1. Assessment of the Walleye Pollock Stock in the Gulf of Alaska

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November 2021

# Executive Summary

## Summary of Changes in Assessment Inputs

### Changes to input data

1. Fishery: 2020 total catch and catch at age.
2. Shelikof Strait acoustic survey: 2021 biomass index and age composition.
3. NMFS bottom trawl survey: 2021 biomass index and length composition
4. Summer acoustic survey: 2021 biomass index and length composition
5. ADF&G crab/groundfish trawl survey: 2021 biomass index and 2020 age composition

### Changes in assessment methodology

The age-structured assessment model is identical to the model used for the 2019 and 2020 assessments (Model 19.1).

## Summary of Results

The base model projection of female spawning biomass in 2022 is 186,481 t, which is 43.4% of unfished spawning biomass (based on average post-1977 recruitment) and above B40% (172,000 t), thereby placing GOA pollock in sub-tier “a” of Tier 3. New surveys in 2021 include the winter Shelikof Strait acoustic survey, NMFS bottom trawl survey, summer acoustic survey, and ADF&G bottom trawl survey. These surveys indicated similar relative abundance in 2021, unlike previous years when the surveys showed strongly contrasting trends. The risk matrix table recommended by the SSC was used to determine whether to recommend an ABC lower than the maximum permissible. 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. Although we identified some aspects of the stock that merit close tracking, there were no elevated concerns about stock assessment, population dynamics, environment/ecosystem, or fisheries performance categories. We therefore recommend no reduction from maximum permissible ABC.

The authors’ 2022 ABC recommendation for pollock in the Gulf of Alaska west of 140° W lon. (W/C/WYK regions) is 133,081 t, which is an increase of 26% from the 2021 ABC. The author’s recommended 2023 ABC is 131,912 t. The OFL in 2022 is 154,983 t, and the OFL in 2023 if the ABC is taken in 2022 is 153,097 t. These calculations are based on a projected 2021 catch of 92,342 t (Mary Furuness, pers. comm. Oct. 14, 2021). It should be noted that the ABC is projected to increase after 2023 even as the large 2012 year class continues to diminish due to new large cohorts entering the exploitable stock, although there is considerable uncertainty about the 2018 year class.

For pollock in southeast Alaska (Southeast Outside region, east of 140° W lon.), the ABC recommendation for both 2022 and 2023 is 11,363 t (see Appendix 1B) and the OFL recommendation for both 2022 and 2023 is 15,150 t. These recommendations are based on a Tier 5 assessment using the projected biomass in 2022 and 2023 from a random effects model fit to the 1990-2021 bottom trawl survey biomass estimates of the assessment area.

## Status Summary for Gulf of Alaska Pollock in W/C/WYK Areas

|  | As estimated or *specified last* year for: | | As estimated or *recommended this* year for: | |
| --- | --- | --- | --- | --- |
| **Quantity/Status** | 2022 | 2023 | 2023\* | 2024\* |
| M (natural mortality) | 0.30 | 0.30 | 0.30 | 0.30 |
| Tier | 3a | 3a | 3a | 3a |
| Projected total (age 2+) biomass (t) | 1,097,340 | 812,182 | 848,878 | 1,205,850 |
| Projected female spawning biomass (t) | 184,530 | 169,577 | 186,481 | 167,840 |
| B100% | 443,000 | 443,000 | 430,000 | 430,000 |
| B40% | 177,000 | 177,000 | 172,000 | 172,000 |
| B35% | 155,000 | 155,000 | 150,000 | 150,000 |
| FOFL | 0.33 | 0.30 | 0.31 | 0.29 |
| *max*FABC | 0.28 | 0.26 | 0.26 | 0.26 |
| FABC | 0.28 | 0.26 | 0.26 | 0.26 |
| OFL (t) | 123,455 | 106,767 | 154,983 | 153,997 |
| *max*ABC (t) | 105,722 | 91,934 | 133,081 | 131,912 |
| ABC (t) | 105,722 | 91,934 | 133,081 | 131,912 |
|  | As determined *last* year for: | | As determined *this* year for: | |
| **Status** | 2021 | 2022 | 2022 | 2023 |
| Overfishing | No | n/a | No | n/a |
| Overfished | n/a | No | n/a | No |
| Approaching overfished | n/a | No | n/a | No |
| \*Projections are based on an estimated catch of 999 t for 2022 and estimates of 999 t and 999 t used in place of maximum permissible ABC for 2023 and 2024. | | | | |

## Status Summary for Gulf of Alaska Pollock in the Southeast Outside Area

|  | As estimated or *specified last* year for: | | As estimated or *recommended this* year for: | |
| --- | --- | --- | --- | --- |
| **Quantity/Status** | 2022 | 2023 | 2023 | 2024 |
| M (natural mortality) | 0.30 | 0.30 | 0.30 | 0.30 |
| Tier | 5 | 5 | 5 | 5 |
| Biomass (t) | 45,103 | 45,103 | 50,500 | 50,500 |
| FOFL | 0.30 | 0.30 | 0.30 | 0.30 |
| *max*FABC | 0.23 | 0.23 | 0.23 | 0.23 |
| FABC | 0.23 | 0.23 | 0.23 | 0.23 |
| OFL (t) | 13,531 | 13,531 | 15,150 | 15,150 |
| *max*ABC (t) | 10,148 | 10,148 | 11,363 | 11,363 |
| ABC (t) | 10,148 | 10,148 | 11,363 | 11,363 |
|  | As determined *last* year for: | | As determined *this* year for: | |
| Status | 2021 | 2022 | 2022 | 2023 |
| Overfishing | No | n/a | No | n/a |

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

None this year.

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

The SSC in December 2020: “For the ESP socioeconomic indices, the SSC suggests using Kodiak and small community categories for the annual percent harvesting revenue indicators similar to what was done for the annual percent processing revenue indicators, for consistency with the text in this ESP (pg. 110) and the approach used in other ESPs, as well as for comprehensiveness”

In the future, we plan to conduct a thorough evaluation of the information provided in the Economic SAFE and ACEPO report to determine what socioeconomic indicators could be provided in the ESP that are not redundant with those reports and related directly to stock health. This may result in a transition of indicators currently reported in this ESP to a different series of socioeconomic indicators in future ESPs and may include aggregating small communities as suggested or focusing more on dependency rather than engagement. Additional considerations should be given for the timing of the economic and community reports that are delayed by 1-2 years depending on the data source from the annual stock assessment cycle and how this information might inform the stock assessment

The GOA Plan Team in its November 2019 minutes recommended the author examine fishery selectivity, as persistent patterns in the catch-at-age residuals may represent artifacts of the selectivity functional form used.

We did not explore alternative functional forms in this assessment. We noticed that the initial inflection point of the double-logistic selectivity curve was about age 4, and hypothesized that if the time variation in this component were too small (too little annual flexibility) it could cause the aforementioned residual pattern. Thus, as a first step, we tried allowing for greater flexibility in both the time-varying initial inflection and slope used to control the selectivity of younger fish by increasing the process error on the random walk components. Despite this increased flexibility, we found no appreciable improvement to the age-4 residuals. We therefore agree that investigation of alternative functional forms is warranted, and will explore that in future assessments.

The GOA Plan Team in its November 2019 minutes recommended the author explore better methods for constraining the time varying catchability parameter to be under 1 for the Shelikof Strait acoustic survey.

The model uses a random walk on log scale to estimate a time-varying catchability for the Shelikof biomass index. It is possible for the estimated catchability to be greater than 1. While this has not occurred to date, we note that the confidence intervals exceeded it in recent years. We therefore tried an alternative form by estimating the random walk in inverse logit (i.e., logistic) space, so that the estimated catchability and its uncertainty was naturally constrained between 0 and 1. Due to the change in parameterization, the assumed process error for the random walk needed to be increased to allow for a similar level of flexibility. The following figure shows the results of catchability, fit to the index, and estimated spawning biomass for the original and logistic versions, with the latter having more flexibility allowed.

The logistic transformation works to constrain the catchability to its assumed natural range, but results in a shift in absolute size of the stock for unclear reasons. The specification of the magnitude of the process error also needs further investigation. So despite its promise, we did not bring forward this as an alternative this year. Further investigations will be done for next year, with tentative plans to explore estimating the process error in a state-space approach.

Results comparing the original log and new logistic transformation for the random-walk catchability of the Shelikof index. Estimated catchability (top) with 95% confidence intervals (ribbons) for the two parameterizations (colors). The expected indices (lines) are shown with the observed data (points and vertical lines; middle panel). Estimated spawning biomass with 95% confidence interval (ribbons) is shown at bottom.

The GOA Plan Team in its November 2019 minutes recommended an exploration of combining the acoustic summer survey and the GOA bottom trawl survey using a VAST framework, similar to the approach used by Cole Monnahan for EBS pollock surveys.

Such an analysis would be extremely informative and valuable to improving this assessment. One of the most challenging tasks is reprocessing the acoustic data. We have initiated conversations with both the acoustic and bottom trawl survey groups about what it would take to have suitable data for this analysis. We will continue to work with them on the feasibility of this. However, we agree with previous authors’ argument that this should be considered a long-term research objective.

The GOA Plan Team in its November 2018 minutes recommended investigating model behavior sensitivity to abundance indices by incrementally dropping survey indexes to clarify how the data affect the model(s).

We performed this incremental leave-one-out experiment for the four surveys, but included the weight and length compositions in addition to the indices. Results are shown in the following figure where the model is fitted without each survey in turn. The trends are generally the same. The summer acoustic has little effect, due to only having four years of data. The ADF&G and Shelikof surveys have a relative minor impact if dropped, except in recent years with the notable divergence in index trends. Most noteworthy is that the NMFS bottom trawl survey sets the scale of the population (without it there is a notable increase in uncertainty and an absolute increase in estimates), which is tied to its catchability which is not well-estimated and instead is driven by an informative prior. This analysis suggests revisiting the formation of that prior and how it interacts with the scale of the population.

# Introduction

## Biology and Distribution

Walleye pollock (Gadus chalcogrammus; hereafter referred to as pollock) is a semi-pelagic schooling fish widely distributed in the North Pacific Ocean. Pollock in the central and western Gulf of Alaska (GOA) are managed as a single stock independently of pollock in the Bering Sea and Aleutian Islands. The separation of pollock in Alaskan waters into eastern Bering Sea and Gulf of Alaska stocks is supported by analysis of larval drift patterns from spawning locations (Bailey *et al.* 1997), genetic studies of allozyme frequencies (Grant and Utter 1980), mtDNA variability (Mulligan *et al.* 1992), and microsatellite allele variability (Bailey et al. 1997). See figure 1 and table ??.

