Assessment of the Arrowtooth Flounder Stock in the Gulf of Alaska

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Executive summary

Summary of changes in assessment inputs

The following substantive changes have been made in the BSAI Arrowtooth Flounder assessment relative to last year's BSAI SAFE report.

Changes in the data

1. The 2019 NMFS Gulf of Alaska bottom-trawl survey biomass estimates, standard error, and survey length composition data were added.
2. Survey age data were included for the 2017 NMFS Gulf of Alaska bottom-trawl survey.
3. Fishery catch was updated for 2017 and 2018, and was extrapolated through the end of 2019 for an estimate of 20,554 t. Catch of 24,186 t was assumed for 2020 in the projections, which was based on the 5 year average 2014-2018.
4. Fishery length composition data was updated for 2017, 2018, and 2019.

Changes in the assessment methods

The model used for the 2017 assessment is referred to by the same model number as in that assessment, Model 17.0e. The same model used for 2019's assessment is referred to as Model 17.1a. A second model that removed the 1961 and 1975 surveys and starts at 1977 was also included, and referred to as Model 19.0. The rationale for removing those early data points resulted from discussions with the Plan Team and SSC (see section on SSC and Plan Team comments) and a lack of evidence to support low biomass reported by those early surveys. Even if the early survey estimates of Arrowtooth Flounder biomass are correct, it is typical for many AFSC stock asssessments to start in 1977. The model is split sex with different natural mortality for males and females, with natural mortality fixed at 0.2 for females and 0.35 for males.

Summary of Results

Arrowtooth Flounder biomass estimates in the current model have changed relative to previous assessments. The model projection of spawning biomass for 2020, assuming fishing mortality equal to the recent 5-year average, was 756,100 t, 93% of the projected 2020 spawning biomass from the 2018 assessment of 810,158 t. The 2020 and 2021 ABCs using F_{ABC}=0.193 from this assessment model were lower than the 2018 ABC of 145,841 t; 128,060 t and 124,357 t. The 2020 and 2021 OFLs estimated in this assessment were 153,017 t and 148,597 t. The projected estimate of total biomass for 2020 was down by 3% from the 2018 assessment of 1,367,620 t, to 1,325,867 t. Despite the declines, the Arrowtooth Flounder stock in the Gulf of Alaska is not being subjected to overfishing and is not approaching a condition of being overfished.

Area Apportionment

Arrowtooth Flounder is managed as a single stock in the Gulf of Alaska. However, the ABC is apportioned by management area based on the fraction of the survey biomass in each area. The Western region is NMFS

Quantity	As estimated or *specified last* year for: 2019	2020	As estimated or *recommended this* year for: 2020	2021
M (natural mortality rate)	0.35, 0.2	0.35, 0.2	0.35, 0.2	0.35, 0.2
Tier	3a	3a	3a	3a
Total (age 1+) biomass (t)	1,391,460 t	1,367,620 t	1,325,867 t	1,321,075 t
Female spawning biomass (t)	869,399 t	810,159 t	756,100 t	718,325 t
$B_{100\%}$	924,644 t	924,644	1,028,329 t	1,028,329 t
$B_{40\%}$	369,858 t	369,858	411,332 t	411,332 t
$B_{35\%}$	323,625 t	323,625	359,915 t	359,915 t
F_{OFL}	0.238	0.238	0.234	0.234
$maxF_{ABC}$	0.196	0.196	0.193	0.193
F_{ABC}	0.196	0.196	0.193	0.193
OFL	174,598 t	168,634 t	153,017 t	148,597 t
$maxABC$	145,841 t	140,865 t	128,060 t	124,357 t
ABC	145,841 t	140,865 t	128,060 t	124,357 t
Status	2017	2018	2018	2019
Overfishing	No	n/a	No	n/a
Overfished	n/a	No	n/a	No
Approaching overfished	n/a	No	n/a	No

Projections were based on estimated catches of 20,554 t for 2019 which was estimated from an average of 97.6% of the catch caught by October 5 over the years 2014-2018, and 24,186 for 2020 which is based on the 5 year average (2014-2018) used in place of maximum ABC for and 2021.

reporting area 610 (Shumagin), Central is 620 and 630 (Chirikof and Kodiak), and West Yakutat and East Yakutat/SE Alaska result from the combined NMFS areas 640 and 650 redistributed such that the West Yakutat area is between 147°W and 140°W and the East Yakutat/SE is the portion east of 140°W. The fraction of the biomass in the four areas was determined by applying a time series of survey biomass estimates (Table 7.1) and their coefficients of variation, CV's, to a random effects model (Table 7.2). The Central region has shown a decline in biomass since 2003, while the other regions have remained relatively constant (Figure 7.1).

Arrowtooth ABC by area

	Western	Central	West Yakutat	East YakutatSE	Total
2017 survey biomass percent by area	24.68%	48.68%	10.91%	15.73%	100%
2018 ABC	37,253	73,480	16,468	23,744	150,945
2019 ABC	35,844	70,700	15,845	22,845	145,234
2019 survey biomass percent by area	24.56 %	53.62 %	8%	13.82%	100%
2020 ABC	31,455	68,669	10,241	17,694	128,060
2021 ABC	30,545	66,683	9,945	17,183	124,357

Responses to SSC and Plan Team Comments on Assessments in General

SSC December 2017

1.The SSC reminds authors of the need to balance the desire to improve model fit with increased risk of model misspecification.

Authors' response

Noted.

SSC December 2018

1. The SSC requests that all authors fill out the risk table in 2019, and that the PTs provide comment on the author's results in any cases where a reduction to the ABC may be warranted (concern levels 2-4).

Authors' response

A risk table was included in this assessent.

Responses to SSC and Plan Team Comments Specific to this Assessment

Comments from the SSC December 2017

There has been ongoing consideration about how to treat survey data from 1961-1962 (IPHC trawl survey) and 1973-1976 (NMFS exploratory trawl survey), given the use of different gears, survey designs, etc. The current assessment noted significant issues with survey design. Removal of these surveys leads to biomass estimates in the 1960s-1970s that are relatively similar to those of the 1980s-early 1990s; including these early surveys results in lower estimates of biomass in the 1960s-1970s and a greater increase in biomass over time. In this regard, the SSC supports the Plan Team's recommendation that the assessment authors continue to reevaluate the use of these early survey data. Specifically:

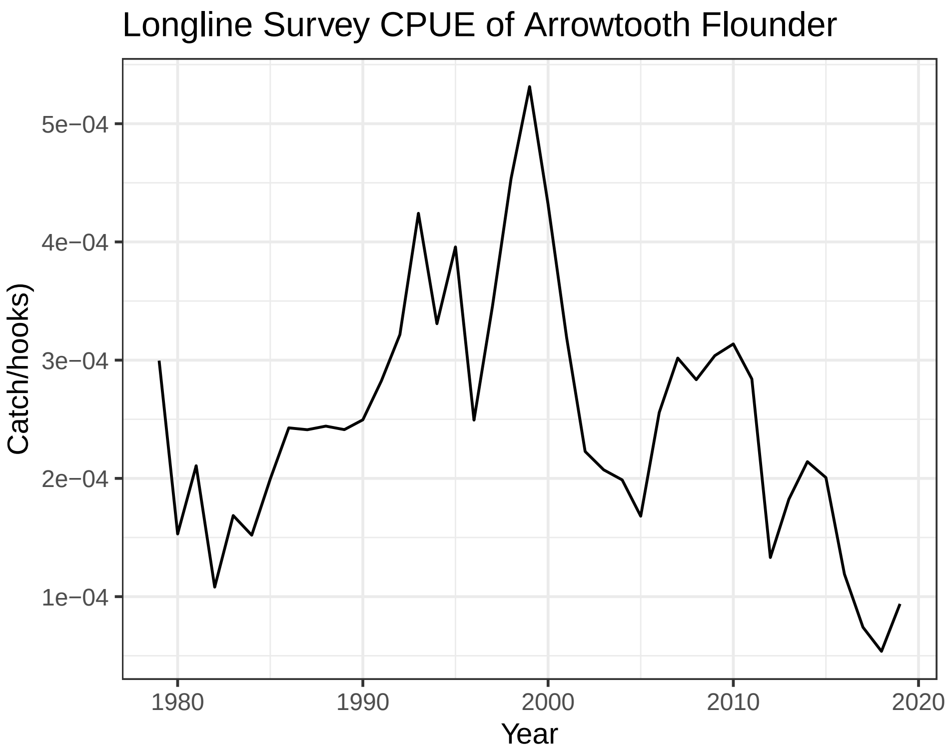
1. The Plan Team recommended documenting the survey design and spatial distribution in 1961 and 1975 to evaluate the comparability of these early surveys to recent surveys.
2. The Team also recommended evaluating the cooperative US-Japan longline surveys, as they may provide information on stock trends over the period from 1979 – 1992.
3. In addition, the SSC recommends that the authors look into the availability of ADF&G bottom trawl surveys in the central and western Gulf of Alaska to see if any of them span the years in question.

Comments from the Gulf of Alaska Plan Team November 2017

1. The Team recommends documenting the survey design and spatial distribution of tows in the 1961 and 1975 surveys in order to evaluate comparability with recent surveys.
2. The Team also recommends evaluating the cooperative US-Japan longline surveys, and this may provide information on stock trends from 1979 – 1992.

Authors' responses (for the SSC and Plan Team combined)

1. US-Japan longline surveys: These longline surveys have recorded Arrowtooth Flounder catches since 1979. CPUE by year is shown in the plot below, and indicates higher catch relative to the 1961-1962 (IPHC trawl survey) and 1973-1976 (NMFS exploratory trawl survey).

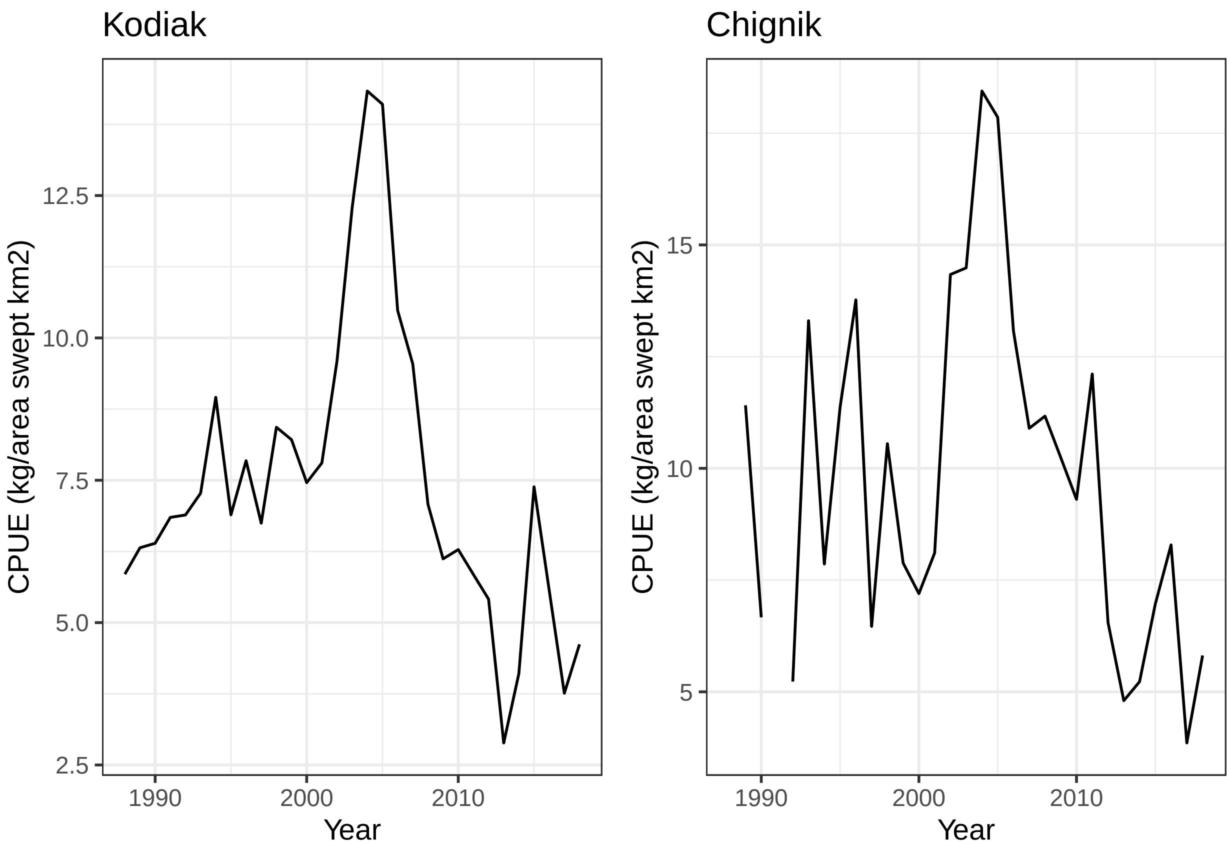


2. Survey design and spatial distribution of the 1961-1962 (IPHC trawl survey) and 1973-1976 (NMFS exploratory trawl survey):

