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 2021 were updated and preliminary federal and state catch data for 2022 were included;
2. Commercial federal and state fishery size composition data for 2021 were updated, and preliminary commercial federal and state fishery size composition data for 2022 were included;
3. AFSC longline survey Pacific cod abundance index and length composition data for the GOA for 2022 were included;

### 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 were no model changes made in this year’s assessment.

## Summary of Results

Write summary with following

Text table showing *M*; recommended Tier; projected total biomass (give age range); female spawning biomass; equilibrium female spawning biomass values for *B0* and *BMSY* (Tier 1 only) or *B100%*, *B40%*, and *B35%* (Tier 3 only); *FOFL*; the maximum allowable value for *FABC*; the recommended value for *FABC*; OFL; the maximum allowable ABC, and the recommended ABC. State whether the stock or complex is being subjected to overfishing, is currently overfished, or is approaching a condition of being overfished. Compare all of the above to the corresponding values from last year’s final assessment (or final specifications, if different from the assessment values). Tier-specific templates for this table are shown on the following pages (**notes: 1) the rows labeled “Female spawning biomass (t)” and “Projected” for Tiers 1 and 3 and the row labeled “Biomass (t)” for Tier 5 are headers, so please do not put anything in those rows; 2) the “x” in “age x+” should be replaced with the appropriate value for stocks in Tiers 1 or 3; and 3) cells with “current year…” should be replaced with the appropriate number, where “current year” means *this year***). A brief discussion of substantial changes in results from last year may be included if it helps explain the summary table.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Quantity** | As estimated or *specified last* year for: | | As estimated or *specified this* year for: | |
| 2021 | 2022 | 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 | 118,118 | 143,384 |
| Female spawning biomass (t) |  |  |  |  |
| Projected | 39,977 | 50,813 | 39,873 | 35,050 |
|  |  |  |  |  |
| *B100%* | 180,111 | 180,111 | 162,426 | 162,426 |
| *B40%* | 72,045 | 72,045 | 64,970 | 64,970 |
| *B35%* | 63,039 | 63,039 | 56,849 | 56,849 |
| *FOFL* | 0.41 | 0.54 | 0.54 | 0.52 |
| *maxFABC* | 0.33 | 0.43 | 0.44 | 0.42 |
| *FABC* | 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** | As determined *last* year for: | | As determined *this* year for: | |
| 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, 23,627t . For 2023 projections the 2022 catch was assumed to be at the projected ABC.*

## Area apportionment

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

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Western | Central | Eastern | Total |
| Random effects area apportionment | 30.3% | 60.2% | 9.5% | 100% |
| 2023 ABC |  |  |  |  |
| 2024 ABC |  |  |  |  |

## Summaries for Plan Team

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Species** | **Year** | **Biomass1** | **OFL** | **ABC** | **TAC** | **Catch2** |
| Pacific ocean perch | 2020 | 544,569 | 37,092 | 31,238 | 31,238 | 25,191 |
| 2021 | 613,522 | 42,977 | 36,177 | 36,177 | 25,149 |
| 2022 | 650,832 | 45,580 | 38,268 |  |  |
| 2023 | 634,907 | 44,196 | 37,104 |  |  |

1Total biomass from the age-structured model

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Stock** |  | **2021** | | | | **2022** | | **2023** | |
| **Area** | **OFL** | **ABC** | **TAC** | **Catch2** | **OFL** | **ABC** | **OFL** | **ABC** |
| Pacific ocean perch | W |  | 1,643 | 1,643 | 1,515 |  | 2,602 |  | 2,523 |
| C |  | 27,429 | 27,429 | 21,972 |  | 30,806 |  | 29,869 |
| WYAK |  | 1,705 | 1,705 | 1,662 |  | 1,409 |  | 1,366 |
| SEO | 6,414 | 5,400 | 5,400 | 0 | 4,110 | 3,451 | 3,985 | 3,346 |
| W/C/WYK | 36,563 |  |  |  | 41,470 |  | 40,211 |  |
| Total | 42,977 | 36,177 | 36,177 | 25,149 | 45,580 | 38,268 | 44,196 | 37,104 |

2Current as of September 25, 2021, Source: NMFS Alaska Regional Office via the Alaska Fisheries Information Network (AKFIN).

## Responses to SSC and Plan Team Comments on Assessments in General

Responses to SSC and Plan Team comments on assessments in general (for each comment that is addressed in the main text, list comment, and reference the section where it is discussed). **If the SSC or Plan Team did not make any comments on assessments in general, say so.**

## Responses to SSC and Plan Team Comments Specific to this Assessment

Responses to SSC and Plan Team comments specific to this assessment (for each comment that is addressed in the main text, list comment and reference the section where it is discussed). **If the SSC or Plan Team did not make any comments specific to this assessment, say so**.

# Introduction

Pacific cod (*Gadus macrocephalus*) is a transoceanic species, occurring at depths from shoreline to 500 m. The southern limit of the species’ distribution is about 34° N latitude, with a northern limit of about 63° N latitude. Pacific cod is distributed widely over Gulf of Alaska (GOA), as well as the eastern Bering Sea (EBS) and the Aleutian Islands (AI) area. The Aleut word for Pacific cod, *atxidax*, literally translates to “the fish that stops” (Betts *et al.* 2011). Recoveries from archeological middens on Sanak Island in the Western GOA show a long history (at least 6,000 years) of exploitation. Over this period, the archeological record reveals fluctuations in Pacific cod size distribution which Betts et al. (2011) tie to changes in abundance due to climate variability (Fig. 2.1). Over this long period colder climate conditions appear to have consistently led to higher abundance with more small/young cod in the population and warmer conditions to lower abundance with fewer small/young cod in the population. Recent comparisons of Pacific cod length distributions extrapolated from bones retrieved from middens and those from the modern domestic fishery show a cline in size from larger fish in the west to smaller fish in the southeastern GOA that has been consistent for over 6,000 years (West *et al.* 2020).

Tagging studies (e.g., Shimada and Kimura 1994) have demonstrated significant migration both within and between the eastern Bering Sea (EBS), Aleutian Islands (AI), and Gulf of Alaska (GOA) outside of their winter (January – April) spawning season. In March 2021 and 2022, a cooperative tagging study between the Alaska Fisheries Science Center (AFSC) and the Aleutian East Borough (AEB) was initiated to examine the seasonal movements of Pacific cod captured in the western GOA during the winter spawning season. The goal of this study was to better understand the seasonal connectivity between winter spawning locations of Pacific cod in the western GOA and foraging locations in GOA and EBS during the summer months when both Alaska Fisheries Science Center's bottom-trawl surveys are conducted. In March 2021, Pacific cod were tagged and released with 25 pop-up satellite tags and 957 conventional within 8 subareas of the western GOA near Shumagin and Sanak Islands in 2021 (Fig. 2.2). In April 2022, Pacific cod with 27 pop-up satellite tags were released along with 760 conventional tags in several of the same subareas as in 2021. Pop-up satellite tags will release and transmit data to satellites at predetermined lengths of time (e.g. 180 days), whereas conventional tags require a platform of recovery such as a fishery. In 2021, pop-up locations of satellite tagged Pacific cod within 3 months of release were largely located within the vicinity of the release areas (March-May). However, more than half the fish with tags recovered between June through October (10 of 17 satellite-tagged fish with summer recovery locations) had moved substantial distances into the EBS, AI, northern Bering Sea (NBS), Russia, and the Chukchi Sea. These results contrasted with Pacific cod movement in 2022, where from June through October only 3 out of 23 satellite-tagged fish with summer recovery locations moved into the EBS (n=2) and NBS (n=1) and most fish stayed close to their original spawning areas. These movement patterns suggest seasonal connectivity between the western GOA and other management regions, such as the EBS, but with an unknown amount of interannual variability in these movement patterns. The research has also provided insights into resident vs. migratory fish. Some tagged fish are still at large with winter 2023 pop-up dates. Work is in progress to reconstruct movement paths of individual fish with a geolocation model which will provide valuable information on migration timing and pathways. Additional satellite and conventional tag releases are planned for March 2023.

Two genetics studies using Restriction-site Associated DNA sequencing have indicated significant genetic differentiation among spawning stocks of Pacific cod in the GOA and the EBS (Drinan *et al.* 2018; Spies *et al.* 2019). The most recent genomic analysis of Pacific cod includes a new publication that used pooled whole genome sequencing (Pool-Seq; Spies et al. 2022), as well as a new study conducted during 2021 and 2022 that used low coverage whole genome sequencing (lcWGS). Low-coverage whole-genome sequencing analysis of 429 samples of Pacific cod from known spawning regions during spawning season indicated population structure similar to what was previously known, but with finer resolution and greater power owing to the larger number of markers. Using 1,922,927 polymorphic SNPs (Fig. 2.3), the pattern of population structure mostly resembles isolation-by-distance, in which samples from proximate spawning areas are more genetically similar than samples from more distant areas. Isolation-by-distance was observed from western Gulf of Alaska (Kodiak and the Shumagin Islands) through Unimak Pass and the eastern Aleutian Islands. Previous studies have reported an isolation-by-distance pattern in Pacific cod using microsatellite markers (Cunningham et al. 2009 and Spies 2012) and reduced-representation sequencing (Drinan et al. 2018). Within the isolation-by-distance pattern, there were some distinct breaks in the population structure. The most significant genetic break occurs between western and eastern Gulf of Alaska (GOA) spawning samples (Fig. 2.3), and was supported by previous research that highlighted the zona pellucida gene region (Spies et al. 2021).