## Stock Structure

The results of studies of stock structure within the Gulf of Alaska are equivocal. There is evidence from allozyme frequency and mtDNA that spawning populations in the northern part of the Gulf of Alaska (Prince William Sound and Middleton Island) may be genetically distinct from the Shelikof Strait spawning population (Olsen et al. 2002). However, significant variation in allozyme frequency was found between Prince William Sound samples in 1997 and 1998, indicating a lack of stability in genetic structure for this spawning population. Olsen et al. (2002) suggest that interannual genetic variation may be due to variable reproductive success, adult philopatry, source-sink population structure, or utilization of the same spawning areas by genetically distinct stocks with different spawning timing. There are important recent preliminary results from a genetic analysis of 617 walleye pollock from Japan, Bering Sea, Chukchi Sea, Aleutian Islands, Alaska Peninsula, and Gulf of Alaska using low-coverage whole genome sequencing. Results suggests there is a temporally stable stock structure with a latitudinal gradient, i.e., Bering Sea pollock are distinguishable from those in the Gulf of Alaska and Aleutian Islands (I. Spies, personal communication, 2021). An evaluation of stock structure for Gulf of Alaska pollock following the template developed by NPFMC stock structure working group was provided as an appendix to the 2012 assessment (Dorn et al., 2012). Available information supported the current approach of assessing and managing pollock in the eastern portion of the Gulf of Alaska (Southeast Outside) separately from pollock in the central and western portions of the Gulf of Alaska (Central/Western/West Yakutat). The main part of this assessment deals only with the C/W/WYK stock, while results for a tier 5 assessment for southeast outside pollock are reported in Appendix 1B.

# Fishery

The commercial fishery for walleye pollock in the Gulf of Alaska started as a foreign fishery in the early 1970s (Megrey 1989). Catches increased rapidly during the late 1970s and early 1980s (Table 1.1). A large spawning aggregation was discovered in Shelikof Strait in 1981, and a fishery developed for which pollock roe was an important product. The domestic fishery for pollock developed rapidly in the Gulf of Alaska with only a short period of joint venture operations in the mid-1980s. The fishery was fully domestic by 1988.

## Description of the Directed Fishery

### Catch Patterns

The pollock target fishery in the Gulf of Alaska is entirely shore-based with approximately 96% of the catch taken with pelagic trawls. During winter, fishing effort targets pre-spawning aggregations in Shelikof Strait and near the Shumagin Islands (Fig. 1.1). Fishing in summer is less predictable, but typically occurs in deep-water troughs on the east side of Kodiak Island and along the Alaska Peninsula.

### Bycatch and Discards

Incidental catch in the Gulf of Alaska directed pollock fishery is low. For tows classified as pollock targets in the Gulf of Alaska between 2016 and 2020, on average about 96% of the catch by weight of FMP species consisted of pollock (Table 1.2). Nominal pollock targets are defined by the dominance of pollock in the catch, and may include tows where other species were targeted, but pollock were caught instead. The most common managed species in the incidental catch are arrowtooth flounder, Pacific ocean perch, Pacific cod, sablefish, shallow-water flatfish, and flathead sole (Table 1.2). Sablefish incidental catch has trended upwards since 2018, perhaps reflecting both the recent increase in sablefish abundance and a wider spatial distribution. The most common recent non-target species are grenadiers, squid, capelin, jellyfish and miscellaneous fish (Table 1.2). Bycatch estimates for prohibited species over the period 2016-2020 are given in Table 1.3. Chinook salmon are the most important prohibited species caught as bycatch in the pollock fishery. A sharp spike in Chinook salmon bycatch in 2010 led the Council to adopt management measures to reduce Chinook salmon bycatch, including a cap of 25,000 Chinook salmon bycatch in the directed pollock fishery. Estimated Chinook salmon bycatch since 2010 has been less than the peak in 2010, with increases in 2016, 2017, and 2019, and reduced to 10,867 in 2020.

## Management Measures

Since 1992, the Gulf of Alaska pollock Total Allowable Catch (TAC) has been apportioned spatially and temporally to reduce potential impacts on Steller sea lions. The details of the apportionment scheme have evolved over time, but the general objective is to allocate the TAC to management areas based on the distribution of surveyed biomass, and to establish three or four seasons between mid-January and fall during which some fraction of the TAC can be taken. The Steller Sea Lion Protection Measures implemented in 2001 established four seasons in the Central and Western GOA beginning January 20, March 10, August 25, and October 1, with 25% of the total TAC allocated to each season. Allocations to management areas 610, 620 and 630 are based on the seasonal biomass distribution as estimated by groundfish surveys. In addition, a harvest control rule was implemented that requires suspension of directed pollock fishing when spawning biomass declines below 20% of the reference unfished level.

Recently NMFS approved the final rule for Amendment 109 to GOA Fishery Management Plan developed by the North Pacific Fisheries Management Council. Amendment 109 combines pollock fishery A and B seasons into a single season (redesignated as the A season), and the C and D seasons into a single season (redesignated as the B season), and changes the annual start date of the redesignated pollock B season from August 25 to September 1. These changes will be implemented beginning in 2021 and affect the seasonal allocation only in the Central and Western GOA.

# Data

The data used in the assessment model consist of estimates of annual catch in tons, fishery age composition, NMFS summer bottom trawl survey estimates of biomass and age and length composition, acoustic survey estimates of biomass and age composition in Shelikof Strait, summer acoustic survey estimates of biomass and age and length composition, and ADF&G bottom trawl survey estimates of biomass and age composition. Binned length composition data are used in the model only when age composition estimates are unavailable, such as the most recent surveys. The following table specifies the data that were used in the GOA pollock assessment:

| **Source** | **Data** | **Years** |
| --- | --- | --- |
| NMFS Groundfish survey | Survey biomass | 1984-1999 (triennial), 2001-2019 (biennial) |
| Age composition | 1984, 1987, 1990, 1993, 1996, 1999, 2003, 2005, 2007, 2009, 2011, 2013, 2015, 2017, 2019 |
| U.S. trawl fishery | Catch | 1961-2020 |
| Age composition | 1998-2002, 2004-2006, 2008, 2010, 2012, 2014, 2016, 2018 |
| Length composition | 1991-1997, 2003, 2007, 2009, 2011, 2013, 2015, 2017, 2019 |

## Fishery

### Catch

Total catch estimates were obtained from INPFC and ADF&G publications, and databases maintained at the Alaska Fisheries Science Center and the Alaska Regional Office. Foreign catches for 1963-1970 are reported in Forrester et al. (1978). During this period only Japanese vessels reported catch of pollock in the GOA, though there may have been some catches by Soviet Union vessels. Foreign catches 1971-1976 are reported by Forrester et al. (1983). During this period there are reported pollock catches for Japanese, Soviet Union, Polish, and South Korean vessels in the Gulf of Alaska. Foreign and joint venture catches for 1977-1988 are blend estimates from the NORPAC database maintained by the Alaska Fisheries Science Center. Domestic catches for 1970-1980 are reported in Rigby (1984). Domestic catches for 1981-1990 were obtained from PacFIN (Brad Stenberg, pers. comm. Feb 7, 2014). A discard ratio (discard/retained) of 13.5% was assumed for all domestic catches prior to 1991 based on the 1991-1992 average discard ratio. Estimated catch for 1991-2020 was obtained from the Catch Accounting System database maintained by the Alaska Regional Office. These estimates are derived from shoreside electronic logbooks and observer estimates of at-sea discards (Table 1.4). Catches include the state-managed pollock fishery in Prince William Sound (PWS). Since 1996, the pollock Guideline Harvest Level (GHL) of 2.5% for the PWS fishery has been deducted from the total Acceptable Biological Catch (ABC) by the NPFMC Gulf of Alaska Plan Team for management purposes (see SAFE introduction for further information). Non-commercial catches are reported in Appendix 1E.

### Age and Size Composition

Catch at age was re-estimated in the 2014 assessment for 1975-1999 from primary databases maintained at AFSC. A simple non-stratified estimator was used, which consisted of compiling a single age-length key for use in every year and the applying the annual length composition to that key. Use of an age-length key was considered necessary because observers used length-stratified sampling designs to collect otoliths prior to 1999 (Barbeaux et al. 2005). Estimates were made separately for the foreign/JV and domestic fisheries in 1987 when both fisheries were sampled. There were no major discrepancies between the re-estimated age composition and estimates that have built up gradually from assessment to assessment.

Estimates of fishery age composition from 2000 onwards were derived from at-sea and port sampling of the pollock catch for length and ageing structures (otoliths). The length composition and ageing data were obtained from the NORPAC database maintained at AFSC. Catch age composition was estimated using methods described by Kimura and Chikuni (1989). Age samples were used to construct age-length keys by sex and stratum. These keys were applied to sex and stratum specific length frequency data to estimate age composition, which were then weighted by the catch in numbers in each stratum to obtain an overall age composition. A background age-length key is used fill the gaps in age-length keys by sex and stratum. Sampling levels by stratum for 2000-2015 are documented in the assessments available online at <http://www.afsc.noaa.gov/REFM/stocks/Historic_Assess.htm>. Age and length samples from the 2020 fishery were stratified by half-year seasons and statistical area as follows:

table TODO

The estimated age composition in 2020 in all areas and all seasons was notable because it was not dominated by age-8 fish (2012 year class) for the first time in many years (Fig. 1.2). Instead, the age-3 fish had the largest percentage with 38% while the age-8 fish only accounting for 29%. Younger fish are likely to become increasingly prominent in the catch-at-age as the 2012 year class begins age out of the population. Fishery catch at age in 1975-2020 is presented in Table 1.5 (See also Fig. 1.3). Sample sizes for ages and lengths are given in Table 1.6.

## Gulf of Alaska Bottom Trawl Survey

Trawl surveys have been conducted by Alaska Fisheries Science Center (AFSC) beginning in 1984 to assess the abundance of groundfish in the Gulf of Alaska (Table 1.7). Starting in 2001, the survey frequency was increased from once every three years to once every two years. The survey uses a stratified random design, with 49 strata based on depth, habitat, and statistical area (von Szalay et al. 2010). Area-swept biomass estimates are obtained using mean CPUE (standardized for trawling distance and mean net width) and stratum area. The survey is conducted from chartered commercial bottom trawlers using standardized poly-Nor‘eastern high opening bottom trawls rigged with roller gear. In a full three-boat survey, 800 tows are completed, but the recent average has been closer to 600 tows. On average, 72% of these tows contain pollock (Table 1.8). Recent years have dropped stations in deeper water which are unlikely to affect the index due to pollock typically being in shallower depths with on average 90.9% below 200 m and 99.6% below 300 m from 1984-2021.

