastern Alaska and potentially other regions in GOA; Hebert 2021), a continued moderate presence of sand lance in moderate in piscivorous seabird diets (Middleton Island), and reduced abundance of capelin (a trend since the 2014-2016 marine heatwave) (AFSC summer Acoustic Trawl Survey & AFSC Bottom Trawl Survey: McGowan 2021, Middleton Island seabird diets: Hatch 2021). In general, piscivorous seabirds had average to above average reproductive success, suggesting foraging success (Drummond 2021). Tanner crab around Kodiak (Eastern GOA crab status is not known) have been increasing (ADF&G trawl survey, Worton 2021) and shrimp have been increasing around Chirikof, Yakutat, and southeastern GOA regions, but declining around Kodiak over the past 5 years (AFSC Bottom Trawl Survey, Palsson 2021).

Predators and Competitors: There is no cause to suspect increased predation pressure on Pacific cod. In general predators of Pacific cod (including Pacific cod, halibut, salmon shark, northern fur seals, Steller sea lions, harbor porpoises, various whale species, and tufted puffin) appear to be stable or at relatively low population levels. The most recent data available suggest that Steller sea lion trends have stabilized (EGOA) or continued to be at low levels (Western GOA) in the Gulf of Alaska. Pacific halibut, large Pacific cod (representing cannibalistic predation) are estimated at low biomass. In general, apex fish predators in the GOA are at relatively low abundances (including cod and arrowtooth flounder, although sablefish are increasing in abundance) (Whitehouse 2021). Planktivorous juvenile cod may experience moderate levels of competition from recent strong sablefish year classes (2016 and 2018, although they are moving to the slope as they mature), and high returns of pink salmon (Murphy 2021, Shaul 2021).

Fishery Performance. Where data were available catch per unit effort measures in the GOA fisheries showed mixed signals. Condition of fish in the fisheries for 2021 were above average where available. It should be noted that catch levels and fishery participation have been low over the past 4 years in comparison with previous years. Bycatch in other fisheries still remain low compared to prior to the 2014-2016 marine heatwave.

We 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 1: Normal	Level 1: Normal	Level 1: Normal	Level 1: Normal	Level 1: Normal

The overall score of level 1 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 2021 (Fig. 2.99), the area-apportioned ABCs for the two projections of Model 21.2 would be:

Projection A:

	Western	Central	Eastern	Total
Random effects area apportionment	30.3%	60.2%	9.5%	100%
2022 ABC	7,285	14,474	2,284	24,043
2023 ABC	6,933	13,775	2,174	22,882

Projection B:

	Western	Central	Eastern	Total
Random effects area apportionment	30.3%	60.2%	9.5%	100%
2022 ABC	6,999	13,905	2,194	23,099
2023 ABC	5,505	10,938	1,726	18,170

Harvest and Recruitment Scenarios and Projection Methodology

A standard set of projections is required for each stock managed under Tiers 1, 2, or 3 of Amendment 56. This set of projections encompasses seven harvest scenarios designed to satisfy the requirements of Amendment 56, the National Environmental Policy Act, and the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA). Prior to this assessment, the standard harvest scenarios were made using the AFSC's "Proj" program. Beginning this year, however, the projections have been made within SS. Year-end catch for 2021 was estimated to be 23,627 t, equal to the 2021 ABC. In each subsequent year, the fishing mortality rate is prescribed on the basis of the spawning biomass in that year and the respective harvest scenario.

Selectivity used in the projections was the mean selectivity over 2000-2019 (provided for Projection A in the Appendix 2.5 and for Projection B in Appendix 2.6), growth, mortality, and recruitment was based on the ecosystem link relationships fit in the model and environmental conditions assumed post-2021. There were two projections examined both assumed constant conditions post-2021. Projection A assumed the environmental conditions will be at the 1977-2021 mean of each environmental indicator used in the model. Projection B assumed the environmental conditions will be at the 2010-2021 mean of each environmental indicator used in the model. The Stock Synthesis data and forecast files have been provided for all models and projections in the appendices as zip files (see above).

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 2021, 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 2017-2021 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 2021 and above its B_{MSY} level in 2031 under this scenario, then the stock is not overfished.)

Scenario 7: In 2022 and 2023, F is set equal to max F_{ABC}, and in all subsequent years, F is set equal to F_{OFL}. (Rationale: This scenario determines whether a stock is approaching an overfished condition. If the stock is 1) above its MSY level in 2023 or 2) above 1/2 of its MSY level in 2023 and expected to be above its MSY level in 2033 under this scenario, then the stock is not approaching an overfished condition.)

Scenarios 1 through 7 were projected 15 years from 2021 in Model 21.2 for Projection A (Table 2.36) and Projection B (Table 2.37). Note that the scenarios are also presented for Model 19.1 (Table 2.34) and Model 21.1 (Table 2.35) for comparison purposes.

<u>Projection A</u>

Scenarios 3, 4, and 5 (no fishing) project the stock to be below $B_{35\%}$ until 2025, scenarios 1, 2, 6, and 7 have the stock below $B_{35\%}$ until 2026. Fishing at the maximum permissible rate indicate that the spawning stock (Fig. 2.97) will be below $B_{35\%}$ in 2022 through 2025 due to poor recruitment and high mortality in 2015-2017 and 2019. Under an assumption of environmental conditions at the 1977-2021 mean, the stock recovers above $B_{35\%}$ by 2026.

Our projection model run under these conditions indicates that for Scenario 6, the GOA Pacific cod stock although below $B_{35\%}$ in 2022 at 39,873 t will be above its MSY value in 2031 at 65,191 t and therefore would not be classified as overfished.

Projections 7 with fishing at the OFL after 2022 results in an expected spawning biomass of 65,175 t by 2033.

Under Scenarios 6 (Fig. 2.97) and 7 for Projection A of Model 21.2 the Gulf of Alaska Pacific cod stock would not currently be considered overfished, nor would it be approaching an overfished status.

<u>Projection B</u>

Scenarios 4 and 5 (no fishing) project the stock to be below $B_{35\%}$ until 2026, all other scenarios have the stock below below $B_{35\%}$ for the duration of the projection. Fishing at the maximum permissible rate indicate that the spawning stock (Fig. 2.98) will be below $B_{35\%}$ in 2021 through the end of the projection and stabilizes at $B_{29\%}$, but for the duration of the projection does not rise above $B_{29\%}$ due to the reduction in recruitment and increase in natural mortality tied to environmental conditions set at the mean for 2010-2021.

Projection B indicates that for Scenario 6 the GOA Pacific cod stock is currently below $B_{35\%}$ in 2022 at 39,873 t and will remain below its MSY value through 2031 (44,469 t, or $B_{27\%}$) and would therefore be classified as overfished.

Projections 7 with fishing at the OFL after 2022 results in an expected spawning biomass of 44,472 t in 2033 and therefor below MST. Projection B therefore finds the stock as approaching an overfished condition.

Under Scenarios 6 (Fig. 2.98) and 7 of Model 21.2 under Projection B the projected spawning biomass for Gulf of Alaska Pacific cod would be considered currently overfished and would be approaching an overfished status.

The 2020 OFL given Model 21.2 would have produced a sum of apical F of 0.3564 in 2020.

The 2021 OFL given Model 21.2 would have produced a sum of apical F of 0.4744 in 2021.

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 indices and parameters to improve the stock assessment (e.g. mortality, growth, maturity),

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

3) **Resolving stock spatial structure, migration patterns, and connectivity** based on tagging and new genetics/genomics approaches. Research was discussed that covered a wide range of methods, including understanding early life history, satellite 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 Western GOA and Central GOA will generate better estimates of growth and survival for juvenile cod in the stock assessment model. Expanding the temporal scale of Kodiak surveys would help identify the timing of settlement to nearshore habitat, validate a spatial-temporal spawning model and understand overwintering ecology/survival. Larger projects (3-5 years) would include linking observations of spawning - larvae - juvenile surveys to identify climate-driven reproductive output.

Tagging to determine cod movement

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

Improved stock assessment modeling

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

Survey

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

Genetics

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

Maturity

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

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Tables

Table 2.1. 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 2021 by jurisdiction and gear type (as of 2021-10-04)

	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	3,427	459	30	0	3,916	50	1,780	488	2,318	6,233
2021	5,257	2,967	2,653	52	10,930	276	4,229	1,068	5,573	16,502

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 2021 is current through 2021-10-04 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	6,233	6,431	14,621	17,794	2,537
*2021	16,502	17,321	23,627	28,977	5,864

*As of 10/04/2021

Table 2.4. History of GOA Pacific cod allocations by regulatory area (in percent) for 1991-2021 and proposed for 2022. 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
2003	38	56	6
2004	35.3	56.5	8.2
2005	35.3	56.5	8.2
2006	38.54	54.35	7.11
2007	38.54	54.35	7.11
2008	38.69	56.55	4.76
2009	38.69	56.55	4.76
2010	34.86	61.75	3.39
2011	35	62	3
2012	32	65	3
2013	38	60	3
2014	37	60	3
2015	38	60	3
2016	41	50	9
2017	41	50	9
2018	44.9	45.1	10
2019	44.9	45.1	10
2020	33.8	57.8	8.4
2021	33.8	57.8	8.4
2022	*30.3*	*60.2*	*9.5*

Table 2.5 Estimated retained-and discarded GOA Pacific cod (*as of 2021-10-04)

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	1,492	4,741	6,233
*2021	1,237	15,266	16,502

Table 2.6 – Weight of groundfish bycatch (t), discarded (D) and retained (R), for 2017 – 2021 for GOA Pacific cod as target species (AKFIN; as of 2021-10-04). For 2018 and later the discard of halibut bycatch is no longer reported in the AKFIN tables.

	2017		2018		2019		2020		2021		Grand Total
	D	R	D	R	D	R	D	R	D	R	
Bering flounder									0.00006		0.00
flounder, Alaska plaice	0.03		0.06		0.06				0.00009		0.15
flounder, arrowtooth	226.87	262.27	89.91	5.11	220.24	17.13	50.25	0.26	41.32	0.18	913.54
flounder, general		1.46	0.11						0.00004	0.003	1.57
flounder, starry	3.55	2.66	0.17		0.06				0.0001		6.44
greenling, atka mackerel	351.62	31.80	3.01	0.24	32.79	0.24			2.88	0.01	422.59
groundfish, general	5.85		3.63		2.96		3.31		5.07		20.82
halibut, Pacific	11.04	24.67	1.81	11.35	1.40	4.31		0.21	2.75	5.13	62.67
Kamchatka flounder	11.77	0.04	0.03	0.00	0.15	0.01	0.0008		0.02		12.02
octopus, North Pacific	26.58	196.91	10.25	142.35	39.70	192.28	0.03	12.01	9.42	9.78	639.31
Pacific sleeper shark	1.79		6.27		10.19		0.20		0.36		18.81
perch, Pacific ocean	46.27	30.56	0.07	0.01	0.16	19.37	0.01	7.76	0.16	1.48	105.85
pollock, walleye	316.62	485.93	24.59	71.58	71.50	31.05	11.37	4.38	219.19	18.92	1255.13
rockfish, bocaccio											0.00
rockfish, canary		0.06		0.15	0.11	0.05	0.002	0.03		0.12	0.52
rockfish, china		0.02		0.00		0.01	0.002		0.00022	0.002	0.03
rockfish, copper		0.01		0.00		0.01				0.004	0.02
rockfish, dusky	77.72	17.34	3.45	3.94	2.34	5.44	0.00001	0.81	0.45	1.92	113.41
rockfish, harlequin	0.64		0.02						0.00		0.66
rockfish, northern	44.34	9.22	3.57	1.40	3.33	0.25		0.00	0.03	0.20	62.34
rockfish, other	15.88	0.04	3.84		0.74		0.06		0.44		21.00
rockfish, quillback	1.54	7.67	0.07	2.10	0.90	2.98	0.01	0.33	0.28	6.83	22.71
rockfish, redbanded	1.38	0.53	0.61	0.02	0.07	0.02	0.27	0.07	0.01	0.03	3.01
rockfish, redstripe	0.25	0.13		0.00		0.00			0.003	0.01	0.39
rockfish, rosethorn		0.01	0.01	0.00	0.04				0.00001	0.01	0.07
rockfish, rougheye	8.16	2.46	5.95	1.72	0.62	1.22	0.03	0.22	2.03	0.80	23.21
rockfish, sharpchin									0.00		0.00
rockfish, shortraker	5.25	2.60	7.61	0.31	1.17	0.18	0.04	0.03	4.52	0.38	22.09
rockfish, silvergray	0.08	0.36	0.06	0.10	0.01	0.04		0.03	0.00	0.32	1.00
rockfish, thornyhead (idiots)	11.27	24.59	0.52	1.99	0.61	1.16	0.02		0.01	0.60	40.77
rockfish, tiger	0.16	0.22	0.03	0.03	0.16	0.05			0.004	0.20	0.85
rockfish, widow					0.15				0.001		0.15
rockfish, yelloweye (red snapper)	44.57	34.44	1.55	15.88	3.34	13.45	0.10	0.23	3.90	4.83	122.29
rockfish, yellowtail				0.01						0.01	0.02
sablefish (blackcod)	84.53	22.55	55.95	2.88	36.44	53.04	5.32	24.37	48.54	11.33	344.95
sculpin, bigmouth	16.51		0.36		1.18						18.05
sculpin, general	0.52	2.76	0.05	0.32		0.24		0.20			4.09
sculpin, great	324.91		18.62		4.28		0.01				347.82
sculpin, other large	226.33		42.93		79.41		0.34				349.01
sculpin, plain	0.07				0.12						0.19
sculpin, warty											0.00
sculpin, yellow irish lord	407.76		21.33		15.90		0.22				445.21
shark, other					0.61	0.45			0.005	0.01	1.08
shark, salmon			0.45					0.28			0.73
shark, spiny dogfish	242.25		104.24	0.00	104.22	0.00	12.84		49.32		512.87
skate, Alaskan		1.14		0.07		0.08				0.004	1.29
skate, Aleutian		18.18		2.11		1.13				0.33	21.75
skate, big	459.55	148.88	54.26	20.65	133.55	29.95	3.26	1.10	145.74	45.13	1042.07
skate, longnose	321.56	91.79	30.54	39.74	50.28	35.96	4.44	3.05	59.76	36.20	673.32
skate, other	943.29	85.13	170.91	12.66	202.34	32.58	3.47	0.09	119.07	8.49	1578.03
skate, Whiteblotched		0.74		0.01							0.75
sole, butter	1.87	9.29	2.79		0.17	0.05			0.04		14.21
sole, dover	0.41	0.50	0.02	0.01	0.02		0.10	0.001	0.49		1.55
sole, English	2.46	0.98	0.54		3.50	0.46	0.06		2.08		10.08
sole, flathead	51.79	93.20	22.12	0.68	92.54	8.53	0.10	0.002	12.68	2.77	284.41
sole, rex	2.75	14.93	4.51	0.01	27.68	2.00	0.15		1.50	0.02	53.55
sole, rock	263.62	547.33	19.51	0.37	36.27	37.47		0.04	14.00	0.005	918.62
sole, sand									0.00002		0.00
sole, yellowfin	1.57	0.02	4.56	0.00	0.90						7.05
squid, majestic	0.02	0.11					0.001		0.00005	0.38	0.51
turbot, Greenland	6.56		0.00		0.47				0.003		7.03
Grand Total	4571.54	2173.52	720.91	337.81	1182.67	491.19	96.02	55.50	746.08	156.44	10531.67

Table 2.7 - Incidental catch (t or *birds by number*) of non-target species groups by GOA Pacific cod fisheries, 2017-2021 (as of 2021-10-14). 0.0 indicates less and 0.005 tons, a blank indicates no catch.

Species Group	2021	2020	2019	2018	2017
Benthic urochordata			0.233	0.006	1.368
Birds	*42*		*23*	*337*	*379*
Bivalves			0.234	2.737	0.922
Brittle star unidentified				0.000	0.041
Corals Bryozoans - Corals Bryozoans Unidentified	0.098	0.172	1.548	1.461	1.890
Eelpouts			0.187		0.110
Eulachon					0.004
Giant Grenadier	124.671		0.116	0.125	13.784
Greenlings	0.150		0.769	0.769	5.460
Grenadier - Rattail Grenadier Unidentified	0.090		0.146	0.594	0.029
Hermit crab unidentified	0.013		0.923	0.088	0.136
Invertebrate unidentified	0.008	0.109	0.083	0.082	0.626
Misc crabs	0.157		0.143	0.427	0.802
Misc crustaceans			0.000		0.008
Misc fish	29.114	7.708	15.349	31.400	177.898
Pacific Sand lance					0.013
Sculpin (ecosystem component in 2021)	128.18				
Scypho jellies	0.367	0.019	2.649		0.893
Sea anemone unidentified	0.296	0.002	1.313	2.633	12.569
Sea pens whips	0.020		0.456	0.335	0.798
Sea star	16.376	1.594	37.471	37.687	385.659
Snails	0.419	0.060	4.741	6.782	9.464
Sponge unidentified	0.038		5.357	2.094	2.338
State-managed Rockfish	1.822		3.446	2.798	68.548
Stichaeidae					0.275
urchins dollars cucumbers	0.014		0.315	0.393	4.562

Table 2.8 – Pacific cod catch (t) by trip target in Gulf of Alaska groundfish fisheries. *Data for 2021 is as of 10/04/2021.

Trip Target	2021	2020	2019	2018	2017
Arrowtooth Flounder	364	1,237	1,439	880	1,256
Atka Mackerel				2	5
Flathead Sole			18	2	2
Halibut	415	461	284	273	194
Other Species					2
Pacific Cod	12,431	2,330	11,977	12,009	45,318
Pollock - bottom	2,477	899	711	782	819
Pollock - midwater	50	141	100	65	68
Rex Sole - GOA		14	83	76	6
Rockfish	523	170	322	401	253
Sablefish	29	44	39	39	75
Shallow Water Flatfish - GOA	214	938	405	251	124
Grant Total	16,502	6,233	15,377	14,779	48,121
Non-Pacific cod trip target total	4,071	3,903	3,400	2,770	2,803

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 2021-10-29)

Source	2020	2019	2018	2017	2016
AFSC Annual Longline Survey	10,200	5,530	10,242	15,597	24,203
Bait for Crab Fishery	-	-	-	-	498
GOA Shelf and Slope Walleye Pollock Acoustic-Trawl Survey	-	-	-	53	-
Gulf of Alaska Bottom Trawl Survey	-	7,796	-	5,197	-
IPHC Annual Longline Survey	30,032	104,968	89,231	38,927	46,273
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	7,921	7,317	6,361	6,597	6,076
Prince William Sound Large Mesh Trawl Survey	-	-	-	164	-
Scallop Dredge Survey	-	-	-	-	-
Shumagin Islands Walleye Pollock Acoustic-Trawl Survey	-	-	23	11	-
Small-Mesh Trawl Survey	664	341	151	161	160
Sport Fishery	70,054	78,575	42,446	56,994	122,501
Spot Shrimp Survey	3	4	1	-	2
Summer Acoustic-Trawl Survey of Walleye Pollock in the Gulf of Alaska	-	70	-	-	-
Winter Acoustic-Trawl Survey of Walleye Pollock in Shelikof Strait and Vicinity	5	-	-	-	-
Total	118,879	204,601	148,489	124,971	199,713

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
2021	174,414	0.088	90,914	0.087

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	2021	30,830	0.162
2005	29,864	0.214			
2006	34,316	0.197			

Table 2.12 – Age-0 Pacific cod beach seine index (number/haul) and CVs.

Year	Number/haul	CV
2006	113.28	0.32
2007	7.42	0.39
2008	26.23	0.38
2009	26.58	0.57
2010	9.19	0.52
2011	30.58	0.41
2012	170.75	0.37
2013	8.14	0.43
2014	7.68	0.55
2015	1.04	0.96
2016	1.66	0.48
2017	74.71	0.32
2018	103.57	0.24
2019	1.84	0.58
2020	179.03	0.29
2021	20.2	0.28

Table 2.13 – IPHC Longline Relative Population Numbers (RPNs) and CVs for Pacific cod. A full survey was not conducted in 2020 due to COVID-19.

Year	RPN	CV	Year	RPN	CV
1997	16,315	0.054	2010	28,066	0.038
1998	12,357	0.060	2011	31,833	0.039
1999	14,591	0.055	2012	23,397	0.043
2000	12,256	0.062	2013	26,382	0.043
2001	16,585	0.058	2014	27,856	0.038
2002	15,379	0.058	2015	18,044	0.047
2003	16,073	0.058	2016	11,888	0.055
2004	16,335	0.066	2017	10,343	0.065
2005	15,757	0.049	2018	13,922	0.054
2006	18,114	0.050	2019	13,409	0.048
2007	22,269	0.044	2020	No survey	
2008	30,477	0.037	2021	17,194	0.075
2009	16,315	0.054			

Table 2.14 – ADFG trawl survey deltaGLM biomass index and CVs for Pacific cod.

Year	Index	CV	Year	Index	CV
1988	2.747	0.093	2005	1.037	0.092
1989	3.641	0.086	2006	0.892	0.088
1990	2.721	0.080	2007	1.064	0.080
1991	1.851	0.138	2008	1.230	0.066
1992	2.818	0.084	2009	1.238	0.070
1993	2.281	0.086	2010	1.049	0.072
1994	2.048	0.082	2011	1.347	0.070
1995	2.264	0.109	2012	2.550	0.090
1996	2.295	0.085	2013	1.924	0.098
1997	2.473	0.079	2014	1.320	0.097
1998	2.228	0.085	2015	1.191	0.096
1999	1.235	0.071	2016	0.821	0.112
2000	0.960	0.077	2017	0.867	0.106
2001	0.845	0.075	2018	1.132	0.097
2002	1.068	0.069	2019	0.953	0.092
2003	0.857	0.079	2020	1.347	0.090
2004	1.313	0.073	2021	1.079	0.091

Table 2.15 – CFSR bottom temperature index for 0-10 cm and 40-60 cm Pacific cod in June and marine heatwave cumulative intensity index (MHCI) in °C days for full year, winter (Jan-Mar & Oct-Dec), and spawning (Feb-Mar) for 1979-2021. Note that the MHCI for 2021 are only through October 16.

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

Table 2.16 – Number of parameters by category for model configurations presented.

	M19.1	M21.1	M21.2
Recruitment			
Early Init Ages	10	10	10
Early Rec. Devs (1977)	1	1	1
Main Rec. Devs (1978-2018)	39	39	39
Late Rec. Devs (2019-2021)	3	3	3
Future Rec. Devs. (2022-2036)	15	15	15
R_0	1	1	2
1976 R reg.	1	1	1
Steepness (H)	0	0	0
Natural mortality	2	2	2
Growth	5	5	8
Aging Bias	2	2	2
Catchability			
Q_{trawl}	1	1	1
$Q_{longline}$	2	2	2
Q_{Seine}	0	0	2
Initial F	0	0	0
Selectivity			
Trawl Survey	16	16	16
Longline survey	5	5	5
Trawl Fishery	58(39 dev)	58(39 dev)	58(39 dev)
Longline Fishery	39(24 dev)	39 (24 dev)	39 (24 dev)
Pot Fishery	8	8	8
Total	210	210	216

Table 2.17 – Likelihood components and derived quantities for models reviewed in 2021.

	Model 19.1	Model 21.1	Model 21.2
TOTAL_like	3567.18	3549.61	3547.06
Survey_like	-15.70	-16.00	10.54
Length_comp_like	1631.89	1623.05	1628.95
Age_comp_like	1939.10	1937.28	1908.45
Recruitment	-3.46	-8.52	-12.12
InitEQ_Regime	1.60	1.94	2.71
Forecast_Recruitment	5.68	5.20	1.97
Parm_priors_like	1.44	0.07	0.01
Recr_Virgin_millions	516.69	480.53	585.72
SR_LN(R0)	13.16	13.08	13.29
SR_LN(R0)_ENV_mult			-0.01
NatM (min)	0.50	0.49	0.48
NatM (max)	0.87	0.94	1.07
L_at_Amin	6.39	6.47	1.10
L at Amin ENV mult.			1.80
L_at_Amax	99.46	99.46	99.46
L at Amax ENV mult.			0.05
VonBert K	0.19	0.19	0.19
VonBert K ENV mult			-0.03
Q bottom trawl index	1.11	1.15	1.06
SSB unfished 1000's t	165.51	159.95	162.43
SSB unfished CV	0.075	0.076	0.075
F_{MSY} (sum apical F)	0.696	0.687	0.734
2022 F_{ABC} (sum apical F)	0.495	0.447	0.44
SSBratio 2021	0.27	0.25	0.23
SSBratio 2022	0.29	0.27	0.25
Root mean squared standard residual (RMSSR)			
Bottom trawl survey	1.47	1.82	1.85
Longline survey	1.89	1.73	1.93
Beach seine survey	NA	NA	0.99
Std.Dev(Ln(age-0)) 1978-2019	0.50	0.45	0.41

Table 2.18 – Likelihood components by fleet for all proposed models.

Label	ALL	FshTrawl	FshLL	FshPot	Srv	LLSrv	Seine	Model
Age_like	1939.10	409.58	448.61	378.12	702.80			19.1
Age_like	1937.28	409.94	448.17	377.92	701.25			21.1
Age_like	1908.45	401.97	441.67	374.19	690.62			21.2
Catch_like	2.25E-12	6.71E-13	7.60E-13	8.18E-13				19.1
Catch_like	3.35E-12	1.01E-12	1.14E-12	1.20E-12				21.1
Catch_like	2.25E-12	6.74E-13	7.65E-13	8.08E-13				21.2
Length_like	1631.89	492.69	319.11	375.57	205.37	239.15		19.1
Length_like	1623.05	487.66	315.63	374.19	205.47	240.09		21.1
Length_like	1628.95	490.73	319.19	379.59	201.03	238.42		21.2
Surv_like	-15.70				-10.87	-4.83		19.1
Surv_like	-16.00				-2.03	-13.97		21.1
Surv_like	10.54				-1.58	-2.20	14.32	21.2

Table 2.19 – Retrospective analysis results for 10-year peal.

	Spawning stock biomass			Age-0 Recruitment		
Model	Mohn's ρ	Woodshole ρ	RMSE	Mohn's ρ	Woodshole ρ	RMSE
19.1	-0.0002	0.0837	0.1159	0.1084	0.1195	0.1737
21.1	0.0440	0.1280	0.1476	0.0564	0.1339	0.1503
21.2	0.0557	0.0841	0.1230	0.0448	0.1034	0.1716

Table 2.20 – Jitter analysis, all jitters set with a jitter fraction of 0.05.

Model	Total #	Not Converged	At MLE	Below MLE	% converged at MLE
19.1	50	1	32	0	65%
21.1	50	3	37	0	79%
21.2	50	12	23	0	61%

Table 2.21 – Leave-one-out bias analysis results. MLE are the maximum likelihood estimated values. Mean bias is the average difference from the MLE. Note that the SSB is female spawning biomass.

	MLE			Leave-one-out		
Label	Value	σ	CV	Mean bias	Mean bias/MLE Value	Model
ABC_{2022}	32811	6335	0.193	2860.32	0.0872	19.1
ABC_{2022}	26759	5513	0.206	1873.84	0.0700	21.1
ABC_{2022}	23099	4345	0.188	1378.89	0.0597	21.2
$F_{40\%}$	0.696	0.054	0.077	0.0054	0.0078	19.1
$F_{40\%}$	0.687	0.056	0.086	0.0067	0.0098	21.1
$F_{40\%}$	0.734	0.051	0.082	0.0066	0.0090	21.2
M_{base}	0.499	0.019	0.038	0.0024	0.0049	19.1
M_{base}	0.499	0.022	0.044	0.0032	0.0066	21.1
M_{base}	0.369	0.020	0.054	0.0033	0.0090	21.2
$Q_{Bottom\ trawl}$	0.101	0.081	NA	-0.0045	-0.0041	19.1
$Q_{Bottom\ trawl}$	0.091	0.088	NA	-0.0060	-0.0052	21.1
$Q_{Bottom\ trawl}$	0.063	0.080	NA	-0.0055	-0.0052	21.2
$SSB_{Unfished}$	165508	12407	0.075	1755.86	0.0106	19.1
$SSB_{Unfished}$	159948	12114	0.076	1645.18	0.0103	21.1
$SSB_{Unfished}$	162426	12205	0.075	1178.41	0.0073	21.2
SSB_{2022}	48061	4476	0.093	1934.96	0.0403	19.1
SSB_{2022}	42763	4175	0.098	1354.25	0.0317	21.1
SSB_{2022}	39873	3651	0.092	1109.95	0.0278	21.2

Table 2.22 – Leave-one-out deviance analysis. MLE are the maximum likelihood estimated values. Mean SD are the standard deviation of the leave-one-out runs, SD of SD is the standard deviation of the LOO runs standard deviations, and CV is the SD of SD/Mean SD. Note that the SSB is female spawning biomass.

		Leave-one-out			
Label	**MLE σ**	**Mean SD**	**SD of SD**	**CV of SD**	**Model**
ABC_{2022}	6335	7335	2644	0.360	19.1
ABC_{2022}	5513	6298	1946	0.309	21.1
ABC_{2022}	4345	4961	1365	0.275	21.2
$F_{40\%}$	0.054	0.055	0.0014	0.026	19.1
$F_{40\%}$	0.056	0.057	0.0021	0.037	21.1
$F_{40\%}$	0.051	0.052	0.0026	0.051	21.2
M_{base}	0.019	0.019	0.0013	0.067	19.1
M_{base}	0.022	0.021	0.0008	0.039	21.1
M_{base}	0.020	0.020	0.0008	0.037	21.2
$Q_{Bottom\ trawl}$	0.081	0.082	0.0042	0.051	19.1
$Q_{Bottom\ trawl}$	0.088	0.088	0.0025	0.028	21.1
$Q_{Bottom\ trawl}$	0.080	0.080	0.0073	0.091	21.2
$SSB_{Unfished}$	12407	12595	352	0.028	19.1
$SSB_{Unfished}$	12114	12342	407	0.033	21.1
$SSB_{Unfished}$	12204	12275	159	0.013	21.2
SSB_{2022}	4476	4969	1226	0.247	19.1
SSB_{2022}	4175	4623	1024	0.221	21.1
SSB_{2022}	3651	4053	919	0.227	21.2

Table 2.23 – Model 21.2 MCMC and MLE estimates of environmental link parameters. The p column indicates the proportion of the MCMC with a value above (for negative parameters) or below (for positive parameters) 0.

		MCMC link posterior percentile				Link MLE		
Parameter	**Link**	**2.50%**	**50%**	**97.50%**	**p**	**Value**	**σ**	**Gradient**
M	η	1.0974	1.3865	1.7005	< 0.002	1.4098	0.14725	-3.91E-06
L_1	γ	1.3676	1.7659	2.1559	< 0.002	1.8003	0.20917	5.98E-07
L_2	ν	0.0023	0.0434	0.0854	0.02	0.0476	0.02208	2.68E-06
K	ϕ	-0.0893	-0.0235	0.0423	0.25	-0.0299	0.03510	1.32E-06
R_0	ω	-0.0141	-0.0076	-0.0015	0.002	-0.0072	0.00351	-2.66E-06
Q_{BT}	τ	0.5235	1.1259	2.2078	< 0.002	1.3188	0.56170	9.55E-0.8

Table 2.24 – Model 21.2 analysis of environmental link parameters using priors. This shows the change in value of the environmental link parameter as the CV of a normal prior with mean of 0 was reduced. %Δ is the percent change in the value from using an uninformative prior. LLΔ is the change in log likelihood from a uniform prior. This test was proposed by the October 2021 SSC.

Prior μ	Prior CV	Prior σ	Parameter	Link	Value	% Δ	LL Δ
0	0.1	0.002990	K	ϕ	-0.00022	99.3%	0.364
0	0.25	0.007474	K	ϕ	-0.00131	95.6%	0.350
0	0.5	0.014949	K	ϕ	-0.00464	84.5%	0.309
0	1	0.029898	K	ϕ	-0.01264	57.7%	0.211
0	0.1	0.004763	L_2	ν	0.00223	95.3%	2.301
0	0.25	0.011909	L_2	ν	0.011098	76.7%	1.843
0	0.5	0.023817	L_2	ν	0.025918	45.6%	1.084
0	1	0.047635	L_2	ν	0.039279	17.5%	0.412
0	0.1	0.180026	L_1	γ	0.755919	58.0%	21.564
0	0.25	0.450065	L_1	γ	1.499503	16.7%	6.434
0	0.5	0.900130	L_1	γ	1.709467	5.0%	1.899
0	1	1.800260	L_1	γ	1.776392	1.3%	0.493
0	0.1	0.140976	M	η	0.656814	53.4%	23.445
0	0.25	0.352440	M	η	1.197071	15.1%	6.799
0	0.5	0.704880	M	η	1.350543	4.2%	1.916
0	1	1.409760	M	η	1.39453	1.1%	0.495
0	0.1	0.000716	R_0	ω	-0.0003	95.9%	2.046
0	0.25	0.001791	R_0	ω	-0.00151	78.8%	1.679
0	0.5	0.003581	R_0	ω	-0.00369	48.5%	1.026
0	1	0.007163	R_0	ω	-0.00578	19.3%	0.404

Table 2.25 –Harmonic mean effective N for length and age compositions, and recruitment variability for selected assessed models.

		M19.1	M21.1	M21.2
Size Comp				
Har. Mean EffN	Trawl	299.387	300.474	298.93
	Longline	465.929	470.819	461.600
	Pot	355.708	357.580	351.420
	AFSC Trawl	314.485	314.845	316.110
	AFSC Longline	300.479	301.330	298.837
Mean input N	Trawl		**148.591**	
	Longline		**151.976**	
	Pot		**168.625**	
	AFSC Trawl		**100.000**	
	AFSC Longline		**100.000**	
Age Data				
Har. Mean EffN	Trawl	1.728	1.724	1.752
	Longline	2.354	2.353	2.402
	Pot	2.278	2.275	2.335
	AFSC Trawl	2.824	2.832	3.001
Mean input N	Trawl		**0.424**	
	Longline		**1.183**	
	Pot		**0.872**	
	AFSC Trawl		**1.124**	

Table 2.26 – Female spawning biomass, ABC, and OFL results for evaluated models.

<table>
<tr><th></th><th>M19.1</th><th>M21.1</th><th>M21.2A</th><th>M21.2B</th></tr>
<tr><td>Results</td><td></td><td></td><td></td><td></td></tr>
<tr><td>SSB_{1978} (t)</td><td>117,226</td><td>111,119</td><td colspan="2">128,478</td></tr>
<tr><td>$SSB_{100\%}$ (t)</td><td>165,508</td><td>159,948</td><td colspan="2">162,426</td></tr>
<tr><td>SSB_{2021} (t)</td><td>46,190</td><td>40,128</td><td colspan="2">38,019</td></tr>
<tr><td>$SSB_{2021\%}$</td><td>0.279</td><td>0.251</td><td colspan="2">0.234</td></tr>
<tr><td>SSB_{2022}(t)</td><td>48,061</td><td>42,763</td><td colspan="2">39,873</td></tr>
<tr><td>$SSB_{2022\%}$</td><td>0.290</td><td>0.267</td><td colspan="2">0.245</td></tr>
<tr><td>SSB_{2023}(t)</td><td>44,530</td><td>42,873</td><td>38,594</td><td>35,050</td></tr>
<tr><td>$SSB_{2023\%}$</td><td>0.269</td><td>0.268</td><td>0.238</td><td>0.216</td></tr>
<tr><td>$F_{35\%}$</td><td>0.866</td><td>0.854</td><td colspan="2">0.913</td></tr>
<tr><td>$F_{40\%}$</td><td>0.696</td><td>0.687</td><td colspan="2">0.734</td></tr>
<tr><td>2022 ABC (t)</td><td>32,811</td><td>26,759</td><td>24,043</td><td>23,099</td></tr>
<tr><td>F_{ABC}</td><td>0.495</td><td>0.447</td><td>0.436</td><td>0.436</td></tr>
<tr><td>OFL (t)</td><td>39,555</td><td>32,366</td><td>29,131</td><td>28,000</td></tr>
<tr><td>F_{OFL}</td><td>0.616</td><td>0.556</td><td>0.542</td><td>0.542</td></tr>
<tr><td>2023 ABC (t)</td><td>28,708</td><td>27,195</td><td>22,882</td><td>18,170</td></tr>
<tr><td>F_{ABC}</td><td>0.456</td><td>0.448</td><td>0.421</td><td>0.379</td></tr>
<tr><td>OFL (t)</td><td>34,673</td><td>32,869</td><td>27,715</td><td>22,072</td></tr>
<tr><td>F_{OFL}</td><td>0.568</td><td>0.558</td><td>0.523</td><td>0.471</td></tr>
</table>

Table 2.27 – Natural mortality for all models evaluated. Darker red indicates higher value.

Year	Model 19.1	Model 21.1	Model 21.2	Year	Model 19.1	Model 21.1	Model 21.2
1977	0.4992	0.4879	0.4783	2000	0.4992	0.4879	0.4783
1978	0.4992	0.4879	0.4783	2001	0.4992	0.4879	0.5030
1979	0.4992	0.4879	0.4783	2002	0.4992	0.4879	0.5055
1980	0.4992	0.4879	0.4783	2003	0.4992	0.4879	0.6227
1981	0.4992	0.4879	0.4783	2004	0.4992	0.4879	0.5487
1982	0.4992	0.4879	0.4783	2005	0.4992	0.4879	0.6987
1983	0.4992	0.4879	0.4946	2006	0.4992	0.4879	0.4964
1984	0.4992	0.4879	0.5284	2007	0.4992	0.4879	0.4783
1985	0.4992	0.4879	0.4908	2008	0.4992	0.4879	0.4783
1986	0.4992	0.4879	0.4865	2009	0.4992	0.4879	0.4783
1987	0.4992	0.4879	0.4811	2010	0.4992	0.4879	0.4815
1988	0.4992	0.4879	0.4783	2011	0.4992	0.4879	0.4783
1989	0.4992	0.4879	0.4783	2012	0.4992	0.4879	0.4783
1990	0.4992	0.4879	0.4826	2013	0.4992	0.4879	0.4783
1991	0.4992	0.4879	0.4783	2014	0.8748	0.4879	0.6970
1992	0.4992	0.4879	0.4783	2015	0.8748	0.9377	0.8300
1993	0.4992	0.4879	0.4879	2016	0.8748	0.9377	1.0658
1994	0.4992	0.4879	0.4783	2017	0.4992	0.9377	0.5065
1995	0.4992	0.4879	0.4783	2018	0.4992	0.4879	0.5566
1996	0.4992	0.4879	0.4783	2019	0.4992	0.4879	0.9360
1997	0.4992	0.4879	0.5670	2020	0.4992	0.4879	0.5383
1998	0.4992	0.4879	0.5739	2021	0.4992	0.4879	0.4860
1999	0.4992	0.4879	0.4783				

Table 2.28 – Estimated beginning year weight and length at age from Model 19.1.

Age	Weight (kg)	Length (cm)
0	0.0004	0.5
1	0.03	14.8
2	0.24	29.4
3	0.68	41.4
4	1.33	51.4
5	2.11	59.7
6	2.95	66.5
7	3.80	72.2
8	4.62	76.9
9	5.39	80.8
10+	7.26	88.9

Table 2.29 – Estimated beginning year weight and length at age from Model 21.1 and Model 21.2.

Model 21.1			Model 21.2		
Age	**Weight (kg)**	**Length (cm)**	**Age**	**Weight (kg)**	**Length (cm)**
0	0.0004	0.5	0	0.0004	0.5
1	0.03	14.8	1	0.04	15.0
2	0.24	29.4	2	0.26	33.4
3	0.68	41.4	3	0.72	42.8
4	1.33	51.4	4	1.38	52.0
5	2.10	59.6	5	2.17	62.0
6	2.94	66.5	6	3.03	69.2
7	3.79	72.1	7	3.90	73.4
8	4.61	76.8	8	4.75	77.7
9	5.37	80.7	9	5.54	81.6
10+	7.25	88.8	10+	6.59	86.2

Table 2.30 – Estimated female spawning biomass (t) from the last year's assessment and the author's recommended Model 21.2.

	Last Year's Model			Model 21.2		
	Sp.Bio	St.dev	Tot. Bio. 0+	Sp.Bio	St.dev	Tot. Bio. 0+
1977	110,410	24,581	364,209	114,766	24,011	367,899
1978	119,850	25,067	405,023	128,475	25,792	387,984
1979	117,990	23,590	471,526	126,181	24,678	448,597
1980	120,265	22,926	530,446	125,789	23,272	536,489
1981	143,780	27,033	556,366	154,447	27,302	596,105
1982	166,785	30,771	579,603	199,210	34,239	666,234
1983	172,375	30,733	618,424	207,011	34,384	702,843
1984	173,590	29,945	651,063	216,064	34,546	753,449
1985	188,540	30,012	690,522	228,933	33,424	760,530
1986	211,100	29,897	742,523	248,705	32,098	786,725
1987	227,490	28,914	787,267	258,935	29,584	816,227
1988	233,010	26,573	794,280	265,790	27,189	845,182
1989	243,170	24,688	787,561	275,204	24,667	839,938
1990	243,230	22,323	769,439	266,736	21,249	801,170
1991	223,300	19,714	736,250	239,931	18,319	750,211
1992	205,080	17,718	707,463	219,830	16,472	725,674
1993	191,450	16,417	665,035	212,183	15,750	708,781
1994	194,485	15,679	628,624	216,130	15,082	679,288
1995	194,410	14,283	585,143	218,287	14,167	641,051
1996	172,765	12,123	519,793	195,737	12,660	569,401
1997	146,845	10,039	465,313	170,765	11,155	523,091
1998	123,625	8,519	416,933	134,686	8,715	444,086
1999	110,480	7,689	377,406	118,872	7,393	394,747
2000	97,345	7,072	338,761	106,767	7,112	360,248
2001	87,890	6,394	324,757	100,344	6,925	356,364
2002	83,510	5,809	328,461	98,767	6,647	379,910
2003	82,880	5,531	323,780	97,608	6,488	389,894
2004	83,425	5,551	300,952	95,757	5,866	348,192
2005	79,040	5,302	274,389	91,629	5,484	311,004
2006	70,960	4,687	266,500	70,562	3,852	249,486
2007	62,375	4,190	284,405	62,041	3,472	257,368
2008	58,345	4,129	321,322	56,418	3,344	287,118
2009	63,025	4,683	365,206	60,904	3,780	326,772
2010	82,160	5,914	412,065	75,943	4,722	365,593
2011	93,315	7,026	425,550	91,344	5,808	394,309
2012	99,360	8,160	431,913	98,574	6,903	398,698
2013	102,620	9,141	475,139	99,812	7,792	414,466
2014	106,775	10,451	553,456	102,241	9,009	486,477
2015	78,265	6,746	408,888	85,984	7,950	455,312
2016	62,895	4,957	266,608	81,032	7,008	350,920
2017	44,961	3,601	157,240	55,125	4,085	191,168
2018	35,940	3,578	131,650	48,374	4,193	172,440
2019	34,794	3,513	149,969	46,938	3,931	184,803
2020	34,631	3,762	186,666	34,006	2,823	141,337
2021	44,559	5,019	247,415	38,019	2,982	150,093
2022				39,873	3,651	160,755

Table 2.31 – Age-0 recruitment and standard deviation of age-0 recruits by year for last year's model and Model 21.2. Highlighted are the 1977 and 2012 year classes.

	M19.1 - 2020		M21.2	
Year	Age-0 x 10^9	Stdev	Age-0 x 10^9	Stdev
1977	1.208	0.335	1.263	0.321
1978	0.378	0.132	0.604	0.189
1979	0.370	0.118	0.507	0.150
1980	0.624	0.180	0.496	0.146
1981	0.690	0.185	0.981	0.214
1982	0.756	0.205	0.982	0.237
1983	0.539	0.167	0.570	0.169
1984	0.709	0.196	0.699	0.182
1985	0.887	0.211	1.125	0.215
1986	0.499	0.135	0.444	0.118
1987	0.588	0.133	0.663	0.123
1988	0.598	0.132	0.734	0.131
1989	0.632	0.137	0.786	0.142
1990	0.749	0.152	0.850	0.150
1991	0.445	0.100	0.496	0.102
1992	0.385	0.083	0.500	0.091
1993	0.310	0.068	0.375	0.074
1994	0.348	0.072	0.449	0.080
1995	0.438	0.082	0.615	0.098
1996	0.309	0.061	0.390	0.072
1997	0.294	0.057	0.397	0.073
1998	0.272	0.052	0.316	0.054
1999	0.367	0.066	0.577	0.087
2000	0.439	0.076	0.574	0.090
2001	0.251	0.048	0.496	0.079
2002	0.193	0.037	0.304	0.055
2003	0.244	0.043	0.367	0.057
2004	0.308	0.053	0.427	0.062
2005	0.420	0.070	0.550	0.077
2006	0.687	0.112	0.725	0.095
2007	0.443	0.079	0.490	0.071
2008	0.652	0.112	0.689	0.096
2009	0.392	0.076	0.391	0.068
2010	0.507	0.097	0.447	0.071
2011	0.655	0.132	0.696	0.116
2012	1.215	0.261	1.332	0.239
2013	0.638	0.159	0.924	0.198
2014	0.211	0.060	0.367	0.093
2015	0.260	0.064	0.224	0.061
2016	0.168	0.042	0.512	0.102
2017	0.246	0.058	0.322	0.062
2018	0.390	0.108	0.361	0.074
2019	0.399	0.160	0.207	0.059
2020	0.464	0.223	0.315	0.080
2021			0.473	0.215
Mean 1977-2019	0.493		0.587	
Stdev(Ln(x))		0.471		0.422

Table 2.32 – Estimated fishing mortality in Apical F and Total exploitation for Model 21.2.

	Sum Apical F		Total		Sum Apical F		Total
Year	F	σ	**Exploitation**	**Year**	F	σ	**Exploitation**
1977	0.009	0.002	0.007	2001	0.273	0.021	0.142
1978	0.042	0.009	0.036	2002	0.286	0.021	0.134
1979	0.055	0.012	0.047	2003	0.381	0.026	0.156
1980	0.127	0.027	0.076	2004	0.422	0.027	0.179
1981	0.079	0.014	0.068	2005	0.577	0.096	0.177
1982	0.059	0.010	0.051	2006	0.674	0.103	0.230
1983	0.076	0.013	0.065	2007	0.623	0.045	0.262
1984	0.049	0.008	0.036	2008	0.759	0.061	0.276
1985	0.043	0.009	0.021	2009	0.608	0.049	0.194
1986	0.064	0.011	0.036	2010	0.707	0.057	0.260
1987	0.056	0.010	0.047	2011	0.661	0.052	0.244
1988	0.056	0.006	0.043	2012	0.562	0.048	0.232
1989	0.070	0.009	0.058	2013	0.473	0.045	0.205
1990	0.179	0.016	0.101	2014	0.641	0.064	0.233
1991	0.210	0.018	0.113	2015	0.720	0.071	0.206
1992	0.238	0.020	0.125	2016	0.686	0.059	0.199
1993	0.172	0.014	0.087	2017	0.671	0.082	0.291
1994	0.142	0.011	0.076	2018	0.209	0.024	0.116
1995	0.213	0.015	0.115	2019	0.251	0.026	0.107
1996	0.233	0.017	0.131	2020	0.120	0.011	0.060
1997	0.279	0.020	0.147	2021	0.422	0.043	0.185
1998	0.314	0.022	0.154				
1999	0.407	0.029	0.196				
2000	0.352	0.026	0.174				

Table 2.33 – Biological reference points from GOA Pacific cod SAFE documents for years 2002 – 2021, and recommended for 2022 from Model 21.2 Projection B.

Year	$SB_{100\%}$	$SB_{40\%}$	$F_{40\%}$	SB_{y+1}	ABC_{y+1}
2002	212,000	85,000	0.41	82,000	57,600
2003	226,000	90,300	0.35	88,300	52,800
2004	222,000	88,900	0.34	103,000	62,810
2005	211,000	84,400	0.31	91,700	58,100
2006	329,000	132,000	0.56	165,000	68,859
2007	259,000	103,000	0.46	136,000	68,859
2008	302,000	121,000	0.49	108,000	66,493
2009	255,500	102,200	0.52	88,000	55,300
2010	291,500	116,600	0.49	117,600	79,100
2011	256,300	102,500	0.42	124,100	86,800
2012	261,000	104,000	0.44	121,000	87,600
2013	234,800	93,900	0.49	111,000	80,800
2014	227,800	91,100	0.54	120,100	88,500
2015	316,500	126,600	0.50	155,400	102,850
2016	325,200	130,000	0.41	116,600	98,600
2017	196,776	78,711	0.53	105,378	88,342
2018	168,583	67,433	0.80	35,973	18,972
2019	172,240	68,896	0.76	34,515	19,665
2020	187,780	75,112	0.67	32,957	14,621
2021	180,111	72,045	0.62	39,977	23,627
2022	*162,426*	*64,970*	*0.73*	*28,000*	*23,099*

Table 2.34 – Results for the projection scenarios from Model 19.1. Catch in tons, fishing mortality (F), and Female spawning stock biomass (SSB) in tons for the 7 standard projection scenarios.

Catch	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
2021	23,627	23,627	23,627	23,627	23,627	23,627	23,627
2022	32,811	32,811	22,067	8,083	0	39,555	32,811
2023	28,708	28,708	22,623	10,156	0	31,283	28,708
2024	30,798	30,798	25,381	12,702	0	33,156	37,294
2025	50,300	50,300	40,435	17,912	0	55,398	56,719
2026	70,067	70,067	52,085	22,978	0	80,110	80,064
2027	76,440	76,440	59,331	27,348	0	84,912	84,829
2028	78,921	78,921	63,161	30,321	0	86,185	86,143
2029	79,757	79,757	64,927	32,091	0	86,434	86,418
2030	80,068	80,068	65,771	33,180	0	86,499	86,493
2031	80,211	80,211	66,217	33,893	0	86,533	86,531
2032	80,257	80,257	66,404	34,276	0	86,540	86,539
2033	80,272	80,272	66,483	34,481	0	86,541	86,541
2034	80,277	80,277	66,516	34,591	0	86,541	86,541
F							
2021	0.34	0.34	0.34	0.34	0.34	0.34	0.34
2022	0.50	0.50	0.32	0.11	0.00	0.62	0.50
2023	0.46	0.46	0.32	0.12	0.00	0.53	0.46
2024	0.46	0.46	0.34	0.14	0.00	0.54	0.58
2025	0.61	0.61	0.43	0.15	0.00	0.71	0.73
2026	0.70	0.70	0.45	0.15	0.00	0.87	0.87
2027	0.70	0.70	0.45	0.15	0.00	0.87	0.87
2028	0.70	0.70	0.45	0.15	0.00	0.87	0.87
2029	0.70	0.70	0.45	0.15	0.00	0.87	0.87
2030	0.70	0.70	0.45	0.15	0.00	0.87	0.87
2031	0.70	0.70	0.45	0.15	0.00	0.87	0.87
2032	0.70	0.70	0.45	0.15	0.00	0.87	0.87
2033	0.70	0.70	0.45	0.15	0.00	0.87	0.87
2034	0.70	0.70	0.45	0.15	0.00	0.87	0.87
SSB							
2021	46,190	46,190	46,190	46,190	46,190	46,190	46,190
2022	48,061	48,061	48,061	48,061	48,061	48,061	48,061
2023	44,530	44,530	48,429	53,594	56,623	42,117	44,530
2024	45,293	45,293	50,615	59,378	65,652	42,449	45,293
2025	58,145	58,145	64,077	75,373	84,942	55,197	55,977
2026	72,672	72,672	80,519	97,126	111,113	68,760	68,773
2027	79,894	79,894	92,298	115,876	135,329	73,429	73,366
2028	82,927	82,927	98,898	129,259	154,767	74,815	74,778
2029	84,015	84,015	102,102	137,596	168,408	75,126	75,110
2030	84,446	84,446	103,723	143,032	178,533	75,216	75,210
2031	84,655	84,655	104,631	146,807	186,409	75,265	75,263
2032	84,721	84,721	105,010	148,828	191,190	75,274	75,273
2033	84,742	84,742	105,170	149,913	194,092	75,276	75,275
2034	84,750	84,750	105,237	150,494	195,854	75,276	75,276

Table 2.35 – Results for the projection scenarios from Model 21.1. Catch in tons, fishing mortality (F), and Female spawning stock biomass (SSB) in tons for the 7 standard projection scenarios.

Catch	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
2021	23,627	23,627	23,627	23,627	23,627	23,627	23,627
2022	26,759	26,759	18,412	6,519	0	32,366	26,759
2023	27,195	27,195	21,371	9,134	0	30,064	27,195
2024	31,082	31,082	25,675	12,321	0	33,675	37,609
2025	50,391	50,391	41,175	17,404	0	55,416	56,685
2026	67,753	67,753	51,564	22,371	0	77,355	77,319
2027	74,258	74,258	58,796	26,676	0	82,448	82,373
2028	76,938	76,938	62,675	29,648	0	83,986	83,947
2029	77,890	77,890	64,483	31,438	0	84,359	84,344
2030	78,257	78,257	65,354	32,556	0	84,471	84,465
2031	78,425	78,425	65,813	33,292	0	84,522	84,520
2032	78,480	78,480	66,007	33,692	0	84,535	84,534
2033	78,499	78,499	66,089	33,909	0	84,538	84,538
2034	78,506	78,506	66,125	34,027	0	84,539	84,539
F							
2021	0.41	0.41	0.41	0.41	0.41	0.41	0.41
2022	0.45	0.45	0.30	0.10	0.00	0.56	0.45
2023	0.45	0.45	0.32	0.12	0.00	0.53	0.45
2024	0.47	0.47	0.35	0.14	0.00	0.55	0.59
2025	0.62	0.62	0.45	0.15	0.00	0.73	0.74
2026	0.69	0.69	0.45	0.15	0.00	0.85	0.85
2027	0.69	0.69	0.45	0.15	0.00	0.85	0.85
2028	0.69	0.69	0.45	0.15	0.00	0.85	0.85
2029	0.69	0.69	0.45	0.15	0.00	0.85	0.85
2030	0.69	0.69	0.45	0.15	0.00	0.85	0.85
2031	0.69	0.69	0.45	0.15	0.00	0.85	0.85
2032	0.69	0.69	0.45	0.15	0.00	0.85	0.85
2033	0.69	0.69	0.45	0.15	0.00	0.85	0.85
2034	0.69	0.69	0.45	0.15	0.00	0.85	0.85
SSB							
2021	40,128	40,128	40,128	40,128	40,128	40,128	40,128
2022	42,763	42,763	42,763	42,763	42,763	42,763	42,763
2023	42,872	42,872	45,902	50,286	52,721	40,862	42,872
2024	45,207	45,207	49,795	57,929	63,384	42,543	45,207
2025	57,946	57,946	63,397	74,596	83,492	55,006	55,747
2026	71,849	71,849	79,211	96,402	109,852	67,911	67,927
2027	79,312	79,312	90,841	115,192	134,211	72,900	72,842
2028	82,600	82,600	97,423	128,739	153,917	74,553	74,518
2029	83,837	83,837	100,641	137,251	167,836	74,992	74,976
2030	84,342	84,342	102,281	142,876	178,273	75,134	75,127
2031	84,587	84,587	103,196	146,793	186,396	75,202	75,200
2032	84,666	84,666	103,581	148,919	191,383	75,218	75,217
2033	84,694	84,694	103,745	150,073	194,444	75,222	75,222
2034	84,703	84,703	103,815	150,700	196,324	75,223	75,223

Table 2.36 – Results for the projection scenarios from Model 21.2A. Catch in tons, fishing mortality (F), and Female spawning stock biomass (SSB) in tons for the 7 standard projection scenarios.

Catch	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
2021	23,627	23,627	23,627	23,627	23,627	23,627	23,627
2022	24,043	24,043	13,375	5,811	0	29,131	24,043
2023	22,882	22,882	15,261	7,535	0	25,403	22,882
2024	25,806	25,806	18,396	9,804	0	28,191	31,320
2025	43,314	43,314	30,310	16,146	0	48,150	49,215
2026	64,305	64,305	41,282	20,492	0	70,371	70,372
2027	68,833	68,833	46,850	24,162	0	77,675	77,609
2028	70,512	70,512	49,955	26,611	0	77,729	77,696
2029	71,046	71,046	51,480	28,073	0	77,474	77,462
2030	71,217	71,217	52,199	28,909	0	77,338	77,335
2031	71,275	71,275	52,535	29,380	0	77,290	77,288
2032	71,295	71,295	52,690	29,640	0	77,274	77,274
2033	71,302	71,302	52,760	29,782	0	77,269	77,269
2034	71,305	71,305	52,792	29,859	0	77,268	77,268
F							
2021	0.42	0.42	0.42	0.42	0.42	0.42	0.42
2022	0.44	0.44	0.23	0.10	0.00	0.54	0.44
2023	0.42	0.42	0.25	0.11	0.00	0.50	0.42
2024	0.44	0.44	0.27	0.13	0.00	0.52	0.55
2025	0.59	0.59	0.35	0.16	0.00	0.69	0.70
2026	0.73	0.73	0.39	0.16	0.00	0.86	0.86
2027	0.73	0.73	0.39	0.16	0.00	0.91	0.91
2028	0.73	0.73	0.39	0.16	0.00	0.91	0.91
2029	0.73	0.73	0.39	0.16	0.00	0.91	0.91
2030	0.73	0.73	0.39	0.16	0.00	0.91	0.91
2031	0.73	0.73	0.39	0.16	0.00	0.91	0.91
2032	0.73	0.73	0.39	0.16	0.00	0.91	0.91
2033	0.73	0.73	0.39	0.16	0.00	0.91	0.91
2034	0.73	0.73	0.39	0.16	0.00	0.91	0.91
SSB							
2021	38,019	38,019	38,019	38,019	38,019	38,019	38,019
2022	39,873	39,873	39,873	39,873	39,873	39,873	39,873
2023	38,594	38,594	42,322	45,006	47,090	36,842	38,594
2024	40,343	40,343	45,963	50,865	55,271	38,097	40,343
2025	52,585	52,585	59,222	65,859	72,657	50,164	50,811
2026	64,928	64,928	74,101	83,856	94,603	61,604	61,627
2027	69,902	69,902	84,576	99,225	114,704	65,390	65,339
2028	71,904	71,904	90,708	109,904	130,342	65,560	65,531
2029	72,592	72,592	93,891	116,618	141,531	65,362	65,350
2030	72,824	72,824	95,459	120,625	149,154	65,239	65,235
2031	72,905	72,905	96,214	122,952	154,201	65,191	65,190
2032	72,933	72,933	96,570	124,267	157,449	65,175	65,175
2033	72,942	72,942	96,733	124,995	159,496	65,170	65,170
2034	72,946	72,946	96,808	125,391	160,766	65,168	65,168

Table 2.37 – Results for the projection scenarios from Model 21.2B. Catch in tons, fishing mortality (F), and Female spawning stock biomass (SSB) in tons for the 7 standard projection scenarios.

Catch	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
2021	23,627	23,627	23,627	23,627	23,627	23,627	23,627
2022	23,099	23,099	12,837	5,574	0	28,000	23,099
2023	18,170	18,170	12,067	5,935	0	20,205	18,170
2024	17,720	17,720	12,385	6,481	0	19,502	21,596
2025	25,540	25,540	17,375	9,097	0	28,662	29,397
2026	32,194	32,194	22,435	12,057	0	35,753	35,847
2027	33,658	33,658	24,564	13,831	0	36,710	36,673
2028	33,455	33,455	25,048	14,624	0	36,246	36,225
2029	33,256	33,256	25,087	14,940	0	36,020	36,015
2030	33,193	33,193	25,059	15,055	0	35,976	35,976
2031	33,183	33,183	25,040	15,085	0	35,978	35,978
2032	33,184	33,184	25,031	15,089	0	35,981	35,981
2033	33,185	33,185	25,027	15,091	0	35,982	35,982
2034	33,185	33,185	25,026	15,091	0	35,982	35,982
F							
2021	0.42	0.42	0.42	0.42	0.42	0.42	0.42
2022	0.44	0.44	0.23	0.10	0.00	0.54	0.44
2023	0.38	0.38	0.22	0.10	0.00	0.45	0.38
2024	0.37	0.37	0.22	0.10	0.00	0.43	0.46
2025	0.45	0.45	0.27	0.12	0.00	0.53	0.54
2026	0.51	0.51	0.31	0.14	0.00	0.61	0.61
2027	0.53	0.53	0.32	0.15	0.00	0.62	0.62
2028	0.53	0.53	0.33	0.16	0.00	0.61	0.61
2029	0.52	0.52	0.33	0.16	0.00	0.61	0.61
2030	0.52	0.52	0.33	0.16	0.00	0.61	0.61
2031	0.52	0.52	0.33	0.16	0.00	0.61	0.61
2032	0.52	0.52	0.33	0.16	0.00	0.61	0.61
2033	0.52	0.52	0.33	0.16	0.00	0.61	0.61
2034	0.52	0.52	0.33	0.16	0.00	0.61	0.61
SSB							
2021	38,019	38,019	38,019	38,019	38,019	38,019	38,019
2022	39,873	39,873	39,873	39,873	39,873	39,873	39,873
2023	35,050	35,050	38,437	40,876	42,770	33,458	35,050
2024	34,117	34,117	38,571	42,406	45,820	32,318	34,117
2025	41,139	41,139	45,830	50,367	54,870	39,386	39,947
2026	46,380	46,380	52,118	57,876	63,960	44,240	44,318
2027	47,516	47,516	54,611	61,989	70,229	44,911	44,892
2028	47,405	47,405	55,228	63,846	74,183	44,639	44,627
2029	47,269	47,269	55,310	64,615	76,586	44,497	44,494
2030	47,224	47,224	55,293	64,909	78,005	44,469	44,468
2031	47,216	47,216	55,275	65,015	78,832	44,469	44,469
2032	47,216	47,216	55,265	65,050	79,299	44,471	44,471
2033	47,217	47,217	55,261	65,061	79,559	44,472	44,472
2034	47,217	47,217	55,259	65,064	79,702	44,472	44,472

Figures

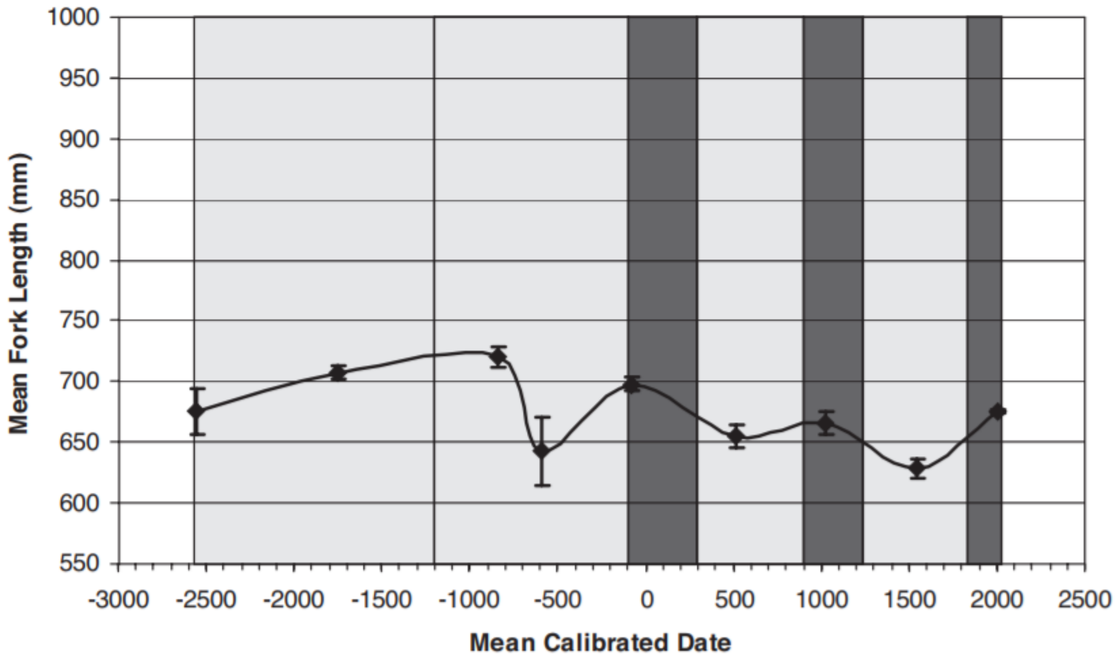


Figure 2.1 Gulf of Alaska mean lengths with climate reconstruction. The shaded boxes represent periods of significant changes in air temperature, sea surface temperature, storminess, and ocean circulation that drive ocean productivity. The lightly shaded boxes represent periods of cooler and stormier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

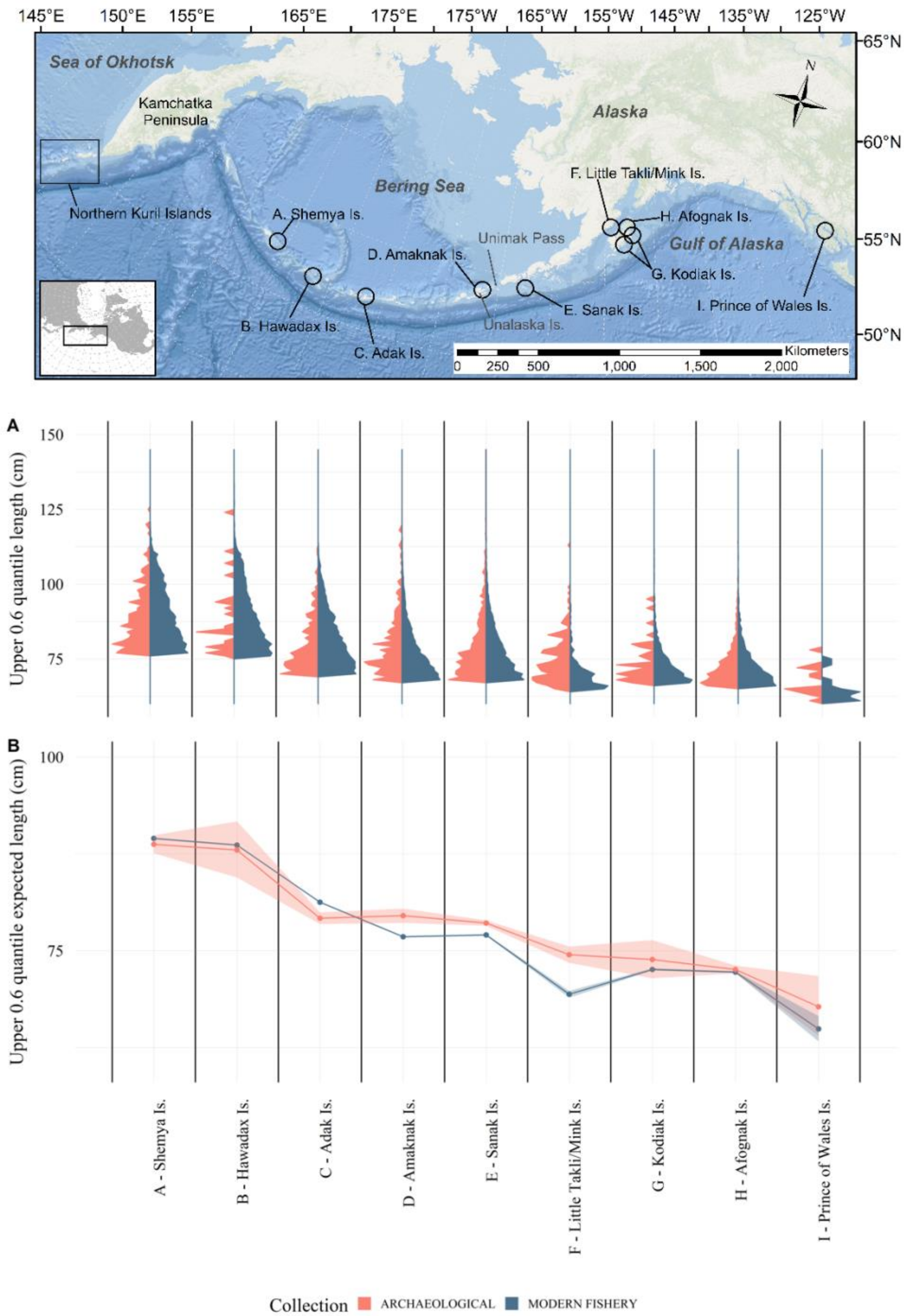


Figure 2.2 (A) The 0.6 quantile of the length distribution of Pacific cod from the Alaska archaeological collections (red) and modern longline and jig commercial fishery data (blue) within 50 km of the archaeological sites; and (B) log-linked gamma generalized linear regression results of Alaska modern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

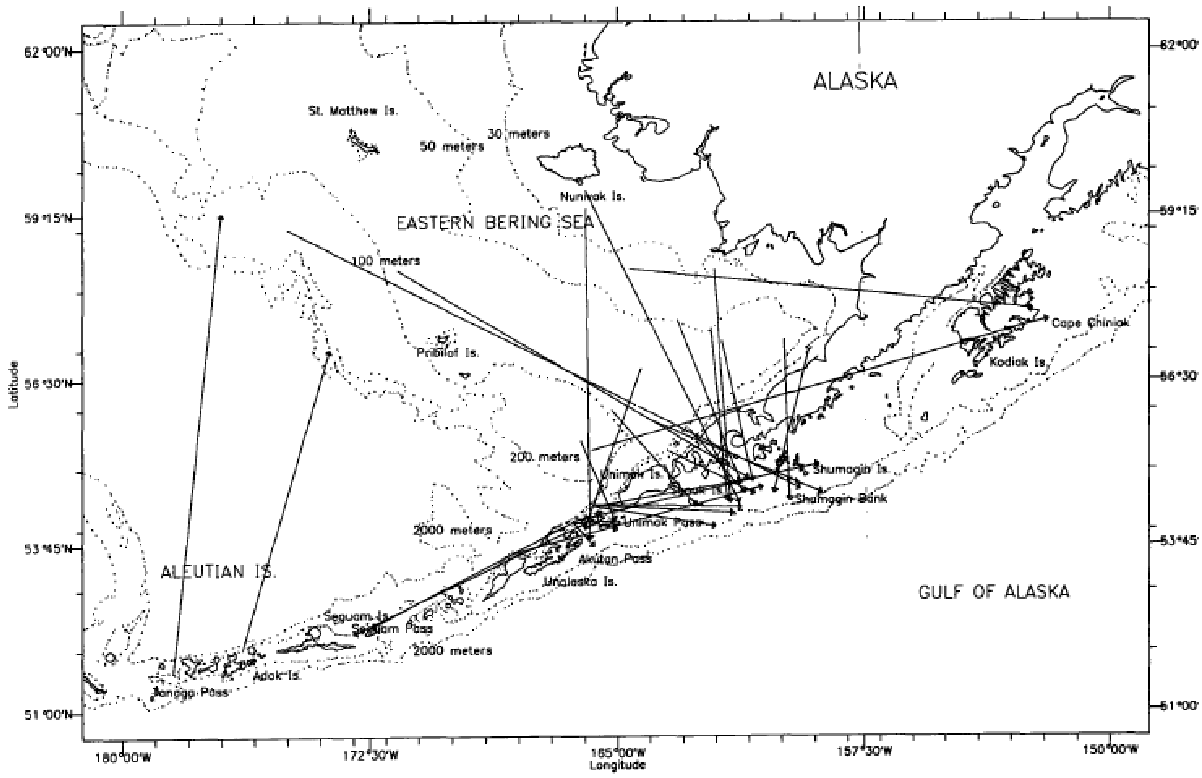


Figure 2.3 Tag recoveries from Shimada and Kimura 1994 (Figure 8), showing movement of individual tagged Pacific cod from eastern Bering Sea into the Gulf of Alaska and other interregional migrations.