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

A detailed account of Pacific cod life history, environmental drivers, economic and social indicators can be found in the GOA Pacific cod ecosystem and social processes (ESP) in the 2021 assessment (Barbeaux *et al.* 2021).

# Fishery

## Fishery history and management measures

During the two decades prior to passage of the Magnuson Fishery Conservation and Management Act (MFCMA) in 1976, the fishery for Pacific cod in the GOA was small, averaging around 3,000 t per year. Most of the catch during this period was taken by the foreign fleet, whose catches of Pacific cod were usually incidental to directed fisheries for other species. By 1976, catches had increased to 6,800 t. Catches of Pacific cod since 1991 by gear type and jurisdiction are shown in Table 2.1; catches prior to that are listed in Thompson *et al.* (2011). Presently, the Pacific cod stock is exploited by a multiple-gear fishery, including trawl, longline, pot, and jig components. Trawl gear took the largest share of the catch in every year but one from 1991-2002, although pot gear has taken the largest single-gear share of the catch in each year since 2003. Figure 2.4 shows landings by gear since 1977.

The history of acceptable biological catch (ABC) and total allowable catch (TAC) levels is summarized and compared with the time series of aggregate commercial catches in Table 2.2. Changes in ABC over time are typically attributable to three factors: 1) changes in resource abundance, 2) changes in management strategy, and 3) changes in the stock assessment model. Assessments conducted prior to 1988 were based on survey biomass alone. From 1988-1993, the assessment was based on stock reduction analysis (Kimura *et al.* 1984). From 1994-2004, the assessment was conducted using the Stock Synthesis 1 modeling software (Methot 1986, 1990) with length-based data. The assessment was migrated to Stock Synthesis 2 (SS2) in 2005 (Methot 2005), at which time age-based data began to enter the assessment. Several changes have been made to the model within the SS2 framework (renamed “Stock Synthesis” or “SS3”, in 2008) each year since then.

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

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

Historically, the majority of the GOA catch has come from the Central regulatory area. To some extent the distribution of effort within the GOA is driven by regulation, as catch limits within this region have been apportioned by area throughout the history of management under the MFCMA. Changes in area-specific allocation between years have usually been traceable to changes in biomass distributions estimated by Alaska Fisheries Science Center (AFSC) trawl surveys or management responses to local concerns. Currently the area-specific ABC allocation is derived from the random effects model. The complete history of allocation (in percentage terms) by regulatory area within the GOA is shown in Table 2.3. Table 2.1 and Table 2.2 include discarded Pacific cod, estimated retained and discarded amounts are shown in Table 2.4.

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

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

“Amendment 83 allocates the Pacific cod TAC in the Western and Central regulatory areas of the GOA among various gear and operational sectors, and eliminates inshore and offshore allocations in these two regulatory areas. These allocations apply to both annual and seasonal limits of Pacific cod for the applicable sectors. These apportionments are discussed in detail in a subsequent section of this rule. Amendment 83 is intended to reduce competition among sectors and to support stability in the Pacific cod fishery. The final rule implementing Amendment 83 limits access to the Federal Pacific cod TAC fisheries prosecuted in State of Alaska (State) waters adjacent to the Western and Central regulatory areas in the GOA, otherwise known as parallel fisheries. Amendment 83 does not change the existing annual Pacific cod TAC allocation between the inshore and offshore processing components in the Eastern regulatory area of the GOA.

“In the Central GOA, NMFS must allocate the Pacific cod TAC between vessels using jig gear, catcher vessels (CVs) less than 50 feet (15.24 meters) length overall using hook-and-line gear, CVs equal to or greater than 50 feet (15.24 meters) length overall using hook-and-line gear, catcher/processors (C/Ps) using hook-and-line gear, CVs using trawl gear, C/Ps using trawl gear, and vessels using pot gear. In the Western GOA, NMFS must allocate the Pacific cod TAC between vessels using jig gear, CVs using hook-and-line gear, C/Ps using hook-and-line gear, CVs using trawl gear, and vessels using pot gear. Table 3 lists the proposed amounts of these seasonal allowances. For the Pacific cod sector splits and associated management measures to become effective in the GOA at the beginning of the 2012 fishing year, NMFS published a final rule (76 FR 74670, December 1, 2011) and will revise the final 2012 harvest specifications (76 FR 11111, March 1, 2011).”

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

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

## Recent fishery performance

Data for managing the Gulf of Alaska groundfish fisheries are collected in multiple ways. The primary source of catch composition data in the federally managed fisheries for Pacific cod are collected by on-board observers (Faunce *et al.* 2017). The Alaska Department of Fish and Game (ADFG) sample individual deliveries for state managed fisheries (Nichols *et al.* 2015). Overall catch delivered is reported through a (historically) paper and electronic catch reporting system. Total catch is estimated through a blend of catch reporting, observer, and electronic monitoring data (Cahalan *et al.* 2014).

The distribution of directed cod fishing is distinct to gear type, Figure 2.5 shows the historical distribution of catch from 1990-2015 for the three major gear types. Figure 2.6 shows the distribution of observed catch for the most recent full year of catch data (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 2.1 and Fig. 2.4). The portion of catch caught by the pot sector steeply increased in 2003 with incoming Steller sea lion regulations and halibut bycatch limiting trawl and for 2003 through 2021 the pot sector caught on average 58% of the total catch of Pacific cod in the Gulf of Alaska annually.

In 2015 combined state and federal catch was 79,489t (23% below the ABC) while in 2016 combined catch was 64,087 t (35% below the ABC) and in 2017 catch was 48,734 t (45% below the ABC) (Table 2.1). The ABC was substantially reduced for 2018 to 18,000 t from 88,342 t in 2017, an 81% reduction. This was a 65% reduction from the realized 2017 catch. In 2018 the total catch was 15,247 t. For 2019 the ABC was set below the maximum ABC at 17,000 t and combined fishery caught 15,411 t which was 91% of the ABC.

In 2020 the spawning stock biomass was projected to have dropped below 20% of the unfished spawning biomass (*B20%*) and the federal Pacific cod fishery in the GOA was closed by regulation to directed Pacific cod fishing. *B20%* 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 2.1), the state having taken 2,318 t (91% of the GHL) and federal fisheries haven taken 3,916 t (61% of the federal TAC). The catch in the federal fisheries were split primarily between the arrowtooth flounder (1,237 t), walleye pollock (1,040 t), and shallow water flatfish fisheries (938 t).

In 2021 the stock was projected to be above *B20%*and the federal fishery was once again allowed to open. In 2022 the federal TAC was set at 24,111 t and state GHL set at 8,700 t (Table 2.2). As of October 25, 2022 a total of 23,211 t (71% of the ABC) have been harvested (Table 2.1). State fisheries have harvested 6,998 t (80% of the GHL) and federal fisheries 16,219 t (67% of the TAC). In 2022 42% of the Pacific cod catch was by trawl, 29% by pot gear, and 28% by longline, while jig and other gear harvested less than 1% (Table 2.1).

The largest component of incidental catch of other targeted groundfish species in the GOA Pacific cod fisheries by weight are skate species in combination followed by walleye pollock, arrowtooth flounder, and octopus (Table 2.5). Spiny dogfish, sablefish, and sculpin species also make up a major component of the bycatch in these fisheries. Incidental catch of non-target species in the GOA Pacific cod fishery are listed in Table 2.6.

### Longline

For 1990-2015 the longline fishery had been dispersed across the Central and Western GOA, and while the majority of longline catch was taken to the west of Kodiak, there was some longline fishing occurring in Barnabus trough and a small concentration of sets along the Seward Peninsula (Fig. 2.5). The 2017 longline fishery was predominantly conducted on the border of the Central and Western GOA management areas, in deeper waters south of the Shumagin Islands, and South of Unimak Island to the western edge of the Western GOA management area shelf. In 2018 and 2019, with the drastic cut in TAC, the fishery showed very little effort and the majority of catch was south of the Shumagin Islands straddling the Central and Western GOA management area edges. In 2020 there was no directed Pacific cod longline fishery in federal waters. In 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. 2.6). The mean size of Pacific cod caught in the longline fishery is 64 cm (annual mean varies from 58cm to 70cm, Fig. 2.7). There was a drop in the mean length of fish in the longline fishery between 1990 and 2010, however this trend has been more variable over the last 10 years. In 2018 and 2019 fewer boats participated in the fishery (Fig. 2.8) and catch was substantially slower and lower than previous years (Fig. 2.9 and Fig. 2.10), this trend continued in 2020 when the federal fishery was closed. There was an increase in vessels participating in the Pacific cod longline fishery in the Central GOA from 3 in 2020 to 37 in 2021 and 31 in 2022. There were only 3 longline vessels fishing Pacific cod in the Western GOA in 2022, up from 1 in 2021 and none in 2020.