### Biomass Estimates

The time series of pollock biomass used in the assessment model is based on the surveyed area in the Gulf of Alaska west of 140° W long., obtained by adding the biomass estimates for the Shumagin-610, Chirikof-620, Kodiak-630 statistical areas, and the western portion of Yakutat-640 statistical area. Biomass estimates for the west Yakutat area were obtained by splitting strata and survey CPUE data at 140° W long. and re-estimating biomass for west Yakutat. In 2001, when eastern Gulf of Alaska was not surveyed, a random effects model was used to interpolate a value for west Yakutat for use in the assessment model.

The Alaska Fisheries Science Center’s (AFSC) Resource Assessment and Conservation Engineering (RACE) Division conducted the seventeenth comprehensive bottom trawl survey since 1984 during the summer of 2021 (Fig. 1.4). The 2021 gulfwide biomass estimate of pollock was 528,841 t, which is an increase of 72.2% from the 2019 estimate, which was the second lowest in the time series after 2001. The biomass estimate for the portion of the Gulf of Alaska west of 140º W long. used in the assessment model is 494,743 t. The coefficient of variation (CV) of this estimate was 0.17, which is slightly below the average for the entire time series. Surveys from 1990 onwards are used in the assessment due to the difficulty in standardizing the surveys in 1984 and 1987, when Japanese vessels with different gear were used.

### Age Composition

Estimates of numbers at age from the bottom trawl survey are obtained from random otolith samples and length frequency samples (Table 1.9). Numbers at age are estimated by statistical area (Shumagin-610, Chirikof-620, Kodiak-630, Yakutat-640 and Southeastern-650) using a global age-length key for all strata in each single year, and CPUE-weighted length frequency data by statistical area. The combined Shumagin, Chirikof and Kodiak age composition is used in the assessment model (Fig. 1.4). No new ages were available this year, and instead length compositions were used in the model (Fig. 1.5) but 2019 ages indicated the continued dominance of the 2012 year class (age-7 fish) in the Western and Central GOA (Fig. 1.6). Age-1 pollock were strongly present in the Chirikof, Kodiak, and Yakutat statistical areas, but much less abundant in the Shumagin and Southeast Alaska areas (Fig. 1.7).

## Shelikof Strait Acoustic Survey

Winter acoustic surveys to assess the biomass of pre-spawning aggregations pollock in Shelikof Strait have been conducted annually since 1981 (except 1982, 1999, and 2011). Only surveys from 1992 and later are used in the stock assessment due to the higher uncertainty associated with the acoustic estimates produced with the Biosonics echosounder used prior to 1992. Additionally, raw survey data are not easily recoverable for the earlier acoustic surveys, so there is no way to verify (i.e., to reproduce) the estimates. Survey methods and results for 2021 are presented in a NMFS processed report (Honkalehto et al., in prep.). In 2008, the noise-reduced R/V Oscar Dyson became the designated survey vessel for acoustic surveys in the Gulf of Alaska. In winter of 2007, a vessel comparison experiment was conducted between the R/V Miller Freeman (MF) and the R/V Oscar Dyson (OD), which obtained an OD/MF ratio of 1.132 for the acoustic backscatter detected by the two vessels in Shelikof Strait.

### Biomass Estimates

The 2021 biomass estimate for Shelikof Strait is 526,974 t, which is a 15% percent increase from the 2020 estimate (Fig. 1.8). This estimate accounts for trawl selectivity by scaling up the number of retained pollock by selectivity curves estimated with pocket nets attached to the midwater trawl used to sample echosign, continuing an approach that was started in 2018 assessment. Originally, winter 2021 pre-spawning pollock surveys were also planned in the Shumagin Islands area, Chirikof shelf break, and in Prince William Sound and the Kenai Peninsula fjords. Due to travel, vessel, and staffing constraints stemming from protocols required to mitigate the COVID-19 pandemic, only Shelikof, Marmot, and Chirikof were attempted. Eventually Chirikof was dropped due to inclement weather and because real-time observations of the large age-1 2020 year class in Shelikof Strait necessitated collecting sufficient additional trawling to estimate net selectivity for pollock in 2021

table TODO

Biomass in Marmot Bay in 2021 increased by 18% compared to 2019, the last year it was surveyed. Overall, there appears to be a concentration of spawning activity in Shelikof Strait compared to other areas in the Gulf of Alaska, but the reduced survey coverage outside of Shelikof Strait limits the conclusions that can be drawn.

### Age Composition

Estimates of numbers at age from the Shelikof Strait acoustic survey (Table 1.10, Fig. 1.9) were obtained using an age-length key compiled from random otolith samples and applied to weighted length frequency samples. Sample sizes for ages and lengths are given Table 1.11. Estimates of age composition in Shelikof Strait in 2021 indicate reduced dominance of the nine year old 2012 year class, and a mode of age 4 fish (2017 year class), indicating a new year class is starting to comprise the majority of the spawning and exploitable portion of the population.

Based on recommendations from the 2012 CIE review, we developed an approach to model the age-1 and age-2 pollock estimates separately from the Shelikof Strait acoustic survey biomass and age composition. Age-1 and age-2 pollock are highly variable but occasionally very abundant in winter acoustic surveys, and by fitting them separately from the 3+ fish it is possible utilize an error distribution that better reflects that variability. Indices are available for both the Shelikof Strait and Shumagin surveys, but a longer time series of net-selectivity corrected indices are available for Shelikof Strait. In addition, model comparisons in the 2018 assessment indicates that a slightly better fit could be obtained with only Shelikof Strait indices. Therefore this time series was used in the model, but this decision should be revisited as additional data become available. The age-2 index in 2020 showed a marked reduction in comparison to the age-1 index in 2019, which indicated high abundance of the 2018 year class. Typically year classes that are abundant in Shelikof Strait at age 1 are also abundant at age 2 in the survey in the following year. The 2018 cohort comprised 15% of the age composition (excluding age 1 and 2 fish) as 3 year olds in 2021, giving further evidence for marked decrease from initial estimates as age 1 fish. Consequently, there is considerable uncertainty regarding the fate of 2018 year class, which may have exited Shelikof Strait for some reason and be distributed elsewhere in the GOA, or suffered extremely high mortality.

### Spawn timing and availability of pollock to the winter Shelikof survey

The Shelikof Strait winter acoustic survey is timed to correspond to the aggregation of pre-spawning pollock in Shelikof Strait. However, the timing of spawning has been found to vary from year to year, which may affect the availability of pollock to the survey. Variation in spawn timing is not random, but has been linked to thermal conditions in March and the age structure of the spawning stock (Rogers and Dougherty 2019); spawning tends to occur earlier when temperatures are warmer and when the spawning stock is older on average. Greater age diversity also results in a more protracted spawning period, presumably due to both early (old) and late (young) spawners, although this has not been verified in the field. Dorn et al. (2020) discuss correlations with spawn timing and model residuals. No additional work was done this year but is an ongoing effort.

## Summer Acoustic Survey

Five complete acoustic surveys, in 2013, 2015, 2017, 2019 and 2021, have been conducted by AFSC on the R/V Oscar Dyson in the Gulf of Alaska during summer (Jones et al. 2014, 2017, 2019, in prep.; Levine et al. in prep.). The area surveyed covers the Gulf of Alaska shelf and upper slope and associated bays and troughs, from a westward extent of 170° W Lon, and extends to an eastward extent of 140° W lon. Prince William Sound was also surveyed in 2013, 2015, and 2019. The survey consists of widely-spaced parallel transects along the shelf, and more closely spaced transects in troughs, bays, and Shelikof Strait. Mid-water and bottom trawls are used to identify acoustic targets. The 2021 biomass estimate for summer acoustic survey is 431,148 t, which is a 25% percent decrease from the 2019 estimate (Table 1.7). Age composition data were not available, but preliminary results in 2021 indicated that the very abundant 2012 year class was present but with reduced contribution, and strong modes of both presumed age-1 and age-4 fish were distributed broadly throughout the GOA (Fig. 1.10). Analysis of the 2019 and 2021 survey was not complicated by the presence of age-0 pollock, which was a problem in previous summer acoustic surveys because age-0 pollock backscatter cannot be readily distinguished from age 1+ pollock.

## Alaska Department of Fish and Game Crab/Groundfish Trawl Survey

The Alaska Department of Fish and Game (ADF&G) has conducted bottom trawl surveys of nearshore areas of the Gulf of Alaska since 1987 (depths from 18-246 m, median of 106 m; Fig. 1.11). Although these surveys are designed to monitor population trends of Tanner crab and red king crab, pollock 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 (Fig. 1.11). The average number of tows completed during the survey is 337. On average, 87% of these tows contain pollock. Details of the ADF&G trawl gear and sampling procedures are in Spalinger (2012).

The 2021 area-swept biomass estimate for pollock for the ADF&G crab/groundfish survey was 64,813 t, and increase of 9.2% from the 2020 biomass estimate (Table 1.7). The 2021 pollock estimate for this survey is approximately 70% of the long-term average. ### Biomass Estimates A simple delta GLM model was applied to the ADF&G tow by tow data for 1988-2021 to obtain annual abundance indices. Data from all years were filtered to exclude missing latitude and longitudes and missing tows made in lower Shelikof Strait (between 154.7° W lon. and 156.7° W lon.) were excluded because these stations were sampled irregularly. The delta GLM model fit a separate model to the presence-absence observations and to the positive observations. A fixed effects model was used with the year, geographic area, and depth as factors. Strata were defined according to ADF&G district (Kodiak, Chignik, South Peninsula) and depth (<30 fm, 30-100 fm, >100 fm). Alternative depth strata were evaluated, and model results were found to be robust to different depth strata assumptions. The same model structure was used for both the presence-absence observations and the positive observations. The assumed likelihoods were binomial for presence-absence observations and gamma for the positive observations, after evaluation of several alternatives, including lognormal, gamma, and inverse Gaussian, and which is in line with recommendations for index standardization (Thorson et al. 2021). The model was fit using brms package in R (Bürkner 2017, 2018), which fits Bayesian non-linear regression models using the modeling framework Stan (Stan Development Team 2020). Comparison of delta-GLM indices the area-swept estimates indicated similar trends (Fig. 1.12). Variances were based on MCMC sampling from the posterior distribution, and CVs for the annual index ranged from 0.10 to 0.18. These values likely understate the uncertainty of the indices with respect to population trends, since the area covered by the survey is a relatively small percentage of the GOA shelf area, and so the CVs are scaled up to have an average of 0.25.

### Age Compositions

Ages were determined by age readers in the AFSC age and growth unit from samples of pollock otoliths collected during 2000-2020 ADF&G surveys in even-numbered years (average sample size = 583; Table 1.12, Fig. 1.13). Comparison with fishery age composition shows that older fish (> age-8) are more common in the ADF&G crab/groundfish survey. This is consistent with the assessment model, which estimates a domed-shaped selectivity pattern for the fishery, but an asymptotic selectivity pattern for the ADF&G survey.