The following text in the assessment describes the survey design and spatial distribution of the 1960s and 1970s surveys:

- Biomass estimates from the surveys in the 1960's and 1970's were analyzed using the same strata and methods as the triennial survey (Brown 1986). Selectivity of the different surveys was assumed to be equal. The data from the 1961 and 1962 IPHC surveys were combined to provide total coverage of the GOA area. The NMFS surveys in 1973 to 1976 were also combined to provide total coverage of the survey area. However, sample sizes were lower in the 1970's surveys (403 hauls) than for other years, and some strata had less than 3 hauls. The IPHC and NMFS 1970's surveys used a 400 mesh Eastern trawl, while the triennial surveys used a noreastern trawl. The trawl used in the early surveys had no bobbin or roller gear, which would cause the gear to be more in contact with the bottom than current trawl gear. Also the locations of trawl sites may have been restricted to smooth bottoms in the earlier surveys because the trawl could not be used on rough bottoms. There is limited size composition data for the 1970's surveys and none for the 1960's surveys.
- The 400 mesh eastern trawl used in the 1960's and 1970's surveys was estimated to be 1.61 times as efficient at catching Arrowtooth Flounder than the noreastern trawl used in the NMFS triennial surveys. The 1960's and 1970's survey abundance estimates have been lowered by dividing by 1.61. A coefficient of variation (cv) of 0.2 for the efficiency estimate was assumed since variance estimates were unavailable. Even the uncorrected estimates would be much lower than more recent survey estimates. Without dividing by 1.61, the 1960's biomass estimate would be lower than standard survey estimates from 1984-2017, 454,078 t and the 1970's estimate would be 233,190 t.

3. ADF&G surveys: The ADF&G survey data extends back only to 1988. CPUE (kg/area swept kg^2) is shown here for those years in the vicinity of Kodiak Island. It reflects a general trend of low biomass in the 1990s followed by a peak in the early 2000s. However, it does not provide information on abundance in the 1970s or 1960s.



Summary: The US-Japan longline surveys extend back to 1979 and survey the four NMFS management areas in the GOA, Central GOA, East Yakutat/SE, West Yakutat, and the Western GOA. The ADF&G surveys extended as far back as 1988, but only surveyed in the vicinity of Kodiak Island. Neither survey provides evidence to confirm the much lower survey estimates of Arrowtooth Flounder that were reported by the 1961-1962 IPHC trawl survey or the 1973-1976 NMFS exploratory trawl surveys. Likewise, there is little data to refute results of the early surveys, as neither covered the same time periods. Although the GOA Arrowtooth Flounder assessment has always used the 1961-1962 IPHC trawl survey or the 1973-1976 NMFS exploratory trawl surveys, it is standard practice to only include surveys with standardized methodology. Therefore, we recommend removing those surveys from the assessment. An exploration of models without the 1961-1962 IPHC trawl survey or the 1973-1976 NMFS exploratory trawl surveys was performed in the 2017 assessment, and it did not have a strong effect on reference points for current years of the Gulf of Alaska stock of Arrowtooth Flounder. Model 19.0 presented in this assessment does not include the 1961 and 1975 assessments and starts at 1977.

Introduction

Arrowtooth Flounder (*Atheresthes stomias*) range from central California to the Gulf of Alaska (GOA), Aleutian Islands, and northern Bering Sea. Arrowtooth Flounder (ATF) was considered the most abundant groundfish species in the Gulf of Alaska during the first decade of this century, but its biomass shifted to less than that of Pacific Ocean Perch, based on the 2017 Gulf of Alaska groundfish survey. Projections for 2016 from the 2015 GOA assessments estimated Pacific Ocean Perch at 457,768 t and ATF at 2,103,860 t. However, survey biomass estimates of Pacific Ocean Perch in the 2017 survey were higher than arrowtoooth (over 1.5 million t vs. 1,053,695 t).

Arrowtooth Flounder occur in waters from about 20m to 800m, but catch per unit effort (CPUE) from survey data is highest between 100m and 300m. Migration patterns are not well known for Arrowtooth Flounder; however, there is some indication that Arrowtooth Flounder move into deeper water as they grow, similar to other flatfish (Zimmerman and Goddard 1996). Fisheries data off Washington suggest that larger fish may migrate to deeper water in winter and shallower water in summer (Rickey 1995). Arrowtooth Flounder spawn in deep waters (>400m) along the continental shelf break in winter (Blood et al. 2007). They are batch spawners, spawning from fall to winter off Washington State at depths greater than 366m (Rickey 1995).

Trophic studies (Yang 1993, Hollowed, et al. 1995, Hollowed et al. 2000) suggest Arrowtooth Flounder are an important component in the dynamics of the Gulf of Alaska benthic ecosystem. They are an apex predator in the Gulf of Alaska and are habitat and prey generalists (Doyle et al. 2018). The majority of the prey by weight of arrowtooth larger than 40 cm was pollock, the remainder consisting of herring, capelin, euphausids, shrimp and cephalopods (Yang 1993). The percent of pollock in the diet of Arrowtooth Flounder increases for sizes greater than 40 cm (Figure 7.2, Doyle et al. 2018). Arrowtooth Flounder 15 cm to 30 cm consume mostly shrimp, capelin, euphausiids and herring, with small amounts of pollock and other miscellaneous fish. Groundfish predators include Pacific cod and halibut (see Ecosystem Considerations section).

The age composition of the species shows fewer males relative to females as fish increase in age, which suggests higher natural mortality (M) for males (Wilderbuer and Turnock 2009). To account for this process, natural mortality has typically been fixed at 0.2 for females and 0.35 for males in the model. Different options for natural mortality were considered in the 2017 assessment, which consider natural mortality as a function of the size of the fish (Charnov 1982, Gislason et al. 2010, Lorenzen 1996). The distribution of ages appears to vary by region and sex; male arrowtooth as old as 36 years have been observed in the Aleutian Islands, but are not commonly observed older than age 10 on the Bering Sea shelf. Males were not observed older than age 20 prior to 2005 in the Gulf of Alaska; however, males age 21 have been observed in every survey since that time. The sex ratio of Arrowtooth Flounder also varies by region. In the Gulf of Alaska, the observed ratio from fishery observer length frequency collections is 69% female, 31% male. Survey length compositions from the Bering Sea indicate that the proportion female is 70% on the Bering Sea shelf, 72% on the Bering Sea slope, and 62% in the Aleutian Islands. In British Columbia catches have been over 70% female since 1996 and the stock is assessed solely based on female numbers (DFO 2015).

Differences in distribution of Arrowtooth Flounder were compared between warm and cold years, where warm years included 1984, 1987, 1990, 1993, 2001, 2003, 2005, 2015 and cold years included 1996, 1999, 2007, 2009, 2011, and 2013 (Doyle et al. 2018). Results showed some effect of temperature on distribution (Figure 7.3). Fish less than 300mm were found typically <400m in warm years but deeper in cold years. Younger fish <100m were found >200m only in colder years. ATF 300-600mm were found in the deepest stations >800m in warm years. High densities of fish were greater at 200-400m in cold years. Highest densities of larger, older fish >600mm were found over the slope in cold years (Doyle et al. 2018).

Information concerning the genetic stock structure of ATF is not currently available, although efforts are underway to initiate research.

Fishery

Management of the Arrowtooth Flounder stock in the GOA has changed over time. Prior to 1990, flatfish catch in the Gulf of Alaska was reported as an aggregate of all flatfish species. The bottom trawl fishery in the Gulf of Alaska primarily targets rock, rex and Dover sole. The North Pacific Fisheries Management Council divided the flatfish assemblage into four categories for management in 1990; "shallow flatfish" and "deep flatfish", flathead sole, and Arrowtooth Flounder. Arrowtooth Flounder was separated from the group and managed under a separate acceptable biological catch (ABC) because of its present high abundance and low commercial value. In the Gulf of Alaska, Arrowtooth Flounder were first managed under a separate assessment in 2001. They are currently managed as a single stock but the ABC is specified separately for the Western (NMFS area 610), Central (620, 630), West Yakutat, and East Yakutat/Southeast.

The area of highest abundance of Arrowtooth Flounder in the GOA is in the central and western gulf (Figure 7.4). The directed fishery takes place throughout the GOA, but is primarily in the central GOA (NMFS area 630). Arrowtooth Flounder are typically caught with bottom trawl nets. Outside of the directed fishery, they are primarily caught as bycatch in the Other Flatfish fisheries. Catch of Arrowtooth Flounder since 1964 is shown in Table 7.3. Table 7.4 presents discard rates since 1991, which were calculated from observed at-sea sampling and industry reported retained catch. Under current fishing practices, the percent retained has increased from below 10% in the early 1990's to over 70% from 2010-2013, and 90% or greater since that time.

Viable products were developed for Arrowtooth Flounder around 2008, which prevented the muscle from degrading rapidly when heated (Greene and Babbitt 1990, Wasson et al. 1992, Porter et al. 1993). Until that time it was not targeted as a commercial fishery. Several methods exist to neutralize the enzymes that cause the flesh to degrade, including chilling to near zero or immediate processing and freezing (Reppond et al. 1993). The Arrowtooth Flounder currently caught, processed, and sold each year from the Gulf of Alaska are typically exported to China for reprocessing, with some product going to South Korea and Japan. Reprocessed arrowtooth from China may also be sold to Japan as fillets and engawa (frills), the US and Europe as fillets, among other countries. They are eaten as less expensive fillets, used raw in sashimi, or used to manufacture surimi.

The catches for Arrowtooth Flounder remain below the TAC (Table 7.3); and have ranged from 19,964 - 36,300 t since the year 2000, averaging 24,008 t, and catch/TAC averaged 39%. Catches were below 10,000 t, on average, prior to 1990, and increased to an average of approximately 16,000 t in the 1990's and 24,000 t in the 2000's. Catch as of October 5, 2019 was 20,061 t. Total allowable catch for 2018 and 2019 was 76,300 t and 99,295 t.

Data

The model simulates the dynamics of the population and compares the expected values of the population characteristics to data observed from surveys and fishery sampling programs.

The following data sources (and years of availability) were used in the preferred model:

Data source	Year
Fishery catch	1977 - 2019
NMFS trawl survey biomass and S.E.	1984,1987,1990,1993,1996,1999,2001,2003, 2005,2007,2009,2011,2013,2015,2017,2019
Fishery size compositions	1977-1993,1995-2019
NMFS survey size compositions	1985,1986,1989,2019
NMFS trawl survey age composition data	1984,1987,1990,1993,1996,1999,2001, 2003,2005,2007,2009,2011,2013,2015,2017

Note: Fishery size composition data is available for all years from which NMFS trawl surveys occurred. For years in which age compositions are not available, length composition is used directly in the model.

Length frequency data was collected opportunistically for Arrowtooth Flounder on three GOA surveys, conducted in 1985, 1987, and 1989 using standard methodology. These surveys were not part of the standard NMFS GOA surveys but length frequency data were included in the assessment.