In both the Central and Western GOA catch in 2022 was similar to 2021 and was earlier than in 2018 or 2019, but like those years the A-season was completed by week 10 (Fig. 2.9 and Fig. 2.10).

Although CPUE figures were produced for the longline fisheries in the GOA in previous assessments (Barbeaux *et al.* 2021), 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, thus, we do not present CPUE in this assessment but will continue to monitor developments in estimating CPUE.

### Pot

The pot fishery is a relatively recent development (Table 2.1) and predominately pursued using smaller catcher vessels. In the 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. 2.5). 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. In 2021 the majority of catch from the pot fishery was centered around Kodiak, in 2022 blah blah (Fig. 2.6). The pot fishery in the Central GOA moved to deeper water in 2017 through 2019 than previous years, and this trend continues (add figure of catch-weighted mean depth). Like the longline fishery CPUE figures were produced for the pot fisheries in the GOA in previous assessments (Barbeaux *et al.* 2021) 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. 2.11), but like the longline fishery there was a declining trend in Pacific cod mean length in the fishery from 1998 through 2016 with the smallest fish at less than 60cm on average caught during the 2016 fishery. The 2017 through 2021 fishery data show a sharp increase in mean length, and in 2022 the mean length was significantly larger than any other mean length in the pot fishery time series. This is potentially due to a combination of the fishery moving to deeper water (Fig. 2.12) and lower recruitment since 2014, however, it could also be driven by lack of length frequency sampling in the pot fishery, particularly in the Western GOA (Fig. 2.13).

In the Western GOA, approximately half the catch of the pot fishery was caught in a single week in March (Fig. 2.9). In the Central GOA the pot fishery increased in the spring at a higher rate than that since 2018 (Fig 2.10). In 2020 pot fishing was greatly reduced with 15 vessels in the Central GOA and 19 in the Western GOA compared to 27 and 33 the year previously (Fig. 2.8). In 2022 the number of participating vessels increased again to pre-closure levels with 31 vessels in the Central GOA and 41 in the Western GOA. In 2020 there was no observer coverage and since 2021 there has been little observer coverage of the pot fishery in the Western GOA (Fig. 2.12) despite substantial participation and catch. There was, however, biological data collected from the Western GOA region by the ADF&G port samplers which were incorporated into the stock assessment as a supplement to the observer data.

### Trawl

The Gulf of Alaska Pacific cod trawl fishery rapidly developed starting in 1987, surpassing the catch from the foreign longline fishery pursued in the 1970’s to mid-1980s in 1987. The trawl fishery dominated the catch into the early-2000s, but was then replaced by increases in pot fishing in the mid-2000’s. This transition to pot fishing was partially due to Steller sea lion regulations, halibut bycatch caps, and development of an 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. 2.5) with the highest concentration of catch coming from southeast of Kodiak Island in the Central GOA and around the Shumigan Islands in the Western GOA. In 2016 trawl fishing in the Western GOA shifted away from the Shumigan Islands further to the west around Sanak Island and near the Alaska Peninsula, this shift continued through 2017. Trawl fishing in 2018 for the A-season had a similar pattern as 2017 with large catches from around Sanak Island, but some increased effort on Portlock Bank to the southeast of Kodiak. There was substantially less catch and observed effort in 2018 and 2019 than previous years. Although the 2020 directed federal Pacific cod fishery was closed there was observations of Pacific cod catch in other fisheries, these observations primarily surrounded Kodiak from the pollock and shallow water flatfish fisheries. In 2021, with the reopening of the directed Federal Pacific cod fishery, there were observed catches in the Western GOA and in 2022 (Fig. 2.6). Trawl catch in the Western and Central GOA in 2022 have exceeded catches since 2018 (Fig 2.9 and Fig. 2.10). Due to bycatch in other fisheries trawl catch of Pacific cod in 2020 remained above 3,000 t despite the closure of the federal directed fishery.

The trawl fishery generally catches smaller fish than the other two gear types with fish as small as 10 cm appearing in the observed length composition samples (Fig. 2.14). The average size of Pacific cod caught by trawl in the 1980’s was on average smaller and more variable than those caught later. The trawl fishery showed an increase in average size in the 1990s with the maturation of the domestic fishery. The decline in the mean length from the mid-1990s until 2015 mimics that observed in the longline and pot fisheries with some prominent outliers (2005-2006). The years 2005 and 2006 shows little observed fishing in the B-season when smaller fish are more often encountered with this gear type. The mean size shows a sharp increase in 2016 through 2022 (with the exception of 2020, which was when the directed fishery was closed) which is similar to the mean length trend in the logline and pot fisheries. The change to deeper depth and a larger proportion of the catch coming from the Western GOA might partially explain this recent increase (Fig. 2.12 and Fig. 2.13) as well as lower recruitment in recent years leading to a larger overall population on average as older fish make up higher percentage of the population age structure.

The 2018-2019, directed A-season trawl fishery in the Central GOA started much later than previous years, catch rates were lower and the fishery did not take the full TAC (Fig. 2.10). Since 2018, despite there being 14 to 26 vessels participating in the Western GOA trawl fishery, there was no observed effort from 2018 – 2020 and little observed effort compared to other fisheries (Fig. 2.12). There were no vessels participating in the directed Pacific cod fishery in the Central GOA for 2018-2020 and only 2 vessels in 2021 and 6 in 2022 (Fig. 2.8).

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

There is a small jig fishery for Pacific cod in the GOA, 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 2.1; Fig. 2.9 and Fig. 2.10). In 2017 there were 35 jig vessels participating in the GOA Pacific cod fishery, 27 in 2018, 61 vessels in 2019, 41 vessels in 2020, a sharp increase in 2021 to 65 vessels, and a decrease to 46 vessels in 2022 (Fig. 2.8). Catch of jig vessels has increased since 2017, with the majority of catch coming from the Central GOA since 2020.

Pacific cod is also caught as bycatch in other commercial fisheries. Although historically the shallow water flatfish fishery caught the most Pacific cod, since 2018, the greatest sources of Pacific cod bycatch have been the bottom pollock, arrowtooth, halibut, and rockfish fisheries (Table 2.7).

Non-commercial catch of Pacific cod in the Gulf of Alaska is considered to be relatively small at less than 400 t; data are available through 2021 (Table 2.8). The largest component of this catch comes from the recreational fishery, generally taking approximately one-third to one-half of the accounted for non-commercial catch and the IPHC Annual Longline survey also 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 1999-2022. There is some variability in the length to weight relationships between Pacific cod captured in the Central and Western GOA fisheries and among gear types. However, there is a consistent trend in both areas for Pacific cod captured using longline and pot gear in there being lower condition during 2015-2016 (Fig. 2.15 and Fig. 2.16). In 2018 and 2019, where data are available the condition of fish in both the Central and Western GOA are mixed with differences in condition by gear and season. The Central GOA longline fishery shows improving condition in January through March in 2018 through 2021, but then a decrease in condition in 2022. The Central GOA pot fishery shows improvement in 2018 as well, but there were no data available since 2019. In the Western GOA, longline fishery cod condition in 2019 returned to average, increased in 2021, and was again average in 2022. The Western GOA pot fishery shows improved cod condition in 2017 and 2018 following the heatwave, drops to below average in 2019, and above average in 2022. There were no data for 2019-2021 to evaluate condition in the Western GOA pot fishery.

Indices of fishery catch per unit effort (CPUE) can be informative to the health of a stock, however CPUE in directed fisheries can be hyper-stable with CPUE remaining high even at low abundance (Walters 2003). This phenomenon is believed to have contributed to the decline of the Northern Atlantic cod (*Gadus morhua*) on the eastern coast of Canada (Rose and Kulka 1999). Instead 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. 2.17). There were no haul data available from the pollock fishery in the Western GOA since 2020 due to electronic monitoring and COVID-19 restriction on observer deployment. In the shallow water flatfish fishery, catch rates in tons of Pacific cod per ton of all species catch were examined (Fig. 2.18). For the pollock fishery in areas 620 and 630 of the Central GOA the 2021 value was the low in 620, but increased in 630. The catch of Pacific cod in the shallow water flatfish fisheries was the lowest in 2017 with a generally increasing trend since. It should be noted that none of these indices are controlled for gear, vessel, effort, or fishing practice changes.

# Data

This section describes data used in the current assessment. It does not attempt to summarize all available data pertaining to Pacific cod in the GOA. All data used for model 19.1a presented are provided in Stock Synthesis data files in Appendix 2.2.