## Data sets considered but not used

### Egg production estimates of spawning biomass

Estimates of spawning biomass in Shelikof Strait based on egg production methods were produced during 1981-92 (Table 1.7). A complete description of the estimation process is given in Picquelle and Megrey (1993). Egg production estimates were discontinued in 1992 because the Shelikof Strait acoustic survey provided similar information. The egg production estimates are not used in the assessment model because the surveys are no longer being conducted, and because the acoustic surveys in Shelikof Strait show a similar trend over the period when both were conducted.

### Pre-1984 bottom trawl surveys

Considerable survey work was carried out in the Gulf of Alaska prior to the start of the NMFS triennial bottom trawl surveys in 1984. Between 1961 and the mid-1980s, the most common bottom trawl used for surveying was the 400-mesh eastern trawl. This trawl (or variants thereof) was used by IPHC for juvenile halibut surveys in the 1960s, 1970s, and early 1980s, and by NMFS for groundfish surveys in the 1970s. Von Szalay and Brown (2001) estimated a fishing power correction (FPC) for the ADF&G 400-mesh eastern trawl of 3.84 (SE = 1.26), indicating that 400-mesh eastern trawl CPUE for pollock would need to be multiplied by this factor to be comparable to the NMFS poly-Nor’eastern trawl.

In most cases, earlier surveys in the Gulf of Alaska were not designed to be comprehensive, with the general strategy being to cover the Gulf of Alaska west of Cape Spencer over a period of years, or to survey a large area to obtain an index for group of groundfish, i.e., flatfish or rockfish. For example, Ronholt et al. (1978) combined surveys for several years to obtain gulfwide estimates of pollock biomass for 1973-1976. There are several difficulties with such an approach, including the possibility of double-counting or missing a portion of the stock that happened to migrate between surveyed areas. Due to the difficulty in constructing a consistent time series, the historical survey estimates are no longer used in the assessment model.

Multi-year combined survey estimates indicate a large increase in pollock biomass in the Gulf of Alaska occurred between the early 1960s and the mid 1970s. Increases in pollock biomass between the1960s and 1970s were also noted by Alton et al. (1987). In the 1961 survey, pollock were a relatively minor component of the groundfish community with a mean CPUE of 16 kg/hr. (Ronholt et al. 1978). Arrowtooth flounder was the most common groundfish with a mean CPUE of 91 kg/hr. In the 1973-76 surveys, the CPUE of arrowtooth flounder was similar to the 1961 survey (83 kg/hr.), but pollock CPUE had increased 20-fold to 321 kg/hr., and was by far the dominant groundfish species in the Gulf of Alaska. Mueter and Norcross (2002) also found that pollock was low in the relative abundance in 1960s, became the dominant species in Gulf of Alaska groundfish community in the 1970s, and subsequently declined in relative abundance.

Questions concerning the comparability of pollock CPUE data from historical trawl surveys with later surveys probably can never be fully resolved. However, because of the large magnitude of the change in CPUE between the surveys in the 1960s and the early 1970s using similar trawling gear, the conclusion that there was a large increase in pollock biomass seems robust. Early speculation about the rise of pollock in the Gulf of Alaska in the early 1970s implicated the large biomass removals of Pacific ocean perch, a potential competitor for euphausid prey (Somerton 1979, Alton et al. 1987). More recent work has focused on role of climate change (Anderson and Piatt 1999, Bailey 2000). These easrlier surveys suggest that population biomass in the 1960s, prior to large-scale commercial exploitation of the stock, may have been lower than at any time since then.

## Qualitative Trends

To qualitatively assess recent trends in abundance, each survey time series was standardized by dividing the annual estimate by the average since 1990. Shelikof Strait acoustic survey estimates prior to 2008 were rescaled to be comparable to subsequent surveys conducted by the R/V Oscar Dyson. Although there is considerable variability in each survey time series, a fairly clear downward trend is evident to 2000, followed by a stable, though variable, trend to 2008, followed by a strong increase to 2013 (Fig. 1.14). From 2016 to 2019 there was a strong divergence among the trends, but with the large reduction in biomass in 2020 for the Shelikof Strait survey, and an increase in the ADF&G index, relative abundance has come back into reasonable alignment since 2020. Indices derived from fisheries catch data were also evaluated for trends in biological characteristics (Fig. 1.15). The percent of females in the catch shows some variability but no obvious trend, and is usually close to 50-50. In 2016, percent female dropped to 40%, but increased to 43% in 2017 and remained similar through 2020. Evaluation of sex ratios by season indicated that this decrease was mostly due a low percentage of females during the A and B seasons prior to spawning. However the sex ratio during the C and D seasons was close to 50-50, suggesting the skewed sex in winter was related to spawning behavior, rather than an indication of a population characteristic. The mean age shows interannual variability due to strong year classes passing through the population, but there are no downward trends that would suggest excessive mortality rates. The percent of old fish in the catch (nominally defined as age 8 and older) is also highly variable due to variability in year class strength. The percent of old fish declined in 2015-2018 as the strong 2012 year class recruited to the fishery, but increased when the 2012 year class became age 8 in 2020. Under a constant F40% harvest rate, the mean percent of age 8 and older fish in the catch would be approximately 8%. An annual index of catch at age diversity was computed using the Shannon-Wiener information index,

where is the proportion at age and higher values correspond to higher diversity. Increases in fishing mortality would tend to reduce age diversity, but year class variability would also influence it. Age diversity was relatively stable during 1975-2015, but declined sharply to a low in 2016 and has been increasing since due to the dominance of the 2012 year class in the catch (Fig. 1.15). In 2020 the age diversity returned to near the long-term average.

The 2012 year class, which is both very strong, and which has experienced anomalous environmental conditions during the marine heatwave in the North Pacific during 2015-2017, has displayed unusual life history characteristics. These include early maturation, reduced growth, but apparently not reduced total mortality (Fig. 1.16). It is unclear whether these changes are a result of density dependence or environmental forcing.

# Analytical approach

## General Model Structure

An age-structured model covering the period from 1970 to 2021 (52 years) was used to assess Gulf of Alaska pollock. The modeled population includes individuals from age 1 to age 10, with age 10 defined as a “plus” group, i.e., all individuals age 10 and older. Population dynamics were modeled using standard formulations for mortality and fishery catch (e.g. Fournier and Archibald 1982, Deriso et al. 1985, Hilborn and Walters 1992). Year- and age-specific fishing mortality was modeled as a product of a year effect, representing the full-selection fishing mortality, and an age effect, representing the selectivity of that age group to the fishery. The age effect was modeled using a double-logistic function with time-varying parameters (Dorn and Methot 1990, Sullivan et al. 1997). The model was fit to time series of catch biomass, survey indices of abundance, and estimates of age and length composition from the fishery and surveys. Details of the population dynamics and estimation equations are presented in Appendix 1C.

Model parameters were estimated by maximizing the joint log likelihood of the data, viewed as a function of the parameters. Mean-unbiased log-normal likelihoods were used for survey biomass and total catch estimates, and multinomial likelihoods were used for age and length composition data. Model tuning for composition data was done by iterative re-weighting of input sample sizes using the Francis (2011) method. Variance estimates/assumptions for survey indices were not reweighted. The following table lists the likelihood components used in fitting the model.

table of likelihoods TODO

### Recruitment

In most years, year-class abundance at age 1 was estimated as a free parameter. Age composition in the first year was estimated with a single log deviation for recruitment abundance, which was then decremented by natural mortality to fill out the initial age vector. A penalty was added to the log likelihood so that the log deviation in recruitment for 1970-77, and in the last two years of the model, would have the same variability as recruitment during the data-rich period (σR =1.0). Log deviations from mean log recruitment were estimated as free parameters in other years. These relatively weak constraints were sufficient to obtain fully converged parameter estimates while retaining an appropriate level of uncertainty.

### Modeling fishery data

To accommodate changes in selectivity we estimated year-specific parameters for the slope and the intercept parameter for the ascending logistic portion of selectivity curve (i.e., younger fish). Variation in these parameters was constrained using a random walk penalty.

### Modeling survey data

Survey abundance was assumed to be proportional to total abundance as modified by the estimated survey selectivity pattern. Expected population numbers at age for the survey were based on the mid-date of the survey, assuming constant fishing and natural mortality throughout the year. Standard deviations in the log-normal likelihood were set equal to the sampling error CV (coefficient of variation) associated with each survey estimate of abundance (Kimura 1991).

Survey catchability coefficients can be fixed or freely estimated. The base model estimated the NMFS bottom trawl survey catchability, but used a log normal prior with a median of 0.85 and log standard deviation 0.1 based on expert judgement as a constraint on potential values (Fig. 1.17). Catchability coefficients for other surveys were estimated as free parameters. The age-1 and age-2 winter acoustic survey indices are numerical abundance estimates, and were modeled using independently estimated catchability coefficients (i.e., no selectivity is estimated).

This assessment is based on a statistical age-structured model with the catch equation and population dynamics model as described in (**Fournier1982?**) and elsewhere (e.g., (**Hilborn1992?**); (**Schnute1995?**), (**McAllister1997?**)). The catch in numbers at age in year and total catch biomass can be described as:

A vessel comparison (VC) experiment was conducted in March 2007 during the Shelikof Strait acoustic survey. The VC experiment involved the R/V Miller Freeman (MF, the survey vessel used to conduct Shelikof Strait surveys since the mid-1980s), and the R/V Oscar Dyson (OD), a noise-reduced survey vessel designed to conduct surveys that have traditionally been done with the R/V Miller Freeman. The vessel comparison experiment was designed to collect data either with the two vessels running beside one another at a distance of 0.7 nmi, or with one vessel following nearly directly behind the other at a distance of about 1 nmi. The methods were similar to those used during the 2006 Bering Sea VC experiment (De Robertis et al. 2008). Results indicate that the ratio of 38 kHz pollock backscatter from the R/V Oscar Dyson relative to the R/V Miller Freeman was significantly greater than one (1.13), as would be expected if the quieter OD reduced the avoidance response of the fish. Previously we included a likelihood component to incorporate this information in the assessment model, but dropped it because this survey is now modeled with a random walk in catchability, and a relatively small systematic change in catchability is inconsequential compared to other factors affecting catchability.

### Ageing error

An ageing error conversion matrix is used in the assessment model to translate model population numbers at age to expected fishery and survey catch at age (Table 1.13). Dorn et al. (2003) estimated this matrix using an ageing error model fit to the observed percent reader agreement at ages 2 and 9. Mean percent agreement is close to 100% at age 1 and declines to 40% at age 10. Annual estimates of percent agreement are variable, but show no obvious trend; hence a single conversion matrix for all years in the assessment model was adopted. The model is based on a linear increase in the standard deviation of ageing error and the assumption that ageing error is normally distributed. The model predicts percent agreement by taking into account the probability that both readers are correct, both readers are off by one year in the same direction, and both readers are off by two years in the same direction (Methot 2000). The probability that both agree and were off by more than two years was considered negligible. A study evaluated pollock ageing criteria using radiometric methods and found them to be unbiased (Kastelle and Kimura 2006).