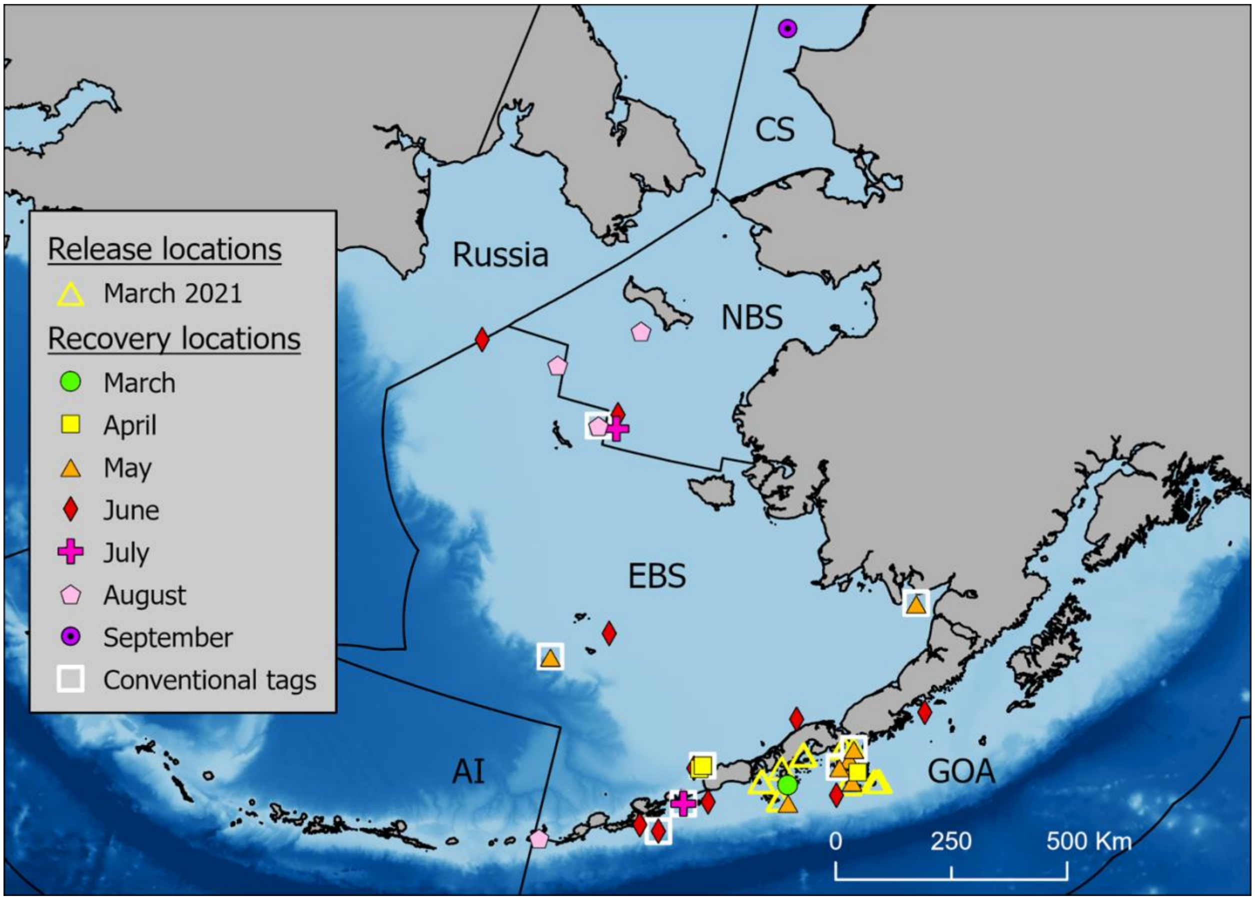


Figure 2.4 Release and monthly satellite and conventional tag recovery locations through September 2021 by region (NBS = Northern Bering Sea, EBS = Eastern Bering Sea, AI = Aleutian Islands, and GOA = Gulf of Alaska, CS = Chukchi Sea). Conventional tag recaptures are indicated by a white square around the symbol.

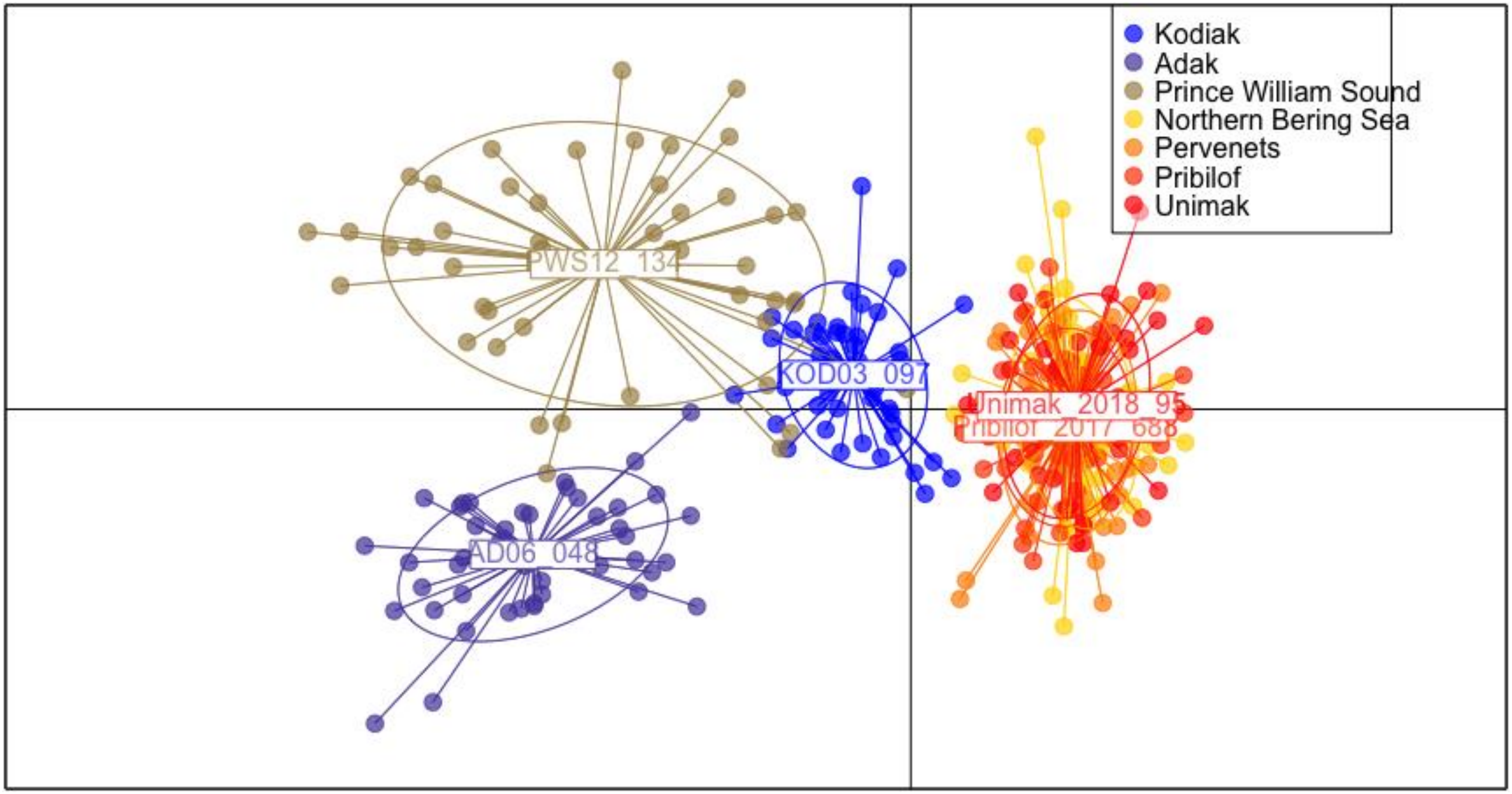


Figure 2.5 Discriminant analysis of principal components (DAPC) scatterplot with the following populations represented: Adak (2006), Prince William Sound, PWS (2012), Kodiak (2003), Unimak (2018), Pervenets (2016), Pribilof (2017), and Norton Sound, NBS (2017). All populations represent spawning groups 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 (Spies et al. 2020).

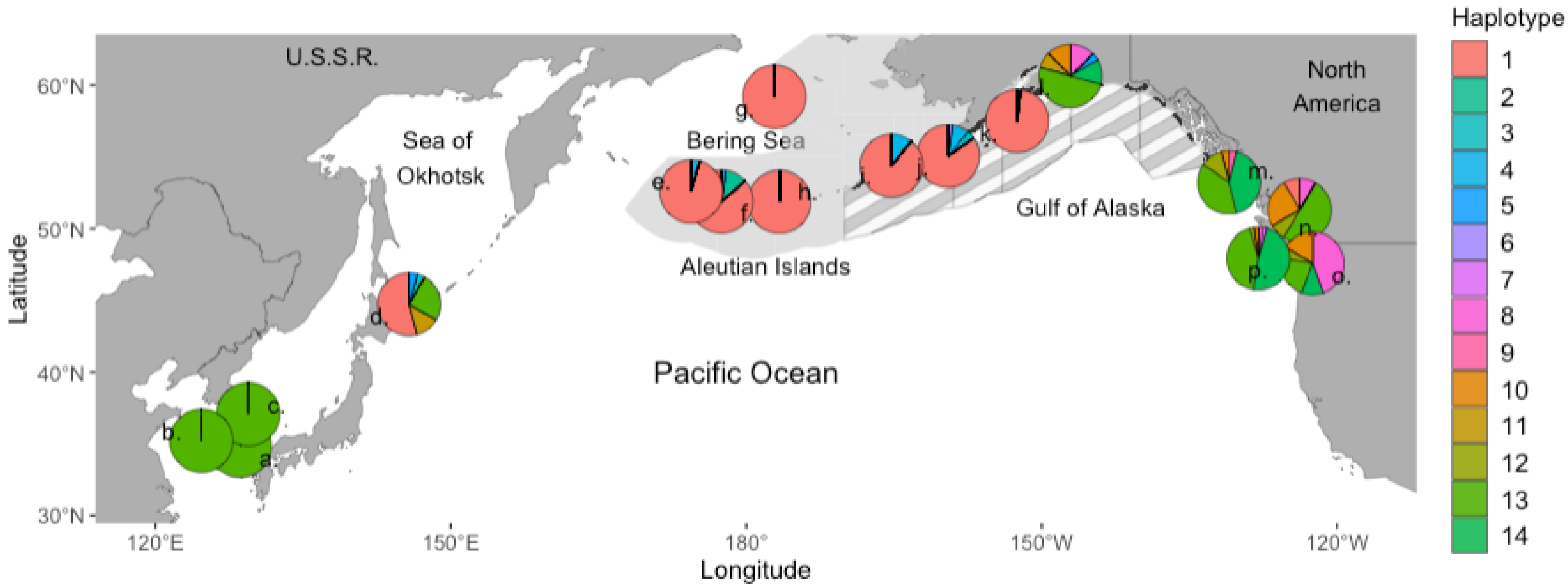


Figure 2.6 Map with pie charts showing relative haplotype frequencies between all collections, and Numbers on map represent the name of the collection, west to east: a. Geoje, Korea, b. Yellow Sea, Korea, c. Jukbyeon, Korea, d. Sea of Okhotsk, Japan, e. Near Islands, f. Kiska Island, g. Pervenets Canyon, h. Adak Island, i. Unimak Island, j. Shumagin Islands, k. Kodiak Island, l. Prince William Sound, m. Hecate Strait, n. Strait of Georgia, o. Puget Sound, p. Washington Coast. The spatial area comprising the Gulf of Alaska Fishery Management Plan is shown with grey stripes and the area comprising the Bering Sea and Aleutian Islands Fishery Management Plan is light grey (Spies et al. 2021).

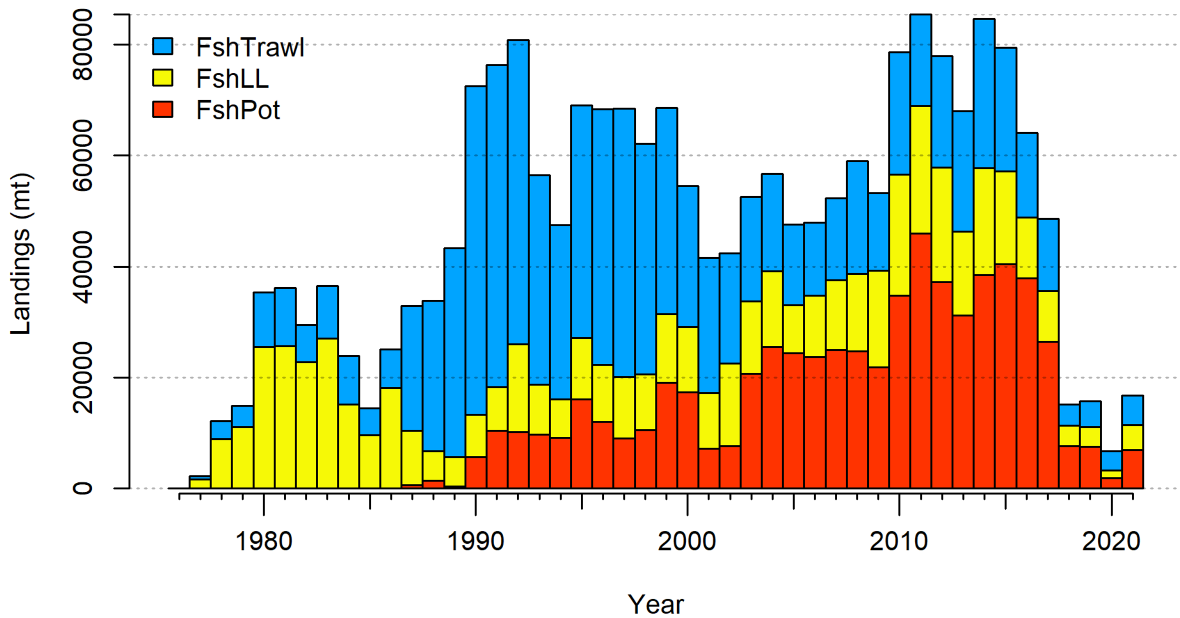


Figure 2.7 Gulf of Alaska Pacific cod catch from 1977-2021. Note that 2021 catch was through October 1.

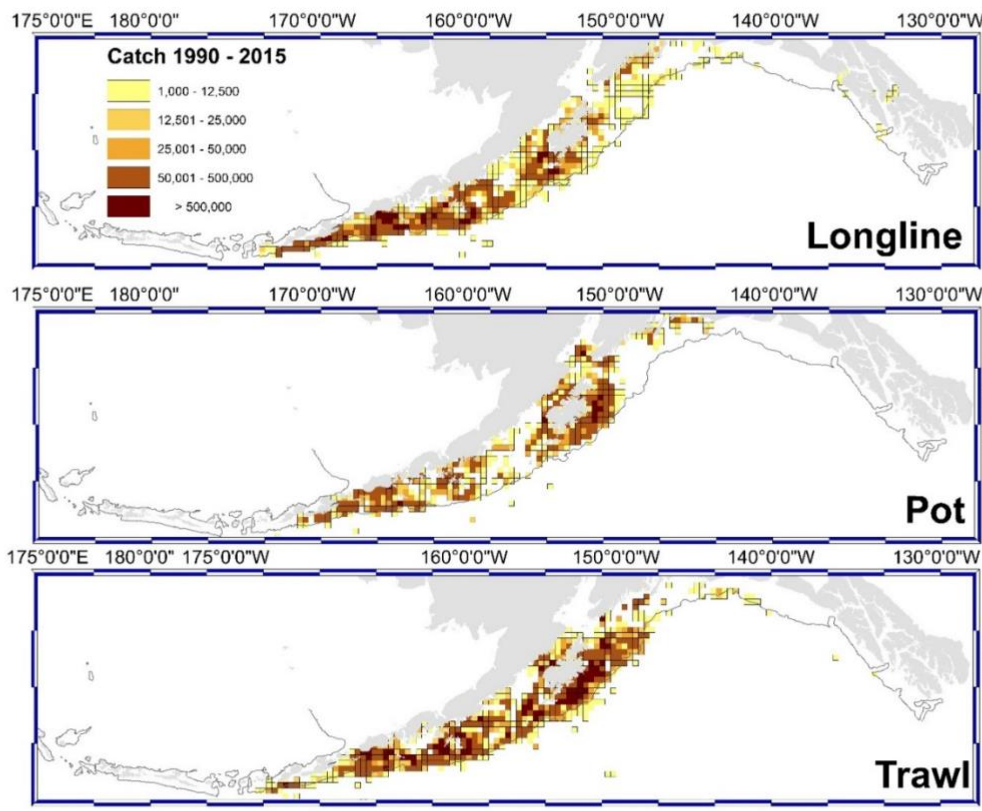


Figure 2.8 Commercial catch of Pacific cod in the Gulf of Alaska by 20km^2 grid for 1990-2015.

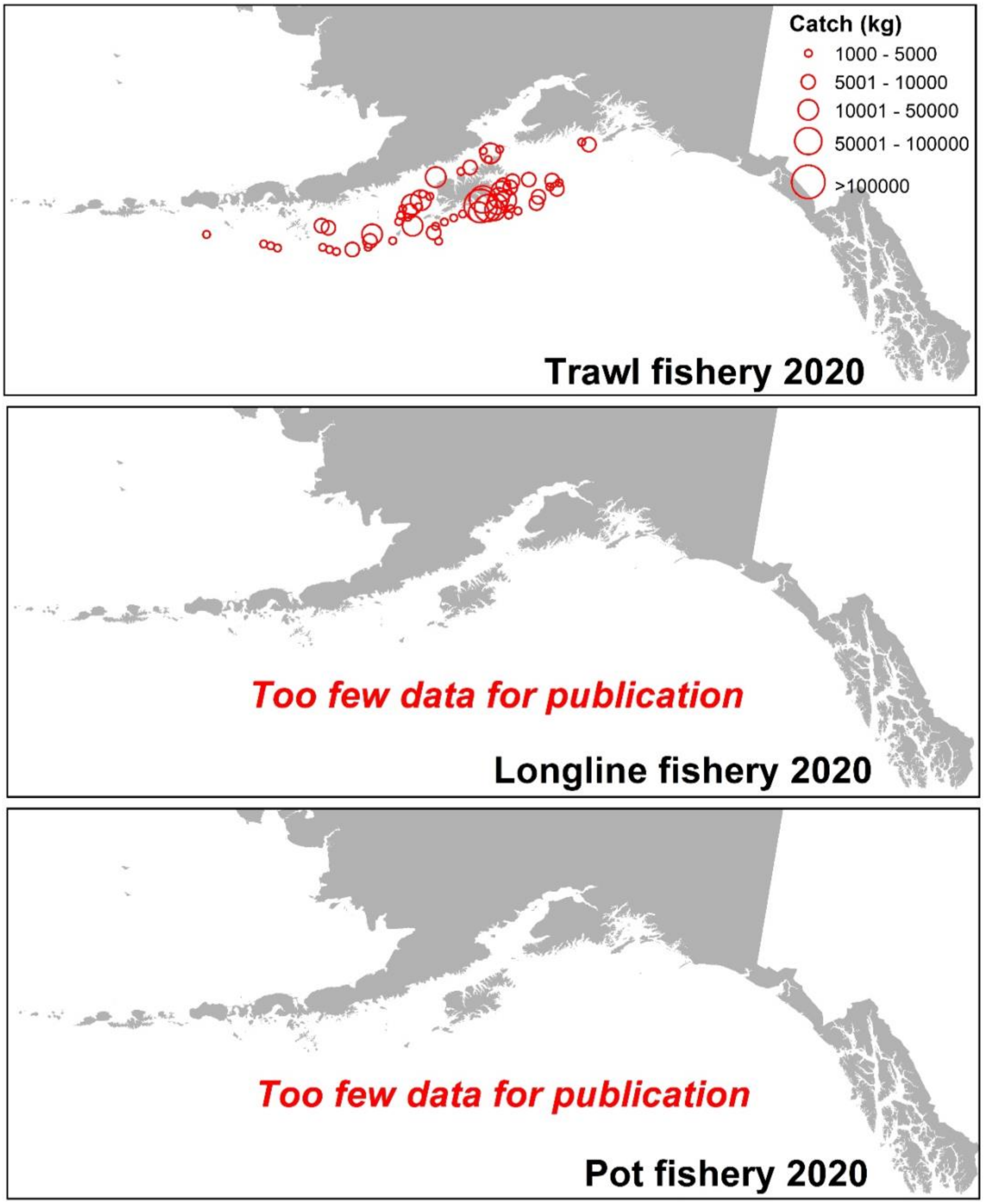


Figure 2.9 Commercial catch of Pacific cod in the Gulf of Alaska by 20km^2 grid for 2020 for catch greater than 1000 kg. Observed catch in red circles and EM catch for longline and pot in blue squares. These data include bycatch Pacific cod.

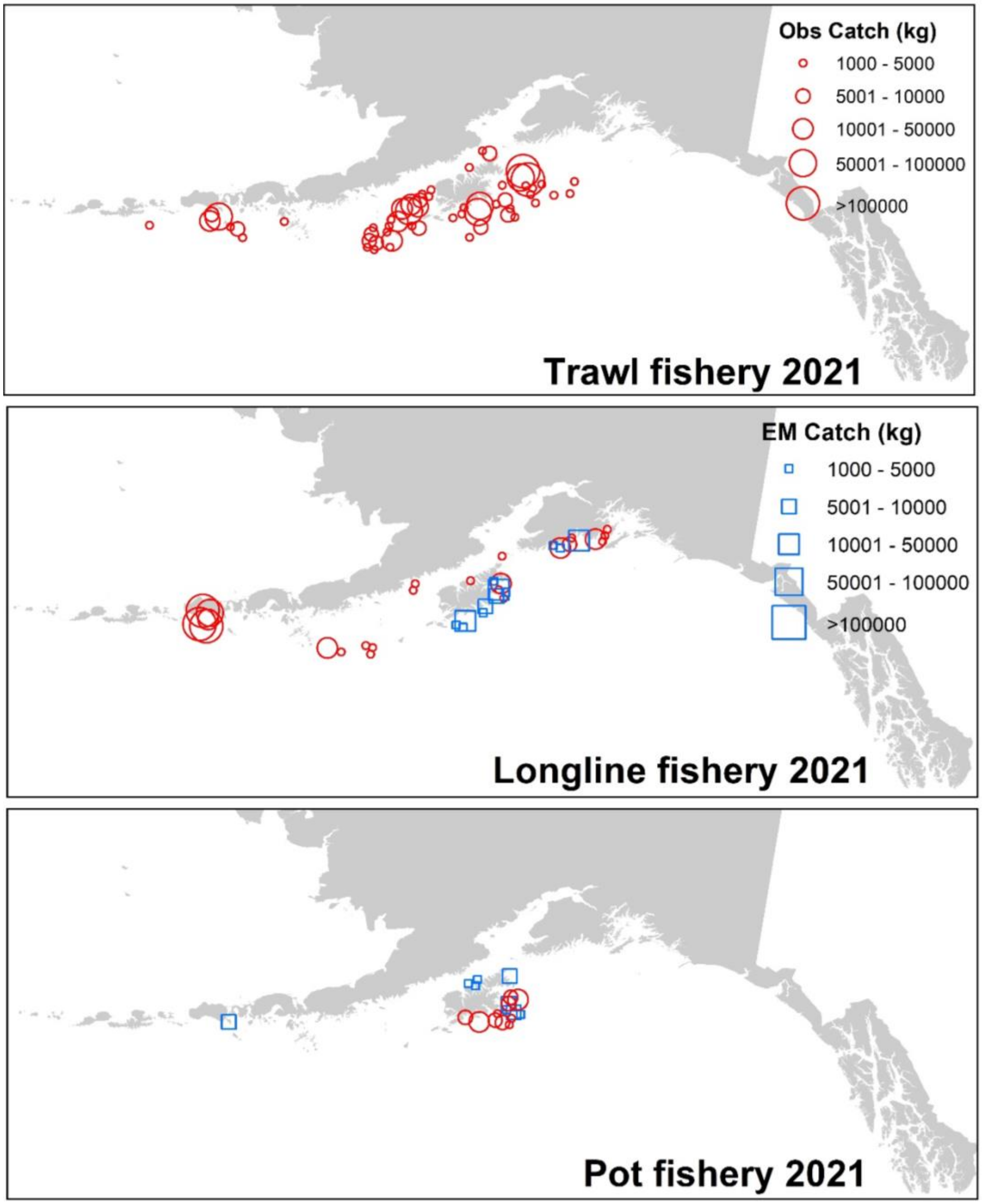


Figure 2.10 Observed commercial catch of Pacific cod in the Gulf of Alaska by $20km^2$ grid for 2021 as of October 23, 2021 for catch greater than 1000 kg. These data include bycatch Pacific cod, but do not include trawl EM data as locations are not yet available.

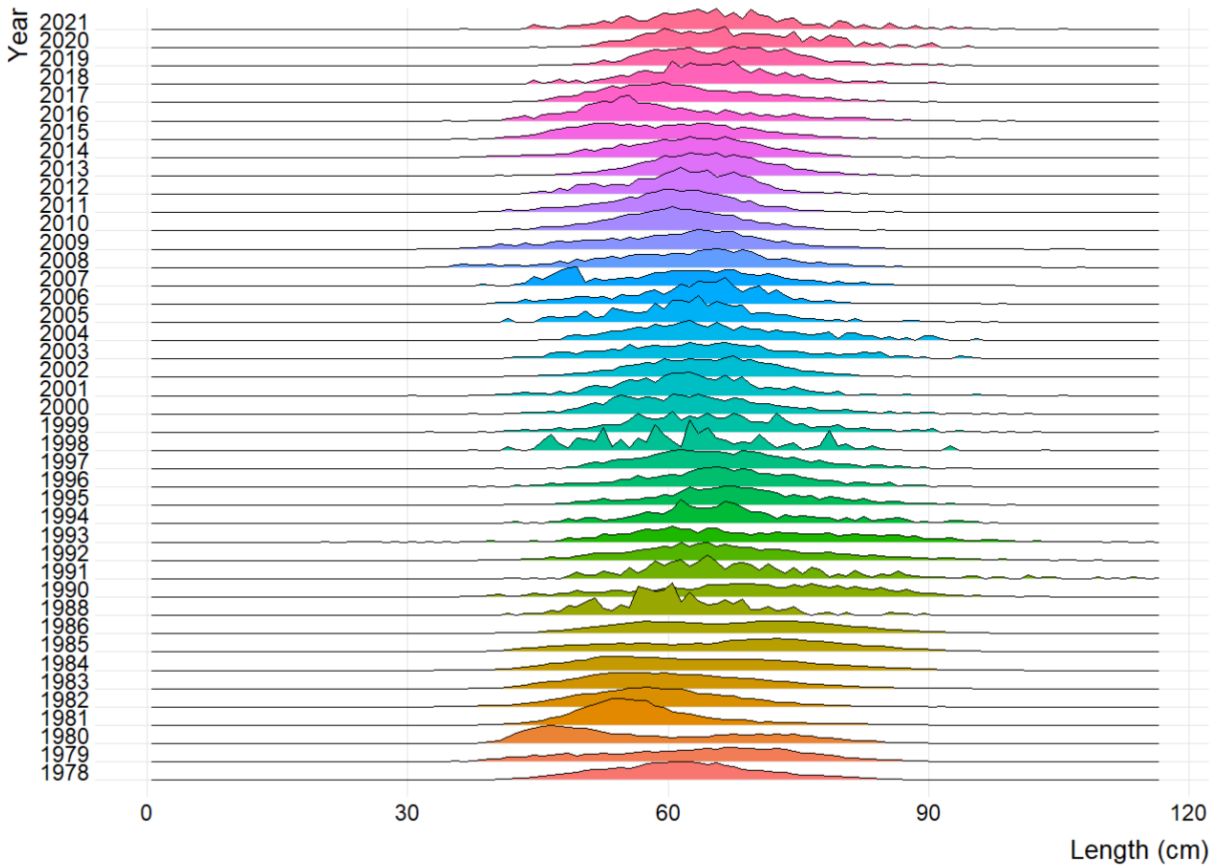


Figure 2.11 Pacific cod length composition by annual proportion from the Gulf of Alaska longline fishery.

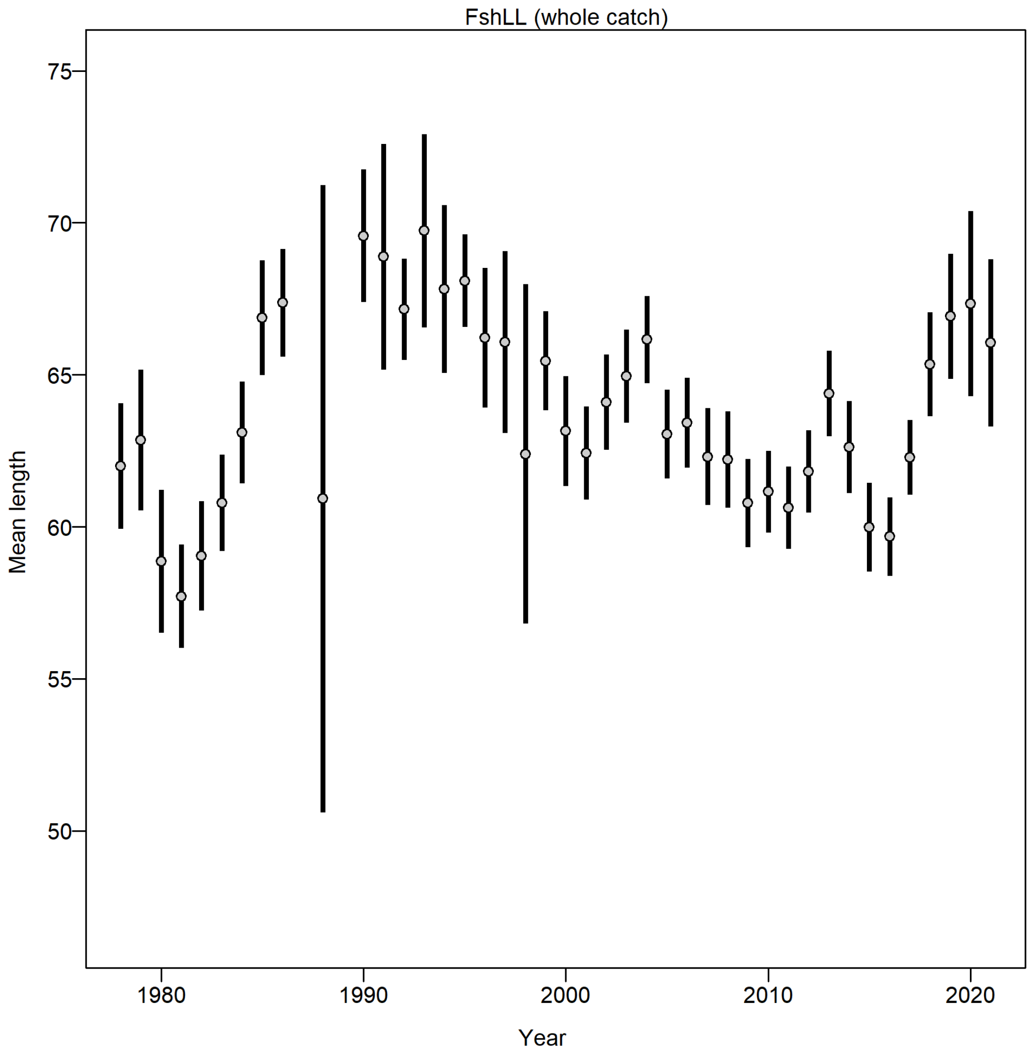


Figure 2.12 Mean length (cm) of Pacific cod from the Gulf of Alaska longline fishery.

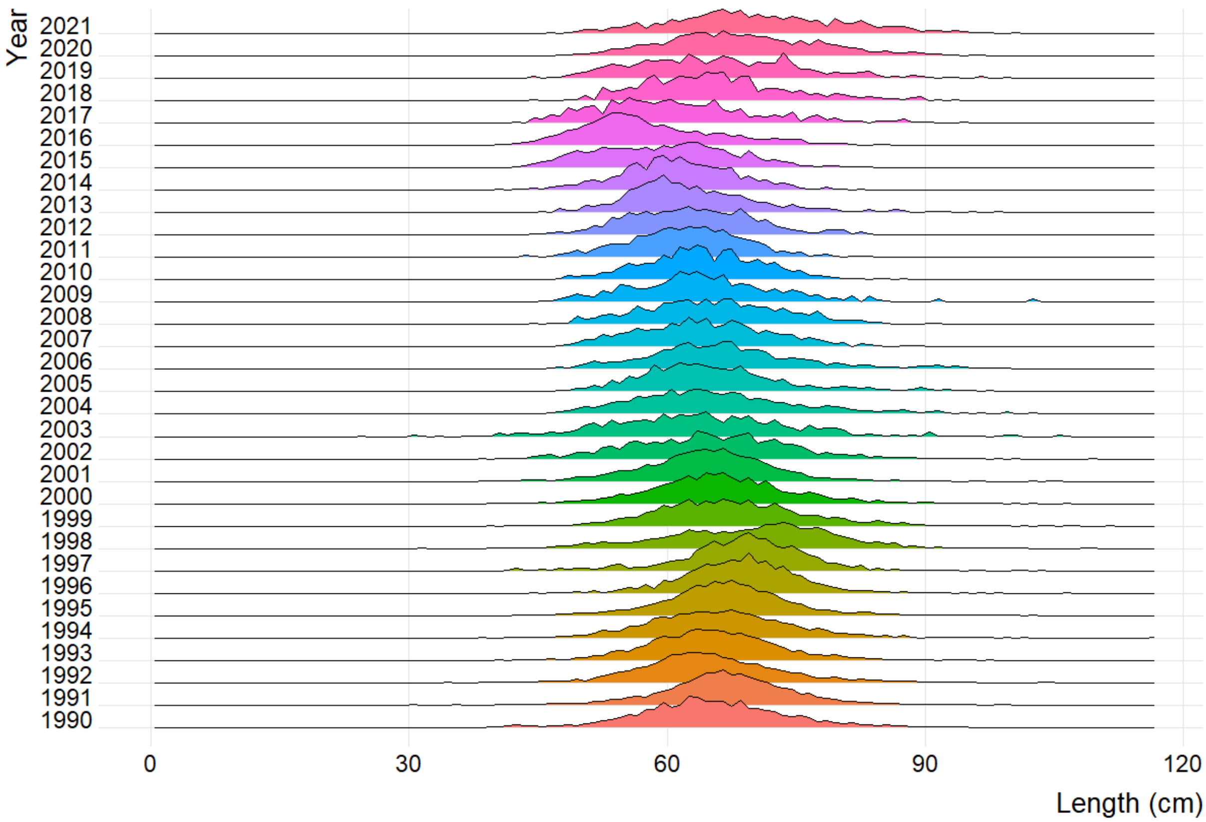


Figure 2.13 Pacific cod length composition by annual proportion from the Gulf of Alaska pot fishery.

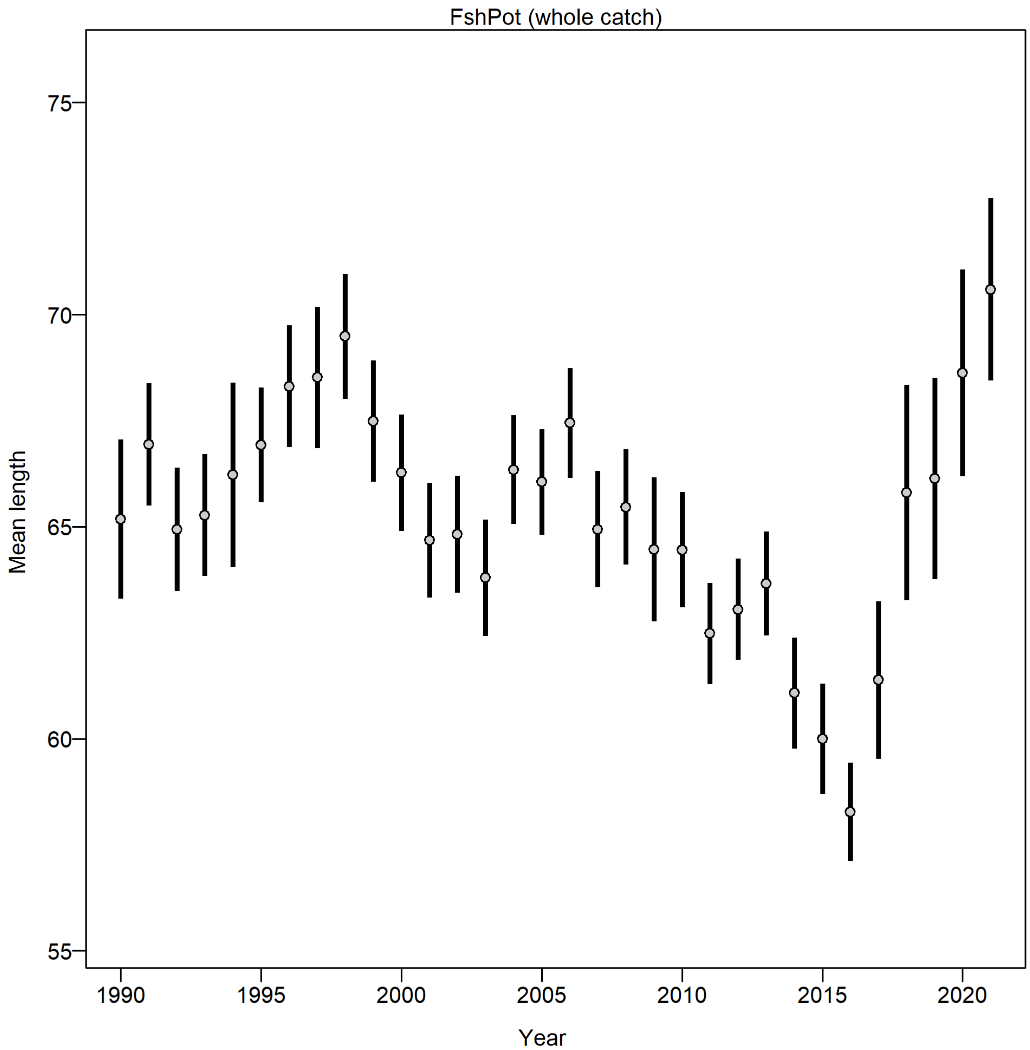


Figure 2.14 Mean length (cm) of Pacific cod from the Gulf of Alaska pot fishery.

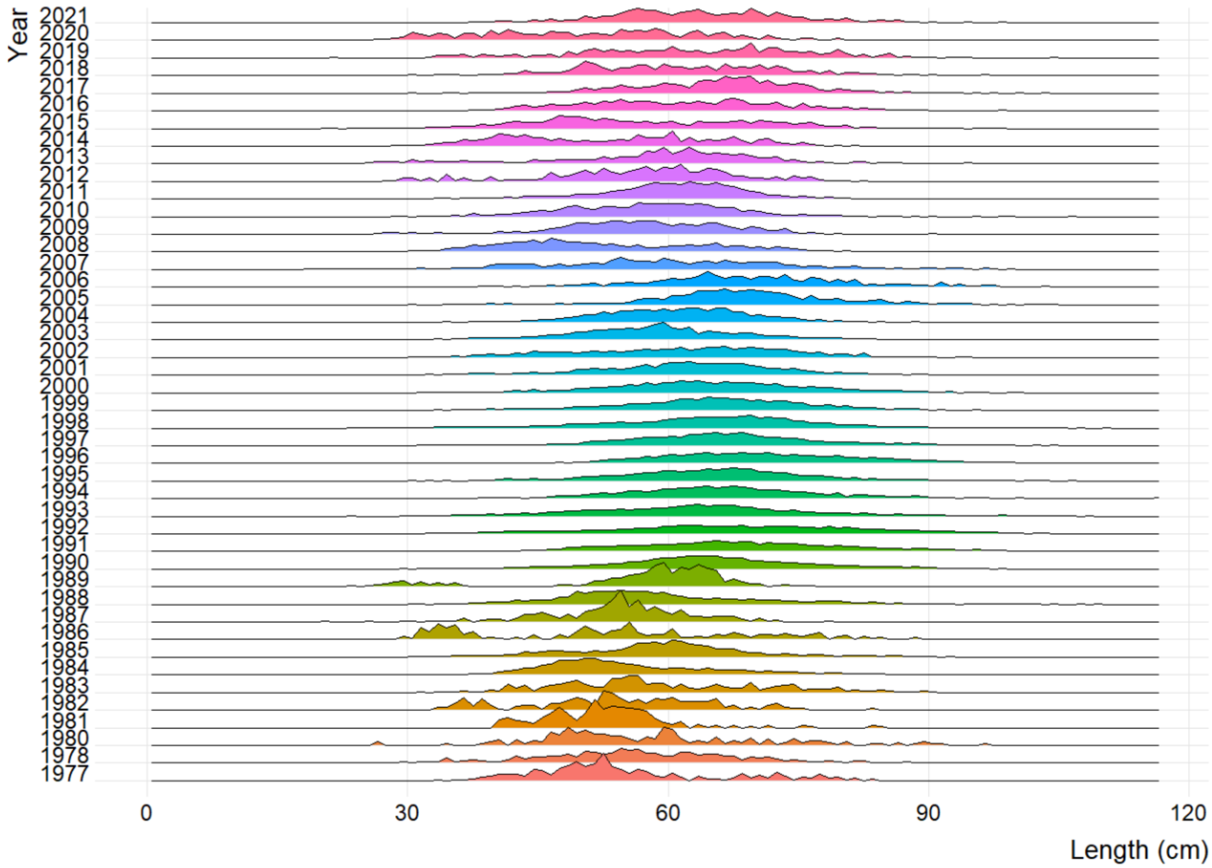


Figure 2.15 Pacific cod length composition by annual proportion from the Gulf of Alaska trawl fishery.

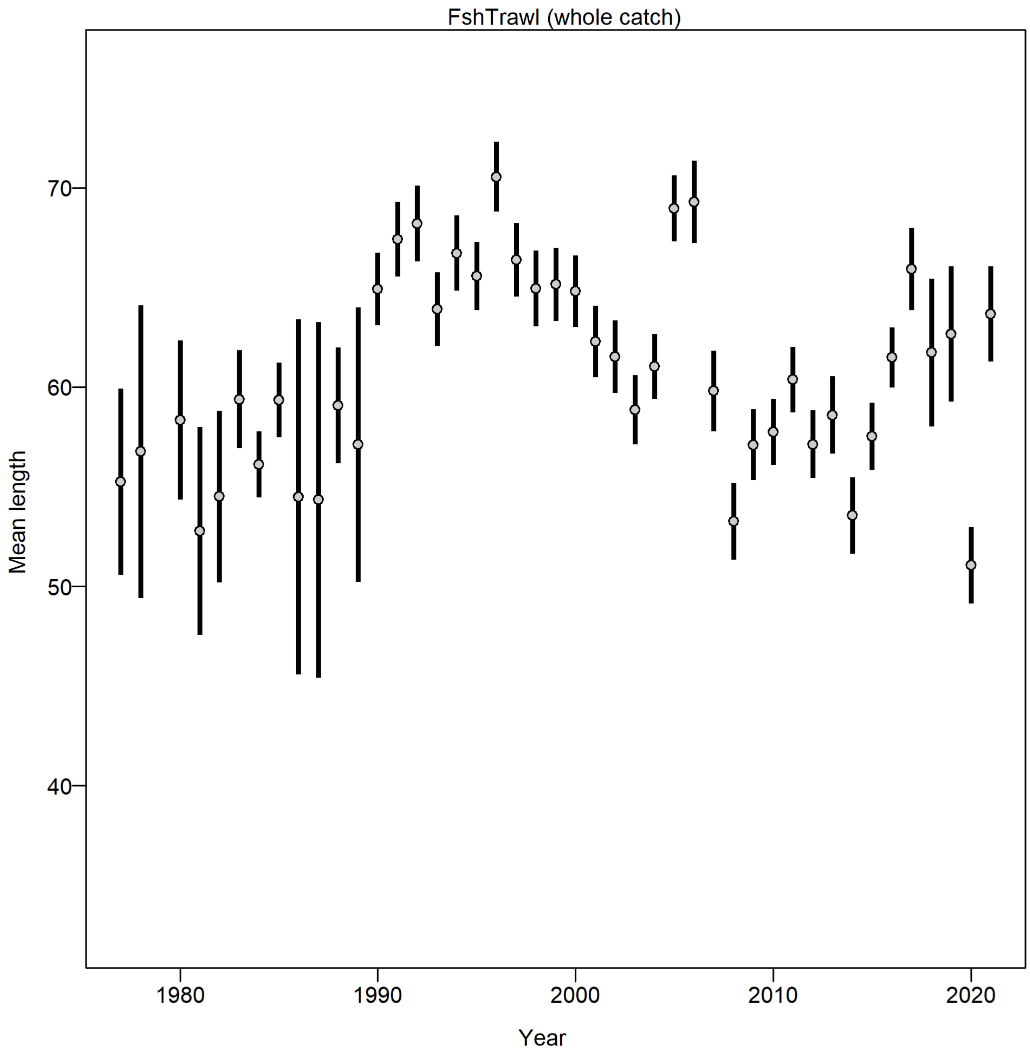


Figure 2.16 Mean length (cm) of Pacific cod from the Gulf of Alaska trawl fishery.

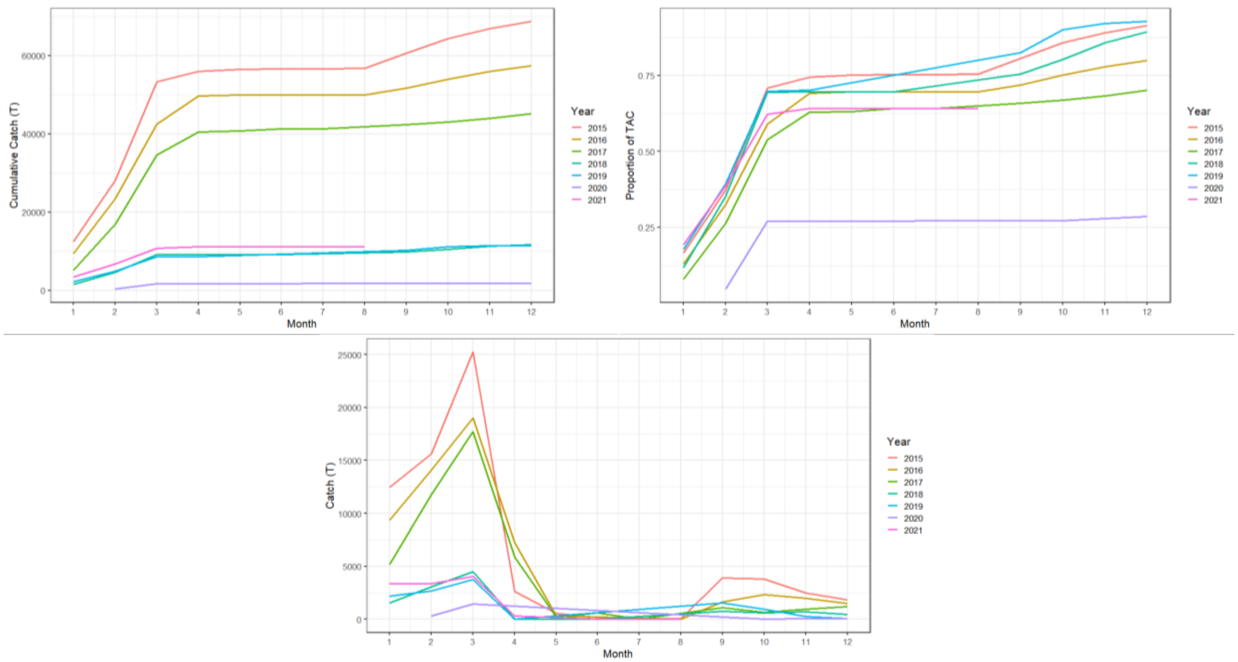


Figure 2.17 Cumulative catch (top left), cumulative proportion of catch (top right), and monthly catch (bottom) by month of the year for 2015-2021.

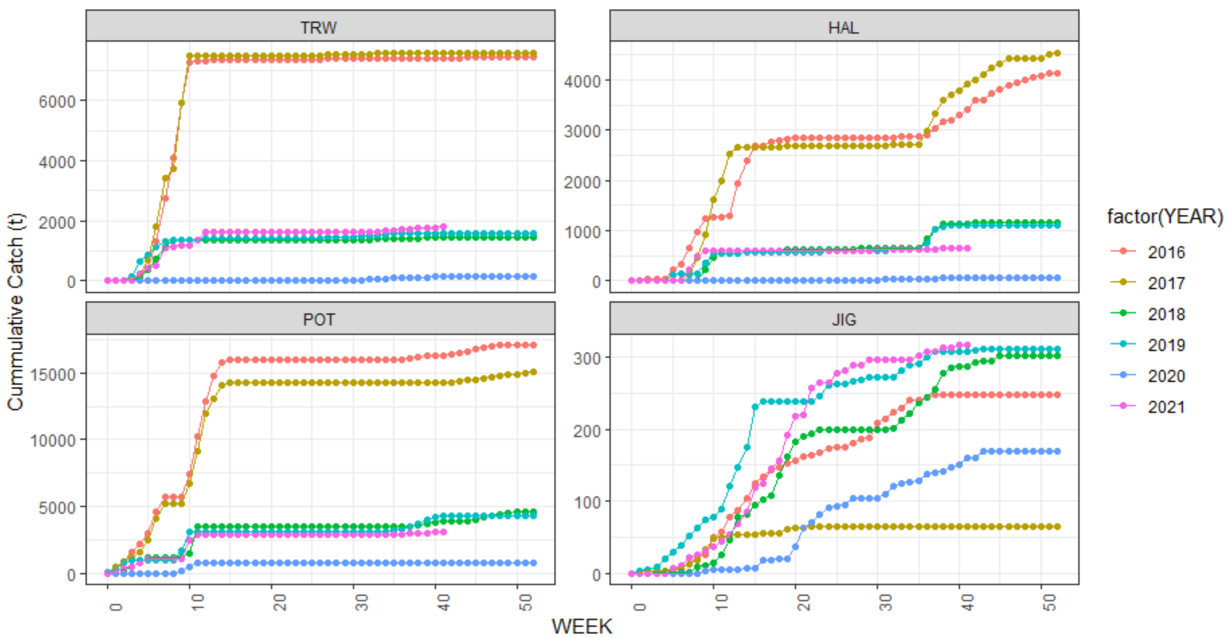


Figure 2.18 Cumulative catch week of the year for 2016-2021 by fleet for the Western Gulf of Alaska.

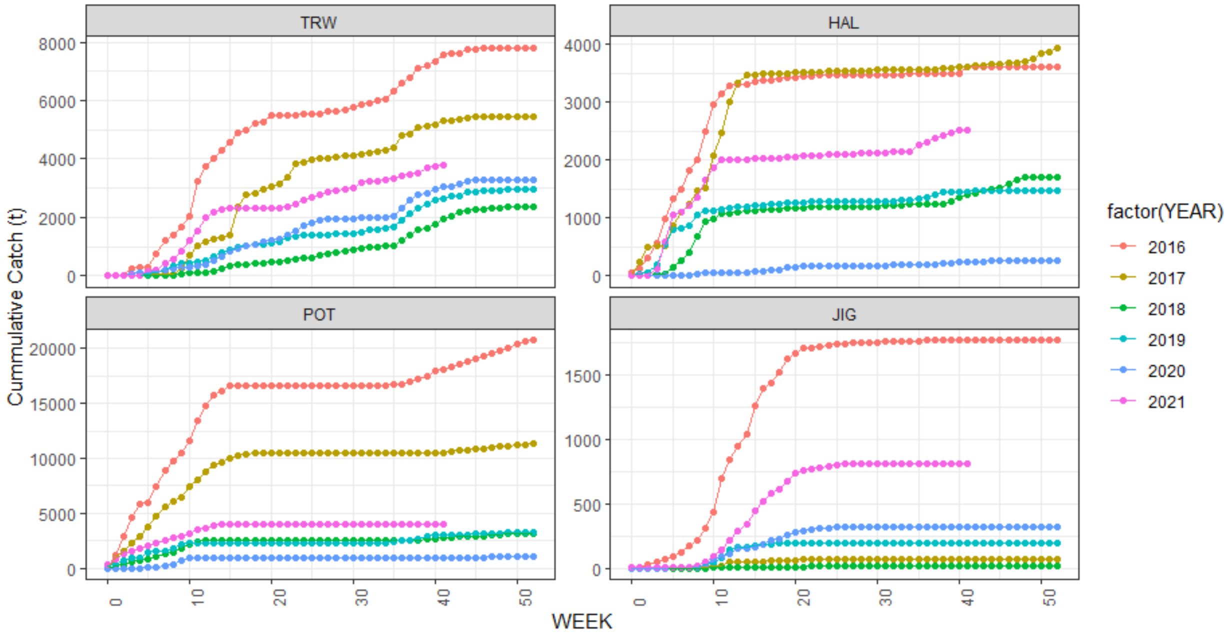


Figure 2.19 Cumulative catch week of the year for 2016-2021 by fleet for the Central Gulf of Alaska.

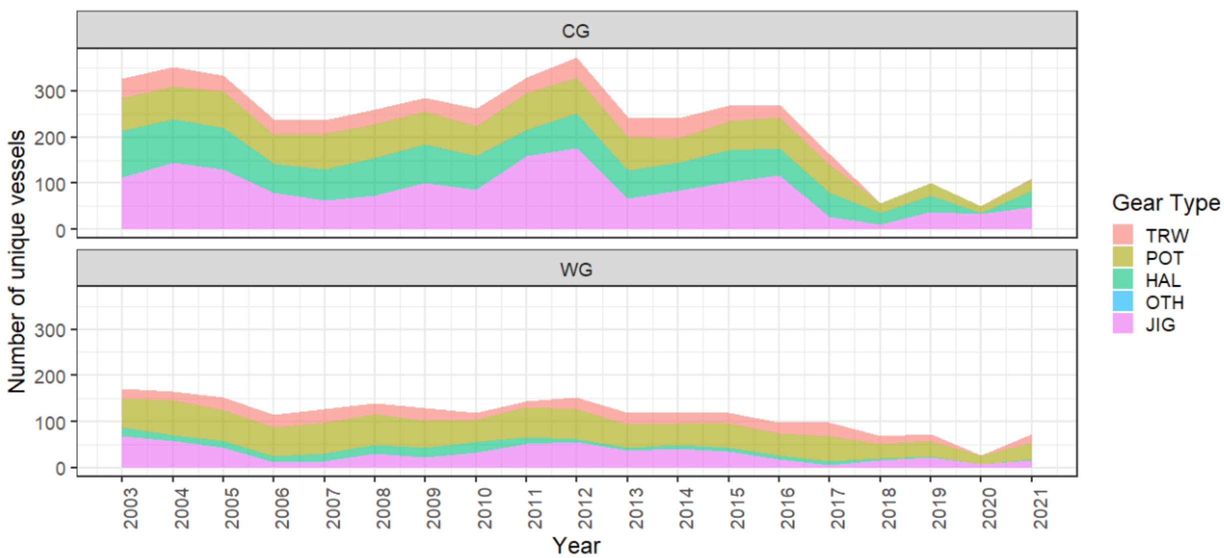


Figure 2.20 Vessel participation in the directed cod fishery by year.

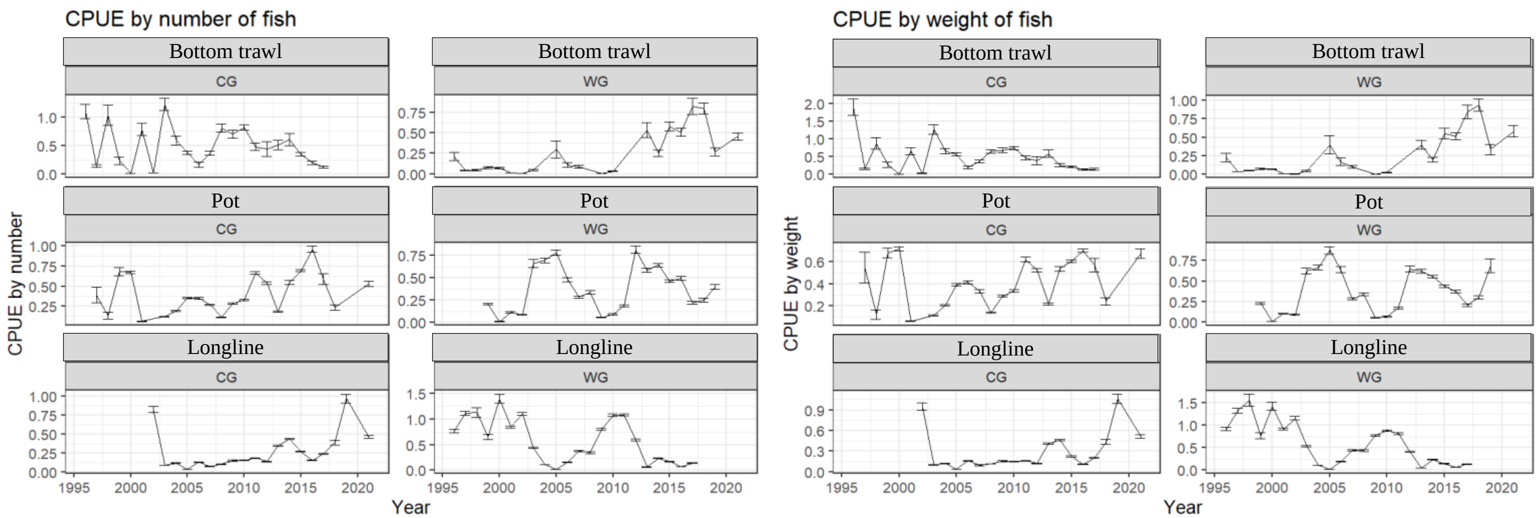


Figure 2.21 Boxplot of CPUE by number (left) and weight (right) from the 1996-2021 Pacific cod CPUE for the Central (CG) and Western (WG) regulatory areas by gear type. Note that the data in these figures are not controlled for vessel or gear differences within a gear type across time, but shows the raw CPUE data distribution for a year. These represent all observed catches and is limited to the directed cod fishery.

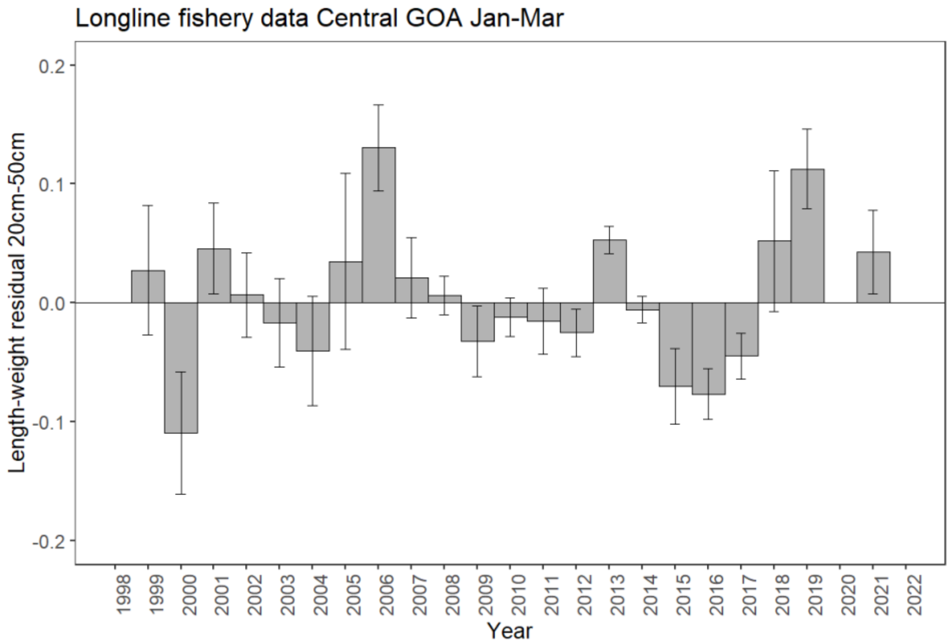


Figure 2.22 Condition of Pacific cod by year in the Central GOA for the longline fishery January-March. Years with zero residuals without error bars are without data.

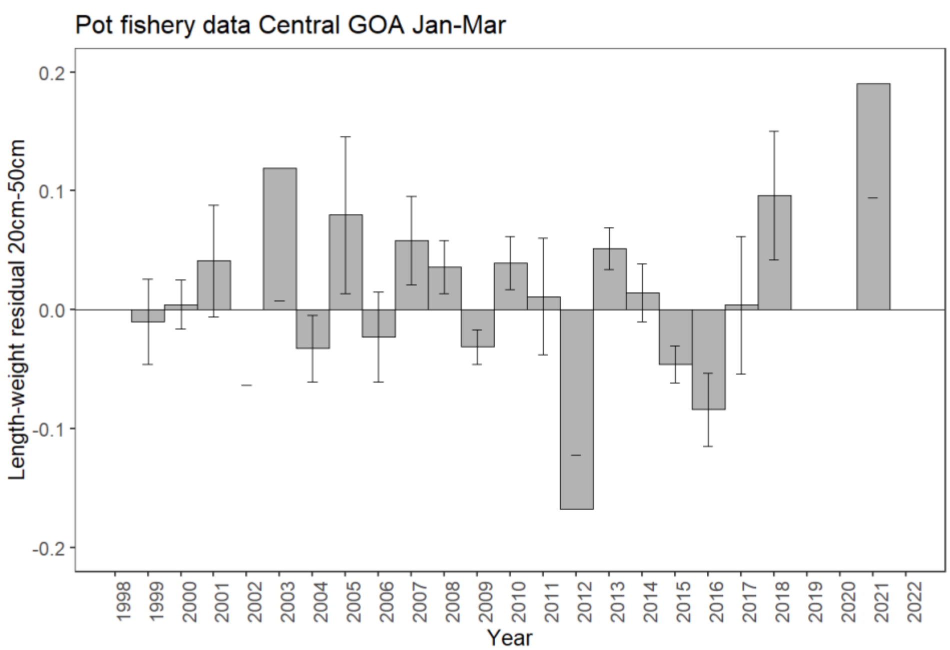


Figure 2.23 Condition of Pacific cod by year in the Central GOA for the pot fishery January-March. Years with zero residuals without error bars are years without data.

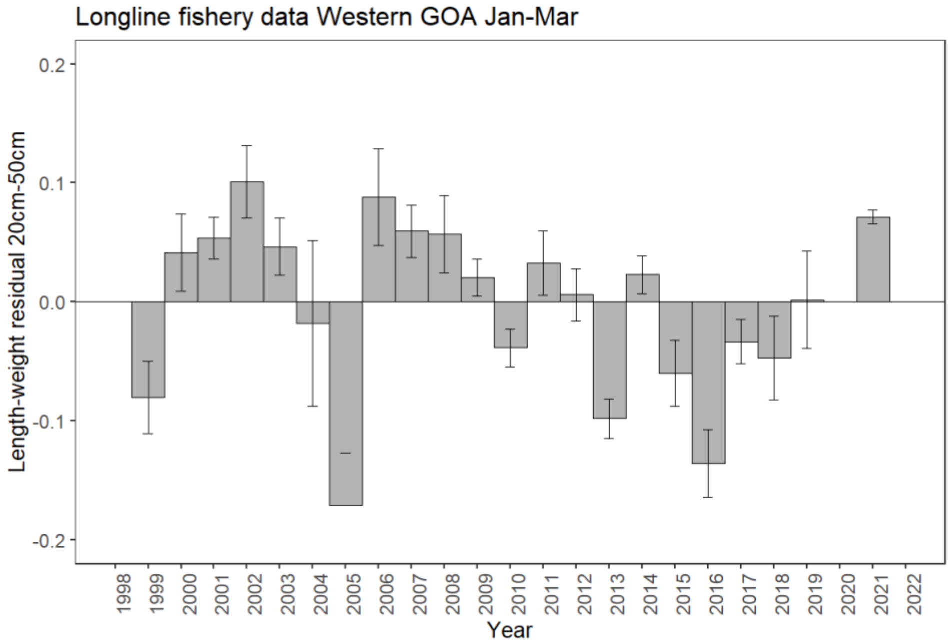


Figure 2.24 Condition of Pacific cod by year in the Western GOA for the longline fishery January-March. Years with zero residuals without error bars are years without data.

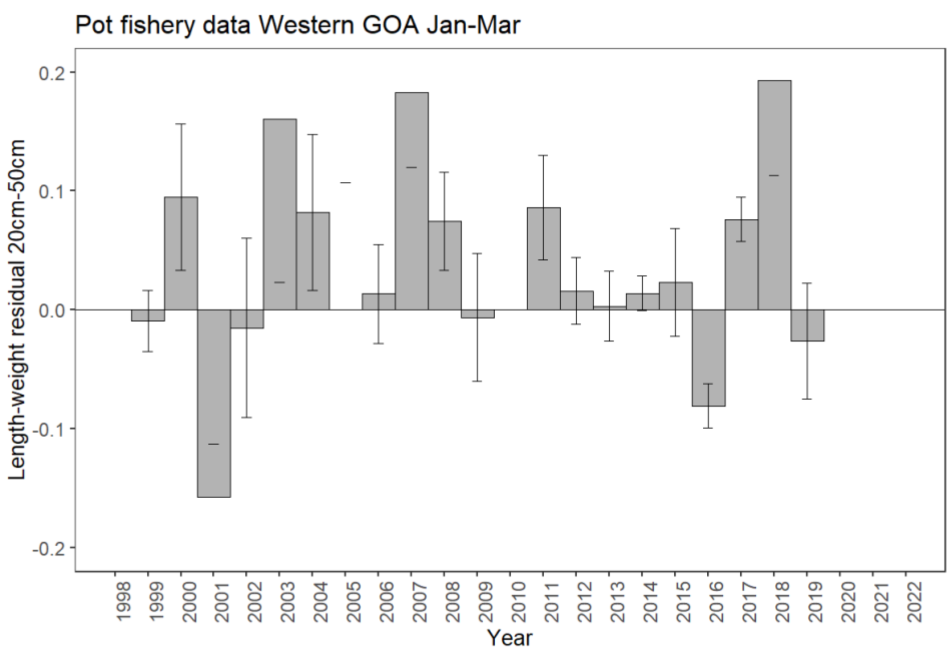


Figure 2.25 Condition of Pacific cod by year in the Western GOA for pot January-March. Years with zero residuals without error bars are years without data.

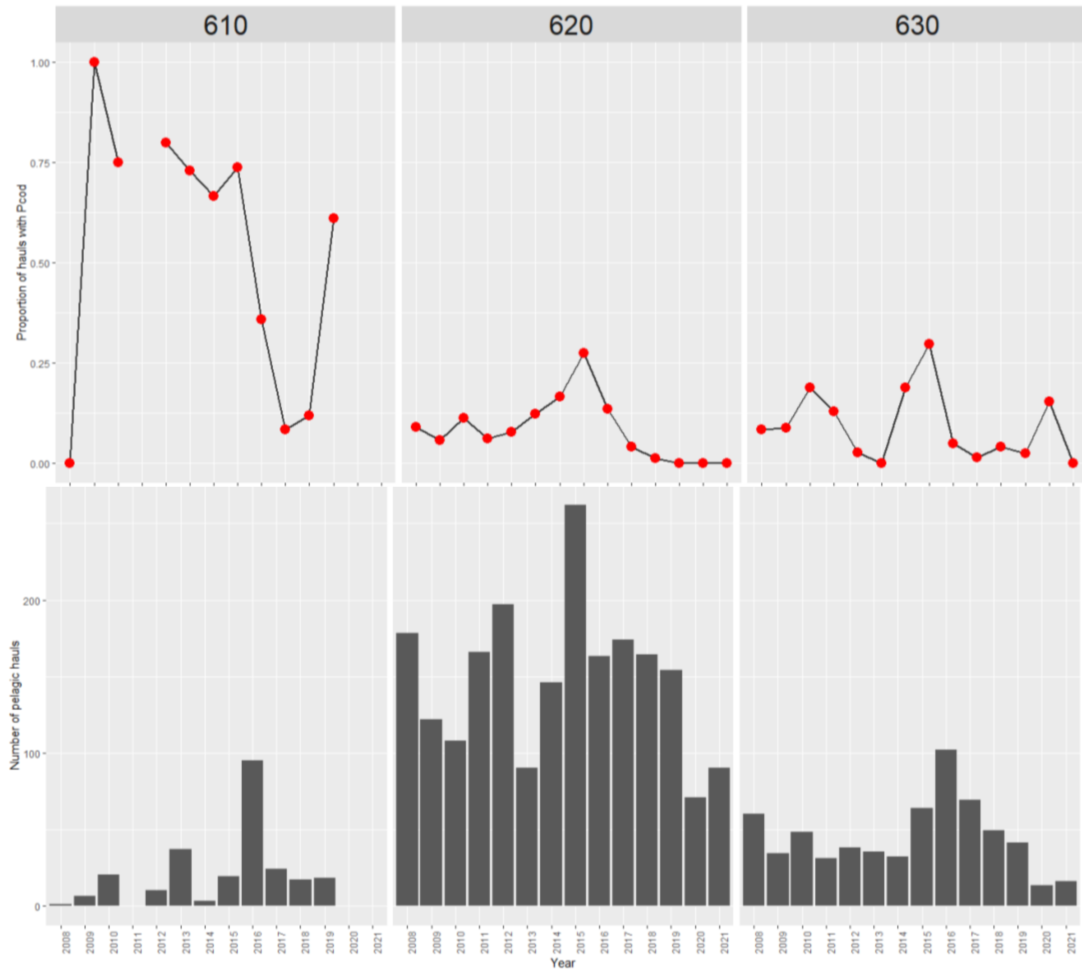


Figure 2.26 Proportion of pelagic trawls in the A Season (January-April) walleye pollock fishery with Pacific cod present by region (top) and number of hauls (bottom).

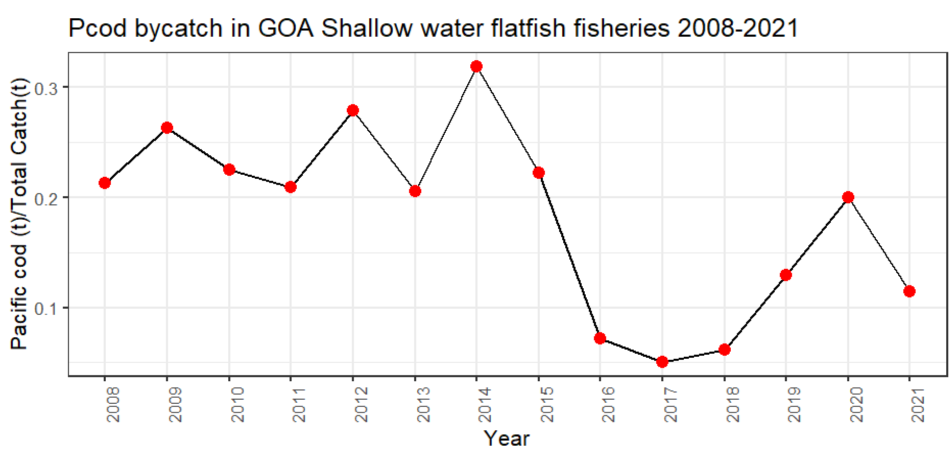


Figure 2.27 Pacific cod bycatch in the Gulf of Alaska shallow water flatfish fishery as tons of Pacific cod per tons of total catch in the fishery by year.