The following table and Figure 2.19 presents the data included in this assessment (the years shown in bold font are those that are new to this assessment).

|  |  |  |  |
| --- | --- | --- | --- |
| **Data** | **Source** | **Type** | **Years** |
| Federal and state fishery catch, by gear type | AKFIN | metric tons | 1977 – **2022** |
| Federal and state fishery catch-at-length, by gear type | AKFIN / FMA / ADF&G | number, by cm bin | 1977 – **2022** |
| GOA NMFS bottom trawl survey biomass | AFSC | metric tons | 1990 – 2021 |
| AFSC Sablefish Longline survey Pacific cod Relative Population Numbers | AFSC | RPN | 1990 – **2022** |
| GOA NMFS bottom trawl survey length composition | AFSC | number, by cm bin | 1990 – 2021 |
| GOA NMFS bottom trawl survey conditional age-at-length | AFSC | mean value and number | 1990 – **2021** |
| AFSC Sablefish Longline survey Pacific Cod length composition | AFSC | number, by cm bin | 1990 – **2022** |
| Federal fishery conditional age-at-length | AFSC | proportion age at length | 2007 – **2021** |
| CFSR bottom temperature indices | National Center for Atmospheric Research | temperature anomaly at mean depth for P. cod size bins 10 cm and 40 cm. | 1979 – **2022** |

## Fishery:

### Catch Biomass

Catches for the period 1991-2022 are shown for the three main gear types in Table 2.1, with the catches for 2022 presented through October 25, 2022. For the assessment model the Oct-Dec catch was assumed to reach the full TAC and state GHL. Three 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 2018 through 2022 are shown in Table 2.5, and incidental catch of non-commercial species for 2018 – 2022 are shown in Table 2.6. Non-commercial catch of Pacific cod in other activities is provided in Table 2.8.

### 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 2022. Size composition data are based on 1-cm bins ranging from 1 to 116 cm. As the maximum percent of fish larger than 110 cm over each year-gear type-season is less than 0.5%, the upper limit of the length bins was set at 116 cm, with the 116-cm bin accounting for all fish 116 cm and larger. The fishery length composition data are provided in the Stock Synthesis data files in Appendix 2.2.

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:

Where *p* is the proportion of fishat 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 the assessments after 2017, the post-1991 length composition was estimated using the total Catch Accounting System (CAS) derived total catch weight for each gear type, NMFS management area, trimester, and year. Data prior to 1991 were unavailable at this resolution so those size composition estimates are unchanged.

“New” method (post-1991):

Where *p* is the proportion of fishat 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:

Where *p* is the proportion of fishat 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 (provided in the Stock Synthesis data files in Appendix 2.2). The age data was also used to develop an annual conditional length-at-age matrix for each fishery.

## Surveys:

### Bottom trawl survey

The AFSC has been conducting standardized bottom trawl surveys for groundfish and crab in the Gulf of Alaska since 1984. From 1984-1997 surveys were conducted every third year, and every two years thereafter. Two or three commercial fishing vessels are contracted to conduct the surveys with fishermen working alongside AFSC scientists. Survey design is stratified random with the strata based on depth and distance along the shelf, with some concentrated strata in troughs and canyons (Raring *et al.* 2016). There are generally between 500 and 825 stations completed during each survey conducted between June and August starting in the western and ending in the southeastern Gulf of Alaska. Some changes in methods have occurred over the years with the addition of electronics to monitor how well the net is tending on-bottom, also to measure differences in net and trawl door dynamics and detect when general problems with the trawl gear occur. Surveys conducted prior to 1996 are considered to have more uncertainty given changes in gear mensuration. Also, the trawl duration was changed in 1996 to be 15 minutes instead of 30. Since 1996, methods have been consistent but in some years the extent of the survey has varied. In 2001 the Southeastern portion of the survey was omitted and in 2011, 2013, 2017, 2019, and 2021 deeper strata had fewer stations sampled than in other years due to budget and/or vessel constraints.

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

The spatial distribution of Pacific cod in the survey has been highly variable (Fig. 2.20) with inconsistent peaks in CPUE. In 2017 the survey had the lowest average density of the time series, but also no high density peaks in CPUE were observed in any survey station. There were some higher than average densities for the 2017 survey located along the Alaska Peninsula and south of Unimak island, but for the most part CPUE was universally low throughout the Gulf of Alaska. The 2019 survey showed an increase in cod in the area of the Central GOA east of Kodiak Island on Portlock Bank and South of Marmot Island, but fewer cod in the Eastern and Western GOA. The distribution of cod in the 2021 survey is comparable to the 2019 survey except the peaks in CPUE east of Kodiak were not observed and more cod were encountered to the west of Kodiak Island and in the Western GOA near the Shumagin Islands.

#### Biomass and abundance estimates

The Pacific cod biomass estimates from the bottom trawl survey are highly variable between survey years (Table 2.9 and Fig. 2.21). For example, the estimates dropped by 48% between the 1996 and 1999 estimates, but subsequent estimates were similar through 2005. The 2009 survey estimate spiked at 2 times the 2006 estimate, but was uncertain (CV = 18.5%). Subsequent surveys showed a decline through 2017 with a slight uptick in 2019 and drop in 2021. The 2017 estimates for abundance and biomass estimates were the lowest in the time series (a 71% drop in abundance and 58% drop in biomass compared to the 2015 estimate). Although the 2019 survey resulted in a 126% increase in abundance over 2017, the estimate remained historically low at 58% of the time series mean. The 2021 survey abundance estimate (90,914,000) was the second lowest in the time series (41% of the time series mean), next only to the 2017 estimate. The 2021 abundance estimate was 73% lower than the 2013 estimate (337,992,000) and 28% lower than the 2019 estimate (127,118,000). The 2021 biomass estimate was only 4% lower than the 2019 biomass estimate and 62% higher than the 2017 biomass estimate. The 2021 biomass and abundance estimate were within the 95% confidence intervals of the 2019 survey estimates.

#### Length Composition

The bottom trawl survey encounters fish as small as 5 cm and generally tracks large year-classes as they grow (e.g., the 1996, 2005-2008, and 2012 year-classes). The mean length in the trawl survey generally increased from 1984-2005 excepting the 1997 and 2001 surveys (Fig. 2.22). The decline in mean length in 2007 and 2009 were apparently due to the large incoming 2005-2008 year-classes. The mean length in the survey increased in the 2011-2017 survey then dropped again in 2019, but then increased again in 2021. The average length of fish for 2007-2021 remains below the 1984-2005 overall average.

The relative length compositions used in the assessment model this year from 1984-2021 are provided in Stock Synthesis data files and in Appendix 2.2.

#### Age Composition

Age compositions and conditional length at age from 1990-2021 trawl surveys are available and included in this year’s assessment model. The age compositions and conditional length at age data are provided in Stock Synthesis data files in Appendix 2.2.

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

Japan and the United States conducted a cooperative longline survey that was targeted for sablefish in the GOA annually from 1978 to 1994, adding the AI region in 1980 and the eastern BS in 1982 (Sasaki 1985; Sigler and Fujioka 1988). Since 1987, the AFSC has conducted annual longline surveys of the upper continental slope, referred to as domestic longline surveys, designed to continue the time series of the Japan-U.S. cooperative survey (Sigler and Zenger 1989). The domestic longline survey began annual sampling of the GOA in 1987, biennial sampling of the AI in 1996, and biennial sampling of the eastern BS in 1997 (Rutecki and Varosi 1997). The domestic survey also samples major gullies of the GOA in addition to sampling the upper continental slope. The order in which areas are surveyed was changed in 1998 to reduce interactions between survey sampling and short, intense fisheries. Before 1998, the order was AI and/or BS, Western Gulf, Central Gulf, Eastern Gulf. Starting in 1998, the Eastern Gulf area was surveyed before the Central Gulf area. International Pacific halibut longline survey.

#### Abundance index

A Relative Population Number (RPN) index of Pacific cod abundance and length compositions for 1990 through 2021 is available from this survey (Table 2.10 and Fig 2.21). Details about these data and a description of the methods for the AFSC sablefish longline survey can be found in Hanselman *et al.* (2016) and Echave *et al.* (2012). This RPN index follows the trend observed in the bottom trawl survey for 1990 through 2018 with a decline in abundance from 1990 through 2008 and a sharp increase (154%) in 2009 and continued increase through 2011 with the maturation of the large 2005-2008 year-classes. In 2012-2013 there appears a decline in the abundance index concurrent with a drop in overall shelf temperature potentially due to changes in availability of Pacific cod in these years as the population moved to shallower areas (Yang *et al.* 2019). In 2014-2016 the index increases but this may reflect increased availability with warmer conditions. The index showed a sharp drop (53%) in abundance from 2016 to 2017, again (40%) from 2017 to 2018, and yet again (37%) from 2018 to 2019. The 2019 estimate was 83% lower than the 2015 abundance estimate. The 2020 RPN showed a 30% increase from 2019, but the 2020 RPN remains the second lowest estimate of the time series. The increasing trend observed in 2020 continued in 2021 with a 58% increase, but then decreased again in 2022 by 24%.