Fishery

Catch

The estimate of annual arrowtooth catch between 1960 and 1993 was extrapolated from the total flatfish catch by multiplying the proportion of arrowtooth in observer sampled flatfish catches (nearly 50%) by the reported flatfish catch (1960-1977 from Murai et al. 1981 and 1978-1993 from Wilderbuer and Brown (1993) (Table 7.3).

Removals from sources other than those that are included in the Alaska Region's official estimate of catch (e.g., removals due to scientific surveys, subsistence fishing, recreational fishing, fisheries managed under other FMPs) are presented in Appendix A.

Age and size composition

Length composition data from 1984-2013 were used to construct the length age conversion matrix. The number of male and female lengths used in the model as length composition data, by year, are shown in Figure 7.5. There are no long term trends in the length composition data from the fishery (Figure 7.6), but there is variation over time.

The number of fisheries length observations taken by fisheries observers, and the number of hauls from which those samples were taken, by year, 1975-2019 are presented in Table 7.5. Arrowtooth Flounder are caught incidentally in the halibut fishery, and these catch weights (in metric tons) are reported by area and year (2003-2019, Table 7.6). Sample sizes for the fishery length data were generally at least 1,000 for the 1970s through 1984 (Table 7.5). Sample sizes were under 800 between 1985-1990, 1992, 1994, 1998, and were not taken in 1989. Domestic data was downloaded from the OBSINT debriefed_length table. The data prior to 1989 is referred to as "foreign" data, but the fishing of the latter years was done predominately by joint venture vessels which eventually replaced the foreign fishers (Table 7.3). Length frequencies from the fishery are presented in Figure 7.6. There is no age data from the fishery but otoliths were collected by observers starting in 2018.

Survey

Biomass estimates

The survey biomass estimates used in this assessment are from International Pacific Halibut Commission (IPHC) trawl surveys and NMFS groundfish surveys (Table 7.7). Biomass estimates from the surveys in the 1960's and 1970's were analyzed using the same strata and methods as the triennial survey (Brown 1986). The data from the 1961 and 1962 IPHC surveys were combined to provide total coverage of the GOA area. The NMFS surveys in 1973 to 1976 were also combined to provide total coverage of the survey area. However, sample sizes were lower in the 1970's surveys (403 hauls, Table 7.7) than for other years, and some strata had less than 3 hauls. The IPHC and NMFS 1970's surveys used a 400 mesh Eastern trawl, while the triennial surveys used a noreastern trawl. The trawl used in the early surveys had no bobbin or roller gear, which would cause the gear to be more in contact with the bottom than current trawl gear. Also the locations of trawl sites may have been restricted to smooth bottoms in the earlier surveys because the trawl could not be used on rough bottoms. Selectivity of the different surveys is assumed to be equal. There is limited size composition data for the 1970's surveys and none for the 1960's surveys.

The 400 mesh eastern trawl used in the 1960's and 1970's surveys was estimated to be 1.61 times as efficient at catching Arrowtooth Flounder than the noreastern trawl used in the NMFS triennial surveys. The 1960's and 1970's survey abundance estimates have been lowered by dividing by 1.61. A coefficient of variation (CV) of 0.2 for the efficiency estimate was assumed since variance estimates were unavailable. Even the uncorrected estimates would be much lower than more recent survey estimates. Without dividing by 1.61, the 1960's biomass estimate would be lower than standard survey estimates from 1984-2017, 454,078 t and the 1970's estimate would be 233,190 t.

The survey catchability coefficient (q) in the assessment model was assumed to be 1.0. NMFS has conducted studies to estimate the escapement under the triennial survey net and herding of fish into the net. The percent of Arrowtooth Flounder caught that were in the path of the net varies by size from about 80% at 27 cm (about age 3) to about 96% at greater than 45cm (equal to or greater than age 7 for females and age 10 for males) (Somerton et al. 2007). Somerton et al. (2007) estimated the effect of herding combined with escapement under the net to be an effective multiplier of about 1.3 on survey catch for Arrowtooth Flounder. The combination of escapement under the net and herding into the net indicates that abundance would be about 23% less than the estimated survey abundance.

Total survey biomass estimates increased from approximately 1 million metric tons in 1984 and 1987, to 2-3 million tons in 2003-2007, and have since declined to approximately 1 million metric tons in 2017 and 2019. Survey abundance estimates were low in the 1960's and 1970's, and increased from about 146,000 t in the early 1970's to a high of 2,819,095 t in 2003. Survey biomass has generally been declining since 2003, and the 2017 estimate of 1,053,695 t was the lowest estimate since 1987. The 2019 estimate was slightly higher, 1,076,727 t. The 1984, 1987, 1999, 2005, 2007, 2009, 2011, and 2015 surveys covered depths to 1000m, the 1990, 1993, 1996, and 2001 surveys to 500m and the 2003, 2013, 2017, and 2019 surveys covered depths to over 650m (Table 7.7). The 2001 survey excluded the eastern Gulf of Alaska. The average biomass estimated for the 1993 to 1999 surveys was used to estimate the biomass in the eastern Gulf for 2001 (Table 7.1). Survey estimates of biomass by area are generally highest in the central Gulf of Alaska, and the eastern and western Gulf of Alaska have similar biomass of Arrowtooth Flounder (Table 7.8). The central Gulf of Alask has experienced the greatest declines in Arrowtooth Flounder biomass since 2003. Survey biomass estimates, standard error, number of hauls, and maximum depth are shown in Table 7.7.

Effort using catch per unit effort (CPUE) data since 1984 is available from the NMFS GOA trawl survey (Figure 7.4). CPUE by haul indicates that the highest abundance has generally occurred between about 149 and 156 degrees longitude, in the central GOA, to the southwest and to the northeast of Kodiak Island (Figure 7.4). Results show that CPUE is typically highest in the Chirikof region of the central GOA, NMFS area 620.

Survey age and length compositions

Otoliths from the 1984 to 2017 NMFS trawl surveys have been aged and are used in the model (Table 7.9). Length composition data from 1975, 1985, 1986, 1989, and 2019 are used in the model since age data are not yet available for 2019 and only length data are available for 1975, 1985, 1986, 1989, 2019. Length frequency data from all NMFS surveys indicates no long term trends, and that females larger than males (Figure 7.7). Fishery length compositions are presented in Table 7.10 and the number of lengths collected from NMFS surveys are shown in Table 7.11.

Other time series data used in the assessment

No other data was used in the assessment.

Analytic Approach

General Model Structure

The assessment is an age-structured statistical model implemented in the Automatic Differentiation Model Builder (ADMB) framework (Fournier et al. 2012). This framework uses automatic differentiation and allows estimation of highly-parameterized and non-linear models. This age-structured population dynamics model is fit to survey abundance data, survey age data, and survey and fishery length composition data with a harvest control rule to model the status and productivity of these stocks and set quotas. The model is fit to the data by minimizing the objective function, analogous to maximizing the likelihood function. The model implementation language provides the ability to estimate the variance-covariance matrix for all parameters of interest. In November 2015, a new generalized model was accepted by the GOA Plan Team, which can be used to assess the status of Arrowtooth Flounder stocks in the Bering Sea and Aleutian Islands (BSAI) and Gulf of Alaska (GOA) management areas. This “generalized model” has been used since 2015, and incorporates ages 1-21+ and estimates selectivity up to age 19. A Markov chain Monte Carlo (MCMC) was performed in ADMB to capture variability in recruitment, female spawning biomass, and total (age 1+) biomass. The MCMC was run with 1,000,000 iterations, and thinning every 1,000.

Recruitment (R) is calculated as an average value, $\overline{log(R)}$, with an estimated lognormal deviation in each year of the model with the exception of the final year, in which the mean value is chosen. Recruitment is informed by subsequent year class strengths and there is little information to inform recruitment in the final few years, particularly because 50% maturity occurs at age 7 in Arrowtooth Flounder. Equilibrium age structure in the unfished population is based on mean recruitment that is subject to a vector of instantaneous rates of natural mortality, M_{sex}, in each subsequent year, and a plus group (x) that includes all ages 21 and older. Natural mortality is subscripted for sex, as males appear to have higher natural mortality than females in this species (Wilderbuer and Turnock 2009).

$$\tilde{N}_{sex,a} = \begin{cases} e^{\overline{log(R)}} & \text{if a=0,} \\ \tilde{N}_{sex,a-1}e^{-M_{sex,a-1}} & \text{if } 1 \leq \text{a} \leq \text{x-1,} \\ \tilde{N}_{sex,x}e^{-M_{sex,x-1}}/(1-e^{-M_{sex,x-1}}) & \text{if a=x.} \end{cases}$$

The numbers-at-age for years 1961 through 2019 are computed allowing for fishery selectivity, fishing and natural mortality, and the same plus group.

$$\tilde{N}_{sex,y+1,a} = \begin{cases} e^{\overline{log(R)}+recdev_y} & \text{if a=0,} \\ N_{sex,y,a-1}e^{-(S_{sex,a-1}F_{sex,y}+M_{sex,a-1})} & \text{if } 1 \leq \text{a} \leq \text{x-1,} \\ N_{sex,y,x-1}e^{-(S_{sex,x-1}F_{sex,y}+M_{sex,x-1})} + N_{sex,y,x}e^{-(S_{sex,x}F_{sex,y}+M_{sex,x})} & \text{if a=x.} \end{cases}$$

where $N_{sex,y+1,a}$ is the number of fish of each sex at age a at the start of year, $S_{sex,a}$ is the selectivity-at-age for the fishery for each sex, F_y is the instantaneous fully-selected fishing mortality rate during year y and is calculated from the log of the mean fishing mortality and a vector of fishing mortality deviations $fmort_{dev}$ is calculated for each year of the model, $F_y = e^{\overline{log(F)}+fmort_{dev}}$.

There were 193 parameters estimated in Model 17.1a. Four of these parameters were not estimated but were included in the final count. These were 2 female and 2 male slope and $a_{50\%}$ for a descending arm of a dome shaped survey selectivity pattern that were not used in this version of the model (they are used in the BSAI Arrowtooth Flounder assessment). There were only 161 parameters in Model 19.0, due to the removal of 16 years from the beginning of the time series.

Parameters were estimating by minimizing the objective function. Several likelihood equations contributed to the final likelihood: recruitment, fishery and survey length compositions, age composition from the survey, and biomass. Observation errors for age and length compositions were assumed to be multinomial distributed, while recruitment deviations, and catch and biomass observation errors were assumed to be lognormally distributed. The recruitment likelihood equation was

$$Likelihood_{Recruitment} = 0.5 \sum_{y=1961}^{2019} \left(\frac{recdev_y}{\sqrt{0.5}} \right)^2.$$

The likelihood component for survey biomass was calculated as follows:

$$Likelihood_{SurveyBiomass} = 0.5 \sum_{y=1961}^{2019} \left(\frac{log(Biomass_{obs,y}) - log(Biomass_{pred,y})}{BiomassSC_{obs,y}/Biomass_{obs,y}} \right)^2,$$

where the observed CV is an estimate of standard deviation. The catch likelihood was calculated as

$$Likelihood_{Catch} = 0.5 \sum_{y=1961}^{2019} \left(\frac{log(Catch_{obs,y} + \delta - log(Catch_{pred,y} + \delta))}{\sqrt{0.5}} \right)^2,$$

where δ is a small value needed in the case of zero catches. The length composition for the fishery and the survey are calculated as:

$$Likelihood_{Length} = \sum_{y=1961}^{2019} \sum_{sex} \sum_{length} Nhauls_{sex,y}(Obsprop_{sex,length,age} + \delta)log(Predprop_{sex,length,age} + \delta).$$

Delta δ is a small number less than 1 added to account for the possibility of zero observations in a length (or age category). The weights ("Nhauls") applied to the fishery length comps are shown in Table 7.5. Lower weights are applied to length compositions in the years prior to 1989 because the number of hauls are not known. Length comps reflect the number of hauls from 1990-1998 and are generally 200 from then through 2017. The proportion of males and females sum to 1 in each year of the model. This also allows for the model to fit the observed skewed sex ratio, approximately 69% females and 31% males, based on the fishery length composition data. Length composition data was only used in the model in years in which there is no age data use length data.