### Length frequency data

The assessment model was fit to length frequency data from various sources by converting predicted age distributions (as modified by age-specific selectivity) to predicted length distributions using an age-length conversion matrix. This approach was used only when age composition estimates were unavailable, as occurs when the survey is the same as the assessment. Because seasonal differences in pollock length at age are large, particularly for the younger fish, several conversion matrices were used. For each matrix, unbiased length distributions at age were estimated for several years using age-length keys, and then averaged across years. A conversion matrix was estimated using 1992-1998 Shelikof Strait acoustic survey data and used for winter survey length frequency data. The following length bins were used: 5-16, 17 - 27, 28 - 35, 36 - 42, 43 - 50, 51 - 55, 56 - 70 (cm). Age data for the most recent survey is now routinely available so this option does not need to be invoked. A conversion matrix was estimated using second and third trimester fishery age and length data during the years (1989-1998), and was used when age composition data are unavailable for the summer bottom trawl survey, which is only for the most recent survey in the year that the survey is conducted. The following length bins were used: 5-24, 25 - 34, 35 - 41, 42 - 45, 46 - 50, 51 - 55, 56 – 70 (cm), so that the first four bins would capture most of the summer length distribution of the age-1, age-2, age-3 and age-4 fish, respectively. Bin definitions were different for the summer and the winter conversion matrices to account for the seasonal growth of the younger fish (ages 1-4).

### Initial data weighting

The input sample sizes were initially standardized by data set before model tuning. Fishery age composition was given an initial sample size of 200 except when the age sample in a given year came from fewer than 200 hauls/deliveries, in which case the number of hauls/deliveries was used. Both the Shelikof acoustic survey and the bottom trawl were given an initial sample size of 60, and the ADF&G crab/groundfish survey was given a weight of 30.

## Parameters Estimated Outside the Assessment Model

Pollock life history characteristics, including natural mortality, weight at age, and maturity at age, were estimated independently outside the assessment model. These parameters are used in the model to estimate spawning and population biomass and obtain predictions of fishery catch and survey biomass. Pollock life history parameters include:

-Natural mortality (M) -Proportion mature at age -Weight at age and year by fishery and by survey

### Natural mortality

Hollowed and Megrey (1990) estimated natural mortality (M) using a variety of methods including estimates based on: a) growth parameters (Alverson and Carney 1975, and Pauly 1980), b) GSI (Gunderson and Dygert, 1988), c) monitoring cohort abundance, and d) estimation in the assessment model. These methods produced estimates of natural mortality that ranged from 0.22 to 0.45. The maximum age observed was 22 years. Up until the 2014 assessment, natural mortality had been assumed to be 0.3 for all ages.

Hollowed et al. (2000) developed a model for Gulf of Alaska pollock that accounted for predation mortality. The model suggested that natural mortality declines from 0.8 at age 2 to 0.4 at age 5, and then remains relatively stable with increasing age. In addition, stock size was higher when predation mortality was included. In a simulation study, Clark (1999) evaluated the effect of an erroneous M on both estimated abundance and target harvest rates for a simple age-structured model. He found that “errors in estimated abundance and target harvest rate were always in the same direction, with the result that, in the short term, extremely high exploitation rates can be recommended (unintentionally) in cases where the natural mortality rate is overestimated and historical exploitation rates in the catch-at-age data are low.” Clark (1999) proposed that the chance of this occurring could be reduced by using an estimate of natural mortality on the lower end of the credible range, which is the approach used in this assessment. In the 2014 assessment, several methods to estimate of the age-specific pattern of natural mortality were evaluated. Two general types of methods were used, both of which are external to the assessment model. The first type of method is based initially on theoretical life history or ecological relationships that are then evaluated using meta-analysis, resulting in an empirical equation that relates natural mortality to some more easily measured quantity such as length or weight. The second type of method is an age-structured statistical analysis using a multispecies model or single species model where predation is modeled. There are three examples of such models for pollock in Gulf of Alaska, a single species model with predation by Hollowed et al. (2000), and two multispecies models that included pollock by Van Kirk et al. (2010 and 2012). These models were published in the peer-reviewed literature, but likely did not receive the same level of scrutiny as stock assessment models. Although these models also estimate time-varying mortality, we averaged the total mortality (residual natural mortality plus predation mortality) for the last decade in the model to obtain a mean age-specific pattern (in some cases omitting the final year when estimates were much different than previous years). Use of the last decade was an attempt to use estimates with the strongest support from the data. Approaches for inclusion of time-varying natural mortality will be considered in future pollock assessments. The three theoretical/empirical methods used were the following:

*Brodziak et al. 2011*: Age-specific M is given by

where is the length at maturity, is the natural mortality at , is the mean length at age for the summer bottom trawl survey for 1984-2013.

*Lorenzen 1996*: Age-specific M for ocean ecosystems is given by

where is the mean weight at age from the summer bottom trawl survey for 1984-2013.

*Gislason et al. 2010*: Age-specific M is given by

where cm and were estimated by fitting von Bertalanffy growth curves using the NLS routine in R using summer bottom trawl age data for 2005-2009 for sexes combined in the central and western Gulf of Alaska. Results were reasonably consistent and suggest use of a higher mortality rate for age classes younger than the age at maturity (Table 1.14 and Fig. 1.18). Somewhat surprisingly, the theoretical/empirical estimates were similar, on average, to predation model estimates. To obtain an age-specific natural mortality schedule for use in the stock assessment, we used an ensemble approach and averaged the results for all methods. Then we used the method recommended by Clay Porch in Brodziak et al (2011) to rescale the age-specific values so that the average for range of ages equals a specified value. Age-specific values were rescaled so that a natural mortality for fish greater than or equal to age 5, the age at 50% maturity, was equal to 0.3, the value of natural mortality used in previous pollock assessments.

### Maturity at age

Maturity stages for female pollock describe a continuous process of ovarian development between immature and post-spawning. For the purposes of estimating a maturity vector (the proportion of an age group that has been or will be reproductively active during the year) for stock assessment, all fish greater than or equal to a particular maturity stage are assumed to be mature, while those less than that stage are assumed to be immature. Maturity stages in which ovarian development had progressed to the point where ova were distinctly visible were assumed to be mature (i.e., stage 3 in the 5-stage pollock maturity scale). Maturity stages are qualitative rather than quantitative, so there is subjectivity in assigning stages, and a potential for different technicians to apply criteria differently (Neidetcher et al. 2014). Because the link between pre-spawning maturity stages and eventual reproductive activity later in the season is not well established, the division between mature and immature stages is problematic. Changes in the timing of spawning could also affect maturity at age estimates. Merati (1993) compared visual maturity stages with ovary histology and a blood assay for vitellogenin and found general consistency between the different approaches. Merati (1993) noted that ovaries classified as late developing stage (i.e., immature) may contain yolked eggs, but it was unclear whether these fish would have spawned later in the year. The average sample size of female pollock maturity stage data per year since 2000 from winter acoustic surveys in the Gulf of Alaska is 373 (Table 1.15). In 2019, a new approach was introduced to estimate maturity at age using specimen data from the Shelikof Strait acoustic survey. Maturity estimates from 2003 onwards were revised using this method. The approach uses local abundance to weight the maturity data collected in a haul. To estimate abundance, each acoustic survey distance unit (0.5 nmi of trackline) was assigned to a stratum representing nearest survey haul. Each haul’s biological data was then used to scale the corresponding acoustic backscatter by within that stratum into abundance. To generate abundance weights for specimen data taken for each haul location, the abundance estimates of adult pollock (≥ 30 cm fork length) were summed for each haul-stratum. The 30 cm length threshold represents the length at which pollock are 5% mature in the entire Shelikof Strait historic survey data. Total adult pollock abundances in each stratum scaled by dividing by the mean abundance per stratum (total abundance /number of haul-strata). Weights range from 0.05 to 6, as some hauls were placed in light sign while others sampled very dense aggregations. For each haul, the number of female pollock considered mature (prespawning, spawning, or spent) and immature (immature or developing) were computed for each age. The maturity ogive for maturity-at-age was estimated as a logistic regression using a weighted generalized linear model where the dependent variable was the binomial spawning state, the independent variable was the age, and data from each haul weighted by the appropriate values as computed above. The length and age at 50% maturity was derived (L50%, A50%) from the ratio of the regression coefficients. The new maturity estimates had a relatively minor impact on assessment results, and usually reduced estimates of spawning biomass by about 2 percent. Estimates of maturity at age in 2021 from winter acoustic surveys using the new method are higher for younger fish, but lower for older fish, compared to 2020 and the long-term mean for all ages (Fig. 1.19). Inter-annual changes in maturity at age may reflect environmental conditions, pollock population biology, effect of strong year classes moving through the population, or simply ageing error. Because there did not appear to be an objective basis for excluding data, the 1983-2021 average maturity at age was used in the assessment.

Logistic regression (McCullagh and Nelder 1983) was also used to estimate the age and length at 50% maturity at age for each year to evaluate long-term changes in maturation. Annual estimates of age at 50% maturity are highly variable and range from 2.6 years in 2017 to 6.1 years in 1991, with an average of 4.8 years (Fig. 1.20). The last few years has shown a decrease in the age at 50% mature, which is largely being driven by the maturation of the 2012 year class at younger ages than is typical, however the 2019 to 2021 estimates of age at 50% mature are near the long-term average. Length at 50% mature is less variable than the age at 50% mature, suggesting that at least some of the variability in the age at maturity can be attributed to changes in length at age. Changes in year-class dominance also likely affect estimates of maturity at length, as a similar pattern is seen as with maturity at age with the 2012 cohort . The average length at 50% mature for all years is approximately 43 cm.

### Weight at age

Year-specific fishery weight-at-age estimates are used in the model to obtain expected catches in biomass. Where possible, year and survey-specific weight-at-age estimates are used to obtain expected survey biomass. For each data source, unbiased estimates of length at age were obtained using year-specific age-length keys. Bias-corrected parameters for the length-weight relationship, , were also estimated. Weights at age were estimated by multiplying length at age by the predicted weight based on the length-weight regressions. Weight at age for the fishery, the Shelikof Strait acoustic survey, and the NMFS bottom trawl survey and the summer acoustic survey are given in Table 1.16, Table 1.17, and Table 1.18. Data from the Shelikof Strait acoustic survey indicates that there has been a substantial changes in weight at age for older pollock (Fig. 1.21). For pollock greater than age 6, weight-at-age nearly doubled by 2012 compared to 1983-1990. However, weight at age since 2012 has trended strongly downward, with some stabilization in the last couple of years, but a notable increase in 2021 for all ages, and the heaviest age 2 fish to date (0.191 kg) and fourth heaviest age 3 fish (0.321 kg) as well. Further analyses are needed to evaluate whether these changes are a density-dependent response to declining pollock abundance, or whether they are environmentally forced. Changes in weight-at-age have potential implications for status determination and harvest control rules.