#### Length composition

Unlike the bottom trawl survey, the longline survey encounters few small fish. The size composition data show consistent and steep unimodal distributions with a stepped decreasing trend in mean size between 1990 and 2015 (Fig. 2.23) and then a generally increasing mean size from 2015-2022. This matches the trend observed in all three fisheries. Changes in mean size appear consistent with changing availability in the survey due to bottom temperatures and changes in the overall population with large year classes. A larger number of smaller fish are encountered during this survey in warm years vs. cold years. There is a sharp decline in mean size in 2009 when the large 2005 year-class would be becoming available to this survey. The even steeper decline in average length in 2015 was encountered in the second warmest year on record for the time series. In 2019 a more severe drop in average length was anticipated due to the increased temperatures on the shelf and an increase in abundance due to increased availability. That we observed neither of these anticipated outcomes portends that either very few small fish were available in the population, or a change in behavior.

### Laurel and Litzow age-0 index

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

A model-based index of annual catch per unit effort (CPUE) for age-0 cod was used to resolve inter-annual differences in sampling across different bays and different days of the year. Specifically, a Bayesian zero-inflated negative binomial (ZINB) model was used invoking year as a categorical variable, day of year as a continuous variable, and site nested within bay as a group-level (random) effect. The day of year effect was modeled with thin plate regression splines to account for non-linear changes in abundance through the season and the number of basis functions was limited to 3 to avoid over-fitting data. This model was fit using Stan 2.21.0, R 4.0.2 and the *brms* package (Carpenter *et al.* 2017, Buerkner 2017, R Core Team 2022). The beach seine age-0 CPUE index showed the large 2012 year class and subsequent drop in CPUE for 2013-2016, and since 2016 there have been alternative small recruitment in 2019 and 2021 with larger recruitment in 2017, 2018, 2020, and 2022 (Table 2.11 and Fig. 2.24).

### International Pacific halibut Commission (IPHC) longline survey

This survey differs from the AFSC longline survey in gear configuration and sampling design, but catches substantial numbers of Pacific cod. More information on this survey can be found in Soderlund *et al.* (2009). A major difference between the two longline surveys is that the IPHC survey samples the shelf consistently from ~ 10-500 meters, whereas the AFSC longline survey samples the slope and select gullies from 150-1000 meters. Because the majority of effort occurs on the shelf in shallower depths, the IPHC survey may catch smaller and younger Pacific cod than the AFSC longline survey. On the other hand, the IPHC uses larger hooks (16/0) than the AFSC longline survey (13/0) which may prevent very small Pacific cod from getting hooked. To compare these two surveys, IPHC relative population number’s (RPN) were calculated using the same methods used to estimate the AFSC longline survey RPNs (but using different depth strata). Stratum areas (km2) from the RACE trawl surveys were used for IPHC RPN calculations.

The IPHC survey estimates of Pacific cod tracks well with both the AFSC longline and AFSC bottom trawl surveys (Table 2.12 and Fig. 2.25). There was an apparent drop in abundance from 1997-1999 followed by a stable but low population through to 2006. The population increases sharply starting in 2007, likely with the incoming large 2005 year class and continues to increase through 2009 as the large 2005-2008 year classes matured. The population then remained relatively stable through to 2014. The RPN index shows a steep decline in 2015 and 2017 consistent with the two AFSC surveys. The 2017 RPN was the lowest on record for the 20-year time series. This index showed a slight increase of the population abundance in 2018 (28% from 2017) to values slightly higher than 2016, but remain the fourth lowest estimate on record after 2001, 2016, and 2017. The 2019 survey estimated a slight decrease (3.5%), however the uncertainty in the estimate is high, and then increased by 29% in 2022. The length composition data available from 2018 and 2019 show the IPHC survey encounters fish greater than 40 cm. The length data in 2018 have a mode at approximately 60 cm in the western GOA. The other management areas have modes slightly higher between 65 and 75 cm. 2019 shows a slight increase in these modes for all three areas.

### Alaska Department of Fish and Game bottom trawl survey

The Alaska Department of Fish and Game (ADFG) has conducted bottom trawl surveys of nearshore areas of the Gulf of Alaska since 1987. Although these surveys are designed to monitor population trends of Tanner crab and red king crab, Pacific cod and other fish are also sampled. Standardized survey methods using a 400-mesh eastern trawl were employed from 1987 to the present. The survey is designed to sample at fixed stations from mostly nearshore areas from Kodiak Island to Unimak Pass, and does not cover the entire shelf area. The average number of tows completed during the survey is 360. On average, 89% of these tows contain Pacific cod. Details of the ADFG trawl gear and sampling procedures are in Spalinger (2006).

To develop an index from these data, a simple delta GLM model was applied covering 1988-2022. Data were filtered to exclude missing latitude and longitudes and missing depths. This model is separated into two components: one that tracks presence-absence observations and a second that models factors affecting positive observations. For both components, a fixed-effects model was selected and includes year, geographic area, and depth as factors. Strata were defined according to ADFG district (Kodiak, Chignik, South Peninsula) and depth (< 30 fathoms, 30-70 fathoms, > 70 fathoms). The error assumption of presence-absence observations was assumed to be binomial but alternative error assumptions were evaluated for the positive observations (lognormal versus gamma). The AIC statistic indicated the lognormal distribution was more appropriate than the gamma. Comparison of delta GLM indices with the area-swept estimates indicated similar trends. Variances were based on a bootstrap procedure, and CVs for the annual index values ranged from 0.06 to 0.14. These values underestimate uncertainty relative to population trends since the area covered by the survey is a small percentage of the GOA shelf area where Pacific cod have been observed.

The ADFG survey index follows the other three indices presented above with a drop in abundance between 1998 and 1999 (-45%) and relatively low abundance throughout the 2000s (Table 2.13 and Fig. 2.25). This survey differs from other indices as the estimates only increased in 2012 (an 89% increase from 2011), and then dropped off steadily afterwards to a record low in 2016. The 2017 survey index was 6% higher than the 2016 survey index. 2018 increased by 31% from 2017. The 2019 survey showed a slight decline (15.8%) from 2018, but 2020 showed a sharp increase of 41% from 2019 and a 64% increase from the 2016 record low, but still below the time series average. 2021 showed a 19.8% decrease from 2020 with a biomass estimate 67% lower than the time series average. 2022 resulted in a slight increase of 4% compared to 2021. Length composition data from this survey show wide multi-modal length distributions are common with modes of age-0 fish at times available at near 10cm, however the 2019 through 2021 surveys have no fish smaller than 22 cm, while there were some fish smaller than 22 cm that occurred in the 2022 survey.

## Environmental indices

### CFSR bottom temperature indices

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

To make the index, the CFSR reanalysis grid points were co-located with the AFSC bottom trawl survey stations. The co-located CFSR oceanic temperature profiles were then linearly interpolated to obtain the temperatures at the depths centers of gravity for 10 cm and 40 cm Pacific cod as determined from the AFSC bottom trawl survey. All co-located grid points were then averaged to get the time series of CFSR temperatures over the period of 1979-2020 (Table 2.14 and Fig. 2.26).

The mean depth of Pacific cod at 0-20 cm and 40-60 cm was found to be 47.9 m and 103.4 m in the Central GOA and 41.9 m and 64.07 m in the Western GOA. The temperatures of the 0-20 cm and 40-60 cm Pacific cod in the CFSR indices are highly correlated (R2 = 0.89). The shallower index is more variable (CV0-20 cm = 12% vs. CV40-60cm= 8%). There are high peaks in water temperature in 1981, 1987, 1998, 2015, 2016 and 2019 with 2019 being the highest in both the 0-10 cm and 40-60 cm indices. There are low valleys in temperature in 1982, 1989, 1995, 2002, 2009, 2012, and 2013. The coldest temperature in the 0-20 cm index was in 2009 and in the 40-60 cm index in 2012. The trend is insignificant for both indices. In 2020 and 2021 the temperatures at both the 0-20 and 40-60 are below the time series mean with 2021 being within 1% of the 2020 temperatures. In 2022 for both 0-20 and 40-60 the temperatures were above the time series mean.

### Sum of annual marine heatwave cumulative intensity index (MHWCI)

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

The marine heatwave analysis using the daily mean Central GOA sea surface temperatures indicated a prolonged period of increased temperatures in the Central GOA from 2 May 2014 to 13 January 2017 with heatwave conditions persisting for 815 of the 917 days in 14 events of greater than 5 days (Fig. 2.27). The longest stretch of uninterrupted heatwave conditions occurred between 14 December 2015 and 13 January 2017 (397 days). By the criteria developed by Hobday *et al.* (2018) for marine heatwave classification the event in the Central GOA reached a Category III (Severe) on 16 May 2016 with a peak intensity (Imax) of 3.02°C. The heatwave had a summed cumulative intensity (Icum) for 2016 of 635.26°C days, more than 25% of the sum of the Icum for the entire time series (1981-2018). The 14 events of this prolonged heatwave period summed to 1291.91°C days or 52% of the summed Icum for the time series.