The likelihood for survey ages assumes that observation error is distributed multinomially. The age composition likelihood is similar to the length likelihood:

$$Likelihood_{Age} = \sum_{y=1961}^{2019} \sum_{sex} \sum_{length} Nhauls_{sex,y}(Obsprop_{sex,length,age} + \delta) log(Predprop_{sex,length,age} + \delta).$$

Age data exists for all standard GOA surveys, and have been read for all but the most recent survey. For the age composition, the number of hauls was assumed to be 200 for each year of data. The number of fish aged in each year ranged from 285-1,534 (Table 7.9). Age composition data for the years 1984-2017 were applied to the model. Detailed cruise information for each survey from which age data were taken is shown in Table 7.7. For the multinomial likelihoods, an offset was calculated which is a component of the multinomial likelihood. The offset decreases as the number of samples increases, and when observations are less frequent than 0.5, and is calculated as follows:

$$Offset = \sum_{y=1961}^{2019} \sum_{length/age} Nhauls_y(Obsprop_{length/age}) log(Obsprop_{length/age}).$$

Catch, in units of fish, was estimated in the model using the standard equation:

$$Catch_{year,age} = \frac{F_{year,age}}{Z_{year,age}}(1 - e^{-Z_{year,age}})N_{year,age},$$

where Z represents total mortality and is the sum of natural and fishery mortality. Female spawning biomass (FSB) was calculated as the product of the weight of mature females in each year.

$$FSB_{year} = \sum_{age} wt_{age}\phi_{age}N_{age,year},$$

where ϕ_{age} is the proportion of mature females at each age (Stark 2008), $N_{age,year}$ is the number of females in the population, and wt_{age} is the weight at age for females.

Yield was calculated as the sum of the weight of the catch,

$$Y_{year} = \sum_{age} wt_{year,age}Catch_{year,age}.$$

Fishing mortality is calculated from the expected mean fishing mortality E and an "fmort_dev" deviation for each year,

$$F_{year,age,sex} = S_{year,age,sex}E_{year}e^{\epsilon_{year}}, \epsilon_{year} \backsim N(0, \sigma_f^2),$$

where S represents fishery selectivity.

The 18 selectivity parameters estimated in the model for the smooth selectivity functions were constrained so that the number of effectively free parameters would be less than 18. The instantaneous natural mortality rate, catchability for the survey and the Von Bertalanffy growth parameters were fixed in the model. No spawner-recruit curve was used in the model. Recruitments were freely estimated but with a modest penalty on extreme deviations from the mean value. Age at recruitment was set at one in the model. Survey selectivity was estimated separately for males and females (4 parameters total). Parameters estimated inside the model are described in Table 7.12.

Model 17.1a

There were 59 fishing mortality deviates in Model 17.1a, plus one mean fishing mortality parameter, to fit the observed catch closely. Twenty-one initial recruitment deviations were estimated to start the population in 1961. Recruitments deviations from 1961 to 2019 account for 59 parameters, plus one parameter for the mean recruitment.

Model 19.0

Model 19.0 was similar to Model 17.1a except the model started in 1977 rather than 1961. Two survey biomass estimates were removed, 1961 and 1975, as well as the 1975 survey length frequency composition. There were 43 fishing mortality deviates in Model 19.0, plus one mean fishing mortality parameter, to fit the observed catch closely. Twenty-one initial recruitment deviations were estimated to start the population in 1977. Recruitments deviations from 1977 to 2019 account for 43 parameters, plus one parameter for the mean recruitment.

Parameters Estimated Outside the Assessment Model

Natural mortality

Natural mortality (M) rates for Gulf of Alaska Arrowtooth Flounder were estimated using the methods of (Wilderbuer and Turnock 2009). A higher natural mortality for males than females was used to fit the age and size composition data, which are about 70% female. A value of M=0.35 for males was chosen so that the survey selectivities for males and females both reached a maximum selectivity close to 1.0. A likelihood profile on male natural mortality resulted in a mean and mode of 0.354 with 95% confidence intervals of 0.32 to 0.38 (Turnock et al 2002, Figure 10.14). Model runs examining the effect of different natural mortality values for male Arrowtooth Flounder can be found in the Appendix of the 2000 SAFE. Differential natural mortality by sex can be a factor that needs consideration in management of targeted fish stocks, however, since GOA Arrowtooth Flounder is currently exploited at low levels, this effect is not a concern for this stock (Wilderbuer and Turnock 2009).

Data used to calculate length at age and weight at length

The data consisted of age data from 1984-2013 GOA RACE groundfish surveys. There were 9,686 such data points, each associated with age, length, and weight for each fish and 12,308 that had age and length (Table 7.9). Ageing methods have changed throughout the time series but this is not expected to cause bias over time or errors in the earlier datasets (D. Anderl, AFSC Age and Growth, pers. comm.).

Weight at Length

The weight-length relationship for Arrowtooth Flounder was evaluated to be: $Weight = 0.004312 * Length^{3.186}$, for both sexes combined, where weight is in grams and length in centimeters. Analysis was performed using nonlinear least squares fit to all weight and length data from the RACE Gulf of Alaska surveys from 1984 to 2013. The nonlinear least squares (nls) method was implemented from the R package stats (Bates and Chambers 1992). The length-weight relationship was the same among male and females (Figure 7.8).

Growth

Growth was estimated from length and age data from RACE Gulf of Alaska surveys from 1984 to 2013 and incorporated in the assessment using a length-age conversion matrix. Length (adjusted for survey length frequencies) was converted to weight with the weight-at-length relationship described above. Length frequencies from stratified sampling for age data was corrected using length frequencies from surveys for which there is more data, averaging 12,000 female and 6,500 male lengths per survey (Table 7.11).

Length at Age

There is a single length-age conversion matrix that converts length frequencies from all years of data to age in the model. This correction is based on Bayes Theorem, as follows (Dorn 1992). The stratified age collections consist of P(Length|Age). These are corrected for the length frequencies in the population by dividing by length frequencies from survey data from the same years, 1984-2013.

$$P(Age|Length) = P(Length|Age)P(Age)/P(Length),$$

Correcting for survey length frequencies reduced the expected length at age in the population as compared to lengths of aged fish from a stratified collection (Figure 7.9).

A vonBertalanffy individual growth model,

$$Length = S_\infty(1 - e^{-(K_{age} - t_0)}),$$

was applied to the corrected length at age data, separately for males and females, using the R package *fishmethods*, resulting in the following parameter estimates. The plus group contains all ages 21 and above, and was calculated as a weighted average of the vonBertalanffy mean length and the proportion estimated to be in each of those upper age categories based on M=0.2 for females and M=0.35 for males.

Sex	S_{inf}	K	t_0	n
Females	837.6	0.07587	-2.57872	
Males	524.1	0.1672	-1.4684	

The coefficient of variation (CV) typically decreases with age. This was not the case with the GOA ATF data, although Bering Sea females data did fit this pattern. Therefore, female CV of length at age was fitted to a straight line and adjusted slightly so that a normal distribution around the vonBertalanffy estimate of length at age did not reach out of the range of lengths observed, $CV = -0.003 * age + 0.14$. Male variance was also fitted to a linear model, but not adjusted, $CV = -0.0008637 * age + 0.1184688$.

The length-age conversion matrix was generated by simulating 10^7 data points for each length observed from survey lengths of Arrowtooth Flounder, from 90 to 880mm. The simulations were generated from a normal distribution, with the mean length at age determined by the male and female vonBertalanffy fit to the length-age data and the CV for each length determined by the parameters of the linear models described above. These data were binned into 26 length categories bounded by the range shown below. These length categories were used for all length composition data in the model. The length-age conversion matrix is shown in Figure 7.10.

	1	2	3	4	5	6	7	8	9	10	11	12	13
Range (mm)	<100	100-160	160-180	180-200	200-220	220-240	240-260	260-280	280-300	300-320	320-340	340-360	360-380
Midpoints	90	130	170	190	210	230	250	270	290	310	330	350	370

	14	15	16	17	18	19	20	21	22	23	24	25	26
Range (mm)	380-400	400-430	430-460	460-490	490-520	520-550	550-580	580-610	610-640	640-670	670-700	700-750	>750
Midpoints	390	415	445	475	505	535	565	595	625	655	685	725	850

Weight at age

Weight at age used in the model is based on length at age corrected as shown in Figure 7.9 by survey length frequencies. Weight at age of females determined by this method is slightly lower than weight at age determined by a weight-at-age vonBertalanffy relationship determined from the stratified age collection. Differences in male weight at age were not as significant as differences in female weight at age (Figure 7.9).

Maturity

Maturity at age estimates in the model was based on a maturity-at-length study by Zimmerman (1997) through 2013. Length at 50% maturity was estimated at 47 cm with a logistic slope of -0.3429 from Arrowtooth Flounder sampled in hauls that occurred in September from the 1993 bottom trawl survey (Zimmerman 1997). Elsewhere in their range, length at 50% maturity was 36.8 cm for females and 28.0 cm for males from survey data in 1992 off Washington, with logistic slopes of -0.54 and -0.893 respectively (Rickey 1995). Arrowtooth Flounder had length at 50% maturity of 44 cm for females and 29 cm for males of the coast of Oregon (Rickey 1995). Spawning fish were found in depths from 108m to 360m in March to August in the Gulf of Alaska (Hirshberger and Smith 1983) from analysis of trawl surveys from 1975 to 1981. Most observations of spawning fish have been in the northeastern Gulf, off Prince William Sound, off Cape St. Elias, and Icy Bay.

A study was conducted in 2008 that examined maturity-at-age that estimates age at maturity rather than length at maturity (Stark 2008). In this study, a sample of 301 fish was taken in February 2002 and a separate collection (226 fish) was taken in July 2003, both from the central GOA. Parameter estimates based on the February sample were used in the current study because Arrowtooth Flounder spawn during winter months. The estimate of logistic 50% maturity was 7 years, the logistic slope (B) was 1.3817 and the intercept (A) was -9.6183. Fish matured at a slightly younger age in the 2008 study compared to the 1997 study. This maturity ogive (Stark 2008) has been used in the model since 2015.

$$Maturity_{age} = \frac{1}{1 + e^{-A+B*ages}}.$$

Likelihood weights

Likelihood weights were adjusted using the methodology of Francis (2011) and are described in more detail in the Model Evaluation section from the 2013 assessment. The parameter s1,

$$s1 = [\chi^2_{0.95,m-1}/(m-1)]^{0.5},$$

was used to evaluate model weighting, where $\chi^2_{0.95,m-1}$ is the 95^{th} percentile of a chi-sqared distribution with m-1 degrees of freedom and m is the number of observations (Francis 2011).

Population dynamics

Several aspects of the Arrowtooth Flounder population dynamics that were not used directly in the model are presented here. Differences in growth show up around the age at maturity at age 6 (Figure 7.11). Age at 50% maturity is age 7 in females, and is 20% in age 6 fish.

Age composition data has been used in the model from all GOA surveys since 1984, except for 2019 (Table 7.9). Differences in ageing methodology exist but are not expected to bias results (D. Anderl, REFM Age and Growth, pers. comm.).

Ageing error matrix

Ageing error in Arrowtooth Flounder is relatively high compared to walleye pollock and Pacific cod. Therefore, we implemented an ageing error transition matrix to convert population numbers at age to expected survey numbers at age. The matrix was computed using the estimated percent agreement among two age readers. We used the percent agreement for ages from 1987-2015. The model incorporates a linear increase in the standard deviation of ageing error and assumes that ageing error is normally distributed (Dorn et al. 2003, Methot 2000). Percent agreement is predicted by the sum probability that both readers are correct, that both readers are off by one year in the same direction, and the probability that both age readers are off by two years in the same direction (Methot 2000). Ageing agreement is 88% at age 1 and declines to 50% at age 5 and 12% at age 15 (Figure 7.12). There is higher variation in the percent agreement at older ages, which could be due to a sampling effect; there are fewer older fish and therefore lower probability of selecting an older fish for double-reading.

Parameters estimated outside the model are summarized in Table 7.13.