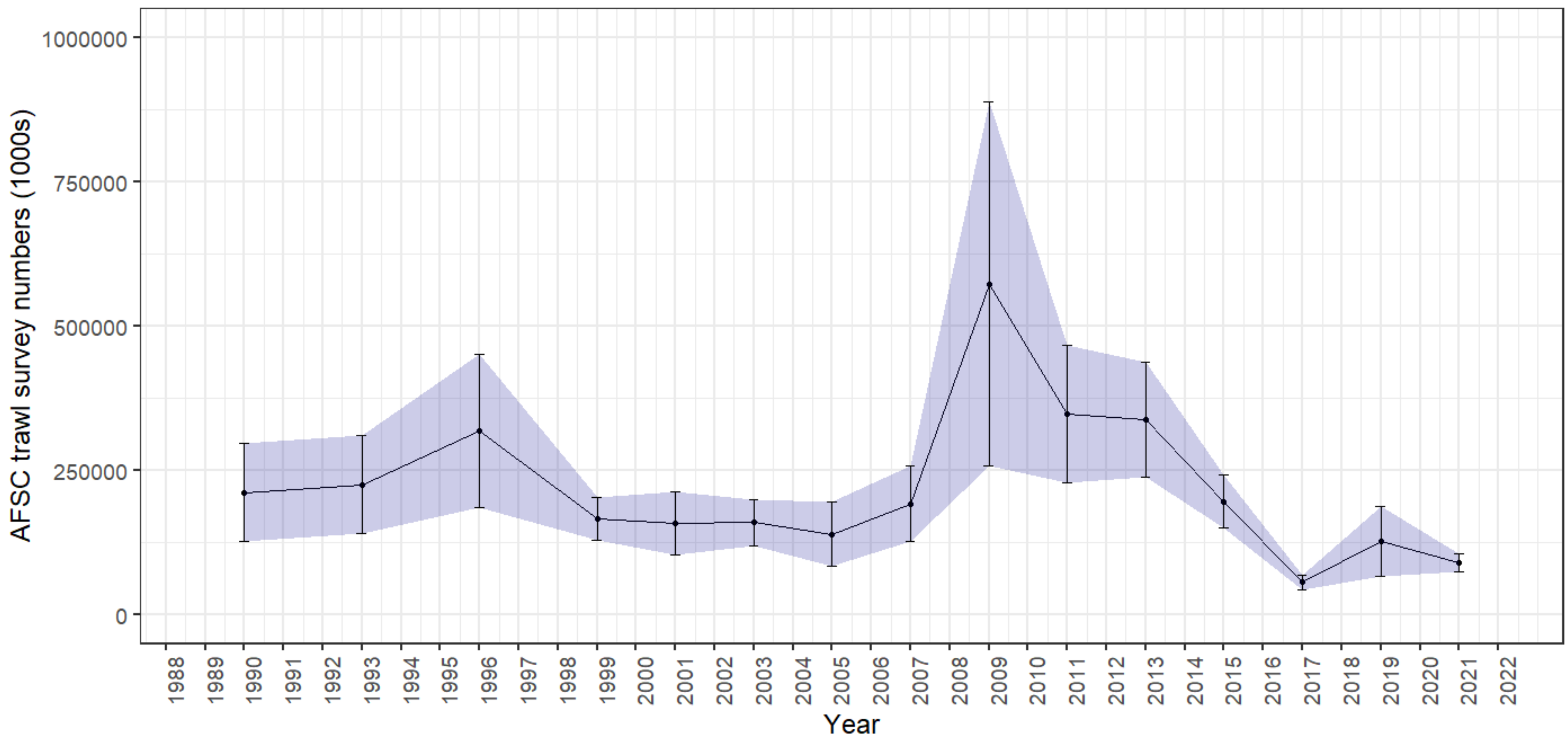


Figure 2.28 GOA bottom trawl survey abundance (numbers) estimate. Bars and shading indicate the 95th percentile confidence intervals.

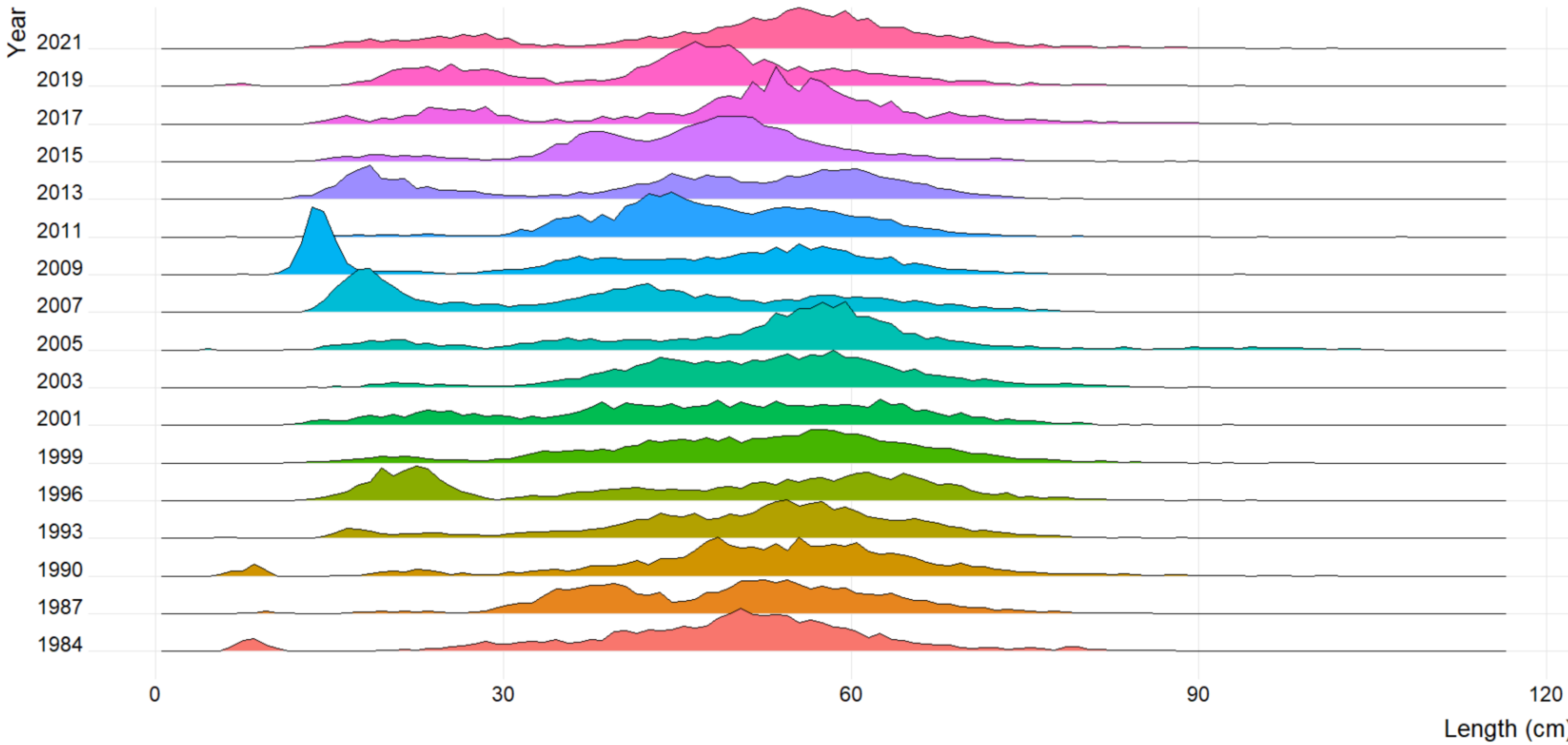


Figure 2.29 GOA bottom trawl survey Pacific cod population numbers at length estimates (max = 0.07).

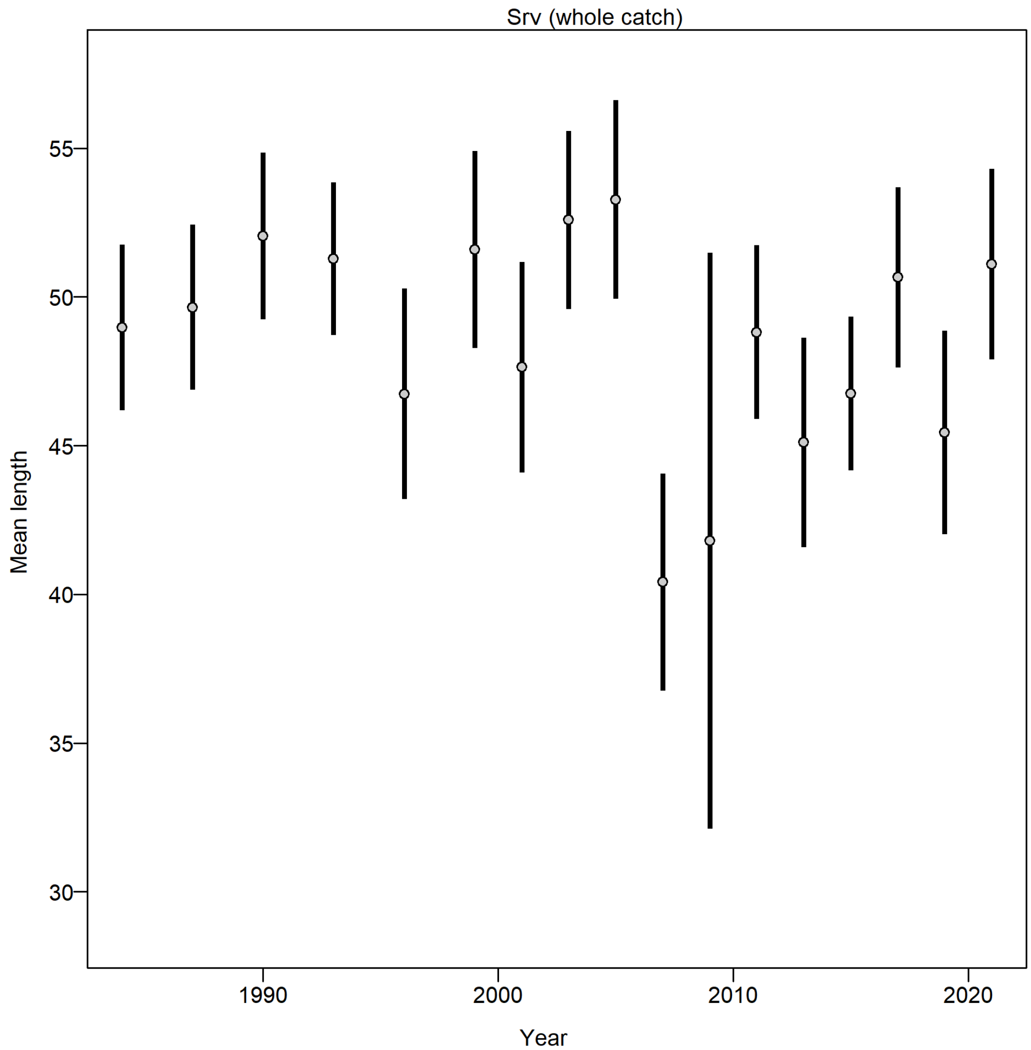


Figure 2.30 Mean length (cm) of Pacific cod in the GOA bottom trawl survey.

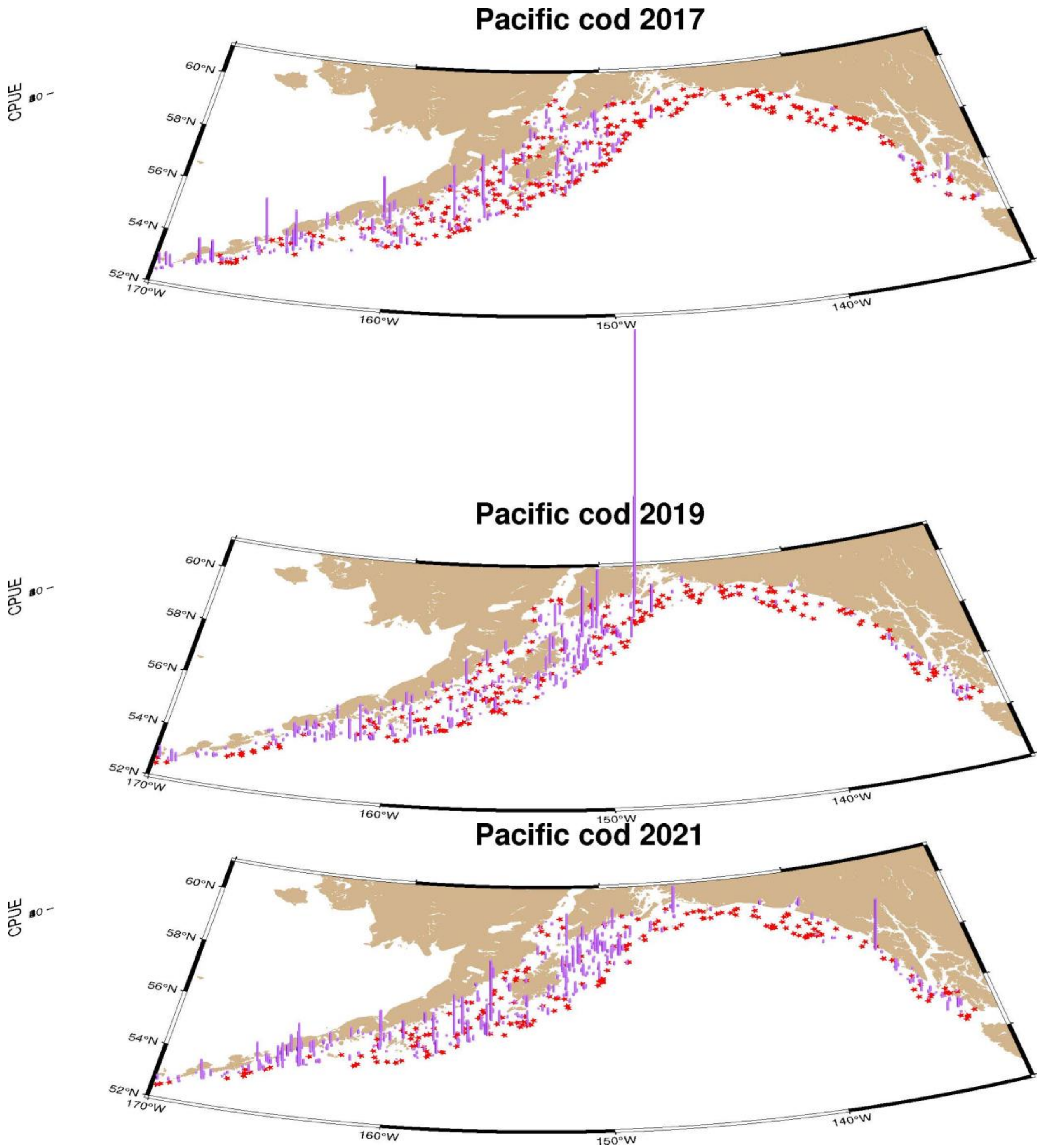


Figure 2.31 Distribution of AFSC bottom trawl survey CPUE of Pacific cod for 2017-2019.

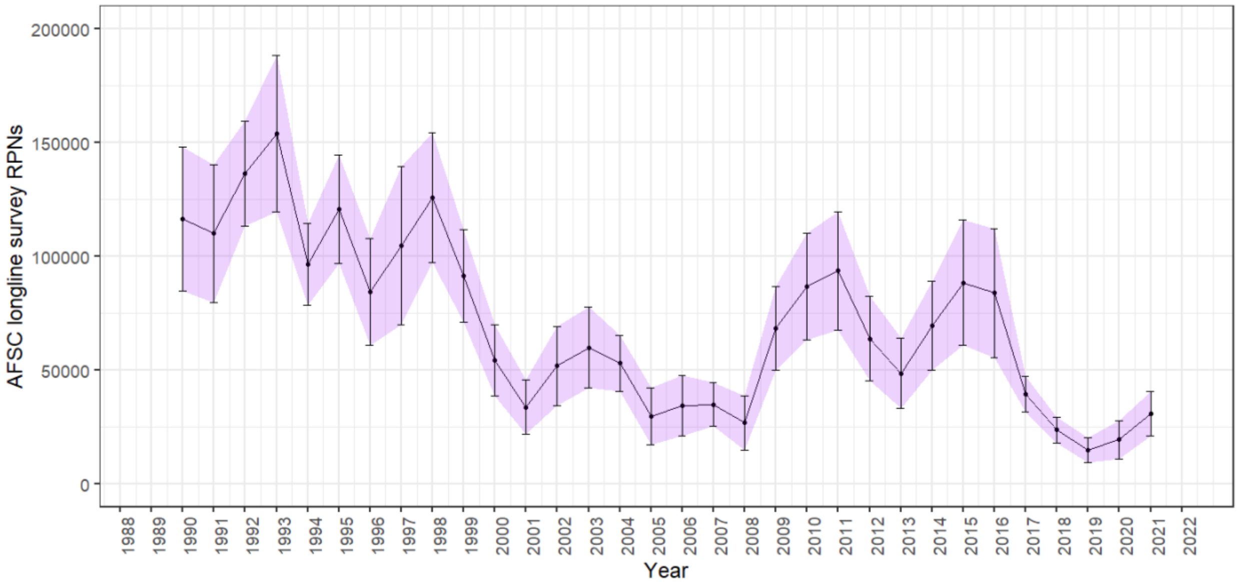


Figure 2.32 AFSC longline survey Pacific cod relative population numbers (RPN) time series. Bars and shading indicate the 95th percentile confidence intervals.

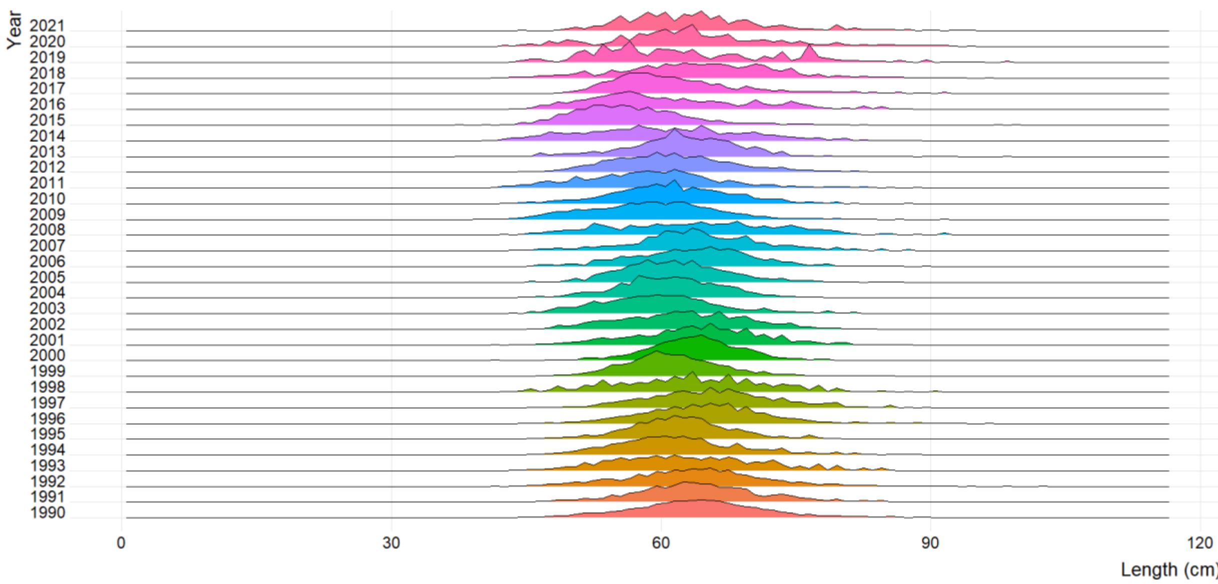


Figure 2.33 AFSC longline survey Pacific cod size composition (max=0.09).

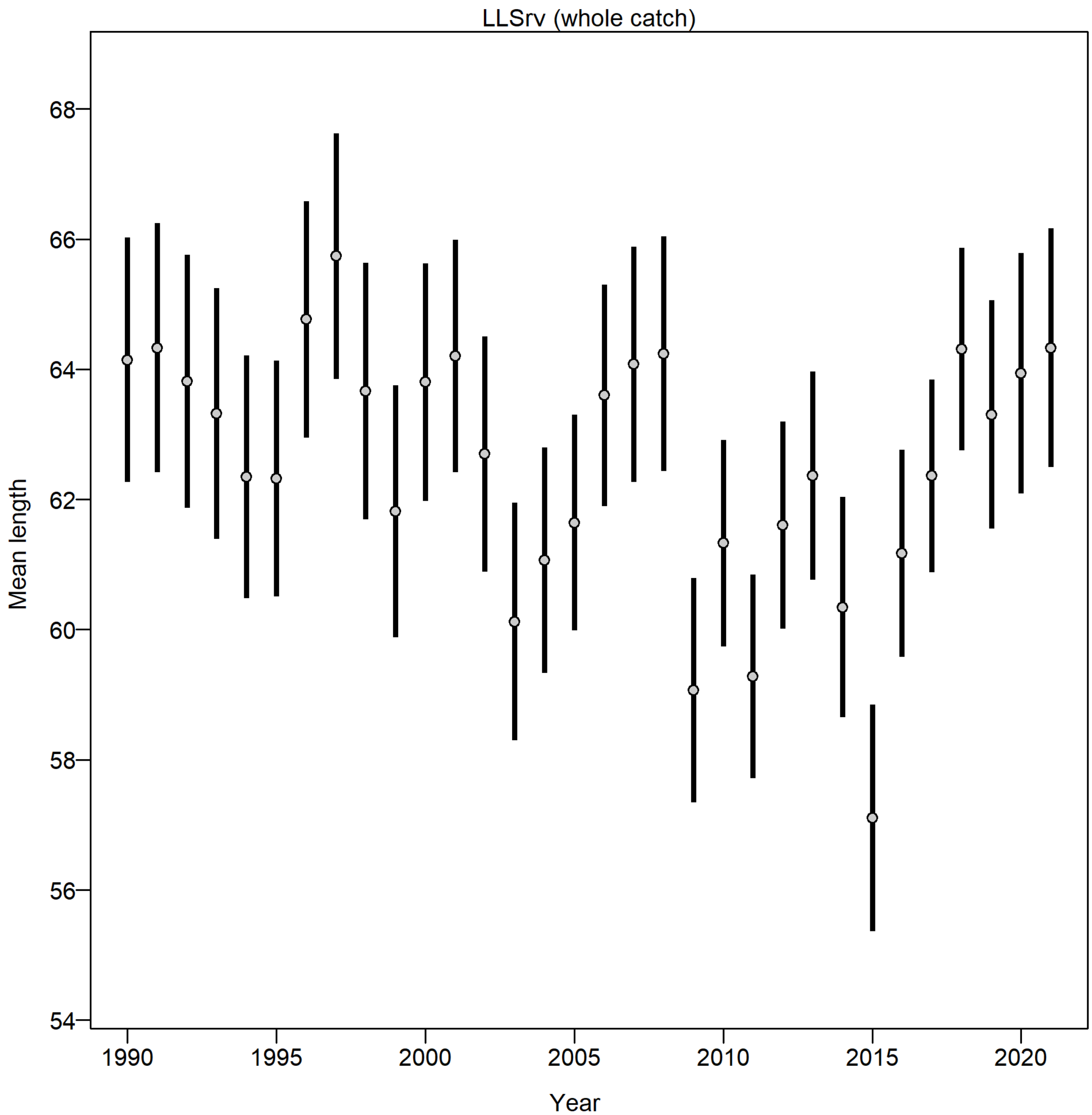


Figure 2.34 Mean length (cm) of Pacific cod from the AFSC longline survey.

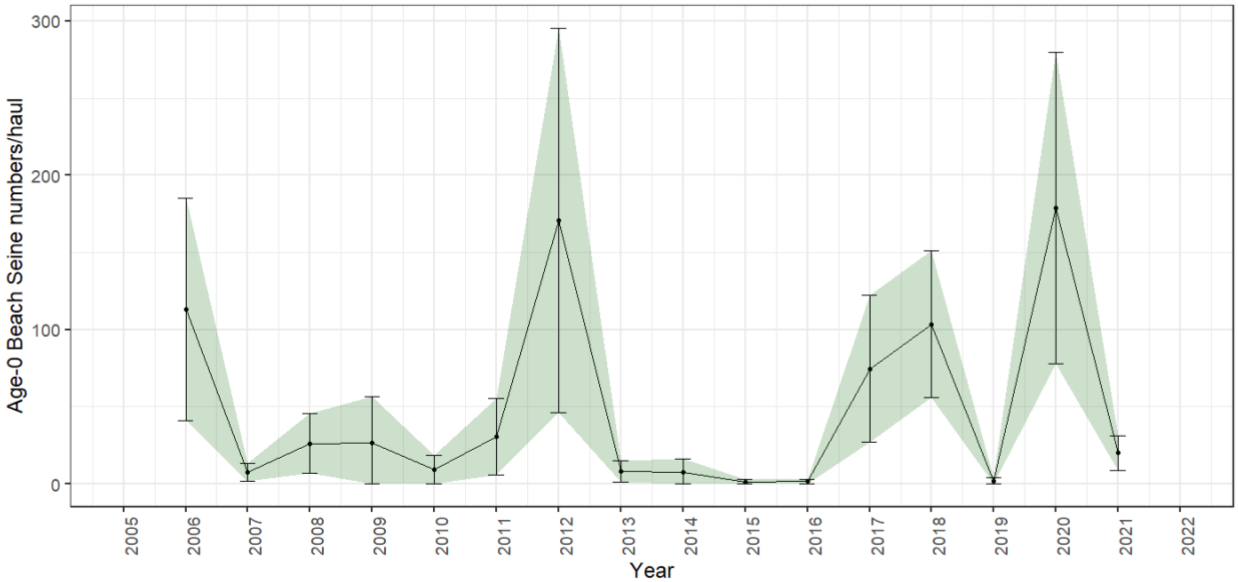


Figure 2.35 Age-0 beach seine survey numbers per haul, bars and shading indicate the 95th percentile confidence intervals.

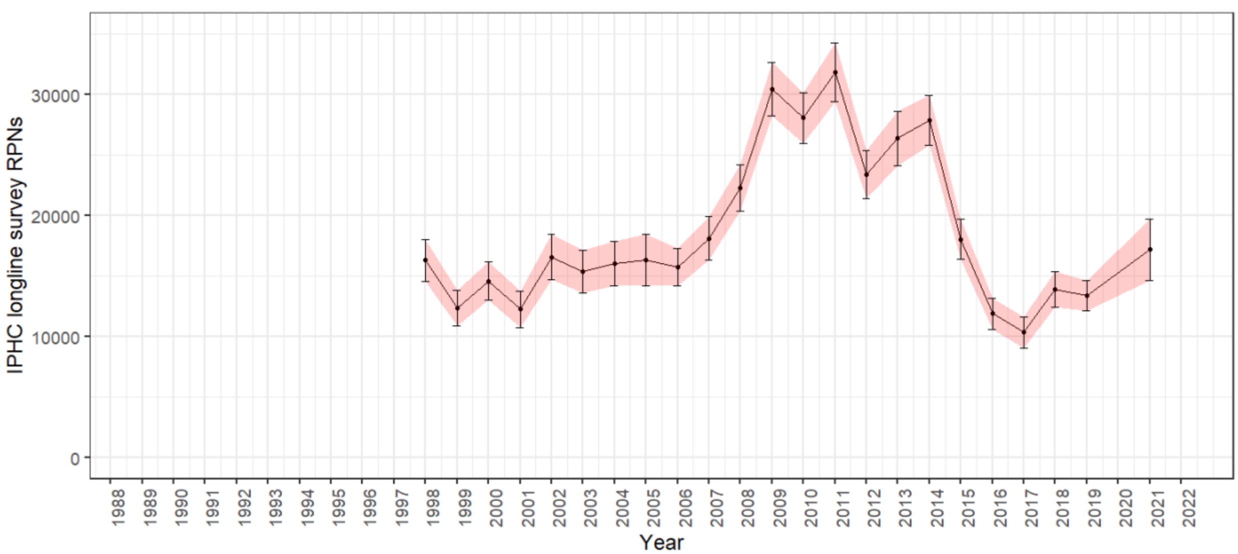


Figure 2.36 IPHC halibut longline survey Pacific cod RPN time series. Bars and shading indicate the 95th percentile confidence intervals.

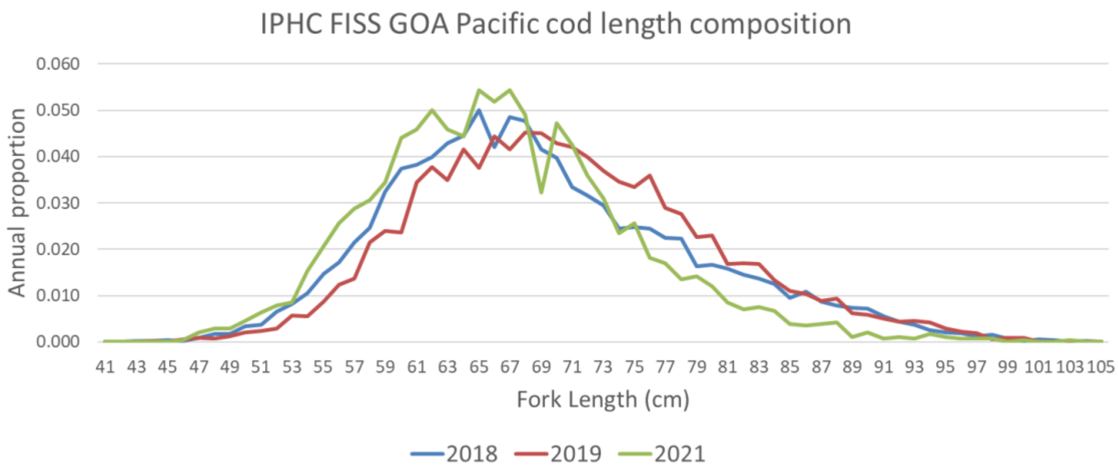


Figure 2.37 IPHC Fishery-independent setline survey (FISS) Pacific cod length composition collection for 2018, 2019, and 2021. These are raw frequency collections and have not been proportioned by FISS RPN.

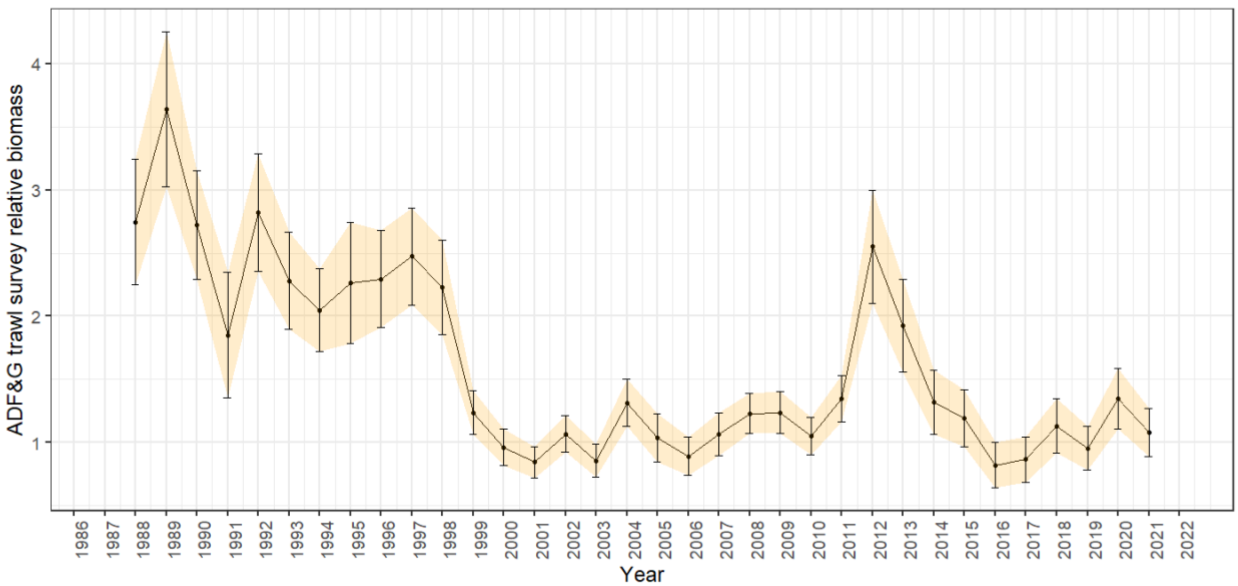


Figure 2.38 ADFG bottom trawl survey delta-glm Pacific cod density index time series. Bars and shading indicate the 95th percentile confidence intervals.

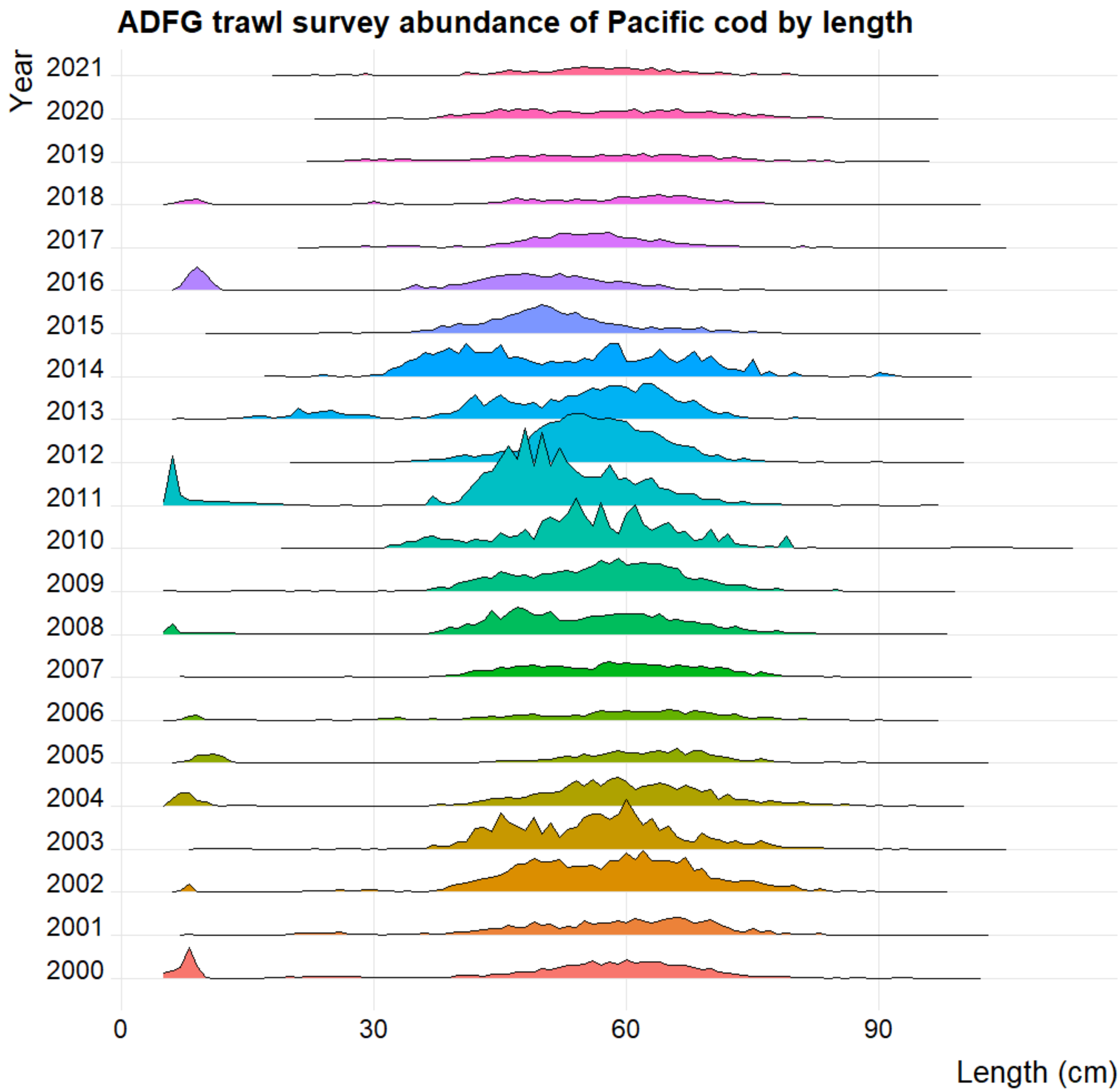


Figure 2.39 ADFG large-mesh trawl survey Pacific cod population numbers at length estimates.

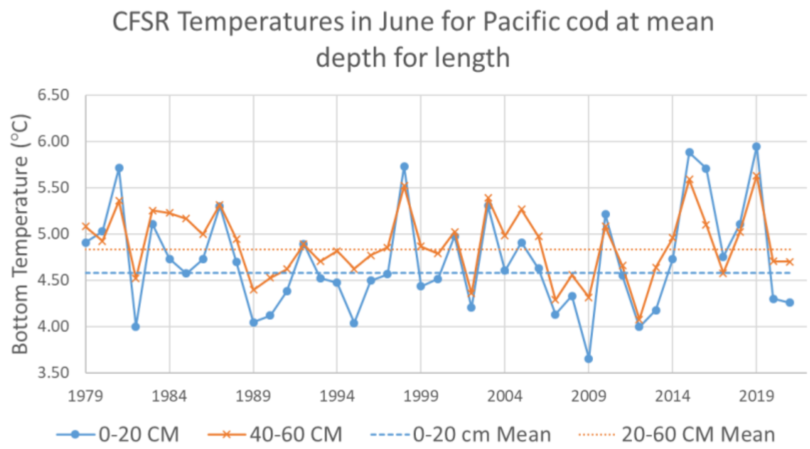


Figure 2.40 Climate Forcast System Reanalysis (CFSR) Central Gulf of Alaska bottom temperatures at the AFSC bottom trawl survey mean depths for 0-20 cm and 40-60 cm Pacific cod in June.

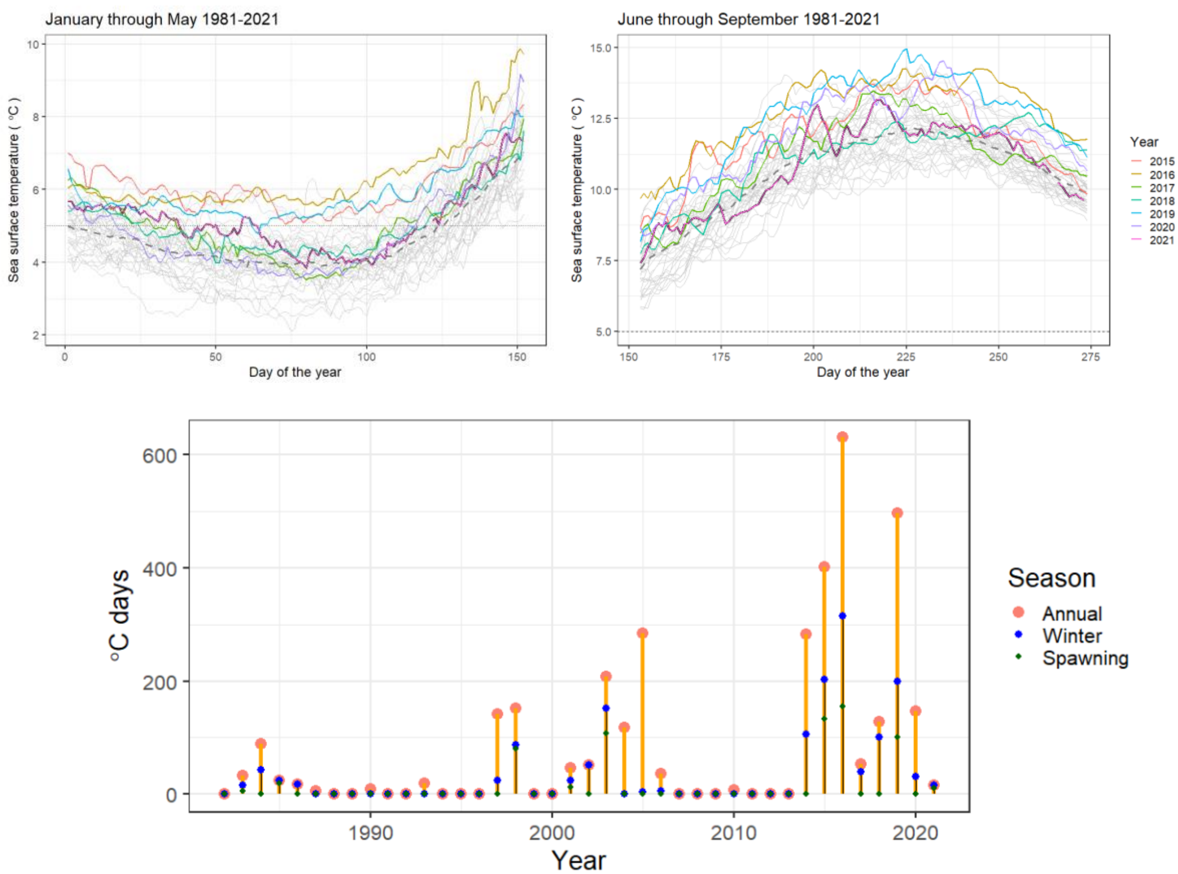


Figure 2.41 Sea surface temperatures (top left) February to March, (top right) June through September, and (bottom) index of the sum of the annual marine heatwave cumulative intensity (℃ days) for 1981-2021 (larger yellow points) and index of the sum of the annual winter marine heatwave cumulative intensity for 1981-2021 (smaller blue points) from the daily mean sea surface temperatures NOAA high resolution blended analysis data for the Central Gulf of Alaska. The 2021 index value is the sum through 30 September 2021.

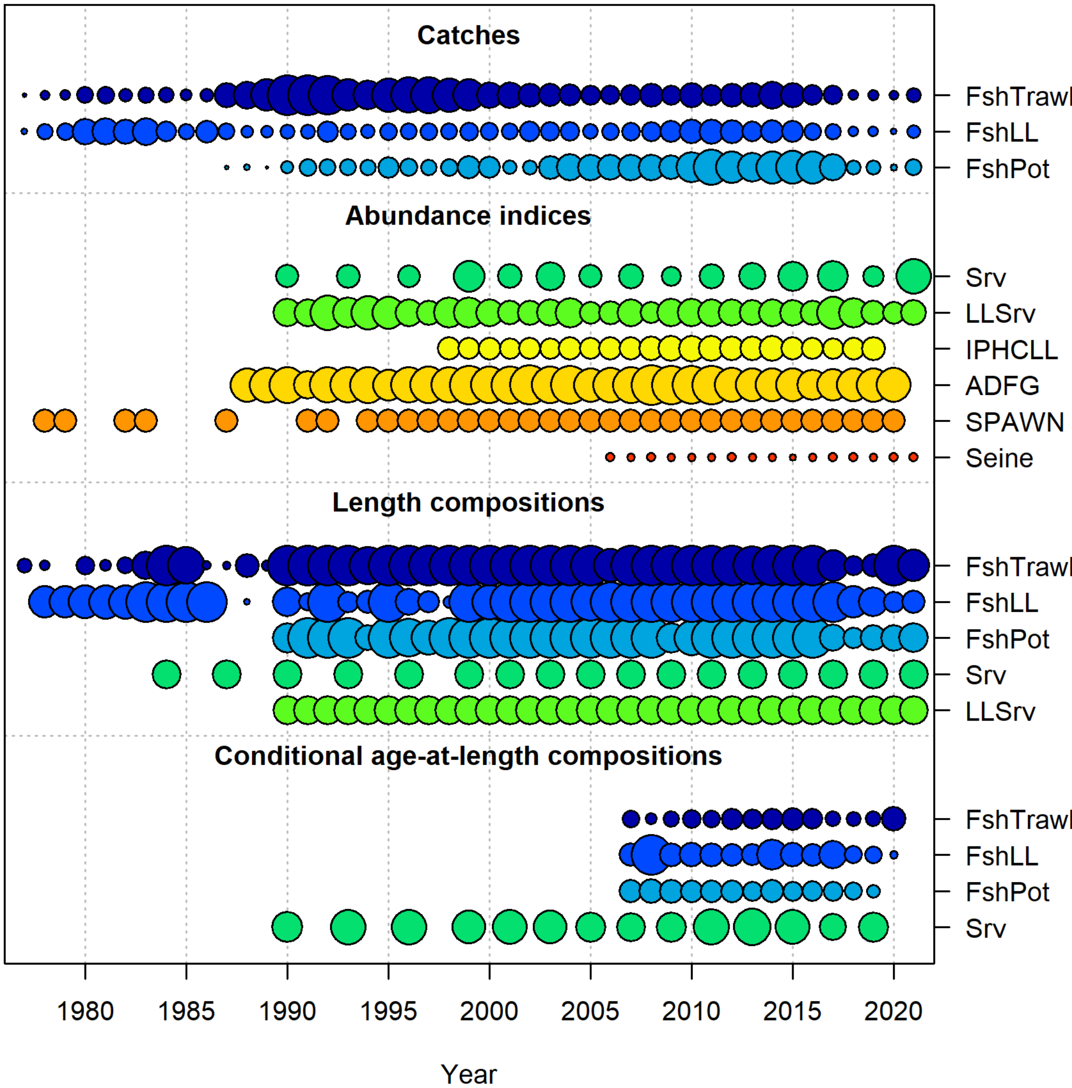


Figure 2.42 Data in the 2021 models, circle area is relative to initial precision within data type. Note that the ADFG, IPHC, and SPAWN are included in the data, but are not fit in any of the models presented this year. In addition the Seine (Age-0 index) data were not included in Models 19.1 or 21.1. Data presence by year for each fleet, where circle area is relative within a data type. Circles are proportional to total catch for catches; to precision for indices and to total sample size for compositions and length-at-age observations. Note that since the circles are scaled relative to maximum within each type, the scaling within separate plots should not be compared.

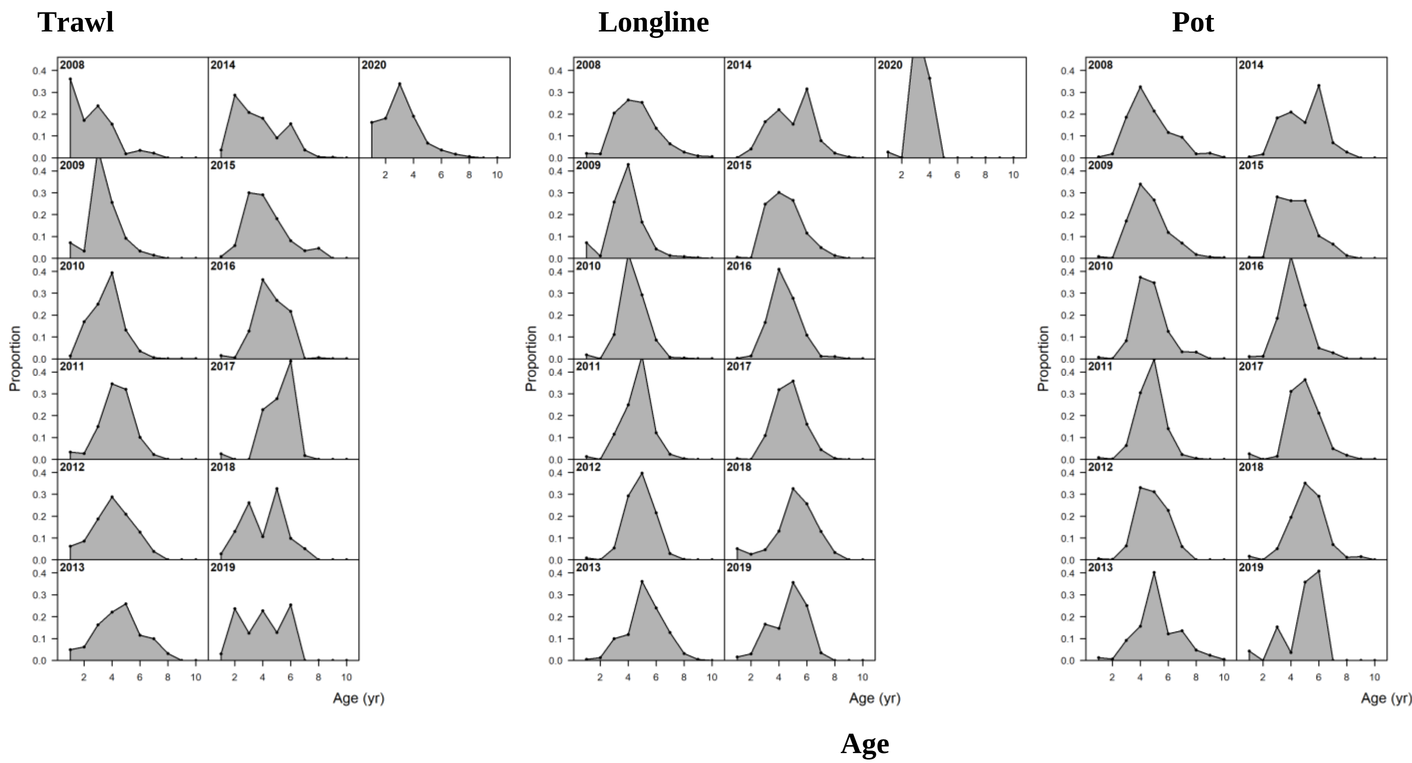


Figure 2.43 Pacific cod age composition data from the Gulf of Alaska fisheries by gear type.

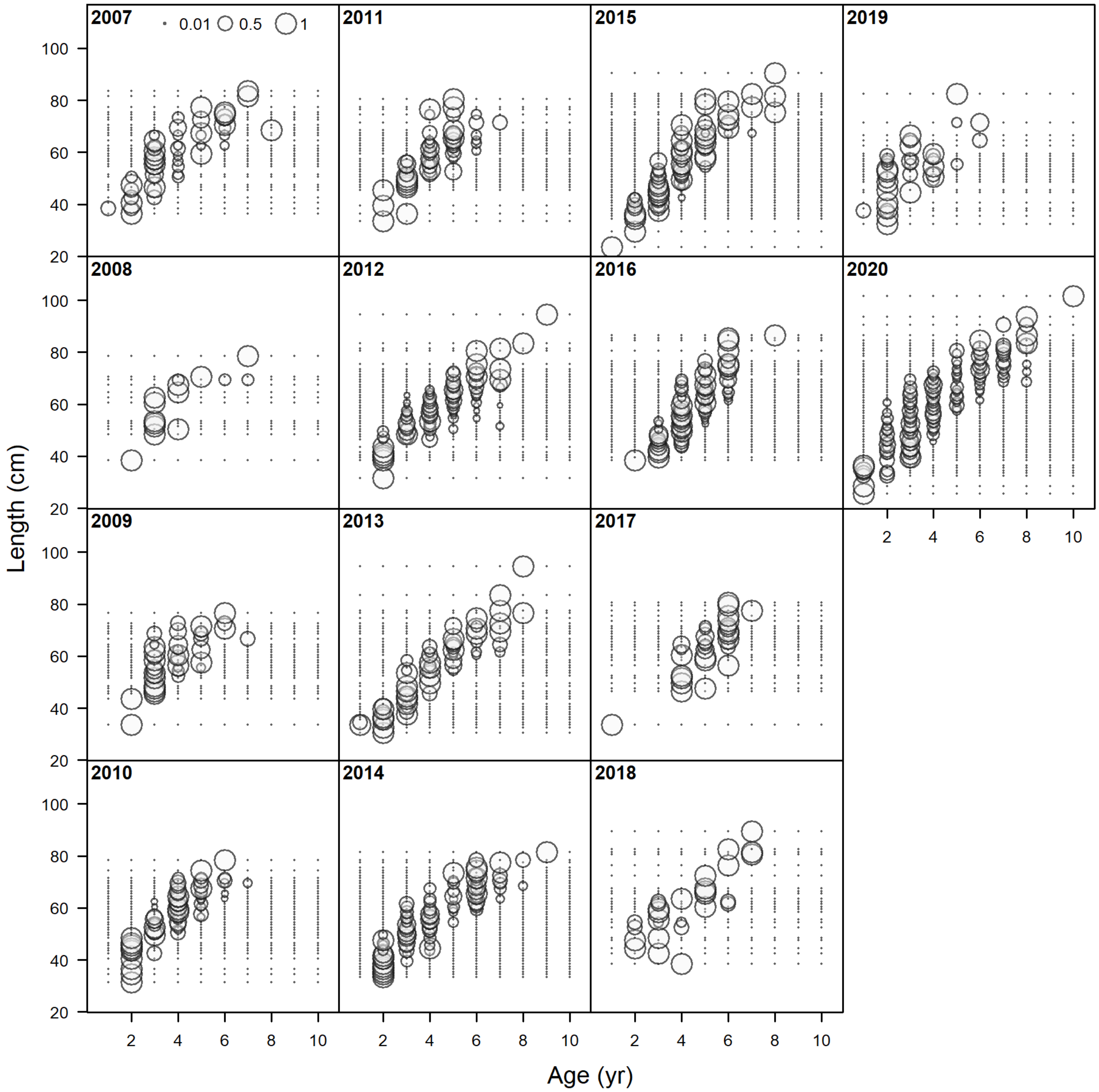


Figure 2.44 Pacific cod conditional length at age from the Gulf of Alaska trawl fishery.

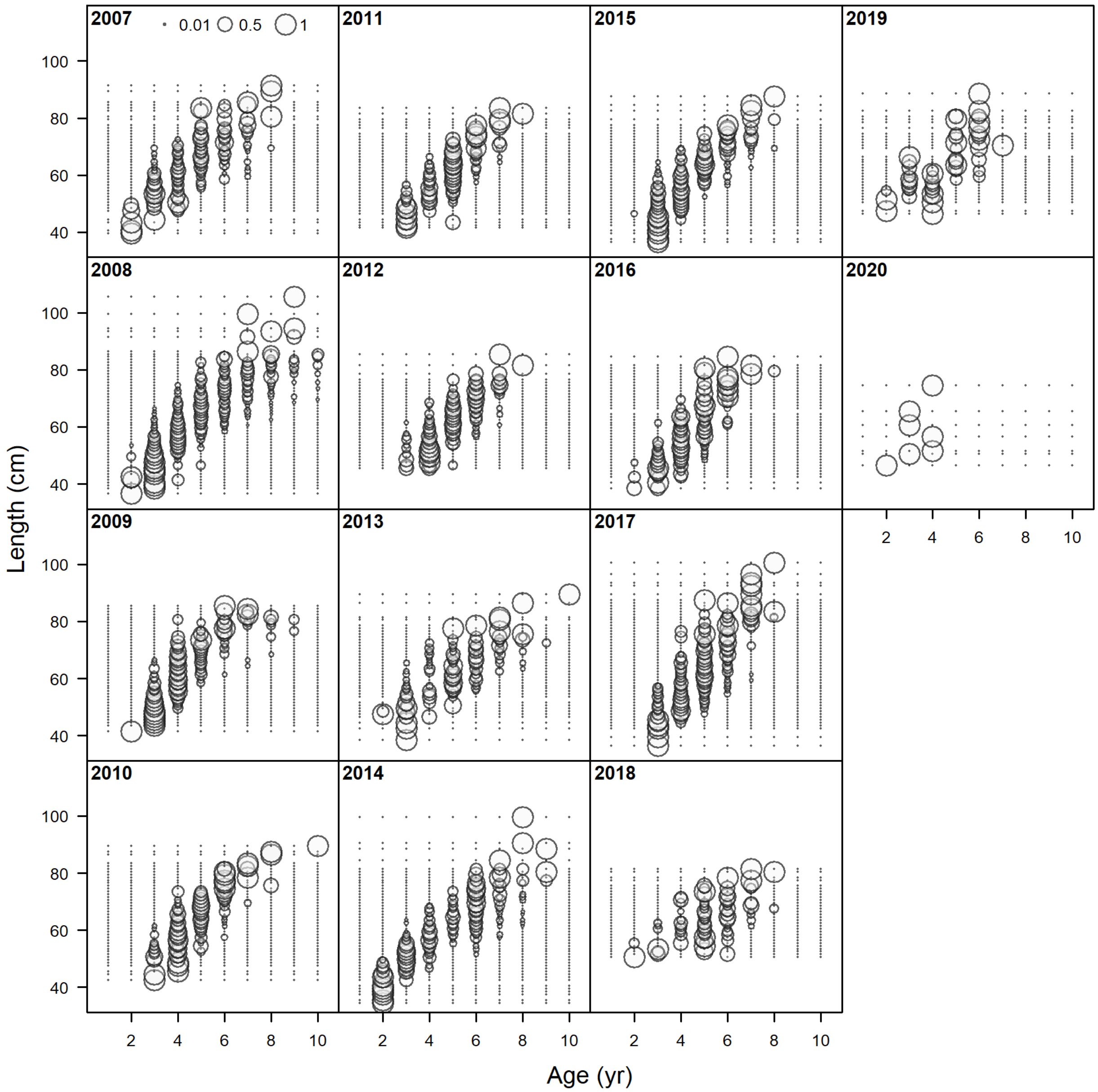


Figure 2.45 Pacific cod conditional length at age from the Gulf of Alaska bottom longline fishery.

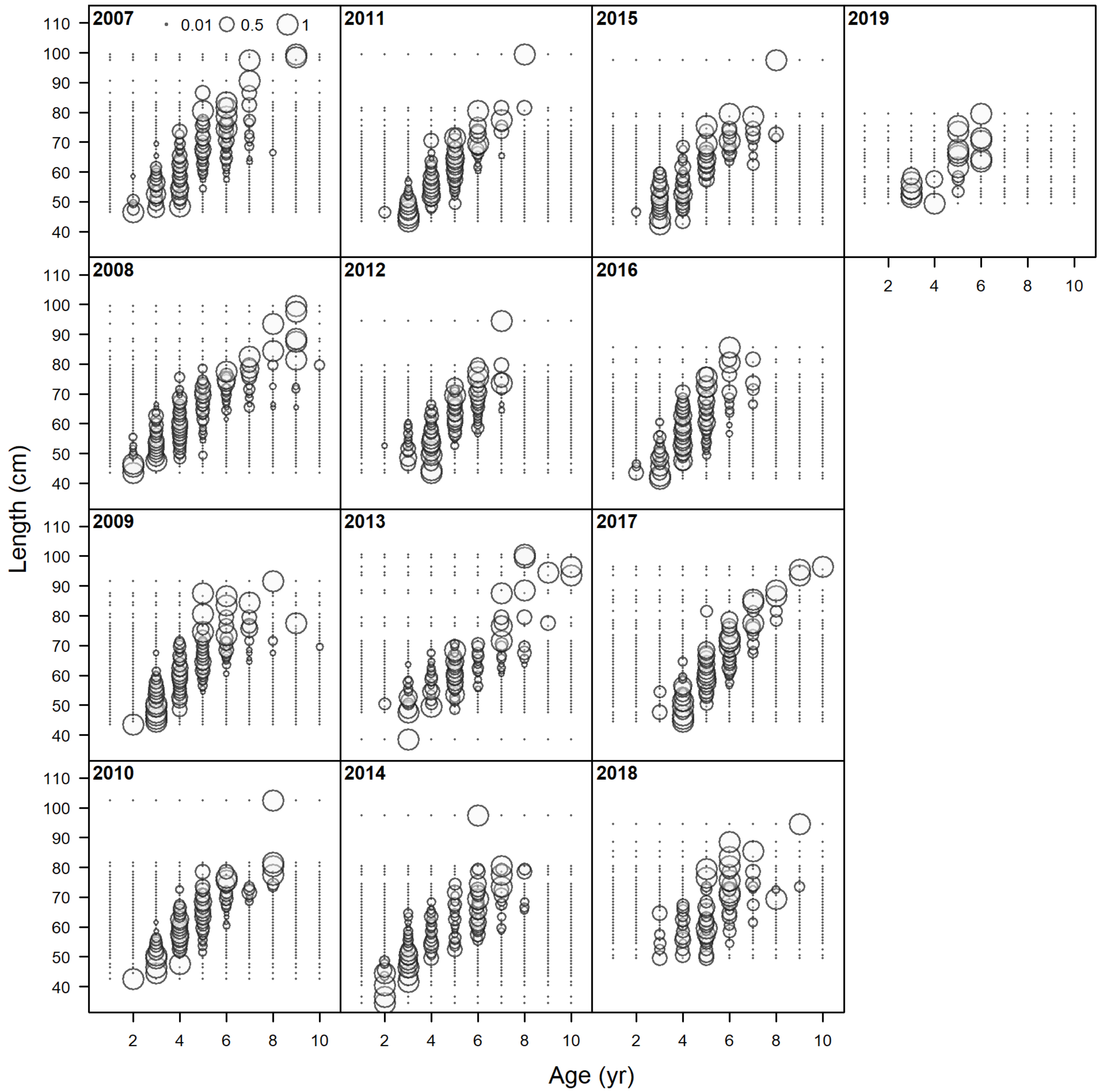


Figure 2.46 Pacific cod conditional length at age from the Gulf of Alaska pot fishery.

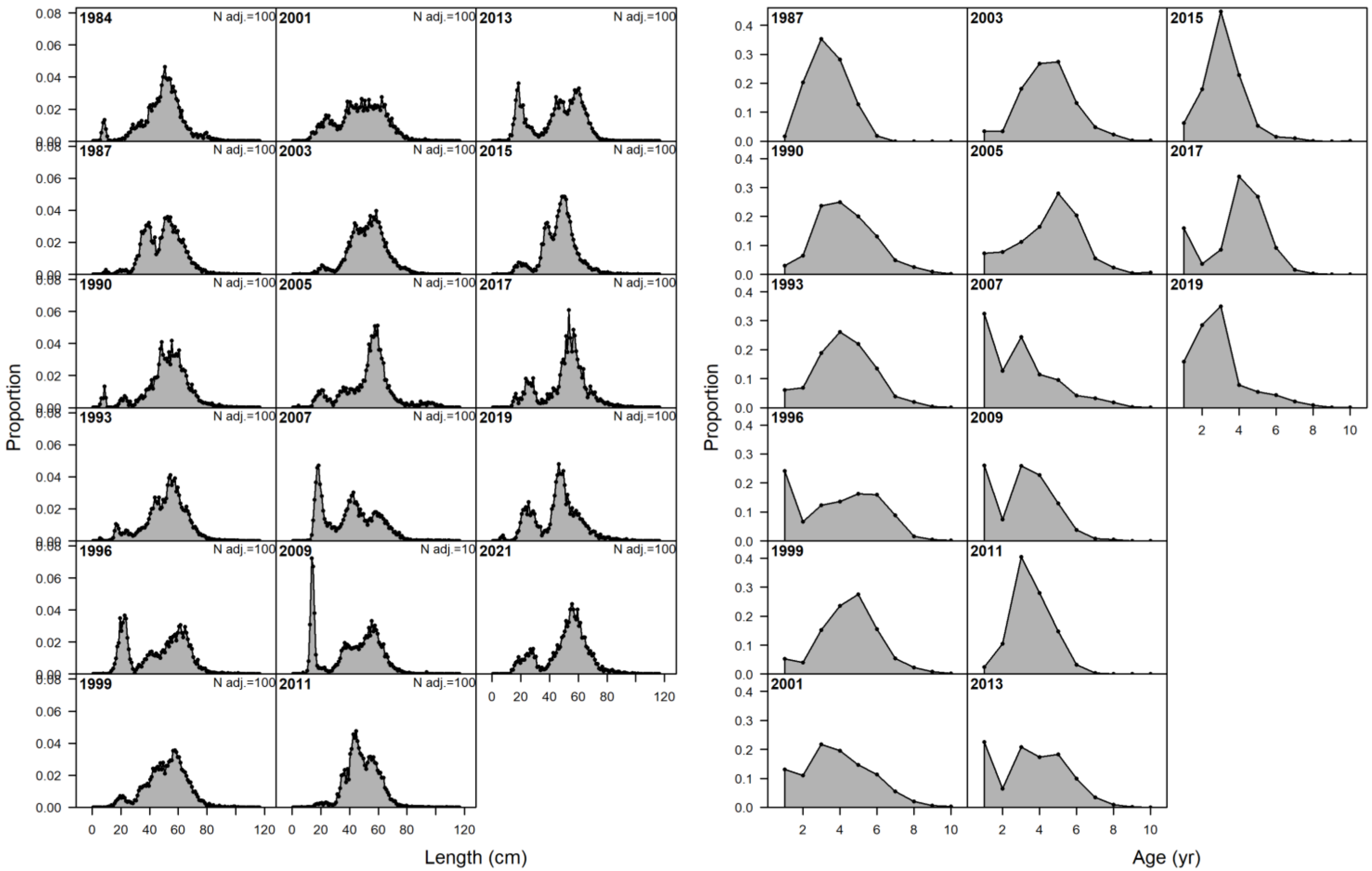


Figure 2.47 Available Pacific cod length (left) and age (right) composition data from the Gulf of Alaska bottom trawl survey 1984-2021.

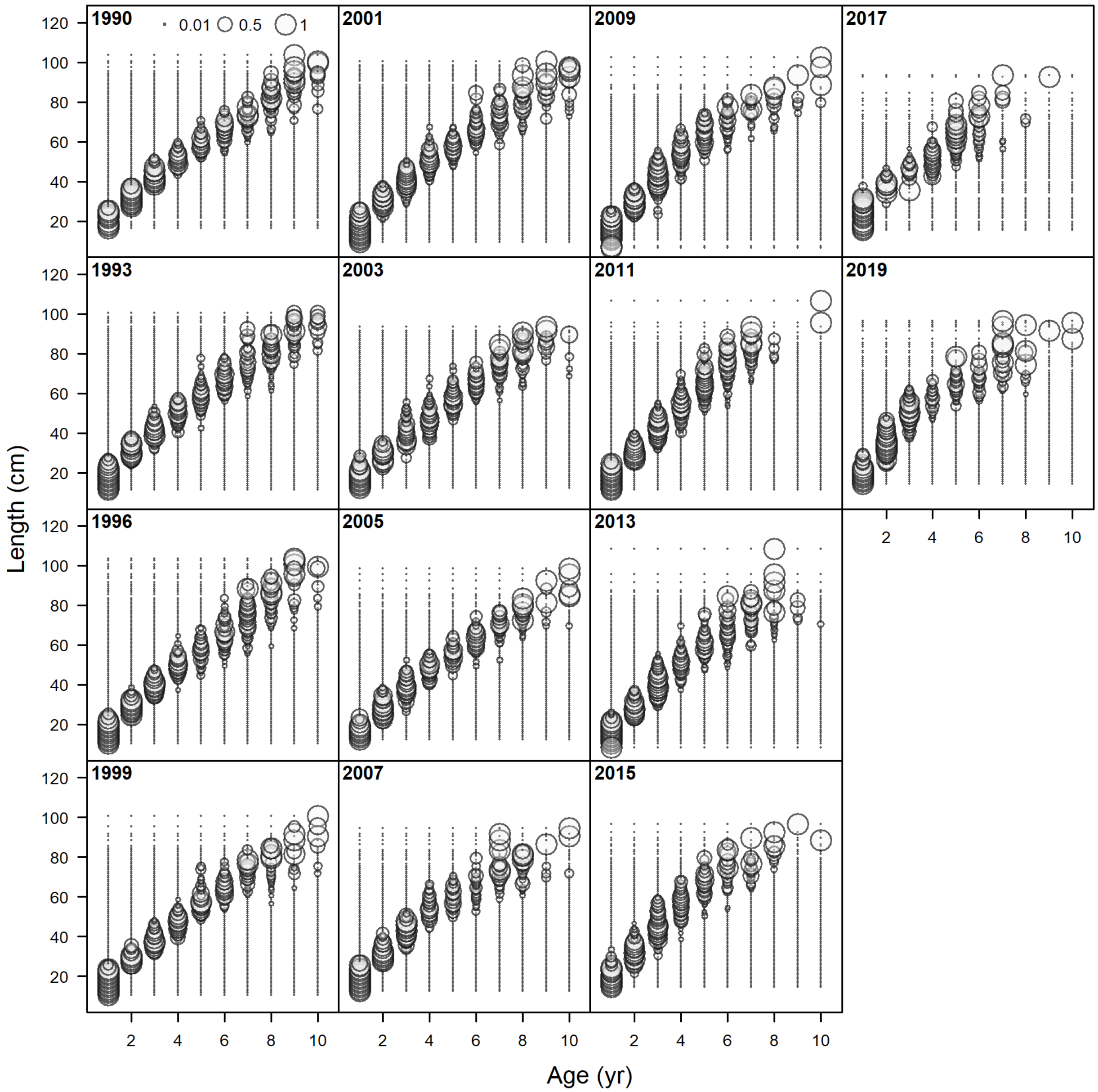


Figure 2.48 Pacific cod conditional length at age from the Gulf of Alaska bottom trawl survey 1990-2019.