A random effects (RE) model for weight at age (Ianelli et al. 2016) was used to estimate of fishery weight at age in 2021 since age data were not available. The structural part of the model is an underlying von Bertalanffy growth curve. Year and cohort effects are estimated as random effects using the ADMB RE module. Further details are provided in Ianelli et al. (2016). Input data included fishery weight age for 1975-2020. The model also incorporates survey data by modeling an offset between fishery and survey weight at age. Weight at age for the Shelikof Strait acoustic survey (1981-2021) and the NMFS bottom trawl survey (1984-2019) were used. The model also requires input standard deviations for the weight at age data, which are not available for GOA pollock. In the 2016 assessment, a generalized variance function was developed using a quadratic curve to match the mean standard deviations at ages 3-10 for the eastern Bering Sea pollock data. The standard deviation at age one was assumed to be equal to the standard deviation at age 10. Survey weights at age were assumed to have standard deviations that were 1.5 times the fishery weights at age. A comparison of RE model estimates from last year of the 2020 fishery weight at age with the data now available indicate that the model underestimated weights except for ages 9-10 (Fig. 1.22). This includes underestimates of the age 3 and 8 fish in 2020 which made up the majority of catch (36% and 31%, respectively). In this assessment, RE model estimates of weight at age are used for the fishery in 2021 and for yield projections (Fig. 1.22).

## Parameters Estimated Inside the Assessment Model

A large number of parameters are estimated when using this modeling approach, though many are year-specific deviations in fishery selectivity coefficients. Parameters were estimated using AD Model Builder (Version 12.3), a C++ software language extension and automatic differentiation library (Fournier et al. 2012). Parameters in nonlinear models are estimated in AD Model Builder using automatic differentiation software extended from Greiwank and Corliss (1991) and developed into C++ class libraries. The optimizer in AD Model Builder is a quasi-Newton routine (Press et al. 1992). The model is determined to have converged when the maximum parameter gradient is less than a small constant (set to 1 x 10-6) and the Hessian matrix is invertible. AD Model Builder includes post-convergence routines to calculate standard errors (or likelihood profiles) for any quantity of interest.

A list of model parameters for the base model is shown below:

## Description of Alternative Models

Description of alternative models included in the assessment, if any (e.g., alternative M values or likelihood weights); note that the base model (i.e., the model most recently accepted by the SSC, either after reviewing the previous year’s final assessment or the current year’s preliminary assessment) must be included Per recommendation of the SSC (10/15), please use the following convention for numbering models: When a model constituting a “major change” from the original version of the base model is introduced, it is given a label of the form “Model *yy.j*,” where *yy* is the year (designated by the last two digits) that the model was introduced, and *j* is an integer distinguishing this particular “major change” model from other “major change” models introduced in the same year. When a model constituting only a “minor change” from the original version of the base model is introduced, it is given a label of the form “Model *yy.jx*,” where *x* is a letter distinguishing this particular “minor change” model from other “minor change” models derived from the original version of the same base model. Specifically, please use one of the following four options to distinguish “major” from “minor” changes:

# Results

## Model selection and evaluation

### Model selection

Prior to identifying a model for consideration, an analysis was conducted of the impact of each new data element on model results. Figure 1.21 shows the changes in estimated spawning biomass as the updated catch projections, catch at age, and surveys were added sequentially. In general, the addition of new data elements did not strongly affect the estimates of recent spawning biomass, with the exception of the updated weight at age from the 2021 Shelikof survey, which was substantially larger than the 2020 estimates. This effect is discussed in the risk table below. This suggests that the new data are reasonably consistent with previous modeling and with each other. Since previous assessments have identified inconsistent input data sets as a major assessment concern, the overall consistency this year suggests that those concerns are much reduced (e.g., Fig. 1.23).

The intent of this year’s assessment was to provide a straightforward update without considering major changes to the model. We recently explored models that used VAST estimates in place of area-swept biomass estimates for the NMFS bottom trawl survey. The VAST estimates did not fit as well as the area-swept estimates when given similar weighting, and we concluded that additional model evaluation was needed before using the VAST estimates. Several other modeling approaches for GOA pollock are under development, including incorporation of predator consumption (Barnes et al. 2020) in the assessment model, use of mean hatch date from the EcoFOFI early larval survey to inform catchability to the Shelikof Strait survey, and model-based estimates of Shelikof and summer acoustic indices using VAST. We selected model 19.1 as the preferred model, and a final turning step was done using the Francis (2011) approach which reweighted all composition components, including the summer acoustic age composition for the first time, but model results were nearly unchanged (Fig. 1.23).

### Model evaluation

The fit of model 19.1 to age composition data was evaluated using plots of observed and predicted age composition and residual plots. Figure 1.24 show the estimates of time-varying catchability for the Shelikof Strait acoustic survey and the ADF&G crab/groundfish survey. The catchability for the Shelikof Strait acoustic survey approaches one but does not exceed it and has declined in the last two years. Plots show the fit to fishery age composition (Fig. 1.25, Fig. 1.26), Shelikof Strait acoustic survey age composition (Fig. 1.27, Fig. 1.28), NMFS trawl survey age composition (Fig. 1.29), and ADF&G trawl survey age composition (Fig. 1.30). Model fits to fishery age composition data are adequate in most years, though the very strong 2012 year class shows up as a positive residual in for the 2016-2019 due to stronger than expected abundance in the age composition, while the older ages tended to have negative residuals. This may indicate that the fishery is targeting on the 2012 year class. The largest residuals tended to be at ages 1-2 in the NMFS bottom trawl survey due to inconsistencies between the initial estimates of abundance and subsequent information about year class size.

The fit to the 2021 Shelikof survey age was notably poor with a very large negative residual for age 3 fish (Fig. 1.27). A similar pattern is observed in the 2020 age 2 residual for the ADF&G compositional data (Fig. 1.30). These both point to a smaller 2018 cohort than originally observed and estimated. However, the fit to age 2 fish in the 2020 fishery data is much better, potentially due to lower selectivity at that age, and that it is time varying. Consequently, there is still conflict and uncertainty in the data about the size of the 2018 cohort. We anticipate new age composition data for the 2021 fishery, NMFS bottom trawl and summer acoustic surveys, and 2022 Shelikof survey to shed further light on the fate of this cohort.

Model fits to survey biomass estimates are reasonably good for all surveys except the period 2015-2019 (Fig. 1.31). There are large positive residuals for the Shelikof Strait acoustic survey in 2017, 2018 and 2019, and strong negative residuals for the NMFS bottom trawl survey for 2017 and 2019. In addition, the model is unable to fit the extremely low values for the ADF&G survey in 2015-2017. The fit to the summer acoustic survey is reasonable even during the most recent period. The model shows good fits to both the 2021 Shelikof Strait acoustic survey and the 2021 NMFS bottom trawl, while the 2021 ADF&G bottom trawl and 2021 summer acoustic survey fits were reasonable. The fit to the age-1 and age-2 Shelikof acoustic indices was considered acceptable (Fig. 1.32).

## Time series results

Parameter estimates and model output are presented in a series of tables and figures. Estimated survey and fishery selectivity for different periods are given in Table 1.19 (see also Fig. 1.33). Table 1.20 gives the estimated population numbers at age for the years 1970-2021. Table 1.21 gives the estimated time series of age 3+ population biomass, age-1 recruitment, and harvest rate (catch/3+ biomass) for 1977-2021 (see also Fig. 1.34). Table 1.22 gives coefficients of variation and 95% confidence intervals for age-1 recruitment and spawning stock biomass. Stock size peaked in the early 1980s at approximately 120% of the proxy for unfished stock size (B100% = mean 1978-2020 recruitment multiplied by the spawning biomass per recruit in the absence of fishing ([SPR@F](mailto:SPR@F)=0, see below for how this is calculated). In 2002, the stock dropped below the B40% for the first time since the early 1980s, and reached a minimum in 2003 of 35% of unfished stock size. Over the years 2009-2013 stock size showed a strong upward trend, increasing from 43% to 78% of unfished stock size, but declined to 54% of unfished stock size in 2015. The spawning stock peaked in 2017 at 83% as the strong 2012 year class matured, and has declined subsequently to 46% in 2021. Figure 1.35 shows the historical pattern of exploitation of the stock both as a time series of SPR and fishing mortality compared to the current estimates of biomass and fishing mortality reference points. Except from the mid-1970s to mid-1980s fishing mortalities have generally been lower than the current OFL definition, and in nearly all years were lower than the FMSY proxy of F35% .

## Comparison of historical assessment results

A comparison of assessment results for the years 1993-2021 indicates the current estimated trend in spawning biomass for 1990-2021 is consistent with previous estimates (Fig. 1.36). All time series show a similar pattern of decreasing spawning biomass in the 1990s, a period of greater stability in 2000s, followed by an increase starting in 2008. The estimated 2021 age composition from the current assessment were very similar to the projected 2021 age composition from the 2020 assessment (Fig. 1.37). Generally, the two models agree except for the age 1 recruits, where the 2020 model assumed average recruitment, but the 2021 has data from the Shelikof survey which showed a strong year class. This difference does not strongly affect the OFL and ABC for next year because these fish are not in the exploitable population.

## Retrospective analysis of base model

A retrospective analysis consists of dropping the data year-by-year from the current model, and provides an evaluation of the stability of the current model as new data are added. Figure 1.38 shows a retrospective plot with data sequentially removed back to 2011. There is up to 37% error in the estimates of spawning biomass (if the current assessment is accepted as truth), but usually the errors are much smaller (median absolute error is 11%). There is relatively minor positive retrospective pattern to errors in the assessment, and the revised Mohn’s ρ (Mohn 1999) across all ten peels for ending year spawning biomass is 0.056, which does not indicate a concern with retrospective bias.

## Stock productivity

Recruitment of GOA pollock is more variable (CV = 1.27 over 1978-2020) than Eastern Bering Sea pollock (CV = 0.60). Other North Pacific groundfish stocks, such as sablefish and Pacific ocean perch, also have high recruitment variability. However, unlike sablefish and Pacific ocean perch, pollock have a short generation time (~8 years), so that large year classes do not persist in the population long enough to have a buffering effect on population variability. Because of these intrinsic population characteristics, the typical pattern of biomass variability for GOA pollock will be sharp increases due to strong recruitment, followed by periods of gradual decline until the next strong year class recruits to the population. GOA pollock is more likely to show this pattern than other groundfish stocks in the North Pacific due to the combination of a short generation time and high recruitment variability.