Parameters Estimated Inside the Assessment Model

Year class strengths

The population simulation specifies the number-at-age in the beginning year of the simulation, the number of recruits in subsequent years, and the survival rate for each cohort as it moves through the population calculated from the population dynamics equations.

Fishing Mortality

The fishing mortality rates (F) for each age and year are calculated to approximate the catch weight by solving for F while still allowing for observation error in catch measurement.

Selectivity

Separate fishery selectivities were estimated non-parametrically for each age, up to age 19, and the shape of the selectivity curve was constrained to be a smooth function (Figure 7.13). Survey selectivities were modeled using a two parameter ascending logistic function. The selectivities by age were estimated separately for females and males. The differential natural mortality and selectivities by sex resulted in a predicted fraction female of about 0.70, which is close to the fraction female in the fishery and survey length and age data. Selectivity was estimated up to age 19 in the model for both fishery and survey, males and females. The previous model estimated selectivity up to age 11. The increase in maximum selectivity parameters estimated improved the overall fit to the data.

Results

Model Evaluation

A table of the likelihood components for Model 17.1a and Model 19.0 (Table 7.14) indicates that the negative log likelihood components, total negative log likelihood, and objective function value are lower for Model 19.0. However, Model 19.0 also had 32 fewer parameters than Model 17.1a and this loss of complexity will naturally improve likelihood values.

The Akaike information criterion (AIC; Akaike 1974) can be an important method for determining model quality. Out of a set of models, the model with the lowest AIC value is preferred. AIC provides lower scores to goodness of fit (via the likelihood function), and includes a penalty for increasing the number of estimated parameters. It can be difficult to compare AIC for models generated in ADMB because the likelihood is not easily obtainable. The hessian, the matrix of second mixed derivatives in transformed space, is created as output from each ADMB model run. Transformed parameters (bounded parameters estimated using a logit transform) were back-transformed by taking the log of the determinant of the hessian, and the marginal likelihood ($Likelihood_{MAR}$) was estimated as in Thorson et al. (2014), where OFV is the objective function value from the ADMB .par file, $Likelihood_{mar} = -0.5Hess_T - OFV$. The marginal likelihood can be used to calculate AIC, as follows:

$AIC = 2k - 2 * Likelihood_{mar}$, where k is the number of parameters used in the model.

Model 19.0 had a lower AIC than Model 17.1a; Model 19.0 AIC = 1258.94 vs. Model 17.a AIC = 1568.33.

The average difference in squared deviations (ADSB) between Model 19.0 and Model 17.1a was greater than 0.1; therefore Model 19.0 was renamed for the current year. Model output in a summary table format is provided for comparison (Table 7.15. Model 17.1a and Model 19.0 fit the survey age frequency data similarly (Figure 7.14 and Figure 7.15). The fit to survey length frequency data is not as close as the fit to ages (Figure 7.16). The fit to fishery length composition data improved throughout the time series (Figure 7.17), likely due to increases in the number of samples and higher weighting of the more recent data (Table 7.5).

Model 19.0 is the preferred model, and data for this model is presented unless specified otherwise.

Time Series Results

Estimates of fishing mortality have increased over the model time series, consistent with the recent trend of decreasing biomass (Figure 7.18). The estimates of fishing mortality were similar for Models 17.1a and 19.0. The fit to survey biomass estimates is shown in Figure 7.19, and shows an increasing trend in biomass through 2007, and decreased since approximately 2007-2009. Models 17.1a and 19.0 estimate lower levels of total and female spawning biomass than Model 17.0e, due to the addition of the 2019 data. Female spawning biomass increased throughout 2002-2008 in the 2017 assessment, peaked at 1,173,220 t, and subsequently declined to 923,548 t in 2017 (Table 7.16, Model 17.0e, Figure 7.20). Model 19.0 and Model 17.1a provide a similar trajectory for total biomass and female spawning biomass, with Model 19.0 increasing from 2002-2008 to a maximum of 1,112,470 t, and decreasing to the 2019 estimate of 794,350 t. Model 19.0 indicated that female spawning biomass in 2019 was 80% of the estimate in 2017 (Table 7.16). Current levels of female spawning biomass are similar to estimates from the early 1990s. The 2017 model estimated total age 1+ biomass of 1,463,110 t in 2017, and the 2019 model estimated a 68% decline to 1,333,540 t in 2019. Model estimates of total and female spawning biomass with 95% credible intervals based on MCMC posterior distributions are presented in Table 7.17. Age 1 recruitment has been below average since 2007 (Figure 7.21 and Table 7.18). Recruitment peaked in 2000 at 1.669e+09 and has declined since that time. Recent estimtates of recruitment are likely not reliable, as the presence of older fish in the time series is needed to lend certainty to recruitment estimates.

Reference fishing mortality rates and yields

Reliable estimates of biomass, $B_{40\%}$, $F_{35\%}$ and $F_{40\%}$, are available for Arrowtooth Flounder. The current projection model (Model 19.0) estimate of female spawning biomass is greater than $B_{40\%}$. The projected estimate of female spawning biomass for 2020 is 756,100, which is 1.83818×10^5% of the estimate of $B_{40\%}$, 411,332 t. Therefore, the Arrowtooth Flounder stock in the Gulf of Alaska is in Tier 3a of the ABC and overfishing definitions. Under this definition, $F_{OFL} = F_{35\%}$, and F_{ABC} is less than or equal to $F_{40\%}$.

The acceptable biological catch (ABC) for 2020 using $F_{40\%} = 0.193$ was estimated at 128,060 t (2017 assessment $F_{40\%} = 0.196$) using the preferred model (Model 19.0). The OFL for 2020 at $F_{35\%} = 0.234$ was estimated at 1.5301711×10^5 t. The ABC for 2020 is 124,357 t, and the OFL for 2020 is 148,597 t. Model estimates of fishing mortality have been below target rates for the entire time series (Figure 7.22). The highest fishing mortality was estimated to be 0.04 in 2014 Table 7.19, which corresponds with the highest catch on record of 36,300 t Table 7.3.

Maximum sustainable yield

Since there is no estimate of the spawner-recruit relationship for Arrowtooth Flounder, no attempt has been made to estimate MSY. However, using the projection model described in the next section, spawning biomass with F=0 was estimated at 1,028,329 t in 2019. The equilibrium spawning biomass with fishing at $F_{35\%}$, $B_{35\%}$ was estimated at 359,915 t and $B_{40\%}$ was 411,332 t.

Retrospective analysis

A retrospective analysis was performed, in which data were sequentially removed from the preferred model for ten years, and spawning biomass was estimated (Figure 7.23). In most retrospective years, the estimate for spawning biomass was slightly higher than the current model during the respective terminal year. The difference between the current model and the retrospective years shows that the difference between the current model was highest for the 2016 retrospective year, indicating a small potential retrospective bias (Figure 7.24). Mohn's rho for Model 17.1a was calculated to be 0.131, slightly higher than the 2017 value of 0.092, but in the range of other Alaska groundfish assessment models, indicating that the effect of the bias is small. Mohn's rho significantly improved under Model 19.0, to 0.022.

Harvest Recommendations

Projected catch and abundance

A standard set of projections is required for each stock managed under Tiers 1, 2, or 3 of Amendment 56. This set of projections encompasses seven harvest scenarios designed to satisfy the requirements of Amendment 56, the National Environmental Protection Act, and the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA).

For each scenario, the projections begin with the vector of 2019 numbers at age estimated in the assessment (Table 7.20). This vector is then projected forward to the beginning of 2032 using the schedules of natural mortality and selectivity described in the assessment and the best available estimate of total (year-end) catch for 2019. In each subsequent year, the fishing mortality rate is prescribed on the basis of the spawning biomass in that year and the respective harvest scenario. In each year, recruitment is drawn from an inverse Gaussian distribution whose parameters consist of maximum likelihood estimates determined from recruitments estimated in the assessment. Spawning biomass is computed in each year based on the time of peak spawning and the maturity and weight schedules described in the assessment. Total catch is assumed to equal the catch associated with the respective harvest scenario in all years. This projection scheme is run 1,000 times to obtain distributions of possible future stock sizes, fishing mortality rates, and catches. Projections were based on estimated catches of 20,554 t for 2019 which was estimated from an average of 97.6% of the catch caught by October 5 over the years 2014-2018, and 24,186 for 2020 which is based on the 5 year average (2014-2018).

- Scenario 1: In all future years, F is set equal to max F_{ABC} . (Rationale: Historically, TAC has been constrained by ABC, so this scenario provides a likely upper limit on future TACs.)
- Scenario 2: In all future years, F is set equal to a constant fraction of max F_{ABC} , where this fraction is equal to the ratio of the F_{ABC} value for the assessment two years ago recommended in the assessment to the max F_{ABC} for the current year. (Rationale: When F_{ABC} is set at a value below max F_{ABC}, it is often set at the value recommended in the stock assessment.)
- Scenario 3: In all future years, the upper bound on F_{ABC} is set at $F_{60\%}$. (Rationale: This scenario provides a likely lower bound on F_{ABC} that still allows future harvest rates to be adjusted downward when stocks fall below reference levels.)
- Scenario 4: In all future years, F is set equal to the average of the five most recent years. (Rationale: For some stocks, TAC can be well below ABC, and recent average F may provide a better indicator of F_{TAC} than F_{ABC}.)
- Scenario 5: In all future years, F is set equal to zero. (Rationale: In extreme cases, TAC may be set at a level close to zero.) Two other scenarios are needed to satisfy the MSFCMA's requirement to determine whether a stock is currently in an overfished condition or is approaching an overfished condition. These two scenarios are as follow (for Tier 3 stocks, the MSY level is defined as $B_{35\%}$):
- Scenario 6: In all future years, F is set equal to F_{OFL}. (Rationale: This scenario determines whether a stock is overfished. If the stock is expected to be above ½ of its MSY level in the current year and above its MSY level in 25 years under this scenario, then the stock is not overfished.)
- Scenario 7: In the next two years, F is set equal to max F_{ABC}, and in all subsequent years, F is set equal to F_{OFL}. (Rationale: This scenario determines whether a stock is approaching an overfished condition. If the stock is expected to be above its MSY level in 25 years under this scenario, then the stock is not approaching an overfished condition.)

Projected catch and abundance for Model 19.0 were estimated using $F_{40\%}$, F equal to the average F from 2014 to 2019 (F=0.029), F equal to one half $F_{40\%}$, and $F = 0$ from 2019 to 2032 (Table 7.20). Under scenario 6 above, the year 2020 female spawning biomass is 153,017 t and the year 2032 spawning biomass is 82,176 t, above the $B_{35\%}$ level of 153,017 t. For scenario 7 above, the year 2032 spawning biomass is 82,132 t, also above $B_{35\%}$. Fishing at $F_{40\%}$, female spawning biomass would still be above $B_{40\%}$ (128,060 t) in year 2032 (77,951 t). Female spawning biomass would be expected to decrease to 53,647 over the next 12 years, if fishing continues at the 5-year average fishing mortality (0.029) (Table 7.20, Scenario 4).

Risk table assessment

Assessment-related Considerations

The GOA Arrowtooth Flounder assessment is based on a time series of all standard NMFS groundfish surveys dating back to 1984. Ages from NMFS surveys are available for most of those years, and in years for which there is no survey, length composition data is used from the survey. The model exhibits good fits to abundance and composition data. The retrospective pattern from the current assessment is good, and Mohn's rho was calculated to be 0.022 for Model 19.0, indicating that there is little effect due to retrospective bias.

Population dynamics considerations

Stock assessment model results that Arrowtooth Flounder biomass (age 1+) was at low levels during the 1960s and 1970s, although surveys used during that time period used unconventional methods. The population increased throughout the 1980's and reached a peak in the 2000's at which time biomass was estimated at approximately 2 million tons. The biomass has recently declined over roughly the past 10 years, and is now in the vicinity of 1 million metric tons, and still well above reference points. Population dynamics are not a concern for this assessment.