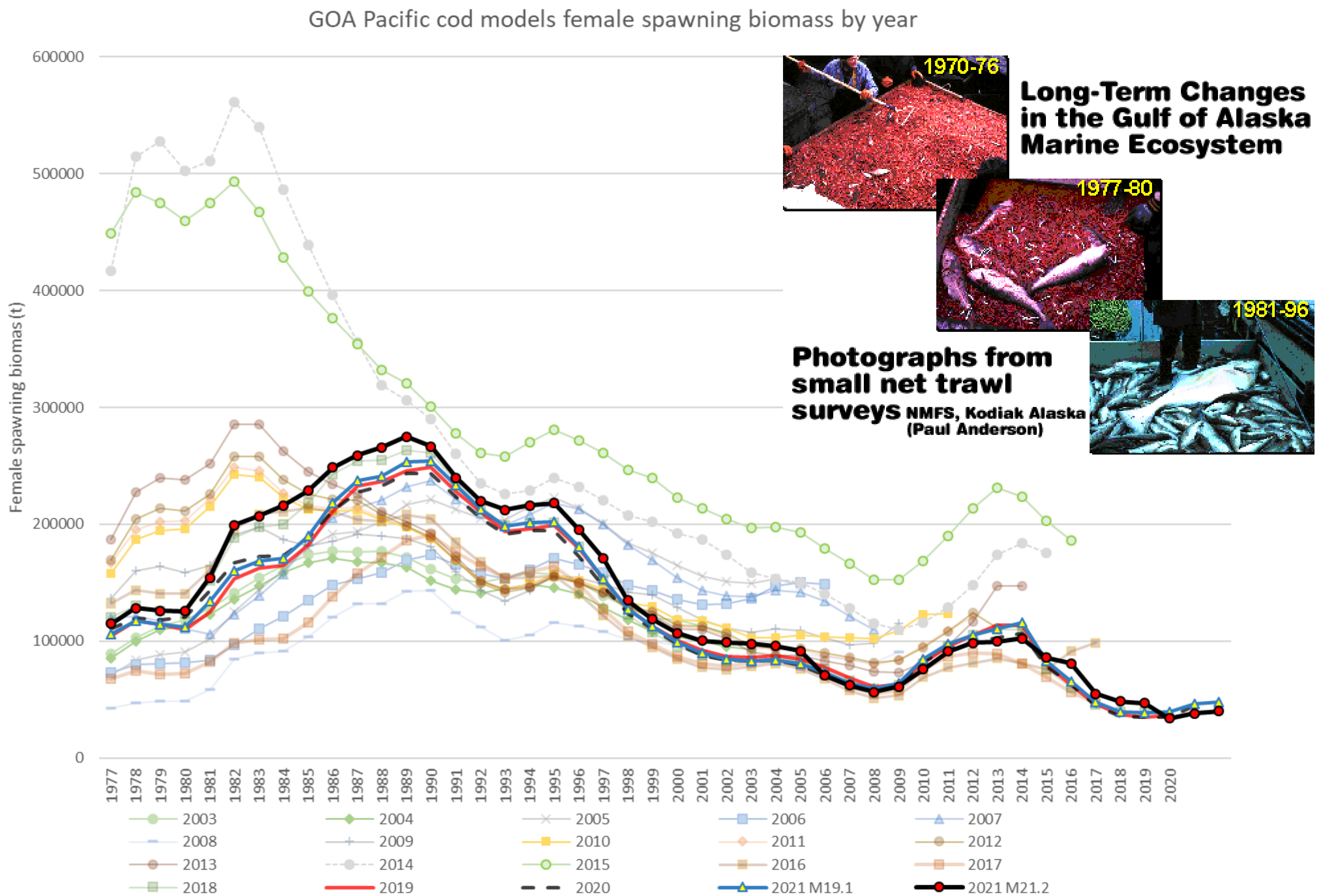


Figure 2.49 1977-2021 Gulf of Alaska Pacific cod female spawning biomass from the 2003 through 2021 stock assessments with estimates from both the author's preferred (Model 21.2) and last year's base model (Model 19.1) model results and (inset) images from the NMFS small net surveys off Kodiak Alaska showing change in species composition over time from: https://www.thenakedscientists.com/articles/science-features/ecosystem-shifts-and-sharks-alaska

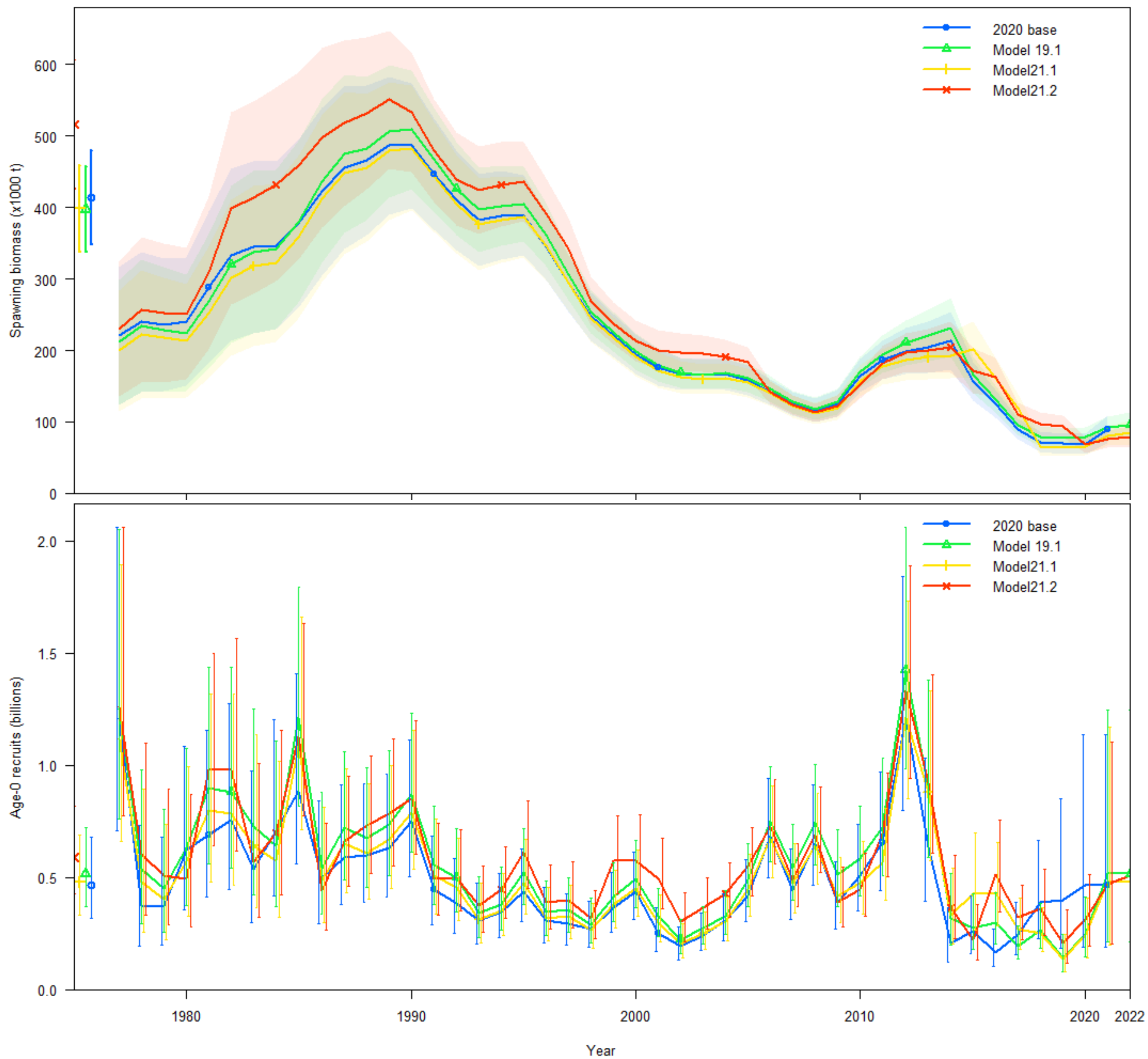


Figure 2.50 Estimates of female spawning biomass (t; top) and age-0 recruits (billions; bottom) for 2020 base model and 2021 proposed models.

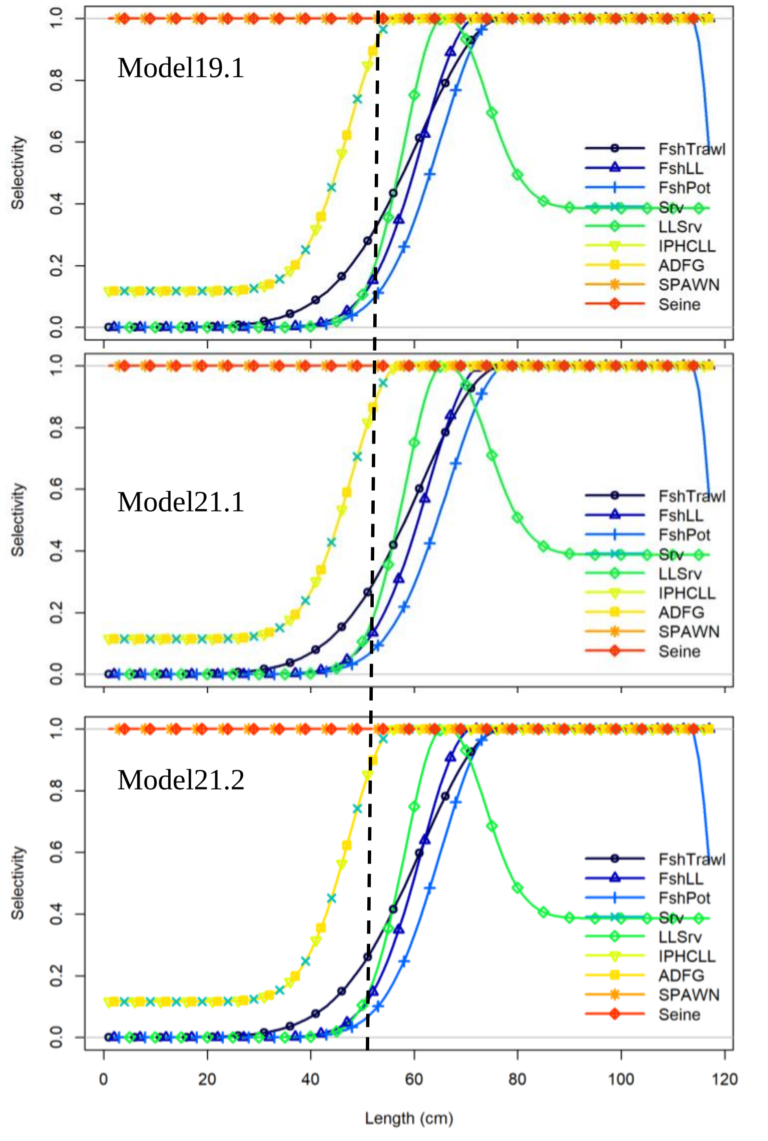


Figure 2.51 Model19.1, Model 21.1, and Model 21.2 selectivity for all size composition components for 2021.

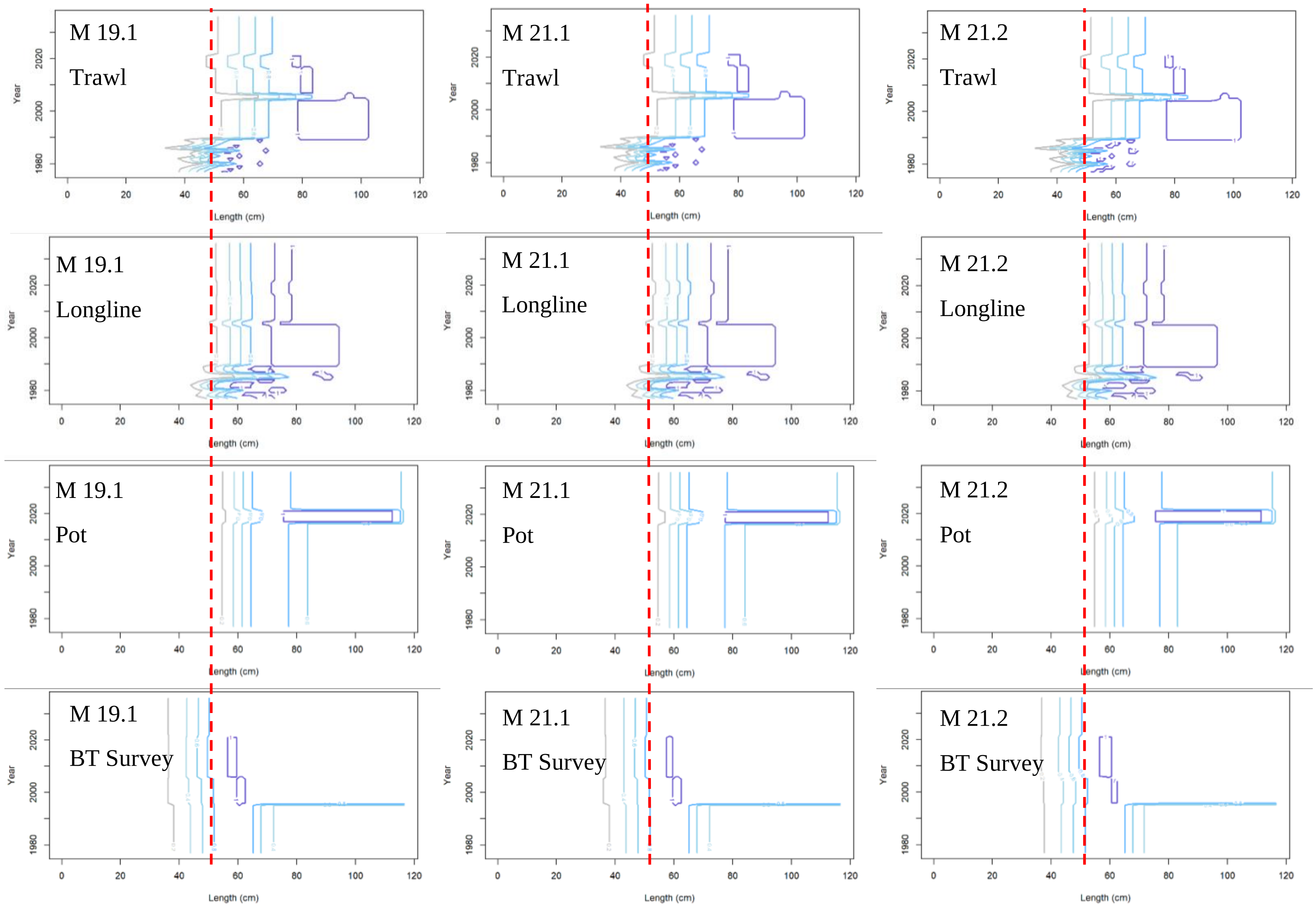


Figure 2.52 Estimates of fishery and AFSC bottom trawl survey selectivities for evaluated models. Red dashed line is the size at 50% mature.

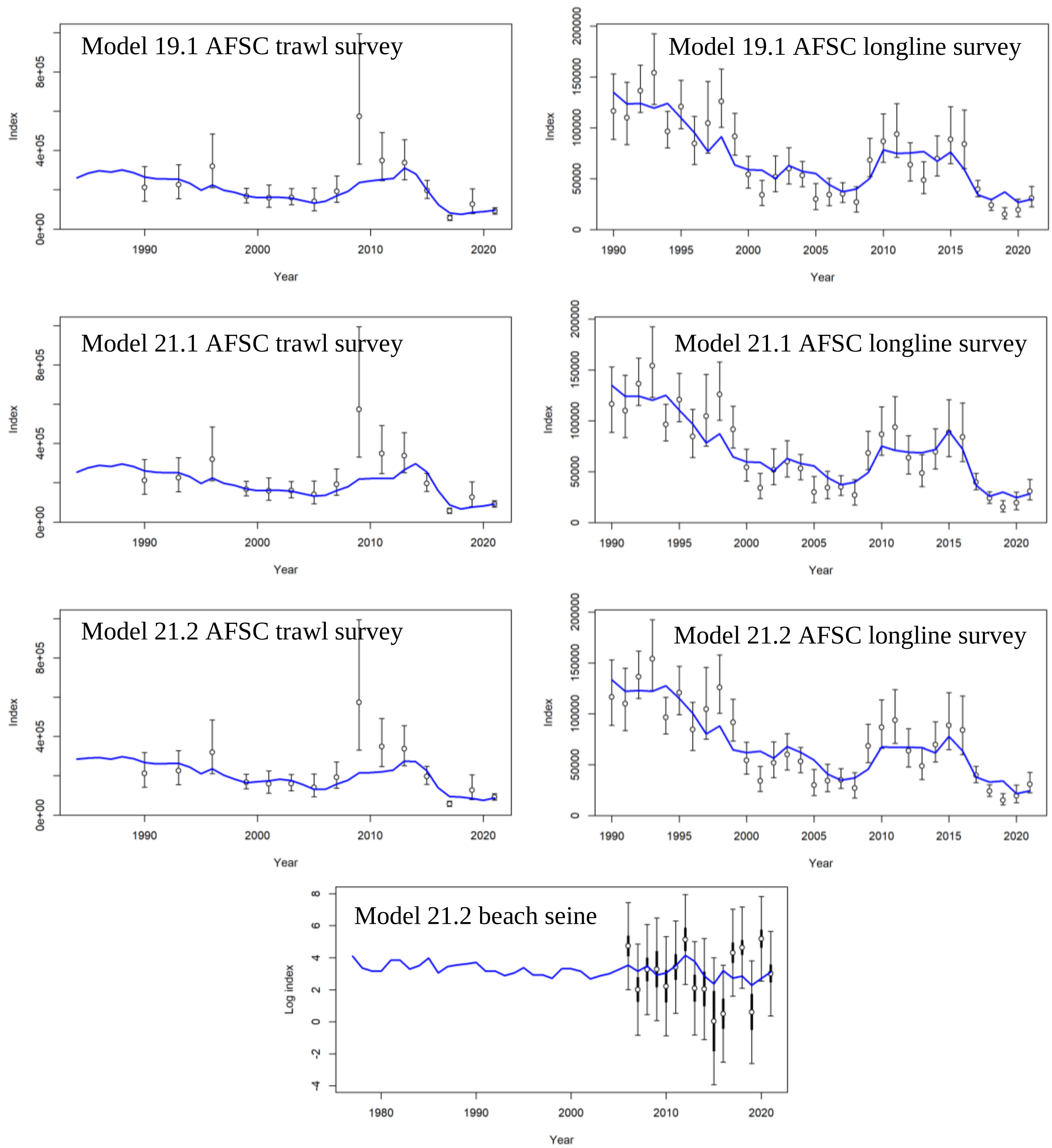


Figure 2.53 Model fits to AFSC bottom trawl (left), AFSC longline (right) survey, and age-0 beach seine (bottom middle) survey indices.

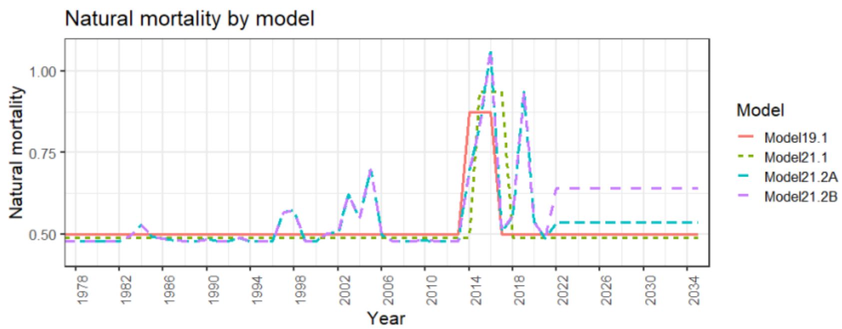


Figure 2.54 Natural mortality over time for the assessed models with projections for 2022-2036.

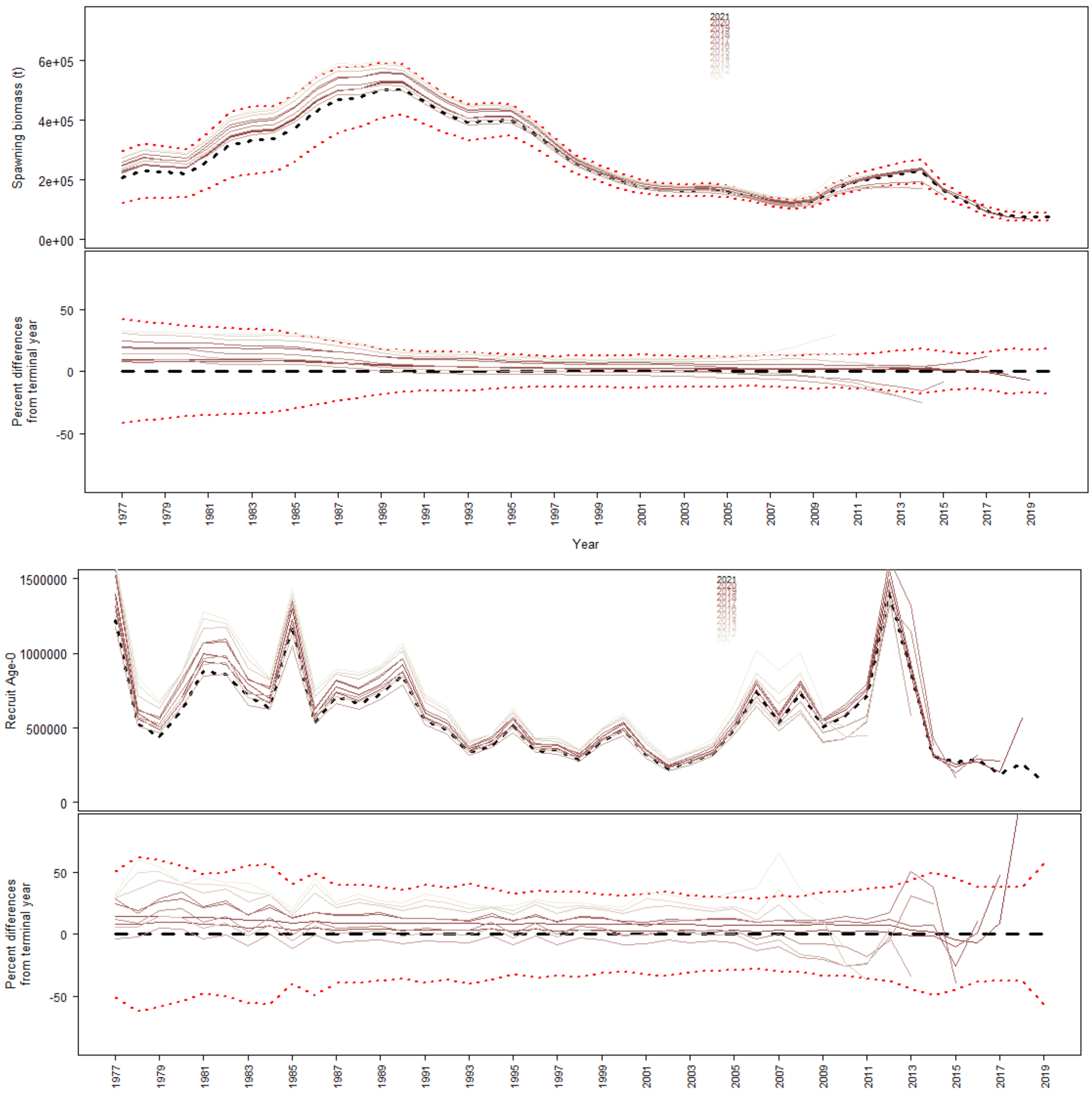


Figure 2.55 Retrospective analysis for Model 19.1 for female spawning biomass (top) and age-0 recruitment (bottom).

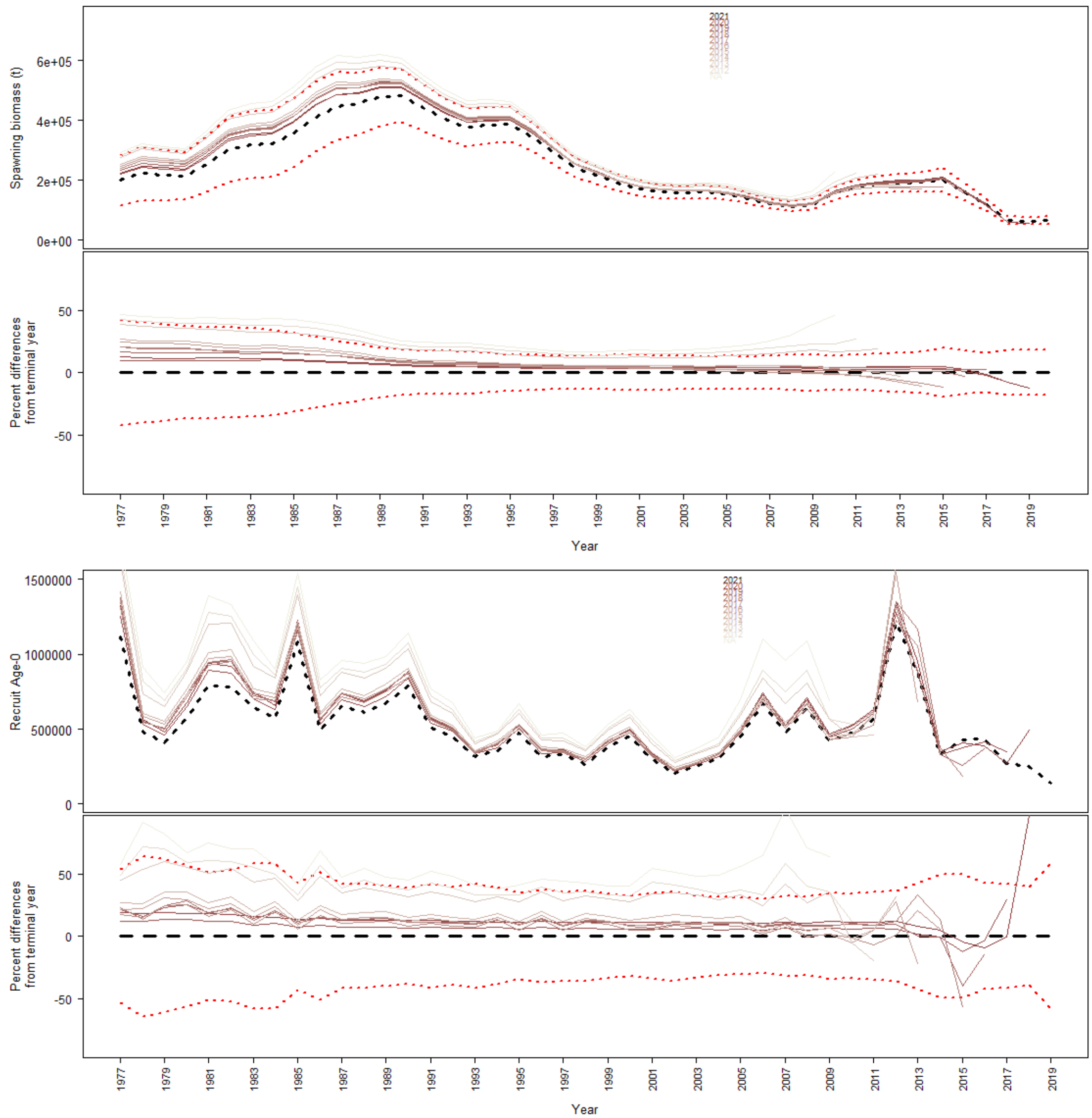


Figure 2.56 Retrospective analysis for Model 21.1 for female spawning biomass (top) and age-0 recruitment (bottom)..

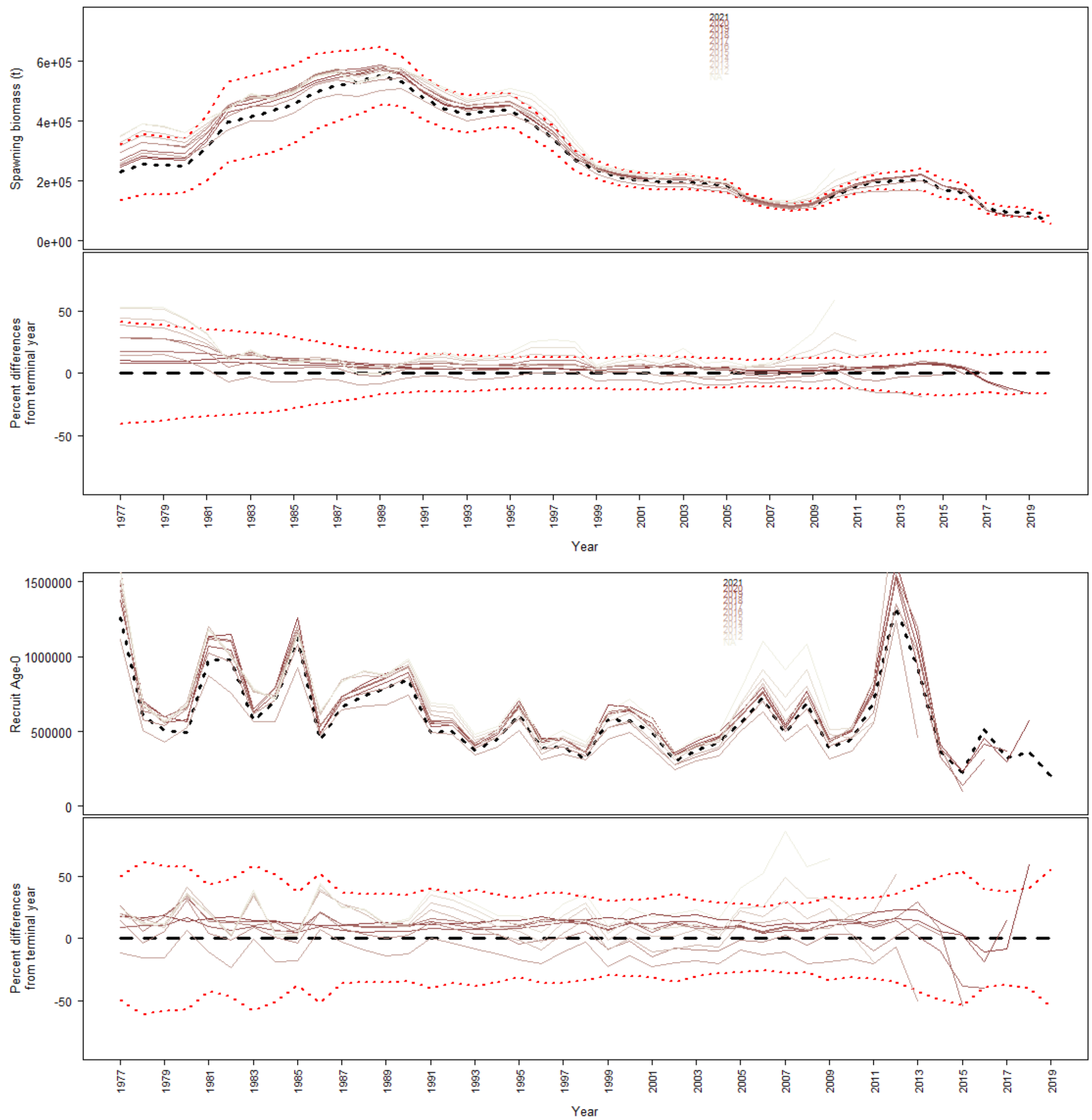


Figure 2.57 Retrospective analysis for Model 21.2 for female spawning biomass (top) and age-0 recruitment (bottom)..

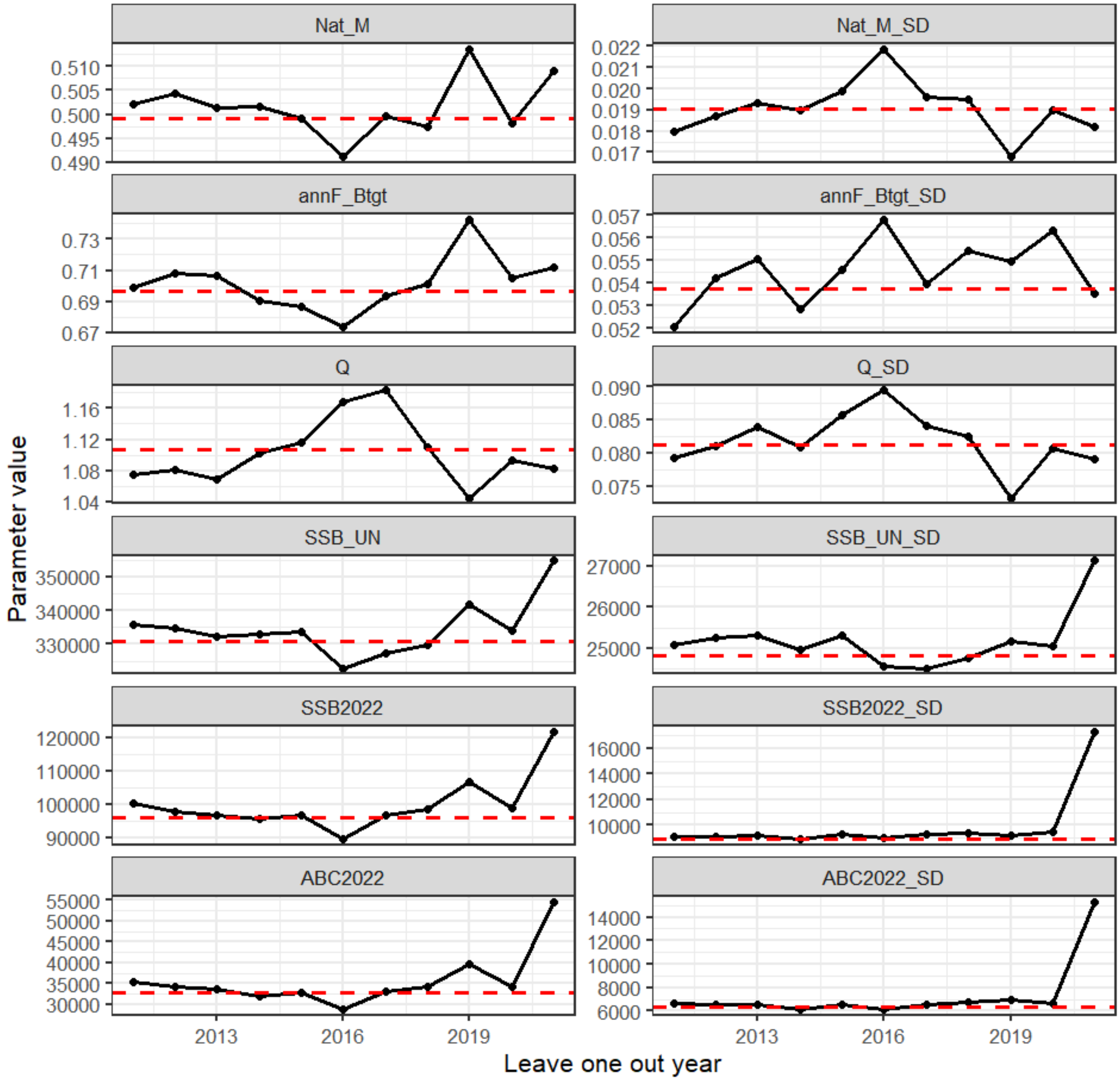


Figure 2.58 Model 19.1 leave-one-out analysis showing parameters and derived quantities as one year of data were removed from the model fit. Nat_M is the base natural mortality, annF_Btgt is the F40%, SSB_UN is the unfished spawning biomass, SSB2022 is the total spawning biomass for 2022 and ABC2022 is the estimated ABC for 2022. The SDs are the standard deviations of the estimates.

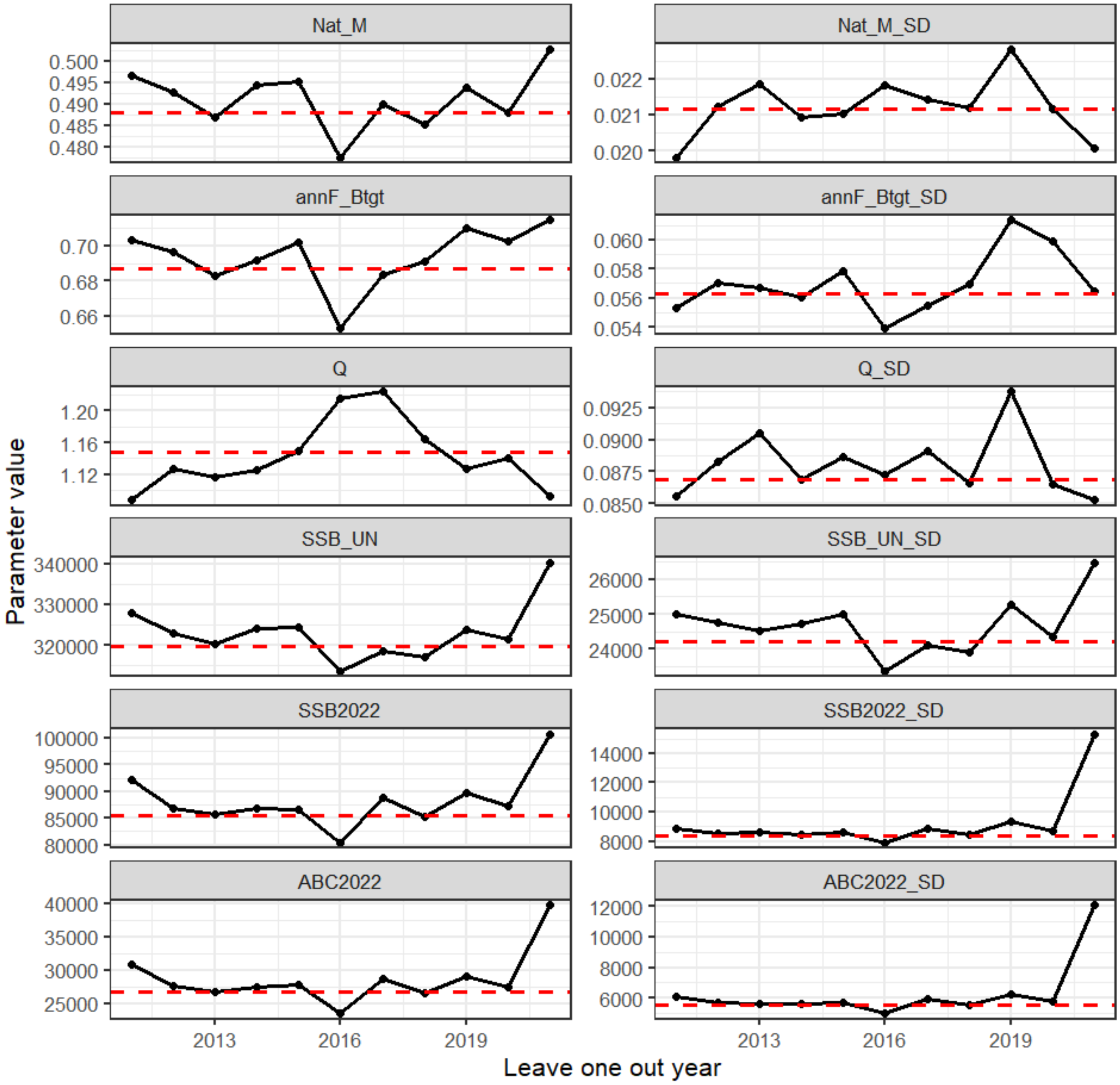


Figure 2.59 Model 21.1 leave-one-out analysis showing parameters and derived quantities as one year of data were removed from the model fit. Nat_M is the base natural mortality, annF_Btgt is the F40%, SSB_UN is the unfished spawning biomass, SSB2022 is the total spawning biomass for 2022 and ABC2022 is the estimated ABC for 2022. The SDs are the standard deviations of the estimates.

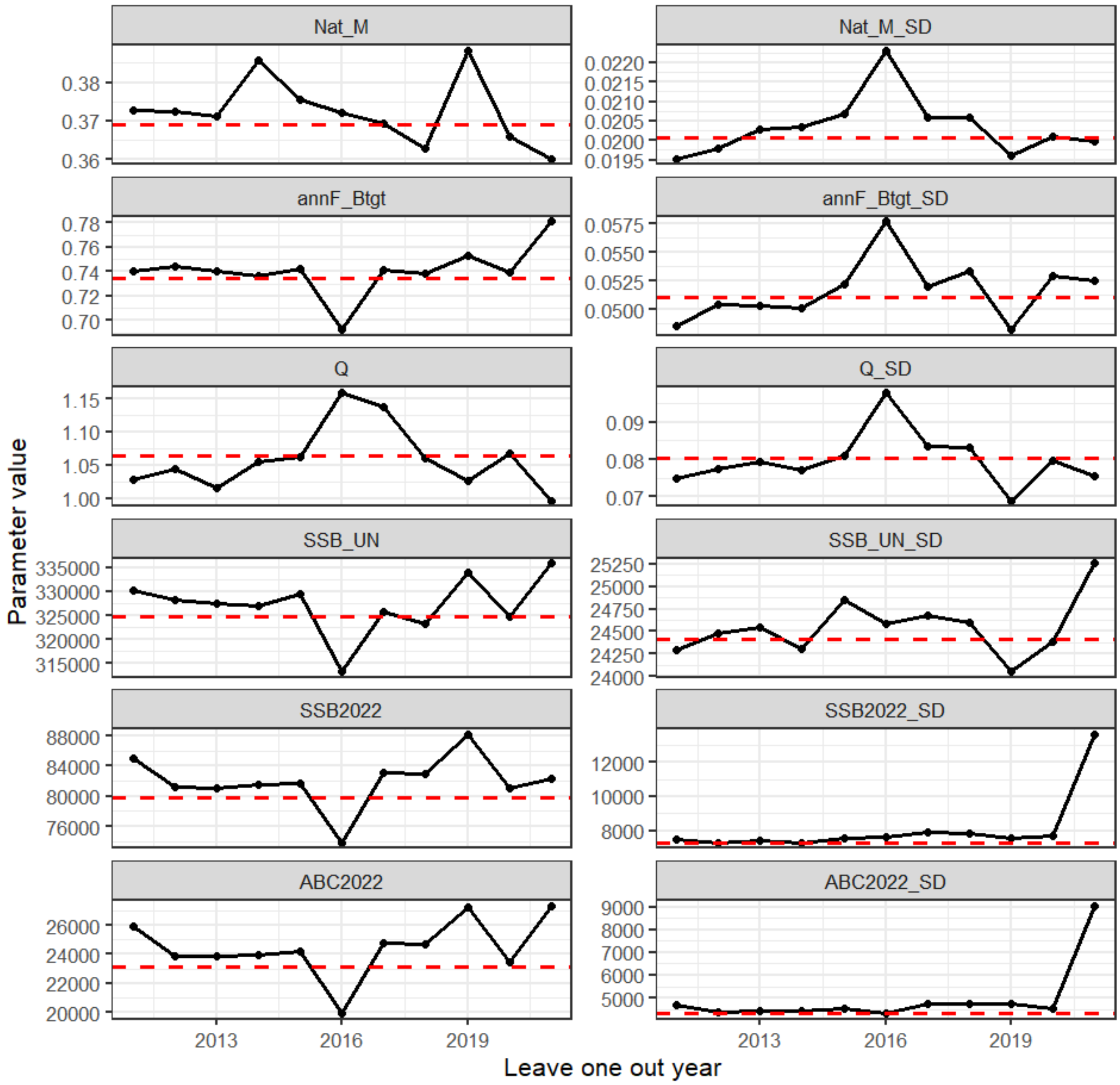


Figure 2.60 Model 21.2 leave-one-out analysis showing parameters and derived quantities as one year of data were removed from the model fit. Nat_M is the base natural mortality, annF_Btgt is the F40%, SSB_UN is the unfished spawning biomass, SSB2022 is the total spawning biomass for 2022 and ABC2022 is the estimated ABC for 2022. The SDs are the standard deviations of the estimates.

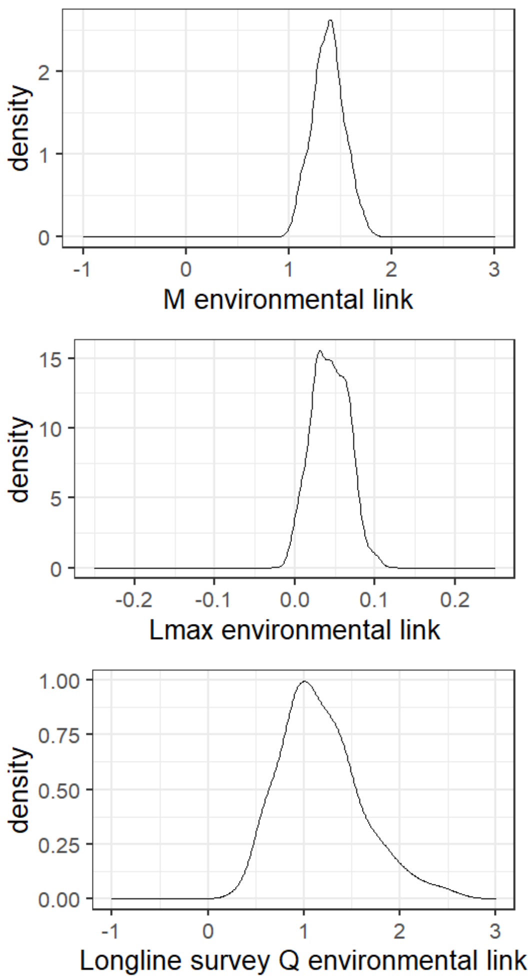


Figure 2.61 MCMC posterior distributions for the environmental link scaling parameters from Model 21.2 with uninformative priors.

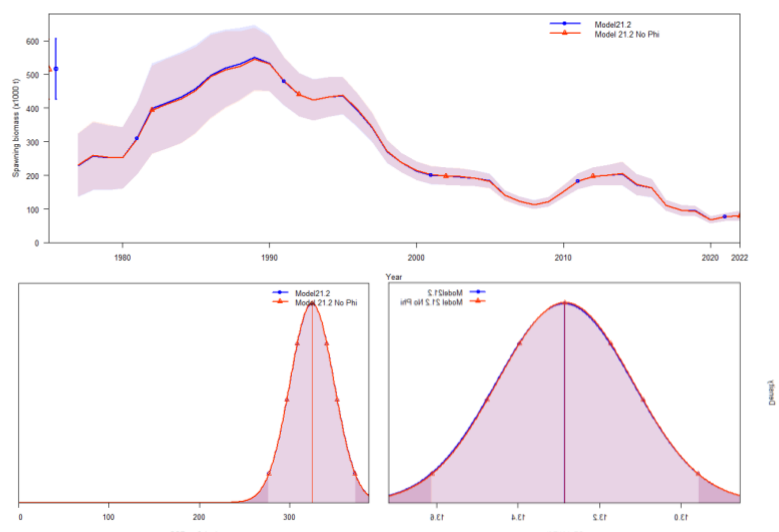


Figure 2.62 Model results from Model 21.2 with and without the ϕ link to K including total spawning biomass (top), unfished spawning biomass (bottom left), and the log of R_0 (bottom right).

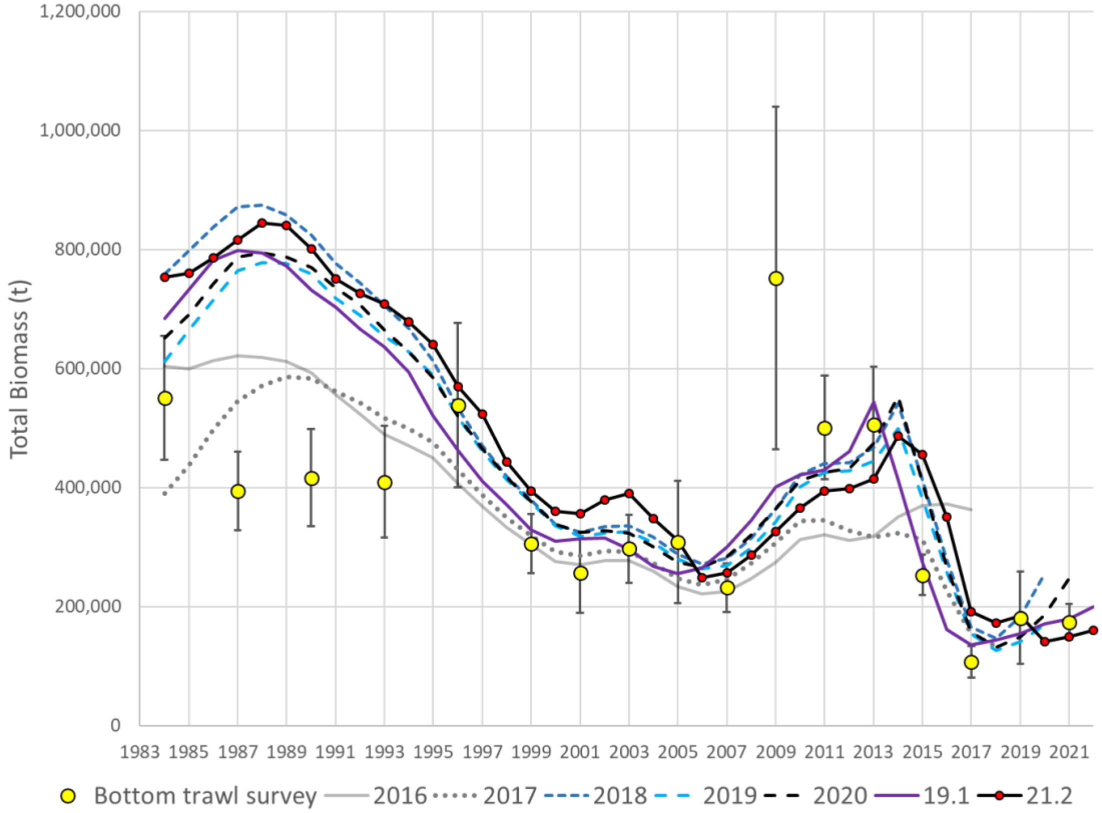


Figure 2.63 Total biomass estimates from reviewed models and NMFS bottom trawl survey biomass estimates with 95% confidence bounds.

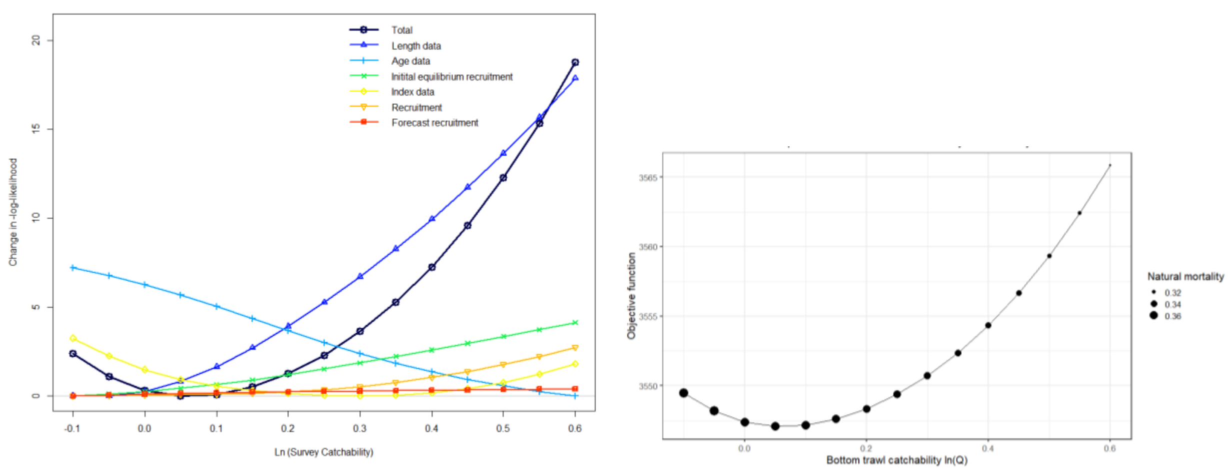


Figure 2.64 Model 21.2 likelihood profile on bottom trawl survey catchability.

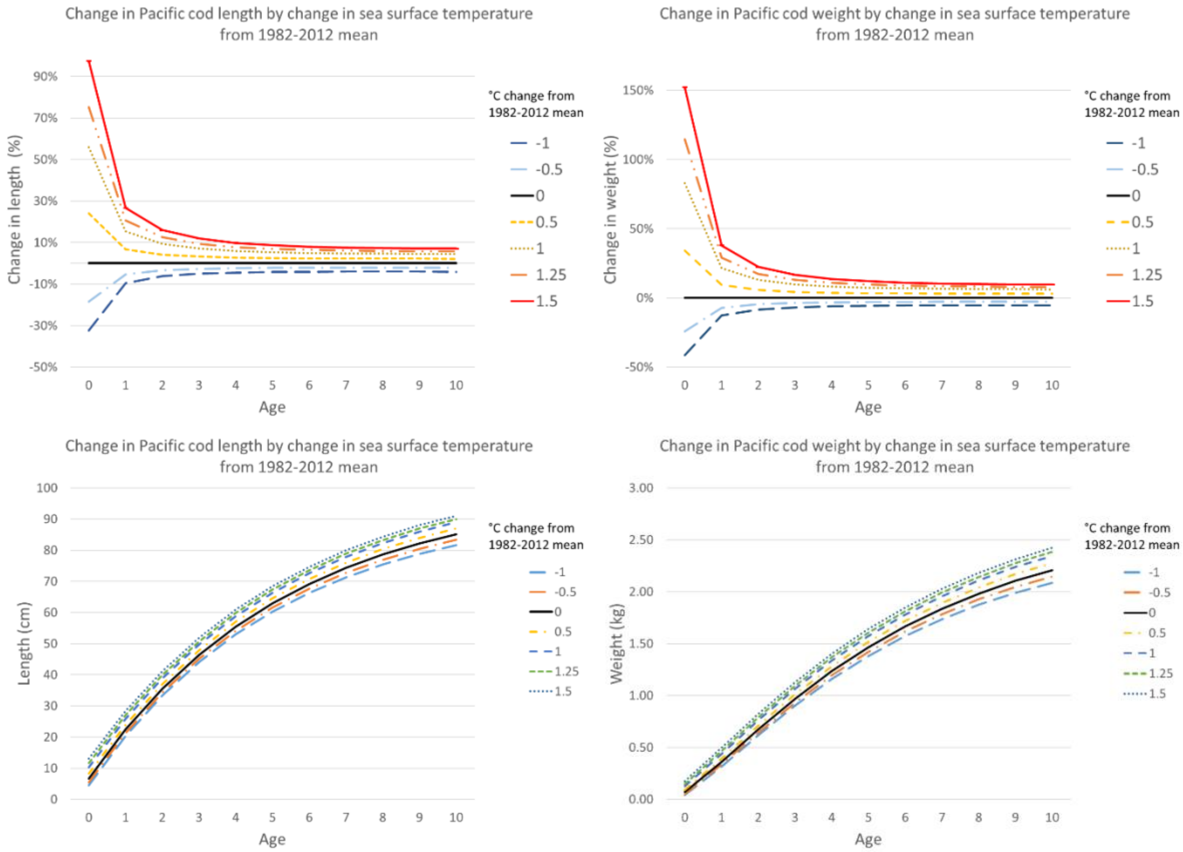


Figure 2.65 Model 21.2 change in length by age (left) and change in weight by age (right) by temperature anomaly from the 1982-2012 mean.

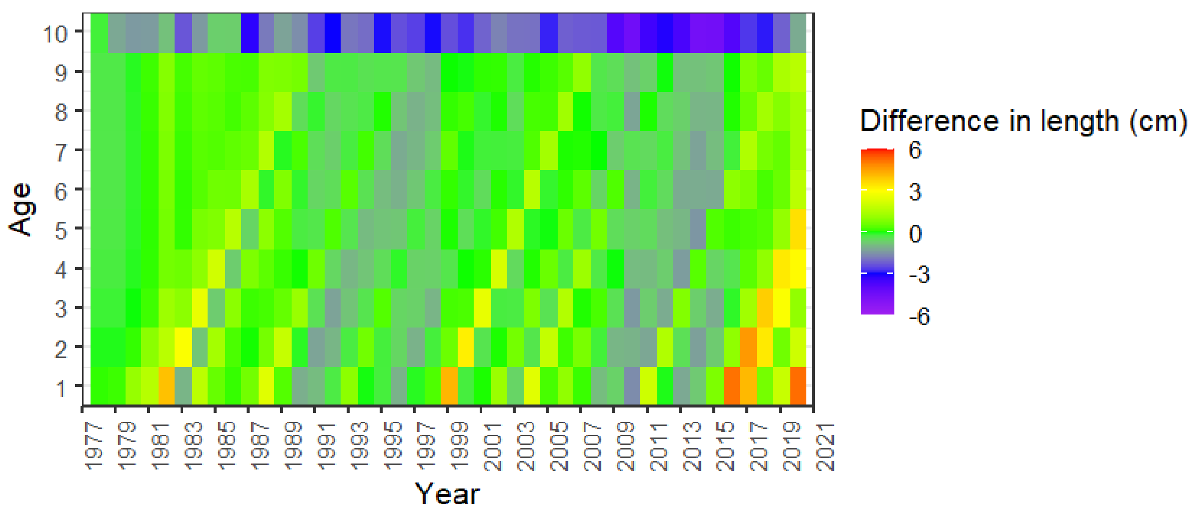


Figure 2.66 Difference in length at age from Model 19.1 with static growth to Model 21.2 with temperature dependent growth.

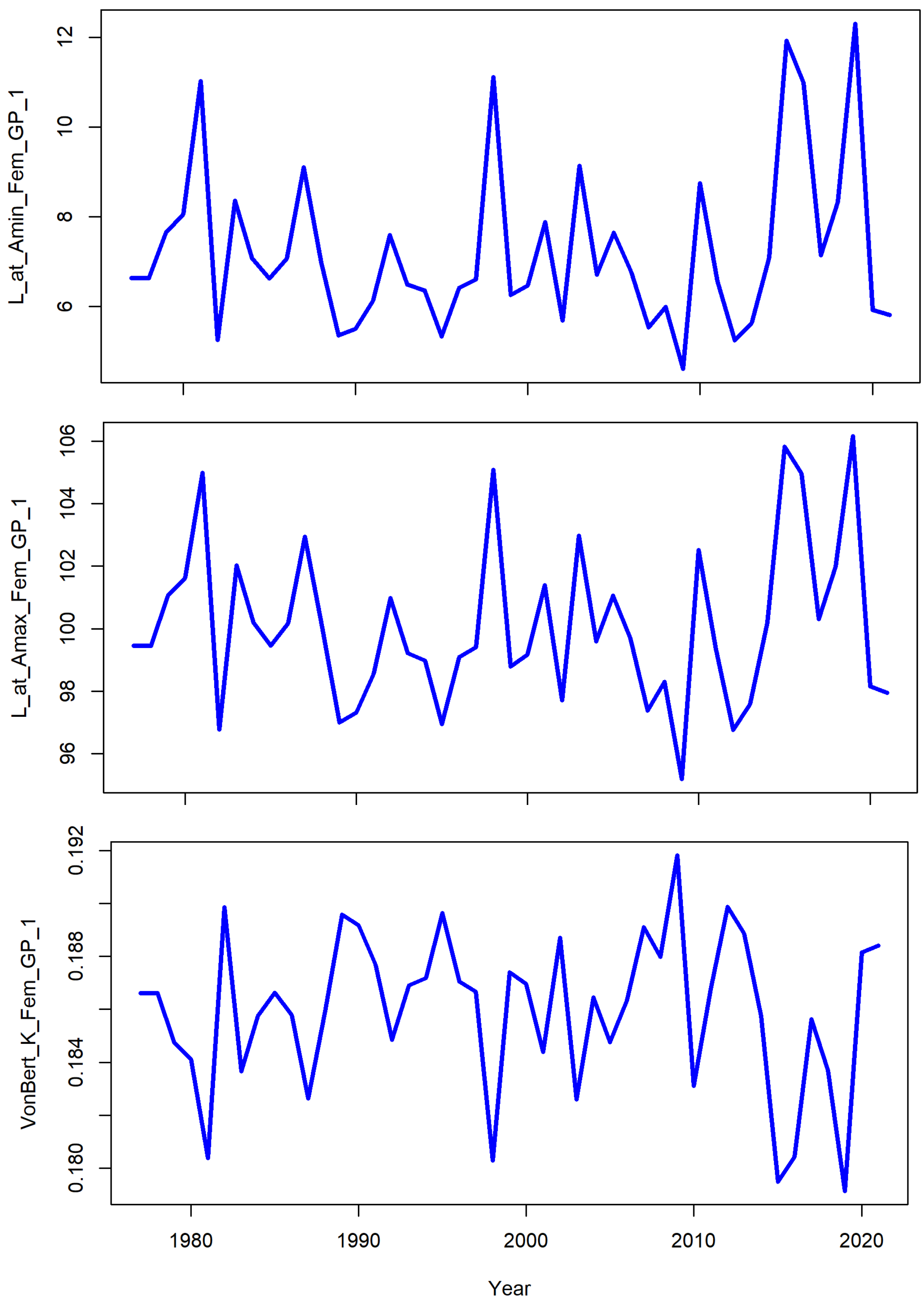


Figure 2.67 Model 21.2 Time-varying growth parameters, L_1 (top), L_2 (middle), and K (bottom).

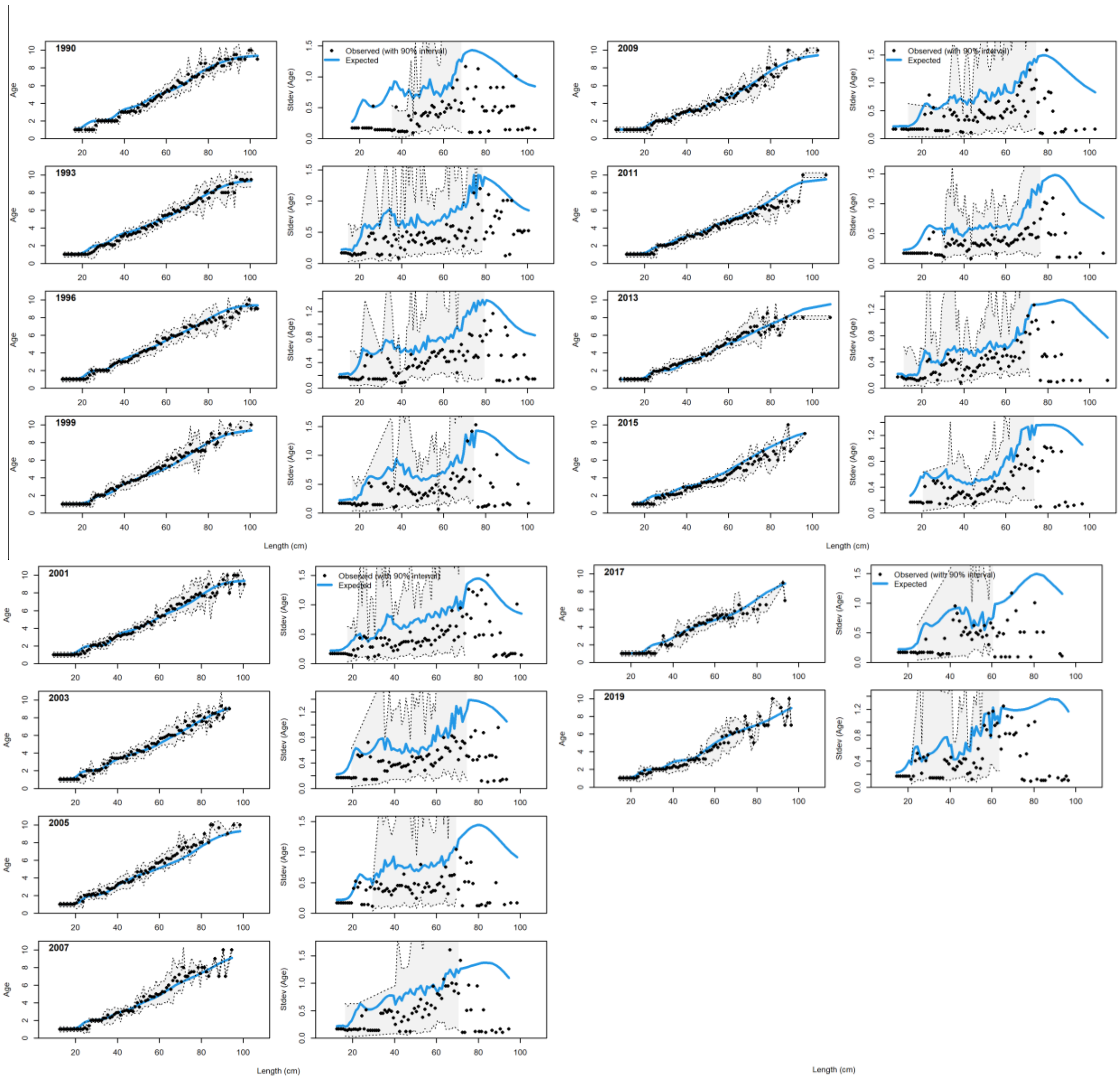


Figure 2.68 NMFS bottom trawl survey conditional age at length data and standard deviation with Model 21.2 fit (blue line).

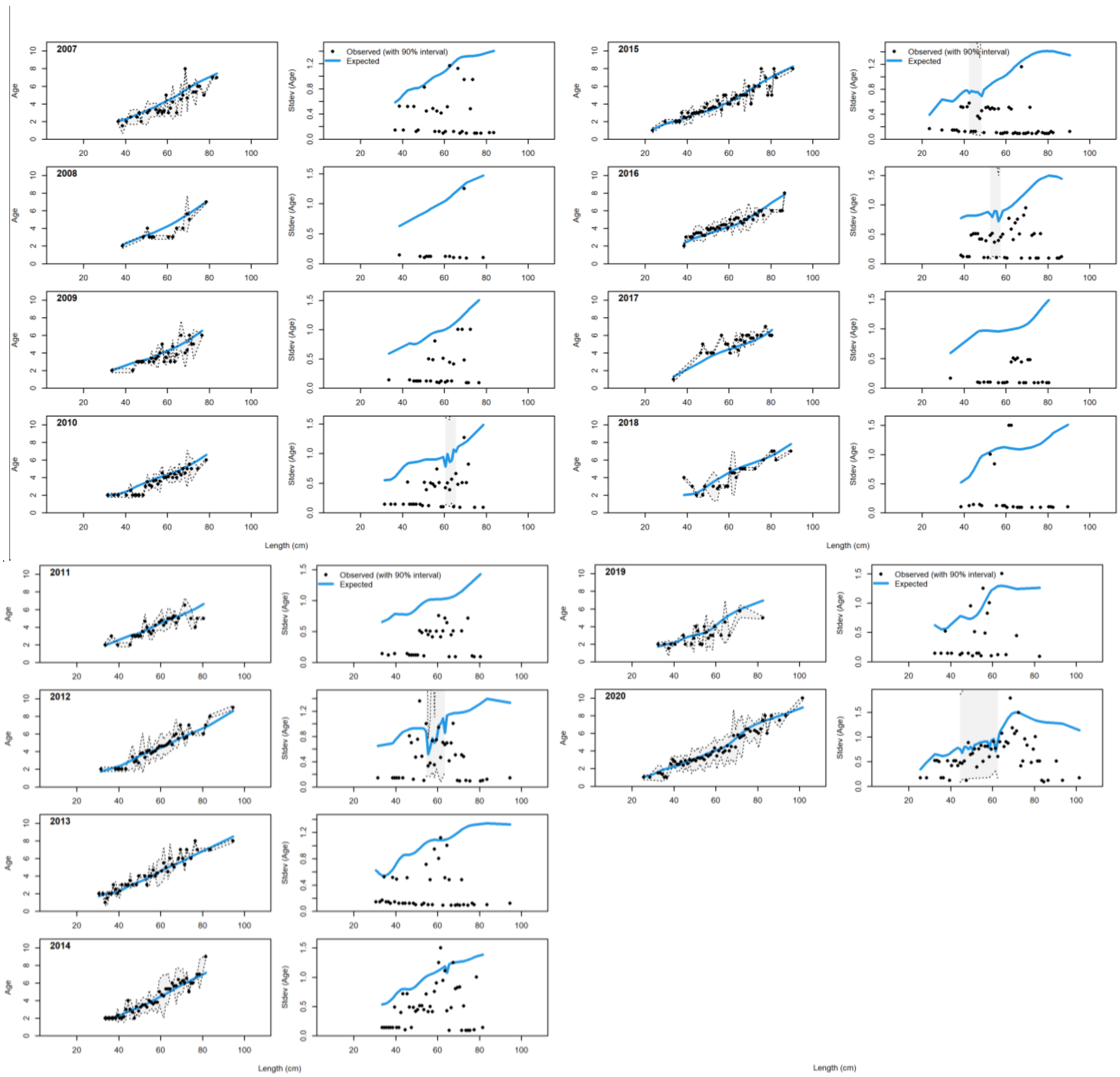


Figure 2.69 Trawl fishery conditional age at length data and standard deviation with Model 21.2 fit (blue line)..

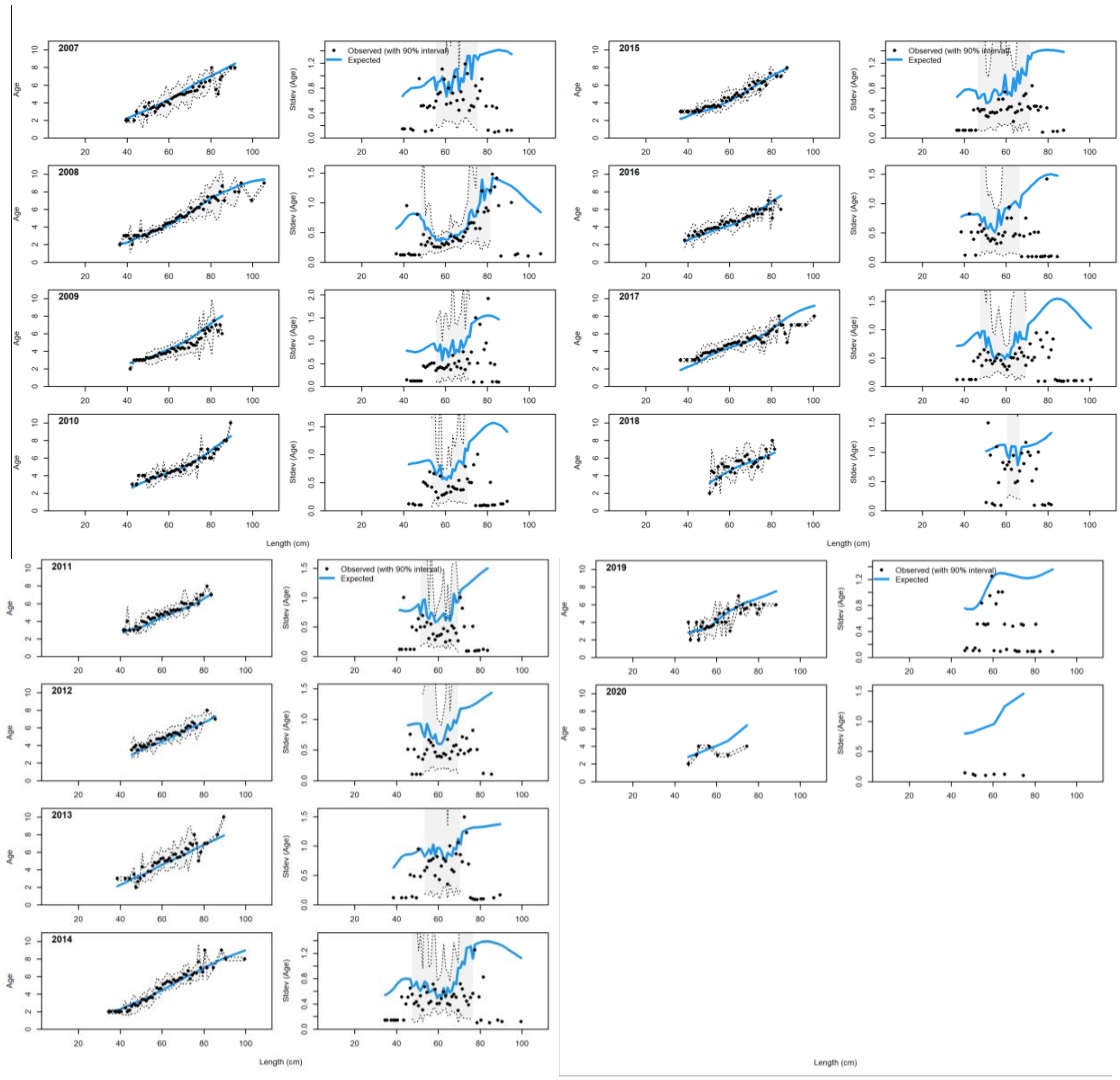


Figure 2.70 Longline fishery conditional age at length data and standard deviation with Model 21.2 fit (blue line)..