There have been three periods of increased winter heatwave activity in the Central GOA (Table 2.14), the first in 1983-1986, second in 2001-2006, and the third 2014-2021. Short winter marine heatwaves (Category I to II) occurred every winter between 1983 and 1986, however none of these exceeded 17 days and the total winter Icum for this period was 84.23°C days over a total of 86 days. In the winter of 1997 there were two short (7 and 12 days) winter heatwave events with a total cumulative intensity of 17.19 °C days. In 1998 there was a strong heatwave from 3 March to the 14 June (102 days) with an Imax of 2.36°C and cumulative intensity of 146.01°C days. From 2001 through 2006 there were 6 winter heatwave events, most were minor and less than two weeks in length, however between 6 November 2002 and 4 March 2003 there were two that lasted in sum 141 days with a cumulative intensity of 165.94°C days and an Imax of 2.04°C. The 2014-2016 series of marine heatwave as described above was substantially longer lasting and more intense than anything experience previously in the region reaching a maximum SST anomaly of 3.12°C on 5 May 2016 and having a cumulative intensity of 1369.24 °C days across the three years. The most recent heatwave began 9 September 2018 to 23 December 2019. There are six distinct events making up the 2018-2019 heatwave with a maximum SST anomaly of 3.03 °C and a cumulative intensity of 625.23 °C days. For 2020 the sea surface temperatures dropped below the long-term mean in March but then increased in April (Fig. 2.27). After April the SST remained above the 1982-2012 mean oscillating into and out of heatwave conditions through October 2020 with four heatwave events occurring between 8 June and mid-October for a cumulative intensity of 131.24 °C days. The highest seasonal anomaly for 2020 was on 22 August at 2.68°C. The longest heatwave event in 2020 has lasted 48 days starting 13 September and continuing to 31 October. In 2021 there were three short heatwaves in January through March, two of 4 days and one of five days with a maximum temperature of 1.79 °C above the seasonal mean. For the most part 2022 remained cool or near average, with no heatwave says during the winter or spawning season.

# Analytic Approach

## General Model Structure

This year we present the accepted model from last year, Model 19.1, with updated data. We denote a new model number, Model 19.1a, to note the 1997 – 2002 State GHL harvest that were omitted from previous assessments but is now included in the current assessment. To see the history of models used in this assessment refer to A’mar and Palsson (2015). The model for this year were run in Stock Synthesis version 3.30.18 (Methot and Wetzell 2013).

Model 19.1 is a single sex, age-based model with length-based selectivity. This model has data from three fisheries (longline, pot, and combined trawl fisheries) with a single season and two survey indices (post-1990 GOA bottom trawl survey and the AFSC Longline survey indices). Length composition data were available for all three fisheries and both survey indices. Conditional length at age were available for the three fisheries and AFSC bottom trawl survey.

**Time varying selectivity components for all models:**

|  |  |
| --- | --- |
| **Component** | **Temporal Blocks/Devs** |
| Longline Fishery | Annually variable 1978-1989  Blocks – 1990-2004, 2005-2006, 2007-2016, 2017-2022 |
| Trawl Fishery |
| Pot Fishery | Blocks – 1977-2012 and 2013-2022 |
| Bottom trawl survey | Blocks – 1990-1995, 1996-2006, 2007-2022 |

The Stock Synthesis control files for this years model are provided in a zip file in Appendix 2.2.

## 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 L50% published. This resulted in the following values: length at 50% maturity = 57.3 cm and slope of linearized logistic equation = -0.27365.

### Aging Error

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

## Parameters Estimated Inside the Assessment Model

Parameters estimated conditionally (i.e., within individual SS runs, based on the data and the parameters estimated independently) in the model include the growth parameters, annual recruitment deviations, gear-specific fishery selectivity parameters, aging bias adjustment parameters, survey catchability, and survey and fishery selectivity parameters (Table 2.15).

### Natural Mortality

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

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

In 2017 it was hypothesized that due to the drop in all available survey indices between 2013 and 2017 it was suspected that there was an increase in natural mortality during the height of the 2014-2016 marine heatwave. The 2017 reference model, Model 17.09.35 used a block for 2015-2016 where M could be fit separately from all other years. In consideration of the marine heatwave analysis, models in 2018 expanded the natural mortality block to 2014-2016. For this Mstandard is fit separate from M2014-2016 with a lognormal prior of log(μ) = -0.81 and σ of either 0.1 or 0.41. The σ of 0.41 was based on a reevaluation of the data presented by Dr. Thompson described above and in Table 2.16, but limited to not include data from the Gulf of Alaska used in the current model.

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

### Growth

For Model 19.1a length at age, , were modeled as three parameter von Bertalanffy growth models with length in June, , maximum asymptotic length, L2, and growth rate, k, as:

,

where a was age.

The initial growth parameters L1, k, and L2 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. Linf was estimated at μ=99.46 CV=0.015, K was μ = 0.1966 CV=0.03, L0 was -0.11 CV=0.25. We recognized that these ‘priors’ are not true priors as they are drawn from the data used in the model, but were necessary in setting structure within the model while allowing some flexibility in the model fitting which we think is a compromise to fixing parameters. Previous modeling effort using uninformative priors on these three parameters has led to model convergence at unreasonable values or non-convergence.

### Recruitment

In Model 19.1a recruitment by year, Ry, were modeled as:

, if y ≥ 1977 → = 0, where ,

was the unfished equilibrium recruitment, was the lognormal recruitment deviation for year y, was the standard deviation among recruitment deviations in log space and was fixed at 0.44, and by was a bias adjustment fraction applied during year, y (Methot and Taylor 2011). To account for an environmental regime change in 1977 (Anderson and Piatt 1999) the parameter was fit for recruitment allowing for a change in R0 prior to the regime change in 1977. Projections in the base model post-2017 assumed average recruitment for 1977-2017 for Ry.

### Survey and Fishery selectivity

The same functional form (pattern 24 for length-based selectivity) used in Stock Synthesis to define the fishery selectivity schedules in previous year’s assessments was used this year for both the fishery and survey. This functional form, the double normal, is constructed from two underlying and rescaled normal distributions, with a horizontal line segment joining the two peaks. This form uses the following six parameters (selectivity parameters are referenced by these numbers in several of the tables in this assessment):

1. Beginning of peak region (where the curve first reaches a value of 1.0)
2. Width of peak region (where the curve first departs from a value of 1.0)
3. Ascending “width” (equal to twice the variance of the underlying normal distribution)
4. Descending width
5. Initial selectivity (at minimum length/age)
6. Final selectivity (at maximum length/age)

All but the “beginning of peak region” parameter are transformed: The widths are log-transformed and the other parameters are logit-transformed.

In this year’s model both fishery and survey selectivities were length-based. Uniform prior distributions were used for all selectivity parameters, except for *dev* vectors in models with annually varying selectivities which were constrained by input standard deviations (“sigma”) of 0.2.

For all parameters estimated within individual SS runs, the estimator used was the mode of the logarithm of the joint posterior distribution, which was in turn calculated as the sum of the logarithms of the parameter-specific prior distributions and the logarithm of the likelihood function.

### Fishing mortality

In model 19.1a the full set of year- and gear-specific fishing mortality rates were also estimated conditionally, but not in the same sense as the selectivity parameters. The fishing mortality rates are determined exactly rather than estimated statistically because SS assumes that the input total catch data are true values rather than estimates, so the fishing mortality rates can be computed algebraically given the other parameter values and the input catch data.

### Ageing bias

For model 19.1a aging bias was estimated for ages 3+ with two parameters, bias at age 3 and bias at age 10, with a linear interpolation between the two, applied to all age data collected prior to 2007 (aged prior to 2008). Age data from post-2007 were assumed to be aged without bias.

### Catchability

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, Qy, was modeled using a multiplicative link as:

,

where 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 was the June CFSR bottom temperature anomaly in the Central GOA in year *y* (Fig. 2.26). An analysis introducing this methodology was presented in 2017 (Barbeaux *et al.* 2017) and a method validating this methodology was presented at the 2018 September Plan team meeting and provided in Barbeaux *et al.* (2018) Appendix 2.1. Bottom trawl survey data show a centroid of distribution for cod greater than 34 cm shifts to deeper water in years with warmer shelf temperatures (Barbeaux *et al.* 2019). This relationship was verified in Yang *et al.* (2019) with a shift to deeper depths in all size classes examined during warm years and shift to shallower waters in cold years. This shift would make cod more available to the AFSC longline survey which starts at 150 m.