Ecosystem/environmental considerations

During the 2019 bottom trawl survey, the average condition (defined as weight-length residuals) was near the time series mean indicating that the overall foraging landscape for Arrowtooth Flounder was sufficient. This is in contrast to 2015 and 2017 when mean body condition was low and record low (respectively), indicating that Arrowtooth Flounder were not able to forage sufficiently to meet energetic demands. This was likely related to the 2014-2016 marine heatwave which caused both increased energetic demands for groundfish due to the warm temperatures and lack of forage fish prey. Condition was slightly above the time series mean from Kodiak to Southeast, but remained slightly below from west of Kodiak to Unimak Pass, indicating the potential for regional variation in Arrowtooth Flounder prey abundance.

Both juvenile and adult Arrowtooth Flounder eat euphausiids. While euphausiids were at record abundance during the September 2018 Seward Line sampling, abundance estimates were low in May 2019. Acoustically-derived estimates of euphausiid abundance during summer 2019 were moderate to low. Additionally, the reproductive success of planktivorous auklets at the Semedi Islands was average. Taken together, these euphausiid indicators suggest moderate to low euphausiid abundance during 2019.

Forage fish indicators suggest mixed signals for abundance during 2019. Spring and late summer surveys for young of year groundfish found very few. However, forage-fish eating seabirds at the Semidis had strong reproductive success, although observations indicated that diets were unusual relative to other years where typical forage fish such as age-0 gadids, capelin, and sand lance predominate. Taken together these indicators suggest poor forage fish prey abundance.

In general predators of juvenile Arrowtooth Flounder appear to be stable or declining. Steller sea lion trends have stabilized or continued to decline in the Gulf of Alaska. Large Pacific cod are estimated at low biomass. Together these suggest no apparent concern for an increase in juvenile arrowtooth predator populations. However, the western GOA shelf area has experienced heatwave conditions since late September 2018. Based on knowledge gained from the 2014-2016 heatwave, we consider this to be unfavorable for arrowtooth as the prolonged increased temperatures likely increased their metabolic demands as well as the metabolic demands of their groundfish predators. It is unknown how long the heatwave in this area will persist. We consider the concern level to be 2—some indicators showing adverse signals relevant to the stock but the pattern is not consistent across all indicators.

Fishery performance considerations

There is no concern regarding the ability of the fishery to catch Arrowtooth Flounder. At the current time, fishery CPUE is not showing a contrasting pattern from the stock biomass trend, unusual spatial pattern of fishing, or changes in the percent of TAC taken, changes in the duration of fishery openings.

The table below summarizes the Risk Assessment results for the 2019 assessment. The overall level of risk is 2. No reduction in ABC is recommended because catch is typically much lower than the ABC and the stock is still much higher than $B_{35\%}$.

Assessment consideration	Population dynamics	Environmental ecosystem	Fishery performance	Overall
Level 1: Only minor, low level of concern	Level 1: Stock trends are typical for the stock and expected given stock dynamics; recent recruitment is within the normal range.	Level 2: Some indicators showing adverse signals relevant to the stock but pattern not consistent across all indicators.	Level 1: Low level of concern.	Level 2: Substantially increased concerns.

ABC and OFL for 2020 and 2021

ABC for 2020 using $F_{40\%} = 0.193$ was estimated at 128,060 t. The projection model was used to estimate the 2021 ABC using an estimated 2020 catch of 24,186 t; the 2021 ABC was 124,357 t. In the 2018 update assessment, the 2019 ABC using $F_{40\%} = 0.196$ was estimated at 140,864 t, (http://www.afsc.noaa.gov/REFM/Stocks/assessments.htm). An ABC of 128,060 t and an OFL of 153,017 t is recommended for 2020, and an ABC of 124,357 t and an OFL of 148,597 t is recommended for 2021. The stock is not currently being subjected to overfishing, as determined by comparing the complete 2017 and 2018 catch to the specified OFL for that year (Table 7.3). The stock is not overfished, and is not approaching a condition of being overfished (Table 7.20). If fishing continues at its current level, the stock will remain above $B_{40\%}$ through 2032 (Figure 7.25).

Data gaps and research priorities

Analysis of the herding and escapement studies for arrowtooth would result in improved estimates of selectivities and catchability. Otoliths have been aged through the 2017 survey, but continued aging will allow monitoring of growth trends. A correlation between bottom temperatures and catchability has been observed in Arrowtooth Flounder and other flatfish; whether a similar relationship exists for GOA ATF would provide helpful information for the estimation of catchability. In addition, an examination of catchability may benefit the model. Examination of genetic stock structure of Arrowtooth Flounder throughout its range is important to delineate stock boundaries and may lead to insight on the migratory behavior and skewed sex ratio of this species.

Ecosystem Considerations (see Appendix B)

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Tables

Table 7.1: Survey estimates of biomass in the four Gulf of Alaska regulatory areas, Western GOA (NMFS area 610), Central GOA (620 and 630), West Yakutat, and East Yakutat/SE Alaska.

	Survey Estimates							
Year	Western		Central		West Yakutat		East Yakutat/SE	
	Biomass	CV	Biomass	CV	Biomass	CV	Biomass	CV
2003	341,620	0.13	2,195,096	0.02	94,184	0.27	188,195	0.19
2005	215,278	0.14	1,440,854	0.04	122,434	0.30	121,021	0.30
2007	263,856	0.13	1,434,851	0.04	104,952	0.38	132,361	0.34
2009	285,427	0.19	1,201,756	0.05	114,665	0.30	170,181	0.25
2011	225,683	0.15	1,175,072	0.06	91,580	0.42	255,004	0.25
2013	205,752	0.24	763,845	0.07	196,318	0.22	124,812	0.28
2015	237,919	0.14	912,713	0.08	129,075	0.29	381,574	0.17
2017	311,318	0.12	519,312	0.09	76,627	0.36	146,437	0.26
2019	275,024	0.12	585,238	0.06	70,680	0.29	145,785	0.20

Table 7.2: Random effects model applied to survey biomass estimates in the four Gulf of Alaska regulatory areas, Western GOA (NMFS area 610), Central GOA (620 and 630), West Yakutat, and East Yakutat/SE Alaska.

	Random Effects Model							
Year	Western		Central		West Yakutat		East Yakutat/SE	
	Biomass	CV	Biomass	CV	Biomass	CV	Biomass	CV
2003	267,220	0.05	1,940,810	0.15	104,406	0.21	178,801	0.18
2004	267,219	0.05	1,691,130	0.15	107,824	0.20	157,685	0.27
2005	267,219	0.05	1,473,580	0.07	111,354	0.18	139,062	0.23
2006	267,219	0.05	1,443,150	0.14	112,171	0.19	141,685	0.29
2007	267,218	0.05	1,413,350	0.08	112,993	0.19	144,357	0.24
2008	267,218	0.05	1,311,450	0.14	115,232	0.19	158,071	0.28
2009	267,218	0.05	1,216,890	0.10	117,516	0.18	173,088	0.20
2010	267,218	0.05	1,161,930	0.15	120,614	0.19	194,491	0.26
2011	267,218	0.05	1,109,440	0.11	123,794	0.18	218,540	0.21
2012	267,218	0.05	962,608	0.15	132,510	0.20	195,576	0.27
2013	267,218	0.05	835,207	0.12	141,839	0.23	175,025	0.25
2014	267,218	0.05	834,698	0.15	130,500	0.20	235,036	0.25
2015	267,218	0.05	834,190	0.10	120,067	0.18	315,622	0.18
2016	267,219	0.05	678,780	0.14	108,310	0.19	233,717	0.25
2017	267,219	0.05	552,323	0.09	97,705	0.22	173,067	0.21
2018	267,219	0.05	567,630	0.13	92,198	0.25	161,293	0.26
2019	267,219	0.05	583,361	0.06	87,001	0.27	150,320	0.19

Table 7.3: Catch, OFL, ABC, and TAC for Arrowtooth Flounder in the Gulf of Alaska from 1964 to October 5, 2019. Values are in metric tons. Arrowtooth Flounder ABC was separated from the Flatfish ABC after 1990. Source: AKFIN database (https://akfinbi.psmfc.org/analytics/).

Year	Catch	OFL	ABC	TAC
1964	514			
1965	514			
1966	2,469			
1967	2,276			
1968	1,697			
1969	1,315			
1970	1,886			
1971	1,185			
1972	4,477			
1973	10,007			
1974	4,883			
1975	2,776			
1976	3,045			
1977	9,449			
1978	8,409			
1979	7,579			
1980	7,848			
1981	7,433			
1982	4,639			
1983	6,331			
1984	3,457			
1985	1,539			
1986	1,221			
1987	4,963			
1988	5,138			
1989	2,584			
1990	7,706		343,300	
1991	10,034		340,100	20,000
1992	15,970	427,220	303,889	25,000
1993	15,559	451,690	321,287	30,000
1994	23,560	275,930	236,240	30,000
1995	18,428	231,420	198,130	35,000
1996	22,583	231,420	198,130	35,000
1997	16,319	280,800	197,840	35,000
1998	12,975	295,970	208,337	35,000
1999	16,207	308,875	217,106	35,000
2000	24,252	173,915	145,361	35,000
2001	19,964	173,546	148,151	38,000
2002	21,231	171,057	146,264	38,000
2003	29,994	181,394	155,139	38,000
2004	15,304	228,134	194,900	38,000
2005	19,770	228,134	194,900	38,000
2006	27,653	207,700	177,800	38,000
2007	25,494	214,828	184,008	43,000
2008	29,293	266,914	226,470	43,000
2009	24,937	261,022	221,512	43,000
2010	24,268	254,271	215,882	43,000
2011	30,903	251,068	213,150	43,000
2012	20,565	250,100	212,882	103,300

2013	21,612	247,196	210,451	103,300
2014	36,300	229,248	195,358	103,300
2015	19,056	226,390	192,921	103,300
2016	19,835	219,430	186,188	103,300
2017	26,866	219,327	186,083	103,300
2018	18,873	180,697	150,945	76,300
2019	20,061	174,598	145,841	99,295

Table 7.4: Percent of the Gulf of Alaska stock of Arrowtooth Flounder retained by commercial fishing operations 1991-2019. Source: AKFIN database (https://akfinbi.psmfc.org/analytics/).Data downloaded October 5, 2019.

Year	Percent retained
1991	12.5%
1992	2.3%
1993	8.1%
1994	2.0%
1995	12.4%
1996	24.2%
1997	18.2%
1998	15.9%
1999	26.4%
2000	42.6%
2001	33.2%
2002	49.7%
2003	43.2%
2004	42.3%
2005	60.1%
2006	57.8%
2007	59.2%
2008	70.1%
2009	51.5%
2010	60.2%
2011	78.6%
2012	77.0%
2013	75.1%
2014	90.6%
2015	89.7%
2016	91.4%
2017	93.0%
2018	91.8%
2019	96.5%

Table 7.5: The number of fisheries length observations taken by fisheries observers, and the number of hauls from which those samples were taken, by year, 1975-2019 (Source: AKFIN database (https://akfinbi.psmfc.org/analytics/, downloaded October 6, 2019).

			Weights applied to fishery length comps	
Year	Number of observations	Number of hauls	Females	Males
1975	121			
1976	0			
1977	868		20	20
1978	5,491		20	20
1979	9,499		20	20
1980	4,500		20	20
1981	2,062		20	20
1982	19,139		20	20
1983	14,963		20	20
1984	7,149		20	20
1985	671		20	20
1986	194		20	20
1987	763		20	20
1988	211		20	20
1989	0			
1990	217	7	7	7
1991	5,892	89	95	89
1992	198	2	2	2
1993	1,223	12	12	12
1994	121			
1995	2,628	10	10	10
1996	889	15	15	15
1997	2,999	14	14	14
1998	472	4	6	4
1999	2,642	122	129	122
2000	6,351	293	200	200
2001	6,266	290	200	200
2002	8,275	396	200	200
2003	15,052	730	200	200
2004	4,961	187	200	200
2005	7,073	285	200	200
2006	8,413	309	200	200
2007	10,004	397	200	200
2008	9,271	390	200	200
2009	8,406	306	200	200
2010	7,600	264	200	200
2011	11,282	426	200	200
2012	9,583	403	200	200
2013	8,182	409	200	200
2014	16,346	678	200	200
2015	11,848	547	200	200
2016	10,979	567	200	200
2017	15,502	805	200	200
2018	7,015	441	200	200
2019	4,109	265	200	200

Table 7.6: Catch (t) of arrowtooth in targeted halibut fisheries by area and year (2003-2019). Source: NMFS AKRO BLEND/Catch Accounting System. Downloaded October 30, 2019.