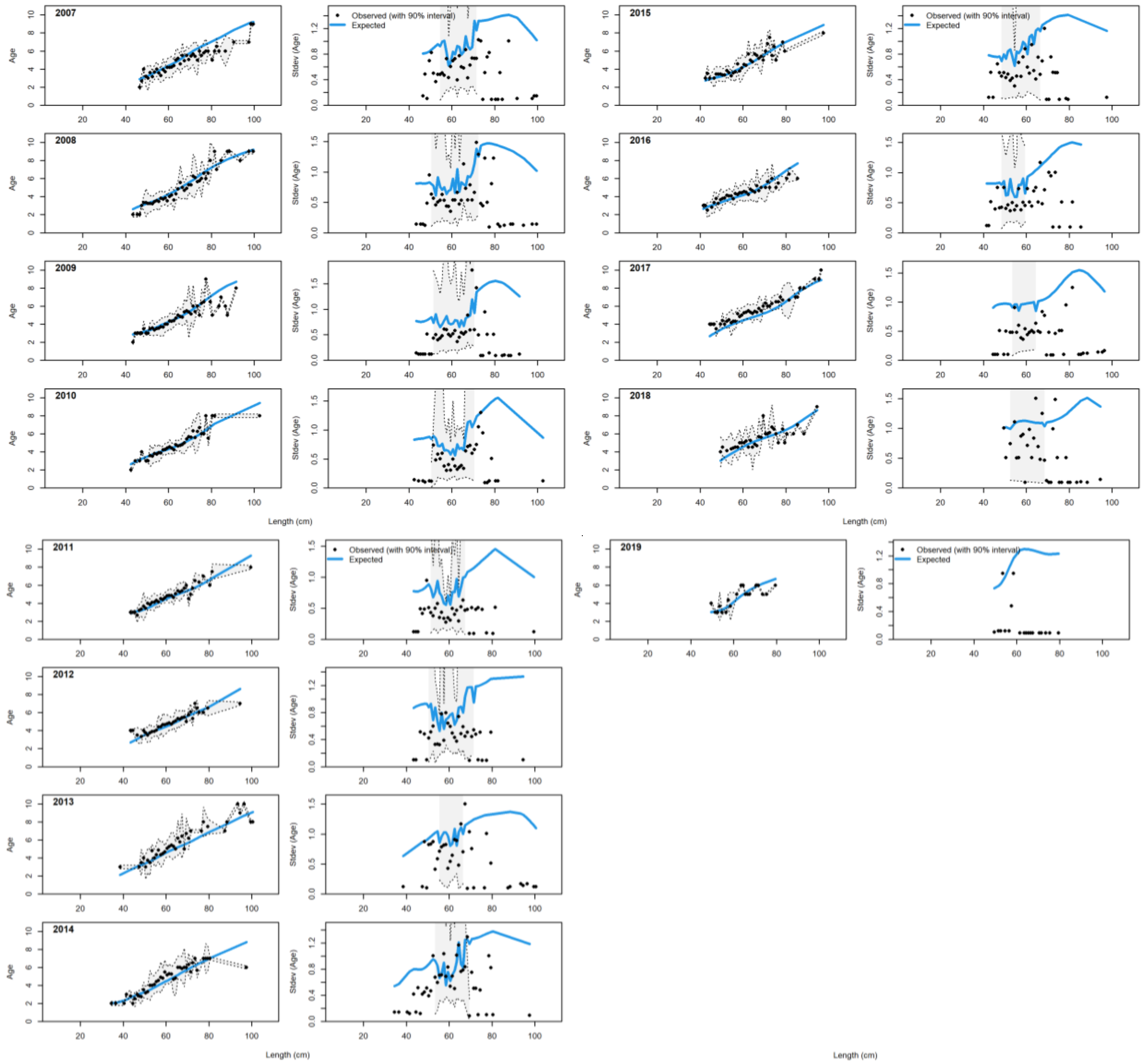


Figure 2.71 Pot fishery conditional age at length data and standard deviation with Model 21.2 fit (blue line).

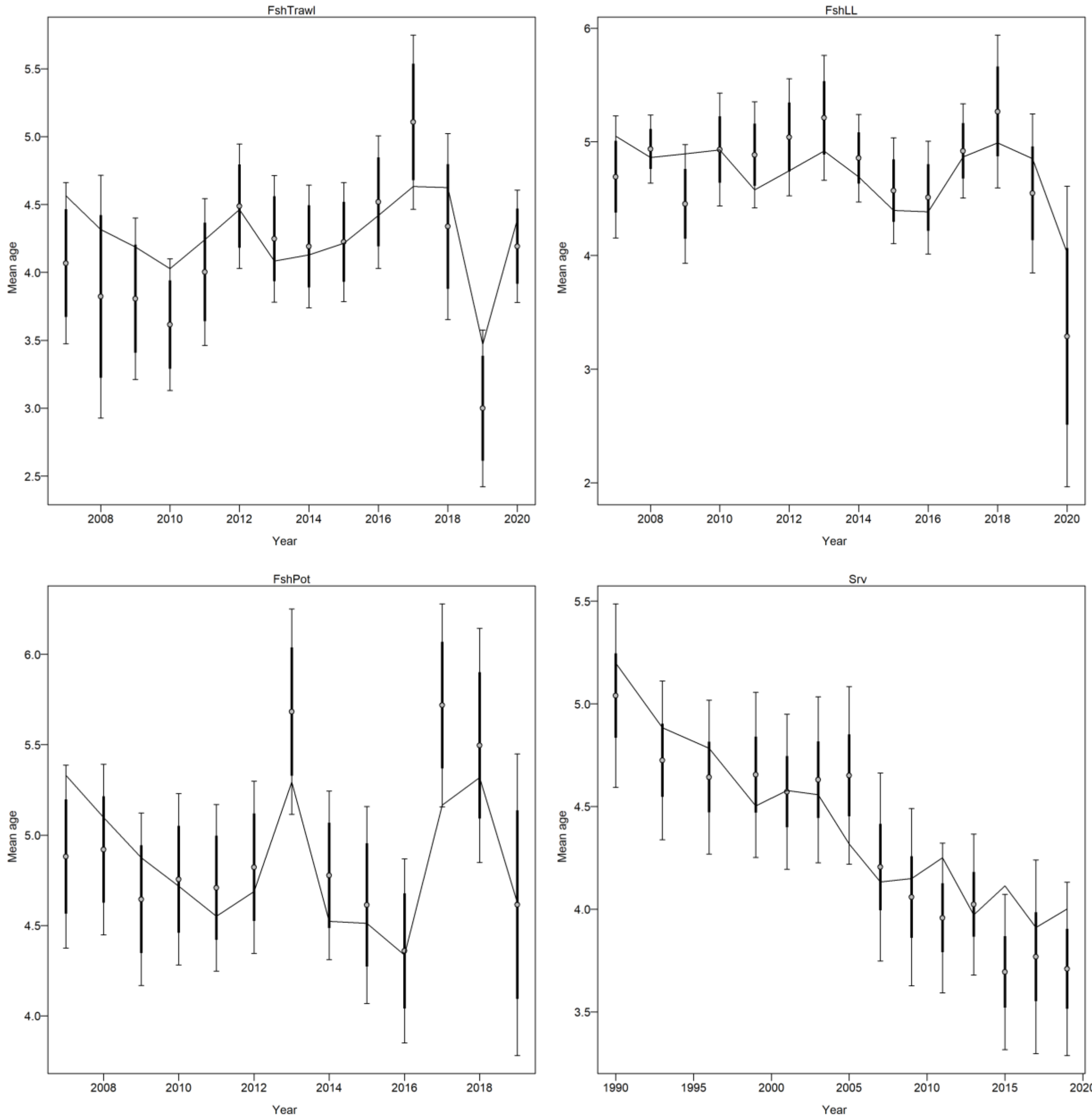


Figure 2.72 Mean age from conditional data (aggregated across length bins) with 95% confidence intervals based on current samples sizes for the trawl fishery (FshTrawl), longline fishery (FshLL), pot fishery (FshPot) and bottom trawl survey (Srv) with Model 21.2 predictions (line).

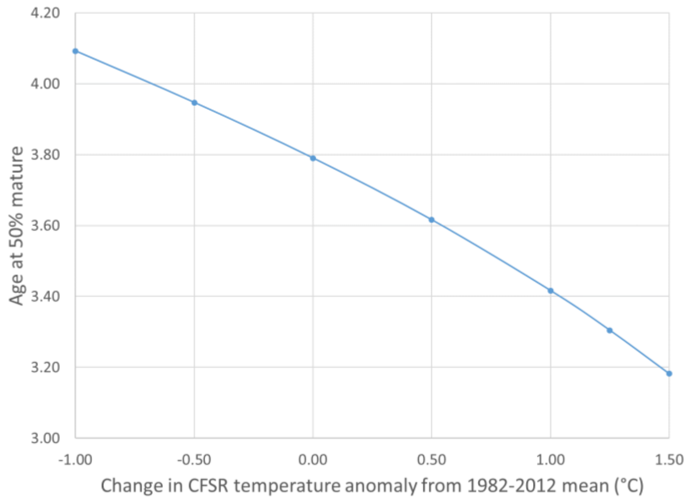


Figure 2.73 Relationship of maturity to temperature anomaly from the 1982-2012 mean for Model 21.2.

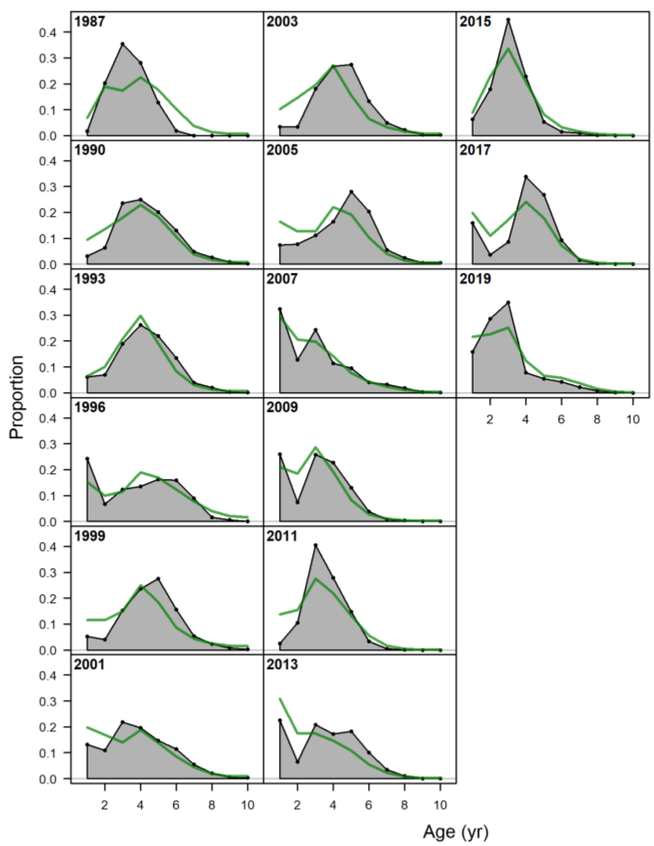


Figure 2.74 NMFS bottom trawl survey age composition and Model 21.2 fit (green line). Note the age data fits are not included in the objective function.

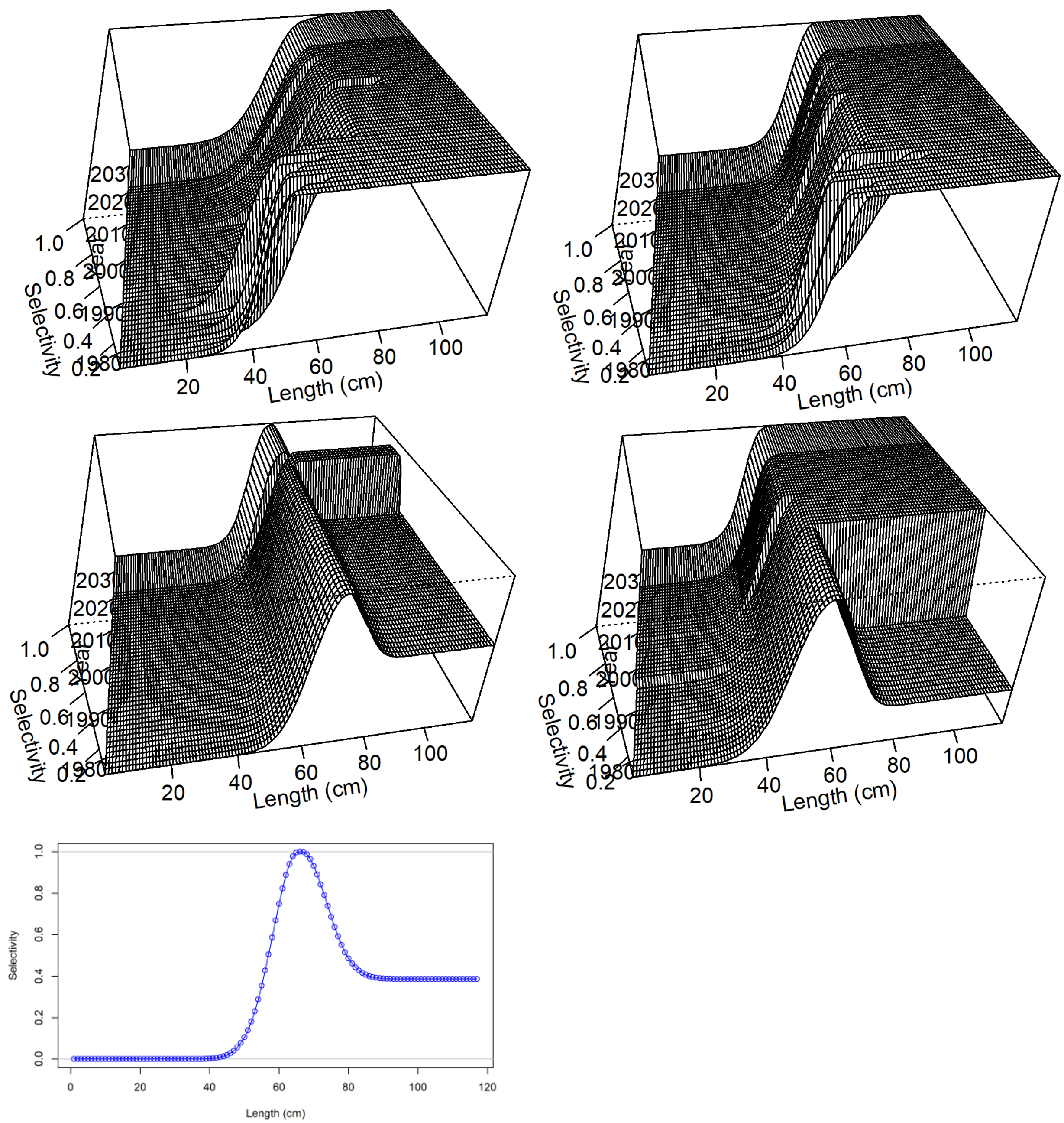


Figure 2.75 Selectivity curves for Model 21.2 Trawl fishery (top left), longline fishery (top right), pot fishery (middle left), NMFS bottom trawl survey (mid right), and AFSC Longline survey (bottom) length composition data.

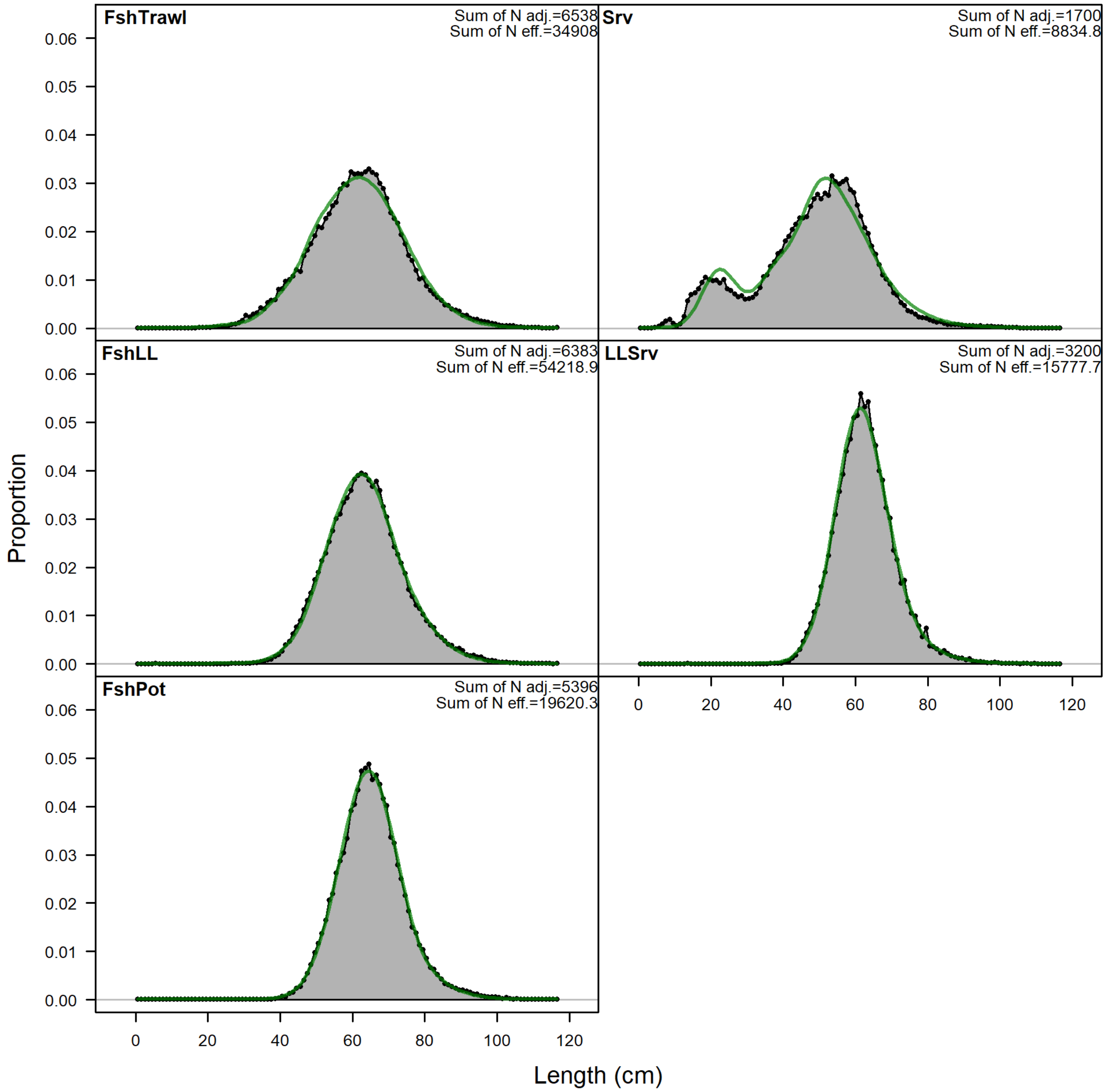


Figure 2.76 Overall Model 21.2 fits to Trawl fishery (FshTrawl), longline fishery (FshLL), pot fishery (FshPot), NMFS bottom trawl survey (Srv), and AFSC Longline survey (LLSrv) length composition data.

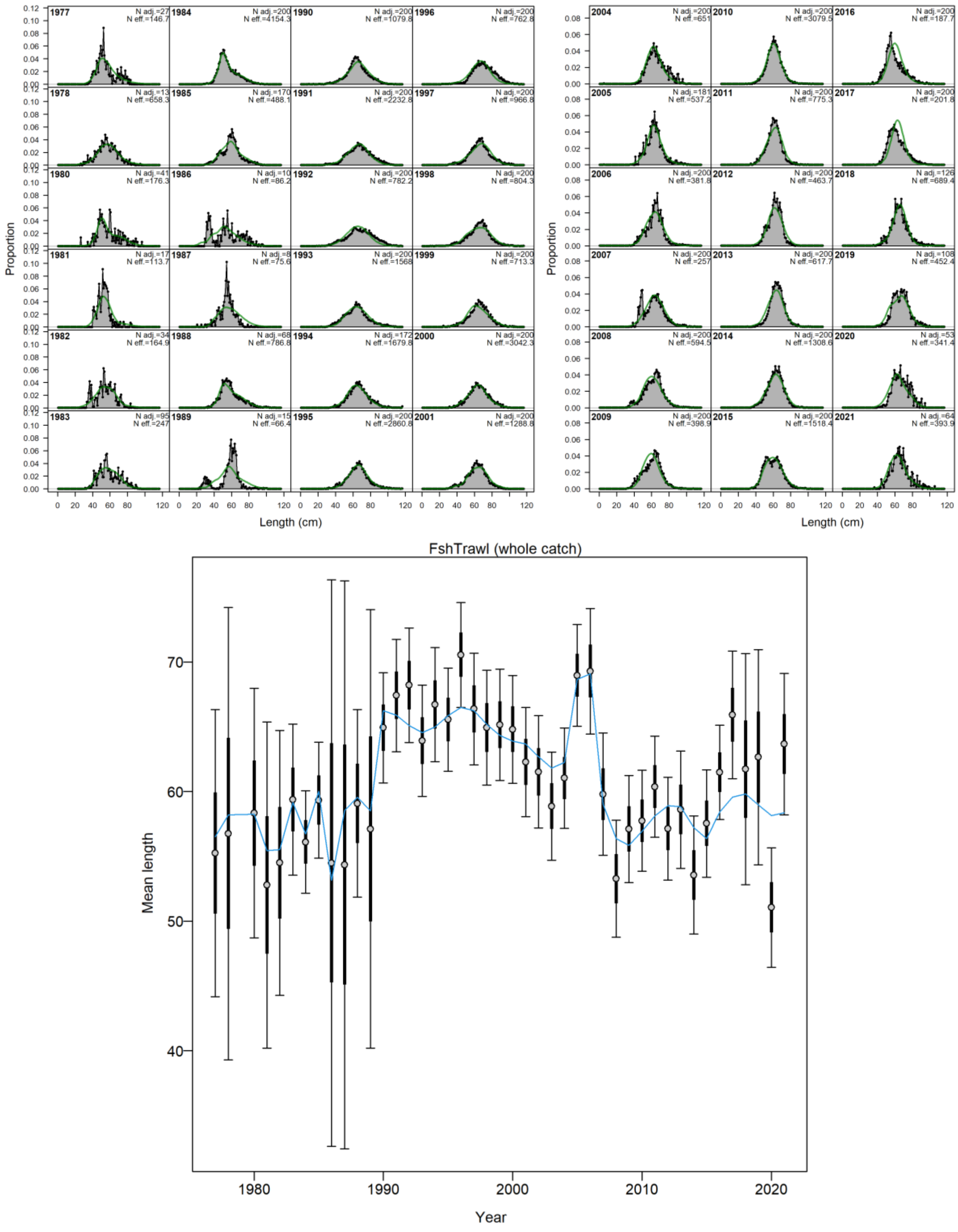


Figure 2.77 Trawl fishery length composition and Model 21.2 fit (top) and mean length (cm; bottom).

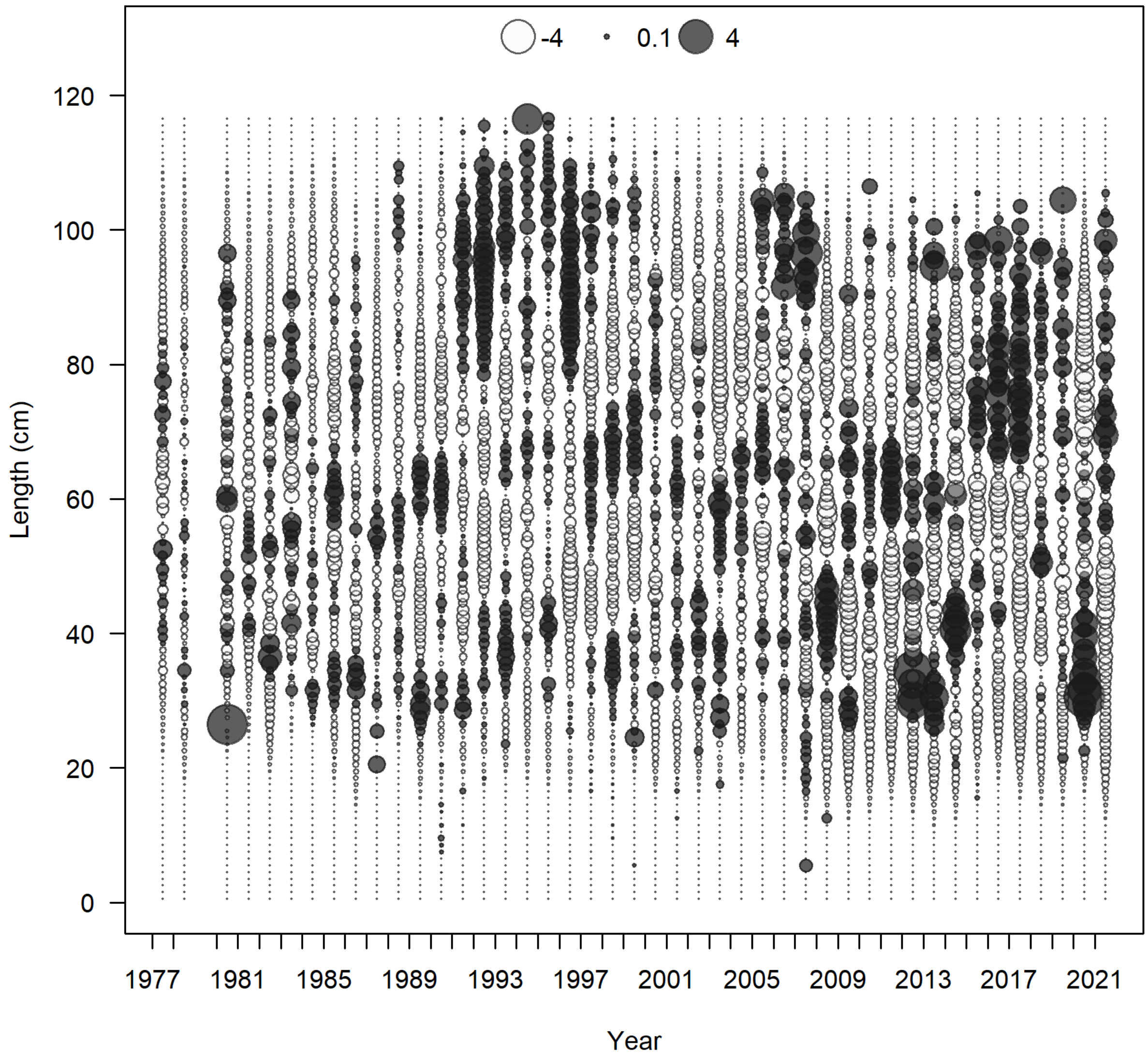


Figure 2.78 Trawl fishery length composition Pearson residuals (max = 5.69) for Model 21.2.

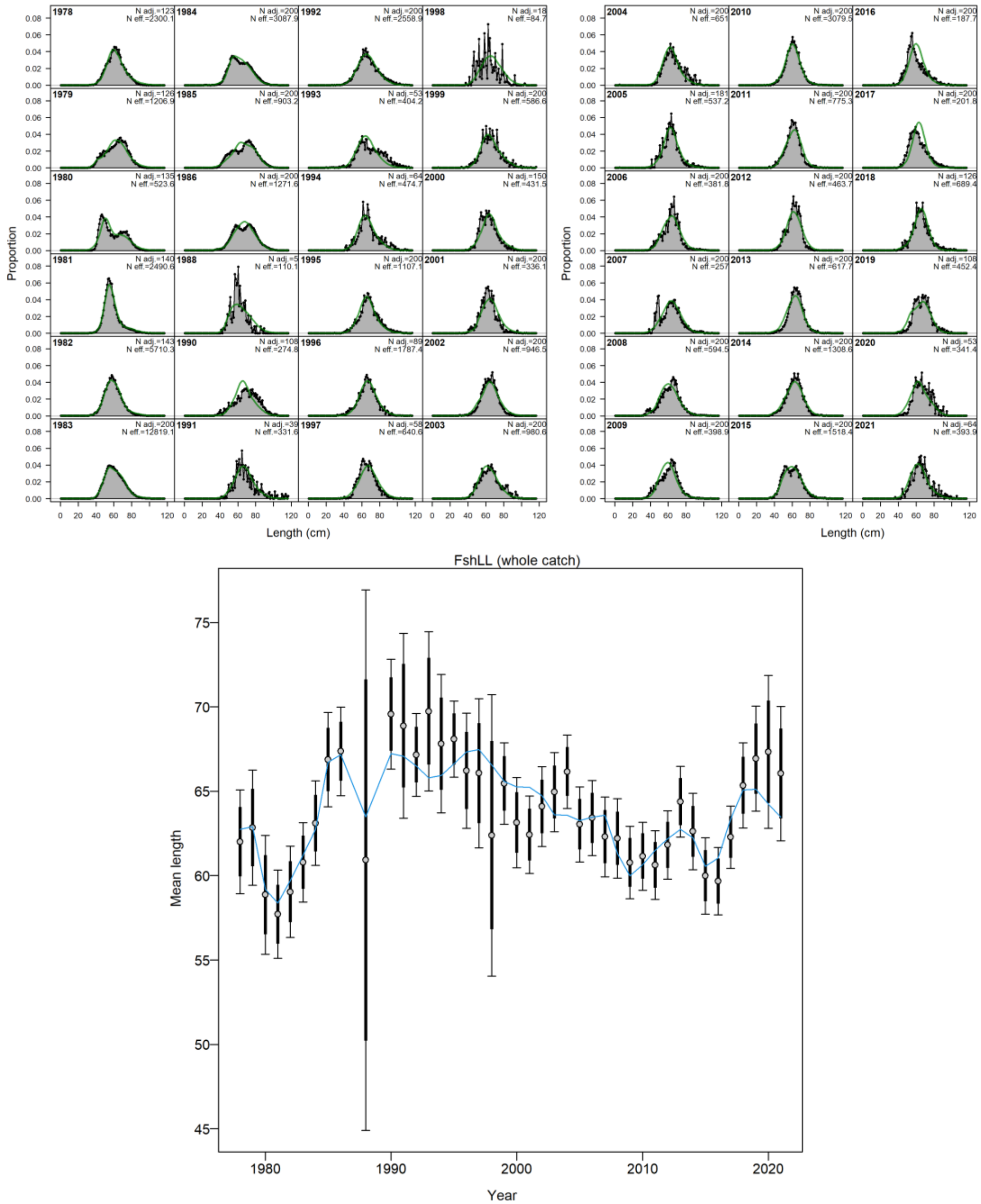


Figure 2.79 Longline fishery length composition and Model 21.2 fit (top) and mean length (cm; bottom).

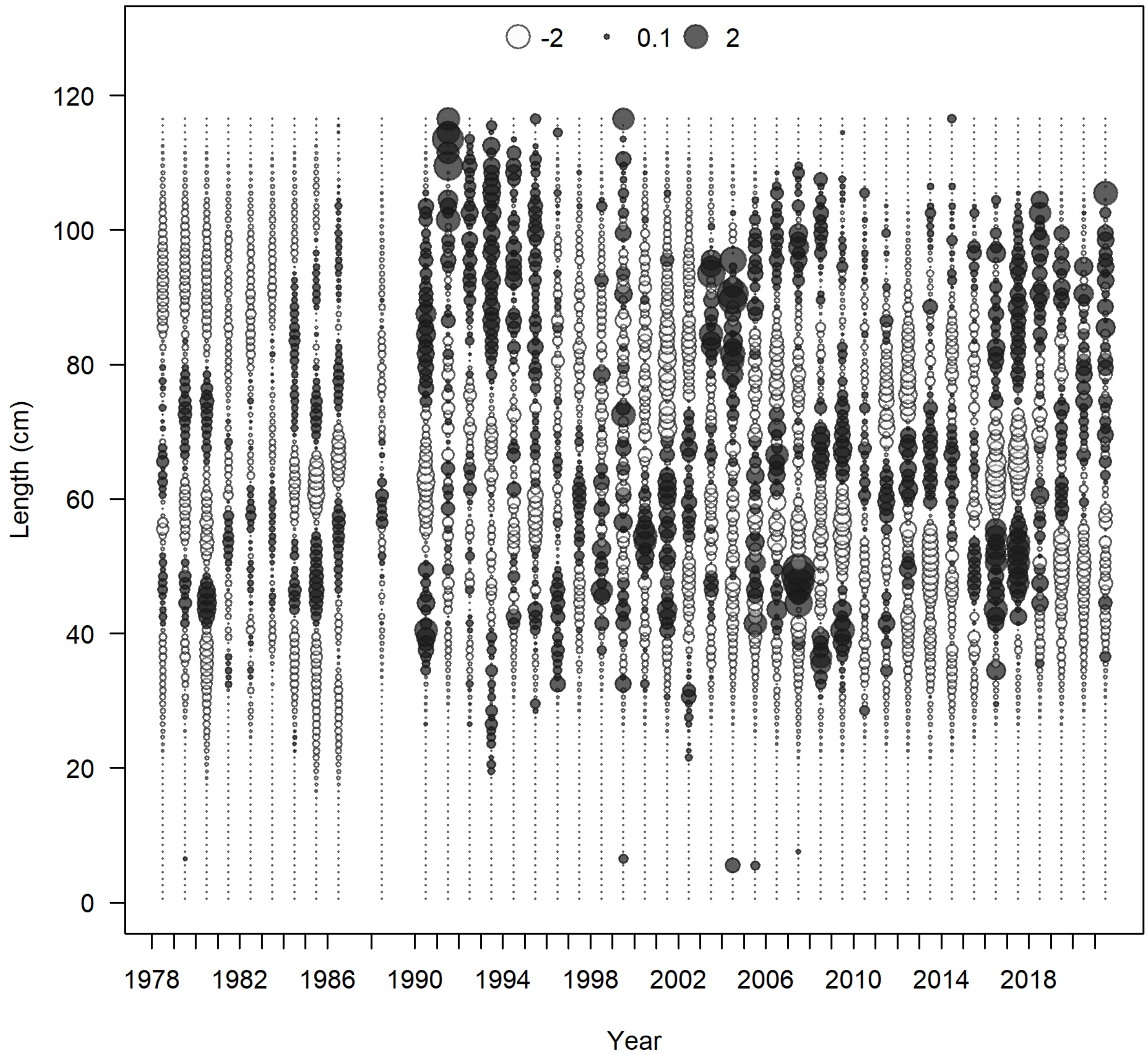


Figure 2.80 Longline fishery length composition and Model 21.2 fit Pearson residuals (max=3.76).

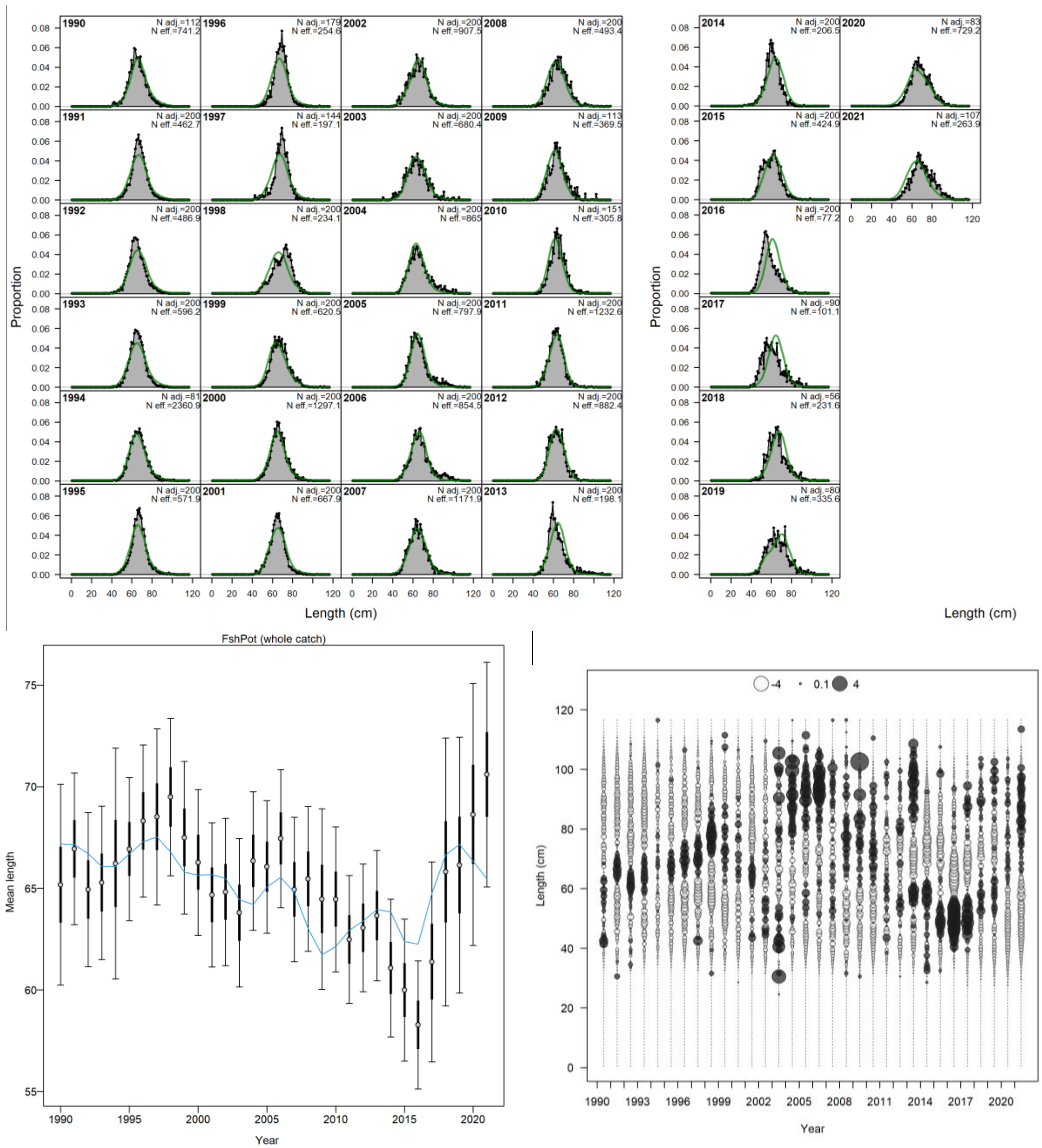


Figure 2.81 Pot fishery length composition and Model 21.2 fit (top), mean length (bottom left), and Pearson residuals (max=5.72; bottom right).

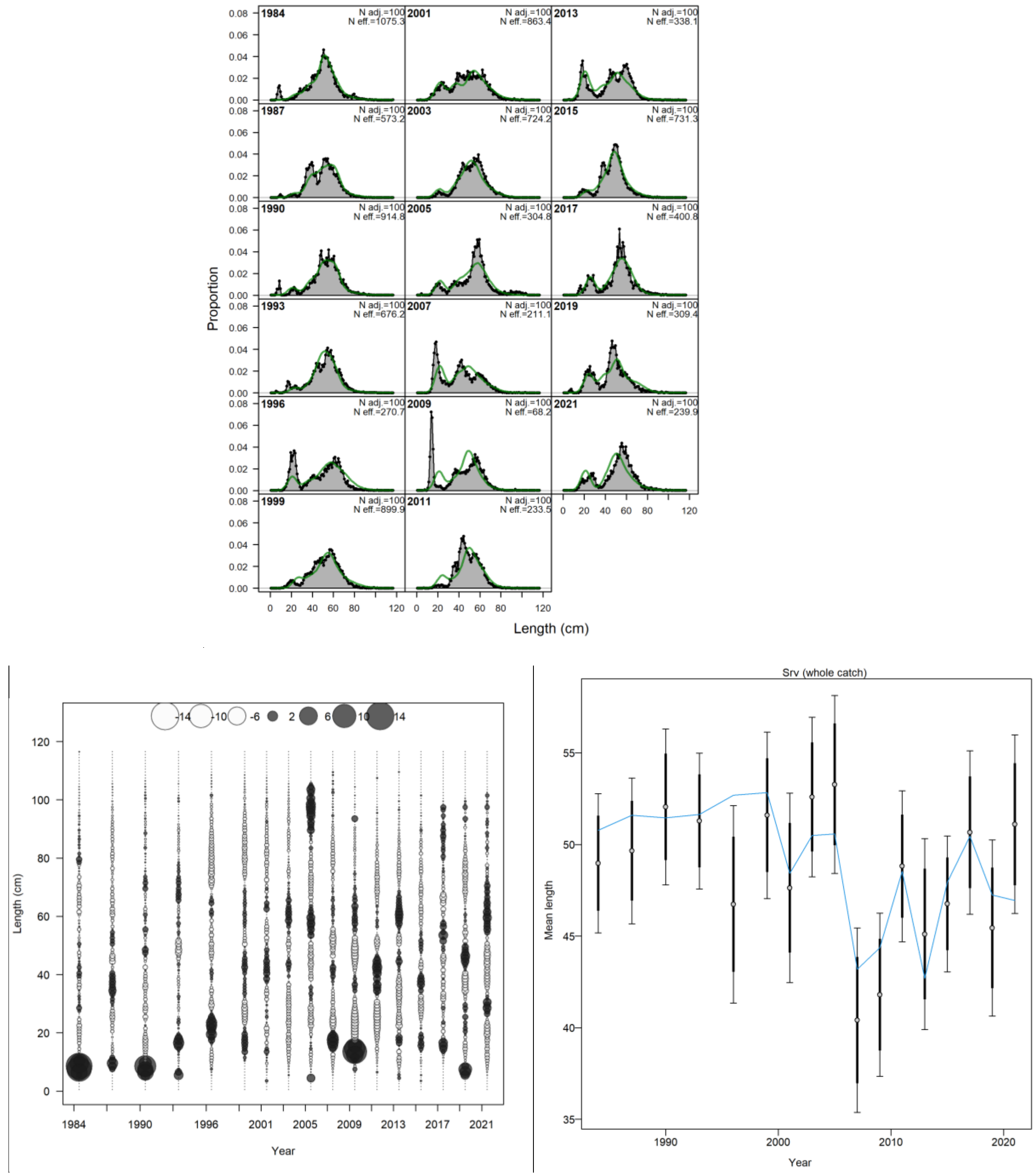


Figure 2.82 NMFS bottom trawl survey length composition and Model 21.2 fit (top), Pearson residuals (left bottom; max = 12.44), and mean length (cm; right bottom).

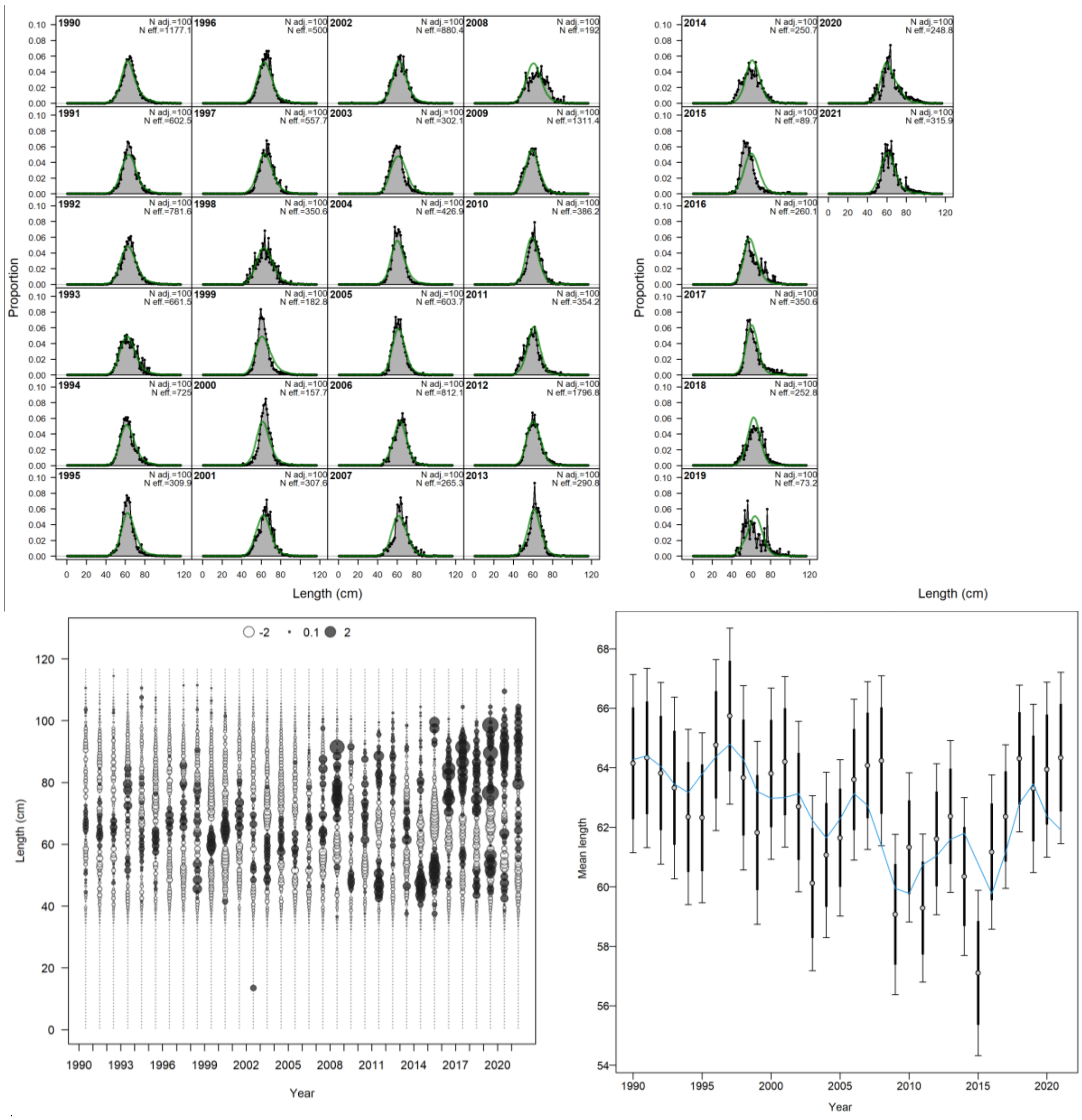


Figure 2.83 AFSC Longline survey length composition and Model 21.2 fit (top), Pearson residuals (left bottom; max=5.19), and mean length (cm; right bottom).

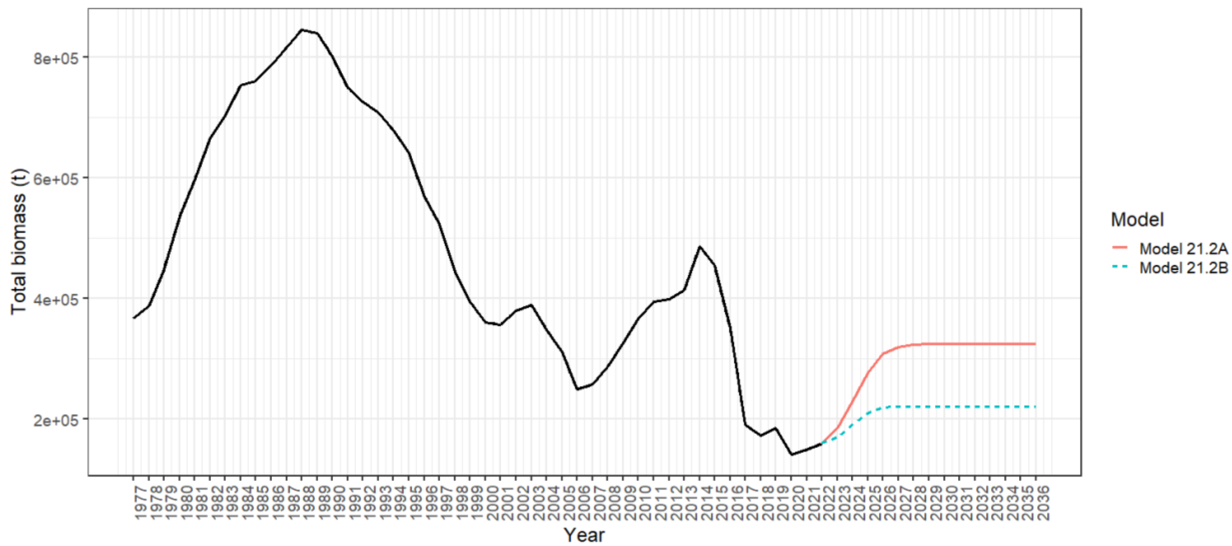


Figure 2.84 Total biomass 1977-2021 for Model 21.2 with Projection A (red solid line) and Projection B (blue dashed line) shown for 2022-2036.

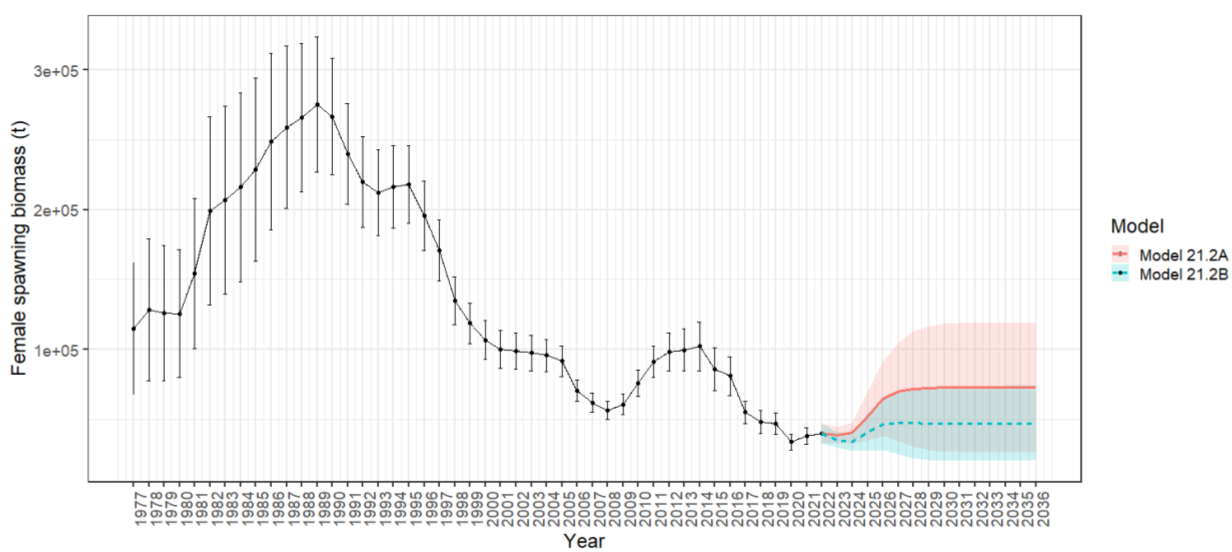


Figure 2.85 Model 21.2 female spawning biomass with 95% asymtotic error intervals with Projection A (red solid line) and Projection B (blue dashed line) shown for 2022-2036.

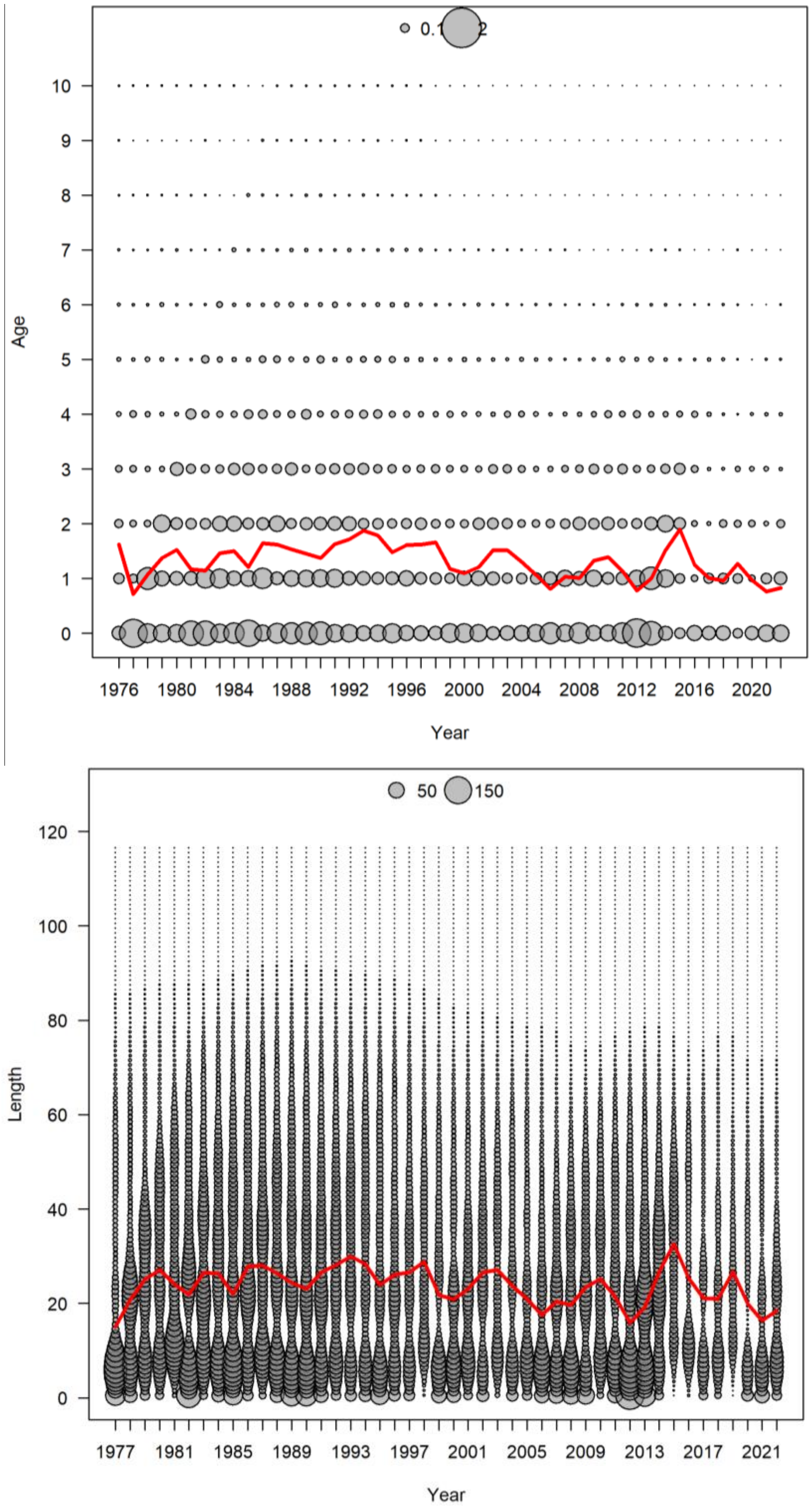


Figure 2.86 Model 21.2 predictions of middle of the year number at age (top) with mean age (red line) and number at length (bottom)with mean length (red line).

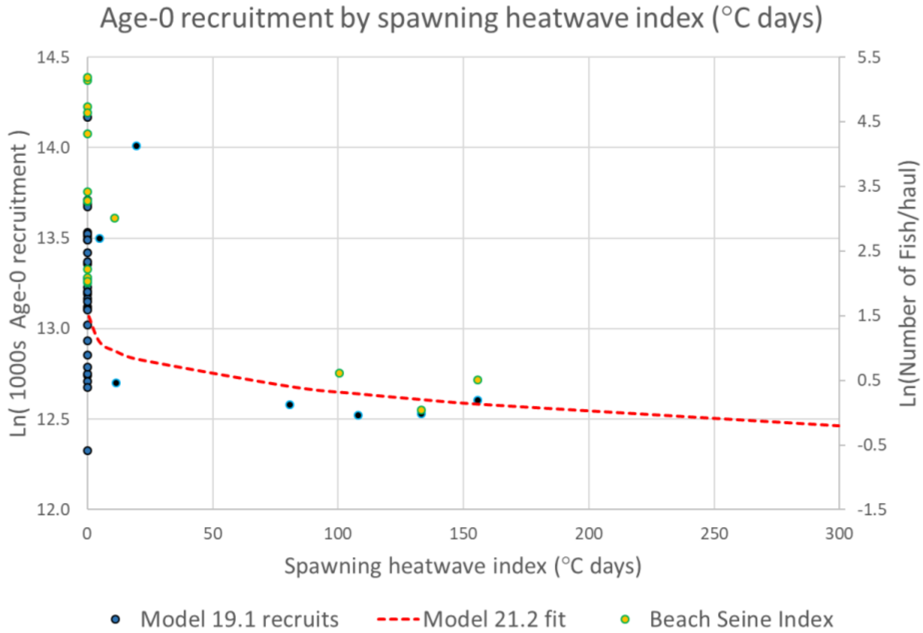


Figure 2.87 Log recruits (1000'1) by spawning heatwave index from the Model 19.1 (blue dots) with spawning heatwave linked recruitment model fit (red line) from Model 21.2. Shown on the secondary y-axis and in yellow are the log of the age-0 beach seine index values (number of fish/haul).

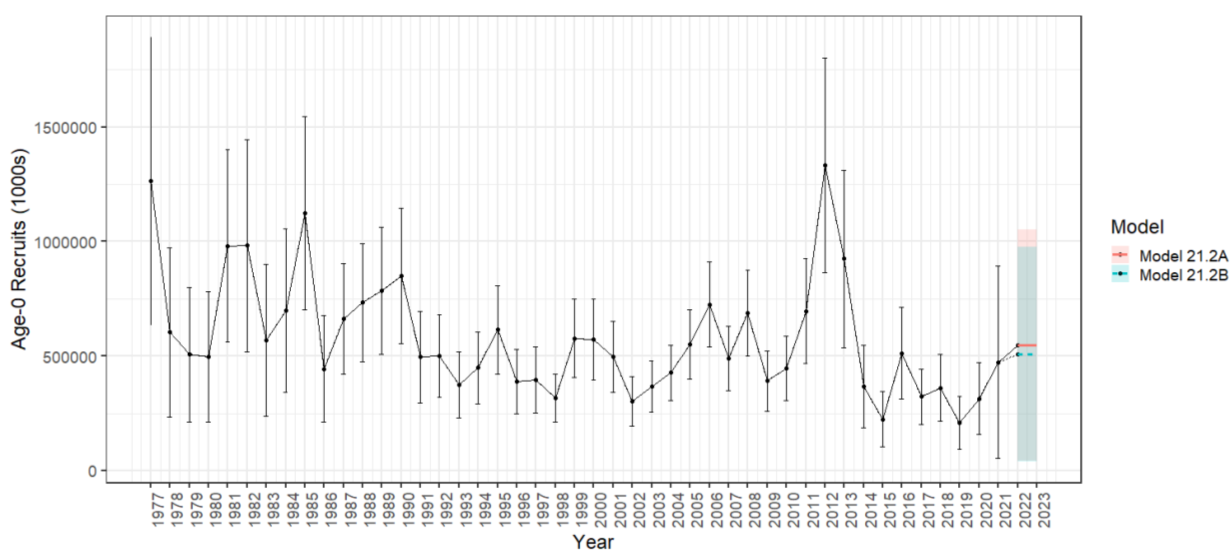


Figure 2.88 Model 21.2 age-0 recruitment (1000's) with 95% asymtotic error intervals with Projection A (solid red line) and Projection B (dashed blue line).

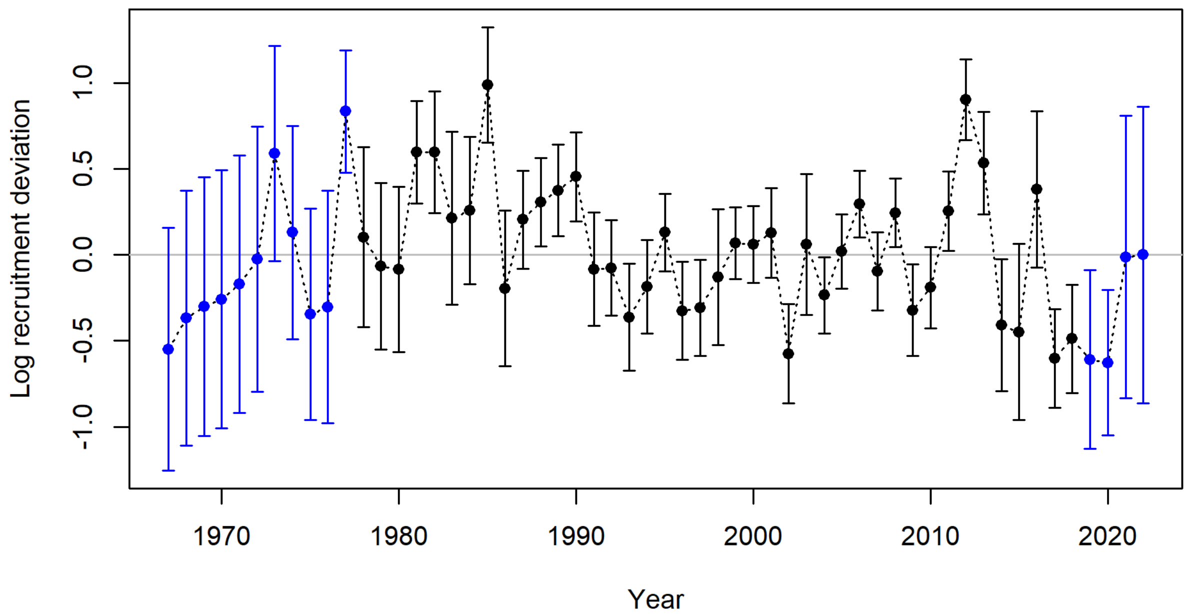


Figure 2.89 Model 21.2 log recruitment deviations with 95% asymtotic error intervals.

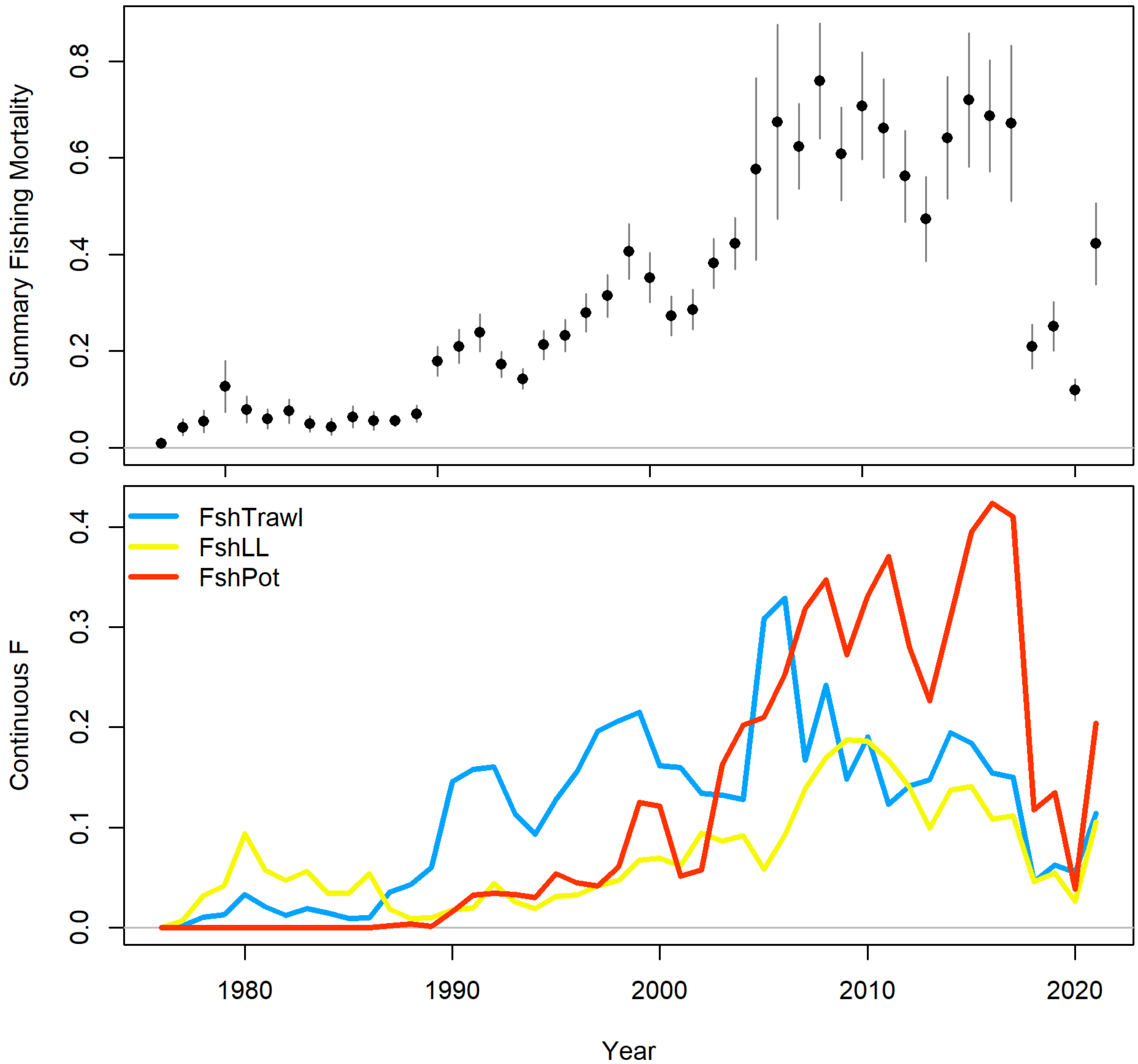


Figure 2.90 Model 21.2 sum of apical fishing mortality (top) and continuos fishing mortality by trawl (FshTrawl), longline (FshLL) and pot (FshPot) fisheries (bottom).

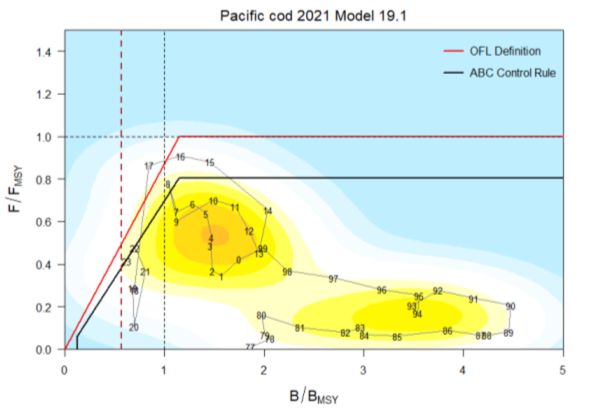


Figure 2.91 For (left) Model 19.1 and (right) Model 21.1 ratio of historical F/F_{msy} versus female spawning biomass relative to B_{msy} for GOA pacific cod, 1977-2023. Note that the proxies for *Fmsy* and *Bmsy* are $F_{35\%}$ and $B_{35\%}$, respectively. The Fs presented are the sum of the full Fs across fleets. Dashed line is at $B_{20\%}$, Steller sea lion closure rule for GOA Pacific cod.

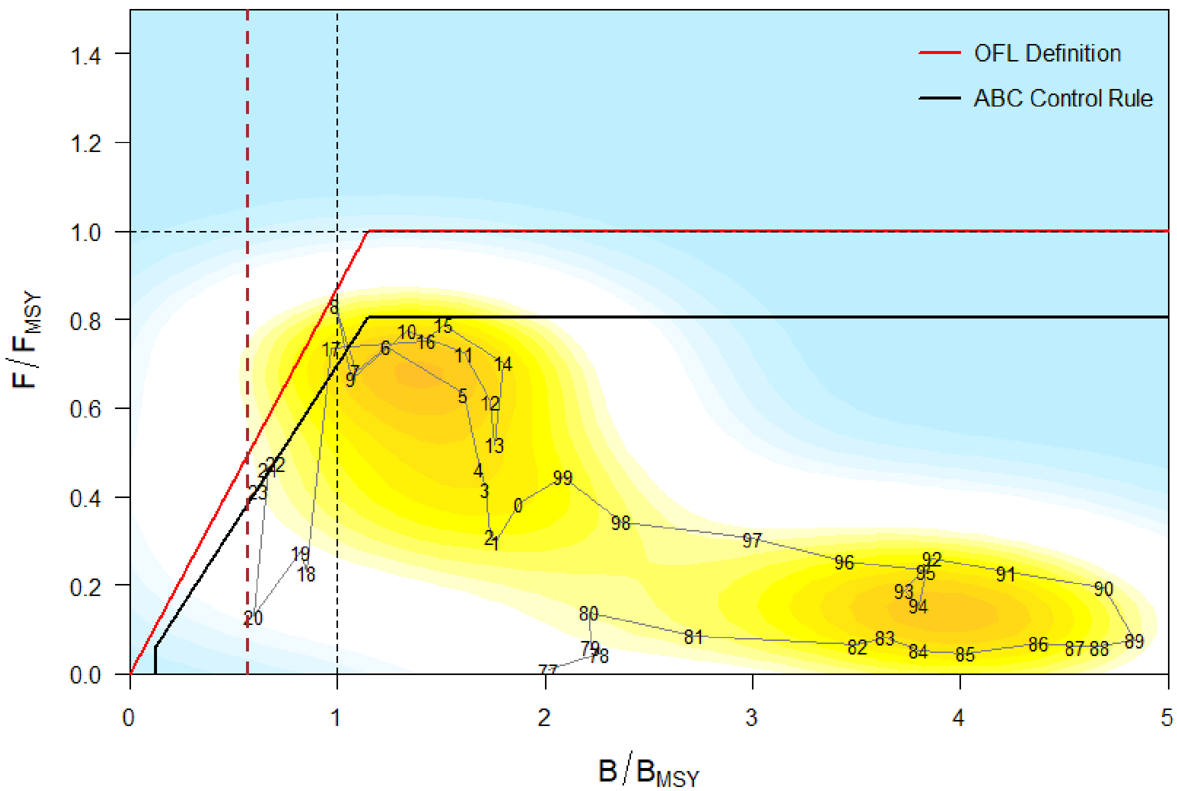


Figure 2.92 For Model 21.2 ratio of historical F/F_{msy} versus female spawning biomass relative to B_{msy} for GOA pacific cod, 1977-2023. Note that the proxies for *Fmsy* and *Bmsy* are $F_{35\%}$ and $B_{35\%}$, respectively. The Fs presented are the sum of the full Fs across fleets. Dashed line is at $B_{20\%}$, Steller sea lion closure rule for GOA Pacific cod.

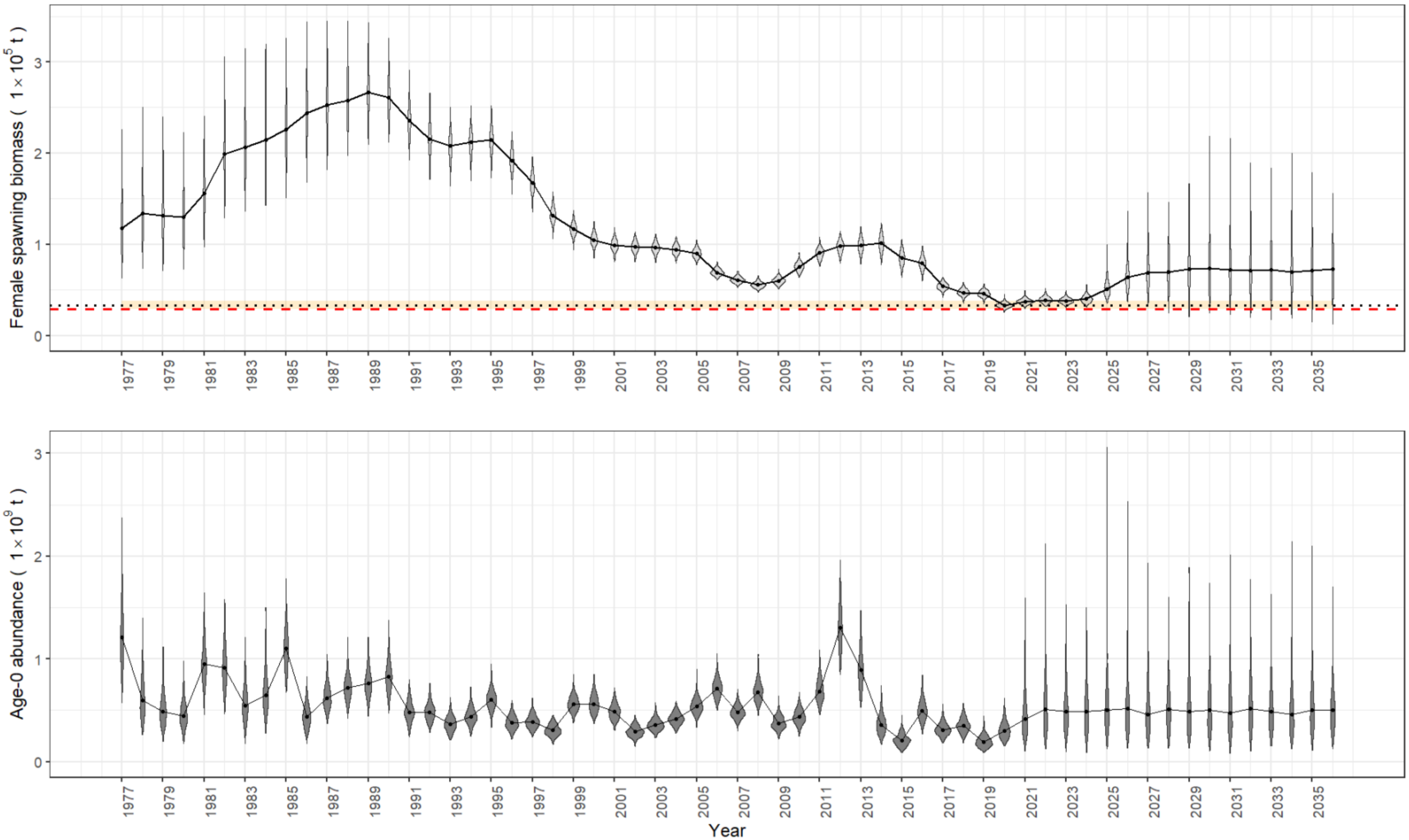


Figure 2.93 Model 21.2 with Projection A MCMC posterior distribitions of beginning of the year female spawning biomass (top) and age-0 abundance (bottom) for 1977-2036. Dotted line is the projected $SSB_{20\%}$ with 95% confidence interval in orange and the red dashed line is $SSB_{17.5\%}$.