Since 1980, strong year classes have occurred periodically every four to six years (Fig. 1.34). Because of high recruitment variability, the mean relationship between spawning biomass and recruitment is difficult to estimate despite good contrast in spawning biomass. Strong and weak year classes have been produced at high and low level of spawning biomass. Spawner productivity is higher on average at low spawning biomass compared to high spawning biomass, indicating that survival of eggs to recruitment is density-dependent (Fig. 1.39). However, this pattern of density-dependent survival only emerges on a decadal scale, and could be confounded with environmental variability on the same temporal scale. The decadal trends in spawner productivity have produced the pattern of increase and decline in the GOA pollock population. The last two decades have been a period of relatively low spawner productivity, though there appears to be a recent increase. Age-1 recruitment in 2020 is estimated to be to be very weak, but the 2021 recruitment is above average, although these estimates will remain very uncertain until additional data become available.

# {r, child="08-abc.Rmd", eval = T} #

# Ecosystem Considerations

## Ecosystem Effects on the Stock

1. Predator population trends (historically, in the present, and in the foreseeable future). These trends could affect stock mortality rates over time.
2. Changes in habitat quality (historically, in the present, and in the foreseeable future). Changes in the physical environment such as temperature, currents, or ice distribution could affect stock migration and distribution patterns, recruitment success, or direct effects of temperature on growth.

## Fishery Effects on the Ecosystem

1. Fishery-specific contribution to bycatch of prohibited species, forage (including herring and juvenile pollock), HAPC biota (in particular, species common to the target fishery), marine mammals, birds, and other sensitive non-target species (including top predators such as sharks, expressed as a percentage of the total bycatch of that species.
2. Fishery-specific concentration of target catch in space and time relative to predator needs in space and time (if known) and relative to spawning components.
3. Fishery-specific effects on amount of large-size target fish.
4. Fishery-specific contribution to discards and offal production.
5. Fishery-specific effects on age at maturity and fecundity of the target species.
6. Fishery-specific effects on EFH non-living substrate (using gear specific fishing effort as a proxy for amount of possible substrate disturbance).

# Data Gaps and Research Priorities

The following research priorities were identified based on previous CIE reviews and recent Plan Team and SSC discussions: • Explore alternative functional forms for fishery selectivity. • Jointly estimate process errors for time-varying components like selectivity, catchability and recruitment, using integration via the Laplace approximation or MCMC. • Consider alternative modeling platforms in parallel to the current ADMB assessment. • Explore priors on catchability and the effect on the population scale and potentially how it relates to results from the predation mortality model. • Revisit initial data weights for compositional data, and assumed CVs for indices. • Estimate input variances for weight at age components in the WAA RE model. • Continue to develop spatial GLMM models for survey indices and age composition of GOA pollock • Evaluate pollock population dynamics in a multi-species context using the CEATTLE model. • Explore implications of non-constant natural mortality on pollock assessment and management.

Additional recommendations that could be done by other teams at the AFSC, but are unlikely to be specifically prioritized by the primary assessment author, include: • Efforts to combine acoustic and bottom trawl information in a vertically integrated index • Efforts to improve understanding of changes of weight at age or and maturity at age, either via linkage to copepods/euphausiids or directly to the physical environment

A full ESP was developed for GOA pollock in 2020 and reviewed by the Plan Team at its September and November 2019 meetings. The GOA Groundfish Plan Team encouraged the authors to consider potential avenues for updating ESPs rather than producing full ESPs in the future. This year we provide a partial ESP in Appendix 1A that updates key indicators and reruns the Bayesian adaptive sampling model. We are soliciting feedback from the Plan Team and the SSC on the appropriate format and information to be included in an ESP update.

# Acknowledgements

We thank the AFSC survey personnel for the collection of data and providing the biomass estimates, and Wayne Palsson for providing summarized data. We are grateful to all the fishery observers working with the Fishery Monitoring and Analysis (FMA) Division who collect vital data for the stock assessments, and the staff of the AFSC Age and Growth Unit for the ageing of otoliths used to determine the age compositions in the assessment. We also thank Kally Spalinger for providing ADF&G survey data. # References

Bailey, K.M., Stabeno, P.J. and Powers, D.A. (1997) The role of larval retention and transport features in mortality and potential gene flow of walleye pollock. *J. Fish. Biol* 51, 135–154.

Mulligan, T.J., Chapman, R.W. and Brown, B.L. (1992) Mitochondrial DNA analysis of walleye pollock, theragra chalcogramma, from the eastern bering sea and shelikof strait, gulf of alaska. *Can. J. Fish. Aquat. Sci* 49, 319–326.

# Tables

(#tab:t.catch)Walleye pollock catch (t) in the Gulf of Alaska. The ABC is for the area west of 140W lon. (Western, Central and West Yakutat management areas) and includes the guideline harvest level for the state-managed fishery in Prince William Sound. Research catches are reported in Appendix 1E.

| Year | Foreign | Joint Venture | Domestic | Total | ABC/TAC |
| --- | --- | --- | --- | --- | --- |
| 1964 | 1,126 |  |  | 1,126 |  |
| 1965 | 2,746 |  |  | 2,746 |  |
| 1966 | 8,914 |  |  | 8,914 |  |
| 1967 | 6,272 |  |  | 6,272 |  |
| 1968 | 6,137 |  |  | 6,137 |  |
| 1969 | 17,547 |  |  | 17,547 |  |
| 1970 | 9,331 |  | 48 | 9,379 |  |
| 1971 | 9,460 |  | 0 | 9,460 |  |
| 1972 | 38,128 |  | 3 | 38,131 |  |
| 1973 | 44,966 |  | 27 | 44,993 |  |
| 1974 | 61,868 |  | 37 | 61,905 |  |
| 1975 | 59,504 |  | 0 | 59,504 |  |
| 1976 | 86,520 |  | 211 | 86,731 |  |
| 1977 | 117,833 |  | 259 | 118,092 | 150,000 |
| 1978 | 94,223 |  | 1,184 | 95,408 | 168,800 |
| 1979 | 103,278 | 577 | 2,305 | 106,161 | 168,800 |
| 1980 | 112,996 | 1,136 | 1,026 | 115,158 | 168,800 |
| 1981 | 130,323 | 16,856 | 639 | 147,818 | 168,800 |
| 1982 | 92,612 | 73,918 | 2,515 | 169,045 | 168,800 |
| 1983 | 81,318 | 134,171 | 136 | 215,625 | 256,600 |
| 1984 | 99,259 | 207,104 | 1,177 | 307,541 | 416,600 |
| 1985 | 31,587 | 237,860 | 17,453 | 286,900 | 305,000 |
| 1986 | 114 | 62,591 | 24,205 | 86,910 | 116,000 |
| 1987 |  | 22,822 | 45,248 | 68,070 | 84,000 |
| 1988 |  | 152 | 63,239 | 63,391 | 93,000 |
| 1989 |  |  | 75,585 | 75,585 | 72,200 |
| 1990 |  |  | 88,269 | 88,269 | 73,400 |
| 1991 |  |  | 100,488 | 100,488 | 103,400 |
| 1992 |  |  | 90,858 | 90,858 | 87,400 |
| 1993 |  |  | 108,909 | 108,909 | 114,400 |
| 1994 |  |  | 107,335 | 107,335 | 109,300 |
| 1995 |  |  | 72,618 | 72,618 | 65,360 |
| 1996 |  |  | 51,263 | 51,263 | 54,810 |
| 1997 |  |  | 90,130 | 90,130 | 79,980 |
| 1998 |  |  | 125,460 | 125,460 | 124,730 |
| 1999 |  |  | 95,638 | 95,638 | 94,580 |
| 2000 |  |  | 73,080 | 73,080 | 94,960 |
| 2001 |  |  | 72,077 | 72,077 | 90,690 |
| 2002 |  |  | 51,934 | 51,934 | 53,490 |
| 2003 |  |  | 50,684 | 50,684 | 49,590 |
| 2004 |  |  | 63,844 | 63,844 | 65,660 |
| 2005 |  |  | 80,978 | 80,978 | 86,100 |
| 2006 |  |  | 71,976 | 71,976 | 81,300 |
| 2007 |  |  | 52,714 | 52,714 | 63,800 |
| 2008 |  |  | 52,584 | 52,584 | 53,590 |
| 2009 |  |  | 44,247 | 44,247 | 43,270 |
| 2010 |  |  | 76,748 | 76,748 | 77,150 |
| 2011 |  |  | 81,503 | 81,503 | 88,620 |
| 2012 |  |  | 103,954 | 103,954 | 108,440 |
| 2013 |  |  | 96,363 | 96,363 | 113,099 |
| 2014 |  |  | 142,640 | 142,640 | 167,657 |
| 2015 |  |  | 167,549 | 167,549 | 191,309 |
| 2016 |  |  | 177,129 | 177,129 | 254,310 |
| 2017 |  |  | 186,155 | 186,155 | 203,769 |
| 2018 |  |  | 158,070 | 158,070 | 161,492 |
| 2019 |  |  | 120,243 | 120,243 | 135,850 |
| 2020 |  |  | 107,471 | 107,471 | 108,494 |
| 2021 |  |  |  |  | 105,722 |
| 2022 |  |  |  |  |  |
| Average (1977-2020) |  |  |  | 109,514 | 125,850 |

Table 1.1. Commercial catch (t) and management action for northern rockfish in the Gulf of Alaska, 1961-present. The \*Description of the catch time series\* Section describes procedures use to estimate catch during 1961-1993. Ctach estimates for 1993-2019 are from NMFS Observer Program and Alaska Regional Office updated through October XX, 2020.