Year	WGOA	CGOA	CGOA	EGOA	EGOA	Total
	Shumagin	Chirikof	Kodiak/PWS	Yakutat	Southeast	
	610	620	630	640	650	
2003	11.68	3.11	17.58	1.07	16.57	50.01
2004	13.55	5.90	14.65	3.41	9.96	47.47
2005	10.31	13.34	22.39	5.96	9.32	61.32
2006	4.84	3.85	14.12	5.55	7.16	35.52
2007	10.53	8.17	30.76	12.70	18.11	80.27
2008	6.76	3.92	10.85	2.00	5.89	29.42
2009	5.94	10.16	25.73	10.44	7.07	59.34
2010	3.01	5.03	18.48	2.86	5.73	35.11
2011	0.57	1.16	2.59	0.68	0.51	5.51
2012	0.59	0.88	2.59	0.26	0.70	5.02
2013	4.00	25.74	55.75	10.30	11.34	107.13
2014	1.89	18.58	13.81	6.81	4.95	46.04
2015	5.19	5.92	10.72	6.87	5.43	34.13
2016	0.86	1.50	10.97	2.58	2.27	18.18
2017	6.30	5.43	18.93	2.92	2.69	36.27
2018	6.75	9.36	20.37	3.37	5.13	44.98
2019	1.44	9.85	6.61	4.55	4.36	26.81

Table 7.7: Biomass estimates, standard errors, coefficient of variation (CV), number of hauls, and maximum depth (m) from bottom trawl surveys, 1961-2019. *The 2001 survey biomass for the eastern gulf was estimated by using the average of the 1993 to 1999 biomass estimates in the eastern gulf.

Survey	Biomass (t)	Standard error	CV	Number of hauls	Maximum depth (m)
IPHC 1961-1962	283,799	61,515	0.22	1,172	
NMFS groundfish 1973-1976	145,744	33,531	0.23	403	
NMFS triennial 1984	1,112,215	71,209	0.06	930	1,000
NMFS triennial 1987	931,598	74,673	0.08	783	1,000
NMFS triennial 1990	1,907,177	239,150	0.13	708	500
NMFS triennial 1993	1,551,657	101,160	0.07	776	500
NMFS triennial 1996	1,639,632	114,792	0.07	804	500
NMFS triennial 1999	1,262,151	99,329	0.08	764	1,000
NMFS 2001	1,621,892*	178,408	0.11	489	500
NMFS 2003	2,819,095	372,326	0.13	809	700
NMFS 2005	1,899,778	125,788	0.07	839	1,000
NMFS 2007	1,939,055	150,059	0.08	820	1,000
NMFS 2009	1,772,029	159,402	0.09	823	1,000
NMFS 2011	1,747,339	179,801	0.10	670	1,000
NMFS 2013	1,290,727	130,348	0.10	548	700
NMFS 2015	1,659,128	133,986	0.08	772	1,000
NMFS 2017	1,053,695	76,190	0.07	536	700
NMFS 2019	1,076,727	67,327	0.06	541	679

Table 7.8: Survey biomass estimates (t) for 1984 to 2019 by area; Western (NMFS area 610), Central (areas 620 and 630), and Eastern (areas 640, 650, 649, 659). The 2001 survey biomass for the eastern gulf was estimated by using the average of the 1993 to 1999 biomass estimates in the eastern gulf.

Year	Western GOA	Central GOA	Eastern GOA	Total
1984	72,863	823,216	216,136	1,112,215
1987	118,584	647,596	165,418	931,598
1990	221,858	1,504,638	180,681	1,907,177
1993	214,240	1,117,361	222,015	1,553,616
1996	202,594	1,176,714	260,324	1,639,632
1999	143,374	845,176	273,601	1,262,151
2001	185,432	1,175,305	251,980	1,360,738
2003	341,620	2,195,096	282,379	2,819,095
2005	215,278	1,440,854	243,454	1,899,587
2007	263,856	1,434,851	237,313	1,936,020
2009	285,427	1,201,756	284,846	1,772,029
2011	225,683	1,175,072	346,584	1,747,339
2013	205,752	763,845	321,130	1,290,727
2015	237,919	912,713	510,649	1,661,281
2017	311,318	519,312	223,065	1,053,695
2019	275,024	585,238	216,465	1,076,727

Table 7.9: The number of fished aged for collection years from 1977-2015. The methods of otolith reading are as follows: 1. No method specified, 3. Otolith surface reading, 4. Break and burn, 5. Thin section, 6. Break burn toasted, 7.Break no burn, 9. Oven bake flame burn. Note: fish collected from the 2017 GOA survey have not been aged yet. The ageing collection includes 14,098, but only 12,308 fish collected from 1984-2013 were used in the length age conversion matrix.

	Ageing method (percentage)						
Year	1	3	4	6	7	9	Total
1977	100						285
1978	100						888
1984	100						1,293
1987		23	41	28	9		1,534
1990			100				325
1993			100				1,043
1996			100				706
1999			100				931
2001			100				1,384
2003			100				1,034
2005		32		62	3	4	729
2007		5		92	3		786
2009		26	72	2			822
2011		9	6	82	3		899
2013		31		67	2		822
2015		29		69	2		617
2017		163	4	721	9		897
Total							14,098

Table 7.10: Length data (cm) from NMFS GOA surveys in 1984 through 2019. The numbers are percentages, where the numbers add to 100 within a year for each sex.

	Females																									
Year	10	16	18	20	22	24	26	28	30	32	34	36	38	40	43	46	49	52	55	58	61	64	67	70	75	75+
1984	0.00	0.07	0.08	0.14	0.67	1.23	2.08	2.21	2.01	2.99	3.51	4.00	4.19	7.50	16.17	15.42	9.93	7.10	5.29	3.79	3.23	2.96	2.81	1.72	0.76	0.13
1987	0.00	0.05	0.17	0.50	1.59	2.09	2.05	2.59	4.82	5.17	4.75	4.50	5.21	4.64	6.25	7.38	9.55	12.10	9.67	5.04	2.55	2.01	1.96	2.33	2.48	0.54
1990	0.00	0.10	0.17	0.54	1.20	1.59	2.17	2.58	3.70	4.44	3.99	4.17	4.83	4.94	10.19	10.45	9.84	8.31	7.68	5.86	4.15	2.90	1.37	1.17	2.11	1.51
1993	0.00	0.10	0.19	1.07	2.38	2.73	2.42	2.51	2.92	3.18	3.49	3.78	3.91	4.51	7.67	8.86	9.47	11.26	11.94	8.19	4.12	2.01	1.19	0.87	0.78	0.43
1996	0.01	0.11	0.26	1.31	2.30	3.17	2.63	2.16	2.69	3.04	3.49	3.47	4.51	5.06	7.87	7.60	8.23	10.81	12.78	8.56	3.98	2.10	1.33	0.89	1.17	0.48
1999	0.01	0.15	0.43	2.00	3.34	2.59	2.42	3.93	4.55	4.32	4.57	5.01	4.84	4.41	5.84	5.40	6.54	8.05	10.13	9.85	5.57	2.50	1.44	0.94	0.72	0.45
2001	0.01	0.07	0.31	2.06	4.58	5.32	3.25	2.61	3.46	4.21	3.75	3.95	4.48	4.27	6.54	7.16	7.73	7.95	7.27	7.45	5.39	2.98	1.78	1.29	1.66	0.46
2003	0.00	0.37	0.39	1.59	3.27	3.10	2.79	3.11	3.86	4.96	5.44	5.10	5.34	4.88	6.06	5.71	5.90	7.45	10.13	9.69	5.78	2.45	1.15	0.52	0.63	0.33
2005	0.01	0.30	0.42	1.22	1.59	1.63	2.70	3.50	3.79	4.26	4.97	5.75	6.62	7.38	11.07	9.52	8.57	6.70	6.37	5.81	3.65	1.88	0.95	0.58	0.50	0.27
2007	0.03	0.07	0.44	1.59	2.69	2.28	2.62	3.69	4.41	4.27	3.32	3.28	3.31	3.98	6.62	7.81	10.77	13.13	10.36	6.71	4.15	2.07	0.96	0.59	0.45	0.41
2009	0.00	0.13	0.53	2.41	3.29	2.54	2.32	3.50	4.62	5.24	5.16	5.30	5.00	5.15	6.51	5.52	6.48	9.59	12.17	7.51	3.62	1.64	0.82	0.41	0.35	0.19
2011	0.03	0.13	0.10	0.37	1.30	2.00	1.97	2.06	2.90	3.50	3.27	4.10	4.73	4.71	7.92	8.55	9.85	10.67	12.58	9.23	5.40	2.25	1.01	0.58	0.51	0.28
2013	0.01	0.63	0.31	0.55	1.97	4.03	4.33	3.82	3.75	4.00	3.53	2.88	2.87	4.23	7.00	8.53	11.43	12.81	10.30	7.43	3.33	1.19	0.44	0.20	0.28	0.16
2015	0.02	0.15	0.25	0.60	1.25	2.86	4.15	5.81	7.22	8.38	6.84	4.37	3.76	3.38	5.30	5.30	7.80	10.24	10.29	6.74	3.34	1.13	0.42	0.20	0.13	0.06
2017	0.01	0.20	0.35	1.47	2.34	3.33	3.67	3.33	4.34	4.71	5.47	6.32	7.20	7.99	9.77	7.91	6.94	7.09	6.29	4.56	3.09	2.02	0.89	0.40	0.22	0.09
2019	0.00	0.33	0.41	1.70	4.61	5.69	5.71	5.39	5.70	6.43	5.55	5.08	4.89	4.83	7.30	8.13	9.18	7.39	4.34	2.40	1.69	1.36	1.02	0.59	0.20	0.05