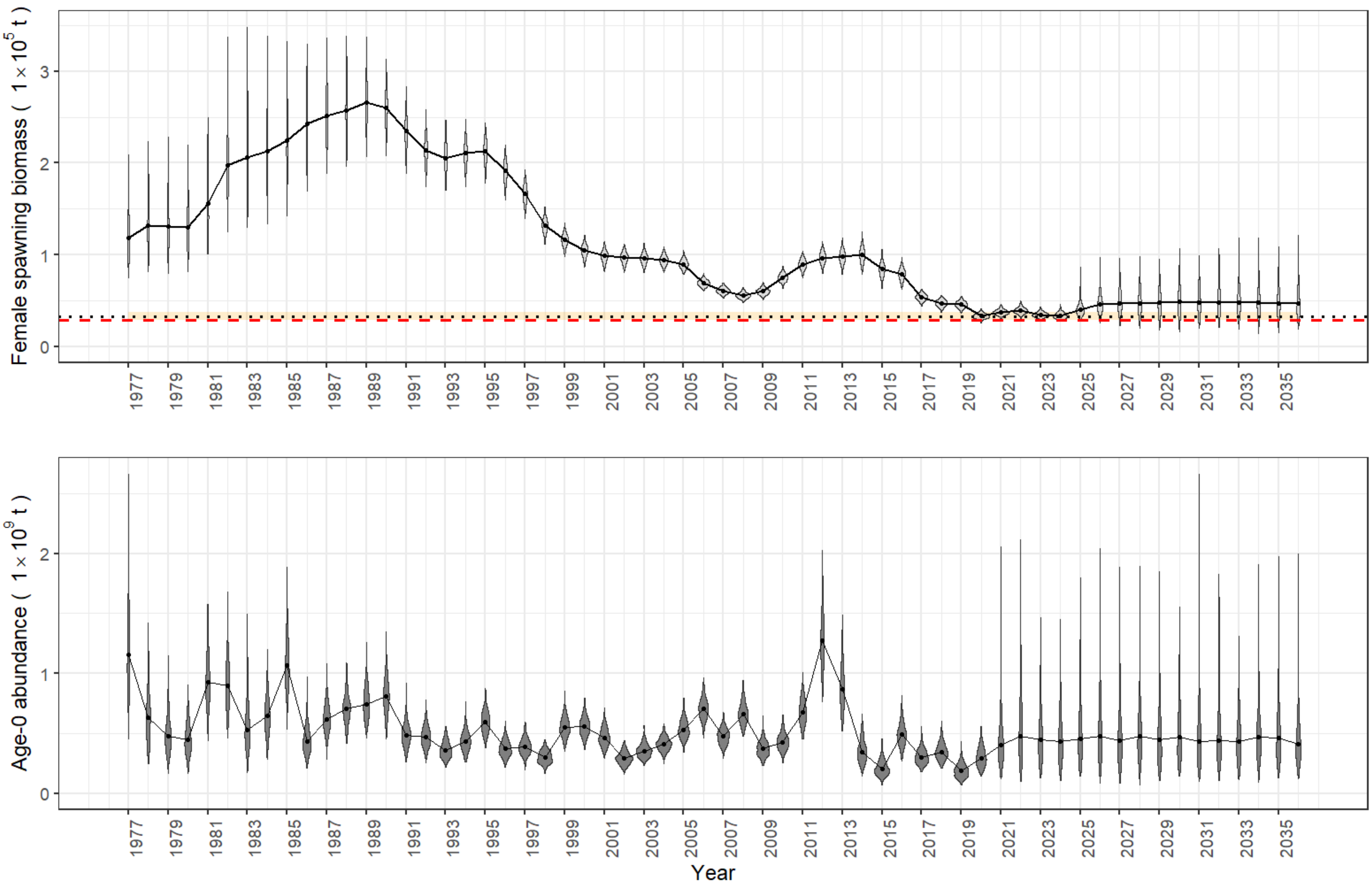


Figure 2.94 Model 21.2 with Projection B MCMC posterior distribitions of beginning of the year female spawning biomass (top) and age-0 abundance (bottom) for 1977-2036. Dotted line is the projected $SSB_{20\%}$ with 95% confidence interval in orange and the red dashed line is $SSB_{17.5\%}$.

Figure 2.95 Model 21.2 MCMC Projection A posterior distribitions of the 2022 (top) and 2023 (bottom) spawning stock biomass ratio with estimates for $SSB_{20\%}$ (orange dotted line) and $SSB_{17.5\%}$ (Red dashed line) from the projection model, and posterior median (blue solid line) for beginning year 2022 and 2023.

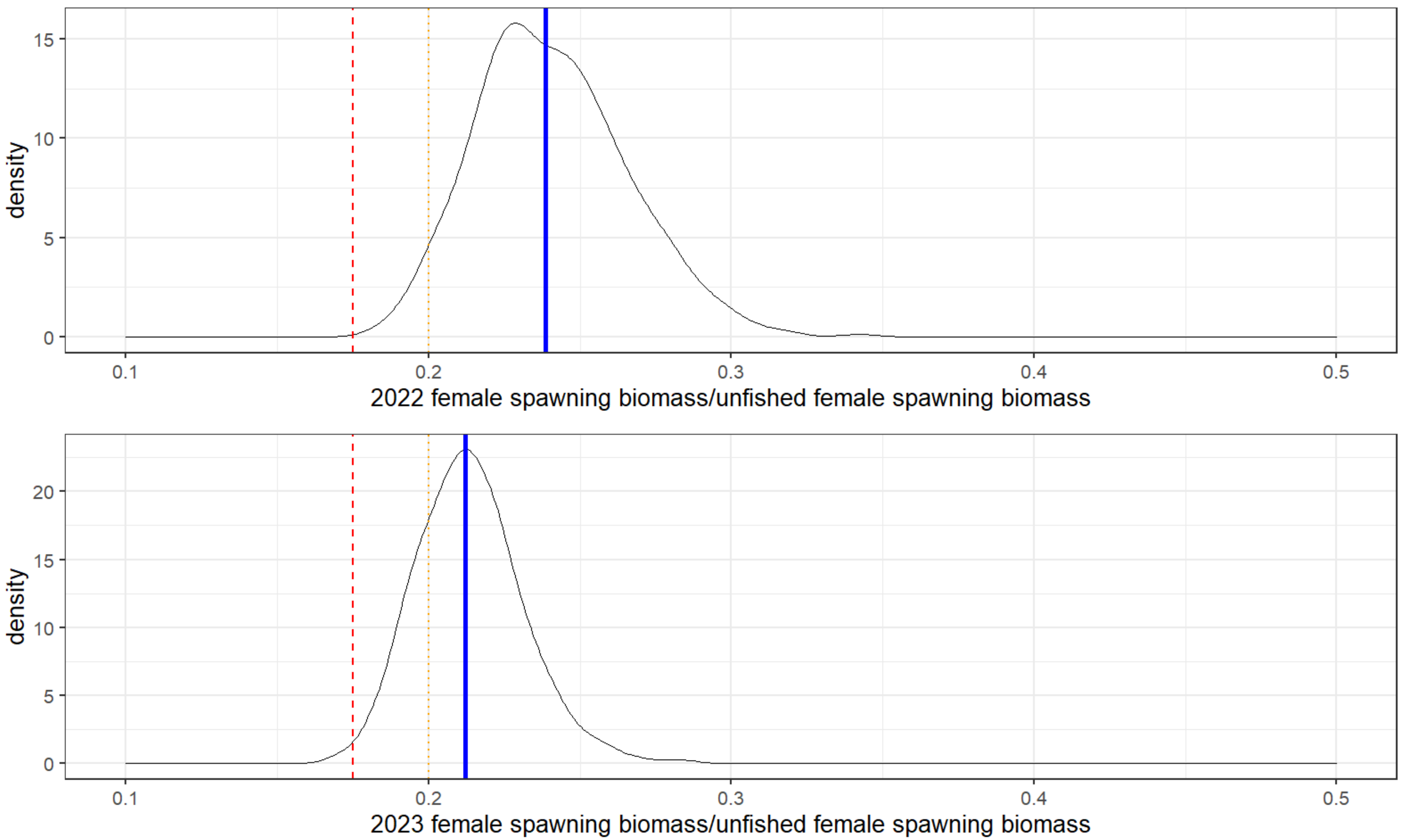


Figure 2.96 Model 21.2 MCMC Projection B posterior distribitions of the 2022 (top) and 2023 (bottom) spawning stock biomass ratio with estimates for $SSB_{20\%}$ (orange dotted line) and $SSB_{17.5\%}$ (Red dashed line) from the projection model, and posterior median (blue solid line) for beginning year 2022 and 2023.

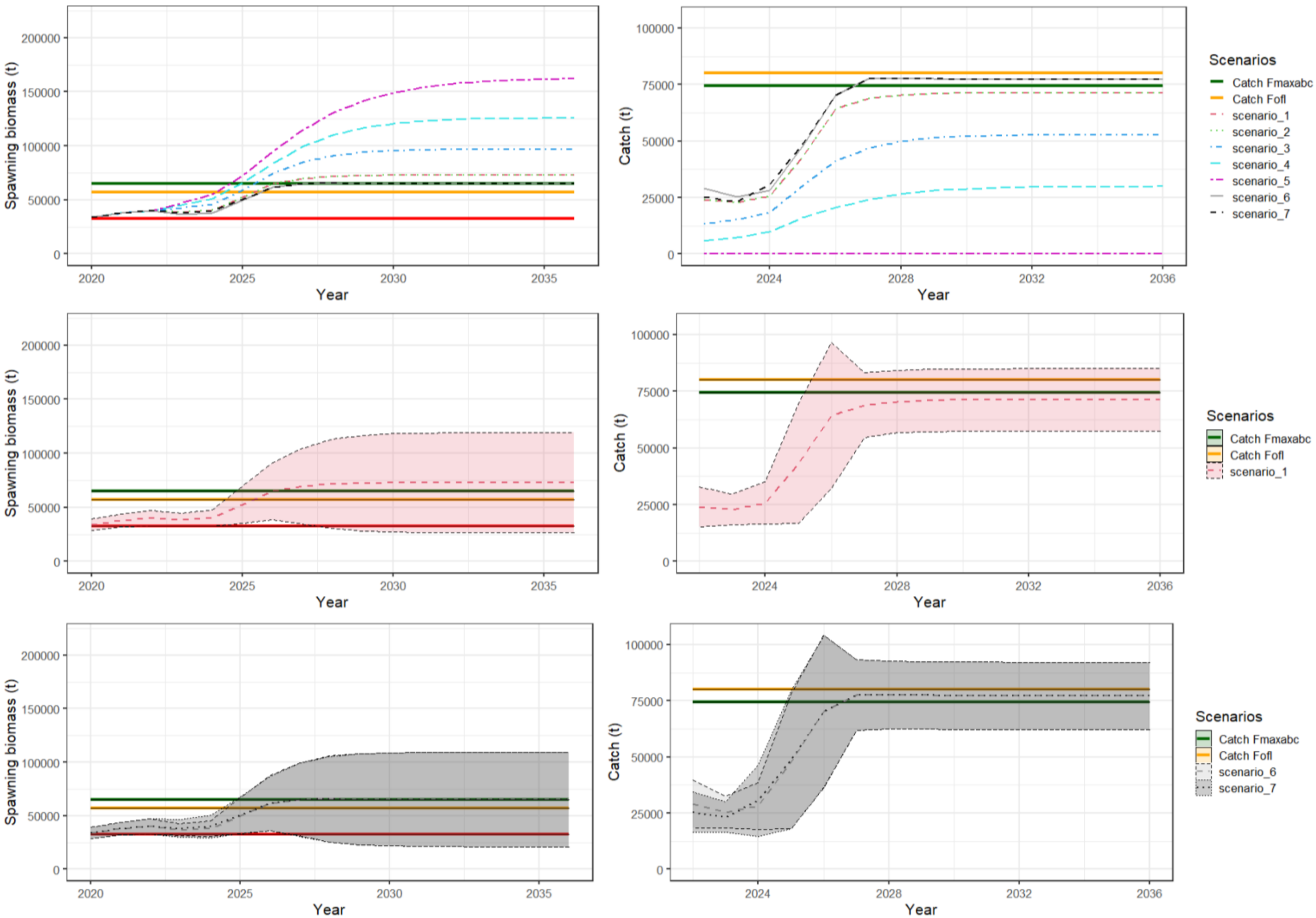


Figure 2.97 Model 21.2A projections of female spawning biomass (top left) and catch (top right) for the seven management scenarios, for scenario 1 a max ABC (middle), and scenarios 6 and 7 for status determination (bottom).

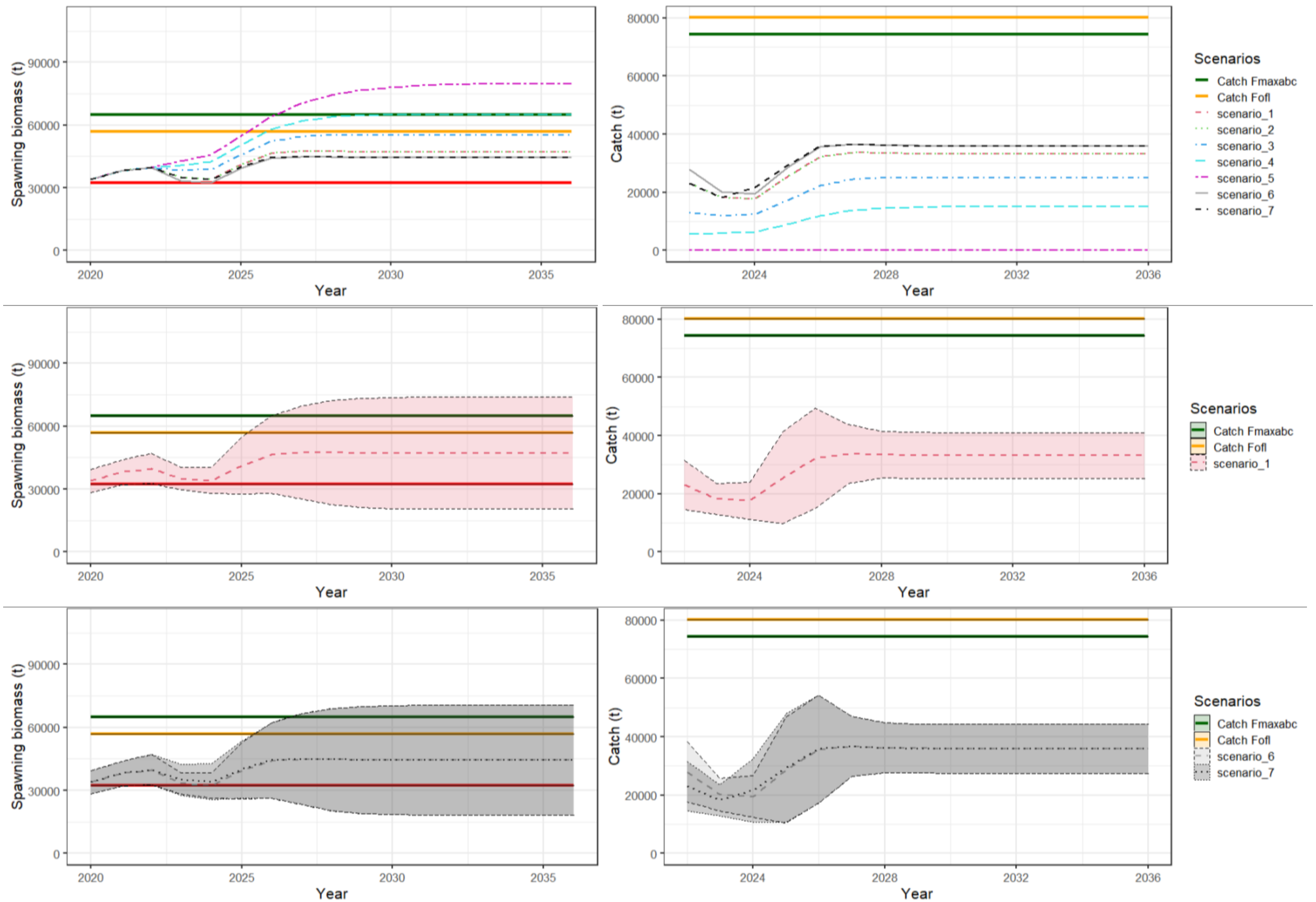


Figure 2.98 Model 21.2B projections of female spawning biomass (top left) and catch (top right) for the seven management scenarios, for scenario 1 a max ABC (middle), and scenarios 6 and 7 for status determination (bottom).

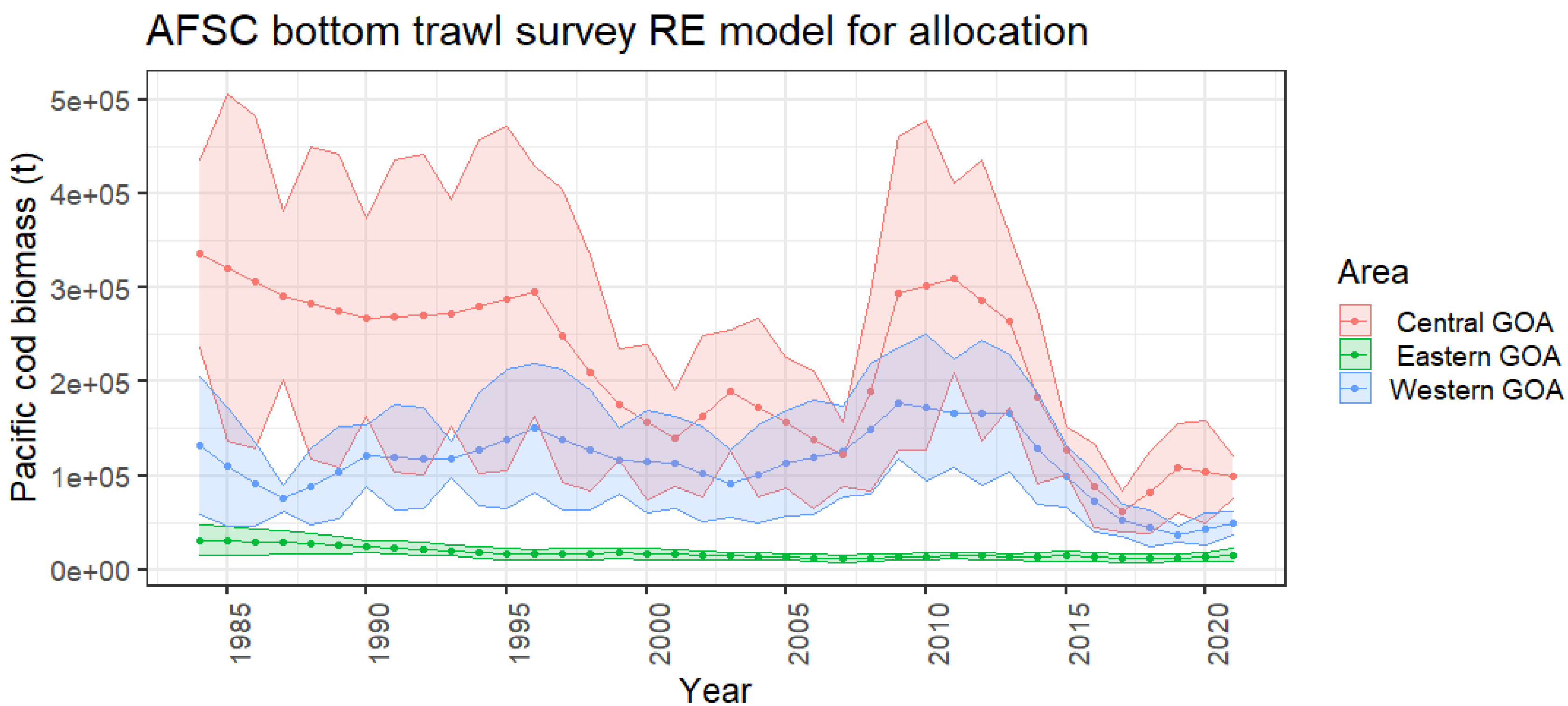
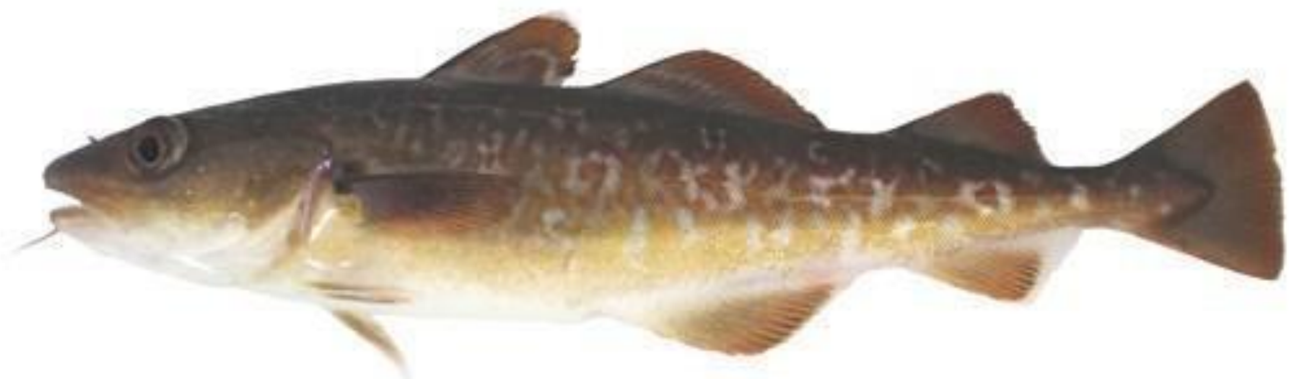


Figure 2.99 Random effects model results for the AFSC bottom trawl survey area used for area allocation.

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

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

November 2021



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 initiatives and AFSC research priorities support 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 4-6^{o}C 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 juveniles 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
- 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 with a slight recovery to near normal conditions in 2017, when the heat in the system was reduced but return to low values in 2018 and 2019, similar to the GOA pollock
- Highest ranked predictor for recruitment regression model was spawning habitat suitability and eddy kinetic energy on the GOA 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)

"The JPT were in support of the current templates and the current 3-stage indicator analysis, but noted concerns of over-emphasizing weighting in the first stage and recommended that indicators should be appropriately caveated to not over-generalize indicators across species. The JPT also fully supported the development of the ESP dashboard on AFKIN that includes metadata for each data source, but suggested a staged approach to the integration of data that have not been thoroughly vetted and published.

The SSC endorses the recommendations, comments, and suggestions from the JPT, all of which are consistent with previous SSC recommendations and guidance." (SSC, October 2020)

We provide a simple score following the SSC recommendation and compare the 1:1 weighting of indicators in the "Beginning Stage: Traffic Light Test" with the results of the "Intermediate Stage, Importance Test" section. In the intermediate stage we use a 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 weigh the indicators in the beginning stage for a more informed score.

We have also initiated a new document called the request for indicators or RFI to initiate the ESP process once an ESP is recommended for a stock. The RFI begins with a summary of the dominant ecosystem and socioeconomic processes influencing the stock and then provides the requested list of potential indicators representing those dominant pressures. Instructions for how to contribute an indicator in response to the stock request are included along with details on the indicator review process and associated guideline criteria, the role and responsibilities of ESP teams and contributors, and use and acknowledgement of the indicator if selected for the ESP. The standardized structure of the RFIs and the included guideline criteria will help with vetting indicators and assist with the review of indicators by the ESP teams. We plan to create RFIs for those stocks that already have an ESP completed using the "Data Gaps and Research Priorities" section and intend to complete these in January to begin the 2022 ESP cycle.

"In general, however, the SSC recommends the continued inclusion of community engagement and dependency indices at varying scales in ESPs, ESRs, and SAFEs. For ESPs specifically, changes in patterns of community engagement and dependency at the stock level have the potential to inform not only stock assessments and analyses that support fishery management, but they may also function as early indicators of larger ecosystem changes." (SSC, December 2020)

Community indicators are currently available in the Annual Community and Participation Overview (ACEPO) report (Wise et al., 2021), that presents social and economic information for communities that are substantially engaged in the commercial groundfish and crab fisheries in Alaska. Moving forward, we plan to include socioeconomic indicators in the ESP that reflect the condition or health of the stock and will be evaluating how to reference the products available in the ACEPO report with what might inform on stock health. We plan to address this in the next full or partial ESP for GOA Pacific cod.

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)

In 2020, we developed a first draft of the ESP for GOA Pacific cod, but some delays in production occurred due to the limitations under COVID-19. In this final ESP report we have updated the life history tables and references and allowed for more internal review of the whole document from the Pacific cod ESP team.

"The Team noted that consideration of expanding the spawning habitat suitability index using ROMS and potentially including wind information should be discussed at the ESP workshop in the spring. While discussion was focused on indices related to recruitment, it was noted that exploration of indices towards informing other assessment model parameters such as natural mortality would also be good to explore.

The climate enhanced model, Model 20.1, was presented and showed similar results to model 19.1 in spawning biomass trends. The Team encourages the author to continue to research this model. It was noted that research models like this could benefit from discussion at the ESP workshop." (GOA GPT, November 2020)

Several climate enhanced models for crab and groundfish stocks were presented at the March 2021 ESP Advice workshop. Specifically, Steve Barbeaux provided an overview of his current ecosystem linked models. Model 19.1 includes a temperature index linked to catchability of the longline survey and a natural mortality time block linked to the heatwave years for 2014-2016. Model 20.1 is the same as Model 20.1 with the addition of a June temperature anomaly linked to growth and a spawning heatwave index (heatwave calculated during Pacific cod spawning season) linked to recruitment. Model 21.1 builds off Model 20.1 but replaces the natural mortality time block with time-varying natural mortality that is linked to the spawning heatwave index.

This presentation was very helpful for the discussion during the ESP workshop regarding the utility of these ecosystem linked models and providing advice for management decisions. The presentation also included climate projections from CMIP5 for Models 20.1 and 21.1. which was used to compare the differences in projected spawning biomass between the two models. The output of these climate projections may be helpful for understanding the future productivity of the stock in response to a shifting climate and very relevant for management strategy evaluations.

There are several age structured ecosystem-linked models in development for the 2021 GOA Pacific cod stock assessment that explore the use of ecosystem indices to inform catchability, natural mortality, growth, and recruitment. Although the spawning habitat suitability index was examined for 2021 as an age-0 index, the age-0 beach seine index provided by Ben Laurel and Mike Litzow was found to perform better for this purpose and will be presented as an alternative in the 2021 assessment. The age-specific mortality estimates from the GOA CEATTLE model are being tested as priors for age-specific mortality within the model, however fitting age-specific annually varying mortality within the model has proven to be challenging given the lack of data on younger fish (age 0-3) and will require further development.

"The first ESP for GOA Pacific Cod was completed during this assessment cycle, and the SSC commends the authors, Dr. Shotwell, and other ESP collaborators and contributors in its development. The SSC supports continued exploration of additional habitat, biological, or environmental indicators that may be appropriate for describing trends in recruitment. With respect to socioeconomic considerations within the

ESP, the SSC recommends trying to separate fishery engagement from fishery dependency, given that a focus only on engagement may provide a biased perspective toward the most successful fishery participants. As such, the SSC supports exploration of dependency indices for inclusion in the next ESP for this stock. The SSC further suggests that ESP authors consider avenues for allowing coastal community members to provide review of, and feedback on, subsequent ESPs. The SSC finds aggregating small communities to address confidentiality concerns to be effective in capturing regional socioeconomic trends." (SSC, December 2020)

We thank the SSC for their support of exploring indicators to describe trends in recruitment for the GOA Pacific cod stock and plan to continue this exploration through the request for indicators (RFI) document in future years. We plan to evaluate the information provided in the Economic SAFE and ACEPO report to determine what socioeconomic indicators could be provided in the ESP that are not redundant with those reports and related directly to stock health. This may result in a transition of indicators currently reported in this ESP to a different series of socioeconomic indicators in future ESPs and may include a shift in focus from engagement to dependency. Additional considerations should be given for the timing of the economic and community reports that are delayed by 1-2 years depending on the data source from the annual stock assessment cycle.

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

National initiatives and AFSC research priorities support conducting an ESP for the GOA Pacific cod stock. The high commercial importance of the stock and the early life history habitat requirements created a high score for both stock assessment and habitat assessment prioritization (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 GOA 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 (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 adults 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 (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 from the lead stock assessment author are also provided (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 (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, 2009). Hatch timing/success is highly temperature-dependent (Laurel *et al.*, 2008), with optimal hatch occurring in waters ranging between 4-6°C (Bian *et al.*, 2016; Laurel and Rogers 2020) over a broad range of salinities (Alderdice and Forrester 1971). Eggs hatch into 4 mm larvae in ~2 weeks at 5°C (Laurel *et al.*, 2008) and become surface oriented and available to pelagic ichthyoplankton nets during the spring (Doyle and Mier 2016). During this period, Pacific cod larvae are feeding principally on eggs, nauplii and early copepodite stages of copepod prey <300 um (Strasburger *et al.*, 2014). Warm surface waters can accelerate larval growth when prey are abundant (Hurst *et al.* 2010), but field observations indicate a negative correlation between temperature and abundance of Pacific cod larvae in the Central and Western 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 affect 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 (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.*, 2019). A fairly narrow and shallow depth range for the early juveniles suggesting the importance of these nearshore habitats for GOA Pacific cod. Tidal current also contributes to the spatial distribution in the early juvenile stage suggesting some influence of transport mechanisms in this stage as well. A preference for mixed mud, sand, and pebble sediments with some structural complexity was also noted (Pirtle *et al.*, 2019). 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 Fisheries Behavioral Ecology (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 suboptimal during the 2014-16 marine heatwave (Barbeaux *et al.*, 2020). However, the absence of age-0 fish arriving to nurseries in years with warm springs strongly suggests pre-settlement processes (egg/larval) are determining annual cohort strength in the GOA. Reductions in spawning habitat from subsurface warming appears to be an important mechanism limiting reproductive output in the GOA (Laurel and Rogers 2020), but it is likely one of several mechanisms driving recruitment dynamics. 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, 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 (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 (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 (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 was 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 being caught in the Western Gulf. Harvests from catcher vessels that deliver to shoreside processors account for approximately 90% of the retained catch (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 (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 (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 (Table 2.1.3c). China's rise as a re-processor is fairly recent. Between 2001 and 2011 exports to China 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 shows 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 (Figure 2.1.4a). Over the last two decades, at sea processors have accounted for 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 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) (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 residents 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 (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 represents 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 heatwaves) 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). Adult 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 a June temperature index (temperature at ~40m which is the average depth of 20-40 m fish) 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 heatwaves), 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 (Table 2.1.2b, 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 Figure 2.1.5a and Figure 2.1.5b, respectively

Ecosystem Indicators:

1. Physical Indicators (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 *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 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 (Laurel and Rogers, 2020). 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 as a measure of mesoscale energy in the ocean system (Ladd, 2020). 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 (Watson *et al.*, 2020). 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 (Figure 2.1.5a.g-i)
    - Summer large copepods for young-of-the-year (YOY) GOA Pacific cod from the EcoFOCI summer surveys (Kimmel *et al.*, 2019), 2000 to 2019, 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 (Ressler *et al.*, 2019), available for variable years historically and biennially since 2013 (contact: P. Ressler).
    - Spring Pacific cod larvae catch-per-unit-of-effort (CPUE) from the EcoFOCI spring surveys (Dougherty *et al.*, 2019), 1981 to 2019, various years (contact: L. Rogers).
    - Summer Pacific cod CPUE of YOY from the AFSC Kodiak beach seine survey, 2006 to 2020 (contact: B. Laurel).
    - Common murre reproductive success at Chowiet Island, 1979 to present, various years (contact: H. Renner).
3. Upper Trophic Indicators (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 (Laman and Rohan, 2020) from data collected randomly for otoliths in the GOA bottom trawl survey, 1984 to present, various years (contact: S. Rohan).
    - We calculate the effective area occupied and center of gravity for abundance (numbers) in the bottom trawl survey for the Gulf of Alaska. Spatio-temporal delta-generalized linear mixed model using recommended settings for an “index standardization” model (Thorson 2019), implemented using the package VAST (Thorson and Barnett 2017) in the R statistical environment. 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 750 “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 include only those cells that were shallower than 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 geographic coordinates to UTM coordinates. This rotation was performed to improve the interpretation of shifts in center of gravity, such that the axes along which this metric was summarized are approximately parallel and perpendicular to the continental shelf within the core distribution of Pacific cod. We also calculated the 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) (contact: Z. Oyafuso).

- Arrowtooth flounder total biomass (metric tons) from the most recent stock assessment model (Shotwell *et al.*, 2020), available 1976 to present (contact: K. Shotwell).
- Steller sea lion non-pup estimates for the GOA portion of the western Distinct Population Segment (known as the west, central and east GOA) (Sweeney and Gelatt, 2020), 1978 to present (contact: K. Sweeney).

Socioeconomic Indicators:

1. Economic Indicators (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 (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 (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 beginning and intermediate stage statistical tests of the indicator monitoring analysis for GOA Pacific cod and a review of current ecosystem linked modeling developments for the advanced stage.

Beginning Stage, Traffic Light Test:

The beginning stage of the indicator analysis is a simple traffic-light style 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 February 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 (Figure 2.1.2, Table 2.1.2b. We then assign a qualitative score based on the value compared 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 ocean temperatures in the GOA ecosystem resulting in a series of major marine heatwaves being declared for 2014-2016 and again in 2019 (Suryan *et al.,* 2021; Figure 2.1.5a.a). The severity, extent, and duration of the ocean warming have had a large impact on the productivity of the GOA Pacific cod stock (Barbeaux *et al.,* 2020, Laurel and Rogers, 2020). 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.,* 2020) and dropped again during the 2019 marine heatwave and is back up to near average conditions in 2020 (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 (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 (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 (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 (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 (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 (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 juveniles 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 (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, Figure 2.1.5a.m-n). This trend may suggest a change in the clustering of the stock over time as there was high biomass in 2009 with a single very large tow and then low stock biomass in 2017 and 2019 that was spread out throughout the survey area. Predator biomass of arrowtooth flounder and Steller sea lions has been decreasing and/or stable for the most recent years (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 decrease 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.*, 2020, Spies *et al.*, 2019, Ormseth *et al.*, 2019, Arimitsu *et al.*, 2021).

For the socioeconomic indicators (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. (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 recent series of marine heatwaves in 2014.

Traffic light scores by category and overall are provided in 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 (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 (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 (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 (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 recent severe marine heatwave years.

Intermediate Stage, Importance Test:

Bayesian adaptive sampling (BAS) was used for the intermediate stage statistical test to quantify the association between hypothesized predictors and GOA Pacific cod recruitment and to assess the strength of support for each hypothesis. 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 intermediate test, the full set of indicators is first winnowed to the predictors that could directly relate to recruitment and highly correlated covariates are removed (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 (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 (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 (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 multivariate 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 statistical approach. Efforts to include mortality switches could be informed by the planned Individual Based Models.

Advanced Stage, Research Model Test:

In the 2020 Pacific cod Stock assessment (Barbeaux et al. 2020) research models which incorporated links for catchability, mortality, growth, and recruitment using CFSR predicted bottom temperatures, NOAA reanalysis predicted surface temperatures, and heatwave indices were presented. The authors indicate in the 2020 assessment that these linked models had not been adequately validated for use in tactical management of the stock. However, projections based on CMIP 5 were provided to the end of the century for strategic considerations and evaluating the performance of the current control rules. Further development and evaluation of these research models is expected for the stock assessment models to be presented in 2021.

In the future, mortality switches could be evaluated in the advanced stage statistical test, which is a modeling application that analyzes predictor performance and estimates risk probabilities within the operational stock assessment model. Output of two new model developments could be used to generate or enhance an ecosystem-linked model for GOA Pacific cod. First, a new multi-species statistical catch-at-age assessment model (known as CEATTLE; Climate- Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics; Holsman *et al.*, 2016) has recently been developed for understanding trends in age-1 total mortality for Pacific cod, walleye pollock, and arrowtooth flounder from the GOA (G. Adams, *pers., commun.*). 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 *et al.*, 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.

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. Indeed, the age-specific mortality estimates from the GOA CEATTLE model are being tested as priors for age-specific mortality within the age-structured model, however fitting age-specific annually varying mortality within the model has proven to be challenging given the lack of data on younger fish (age 0-3) and will require further development. Additionally, the spawning habitat suitability index was examined for use in the 2021 age-structured model as an age-0 index, but the age-0 beach seine index (contact: B. Laurel and M. Litzow) was found to perform better for this purpose and will be presented as an alternative model in the 2021 assessment. Potentially in the future, the kinetic energy in Kodiak indicator could also be used directly to help explain the variability in recruitment deviations and predict pending recruitment events for GOA Pacific cod.

Conclusion

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 4-6^{o}C 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 juveniles 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
- 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 with a slight recovery to near normal conditions in 2017, when the heat in the system was reduced but return to low values in 2018 and 2019, similar to the GOA pollock
- Highest ranked predictor for recruitment regression model was spawning habitat suitability and the eddy kinetic energy temperature on the GOA 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 and the Pacific cod IBM might also allow for the addition of several gap-free indicators 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. Also, a new project has recently been funded involving a multi-model approach including the development of the GOA Ecopath models and an Atlantis ecosystem model. This project is part of the GOA Regional Action Plan and will start in 2021 with the goal of evaluating the biological reference points used for status determination of individual stocks (e.g., Pacific cod) under projected climate scenarios (M. Dorn, *pers., commun.*). The project has a three-year timeline and we hope to incorporate the results of this effort as they become available.

We 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.

Demographic differences in the YOY population need to be evaluated within and among larval and juvenile surveys conducted in the Central and Western GOA (currently sampling ~1000km of coastline). Size shifts in the YOY population have already been observed in marine heatwave years, but it is unclear if one or more of the following processes are involved: 1) spawning (earlier); 2) larval/juvenile growth (higher); and/or 3) larval/juvenile mortality (higher/size-selective). Climate-driven changes in size and age may also impact survival trajectories of YOY cohorts and their potential to recruit to the fishery.

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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*Superscript numbers refer to references in Table 2.1.2a and Table 2.1.2b

Tables

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; Ferriss and Zador, 2020) and the Economic Status Report (Fissel *et al.*, 2019, 2021) 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	Gulf of Alaska annual, biennial
FBE Beach Seine Survey	Age-0 gadid survey in mid-July through late August on 16 fixed-site stations, northeast Kodiak Island using 36-m demersal beach seine, gadids count, length in mm	2006 – present	Kodiak annual
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	Gulf of Alaska 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	Gulf of Alaska annual
AFSC Acoustic Survey	Mid-water acoustic survey in June to August for pollock in the Gulf of Alaska shelf and nearshore bays	1981 – present	Gulf of Alaska 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	Gulf of Alaska
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	Gulf of Alaska annual
Climate Model Output	Daily sea surface temperatures from the NOAA High-resolution Blended Analysis Data	1977 – present	Central GOA
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

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; Ferriss and Zador, 2020) and the Economic Status Report (Fissel et al., 2019, 2021) 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

Table 2.1.2a: Ecological information by life history stage for GOA Pacific cod.

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 (28)	Optimal incubation 3-6°C, 13-23 ppt, 2-3ppm dO_2 (27)	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 mid May, 14 wks(22,29)	3-4.5 mm NL at hatch (13-15,24,28)	Hatch temperature 4.5-5.8°C(2)	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)	1-2 weeks before onset of feeding(28,29)	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 (1-6,10,11,21)	Nearshore settlement in June, deeper water migrations in October(3,10,13-15)	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 (1-5,7-9,11)
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)

Table 2.1.2b. Key processes affecting survival by life history stage for GOA Pacific cod.

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. Spawning Habitat Suitability 2. Distribution	Temperatures outside the 3-6^{o} 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$_{(27)}$
Egg	1. Temperature$_{(14,18,29,30)}$	Eggs are highly stenothermic$_{(27)}$
Yolk-sac Larvae	1. Temperature$_{(14,18,29,30)}$ 2. Timing of spring bloom$_{(13)}$ 3. Onshore shelf transport$_{(13,31,32)}$	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$_{(14,18,29,30)}$ 2. Prey availability 3. Onshore shelf transport$_{(13,31,32)}$	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$_{(33)}$ 2. Predation$_{(33)}$ 3. Temperature$_{(34)}$	Evidence of density-dependent growth in coastal nurseries$_{(33)}$ 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$_{(34)}$
Pre-Recruit	1. Competition$_{(33)}$ 2. Predation$_{(33)}$ 3. Temperature$_{(34)}$	Evidence of density-dependent growth in coastal nurseries$_{(33)}$ 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$_{(34)}$

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 vessels; 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

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

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.

Table 2.1.4a. Beginning 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 creates 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

Table 2.1.4b. Beginning 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 creates 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

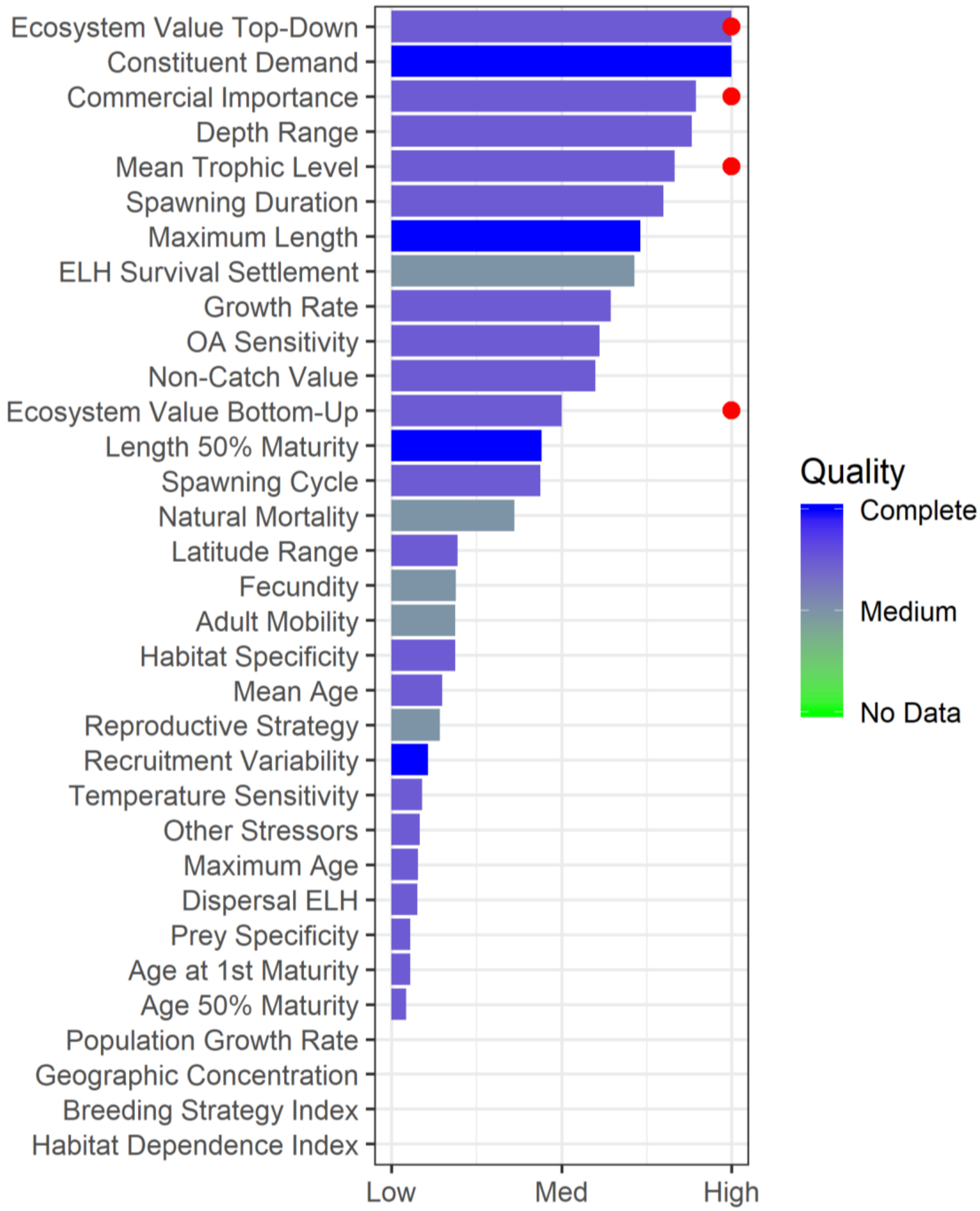

Figure 2.1.1. Baseline metrics for GOA Pacific cod graded as percentile rank over all groundfish in the FMP. Red dots indicate value passes a national threshold for vulnerability. Higher rank values indicate a vulnerability and color of the horizontal bar describes data quality of the metric (see Shotwell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

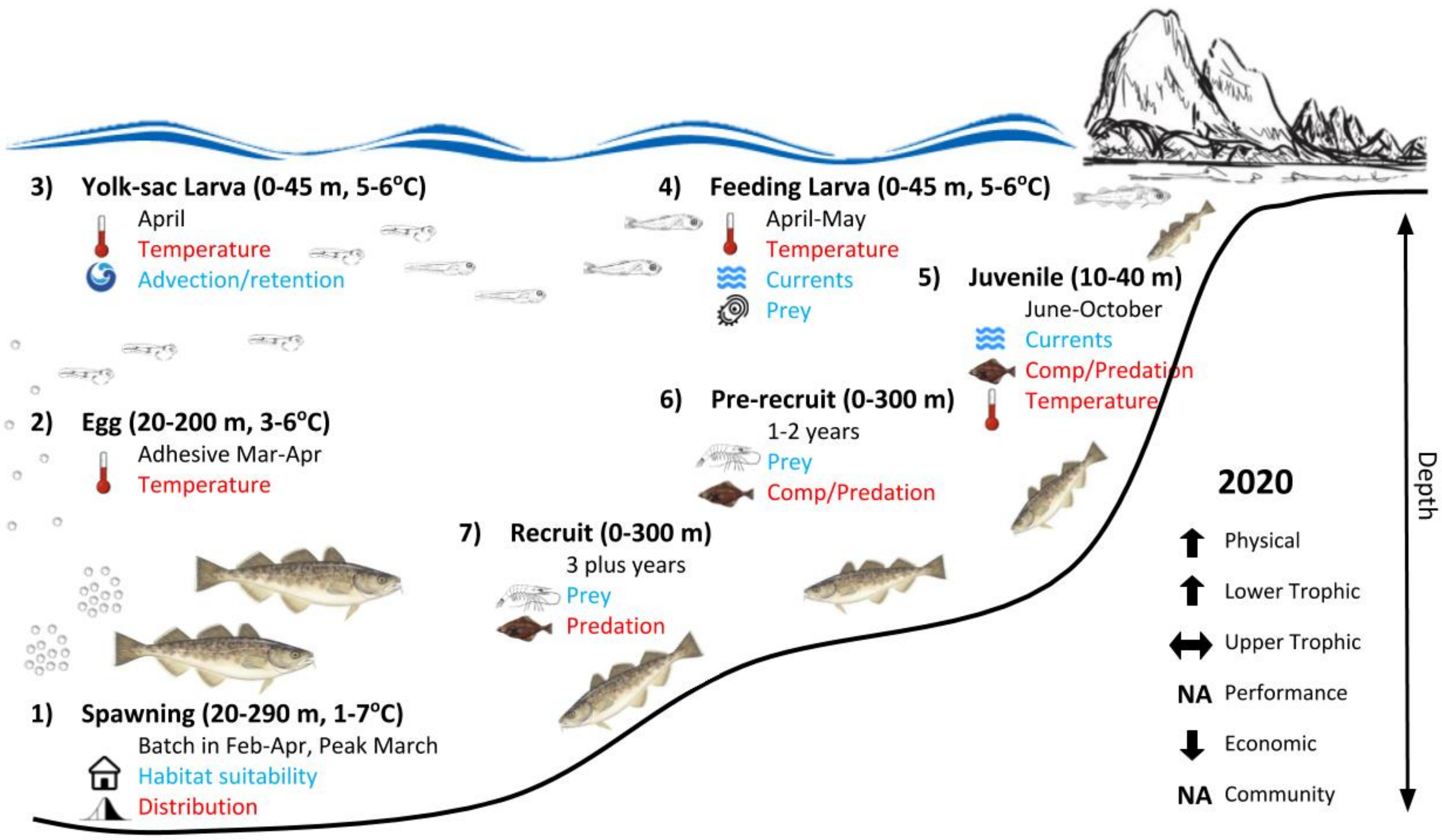

Figure 2.1.2: Life history conceptual model for GOA Pacific cod summarizing ecological information and key ecosystem processes affecting survival by life history stage. Red text means increases in process negatively affect survival, while blue text means increases in process positively affect survival. Trend of current year value compared to last year's value depicted with arrows on the right. NA means no indicators for that category.

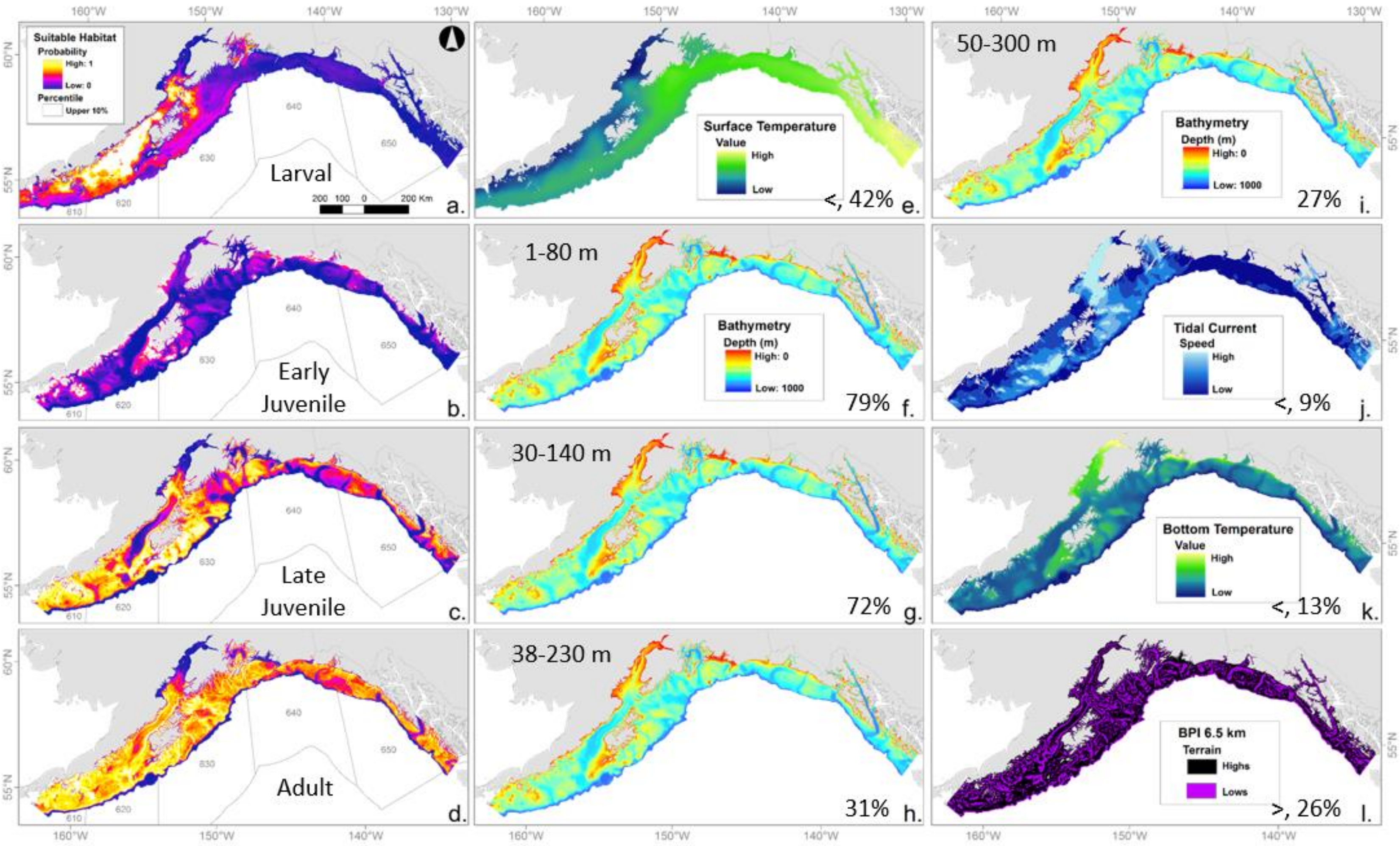

Figure 2.1.3. GOA Pacific cod probability of suitable habitat by life stage (a=larval, b=early juvenile, c=late juvenile, and d=adult) with predictor habitat variables representing the highest (e=depth, f=tidal current speed, g=depth, h=depth) and second highest contribution (i=surface temperature, j=bottom 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.

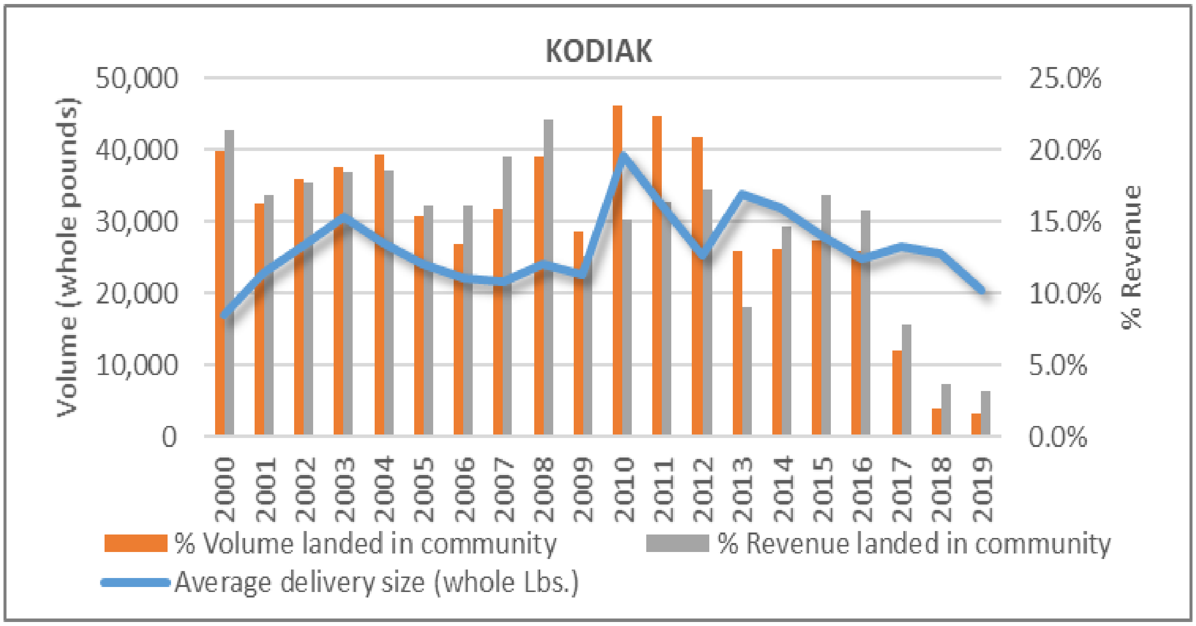

Figure 2.1.4a: Processing engagement for Kodiak: Average pounds delivered and percentage of value landed attributed to GOA Pacific cod for the highly engaged community of Kodiak (2000-2019).

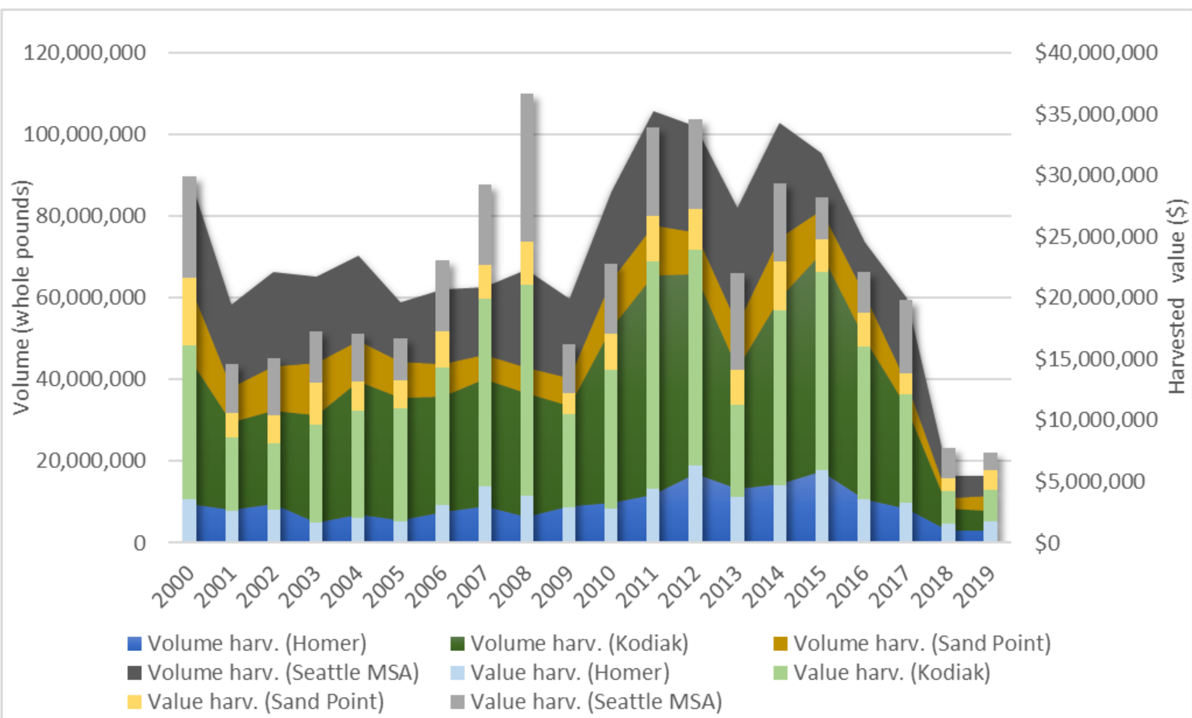

Figure 2.1.4b: Harvesting engagement: Average volume and value of GOA Pacific cod harvested by vessels owned by community residents (2000-2019).

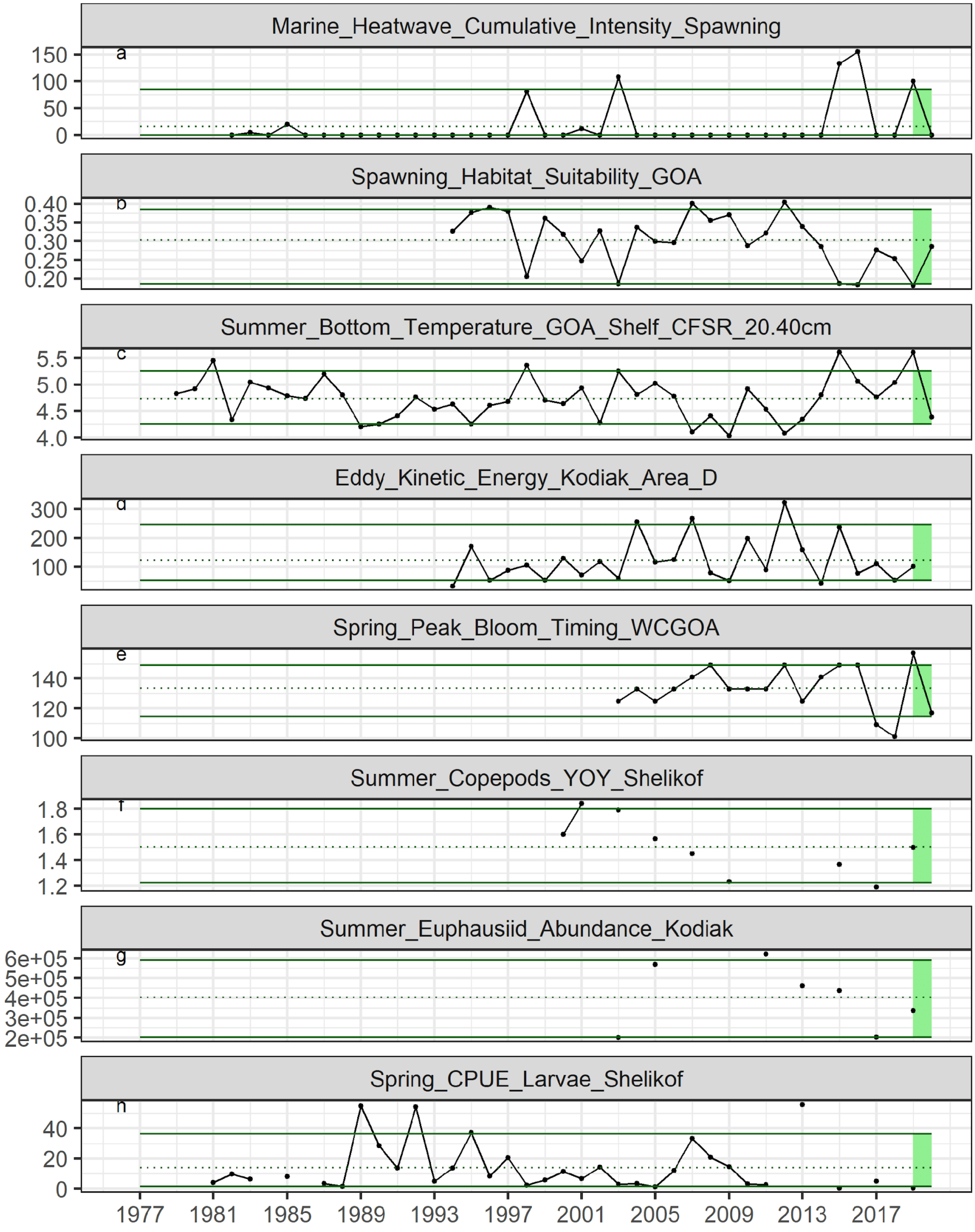

Figure 2.1.5a. Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines are 90th and 10th percentiles of time series. Dotted green horizontal line is mean of time series. Light green shaded area represents most recent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

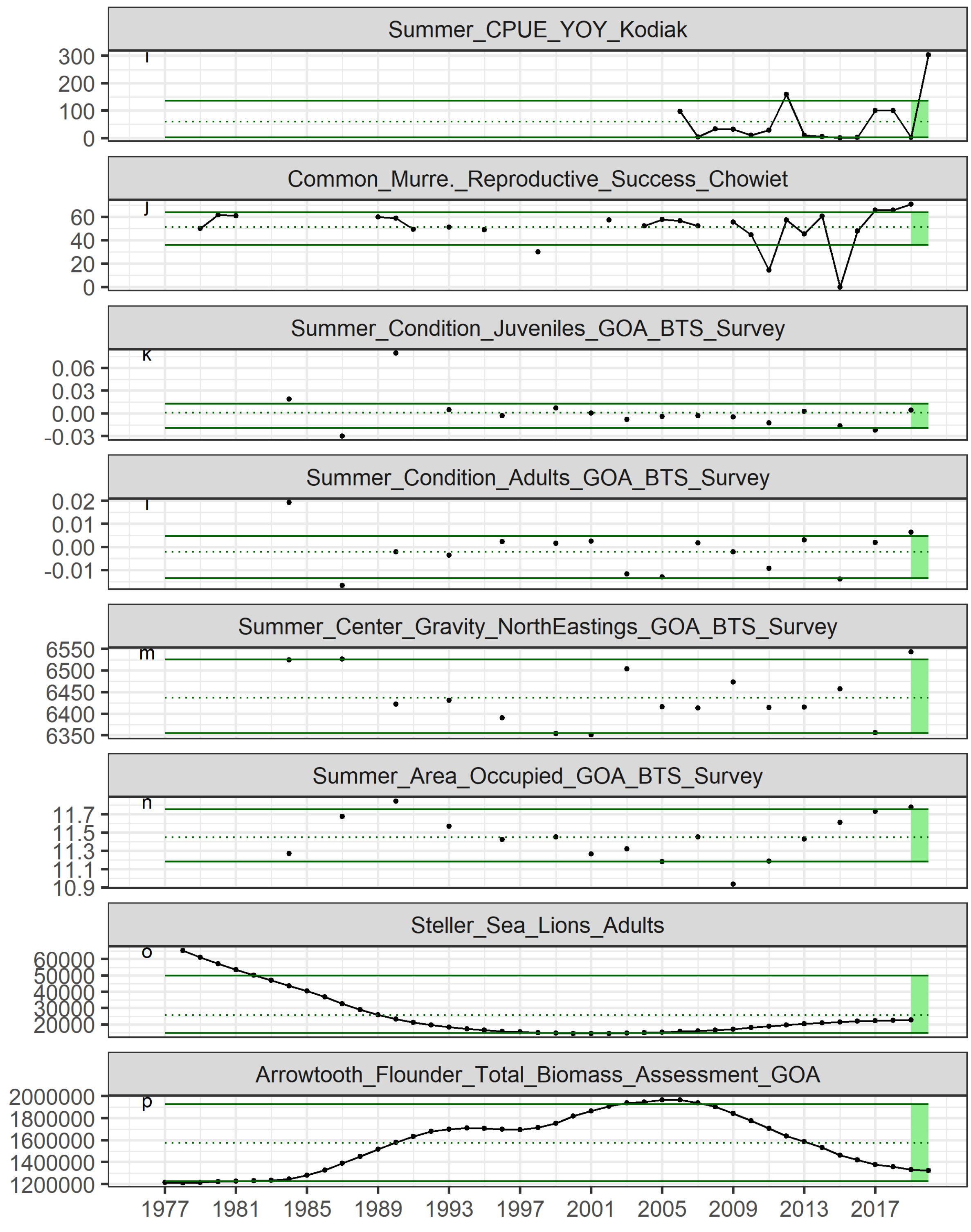

Figure 2.1.5a (cont.). Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines are 90th and 10th percentiles of time series. Dotted green horizontal line is mean of time series. Light green shaded area represents most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

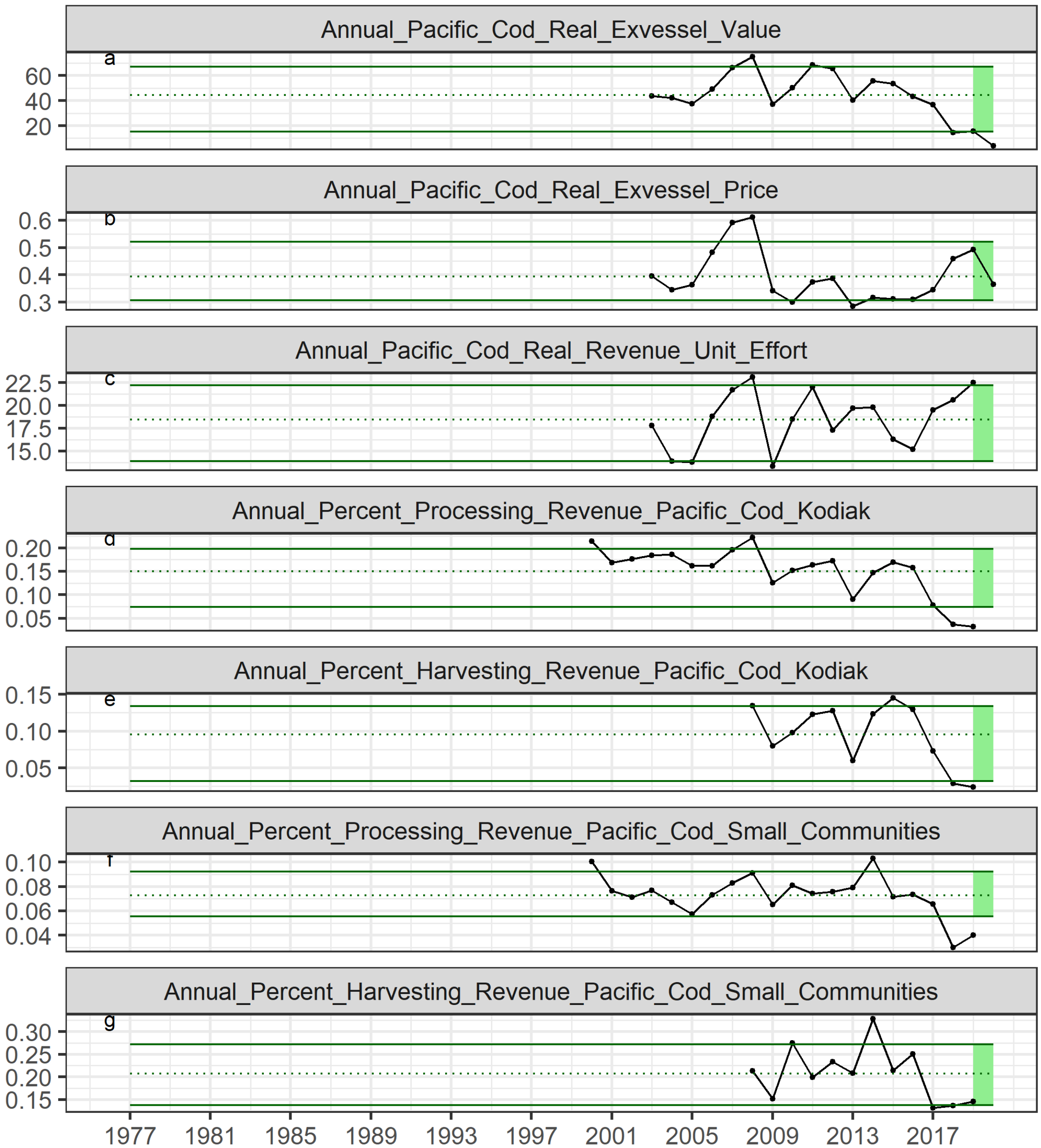

Figure 2.1.5b. Selected socioeconomic indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines are 90th and 10th percentiles of time series. Dotted green horizontal line is mean of time series. Light green shaded area represents most recent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

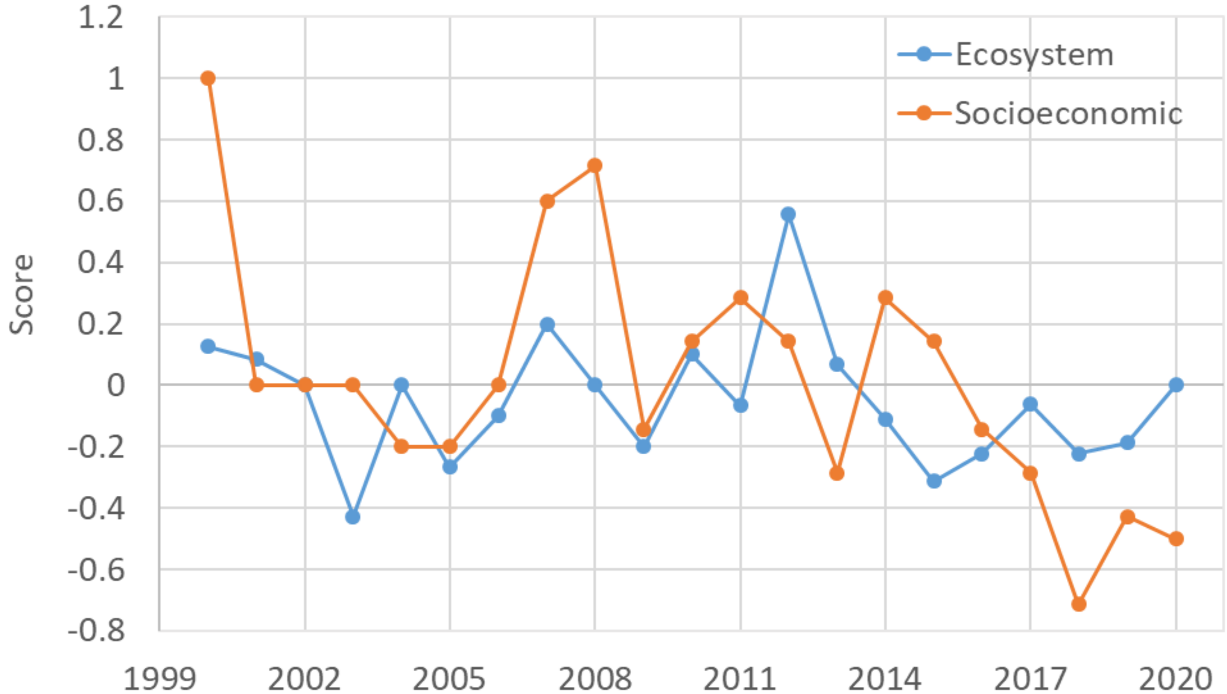

Figure 2.1.6: Beginning stage traffic light score for overall ecosystem and socioeconomic categories from 2000 to present.