## Likelihood Components

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

For model 19.1a there were no parameters near bounds and the likelihoods appear well defined with the gradient of the objective function at less than 1e-5. Model 19.1a was examined by “jittering” starting parameters by a factor of 0.05 over 50 runs to evaluate if models had converged to local minima.

### Use of Size and Age Composition Data in Parameter Estimation

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

# Results

## Model Evaluation

Model evaluation criteria included log likelihood, model adherence to biological principles and assumptions, the relative sizes of the likelihood components, and how well the model estimates fit to the survey indices, the survey and fishery length composition and conditional age-at-length data, reasonable curves for fishery and survey selectivity, retrospective pattern, and model behavior during leave-one-out analysis.

Model likelihoods and key parameter estimates are provided in Table 2.17. Likelihoods by fleet and are provided in Table 2.18. Retrospective results are presented in Figure 2.28. There is little to no retrospective pattern in spawning biomass (Mohn’s rho of -0.041), but a positive retrospective pattern resulted for recruitment (Mohn’s rho of 1.4), indicating that as subsequent years of data are added to the model the estimates of recruitment decrease. Model 19.1a performed reasonably well in a jitter analysis with a CV of 0.05 and 50 runs with a total of 48 of the 50 jitter runs converged with 80% of the converged models resulting in estimates at the lowest MLE from the accepted models. Leave-one-out (LOO) results are presented in Table 2.19 and Figure 2.29. 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, forecast spawning biomass, and ABC). Stability of the model estimates and estimates of variance while removing data provided insights on model performance and sensitivity to noise within the data. For this analysis we focused on bias, i.e. was there a direction of change when data were removed from the complete models, and the variability of the variance estimates as data were removed. Model 19.1a resulted in relatively low bias across all examined parameters and derived quantities (Table 2.19). The highest bias was observed in the forecasted ABC, which remained below 3%. In model 19.1a the removal of the 2022 and 2019 data appear most impactful on the forecasted spawning biomass and ABS (Fig. 2.29). In 2019 the two surveys fit exhibit opposite trends, with the longlined survey decreasing and the trawl survey increasing. Removing the 2022 data, for which the only index data available is from the longline survey, which remained low, caused a sharp increase in spawning biomass and ABC for 2023. Without the 2022 data model 19.1a was expecting a higher abundance in 2022 than observed in the 2022 indices and thus higher biomass estimates for 2023.

Model 19.1a with data updated through 2023 results in reasonable fits to the data, estimates biologically plausible parameters, and produces consistent patterns in abundance compared to previous assessments. It should be noted that the results from the GOA Pacific cod stock assessment have been particularly volatile with a wide-array of models presented over the past 18 years (A’mar and Palsson 2015). Model 19.1a presented this year is well within the bounds of models presented in previous years for the spawning stock biomass time series (Fig. 2.30). Model 19.1a fit to the bottom trawl and longline survey indices, survey and gear specific fishery conditional age-at-length, and survey and gear specific fishery length composition are shown in Figures 2.31-2.41. Overall, model 19.1a yields reasonable results and we continue to use it to recommend the 2023 ABC and OFL.

## Time Series Results

### Definitions

The biomass estimates presented here will be defined in two ways: 1) total biomass was defined as age 0+ biomass, consisting of the biomass of all fish aged 0 years or greater in a given year; and 2) spawning biomass was defined as the biomass of all spawning females in a given year. The recruitment estimates presented here were defined as numbers of age-0 fish in a given year; actual recruitment to fishery and survey depends on selectivity curves as estimated (noting that there are no indices involving age-0 Pacific cod). All results presented are from Model 19.1a.

### Biomass

Total biomass estimates show a long decline from their peak in 1988 (Table 2.20 and Fig. 2.32) to a low in 2006 and then an increase to another peak in 2014, after which there was a sharp decline through 2018 followed by a slight increase through 2022. Spawning biomass (Table 2.20 and Figure 2.30) shows a similar trend of decline since the late 1980s with a peak in 1989 to a low in 2008. There was then a short increase in spawning biomass coincident with the maturation of the 2005-2008 year classes through 2014, after which the decline continued to lowest level in 2019 and 2020. The spawning biomass then slightly increased in 2021 and 2022 and is projected to slightly decrease in 2023.

### Recruitment and Numbers at Age

The recruitment predictions in Model 19.1a (Table 2.21, Fig. 2.43, and Fig. 2.46) show above average recruitment for most of the 1980s, below average recruitment from the mid-1990s to mid-2000s, above average recruitment from the mid-2000s to 2013, and below average recruitment since. Numbers at age and length, with the mean age and length, are shown in Figure 2.42. Overall, in the population estimates the average age and length have both decreased since 2019.

### Fishing Mortality

Fishing mortality appears to have increased steadily with the decline in abundance from 1990 through a peak in 2008 with continued high fishing mortality through 2017 in all models examined (Table 2.22). 2017 had the highest total exploitation rate of the time series. The period between 1990 and 2008 saw both a decline in recruitment paired with increases in catch. The period of increasing fishing mortality was mainly attributed to the rise in the pot fishery, which also shows the largest increase in continuous F (Fig. 2.44). 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. 2.45) show that F was estimated to have been above the ABC control rule advised levels for 2008 and 2015 to 2017 and biomass was below *B35%*in 2008 and again 2017 through 2022, and projected to continue to be below through 2024. It should be noted that this plot shows what the current model predicts, not what the past assessments had estimated.

### Uncertainty Results

MCMC were conducted with 1,000,000 iterations with 10,000 burn-in and thinned to every 2000th iteration leaving 490 iterations for constructing the posterior distributions. Geweke (1992) and Heidelberger and Welch (1983) MCMC convergence tests, as implemented in the *coda* R library (Plummer *et al.* 2006), concluded adequate convergence in the chain. Posterior distributions of key parameters appear well defined and bracket the MLE estimates (Fig. 2.46) Model 19.1a predicts a < 0.1% probability the stock was below B20% in 2022 and projects a < 0.1% probability of the stock being below B20% in 2023 (Fig 2.46).

## 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 (*FOFL*), the maximum permissible ABC, and the fishing mortality rate used to set the maximum permissible ABC. The fishing mortality rate used to set ABC (*FABC*) 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: *B40%*, equal to 40% of the equilibrium spawning biomass that would be obtained in the absence of fishing; *F35%*, 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 *F40%*, 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/B40%* > 1

*FOFL* = *F35%*

*FABC* < *F40%*

*3b) Stock status:* 0.05 < *B/B40%* < 1

*FOFL* = *F35%* × (*B/B40%* - 0.05) × 1/0.95

*FABC* < *F40%* × (*B/B40%* - 0.05) × 1/0.95

*3c) Stock status:* *B/B40%* < 0.05

*FOFL* = 0

*FABC* = 0

Other useful biomass reference points which can be calculated using this assumption are *B100%* and *B35%*, defined analogously to *B40%*. These reference points are estimated as follows, based on this year’s model, Model 19.1a:

|  |  |  |  |
| --- | --- | --- | --- |
| Reference point: | *B35%* | *B40%* | *B100%* |
| Spawning biomass: | 58,105 t | 66,405 t | 166,013 t |

For a stock exploited by multiple gear types, estimation of *F35%* and *F40%* requires an assumption regarding the apportionment of fishing mortality among those gear types. For this assessment, the apportionment was based on this year’s model’s estimates of fishing mortality by gear for the five most recent complete years of data (2017-2021). This apportionment of catch given the projected selectivity for each gear results in estimates of *F35%* and *F40%* of 0.91 and 0.73 in aggregate.

### Specification of OFL and Maximum Permissible ABC

For model 19.1a spawning biomass for 2023 is estimated by this year’s model to be 45,514 t at spawning. This is below the *B40%* value of 66,405 t, thereby placing Pacific cod in sub-tier “b” of Tier 3. Given this, the model estimates OFL, maximum permissible ABC, and the associated fishing mortality rates for 2023 and 2024 as follows (2024 values are predicated on the assumption of the full TAC and GHL being taken in 2022 and that the 2023 catch will be at maximum ABC in the projection):

|  |  |  |  |
| --- | --- | --- | --- |
| Units | Year | Overfishing  Level (OFL) | Maximum  Permissible ABC |
| Harvest amount | 2023 | 33,494 | 27,812 |
| Harvest amount | 2024 | 27,812 | 23,853 |
| Fishing mortality rate | 2023 | 0.55 | 0.44 |
| Fishing mortality rate | 2024 | 0.50 | 0.40 |

The age 0+ biomass projections for 2023 and 2024 from this year’s model are 168,841 t and 194,255 t, respectively.