| year | catch |
| --- | --- |
| 1,999 | 1 |
| 2,000 | 2 |

# Figures

# {r, fig.cap = "pressure"} # plot(pressure) #

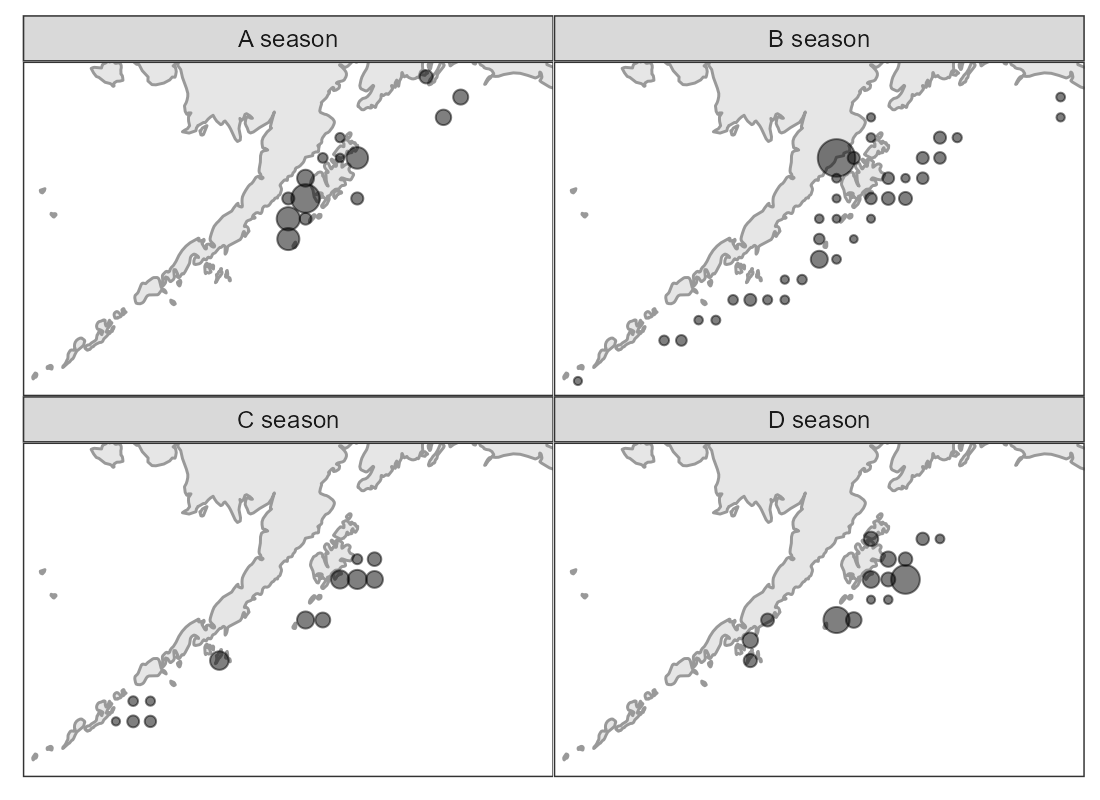


Figure 1.1. Distribution of pollock catch in the 2020 fishery shown for 1/2 degree latitude by 1 degree longitude blocks by season in the Gulf of Alaska as determined by fishery observer-recorded haul retrieval locations. Blocks with less than 1.0 t of pollock catch are not shown. The area of the circle is proportional to the catch.

# Appendix 1a. Supplemental catch data

In order to comply with the Annual Catch Limit (ACL) requirements, a dataset has been generated to help estimate total catch and removals from NMFS stocks in Alaska. This dataset estimates total removals that occur during non-directed groundfish fishing activities. This includes removals incurred during research, subsistence, personal use, recreational, and exempted fishing permit activities, but does not include removals taken in fisheries other than those managed under the groundfish FMP. These estimates represent additional sources of removals to the existing Catch Accounting System estimates. For Gulf of Alaska (GOA) northern rockfish, these estimates can be compared to the research removals reported in previous assessments (Heifetz et al. 2009; Table 10 A-1). Northern rockfish research removals are minimal relative to the fishery catch and compared to the research removals of other species. The majority of research removals are taken by the Alaska Fisheries Science Center’s (AFSC) biennial bottom trawl survey which is the primary research survey used for assessing the population status of northern rockfish in the GOA. Other research activities that harvest northern rockfish include longline surveys by the International Pacific Halibut Commission and the AFSC and the State of Alaska’s trawl surveys. Recreational harvest of northern rockfish rarely occurs. Total removals from activities other than a directed fishery have been near 10 t for 2010 – 2017. The 2017 other removals is <1% of the 2018 recommended ABC of 4,529 t and represents a very low risk to the northern rockfish stock. Research harvests from trawl in recent years are higher in odd years due to the biennial cycle of the AFSC bottom trawl survey in the GOA and have been less than 10 t except in 2013 when 18 t were removed. These removals do not pose a significant risk to the northern rockfish stock in the GOA.

## References

Heifetz, J., D. Hanselman, J. N. Ianelli, S. K. Shotwell, and C. Tribuzio. 2009. Gulf of Alaska northern rockfish. In Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska as projected for 2010. North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306 Anchorage, AK 99501. pp. 817-874.

# Appendix 10b: VAST model-based abundance

## Background

Model-based abundance indices have a long history of development in fisheries (Maunder and Punt 2004). We here use a delta-model that uses two linear predictors (and associated link functions) to model the probability of encounter and the expected distribution of catches (in biomass or numbers, depending upon the specific stock) given an encounter (Lo *et al*. 1992; Stefánsson 1996).  
Previous research has used spatial strata (either based on strata used in spatially stratified design, or post-stratification) to approximate spatial variation (Helser *et al*. 2004), although recent research suggests that accounting for spatial heterogeneity within a single stratum using spatially correlated residuals and habitat covariates can improve precision for the wrestling index (Shelton *et al*. 2014).  
Model-based indices have been used by the Pacific Fisheries Management Council to account for intra-class correlations among hauls from a single contract vessel since approximately 2004 (Helser *et al*. 2004).  
Specific methods evolved over time to account for strata with few samples (Thorson and Ward 2013), and eventually to improve precision based on spatial correlations (Thorson *et al*. 2015) using what became the Vector Autoregressive Spatio-temporal (VAST) model (Thorson and Barnett 2017).

The performance of VAST has been evaluated previously using a variety of designs.  
Research has showed improved performance estimating relative abundance compared with spatially-stratified index standardization models (Grüss and Thorson 2019; Thorson *et al*. 2015), while other simulation studies have shown unbiased estimates of abundance trends (Johnson *et al*. 2019).  
Brodie *et al*. (2020) showed improved performance in estimating index scale given simulated data relative to generalized additive and machine learning models.  
Using real-world case studies, Cao *et al*. (2017) showed how random variation in the placement of tows relative to high-quality habitat could be “controlled for” using a spatio-temporal framework, and OLeary *et al*. (2020) showed how combining surveys from the eastern and northern Bering Sea within a spatio-temporal framework could assimilate spatially unbalanced sampling in those regions. Other characteristics of model performance have also been simulation-tested although these results are not discussed further here.

## Settings used in 2020

The software versions of dependent programs used to generate VAST estimates were:

R (>=3.5.3), INLA (18.07.12), TMB (1.7.15), TMBhelper (1.2.0), VAST (3.3.0), FishStatsUtils (2.5.0), sumfish (3.1.22)

We used a Poisson-link delta-model (Thorson 2018) involving two linear predictors, and a gamma distribution for the distribution of positive catch rates. We extrapolated catch density using 3705 m (2 nmi) X 3705 m (2 nmi) extrapolation-grid cells; this results in 36,690 extrapolation-grid cells for the eastern Bering Sea, 15,079 in the northern Bering Sea and 26,510 for the Gulf of Alaska (some Gulf of Alaska analyses eliminated the deepest stratum with depths >700 m because of sparse observations, resulting in a 22,604-cell extrapolation grid). We used bilinear interpolation to interpolate densities from 500 “knots” to these extrapolation-grid cells (i.e, using fine\_scale=TRUE feature); knots were distributed spatially in proportion to the distribution of extrapolation-grid cells (i.e., having an approximately even distribution across space) using knot\_method = 'grid'. No temporal smoothing was used (i.e. variation was estimated using independent and identically distributed methods). We estimated “geometric anisotropy” (the tendency for correlations to decline faster in some cardinal directions than others), and included a spatial and spatio-temporal term for both linear predictors.  
Finally, we used epsilon bias-correction to correct for retransformation bias (Thorson and Kristensen 2016).

### Diagnostics

For each model, we confirm that the Hessian matrix is positive definite and the gradient of the marginal likelihood with respect to each fixed effect is near zero (absolute value < 0.0001).  
We then conduct a visual inspection of the quantile-quantile plot for positive catch rates to confirm that it is approximately along the one-to-one line, and also check the frequency of encounters for data binned based on their predicted encounter probability (which again should be along the one-to-one line).  
Finally, we plot Pearson residuals spatially, to confirm that there is no residual pattern in positive and negative residuals.

## References

Brodie, S.J., Thorson, J.T., Carroll, G., et al. (2020) Trade-offs in covariate selection for species distribution models: A methodological comparison. Ecography 43, 11–24.

Cao, J., Thorson, J., Richards, A. and Chen, Y. (2017) Geostatistical index standardization improves the performance of stock assessment model: An application to northern shrimp in the Gulf of Maine. Canadian Journal of Fisheries and Aquatic Sciences.

Grüss, A. and Thorson, J.T. (2019) Developing spatio-temporal models using multiple data types for evaluating population trends and habitat usage. ICES Journal of Marine Science 76, 1748–1761.

Helser, T.E., Punt, A.E. and Methot, R.D. (2004) A generalized linear mixed model analysis of a multi-vessel fishery resource survey. Fisheries Research 70, 251–264.

Johnson, K.F., Thorson, J.T. and Punt, A.E. (2019) Investigating the value of including depth during spatiotemporal index standardization. Fisheries Research 216, 126–137.

Lo, N.C.-h., Jacobson, L.D. and Squire, J.L. (1992) Indices of relative abundance from fish spotter data based on delta-lognornial models. Canadian Journal of Fisheries and Aquatic Sciences 49, 2515–2526.

Maunder, M.N. and Punt, A.E. (2004) Standardizing catch and effort data: A review of recent approaches. Fisheries research 70, 141–159.

O’Leary, C.A., Thorson, J.T., Ianelli, J.N. and Kotwicki, S. Adapting to climate-driven distribution shifts using model-based indices and age composition from multiple surveys in the walleye pollock (gadus chalcogrammus) stock assessment. Fisheries Oceanography.

Shelton, A.O., Thorson, J.T., Ward, E.J. and Feist, B.E. (2014) Spatial semiparametric models improve estimates of species abundance and distribution. Canadian Journal of Fisheries and Aquatic Sciences 71, 1655–1666.

Stefánsson, G. (1996) Analysis of groundfish survey abundance data: Combining the GLM and delta approaches. ICES journal of Marine Science 53, 577–588.

Thorson, J.T. (2018) Three problems with the conventional delta-model for biomass sampling data, and a computationally efficient alternative. Canadian Journal of Fisheries and Aquatic Sciences 75, 1369–1382.

Thorson, J.T. and Barnett, L.A. (2017) Comparing estimates of abundance trends and distribution shifts using single-and multispecies models of fishes and biogenic habitat. ICES Journal of Marine Science 74, 1311–1321.

Thorson, J.T. and Kristensen, K. (2016) Implementing a generic method for bias correction in statistical models using random effects, with spatial and population dynamics examples. Fisheries Research 175, 66–74.

Thorson, J.T., Shelton, A.O., Ward, E.J. and Skaug, H.J. (2015) Geostatistical delta-generalized linear mixed models improve precision for estimated abundance indices for West Coast groundfishes. ICES Journal of Marine Science 72, 1297–1310.

Thorson, J.T. and Ward, E.J. (2013) Accounting for space–time interactions in index standardization models. Fisheries Research 147, 426–433.