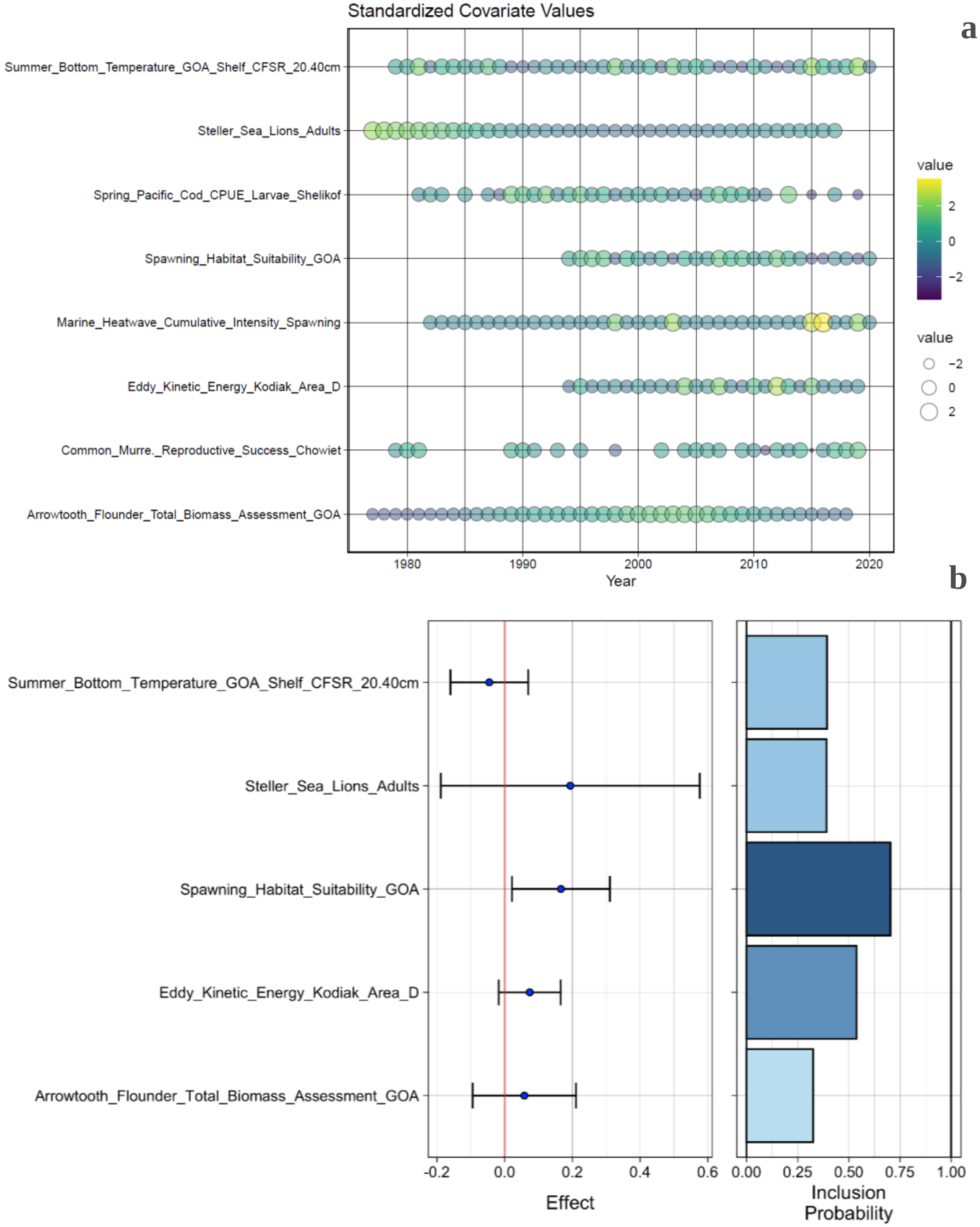

Figure 2.1.7: Bayesian adaptive sampling output showing (a) standardized covariates prior to subsetting and (b) the mean relationship and uncertainty (95% confidence intervals) with log GOA Pacific cod recruitment, in each estimated effect (left bottom graph), and marginal inclusion probabilities (right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

Attachment 2.1.1 Ecosystem and Socioeconomic Profile of the Pacific cod stock in the Gulf of Alaska - Report Card

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November 2021

With Contributions from:

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

Current Year Update

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

When a full ESP is completed in the current year, we provide a shortened version of the report card as an attachment to the full ESP appendix. This allows for providing updated current year information for use in the main SAFE report. Please refer to the main text of this appendix for further information regarding the ecosystem and socioeconomic linkages for this stock.

Management Considerations

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

- Cooling temperatures both at surface and depth in 2021 lower the susceptibility of starvation for larval Pacific cod and impact of mismatch to prey
- Annual eddy kinetic energy has shifted from a lower energy system in 2016 to 2019 to above average energy in 2020 and 2021 due to a strong, persistent eddy around Kodiak
- Survey cancellations and delays limited lower trophic indicators but spring larval Pacific cod were unusually low while reproductive success of seabirds was high in 2021
- Condition of juveniles and adults decreased in 2021, while the spatial distribution of the stock has spread out substantially from 2015 to 2021 with a center shift to the southwest in 2021
- Ex-vessel value and revenue-per-unit-effort are at the lowest in the time series in 2020, cost pressure from COVID-19 mitigation efforts likely had upstream impacts on ex-vessel prices
- The impact of COVID-19 had only marginal effects on first-wholesale and export prices, as retail and food service are both significant components of the market for cod products
- Overall, ecosystem indicators were average to above average in 2021 with socioeconomic indicators low in 2020

Modeling Considerations

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

- Highest ranked predictors for the recruitment importance model were spawning habitat suitability and the eddy kinetic energy (inclusion probability > 0.5)
- New research models are being evaluated as alternatives for the operational assessment using indicators of temperature and nearshore beach seine survey of age-0 Pacific cod

Assessment

Ecosystem and Socioeconomic Processes

Please refer to the full detail of the ecosystem and socioeconomic processes section in the main text of this appendix. The conceptual model (Figure 2.1.1.1) is provided here for reference.

Indicator Suite

The following list of indicators for GOA Pacific cod are organized by categories, three for ecosystem indicators (physical, lower trophic, and upper trophic) and three for socioeconomic indicators (fishery performance, economic, and community). A short description and contact name for the indicator contributor are provided. Please refer to the full ESP document for detailed information regarding the ecosystem and socioeconomic indicator descriptions for this stock (Appendix 2.1). Time series of the ecosystem and socioeconomic indicators are provided in Figure 2.1.1.2a and Figure 2.1.1.2b, respectively.

Ecosystem Indicators:

Physical Indicators (Figure 2.1.1.2a.a-d)

- a.) Spawning marine heatwave cumulative index over the central GOA (contact: S. Barbeaux).
- b.) Winter spring spawning habitat suitability index from January to April in the central GOA shelf at GAK1 station (contact: L. Rogers).
- c.) Summer bottom temperatures where small Pacific cod (0-20 cm) have been sampled by the AFSC GOA bottom trawl survey from the CFSR dataset (contact: S. Barbeaux).
- d.) Annual eddy kinetic energy (EKE) calculated from sea surface height in the Kodiak area (contact: W. Cheng).

Lower Trophic Indicators (Figure 2.1.1.2a.e-i)

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

Upper Trophic Indicators (Figure 2.1.1.2a.j-o)

- j.) Summer condition for juvenile (<420 mm) Pacific cod from the AFSC GOA shelf bottom trawl survey (contact: S. Rohan).
- k.) Summer condition for adult (>=420 mm) Pacific cod from the AFSC GOA shelf bottom trawl survey (contact: S. Rohan).
- l.) Summer Pacific cod center of gravity northeastings estimated by a spatio-temporal model using the package VAST on AFSC GOA bottom trawl survey data (contact: Z. Oyafuso)
- m.) Summer Pacific cod area occupied estimated by a spatio-temporal model using the package VAST on AFSC GOA bottom trawl survey data (contact: Z. Oyafuso)
- n.) Arrowtooth flounder total biomass from the most recent stock assessment model in the GOA (contact: K. Shotwell).
- o.) Steller sea lion non-pup estimates for the GOA portion of the western Distinct Population Segment (contact: K. Sweeney).

Socioeconomic Indicators:

Economic Indicators (Figure 2.1.1.2b.a-c)

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

Community Indicators (Figure 2.1.1.2b.d-g)

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

Indicator Monitoring Analysis

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

Beginning Stage: Traffic Light Test

We use a simple scoring calculation for this beginning stage traffic light evaluation. Indicator status is evaluated based on being greater than (“high”), less than (“low”), or within (“neutral”) one standard deviation of the long-term mean. A sign based on the anticipated relationship between the indicator and the stock (Figure 2.1.1.1) is also assigned to the indicator where possible. If a high value of an indicator generates good conditions for the stock and is also greater than one standard deviation above the mean, then that value receives a +1 score. If a high value generates poor conditions for the stock and is greater than one standard deviation above the mean, then that value receives a -1 score. All values less than or equal to one standard deviation from the long-term mean are average and receive a 0 score. The scores are summed by the three organizational categories within the ecosystem (physical, lower trophic, and upper trophic) or socioeconomic (fishery performance, economic, and community) indicators and divided by the total number of indicators available in that category for a given year. The scores over time allow for comparison of the indicator performance and the history of stock productivity (Figure 2.1.1.3). We also provide five year indicator status tables with a color or text code for the relationship with the stock (Tables 2.1.1.2a,b) and evaluate the current year status in the historical indicator time series graphic (Figures 2.1.1.2a,b) for each ecosystem and socioeconomic indicator.

We evaluate the status and trends of the ecosystem and socioeconomic indicators to understand the pressures on the GOA Pacific cod stock regarding recruitment, stock productivity, and stock health. We start with the physical indicators and proceed through the increasing trophic levels, economic, and community indicators as listed above. Here we concentrate on updates relative to the results presented in the main text of this appendix. Overall both the physical and lower trophic level indicators scored average for 2021, while the upper trophic indicators were above average (Figure 2.1.1.3). Compared to the results presented in the main text of this appendix, this is a drop from above average for the physical indicators, an improvement from below average for the lower trophic indicators, and an improvement from average for the upper trophic indicators. We also note caution when comparing scores between odd to even years as there are many lower and upper trophic indicators missing in even years due to the off-cycle year surveys in the GOA. Also, there have been other cancellations due to COVID-19 or other survey delays in 2020 and 2021 that have limited production of several indicators. Economic and community indicators are all lagged by at least one year due to timing of the availability of the current year information and the production of this report. Economic indicators scored below average for 2020 which is a drop from above average in 2019. There were no updates for community indicators.

For physical indicators, there has been increased sea surface warming and reduced Pacific cod spawning habitat suitability in the GOA ecosystem and the presence of a series of major marine heatwaves for the past several years (Figure 2.1.1.2a.a-c). However, in 2020 and 2021 there were reduced temperatures both at the surface and bottom, near average habitat suitability, and zero to low marine heatwave events during spawning season for Pacific cod. We also see a shift in the annual eddy kinetic energy (EKE) near Kodiak from a period of lower energy in 2016 to 2019 to above average in 2020 and 2021 (Figure 2.1.1.2a.d). This EKE region near Kodiak has an opposite seasonal cycle phase than other regions in the GOA implying separate forcing mechanisms in the western GOA (Cheng, 2021). Sustained EKE may help with retention on the shelf and enhance cross-shelf transport of young-of-the-year Pacific cod to suitable nearshore nursery environments.

For the lower trophic level indicators (Figure 2.1.1.2a.e-i), the peak timing of the spring bloom appears highly variable since the onset of the marine heatwaves in 2014 and continues to oscillate in 2020 and 2021 from early to late, respectively. This may have implications for mismatch between larval Pacific cod and the available plankton abundance. During warm years this may be particularly important for Pacific cod due to their increased metabolic requirements and the implications of a later bloom may be somewhat tempered in a cooler thermal environment such as in 2020 and 2021 (B. Laurel, pers. commun.). CPUE of larvae in the spring EcoFOCI survey continues to be low, although reproductive success of common Murre seabirds on Chowiet continues to be high suggesting sufficient forage fish prey resources. Years of high abundance for the late winter to early spring shelf spawners (i.e., Pacific cod, walleye pollock, and northern rock sole) were associated with cooler winters and enhanced alongshore winds during spring (Deary et al., 2021). Since physical indicators appear average this year the expectation was average abundances of Pacific cod in the larval survey. However, abundances were especially low in 2021 and the highest catches were outside of the core area, which is unusual.

For the upper trophic indicators, the condition of juvenile and adult Pacific cod from the summer bottom trawl survey decreased in 2021, with juveniles now slightly below average and adults still above average (Figure 2.1.1.2a.j-k). Many factors may contribute to the variation in morphometric condition such as temperature-dependent metabolic rates, survey timing, stomach fullness of individual fish, migration patterns, and distribution of samples within survey strata (O’Leary et al., 2021). The thermal environment is cooler in the GOA this year but benthic prey resources were highly variable (Whitehouse and Aydin, 2021). The center of gravity in the northeast direction for the GOA Pacific cod population has decreased from the 2019 survey, while the area occupied estimate remains consistent and high, implying a change in distribution toward the southwest and a fairly large population spread (Figure 2.1.1.2a.l-m). These trends may reflect a shift in the spatial clustering of the stock concurrent with the change in biomass and potentially suggest the stock may be expanding out of preferred habitat. There were no updates for arrowtooth flounder biomass as the stock assessment is currently in review; however, recent survey estimates are slightly larger than in 2019 (bottom trawl survey) and 2020 (longline survey), but still well below average (Shotwell et al., 2021). In general, apex fish predators in the GOA are at relatively low abundances (Whitehouse and Aydin, 2021) suggesting low predation pressure on GOA Pacific cod.

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 2020 these shares fell to 3% and 4%, respectively, with the closure of directed fishing in Federal waters. Catch of Pacific cod in the GOA was down 57% from 2019 with a total catch of 6.7 thousand t and retained catch 4.8 thousand t (Fissel et al., 2021). Ex-vessel prices decreased 20% to $0.39 per pound in 2020. Ex-vessel revenues in 2020 were down 72% to $4.4 million with the decrease in catch and prices (Figure 2.1.1.2b.a-b). The number of vessels has dropped from 360 in 2016 to 102 in 2020. 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 was in the Central Gulf fisheries, 40% in the Western Gulf, and 1-2% occurring in other regions of the GOA. In 2020 with the closure of directed fishing in Federal waters distribution has shifted to about 72% of cod being caught in the Central Gulf (Fissel et al., 2021). The price differential between fixed gear and trawl vessels was $0.07 per pound in 2020. The products made from GOA Pacific cod had a first-wholesale value of $15 million in 2020, which was down 57% from 2019 and below the 2011-2015 average of $112 million (Fissel et al., 2021). The two primary product forms produced from cod in the GOA are fillets and head and gut (H&G), which comprised 68% and 23% of the value in 2020, 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 2020 increased 7% to $2.14 per pound (Figure 2.1.1.2b.b) as fillet prices were stable at $4.11 per pound and H&G prices increased 9% to $1.39 per pound (Fissel et al., 2021). Since 2016 reductions in global supply have put upward pressure on prices resulting in significant year over year price increases in 2017 and 2018. In 2019 prices leveled off, decreasing slightly, as markets have adjusted. In 2020 COVID-19 closures resulted in increased demand for retail products and frozen products, and decreased food service and fresh products. Retail and food service are both significant components of the market for cod products. As such, the impact of COVID-19 on prices appears muted with only marginal changes in first-wholesale and export prices. Cost pressure from COVID-19 mitigation efforts likely had upstream impacts on ex-vessel prices, which decreased significantly.

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

Intermediate Stage: Importance Test

Bayesian adaptive sampling (BAS) was used for the intermediate stage statistical test to quantify the association between hypothesized predictors and GOA Pacific cod recruitment and to assess the strength of support for each hypothesis. In this stage, the full set of indicators is first winnowed to the predictors that could directly relate to recruitment and highly correlated covariates are removed. We further restrict potential covariates to those that can provide the longest model run and through the most recent estimate of recruitment that is well estimated in the current operational stock assessment model (Figure 2.1.1.4a). This results in a model run from 1994 through the 2017 year-class. We then provide the mean relationship between each predictor variable and log GOA Pacific cod recruitment over time (Figure 2.1.1.4b, left side), with error bars describing the uncertainty (95% confidence intervals) in each estimated effect and the marginal inclusion probabilities for each predictor variable (Figure 2.1.1.4b, right side). A higher probability indicates that the variable is a better candidate predictor of GOA Pacific cod recruitment. The highest ranked predictor variables (inclusion probability > 0.5) based on this process continue to be the spawning habitat suitability index in the GOA and the eddy kinetic energy in Kodiak area D (Figure 2.1.1.4).

Advanced Stage: Research Model Test

Please refer to the full detail of the advanced stage research model test section in the main text of this appendix.

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.

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

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

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

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

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Tables

Table 2.1.1.1a. First stage ecosystem indicator analysis for GOA Pacific cod, including indicator title and the indicator status of the last five years. The indicator status is designated with text, (greater than = "high", less than = "low", or within 1 standard deviation = "neutral" of long-term mean). Fill color of the cell is based on the sign of the anticipated relationship between the indicator and GOA Pacific cod (blue or italicized text = good conditions for GOA Pacific cod, red or bold text = poor conditions, white = average conditions). A gray fill and text = "NA" will appear if there were no data for that year.

Indicator category	Indicator	2017 Status	2018 Status	2019 Status	2020 Status	2021 Status
Physical	Spawning Heatwave GOA Model	neutral	neutral	**high**	neutral	neutral
	Winter Spring Pacific Cod Spawning Habitat Suitability GAK1 Model	neutral	neutral	**low**	neutral	neutral
	Summer Temperature Bottom GOA Model	neutral	neutral	**high**	neutral	neutral
	Annual Eddy Kinetic Energy Kodiak Satellite	neutral	neutral	neutral	*high*	neutral
Lower Trophic	Spring Chlorophyll a Peak WCGOA Satellite	**low**	**low**	*high*	**low**	neutral
	Summer Large Copepod Abundance Shelikof Survey	**low**	NA	neutral	NA	NA
	Summer Euphausiid Abundance Kodiak Survey	**low**	NA	neutral	NA	NA
	Spring Pacific Cod CPUE Larvae Shelikof Survey	neutral	NA	neutral	NA	neutral
	Annual Common Murre Reproductive Success Chowiet Survey	neutral	neutral	*high*	NA	neutral
Upper Trophic	Summer Pacific Cod Condition Juvenile GOA Survey	neutral	NA	neutral	NA	neutral
	Summer Pacific Cod Condition Adult GOA Survey	neutral	NA	neutral	NA	neutral
	Summer Pacific Cod Center Gravity Northeast WCGOA Model	*low*	NA	**high**	NA	neutral

Indicator category	Indicator	2017 Status	2018 Status	2019 Status	2020 Status	2021 Status
	Summer Pacific Cod Area Occupied WCGOA Model	neutral	NA	*high*	NA	*high*
	Annual Arrowtooth Biomass GOA Model	neutral	neutral	neutral	neutral	NA
	Annual Steller Sea Lion Adult GOA Survey	neutral	neutral	neutral	NA	NA

Table 2.1.1.1b. First stage socioeconomic indicator analysis for GOA Pacific cod, including indicator title and the indicator status of the last five years. The indicator status is designated with text, (greater than = "high", less than = "low", or within 1 standard deviation = "neutral" of long-term mean). Fill color of the cell is based on the sign of the anticipated relationship between the indicator and GOA Pacific cod (blue or italicized text = good conditions for GOA Pacific cod, red or bold text = poor conditions, white = average conditions). A gray fill and text = "NA" will appear if there were no data for that year.

Indicator category	Indicator	2017 Status	2018 Status	2019 Status	2020 Status	2021 Status
Economic	Annual Pacific Cod Real Exvessel Value GOA Fishery	neutral	**low**	**low**	**low**	NA
	Annual Pacific Cod Real Exvessel Price GOA Fishery	neutral	neutral	*high*	neutral	NA
	Annual Pacific Cod Real Revenue Per Unit Effort GOA Fishery	neutral	neutral	*high*	**low**	NA
Community	Annual Pacific Cod RQ Harvesting Revenue Kodiak Fishery	neutral	**low**	**low**	NA	NA
	Annual Pacific Cod RQ Processing Revenue Kodiak Fishery	**low**	**low**	**low**	NA	NA
	Annual Pacific Cod RQ Harvesting Revenue Small Communities GOA Fishery	**low**	**low**	**low**	NA	NA
	Annual Pacific Cod RQ Processing Revenue Small Communities GOA Fishery	neutral	**low**	**low**	NA	NA

Figures

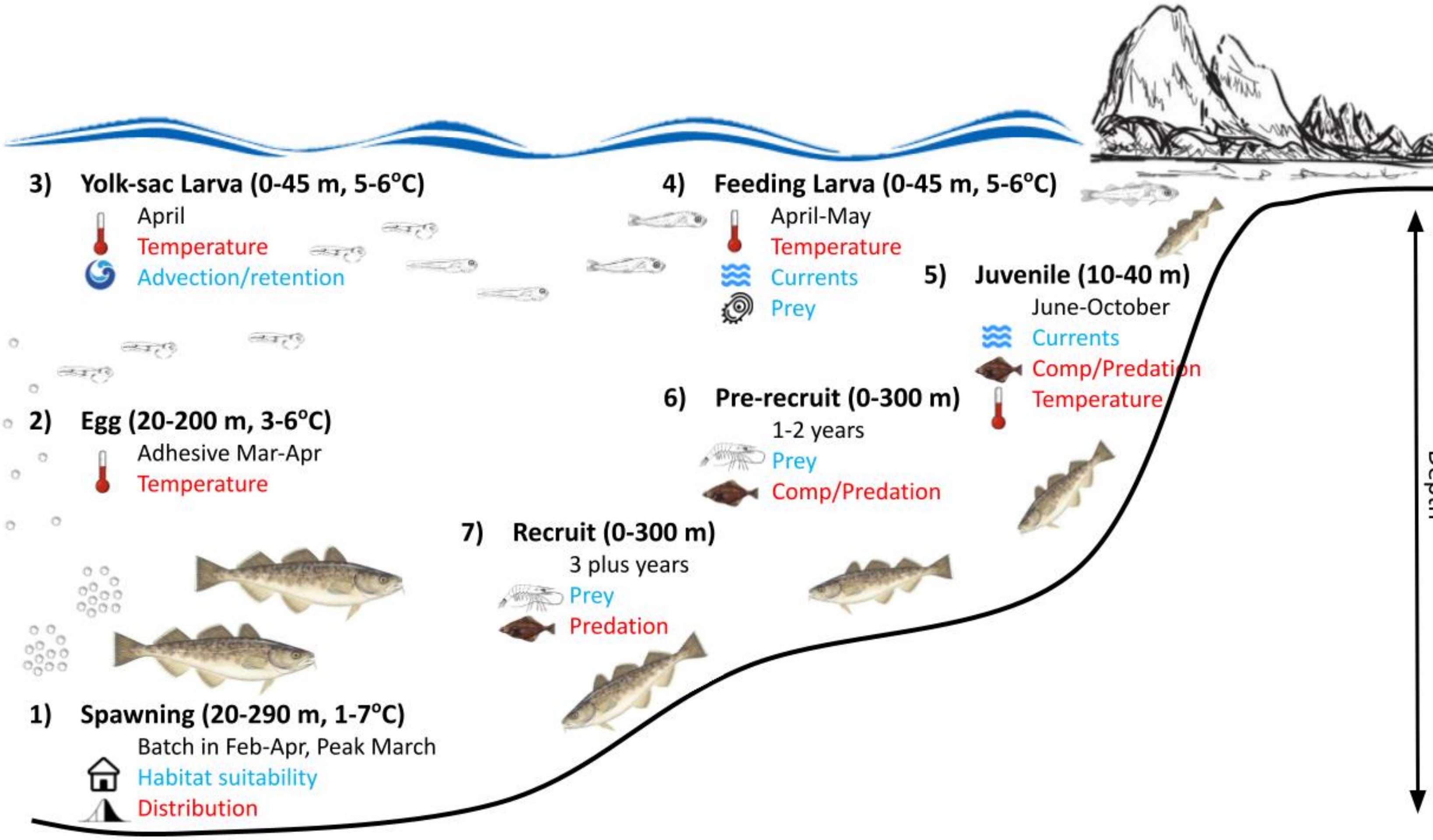

Figure 2.1.1.1: Life history conceptual model for GOA Pacific cod summarizing ecological information and key ecosystem processes affecting survival by life history stage. Red text means increases in process negatively affect survival, while blue text means increases in process positively affect survival.

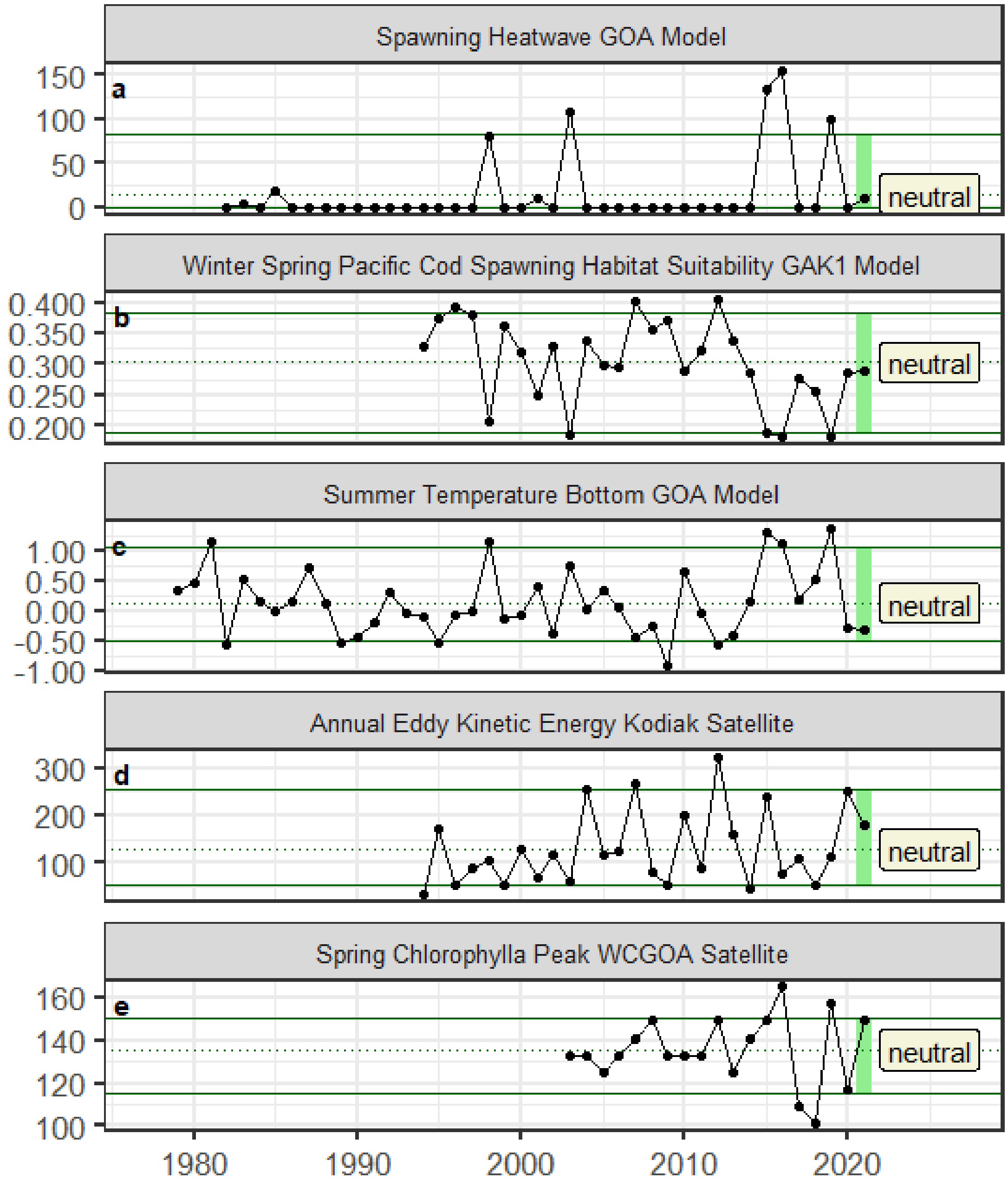

Figure 2.1.1.2a. Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines are 90th and 10th percentiles of time series. Dotted green horizontal line is the mean of the time series. Light green shaded areas represent the most recent year of the traffic light analysis results. Text box follows the traffic light status table for the current year.

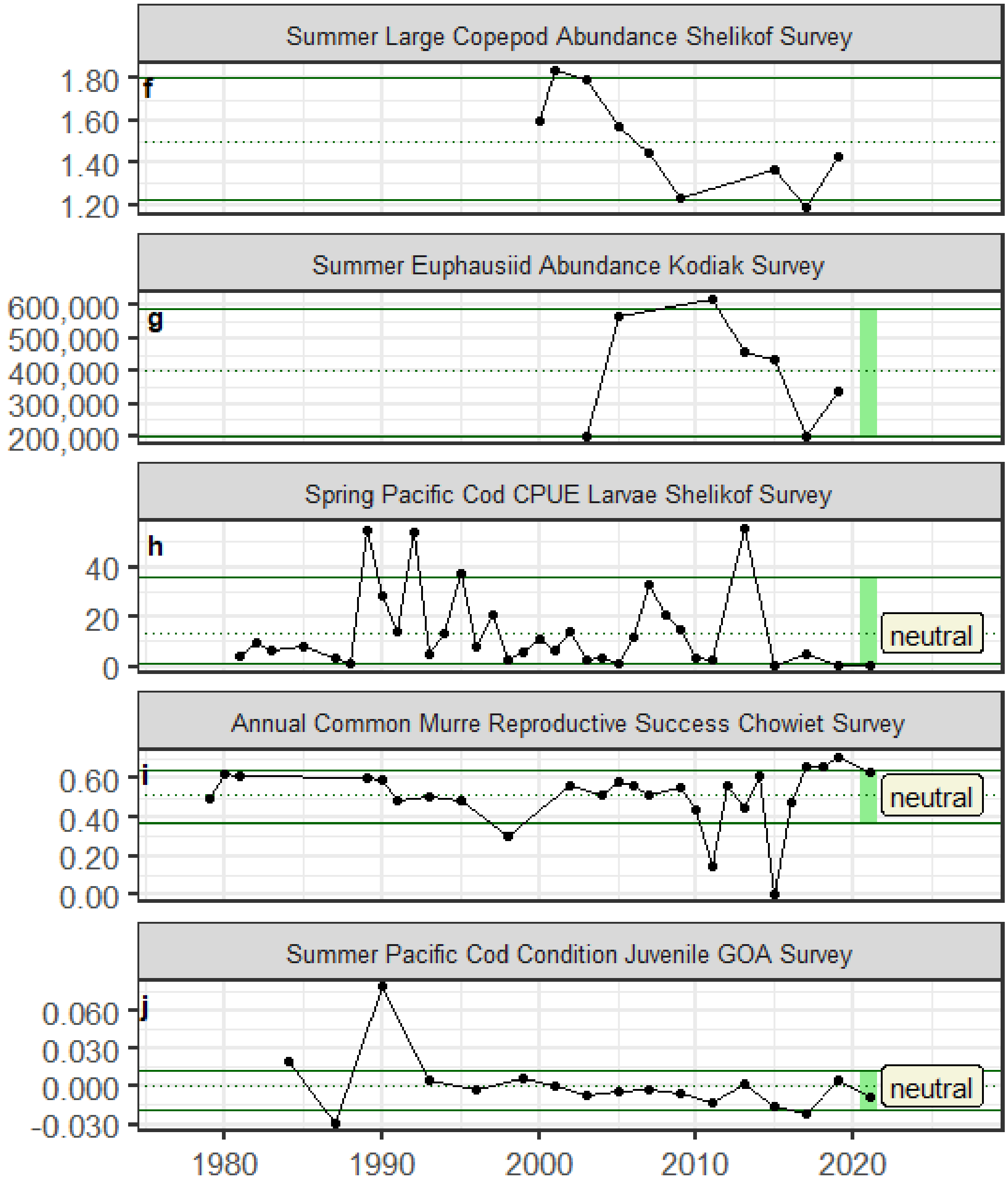

Figure 2.1.1.2a (cont.). Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines are 90th and 10th percentiles of time series. Dotted green horizontal line is the mean of the time series. Light green shaded areas represent the most recent year of the traffic light analysis results. Text box follows the traffic light status table for the current year.

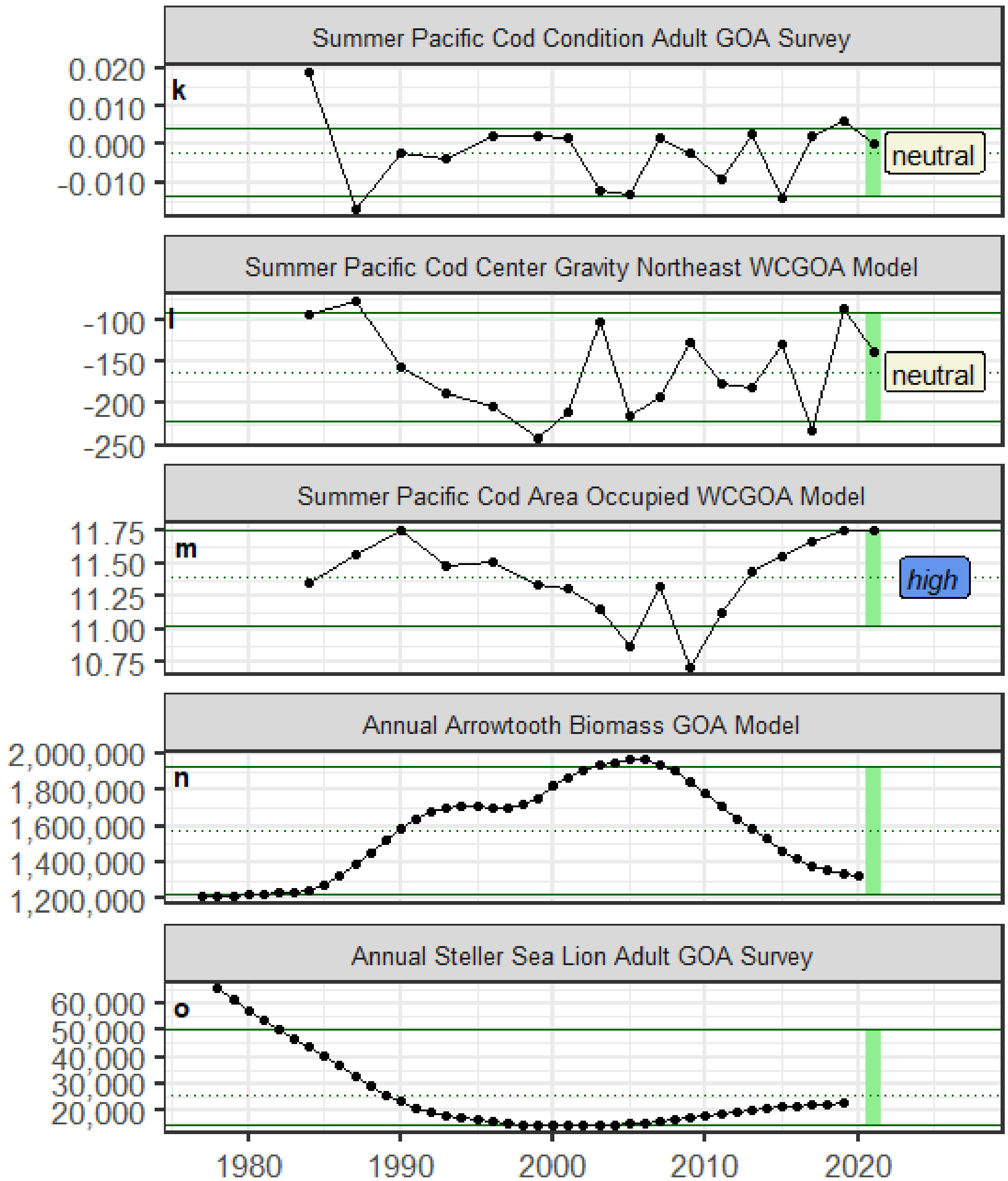

Figure 2.1.1.2a (cont.). Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines are 90th and 10th percentiles of time series. Dotted green horizontal line is the mean of the time series. Light green shaded areas represent the most recent year of the traffic light analysis results. Text box follows the traffic light status table for the current year.

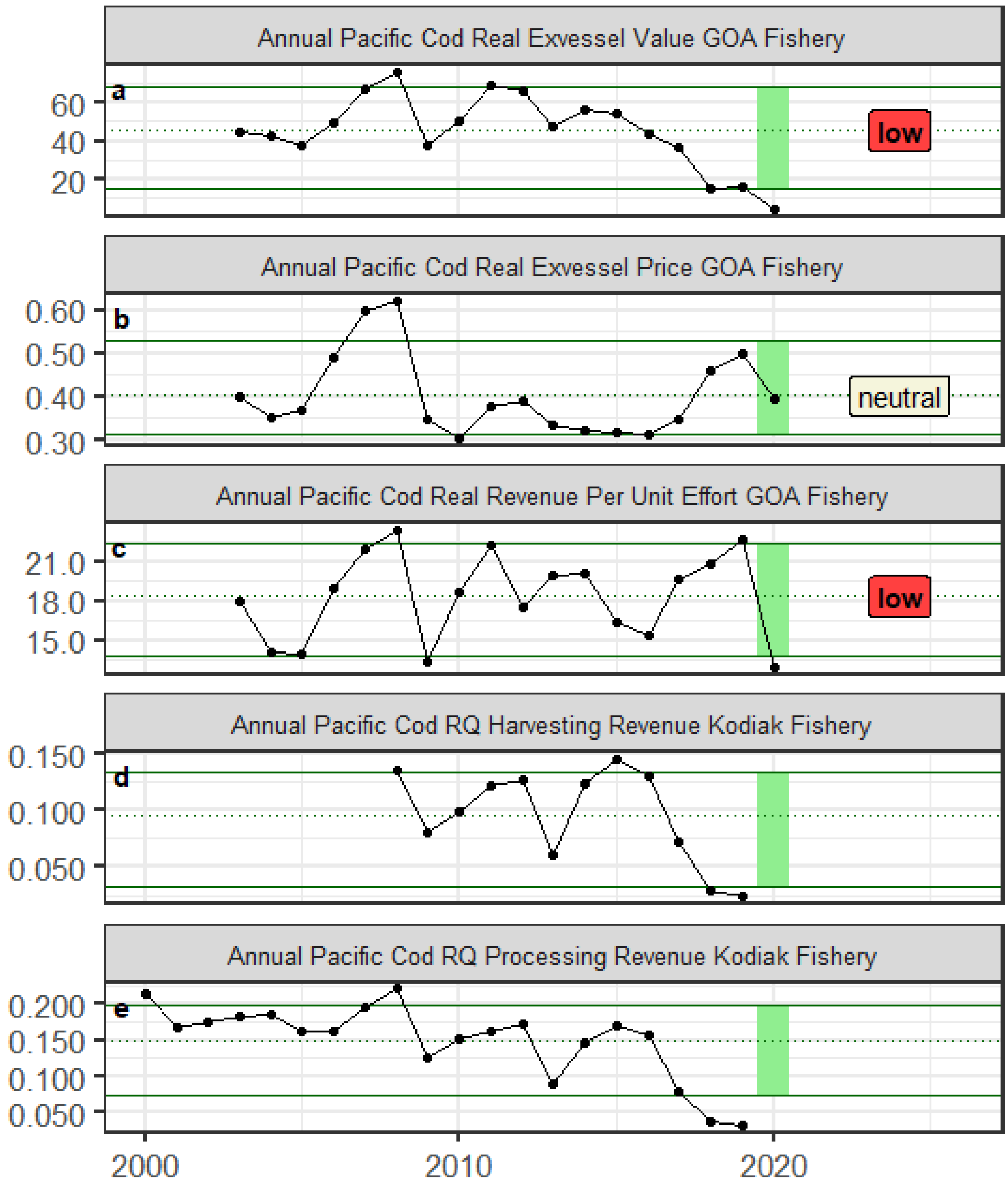

Figure 2.1.1.2b. Selected socioeconomic indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines are 90th and 10th percentiles of time series. Dotted green horizontal line is the mean of the time series. Light green shaded areas represent the most recent year of the traffic light analysis results. Text box follows the traffic light status table for the current year.

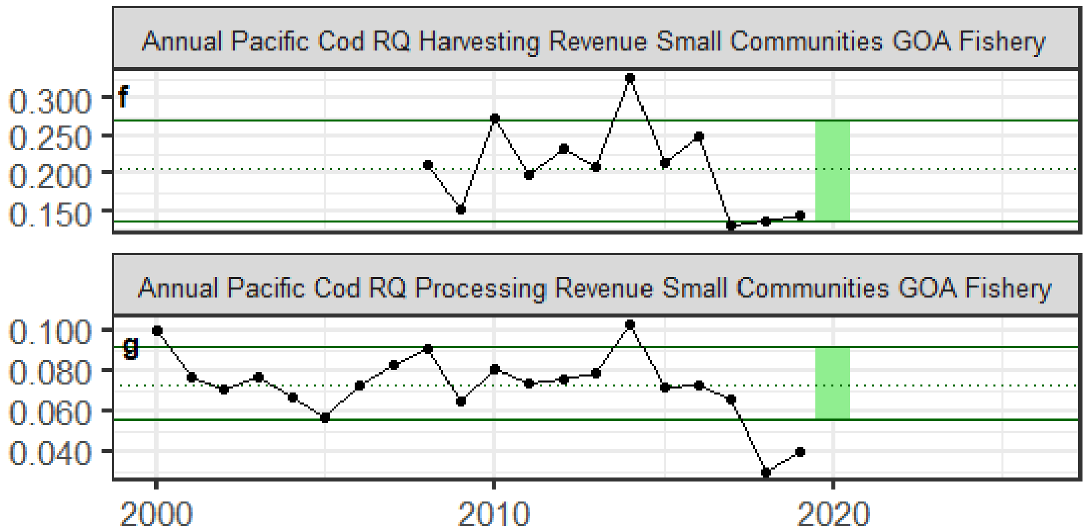

Figure 2.1.1.2b (cont.). Selected socioeconomic indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines are 90th and 10th percentiles of time series. Dotted green horizontal line is the mean of the time series. Light green shaded areas represent the most recent year of the traffic light analysis results. Text box follows the traffic light status table for the current year.

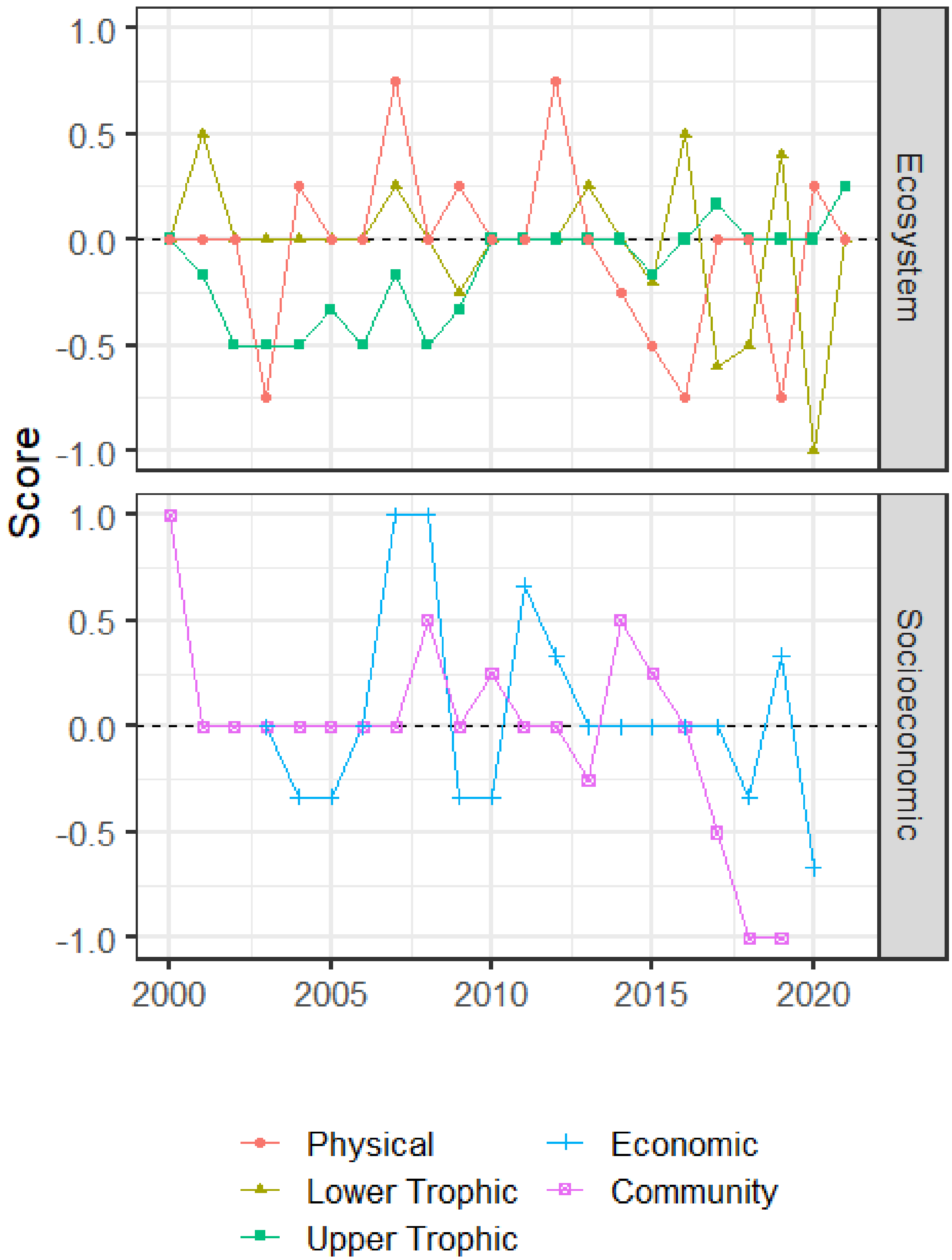

Figure 2.1.1.3: Simple summary traffic light score by category for ecosystem and socioeconomic indicators from 2000 to present.

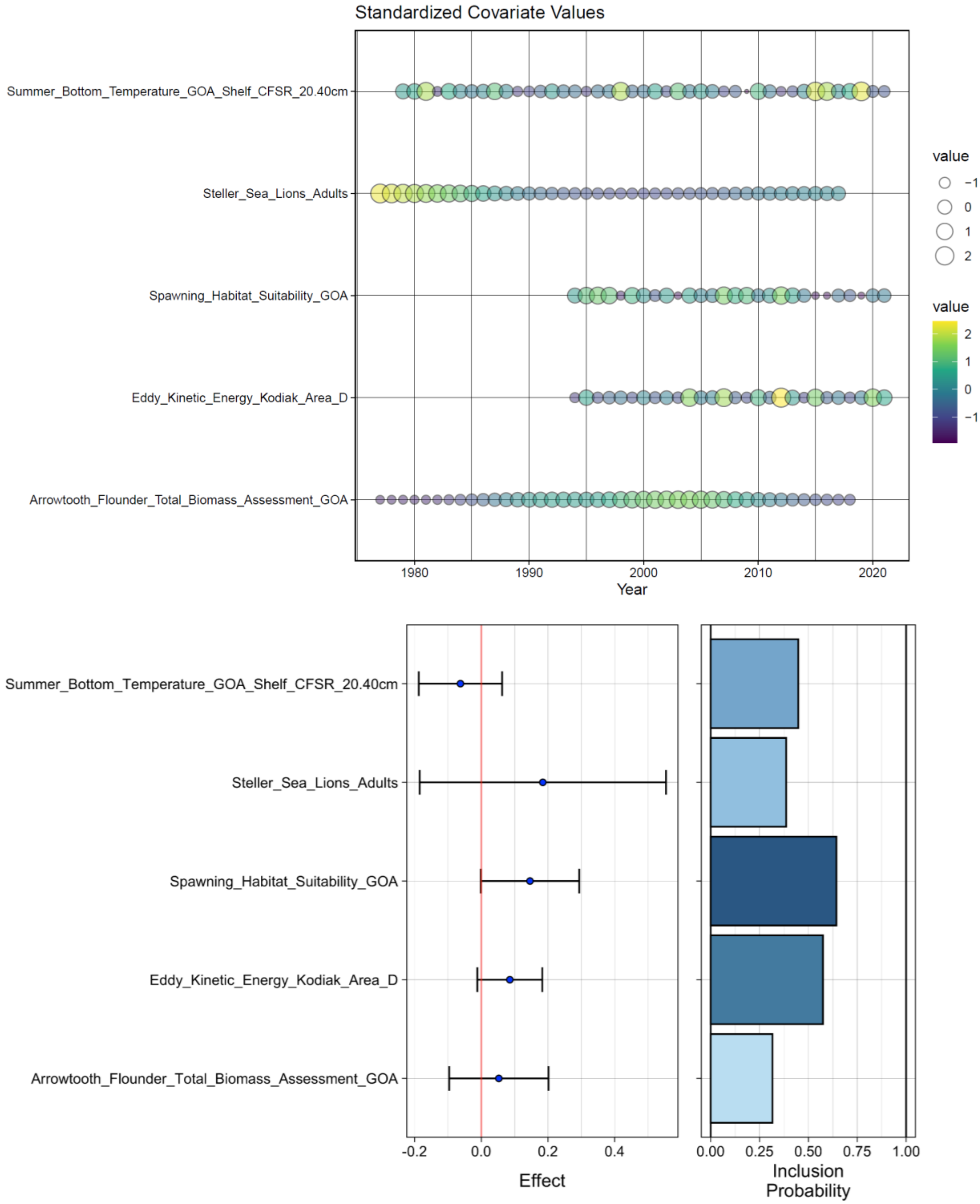

Figure 2.1.1.4: Bayesian adaptive sampling output showing (top graph) standardized covariates and (bottom graph) the mean relationship and uncertainty (95% confidence intervals) with log GOA Pacific cod recruitment, in each estimated effect (left bottom graph), and marginal inclusion probabilities (right bottom graph) for each predictor variable of the covariate set.

Appendix 2.2 GOA Pacific cod 2021 Stock Synthesis model files

https://apps-afsc.fisheries.noaa.gov/Plan_Team/2021/GOAPCOD2021Appendix2.2.zip

Appendix 2.3 GOA Pacific cod 2021 Model 19.1 selected data and model results

https://apps-afsc.fisheries.noaa.gov/Plan_Team/2021/GOAPCOD2021Appendix2.3.xlsx

Appendix 2.4 GOA Pacific cod 2021 Model 21.1 selected data and model results

https://apps-afsc.fisheries.noaa.gov/Plan_Team/2021/GOAPCOD2021Appendix2.4.xlsx

Appendix 2.5 GOA Pacific cod 2021 Model 21.1 selected data and model results for Projection A

https://apps-afsc.fisheries.noaa.gov/Plan_Team/2021/GOAPCOD2021Appendix2.5.xlsx

Appendix 2.6 GOA Pacific cod 2021 Model 21.1 selected data and model results for Projection B

https://apps-afsc.fisheries.noaa.gov/Plan_Team/2021/GOAPCOD2021Appendix2.6.xlsx

Appendix 2.7 GOA Pacific cod 2021 Model 21.2 MCMC results

https://apps-afsc.fisheries.noaa.gov/Plan_Team/2021/GOAPCOD2021Appendix2.7.xlsx

Appendix 2.8 Gulf of Alaska Pacific cod assessment models for Plan Team consideration, September 2021

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Introduction

In this document the authors present a series of bridged models and seek advice on which models the Plan Team would like presented in November. The authors would also like advice on what objective model selection criteria the Plan Team would suggest be presented to aid in model evaluation and selection for November.

For this year we explored five changes to the model from the 2020 reference model (Model 19.1, Barbeaux *et al.* 2020) that resulted in nine bridged models (Table 1). First we looked at the inclusion of a beach seine age-0 index of abundance to the model; second, we examined environmental links on growth, natural mortality, and recruitment; third we examined changing the natural mortality block to 2015-2020; and finally we examined tuning the indices input standard error to the RMSE and tuning composition data using the Francis method. The addition of the age-0 beach seine data as a recruitment index was provided as an improvement to help inform recruitment estimates. Previous models used to manage this stock have had few data to inform abundance at ages younger than 3. The set of environmentally linked models demonstrated issues with fitting these links in single species stock assessment models and the difficulty in model selection where improvements are minimal. The tuned models were presented to demonstrate the sensitivity of the models to differences in data weighting.

Adding environmental links to the base model adds complexity to the models and makes assumptions about the processes that impact the annual variability of the stock that may not yet be well established in the literature. The improvements to the tactical model in all cases were at best minor while changes to the management advice resulting from the models were in some cases substantial. The authors wish to continue to work on these models and present a set of these for November, but are reluctant to recommend any of them for management of the stock at this time.

Environmental Data

Laurel and Litzow age-0 index

Beach seine sampling of age-0 cod was conducted at two Kodiak Island bays during 2006-2021 and an expanded survey was conducted during 2018-21 at 13 additional bays on Kodiak Island, the Alaska Peninsula, and the Shumagin Islands (n = 3 - 9 fixed stations per bay, 95 total stations). Sampling occured during July and August (days of year 184-240), within two hours of a minus tide at the long-term Kodiak sites, and within three hours of a low tide at the expanded survey sites. At all sites, a 36 m long, negatively buoyant beach seine was deployed from a boat and pulled to shore by two people standing a fixed distance apart on shore. Wings on the seine (13 mm mesh) were 1 m deep at the ends and 2.25 m in the middle with a 5 mm delta mesh cod end bag. The seine wings were attached to 25 m ropes for deployment and retrieval from shore. The seine was set parallel to and ~ 25 m, making the effective sampling area ~ 900 m^2 of bottom habitat.

A model-based index of annual catch per unit effort (CPUE) for age-0 cod was used to resolve inter-annual differences in sampling across different bays and different days of the year. Specifically, a Bayesian zero-inflated negative binomial (ZINB) model was used invoking year as a categorical variable, day of year as a continuous variable, and site nested within bay as a group-level (random) effect. The day of year effect was modeled with thin plate regression splines to account for non-linear changes in abundance through the season and the number of basis functions was limited to 3 to avoid over-fitting data. This model was fit using Stan 2.21.0, R 4.0.2 and the *brms* package (Carpenter et al. 2017, Buerkner 2017, R Core Team 2021). The beach seine age-0 CPUE index showed the large 2012 year class and subsequent drop in CPUE for 2013-2016, larger recruitment in 2017 and 2018, a drop again in 2019, and then large 2020 year class (Table 2). The most recent bottom trawl survey included in Model 19.1 was 2019, however Pacific cod don't fully recruit into this survey until approximately age-3. Therefore Model 19.1 would not have much information informing year classes after 2016. The 2006 through 2016 recruitment deviations from Model 19.1 correlate positively with the log CPUE of the beach seine index with an R^2 of 0.67.

CFSR bottom temperature indices

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

To make the index the CFSR reanalysis grid points were co-located with the AFSC bottom trawl survey stations. The co-located CFSR oceanic temperature profiles were then linearly interpolated to obtain the temperatures at the depths centers of gravity for 10 cm and 40 cm Pacific cod as determined from the AFSC bottom trawl survey. All co-located grid points were then averaged to get the time series of CFSR temperatures over the period of 1979-2020 (Table 3).

Sum of annual marine heatwave cumulative intensity index (MHCI)

The daily sea surface temperatures for 1 January 1981 through 31 December 2020 were retrieved from the NOAA High-resolution Blended Analysis Data database (National Oceanic and Atmospheric Administration, 2017) and filtered to only include data from the central Gulf of Alaska between 145°W and 160°W longitude for waters less than 300 m in depth. The overall daily mean sea surface temperatures were 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 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. The 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 an annual winter index of MHCI, and summed for February and March to create an annual spawning index of MHCI (Table 3).

Model Configurations

Except where noted below, the models presented were configured the same as Model 19.1 from Barbeaux et al. (2020), the reference model used to set management advice. All ecosystem-link parameters presented were fit with uninformative uniform priors.

AFSC longline survey catchability

For the base model an ecosystem-linked covariate on AFSC longline survey catchability has been in use since 2017 (Barbeaux et al., 2016) and will continue to be used in all of the models used in this study. Annual catchability, Q_y, was modeled using a multiplicative link as:

$$log\left(Q_y\right) = \log(\bar{Q})e^{\alpha f_{Jy}},$$

where $\bar{Q}$ was the mean catchability for the AFSC longline survey for 1977 through 2020, α was the ecosystem link parameter fit with an uninformative prior, and f_{Jy} was the June CFSR bottom temperature anomaly in the Central GOA in year y.

Growth

For the base model (19.1), 21.1a, 21.1b, and 21.1c length at age, L_a, were modeled as three parameter von Bertalanffy growth models with length in June, L_1, maximum asymptotic length, L_2, and growth rate, k, as:

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

where a was age.

For the ecosystem-linked models 21.1d, 21.1e, 21.1f, 21.5a and 21.5b length at age for each year, L_{ay}, were modeled as six parameter von Bertalanffy growth modeled with annual water temperature covariates on L_1, L_2, and k as:

$$L_{ay} = L_{2y} - \left(L_{2y} - L_{1y}\right)e^{-ak\left(e^{\varphi f_{Jy}}\right)}$$

$$L_{1y} = \bar{L}_1 e^{\left(\gamma \frac{e^{\left(0.2494+0.3216\left(\bar{t}+f_{Jy}\right)-0.0069\left(\bar{t}+f_{Jy}\right)^2-0.0004\left(\bar{t}+f_{Jy}\right)^3\right)}}{e^{\left(0.2494+0.3216(\bar{t})-0.0069(\bar{t})^2-0.0004(\bar{t})^3\right)}}\right)}$$

$$L_{2y} = \bar{L}_2 e^{\upsilon f_{Jy}}$$

where f_{Jy} was the June bottom temperature anomaly in the Central GOA (described above) in year y, γ was the temperature anomaly link parameters for L_1 and an index of the ratio of the annual June temperature, $\bar{t} + f_{Jy}$, dependent juvenile growth (Laurel *et al.* 2015) for a given year over the growth in June for the mean temperature for 1982-2012, $\bar{t}$, υ was the temperature anomaly link parameter for L_2, and φ the temperature anomaly link parameter for *k*.

Natural mortality

Natural mortality in the base Model 19.1, and Models 21.1a, 21.1b, and 21.1d were fit for two time blocks, 2014-2016 and all other years, as a single non-varying parameter for all ages for each block.

Natural mortality in Model 21.1c, 21.1e, and 21.1g was annually varying with a linear ecosystem-link parameter, η, which scaled the non-heatwave year natural mortality, $\widehat{M}$, using the annual central GOA marine heatwave cumulative index (I_{Ay}) as:

$$\mathrm{M_y} = \widehat{M} + \eta l_y$$

$$l_y = \lambda / \left(1 + e^{-\varsigma(I_{Ay} - \psi)}\right)$$

A logistic curve was used to convert the index forcing M to asymptote at higher index values (Table 3). Here the shape of the logistic curve including the asymptote, λ, slope, ς, and inflection point in °C days, ψ, was determined within the model iteratively and the parameters resulting in the lowest negative log-likelihood were selected for projections. The best fit model had λ at 0.65, $\varsigma = 0.005$ and $\psi = 400$ resulting in increased natural mortality estimates for years with positive I_{Ay} values. Note the maximum annual marine heatwave index value in the time series was 631°C-days in 2016, well below future projected values.

For Models 21.5a and 21.5c natural mortality were fit for two time blocks, 2015-2021 and all other years, as a single non-varying parameter for all ages for each block with uninformative priors.

Recruitment

In the base Model 19.1, Model 21.1a, and Model 21.1b recruitment by year, R_y, were modeled as:

$\mathrm{R_y} = \left(\mathrm{R_0 e^{\vartheta}}\right)\mathrm{e}^{-0.5\mathrm{b_y}\sigma_\mathrm{R}^2 + \widetilde{\mathrm{R}}_\mathrm{y}}$, if y ≥ 1977 → $\vartheta = 0$, where $\widetilde{\mathrm{R}}_\mathrm{y} = \mathrm{N}\left(0;\ \sigma_\mathrm{R}^2\right)$,

$\mathrm{R_0}$ was the unfished equilibrium recruitment, $\widetilde{\mathrm{R}}_\mathrm{y}$ was the lognormal recruitment deviation for year y, σ_R^2 was the standard deviation among recruitment deviations in log space and was fixed at 0.44, and b_y was a bias adjustment fraction applied during year, y (Methot Jr and Taylor, 2011). To account for an environmental regime change in 1977 (Anderson and Piatt, 1999) the parameter ϑ was fit for recruitment allowing for a change in R_0 prior to the regime change in 1977. Projections in the base model post-2017 assumed average recruitment for 1977-2017 for R_y.

The ecosystem-linked recruitment (R_y) in models 21.1d, 21.1e, 21.1g, 21.5a, and 21.5c were modeled as Beverton-Holt relationships with parameter (ω) which scaled the unfished equilibrium recruitment, $\mathrm{R_0}$, using the annual spawning Central GOA marine heatwave cumulative index (I_y; described below) as:

$\mathrm{R_y} = \dfrac{4\mathrm{h}\left(e^{\vartheta + \ln\left(\mathrm{R_0} e^{\omega \mathrm{I}_{Sy}^{\frac{1}{3}}}\right)}\right)\mathrm{SB}_y}{\mathrm{SB_0(1-h)+SB_y(5h-1)}} e^{-0.5\mathrm{b_y}\sigma_\mathrm{R}^2 + \widetilde{\mathrm{R}}_\mathrm{y}}$, if y ≥ 1977 → $\vartheta = 0$, where $\widetilde{\mathrm{R}}_\mathrm{Y} = \mathrm{N}\left(0;\ \sigma_\mathrm{R}^2\right)$,

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

Where h=1, the formula reduces to $\mathrm{R_y} = e^{\vartheta + \ln\left(\mathrm{R_0} e^{\omega I_{Sy}^{\frac{1}{3}}}\right)} e^{-0.5\mathrm{b_y}\sigma_\mathrm{R}^2 + \widetilde{\mathrm{R}}_\mathrm{y}}$.

Model tuning

For all models except Model 21.1g and 21.5c the models remained at the base configuration with no additional tuning. For these two models the index input variances were tuned to the RMSE and the length and age composition sample size tuned using the Francis TA1.8 method (Francis 2011).

Results

Beach seine index

The inclusion of the age-0 beach seine index in Model 21.1a resulted in a poorer fit for the majority of data components compared to Model 19.1 (Table 4); however, there was a reduction in the objective function for recruitment (Table 5). Comparisons of overall likelihood and marginal likelihoods were not possible given the inclusion of a new dataset/likelihood component. As one would expect the variance estimates for recruitment deviations for the years in which index data were available were lower than in the model without the beach seine index (Table 6). For 2006-2020 the mean CV for Model 19.1 was 0.25 and for Model 21.1a, with the beach seine age-0 index, was 0.19. The index root-mean-squared-standardized-residual (RMSSR) for the bottom trawl and longline survey showed a reduction in fit and the Effective N for age and length compositions for all components showed a slight degradation in fit from Model 19.1 to Model 21.1a.

Retrospective analysis showed both models had slight positive retrospective bias in the estimates of spawning stock biomass with the Mohn's ρ of 0.081 for Model 19.1 and 0.087 for Model 21.1a. The Woodshole ρ and RMSE for spawning stock biomass were also similar (Table 7) with only slight differences between the two configurations. The retrospective bias for both models was considered to be within acceptable bounds.

The largest change in model results between Model 19.1 and Model 21.1a was the increase in estimates for the 2017, 2018, and 2020 year classes and slight decrease in the 2019 year class estimate (Table 6 and Fig. 2) resulting in an overall increase in 2019-2020 estimates of spawning stock biomass (Table 8 and Fig. 2) and increase in projected 2021 and 2022 spawning biomass. This increasing abundance starting in 2017 due to fit to the age-0 index and inability of the model to compensate with changing M post-2016 resulted in the disagreement in Model 21.1a with the recent reduction in the longline survey abundance. Model 21.1a would recommend a ~200% increase in ABC for 2022. This large increase was mostly due to a drop in the estimated unfished spawning biomass with increases in recruitment (Table 5) and an increase in the projected spawning biomass for 2022 resulting in the spawning biomass ratio being above $B_{40\%}$ and no longer on the sloping portion of the control rule.

As Model 21.1a was configured there was disagreement between the age-0 beach seine index and all other data components. There were at least two possible reasons for this disparity 1) the beach seine survey doesn't capture the GOA-wide trend in age-0 abundance, and/or 2) Model 21.1a with natural mortality modeled across all ages with only a block for 2014-2016 does not adequately capture survival variability between age-0 and age-3. Attempts this year at fitting annually varying age-specific M failed as there was a lack of information for the younger age classes as these younger fish were not consistently caught in the fisheries or surveys. For the remainder of the models presented we assumed that the beach seine survey index captures the trend in GOA age-0 Pacific cod abundance.

Environmentally-linked models

The three new environmental links on growth, natural mortality, and recruitment made improvements to the overall model fits over Model 21.1a as measured by full likelihood and full AIC. However the marginal likelihood (Thorson *et al.* 2019) in some cases suggested some of the changes were not true model improvements. Most of the changes made by the inclusion of the environmental links were minor in terms of fit, but some would result in substantial changes in management advice from the base model. Although the residual plots were not provided due to the volume of possible plots, they were assessed by the authors and can be made available on request for any model. For all the age and length composition data there were no severe trends in the residuals and it was very difficult to ascertain differences in model fits visually as differences were subtle. For all models presented there were no parameters near bounds and the likelihoods appeared well defined with the gradient of the objective function at less than 10e-4. All models were examined by "jittering" starting parameters by 10% over 50 runs to evaluate if models had converged to local minima. All models evaluated were deemed adequate.

Model21.1b: SST-linked growth

The parameterization and fit of the SST-linked growth in Model 21.1b resulted in the model estimating faster growth in warm years and slower growth in cold years (Fig 3). The parameters appeared to be well fit with small gradients and CVs between 0.23 and 0.28. SST-linked growth was most impactful in the age-0 fish creating a cohort effect on length in the model (Fig. 3). The addition of sea surface temperature links to growth in Model 21.1b resulted in an improvement in both length and age composition fits for likelihood and effective N, and a slight improvement to the bottom trawl survey (Table 4), but a larger degradation in the fit to the longline and beach seine survey indices with increases in likelihood and RMSSR. There was an overall improvement in AIC from Model 21.1a, however the marginal AIC suggests that the SST-linked growth was not a model improvement. Although the retrospective bias remained within acceptable bounds the analysis suggests a slight increase in positive retrospective bias from Model 21.1a in the spawning biomass estimates across all three measures (Table 7). Overall model results in terms of reference points and current biomass levels (Table 5 and Table 8) remained similar to Model 21.1a.

Model 21.1c: Annual heatwave linked natural mortality

Adding heatwave-linked natural mortality to the model made the greatest improvement to the objective function, AIC, and Marginal AIC over all of the single eco-linked changes from Model 21.1a. The environmental link parameter was well fit with low gradient and a CV of 0.10. Model 21.1c showed improvement over Model 21.1a in fits to the most recent drop in abundance in the longline survey (Fig. 4), in the trawl and longline fishery length composition data, and in the beach seine index. There was a slight degradation in fit to the other data components (Table 4 and Table 5), however the improvement of fit to the most recent longline survey estimates were greater than the combined negative impacts to fit to the other components. Including annual heatwave index-linked natural mortality in Model 21.1c (Fig. 5) results in natural mortality peaking during heatwave years with the highest in 2016 at 0.92 and second highest in 2019 at 0.81. The retrospective analysis showed the model within acceptable bounds with a slight increase in the Mohn's ρ, but a decrease in both the Woodshole ρ and retrospective RMSE compared to Model 21.1a.

Although the overall trend in abundance and recruitment were similar for most of the time series as were reference points between Models 21.1a and 21.1c, the management implications of the estimated drop in abundance for 2018-2020 and projections in Model 21.1c (Fig. 7) changed recommended harvest advice on ABC considerably from Model 21.1a and 21.1b with a -40% lower ABC in 2022. This difference resulted in an ABC nearer the Model 19.1 value (+23%). The difference from Model 21.1a was partly due to the 2022 Model 21.1c spawning biomass being estimated below $B_{40\%}$ (Table 5) and on the slope of the control rule.

Model 21.1d: Spawning heatwave index linked recruitment

The spawning heatwave index linked recruitment (Fig. 6) in Model 21.1d resulted in a slight improvement of fit compared to model 21.1a based on a lower overall objective function and AIC estimate, however there was an increase in the marginal AIC (Table 7). Minor improvements in the objective function can be attributed to fit to the bottom trawl and longline surveys and reduction in recruitment residuals. There were minor reductions in fit to all of the age and length composition data (Table 4). Retrospective bias remained positive for all measures with a slight improvement over Model 21.1a (Table 7). Estimates for unfished biomass were within 1% of the Model 21.1a values as were the recommended ABC for 2022.