### Risk Table and ABC Recommendation

#### Overview

The following template is used to complete the risk table:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | *Assessment-related considerations* | *Population dynamics considerations* | *Environmental/ecosystem considerations* | *Fishery Performance* |
| Level 1: Normal | Typical to moderately increased uncertainty/minor unresolved issues in assessment. | Stock trends are typical for the stock; recent recruitment is within normal range. | No apparent environmental/ecosystem concerns | No apparent fishery/resource-use performance and/or behavior concerns |
| Level 2: Substantially increased concerns | Substantially increased assessment uncertainty/ unresolved issues. | Stock trends are unusual; abundance increasing or decreasing faster than has been seen recently, or recruitment pattern is atypical. | Some indicators showing adverse signals relevant to the stock but the pattern is not consistent across all indicators. | Some indicators showing adverse signals but the pattern is not consistent across all indicators |
| Level 3: Major Concern | Major problems with the stock assessment; very poor fits to data; high level of uncertainty; strong retrospective bias. | Stock trends are highly unusual; very rapid changes in stock abundance, or highly atypical recruitment patterns. | Multiple indicators showing consistent adverse signals a) across the same trophic level as the stock, and/or b) up or down trophic levels (i.e., predators and prey of the stock) | Multiple indicators showing consistent adverse signals a) across different sectors, and/or b) different gear types |
| Level 4: Extreme concern | Severe problems with the stock assessment; severe retrospective bias. Assessment considered unreliable. | Stock trends are unprecedented; More rapid changes in stock abundance than have ever been seen previously, or a very long stretch of poor recruitment compared to previous patterns. | Extreme anomalies in multiple ecosystem indicators that are highly likely to impact the stock; Potential for cascading effects on other ecosystem components | Extreme anomalies in multiple performance indicators that are highly likely to impact the stock |

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

1. “Assessment considerations—data-inputs: biased ages, skipped surveys, lack of fishery-independent trend data; model fits: poor fits to fits to fishery or survey data, inability to simultaneously fit multiple data inputs; model performance: poor model convergence, multiple minima in the likelihood surface, parameters hitting bounds; estimation uncertainty: poorly-estimated but influential year classes; retrospective bias in biomass estimates.
2. “Population dynamics considerations—decreasing biomass trend, poor recent recruitment, inability of the stock to rebuild, abrupt increase or decrease in stock abundance.
3. “Environmental/ecosystem considerations—adverse trends in environmental/ecosystem indicators, ecosystem model results, decreases in ecosystem productivity, decreases in prey abundance or availability, increases or increases in predator abundance or productivity.
4. “Fishery performance—fishery CPUE is showing a contrasting pattern from the stock biomass trend, unusual spatial pattern of fishing, changes in the percent of TAC taken, changes in the duration of fishery openings.”

#### Assessment considerations.

The GOA Pacific cod assessment does not show a strong retrospective bias, 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 2012-2021 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 B40%. 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 and Zador, 2022). The text below summarizes ecosystem information related to GOA Pacific cod provided from both the ESP and GOA ESR.

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

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

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

*Predators and Competitors:* There is no cause to suspect increased predation pressure on Pacific cod. In general predators of Pacific cod (including Pacific cod, halibut, salmon shark, northern fur seals, Steller sea lions, harbor porpoises, various whale species, and tufted puffin) appear to be stable or at relatively low population levels. The most recent data available suggest that Steller sea lion trends have stabilized (eastern GOA) or continued to be at low levels (western GOA) in the Gulf of Alaska. Pacific halibut, large Pacific cod (representing cannibalistic predation) are estimated at low biomass. In general, apex fish predators in the GOA are at relatively low abundances (including cod and arrowtooth flounder, although sablefish are increasing in abundance) (Whitehouse and Aydin 2021). Planktivorous juvenile cod may experience increased levels of competition from recent strong sablefish year classes, especially the 2019 larger than expected year class (D. Goethel, pers. comm.), although decreased competition from low, even year pink salmon returns.

#### 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.

#### Summary and ABC recommendation

These results are summarized in the table below:

|  |  |  |  |
| --- | --- | --- | --- |
| Assessment-related considerations | Population dynamics considerations | Environmental/ecosystem considerations | Fishery Performance |
| Level 1:  Normal | Level 1:  Normal | Level 1:  Normal | Level 1:  Normal |

From 2008-2017 the GOA Plan Team and SSC recommended setting the ABC at the maximum permissible level under Tier 3. For 2018 through 2019 an ABC was recommended below the maximum ABC in an attempt to ensure the 2019 and 2020 SSB would remain above B20%. For 2020 although the ABC was set at the maximum the stock was below B20%  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 2.25. The overall score of level 1 in the risk table suggests that setting the ABC below the maximum permissible is not warranted at this time.

For 2022 the spawning stock biomass is projected to be above B20% , 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.

### 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. 2.47), the area-apportioned ABCs for the two projections of Model 19.1a would be:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Western | Central | Eastern | Total |
| Random effects area apportionment | 30.3% | 60.2% | 9.5% | 100% |
| 2023 ABC | 8,427 | 16,743 | 2,642 | 27,812 |
| 2024 ABC | 7,227 | 14,360 | 2,266 | 23,853 |

### Status Determination

A standard set of projections is required for each stock managed under Tiers 1, 2, or 3 of Amendment 56. This set of projections encompasses seven harvest scenarios designed to satisfy the requirements of Amendment 56, the National Environmental Policy Act, and the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA). The standard harvest scenarios have been made within Stock Synthesis. Year-end catch for 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, recruitment was based on average recruitment from 1977-2022, and growth and mortality were as estimated in 2022. The Stock Synthesis data and forecast files have been provided for model 19.1a with projections in appendix 2.2.

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* *FABC*” refers to the maximum permissible value of *FABC* under Amendment 56):

*Scenario 1*: In all future years, *F* is set equal to *max* *FABC*. (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 *FTAC* than *FABC*.)

*Scenario 4*: In all future years, *F* is set equal to the *F75%*. (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 *B35%*):

*Scenario 6*: In all future years, *F* is set equal to *FOFL*. (Rationale: This scenario determines whether a stock is overfished. If the stock is expected to be above half of its *BMSY* level in 2021 and above its *BMSY* level in 2031 under this scenario, then the stock is not overfished.)

*Scenario 7:* In 2022 and 2023, F is set equal to max FABC, and in all subsequent years, F is set equal to FOFL. (Rationale: This scenario determines whether a stock is approaching an overfished condition. If the stock is 1) above its MSY level in 2022 or 2) above 1/2 of its MSY level in 2022 and expected to be above its MSY level in 2032 under this scenario, then the stock is not approaching an overfished condition.)

Scenarios 1 through 7 were projected 15 years from 2021 in Model 19.1 (Table 2.26). Scenarios 3, 4, and 5 (no fishing) project the stock to be below *B35%* until 2025, scenarios 1, 2, 6, and 7 have the stock below *B35%* until 2026. Fishing at the maximum permissible rate indicate that the spawning stock will be below *B35%* 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 *B35%* by 2026.

Our projection model run under these conditions indicates that for Scenario 6, the GOA Pacific cod stock although below *B35%* 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 2032.

Under Scenarios 6 and 7 for model 19.1 the Gulf of Alaska Pacific cod stock would not currently be considered overfished, nor would it 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.

*For full assessments of stocks/complexes managed under Tiers 1-3 only: Report the F (based on the author’s recommended model) that would have produced a catch for last year equal to last year’s OFL. Here are two simple options for making this calculation, but authors are feel free to write their own code if they prefer:*

1. *Use* [*this spreadsheet*](https://docs.google.com/spreadsheets/d/1AeaVCSJqnh0kV6_zSPbK41Z2fBsxmsHsY66B36FTPoY/edit#gid=907492102) *(note that separate tabs provide options for models with one sex and one gear, two sexes and two gears, and two sexes and two gears with sex-specific M). The units are kt for OFL, kg for weight at age, and millions of fish for numbers at age. Zeros can be inserted for unused ages.*
2. *For models developed in Stock Synthesis, replace last year’s catch in the data file with last year’s OFL, set maximum phase to 0 in the starter file, and re-run SS from the \*.par file (the answer will be listed in the report file as “F\_20yy,” where 20yy is the previous year). A similar procedure will likely work for many non-SS assessment models programmed in ADMB.*

# Ecosystem Considerations

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

# Data Gaps and Research Priorities

Research is needed around three linked themes:

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

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

3) **Resolving stock spatial structure, migration patterns, and connectivity** based on tagging and new genetics/genomics approaches. Research 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.

# Literature Cited

# Tables

# Figures

## Appendix 2.1 Gulf of Alaska Pacific cod ESP

## Appendix 2.2 GOA Pacific cod 2021 Stock Synthesis model files

<https://apps-afsc.fisheries.noaa.gov/Plan_Team/2021/GOA_PCOD_2021_Appendix_2.2_Stock_Synthesis_Files.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//GOA\_PCOD\_2021\_Appendix\_2.3\_Model 19.1.xlsx](https://apps-afsc.fisheries.noaa.gov/Plan_Team/2021//GOA_PCOD_2021_Appendix_2.3_Model 19.1.xlsx )