Model 21.1e: All three environmental links

Inclusion of all three environmental links in Model 21.1e (Table 5) resulted in a better fit model in regards to the objective function and AIC, however the marginal AIC was higher than Model 21.1c with just heatwave-linked natural mortality. In addition, although still within generally acceptable bounds the retrospective analysis resulted in an increase in the positive bias in the model over all the other models examined for the Mohn's ρ and retrospective RMSE (Table 7). Gradients for the environmental link parameters were all relatively low (Table 9). The ω link parameter on R_0 was the least well defined with a CV of 0.38 and gradient of 0.0001. Compared to Model 21.1a, Model 21.1e improved fits to the longline and beach seine survey indices, the length and age composition data for all three fisheries, the bottom trawl survey age composition data, and the longline survey length composition data (Table 4). Recruitment residuals were improved over all of the other models assessed before tuning (Table 5).

For Model 21.1e the overall trend in abundance and recruitment were similar to the other Model 21.1 series (Fig. 1). Like model 21.1c, Model 21.1e had a drop in abundance for recent years (Fig. 7) and the projections with similar estimates of annually varying natural mortality. Model 21.1e unfished spawning biomass at 345,360 t was the lowest of the un-tuned Model 21.1 series, but was only -5% different from Model 21.1a and -6% from Model 21.1d, the highest of the series, and -16% from Model 19.1. The management implications of the estimated drop in abundance for 2018-2020 and projections in Model 21.1e (Fig. 7) changed recommended harvest advice on ABC considerably from Model 21.1a and 21.1b with a -45% lower ABC in 2022. The Model 21.1e ABC, like Model 21.1c ABC, was nearer the Model 19.1 value (+13%).

Expanding the natural mortality block to 2015-2020

Like Model 21.1e, Model 21.5a had environmental links on recruitment and growth, but unlike Model 21.1e the mortality block first used in Model 19.1 was changed from 2014-2016 to 2015-2020 after iteratively testing combinations of M blocks (Fig. 5). Compared to Model 21.1e, Model 21.5a improved fits to all age composition data and all length composition data except the longline survey length composition and length composition data as well as the longline and beach seine surveys over Model 21.1e while degrading the fit to the bottom trawl survey index. The AIC and marginal AIC were the lowest of all un-tuned models examined for this analysis. Environmentally linked parameter estimates (Table 9) were well estimated with low gradients and relatively low CVs. The estimate for natural mortality for 1978-2014 was the lowest of all the models evaluated at 0.40 and an estimate of M for 2015-2020 at 0.72. Both the bottom trawl and base longline catchability were high for Model 21.5a at 1.359 and 1.413, respectively. The α parameter linking the longline survey catchability to the CFSR surface temperatures was substantially lower than the other non-tuned models from between 0.8 and 1.0 down to 0.5 suggesting less influence of temperature on the longline survey index estimates (Table 9). The retrospective analysis on SSB suggested an increase in the Woodshole ρ and retrospective RMSE over all other models examined (Table 7), but a slight decrease in the Mohn's ρ compared to Model 21.1e, but still higher than other un-tuned models examined. The increased natural mortality in 2015-2020 improved the fit to the large drop in abundance estimated in the longline survey over the last 5 years while degrading the fit to the increasing biomass estimate from the 2019 bottom trawl survey (Fig. 9) making it the worst fit model to this dataset of all examined. While improving the fit to the beach seine survey Model 21.5a increased residuals to estimated recruitment over Model 21.1e.

The trends in spawning biomass and recruitment mirrored the other models examined, however with the lower estimates for natural mortality and higher estimates for catchability the recruitment estimates were lower than other models as were the biomass estimates. Like the other models examined in this document Model 21.5a estimated that the lowest spawning biomass occurred in 2020 (Table 8), however spawning biomass in Model 21.5a was estimated to be below $B_{12\%}$ in 2020 and 2021 and to remain below $B_{20\%}$ through 2022, which would substantially change management advice for this stock compared to the other un-tuned models.

Tuning the models

With the addition of the age-0 index we once again looked into model tuning and the use of the Dirichlet multinomial to handle data weighting for the length and age composition as recommended in Thorson et al. (2019). As in previous attempts with the GOA Pacific cod model, the model fits resulted in the ln(θ) parameters with values >15. In addition when implemented in Stock Synthesis the Dirichlet multinomial option led the models to be highly unstable and sensitivity, jitter, and retrospective runs often failed to converge making it difficult to evaluate the models even with the theta parameters fixed. In this document we chose to run two model configurations (Model 21.1g and 21.5c) with the indices tuned to the Index RMSE and the age and length composition sample sizes tuned using the Francis A1.8 method as implemented in R4SS. These models corresponded with the un-tuned models 21.1e and 21.5a.

Due to differences in the multinomial sample sizes the overall likelihoods between Model 21.1g and 21.5c cannot be compared nor can they be compared with the other models presented. For both tuned models there was a reduced weight on all three survey indices with an increase in variance for all three indices and a reduction in all age and length composition sample sizes (Table 10). However once tuned these models ended up placing more weight on the indices as can be seen in the reduction of the RMSSR for all three (Table 5) to near or below 1.0. The effective sample size in both tuned models were substantially lower than the un-tuned models as would be expected with the lower input sample size. The increase in variance and drop in input sample size placed less weight on the data components and allowed the model to adhere more closely to structural assumptions such as those provided for recruitment. The model then expended less in reducing recruitment residuals where the assumptions conflicted with data. Due to the higher variance for the longline survey index in both tuned models, the environmental link parameter on catchability (α) was substantially lower (0.382 and 0.295 for Model 21.1g and Model 21.5c) than the un-tuned models (between 0.8 and 1.0 for the Model 21.1 series and 0.5 for Model 21.5a), resulting in models with less variability in the longline survey index with sea surface temperature. Similarly, the temperature growth link parameters (φ, γ, and υ) were lower in the tuned models resulting in lower annual variability in growth overall (Table 9).

One issue in the tuned models was a large increase in the catchability for both the bottom trawl and longline surveys (Table 5). Inflating catchability allowed for an overall lower abundance making it easier to fit to the large recent drop in the longline abundance. The larger catchabilities also allowed for lower recruitment with smaller deviations from the spawner-recruit relationship.

Tuning increased the positive retrospective bias for Model 21.1g over the other 21.1 series models. For Model 21.5c, however, the retrospective bias was substantially reduced with a slightly negative bias for Mohn's ρ and Woodshole ρ and lower retrospective RMSE for the spawning biomass estimates making Model 21.5c the best model in terms of least retrospective bias (Table 7 and Fig. 11). Having RMSSR lower than 1.0 for most of the indices may indicate overfitting of the indices in these models and an additional iteration on tuning the input variance warranted.

Discussion

The inclusion of the age-0 beach seine index provided an anchor point for the models and resulted in an improvement in estimates of recruitment with lower recruitment residuals and a reduction in recruitment variability and variability in reference points. However this improvement came at a cost to the fits to the other data components. For the 21.1 and 21.5 series of models we needed to assume the beach seine index captured the overall trend in GOA age-0 Pacific cod abundance. We know that the other survey and fishery data included in this assessment provide poor estimates of young fish between ages 0 and 3. Therefore the degradation in model fit to the other survey indices and composition data we believe identifies model misspecification. This is likely due to the current set of models not having age-varying natural mortality and the likeliness of age-varying natural mortality being time varying. Models should be further explored that do include time and age-varying natural mortality. Attempts this year to develop such models found that fitting both of these in a single model was problematic and led to unlikely results with large differences in natural mortality between adjacent ages.

The exploration of ecosystem-linked models in this document highlight the difficulty in developing environmental links for tactical management advice. Here we saw marginal changes in measured model fit to the data that then produced a wide range of management advice depending on which environmental relationships were included. In the case of the models presented we can examine the partial impacts of increasing temperature and probability of a severe heatwave events, both of which were trending with climate change. Because we have opposing impacts on spawning biomass (faster growth, lower recruitment, and higher natural mortality with increasing temperature), including only one relationship may be problematic where data become scarce and in projections where they may drive estimates in a particular direction. Laboratory studies provide one means of examining the relationships and parameterizing the models; however, interactions within the ecosystem make these relationships less certain. In single species models the uncertainty in the relationships among ecosystem components when environmental conditions exceed the range of those observed in the past is not quantifiable.

It should be noted that when tuning a model, one is shifting weights of the data components in a model and changing the balance between the data components and model structure, including prior assumptions. In the series of models presented in this document, tuning of the model resulted in down-weighting all of the data components by adding variance to the indices and reducing sample size in the composition data. In broad terms the data down-weighting resulted in the model placing more emphasis on model assumptions and structure instead of data, particularly for recruitment. In addition the inflation of catchability in the tuned models was problematic and would lead me to disregard these model configurations.

Overall the variability in model results due to inclusion of different environmental links without a clear objective means of determining which configuration provides the best management advice was problematic. Retrospective analysis with time varying parameters was difficult to interpret particularly where there were time blocks and environmental linked relationships within the retrospective time period assessed. Likelihood and AIC measures were not useful for comparing models with different data components or different data weightings.

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Tables

Table 2.8.1 - Models developed for September 2021

Model name	Data changes from 2020	Model changes from 2020	Description
Model 19.1	None	None	Reference model from 2020
Model 21.1a	Laurel/Litzow larval index	Model 19.1	Addition of the age-0 index from the Kodiak Beach seine surveys conducted by Laurel and Litzow.
Model 21.1b	Laurel/Litzow larval index	Model 21.1a with Temp.-linked growth	SST-linked growth in model
Model 21.1c	Laurel/Litzow larval index	Model 21.1a with heatwave-linked natural mortality	Heatwave-linked natural mortality
Model 21.1d	Laurel/Litzow larval index	Model 21.1a with heatwave-linked recruitment	Heatwave-linked recruitment in model
Model 21.1e	Laurel/Litzow larval index	Model 21.1a with Temp.-linked growth, and heatwave-linked recruitment and mortality.	All environmental links turned on
Model 21.1g	Laurel/Litzow larval index	Model 21.1e with index tuned to RMSE and length composition tuned using the Francis method	Model 21.1e tuned
Model 21.5a	Laurel/Litzow larval index	Model 21.1e with extended M block 2015- 2020	Extended heatwave M to include 2015-2020 instead of environmental link
Model 21.5c	Laurel/Litzow larval index	Model 21.35a with index tuned to RMSE and length composition tuned using the Francis method	Model 21.5a tuned

Table 2.8.2 - Age-0 beach seine index CPUE (fish per set) and standard error and Model 19.1 age-0 recruitment in billions (10^9).

Year	CPUE (#/set)	SE	age-0 (1×10^9)
2006	86.34	0.41	0.687
2007	6.22	0.46	0.443
2008	20.45	0.44	0.652
2009	21.98	0.59	0.392
2010	6.53	0.54	0.507
2011	22.14	0.46	0.655
2012	117.77	0.44	1.215
2013	6.73	0.48	0.638
2014	5.95	0.58	0.211
2015	0.77	0.95	0.260
2016	1.30	0.55	0.168
2017	52.18	0.41	0.246
2018	84.85	0.31	0.390
2019	1.52	0.62	0.399
2020	117.81	0.35	0.464

Table 2.8.3 - Environmental indices used in reviewed 2021 models.

Year	CFSR SST Anomaly (°C)	Annual heatwave index (°C-days)	Spawning heatwave index (°C-days)	Larval growth index	Asymptotic heatwave index
1977	0.00	0.00	0.00	1.00	0.077
1978	0.00	0.00	0.00	1.00	0.077
1979	0.33	0.00	0.00	1.08	0.077
1980	0.45	0.00	0.00	1.11	0.077
1981	1.14	0.00	0.00	1.28	0.077
1982	-0.58	0.00	0.00	0.87	0.077
1983	0.53	31.88	1.68	1.13	0.089
1984	0.15	88.21	0.00	1.04	0.113
1985	0.00	24.61	2.70	1.00	0.086
1986	0.15	16.35	0.00	1.04	0.083
1987	0.72	5.58	0.00	1.18	0.079
1988	0.12	0.00	0.00	1.03	0.077
1989	-0.53	0.00	0.00	0.88	0.077
1990	-0.46	8.72	0.00	0.90	0.081
1991	-0.19	0.00	0.00	0.96	0.077
1992	0.32	0.00	0.00	1.08	0.077
1993	-0.05	19.10	0.00	0.99	0.084
1994	-0.10	0.00	0.00	0.98	0.077
1995	-0.54	0.00	0.00	0.88	0.077
1996	-0.08	0.00	0.00	0.98	0.077
1997	-0.01	142.05	0.00	1.00	0.140
1998	1.15	150.85	4.32	1.29	0.145
1999	-0.14	0.00	0.00	0.97	0.077
2000	-0.06	0.00	0.00	0.99	0.077
2001	0.40	46.91	2.25	1.10	0.095
2002	-0.37	51.27	0.00	0.92	0.097
2003	0.73	207.85	4.76	1.18	0.180
2004	0.03	117.65	0.00	1.01	0.127
2005	0.33	284.60	0.00	1.08	0.234
2006	0.05	35.14	0.00	1.01	0.090
2007	-0.44	0.00	0.00	0.90	0.077
2008	-0.25	0.00	0.00	0.94	0.077
2009	-0.92	0.00	0.00	0.80	0.077
2010	0.63	6.52	0.00	1.15	0.080
2011	-0.03	0.00	0.00	0.99	0.077
2012	-0.58	0.00	0.00	0.87	0.077
2013	-0.40	0.00	0.00	0.91	0.077
2014	0.16	283.02	0.00	1.04	0.233
2015	1.30	402.32	5.11	1.33	0.327
2016	1.13	630.87	5.38	1.28	0.494
2017	0.18	53.03	0.00	1.04	0.097
2018	0.53	128.50	0.00	1.13	0.133
2019	1.37	496.74	4.65	1.34	0.402
2020	-0.28	102.92	0.00	0.94	0.143

Table 2.8.4 - Likelihood components by fleet for models reviewed in 2021. Note that likelihoods for some models are not comparable due to differences in data (Model 19.1 survey ALL) or weighting (Models 21.1g and 21.5c).

LABEL	ALL	FSHTRAWL	FSHLL	FSHPOT	SRV	LLSRV	SEINE	MODEL
AGE_LIKE	1633.74	302.58	362.41	288.45	680.30			19.1
AGE_LIKE	1634.15	303.56	361.95	288.31	680.32			21.1a
AGE_LIKE	1625.46	302.40	358.74	285.91	678.40			21.1b
AGE_LIKE	1635.35	304.22	362.38	288.28	680.48			21.1c
AGE_LIKE	1634.62	303.61	361.98	288.32	680.71			21.1d
AGE_LIKE	1625.20	302.96	358.77	285.56	677.91			21.1e
AGE_LIKE	1562.15	295.63	342.96	276.29	647.27			21.1g
AGE_LIKE	1622.36	302.82	358.11	285.50	675.93			21.5a
AGE_LIKE	1562.75	295.88	343.21	276.65	647.01			21.5c
LENGTH_LIKE	1568.22	467.69	316.81	362.55	170.06	251.10		19.1
LENGTH_LIKE	1576.75	460.93	319.98	367.51	174.35	253.99		21.1a
LENGTH_LIKE	1573.39	462.68	321.19	363.61	176.50	249.41		21.1b
LENGTH_LIKE	1569.87	455.02	316.72	370.02	173.81	254.29		21.1c
LENGTH_LIKE	1577.55	460.64	319.48	368.42	175.40	253.61		21.1d
LENGTH_LIKE	1568.46	456.89	318.00	366.89	176.93	249.76		21.1e
LENGTH_LIKE	525.05	128.03	147.81	61.22	80.41	107.58		21.1g
LENGTH_LIKE	1561.77	455.25	316.78	362.68	176.14	250.92		21.5a
LENGTH_LIKE	521.18	126.74	144.14	62.55	82.25	105.50		21.5c
SURV_LIKE	-16.12				-10.64	-5.48		19.1
SURV_LIKE	-2.36				-7.00	0.49	4.15	21.1a
SURV_LIKE	-0.81				-7.94	2.54	4.59	21.1b
SURV_LIKE	-6.22				-3.20	-6.04	3.02	21.1c
SURV_LIKE	-4.09				-7.37	-0.92	4.20	21.1d
SURV_LIKE	-5.64				-4.02	-4.96	3.34	21.1e
SURV_LIKE	-32.74				-9.23	-21.99	-1.52	21.1g
SURV_LIKE	-11.09				2.89	-14.37	0.40	21.5a
SURV_LIKE	-34.89				-8.13	-25.07	-1.68	21.5c
LENGTH MEAN EFFN		788.6	1312.3	638.9	470.6	429.9		19.1
LENGTH MEAN EFFN		789.0	1314.4	630.2	468.0	420.0		21.1a
LENGTH MEAN EFFN		799.9	1393.7	641.8	450.1	431.6		21.1b
LENGTH MEAN EFFN		786.5	1313.6	633.9	467.5	416.3		21.1c
LENGTH MEAN EFFN		790.4	1318.1	627.3	468.2	422.4		21.1d
LENGTH MEAN EFFN		798.6	1402.7	642.6	449.3	429.4		21.1e
LENGTH MEAN EFFN		727.4	1136.7	622.0	445.5	439.7		21.1g

LENGTH MEAN EFFN	797.7	1440.5	646.6	449.1	431.9	21.5a
LENGTH MEAN EFFN	728.7	1165.2	626.3	446.7	441.0	21.5c
AGE MEAN EFFN	4.7	8.7	7.3	13.7		19.1
AGE MEAN EFFN	4.8	8.6	7.4	13.2		21.1a
AGE MEAN EFFN	4.8	8.9	7.8	12.2		21.1b
AGE MEAN EFFN	4.7	8.6	7.5	13.6		21.1c
AGE MEAN EFFN	4.7	8.6	7.4	13.6		21.1d
AGE MEAN EFFN	4.8	8.8	7.8	12.3		21.1e
AGE MEAN EFFN	5.2	9.4	8.9	12.8		21.1g
AGE MEAN EFFN	4.8	8.7	7.7	12.5		21.5a
AGE MEAN EFFN	5.2	9.3	8.9	12.7		21.5c

Table 2.8.5 - Likelihood components and derived quantities for models reviewed in 2021. For models with environmental links on M and models 21.5a and 21.5c the mortality estimates in brackets and greyed are the maximum and minimum estimates.

	Model 19.1	Model 21.1a	Model 21.1b	Model 21.1c	Model 21.1d	Model 21.1e	Model 21.1g	Model 21.5a	Model 21.5c
TOTAL_like	3190.02	3210.54	3202.85	3194.11	3205.07	3182.09	2039.62	3168.69	2036.43
Survey_like	-16.12	-2.36	-0.81	-6.22	-4.09	-5.64	-32.74	-11.09	-34.89
Length_comp_like	1568.22	1576.75	1573.39	1569.87	1577.55	1568.46	525.05	1561.77	521.18
Age_comp_like	1633.74	1634.15	1625.46	1635.35	1634.62	1625.20	1562.15	1622.36	1562.75
Recruitment	-5.50	-8.37	-5.60	-15.48	-12.34	-15.70	-20.48	-13.67	-18.47
InitEQ_Regime	1.48	1.45	1.90	2.03	1.59	2.67	1.17	2.13	1.30
Forecast_Recruitment	0.06	1.91	2.10	1.60	0.74	0.71	0.54	0.69	0.61
Parm_priors_like	1.59	0.47	0.01	0.47	0.47	0.01	0.00	0.01	0.00
Recr_Virgin_millions	463.71	472.99	406.78	495.07	544.07	485.41	444.55	324.79	310.91
SR_LN(R0)	13.05	13.07	12.92	13.11	13.21	13.09	13.00	12.69	12.65
SR_LN(R0)_ENV_mult					-0.0114	-0.0092	-0.0096	-0.0092	-0.0098
NatM (min M)	0.47	0.47	0.44	min(0.45)	0.47	min(0.44)	min(0.44)	min(0.40)	min(0.41)
NatM for 2014-2016 (max M)	0.82	0.75	0.75	max(0.92)	0.75	max(0.93)	max(0.85)	max(0.72)	max(0.68)
NatM central parameter				0.37		0.35	0.37		
NatM additive				1.12		1.17	0.98		
NatM mult. 2015-2020								0.57	0.51
L_at_Amin	12.09	12.09	7.00	12.08	12.08	6.67	5.67	6.66	5.59
L at Amin ENV mult.			0.56			0.61	0.71	0.61	0.73
L_at_Amax	99.46	99.46	99.46	99.46	99.46	99.46	99.46	99.46	99.46
L at Amax ENV mult.			0.11			0.11	0.10	0.11	0.10
VonBert K	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
VonBert K ENV mult			-0.16			-0.15	-0.13	-0.15	-0.12
Q bottom trawl index	1.16	1.16	1.23	1.10	1.15	1.16	1.43	1.36	1.61
SSB unfished 1000's t	413.55	365.05	361.74	347.33	368.36	345.36	318.94	310.79	300.36
SSB unfished CV	0.081	0.074	0.074	0.075	0.075	0.076	0.080	0.072	0.080
F_{MSY} (sum apical F)	0.668	0.753	0.678	0.795	0.761	0.729	0.753	0.639	0.636
2022 F_{ABC} (sum apical F)	0.448	0.753	0.678	0.620	0.761	0.549	0.648	0.292	0.344
SSBratio 2021	0.22	0.33	0.33	0.23	0.32	0.22	0.25	0.12	0.14
SSBratio 2022	0.28	0.43	0.43	0.32	0.41	0.31	0.35	0.19	0.23
Index root of mean squared standardized residuals (RMSSR)									
Bottom trawl survey	1.416	1.589	1.546	1.752	1.572	1.718	0.926	1.984	1.007
Longline survey	1.878	1.978	2.011	1.868	1.955	1.887	0.938	1.718	0.825
Beach seine survey	NA	1.408	1.429	1.353	1.410	1.369	0.920	1.217	0.908
Std.Dev(Ln(age-0)) 1978-2019	0.443	0.424	0.445	0.342	0.439	0.375	0.342	0.393	0.373

Table 2.8.6 - Age-0 recruitment in thousands of fish and coefficient of variation (CV) for assessed models.

	Model 19.1		Model 21.1a		Model21.1b		Model21.1c		Model21.1d	
Year	Age-0	CV	Age-0	CV	Age-0	CV	Age-0	CV	Age-0	CV
1978	377,556	0.349	379,158	0.345	377,992	0.347	361,736	0.338	417,244	0.342
1979	369,733	0.319	376,339	0.314	373,381	0.317	359,789	0.308	410,868	0.311
1980	624,014	0.288	638,465	0.281	504,666	0.302	607,456	0.277	693,037	0.279
1981	689,951	0.268	698,292	0.262	659,821	0.253	667,217	0.258	752,084	0.259
1982	756,252	0.271	769,099	0.265	729,879	0.268	734,718	0.26	834,698	0.261
1983	538,912	0.31	540,797	0.307	407,980	0.325	520,729	0.299	536,447	0.312
1984	709,138	0.276	722,969	0.27	657,489	0.265	689,984	0.264	809,158	0.264
1985	886,695	0.238	892,515	0.234	799,968	0.231	833,058	0.23	889,248	0.237
1986	499,375	0.271	503,011	0.267	375,480	0.294	478,455	0.26	551,995	0.261
1987	588,083	0.227	595,309	0.222	491,730	0.223	562,530	0.219	618,762	0.219
1988	597,962	0.221	603,810	0.216	538,538	0.21	579,513	0.213	635,484	0.213
1989	632,229	0.217	639,776	0.212	596,082	0.207	621,659	0.209	671,344	0.208
1990	749,185	0.203	754,939	0.198	643,233	0.199	740,039	0.196	791,292	0.195
1991	444,758	0.224	446,710	0.22	346,336	0.23	449,242	0.218	469,281	0.217
1992	385,255	0.216	387,645	0.212	311,307	0.212	402,972	0.211	405,677	0.209
1993	309,854	0.219	313,010	0.215	256,693	0.214	337,543	0.215	327,972	0.212
1994	347,856	0.206	352,879	0.201	312,422	0.194	391,114	0.202	368,422	0.199
1995	438,067	0.187	440,732	0.182	380,762	0.18	503,708	0.184	461,184	0.179
1996	309,470	0.198	312,439	0.194	268,489	0.192	369,782	0.196	323,913	0.192
1997	293,505	0.196	294,918	0.191	231,693	0.2	363,125	0.195	314,388	0.189
1998	272,155	0.192	274,925	0.187	212,963	0.185	329,572	0.19	276,357	0.187
1999	366,527	0.181	370,574	0.177	351,062	0.169	436,357	0.178	391,163	0.174
2000	439,377	0.173	442,541	0.169	359,828	0.169	552,223	0.17	462,909	0.166
2001	250,745	0.192	250,536	0.189	236,532	0.179	335,654	0.19	254,341	0.188
2002	193,147	0.192	194,844	0.189	167,993	0.192	259,680	0.191	209,745	0.185
2003	244,348	0.176	245,085	0.172	212,052	0.169	321,670	0.174	245,080	0.172
2004	307,845	0.171	311,232	0.165	289,611	0.161	366,652	0.165	327,856	0.163
2005	420,358	0.167	410,764	0.161	346,196	0.16	454,397	0.159	424,567	0.158
2006	686,755	0.163	706,285	0.152	631,775	0.148	658,602	0.148	733,076	0.15
2007	443,195	0.178	404,280	0.165	356,507	0.164	379,898	0.159	417,934	0.164
2008	651,882	0.173	601,931	0.158	543,933	0.154	548,979	0.153	624,993	0.156
2009	391,813	0.195	397,704	0.172	334,628	0.176	373,756	0.164	409,121	0.17
2010	506,839	0.192	434,530	0.171	339,557	0.17	401,095	0.163	448,951	0.17
2011	655,108	0.202	567,604	0.175	513,133	0.172	536,803	0.165	583,773	0.174
2012	1,215,110	0.215	1,039,390	0.184	949,610	0.184	1,024,320	0.173	1,069,210	0.183
2013	638,080	0.248	468,547	0.208	433,984	0.209	495,858	0.196	479,472	0.207
2014	211,074	0.286	241,005	0.227	209,402	0.227	272,007	0.211	244,487	0.227
2015	260,163	0.247	240,750	0.22	165,092	0.234	306,902	0.219	237,647	0.22
2016	168,038	0.248	190,432	0.214	180,225	0.202	231,348	0.205	183,224	0.217
2017	246,044	0.235	438,126	0.194	377,592	0.196	475,888	0.182	439,743	0.194
2018	389,895	0.278	698,218	0.189	616,627	0.188	696,969	0.18	713,420	0.189
2019	399,011	0.401	253,131	0.259	213,060	0.26	268,197	0.239	226,550	0.273
2020	463,705	0.482	852,381	0.207	762,533	0.208	812,021	0.196	894,707	0.21
2006-2020 mean	488,447	0.249	502,288	0.193	441,844	0.193	498,843	0.183	513,754	0.193
1978-2020 mean	473,699	0.235	481,340	0.212	420,182	0.213	491,005	0.207	501,880	0.211

Table 2.8.6 Cont. - Age-0 recruitment in thousands of fish and coefficient of variation (CV) for assessed models.

	Model 21.1e		*Model 21.1g*		*Model 21.5a*		*Model21.5c*	
Year	*Age-0*	*CV*	*Age-0*	*CV*	*Age-0*	*CV*	*Age-0*	*CV*
1978	395,269	0.343	405,973	0.397	250,342	0.351	273,273	0.404
1979	385,344	0.316	366,576	0.373	237,661	0.331	244,589	0.384
1980	515,580	0.302	401,744	0.376	320,765	0.318	270,439	0.383
1981	683,986	0.255	518,978	0.338	433,580	0.275	353,499	0.347
1982	759,232	0.267	628,058	0.364	481,087	0.286	425,742	0.369
1983	394,972	0.328	350,884	0.416	259,739	0.338	242,584	0.413
1984	696,500	0.263	618,507	0.354	460,863	0.279	434,964	0.356
1985	759,515	0.235	571,253	0.342	534,252	0.249	417,468	0.342
1986	392,411	0.286	384,481	0.355	273,842	0.3	280,494	0.355
1987	487,543	0.223	463,544	0.302	347,065	0.236	343,380	0.302
1988	550,431	0.211	441,318	0.306	385,336	0.225	322,706	0.306
1989	615,420	0.208	575,463	0.293	423,790	0.224	415,443	0.292
1990	663,983	0.202	538,987	0.297	452,010	0.218	384,469	0.295
1991	368,196	0.231	338,298	0.317	247,678	0.243	239,031	0.313
1992	341,316	0.215	322,690	0.295	225,506	0.225	225,246	0.291
1993	293,828	0.217	305,766	0.289	187,902	0.226	208,267	0.285
1994	366,345	0.198	341,370	0.279	230,233	0.207	228,376	0.273
1995	461,980	0.186	399,468	0.271	277,983	0.194	259,289	0.262
1996	332,732	0.199	316,787	0.28	194,141	0.205	199,809	0.269
1997	308,514	0.206	271,199	0.296	173,363	0.211	165,041	0.281
1998	259,454	0.194	256,860	0.274	154,449	0.197	162,637	0.259
1999	444,120	0.175	378,239	0.266	263,873	0.182	238,206	0.251
2000	475,600	0.176	422,947	0.259	266,965	0.182	252,129	0.244
2001	332,943	0.186	265,022	0.271	175,222	0.192	152,467	0.256
2002	244,538	0.198	233,581	0.268	129,464	0.202	134,300	0.254
2003	286,522	0.177	244,064	0.252	155,503	0.181	144,368	0.237
2004	364,921	0.165	341,839	0.238	222,424	0.17	220,369	0.226
2005	401,823	0.162	358,779	0.235	262,307	0.169	246,100	0.226
2006	614,612	0.147	586,454	0.215	464,906	0.156	457,584	0.206
2007	347,100	0.161	349,904	0.228	266,598	0.167	272,617	0.218
2008	514,246	0.152	470,056	0.221	378,419	0.159	359,218	0.21
2009	320,417	0.171	290,948	0.239	230,732	0.175	217,718	0.226
2010	321,967	0.166	305,709	0.23	227,382	0.166	224,491	0.215
2011	494,854	0.167	478,024	0.232	336,251	0.164	343,155	0.213
2012	958,239	0.177	806,918	0.244	626,495	0.168	573,267	0.219
2013	468,120	0.202	373,191	0.266	319,211	0.187	273,128	0.241
2014	241,961	0.217	228,882	0.285	178,291	0.206	171,794	0.263
2015	205,189	0.24	178,631	0.308	165,812	0.232	144,272	0.29
2016	225,846	0.204	220,776	0.273	182,407	0.2	175,980	0.257
2017	418,118	0.188	461,615	0.255	347,844	0.188	366,859	0.243
2018	639,029	0.184	589,737	0.251	457,327	0.181	435,326	0.236
2019	212,764	0.251	208,246	0.312	160,661	0.241	157,075	0.297
2020	760,536	0.203	674,723	0.263	529,127	0.195	498,365	0.248
2006-2020 mean	449,533	0.189	414,921	0.255	324,764	0.186	311,390	0.239
1978-2020 mean	449,442	0.213	402,011	0.289	299,972	0.219	282,687	0.28

Table 2.8.7 - Negative log likelihood, Akaike information criterion (AIC), negative log marginal likelihood, marginal AIC, and retrospective values for 10-year peal for spawning stock biomass for models reviewed in 2021 showing Mohn's ρ, Woodshole ρ, and retrospective RMSE. Color coding is unique for each column with higher values in red, lower in green. Attributes are G = SST linked growth, Mh = annual heatwave-linked M, R = spawning heatwave-linked recruitment, M20 = 2015-2020 block M, and T = Index variance and composition sample sizes tuned.

							Retrospective analysis (SSB)		
	Attributes	# Parameters	-Log likelihood	AIC	-Marginal log likelihood	Marginal AIC	ρ	Woodshole ρ	RMSE
Model 19.1		201	3,190.0	6,782.0	3,356.6	7,115.3	0.078	0.077	0.148
Model 21.1		202	3,210.5	6,825.1	3,368.7	7,139.3	0.087	0.071	0.162
Model 21.1b	G	204	3,202.8	6,813.7	3,372.1	7,152.3	0.129	0.080	0.178
Model 21.1c	Mh	201	3,194.1	6,790.2	3,352.2	7,106.4	0.101	0.063	0.159
Model 21.1d	R	203	3,205.1	6,816.1	3,368.7	7,141.5	0.086	0.067	0.145
Model 21.1e	G, R, Mh	205	3,182.1	6,774.2	3,356.3	7,122.6	0.164	0.072	0.183
Model 21.1g	G, R, Mh, T	205	2,039.6	4,489.2	2,149.1	4,708.2	0.164	0.120	0.198
Model 21.5a	G, R, M20	205	3,168.7	6,747.4	3,343.6	7,097.2	0.132	0.121	0.223
Model 21.5c	G, R, M20,T	205	2,036.4	4,482.9	2,149.8	4,709.5	-0.047	-0.015	0.078

Table 2.8.8 - Spawning biomass (SSB) in tons for models presented with coefficient of variation (CV).

	Model 19.1		*Model 21.1a*		*Model 21.1b*		*Model 21.1c*		*Model 21.1d*	
Year	*SSB (t)*	*CV*	*SSB (t)*	*CV*	*SSB (t)*	*CV*	*SSB (t)*	*CV*	*SSB (t)*	*CV*
1978	239,697	0.209	247,661	0.203	234,602	0.202	240,390	0.206	265,263	0.206
1979	235,975	0.2	243,100	0.194	231,204	0.195	237,479	0.198	260,113	0.197
1980	240,527	0.191	246,978	0.185	239,307	0.185	242,276	0.188	264,244	0.187
1981	287,555	0.188	294,080	0.183	293,990	0.182	289,829	0.185	315,213	0.183
1982	333,569	0.184	340,448	0.179	364,284	0.178	339,561	0.181	364,838	0.18
1983	344,749	0.178	351,411	0.173	364,603	0.172	355,580	0.175	376,146	0.173
1984	347,180	0.173	353,440	0.168	383,529	0.166	357,296	0.168	377,812	0.167
1985	377,083	0.159	382,980	0.155	419,197	0.154	375,007	0.155	407,388	0.153
1986	422,196	0.142	427,757	0.138	457,103	0.137	417,136	0.137	451,838	0.136
1987	454,985	0.127	460,277	0.124	480,673	0.123	448,565	0.123	481,751	0.122
1988	466,017	0.114	470,623	0.111	505,793	0.112	459,994	0.11	489,655	0.109
1989	486,343	0.102	490,345	0.099	519,829	0.099	482,471	0.098	506,062	0.097
1990	486,461	0.092	489,978	0.089	492,421	0.089	487,076	0.089	502,450	0.088
1991	446,601	0.088	449,667	0.086	437,560	0.085	450,899	0.087	460,138	0.084
1992	410,158	0.086	412,946	0.084	397,392	0.084	419,881	0.085	422,082	0.082
1993	382,899	0.086	385,405	0.083	379,372	0.082	398,215	0.085	393,484	0.081
1994	388,969	0.081	391,230	0.078	382,088	0.077	407,402	0.08	399,183	0.077
1995	388,821	0.073	390,752	0.071	376,714	0.07	413,835	0.074	397,579	0.07
1996	345,532	0.07	347,113	0.068	323,908	0.069	376,731	0.071	353,005	0.067
1997	293,694	0.068	295,099	0.067	273,635	0.068	330,841	0.07	299,826	0.065
1998	247,246	0.069	248,599	0.067	229,602	0.069	269,814	0.07	252,560	0.066
1999	220,957	0.07	222,196	0.068	215,899	0.068	230,759	0.07	225,763	0.067
2000	194,687	0.073	195,821	0.071	185,549	0.071	209,989	0.073	199,068	0.069
2001	175,784	0.073	176,768	0.071	166,102	0.072	197,078	0.074	179,842	0.069
2002	167,020	0.07	167,881	0.068	161,370	0.068	191,560	0.071	170,359	0.067
2003	165,756	0.067	166,546	0.065	155,023	0.066	195,955	0.069	168,727	0.064
2004	166,849	0.067	167,552	0.065	162,136	0.065	186,357	0.066	169,945	0.064
2005	158,075	0.067	158,653	0.066	153,967	0.066	175,612	0.065	160,748	0.064
2006	141,916	0.066	142,365	0.065	141,699	0.065	136,755	0.061	144,081	0.064
2007	124,747	0.067	125,029	0.066	126,129	0.066	119,532	0.063	126,230	0.065
2008	116,691	0.071	116,683	0.069	114,917	0.067	112,403	0.066	117,659	0.068
2009	126,048	0.074	125,263	0.071	122,135	0.069	121,278	0.069	126,597	0.07
2010	164,317	0.072	162,984	0.068	149,085	0.068	158,925	0.066	164,762	0.066
2011	186,628	0.075	182,178	0.069	176,185	0.067	178,513	0.068	184,086	0.068
2012	198,720	0.082	188,101	0.074	182,205	0.072	185,023	0.073	190,017	0.073
2013	205,243	0.089	190,468	0.079	176,541	0.078	188,345	0.078	192,062	0.078
2014	213,549	0.098	192,761	0.084	176,462	0.086	191,957	0.082	193,864	0.084
2015	156,531	0.086	145,963	0.078	131,856	0.08	165,593	0.085	147,059	0.077
2016	125,791	0.079	123,232	0.075	115,357	0.073	147,985	0.083	124,512	0.074
2017	89,922	0.08	94,194	0.08	90,029	0.077	98,459	0.08	95,373	0.079
2018	71,880	0.1	77,567	0.096	72,754	0.095	81,840	0.094	78,264	0.095
2019	69,588	0.101	77,671	0.094	74,533	0.094	78,777	0.091	77,438	0.094
2020	69,263	0.109	82,742	0.097	83,838	0.097	57,944	0.1	81,096	0.097
1978-2020 mean	254,331	0.103	255,872	0.099	253,967	0.098	260,719	0.1	264,144	0.098

Table 2.8.8 Cont. - Spawning biomass (SSB) in tons for models presented with coefficient of variation (CV).

	Model 21.1cd		Model 21.1e		Model 21.1g		Model 21.5a		Model 21.5c	
Year	SSB (t)	CV	SSB (t)	CV	SSB (t)	CV	SSB (t)	CV	SSB (t)	CV
1978	252,650	0.207	240,259	0.212	272,696	0.24	159,924	0.218	193,131	0.258
1979	249,397	0.198	238,047	0.205	265,215	0.234	159,149	0.212	189,158	0.254
1980	254,442	0.189	247,656	0.195	265,775	0.225	165,611	0.204	190,434	0.246
1981	304,840	0.184	307,043	0.19	301,502	0.217	204,890	0.202	216,954	0.238
1982	357,053	0.18	386,189	0.185	359,273	0.213	262,614	0.196	264,576	0.229
1983	373,479	0.174	390,960	0.178	354,935	0.206	269,157	0.19	266,805	0.221
1984	374,939	0.167	410,566	0.171	357,632	0.201	289,105	0.185	276,261	0.214
1985	392,432	0.153	432,416	0.157	360,737	0.186	324,366	0.171	295,569	0.197
1986	434,368	0.135	466,769	0.14	377,566	0.167	363,663	0.151	320,384	0.173
1987	464,061	0.121	486,995	0.126	388,733	0.15	390,650	0.135	338,603	0.153
1988	473,796	0.108	512,399	0.114	406,694	0.137	420,275	0.12	361,031	0.137
1989	494,007	0.096	527,121	0.102	414,118	0.122	439,583	0.106	372,635	0.12
1990	496,327	0.087	501,425	0.092	391,652	0.109	422,272	0.094	355,337	0.106
1991	458,706	0.084	448,277	0.089	347,064	0.107	377,254	0.091	314,875	0.103
1992	426,699	0.083	412,331	0.088	314,412	0.106	343,293	0.089	282,767	0.103
1993	404,222	0.082	400,338	0.087	300,893	0.107	328,001	0.088	266,318	0.104
1994	413,273	0.078	405,879	0.082	307,616	0.1	332,861	0.082	271,672	0.097
1995	418,785	0.071	406,302	0.076	310,736	0.091	332,552	0.075	273,589	0.087
1996	380,882	0.069	357,566	0.075	273,090	0.089	287,602	0.073	236,837	0.084
1997	334,002	0.068	312,180	0.074	239,497	0.089	244,169	0.071	202,634	0.083
1998	272,559	0.068	253,115	0.074	197,549	0.089	204,837	0.072	171,849	0.084
1999	233,359	0.067	227,788	0.072	180,998	0.086	193,687	0.069	164,116	0.082
2000	212,287	0.071	202,479	0.076	160,126	0.091	165,313	0.073	140,580	0.085
2001	199,167	0.072	188,992	0.078	150,122	0.092	147,858	0.074	127,055	0.086
2002	193,090	0.069	187,821	0.074	151,911	0.087	144,519	0.069	126,380	0.08
2003	197,137	0.067	185,962	0.073	149,904	0.084	138,718	0.068	120,905	0.076
2004	187,849	0.064	184,057	0.068	148,854	0.081	145,577	0.066	124,789	0.075
2005	176,854	0.063	173,813	0.067	138,144	0.08	138,088	0.066	115,608	0.076
2006	138,040	0.06	137,703	0.063	110,165	0.074	128,002	0.064	105,080	0.074
2007	120,464	0.061	121,760	0.064	96,026	0.075	114,076	0.064	92,709	0.074
2008	113,153	0.065	111,625	0.066	87,339	0.079	102,979	0.066	83,623	0.077
2009	122,263	0.067	119,405	0.068	93,947	0.083	107,779	0.068	88,541	0.08
2010	160,139	0.064	146,178	0.068	118,836	0.08	129,526	0.066	110,571	0.076
2011	179,657	0.066	173,528	0.067	143,042	0.076	151,603	0.062	131,697	0.07
2012	185,945	0.071	179,629	0.072	146,154	0.08	152,382	0.064	131,625	0.071
2013	188,812	0.076	173,979	0.079	138,857	0.086	142,737	0.068	121,909	0.074
2014	191,787	0.08	174,067	0.086	137,290	0.095	137,492	0.072	116,825	0.079
2015	165,518	0.083	149,549	0.09	119,158	0.102	135,963	0.082	114,577	0.096
2016	148,435	0.081	140,636	0.084	117,154	0.1	125,248	0.077	110,939	0.097
2017	99,600	0.078	96,023	0.08	85,734	0.11	104,598	0.076	96,421	0.105
2018	82,694	0.092	78,415	0.096	69,005	0.139	65,695	0.089	62,398	0.134
2019	79,042	0.089	76,258	0.093	69,397	0.139	49,064	0.094	49,205	0.155
2020	57,957	0.1	57,495	0.102	57,892	0.163	37,099	0.116	39,822	0.197
1978-2020 mean	266,609	0.098	265,837	0.102	220,406	0.123	211,159	0.103	186,902	0.123

Table 2.8.9 – Environmental link parameters, coefficient of variation, gradient by model for all models evaluated.

Environmental link		*Value*	*cv*	*Gradient*	*Model*
Catchability	Q - α	0.941	0.324	1.83E-07	19.1
Catchability	Q - α	0.926	0.340	-6.64E-07	21.1a
Catchability	Q - α	0.802	0.301	1.73E-06	21.1b
Catchability	Q - α	1.064	0.404	1.07E-05	21.1c
Catchability	Q - α	0.992	0.339	-4.74E-08	21.1d
Catchability	Q - α	0.953	0.370	1.61E-05	21.1e
Catchability	Q - α	0.382	0.730	-2.79E-05	21.1g
Catchability	Q - α	0.529	0.285	1.27E-07	21.5a
Catchability	Q - α	0.295	0.714	-2.93E-05	21.5c
Growth	K - φ	-0.159	0.276	-9.84E-06	21.1b
Growth	K - φ	-0.155	0.281	1.45E-05	21.1e
Growth	K - φ	-0.127	0.419	-8.71E-05	21.1g
Growth	K - φ	-0.146	0.292	1.26E-06	21.5a
Growth	K - φ	-0.124	0.428	-2.12E-04	21.5c
Growth	L1 - γ	0.559	0.231	2.68E-05	21.1b
Growth	L1 - γ	0.606	0.217	3.11E-05	21.1e
Growth	L1 - γ	0.714	0.217	-1.09E-04	21.1g
Growth	L1 - γ	0.613	0.211	2.41E-06	21.5a
Growth	L1 - γ	0.728	0.213	-9.99E-05	21.5c
Growth	L2 - υ	0.111	0.248	-1.98E-05	21.1b
Growth	L2 - υ	0.110	0.247	2.43E-05	21.1e
Growth	L2 - υ	0.097	0.352	-1.23E-04	21.1g
Growth	L2 - υ	0.109	0.245	1.98E-06	21.5a
Growth	L2 - υ	0.097	0.351	-4.01E-04	21.5c
Mortality	M - η	1.116	0.099	-4.50E-05	21.1c
Mortality	M - η	1.174	0.099	-6.01E-05	21.1e
Mortality	M - η	0.984	0.160	2.29E-04	21.1g
Mortality	M - η	0.572	0.078	-1.87E-06	21.5a
Mortality	M - η	0.508	0.134	-7.39E-06	21.5c
Recruitment	R0 - ω	-0.011	0.308	1.80E-05	21.1d
Recruitment	R0 - ω	-0.009	0.381	-1.14E-04	21.1e
Recruitment	R0 - ω	-0.010	0.384	-5.69E-03	21.1g
Recruitment	R0 - ω	-0.009	0.393	5.08E-05	21.5a
Recruitment	R0 - ω	-0.010	0.388	7.69E-03	21.5c

Table 2.8.10 – Tuning values for Model 21.1g and Model 21.5c

Component		Tuning	Model 21.1g	Model 21.5c
Index	Beach siene survey	add_to_survey_CV	0.100	0.100
	Bottom trawl survey	add_to_survey_CV	0.162	0.162
	Longline survey	add_to_survey_CV	0.171	0.171
Length	Trawl fishery	mult_by_lencomp_N	0.256	0.257
	Longline fishery	mult_by_lencomp_N	0.417	0.423
	Pot fishery	mult_by_lencomp_N	0.156	0.152
	Bottom trawl survey	mult_by_lencomp_N	0.432	0.420
	Longline survey	mult_by_lencomp_N	0.403	0.412
Age	Trawl fishery	mult_by_agecomp_N	0.511	0.532
	Longline fishery	mult_by_agecomp_N	0.572	0.577
	Pot Fishery	mult_by_agecomp_N	0.346	0.358
	Bottom trawl survey	mult_by_agecomp_N	0.196	0.192

Figures

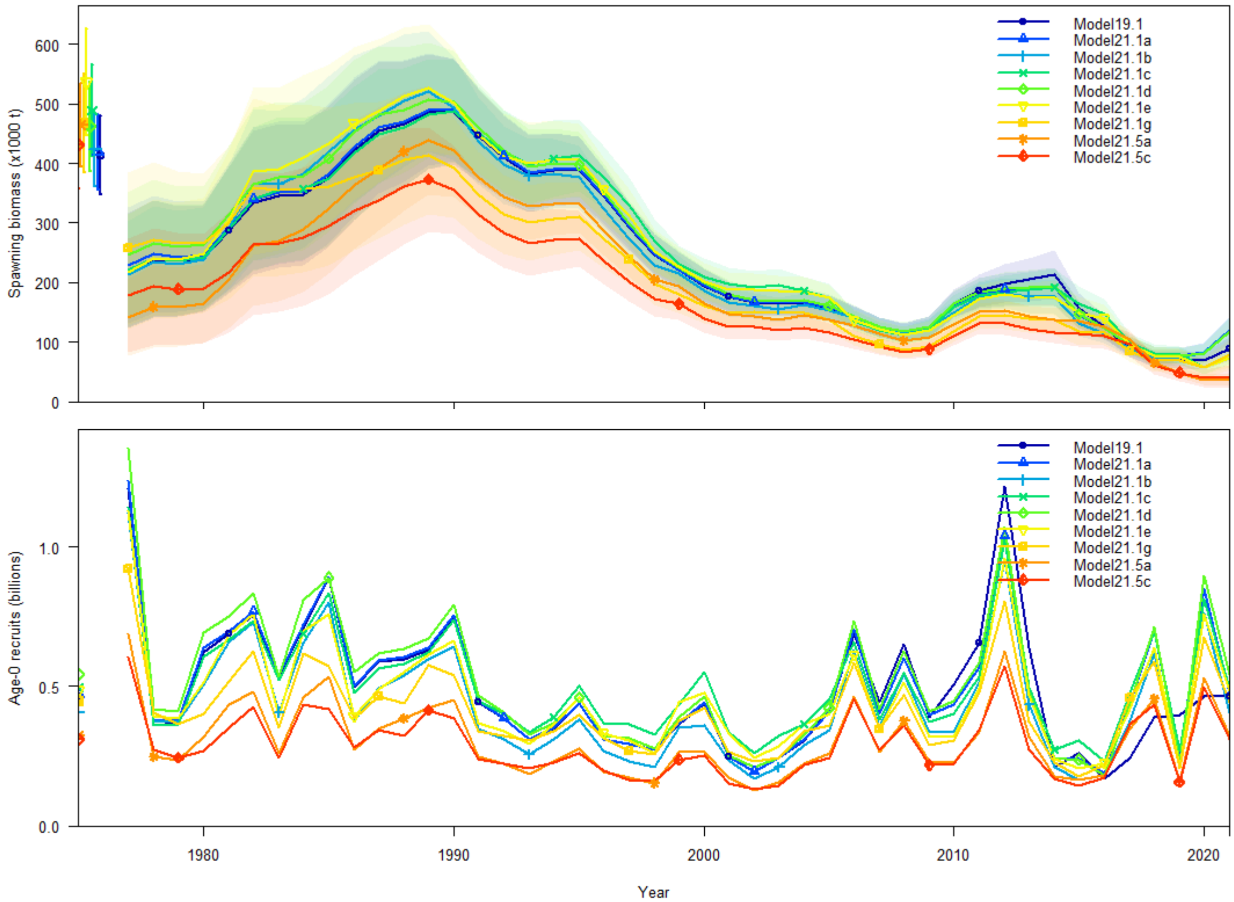

Figure 2.8.1 – (Top) spawning biomass (1000 t), and (Bottom) number of age-0 recruits (billions) for assessed models.

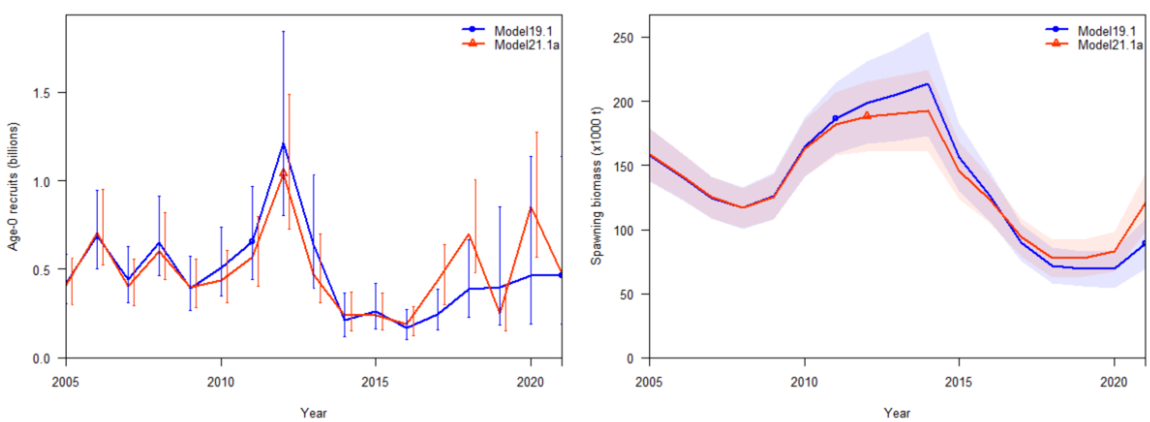

Figure 2.8.2 - (Left) estimate of the number of age-0 recruits for 2006-2021 and (Right) estimate of the 2006-2020 spawning biomass for the base model 19.1 and Model 21.1a with the inclusion of the age-0 beach seine index.

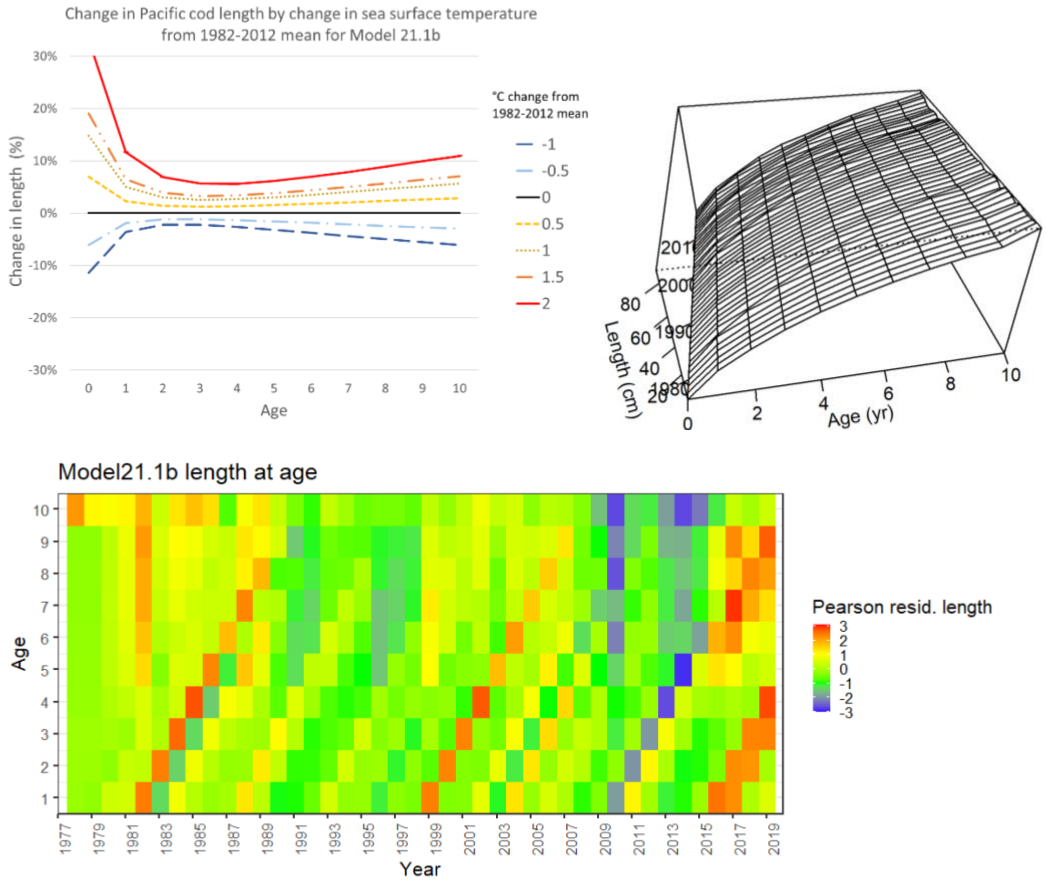

Figure 2.8.3 – For Model 21.1b (Top left) percent change in length from mean temperature by age, (Top right) Length at age over time for 1978-2020, and (bottom) Pearson residuals for length (cm) at age showing temperature effect on growth with larger Pacific cod originating in the warm years.

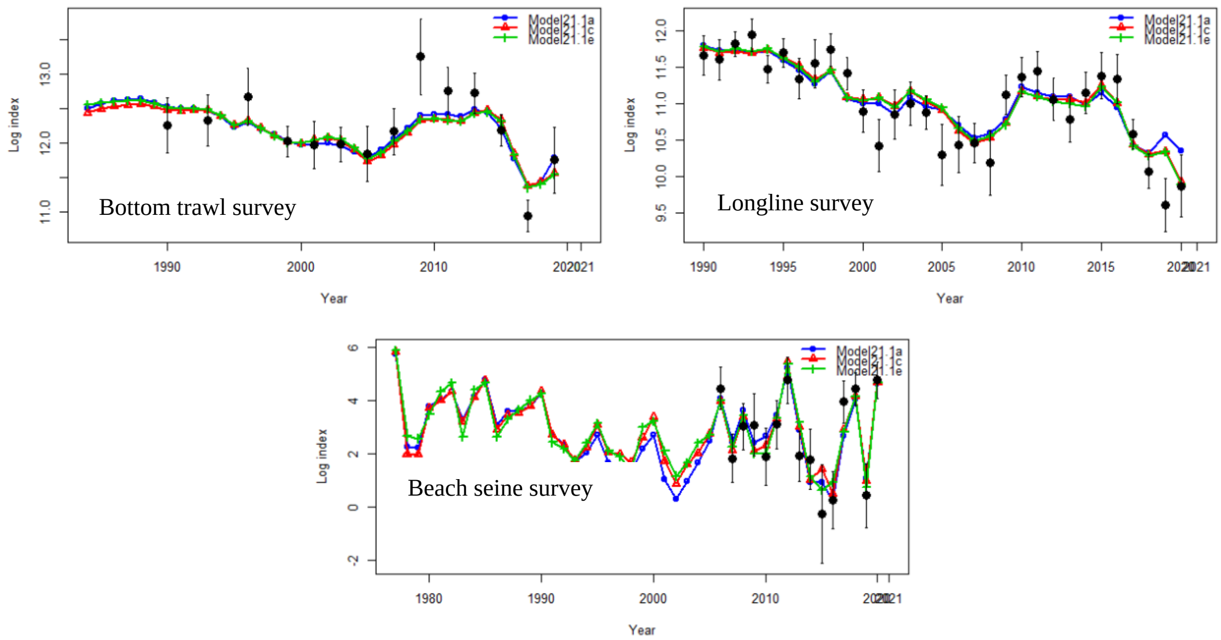

Figure 2.8.4 – Model fits to survey data for (Top left) Bottom trawl survey in tons, (Top left) Longline survey in relative population numbers, and Beach seine age-0 survey in fish per set for Model 21.1a (blue), Model 21.1c (red), and Model 21.1e (green).

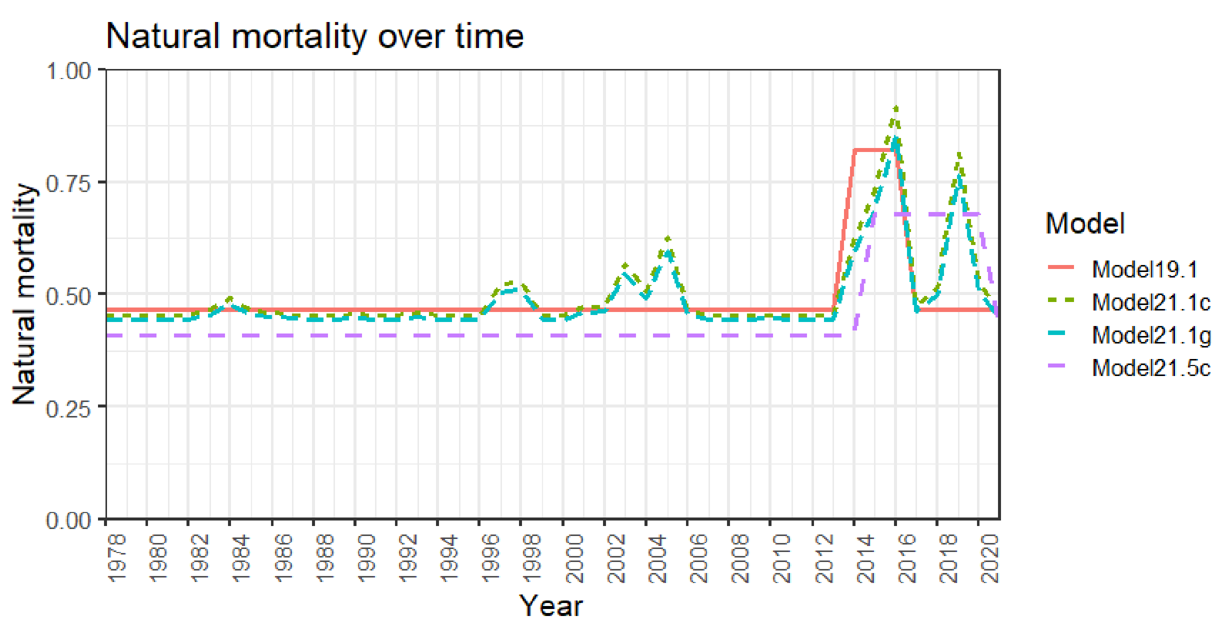

Figure 2.8.5 – Natural mortality over time for Models 19.1, 21.1c, 21.1g, and 21.5c.

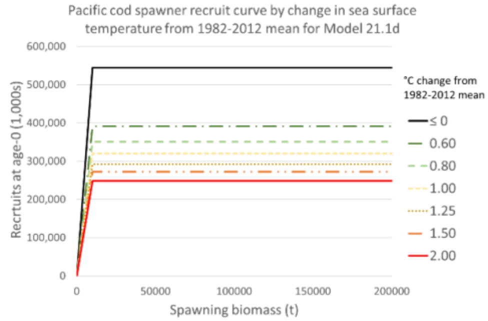

Figure 2.8.6 - Model 21.1d spawner-recruit relationship showing change over mean temperature driven by linking R_0 to the spawning heatwave index. We should note here that as GOA Pacific cod remain a tier 3 stock assessment, steepness was fixed at 1.0.

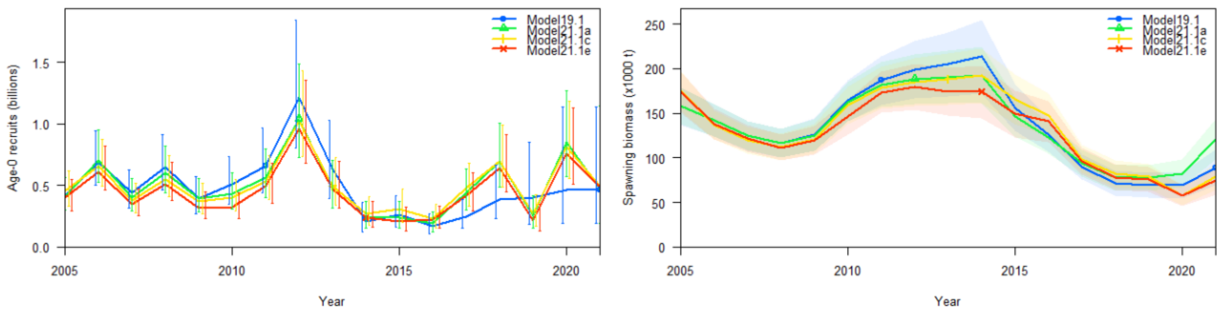

Figure 2.8.7 – (Left) Age-0 recruits and (Right) spawning biomass for 2005-2006 for Model 19.1, Model 21.1a, Model 21.1c, and Model 21.1e.

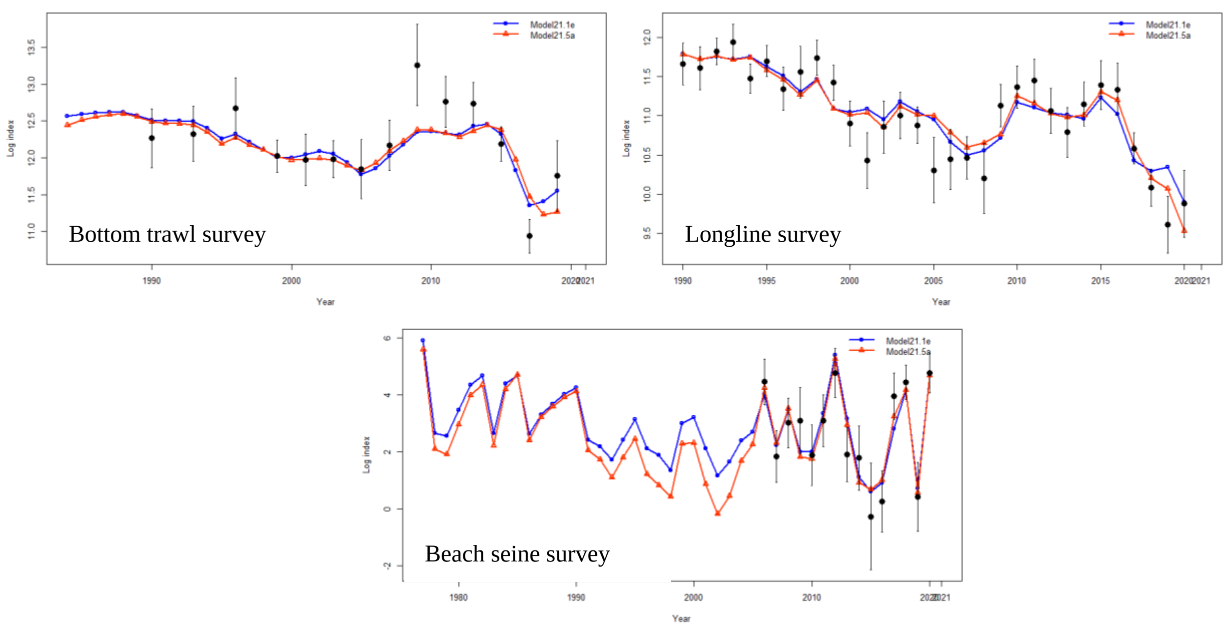

Figure 2.8.8 – Model fits to survey data for (Top left) Bottom trawl survey in tons, (Top left) Longline survey in relative population numbers, and Beach seine age-0 survey in fish per set for Model 21.1e (blue) and Model 21.5a (red).

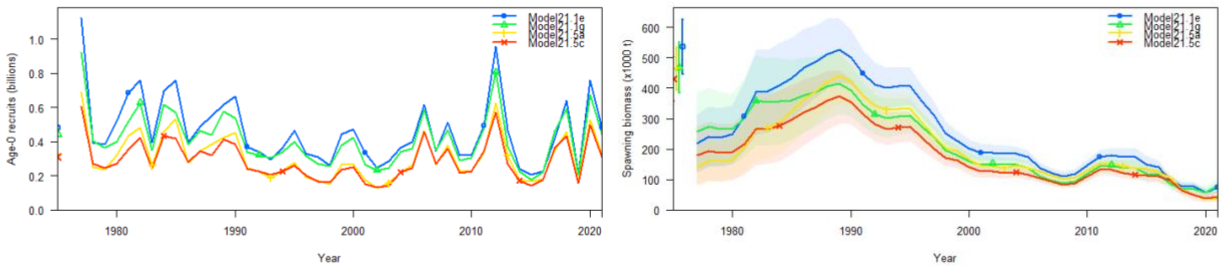

Figure 2.8.9 – (Left) Estimate of the number of age-0 recruits and (Right) estimate of the spawning biomass for 1978-2021for Model 21.1e, 21.1g. 21.5a, and 21.5c.

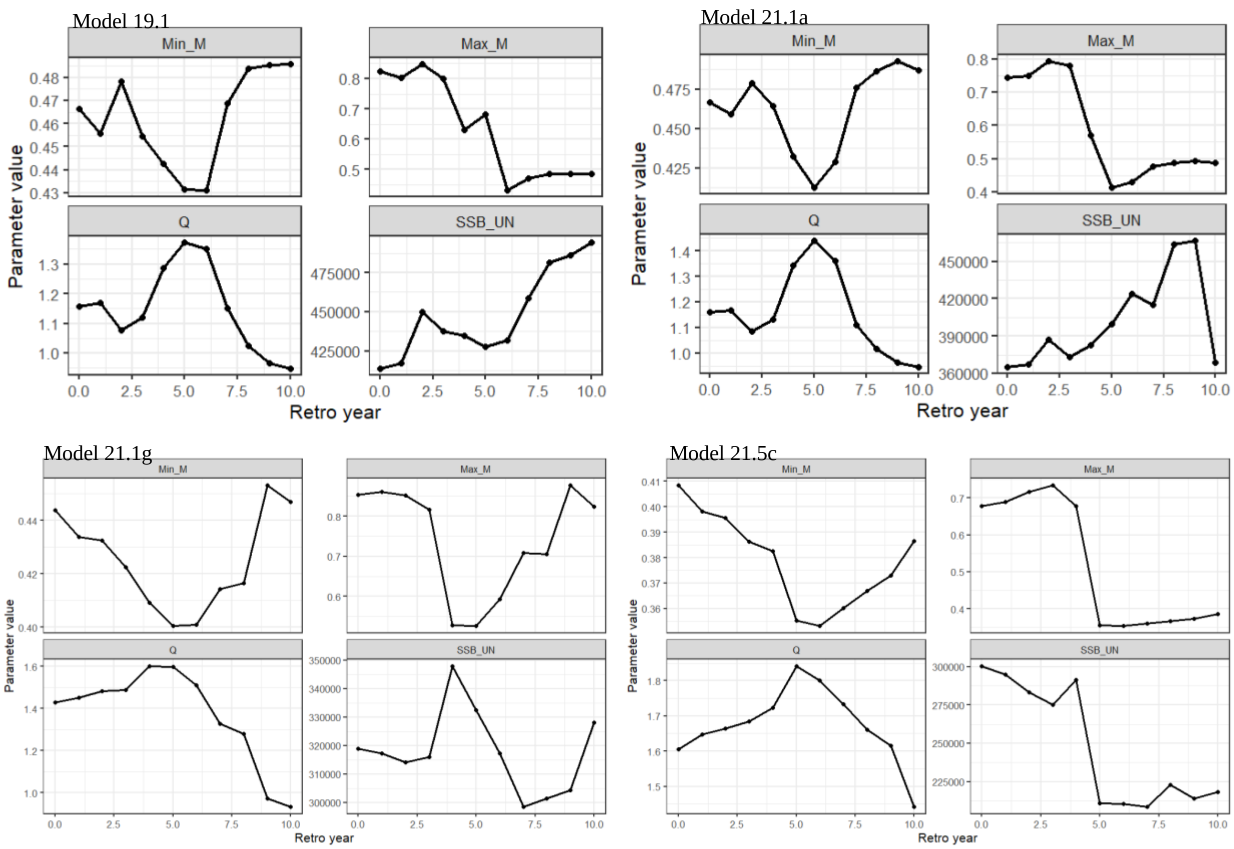

Figure 2.8.10 – Parameter values from retrospective analyses (Min_M=minumum natural mortality, Max_M=maximum natural mortality, Q = catchability, and SSB = unfished spawning biomass) for 10-year peals.

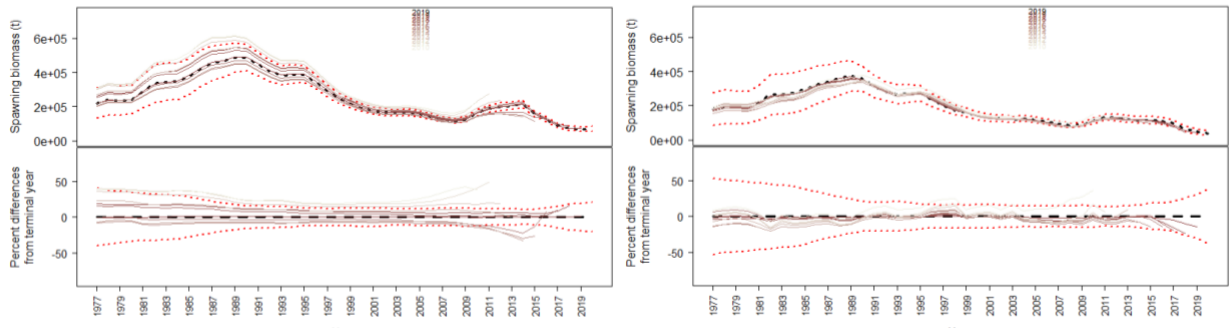

Figure 2.8.11 – Spawning stock biomass estimates from retrospective analyses for 10-year peals showing (top) spawning biomass and (bottom) percent different from terminal year for (left) Model 19.1 and (right) Model 21.5c.