	Males																									
Year	10	16	18	20	22	24	26	28	30	32	34	36	38	40	43	46	49	52	55	58	61	64	67	70	75	75+
1984	0.00	0.27	0.18	0.45	1.17	2.47	3.88	4.99	5.29	6.03	7.26	8.81	12.46	16.74	17.46	8.45	2.56	0.68	0.26	0.19	0.10	0.07	0.13	0.05	0.02	0.02
1987	0.00	0.42	0.37	1.06	2.08	3.39	3.20	4.70	8.28	9.50	8.91	10.17	9.02	8.68	14.13	10.22	3.65	1.16	0.49	0.34	0.08	0.09	0.03	0.02	0.01	0.00
1990	0.00	0.16	0.21	0.77	1.63	2.20	2.83	3.79	5.57	6.07	7.08	7.48	8.46	10.62	18.01	16.17	7.04	1.34	0.38	0.10	0.02	0.03	0.01	0.02	0.00	0.00
1993	0.00	0.16	0.54	2.06	3.68	3.47	3.15	3.76	4.05	4.19	4.28	4.84	6.10	8.14	16.83	18.34	12.43	3.03	0.49	0.17	0.18	0.04	0.05	0.02	0.00	0.00
1996	0.01	0.28	0.54	1.87	4.05	4.19	3.24	2.77	3.46	4.09	4.88	5.74	6.33	7.32	12.32	17.42	14.95	5.29	0.90	0.14	0.10	0.06	0.01	0.03	0.01	0.00
1999	0.05	0.36	0.76	3.51	5.32	3.73	3.50	5.58	6.03	5.92	5.84	6.11	5.93	6.21	10.08	13.25	11.46	5.35	0.74	0.16	0.08	0.01	0.01	0.01	0.00	0.00
2001	0.02	0.21	0.79	4.76	8.87	7.47	4.13	4.66	6.07	5.70	5.54	5.66	5.65	5.55	10.01	9.92	9.16	4.95	0.87	0.02	0.01	0.00	0.00	0.00	0.00	0.00
2003	0.00	1.20	0.73	4.26	6.42	5.25	4.46	4.22	5.59	7.51	7.56	7.57	8.24	6.07	9.18	9.25	6.67	4.40	1.07	0.30	0.02	0.00	0.02	0.00	0.01	0.00
2005	0.01	0.75	1.05	2.09	3.24	3.08	4.43	4.91	5.47	5.75	6.43	7.22	10.03	10.26	15.60	9.79	6.01	2.88	0.82	0.11	0.04	0.02	0.00	0.01	0.01	0.00
2007	0.01	0.13	0.78	2.45	3.60	2.97	3.74	5.53	6.52	5.81	4.77	4.40	5.09	7.51	19.07	16.54	7.37	2.71	0.85	0.11	0.01	0.01	0.01	0.00	0.00	0.00
2009	0.01	0.34	1.26	4.15	4.87	4.12	3.45	5.29	6.28	7.95	7.30	6.65	6.72	6.74	11.23	12.63	7.25	2.73	0.79	0.19	0.01	0.01	0.01	0.00	0.01	0.00
2011	0.00	0.20	0.36	0.65	2.48	3.62	2.95	3.71	5.34	5.37	5.46	6.06	7.51	8.31	16.77	16.14	10.82	3.50	0.63	0.05	0.04	0.01	0.00	0.00	0.01	0.00
2013	0.00	0.33	0.30	0.80	3.42	4.32	4.57	5.14	4.86	5.04	4.18	4.58	5.88	7.48	15.91	17.14	10.75	4.57	0.55	0.18	0.01	0.01	0.00	0.00	0.00	0.00
2015	0.00	0.19	0.28	0.63	2.20	3.39	5.07	6.82	9.03	9.15	6.03	4.65	5.22	5.41	11.71	14.20	10.54	4.45	0.85	0.14	0.02	0.01	0.00	0.01	0.00	0.00
2017	0.02	0.27	0.56	2.00	3.38	4.68	5.46	6.51	6.17	7.03	7.72	9.54	9.80	9.14	10.61	9.31	5.95	1.62	0.13	0.05	0.02	0.00	0.01	0.00	0.00	0.00
2019	0.00	0.44	0.57	2.07	5.03	6.42	6.43	6.19	7.15	7.56	6.75	6.32	7.27	8.49	14.81	8.98	4.10	1.12	0.18	0.05	0.02	0.03	0.00	0.00	0.00	0.00

Table 7.11: The number of male and female Arrowtooth Flounder lengths recorded on NMFS GOA surveys, 1984-2019.

	Females	Males
1984	10,254	5,682
1987	12,741	6,359
1990	12,215	5,921
1993	14,543	6,855
1996	15,448	7,936
1999	15,350	8,076
2001	9,434	4,624
2003	16,879	9,052
2005	17,147	8,680
2007	15,058	7,883
2009	15,468	8,287
2011	12,019	6,518
2013	8,169	4,531
2015	13,178	7,834
2017	9,136	5,393
2019	9,749	6,084

Table 7.12: Estimated parameters for the model. There were 193 total parameters estimated in the model (but 4 were included in the final count and not actually estimated).

Parameter	N	Description
meanlogrec	1	Log of the geometric mean value of age 1 recruitment
$recdev_t$ 1961≤2019-1	58	Recruitment deviation in year t (not estimated in final year)
$recdev_t$ 1940≤t≤1960	21	Recruitment deviation for initial age composition
logavgfmort	1	log of geometric mean value of fishing mortality
$fmortdev_t$ 1961≤t≤2019	59	Deviations in fishing mortality rate in year t
slope and $a_{50\%}$ selectivity parameters	8	Slope and $a_{50\%}$ parameters for male and female, fishery and survey.
Nonparameteric estimates of fishery selectivity	38	19 male and 19 female fishery selectivity parameters, total of 38
$F_{40\%}$, $F_{35\%}$, $F_{30\%}$	3	
Parameters for descending arm of survey selectivity	4	Male and female slope and $a_{50\%}$. This is an option that is not used in this model. Parameters are not estimated but are included in the final count.

Table 7.13: Parameters estimated outside the model, natural mortality, survey catchability, and weight at age.

Parameter	Description
M = 0.2 females, M = 0.35 males	Natural mortality
Q = 1.0	Survey catchability
Weight at age for males and females	Length at age derived from the length-age conversion matrix was converted to weight based on a von Bertalanffy relationship from 1977-2013 survey data.

Table 7.14: Likelihood components for Model 17.1a and 19.0. Likelihood values are given in this order: survey biomass likelihood, fishery length composition likelihood, survey length composition likelihood, survey age composition likelihood, catch likelihood, recruitment likelihood, fishery selectivity likelihood, survey selectivity likelihood, the standard deviation of normalized residuals (SDNR), the number of parameters estimated in the model, the average deviation of spawning biomass from one model to the previous model, and the objective function value.

	Survey Biomass	Fishery Length	Survey Length	Survey Age	Recruitment	Fishery Selectivity
Model 17.1a	50.5932	808.392	105.1390	244.234	20.7069	1.42204
Model 19.0	28.4486	796.457	92.2046	250.048	4.9668	1.46121

	Survey selectivity	SDNR	N. Parameters	Total Likelihood	ADSB	Objective Function
Model 17.1a	5.5239	2.4509	193	1254.011	-	223.355
Model 19.0	5.5941	1.9397	161	1197.180	0.178	183.487

Table 7.15: Comparison of biomass estimates, reference points, and ABC and OFL for Models 17.1a and Model 19.0.

	Model 17.1a *last* year for:		Model 19.0 *this* year for:	
Quantity	2019	2020	2020	2021
M (natural mortality rate)	0.35, 0.2	0.35, 0.2	0.35, 0.2	0.35, 0.2
Tier	3a	3a	3a	3a
Projected total (age 1+) biomass (t)	1,270,359 t	1,251,117 t	1,325,867 t	1,321,075 t
Projected female spawning biomass (t)	746,658 t	706,966 t	756,100 t	718,325 t
$B_{100\%}$	867,147 t	867,147 t	1,028,329 t	1,028,329 t
$B_{40\%}$	346,859 t	346,859	411,332 t	411,332 t
$B_{35\%}$	303,501 t	303,501	359,915 t	359,915 t
F_{OFL}	0.236	0.236	0.234	0.234
$maxF_{ABC}$	0.194	0.194	0.193	0.193
F_{ABC}	0.194	0.194	0.193	0.193
OFL	151,702 t	146,554 t	153,017 t	127,773 t
$maxABC$	126,872 t	122,568 t	128,060 t	124,357 t
ABC	126,872 t	122,568 t	128,060 t	124,357 t

Table 7.16: Estimated total (age 1+) biomass (t) and female spawning biomass (FSB) (t) from Model 19.0, 17.1a, and Model 17.0e.

Year	Model 19.0	Model 17.1a	Model 17.0e	Model 19.0	Model 17.1a	Model 17.0e
Year	Biomass	Biomass	Biomass	FSB	FSB	FSB
1961	-	632,693	660,454	-	388,636	402,550
1962	-	630,373	658,200	-	382,145	396,491
1963	-	628,135	655,709	-	375,625	390,732
1964	-	625,550	652,626	-	369,989	386,077
1965	-	622,230	648,666	-	366,151	383,055
1966	-	618,076	643,784	-	364,378	381,550
1967	-	611,247	636,185	-	362,246	379,158
1968	-	604,744	628,931	-	360,561	376,980
1969	-	599,930	623,424	-	358,917	374,776
1970	-	597,839	621,070	-	356,850	372,125
1971	-	598,701	623,051	-	353,528	368,226
1972	-	605,435	633,921	-	350,279	364,438
1973	-	619,064	654,689	-	344,136	357,812
1974	-	642,552	681,364	-	334,217	347,543
1975	-	681,755	718,011	-	330,976	344,308
1976	-	729,830	765,672	-	332,728	346,894
1977	1,216,610	784,908	820,927	718,406	338,639	355,237
1978	1,211,520	842,490	880,015	711,689	345,751	366,698
1979	1,215,610	910,230	951,243	704,949	363,328	388,751
1980	1,223,200	978,161	1,025,080	697,756	392,077	418,502
1981	1,227,650	1,036,330	1,091,640	689,831	427,295	450,683
1982	1,229,490	1,083,640	1,149,270	683,640	465,211	485,924
1983	1,234,170	1,125,370	1,201,440	683,842	507,655	528,837
1984	1,245,340	1,166,180	1,253,130	688,408	552,521	576,575
1985	1,280,690	1,224,580	1,321,280	700,123	601,332	630,045
1986	1,329,640	1,290,530	1,389,530	713,236	646,278	681,291
1987	1,388,170	1,361,090	1,459,610	721,912	679,720	722,317
1988	1,452,610	1,433,430	1,532,820	723,910	699,262	749,876
1989	1,519,020	1,504,580	1,600,730	728,942	715,899	773,795
1990	1,580,890	1,568,770	1,660,800	747,723	742,158	805,744
1991	1,634,520	1,623,220	1,713,780	778,416	777,528	843,895
1992	1,678,640	1,667,320	1,755,040	818,508	820,072	884,842
1993	1,700,620	1,688,820	1,773,450	857,027	859,506	920,130
1994	1,711,580	1,699,090	1,782,690	895,568	898,009	954,911
1995	1,706,970	1,693,220	1,776,230	923,509	924,706	978,182
1996	1,701,290	1,685,830	1,770,270	948,093	947,331	997,972
1997	1,696,340	1,679,200	1,769,730	962,028	959,140	1,008,190
1998	1,714,770	1,696,530	1,793,380	974,346	969,477	1,017,650
1999	1,753,150	1,734,360	1,835,310	979,604	972,843	1,020,210
2000	1,818,330	1,800,390	1,906,500	973,346	964,637	1,012,410
2001	1,865,510	1,848,190	1,957,130	957,801	947,266	996,990
2002	1,908,910	1,892,300	2,004,400	950,070	938,055	991,159
2003	1,937,550	1,921,520	2,035,310	952,762	939,772	997,947
2004	1,947,320	1,931,980	2,048,680	966,679	953,476	1,016,940
2005	1,964,790	1,950,210	2,069,910	1,011,570	999,018	1,065,750
2006	1,966,630	1,952,810	2,076,580	1,062,000	1,050,790	1,118,770
2007	1,940,850	1,927,450	2,054,040	1,096,690	1,086,850	1,155,680
2008	1,903,920	1,890,820	2,020,760	1,112,470	1,103,510	1,173,220

2009	1,844,400	1,831,210	1,962,540	1,108,960	1,100,510	1,170,930
2010	1,776,750	1,763,230	1,895,200	1,101,150	1,093,100	1,164,890
2011	1,708,910	1,695,040	1,826,620	1,090,360	1,082,770	1,156,880
2012	1,639,270	1,625,280	1,756,300	1,066,940	1,059,730	1,136,320
2013	1,586,650	1,572,520	1,701,770	1,040,800	1,033,720	1,112,380
2014	1,533,040	1,518,330	1,647,660	1,002,030	994,805	1,074,570
2015	1,463,320	1,447,200	1,571,460	942,076	934,489	1,014,240
2016	1,418,830	1,400,310	1,520,290	895,422	887,401	966,248
2017	1,378,080	1,354,840	1,463,110	854,232	845,879	923,548
2018	1,358,200	1,322,660	-	817,371	808,858	-
2019	1,333,540	1,290,370	-	794,350	785,584	-

Table 7.17: Model estimates of Arrowtooth Flounder 1+ total biomass, in tons, and female spawning biomass (FSB) in tons, from Model 19.0 and 17.1a, based on MCMC runs. Lower 95% and upper 95% credible intervals (CIs) are provided for Model 19.0.

Year	M19.0 1+ Biomass	Lower 95% CI	Upper 95% CI	M17.1a 1+ Biomass	M19.0 FSB	Lower 95% CI	Upper 95% CI	M17.1a FSB
1961	-	-	-	605,882	-	-	-	369,856
1962	-	-	-	605,720	-	-	-	364,312
1963	-	-	-	605,093	-	-	-	358,373
1964	-	-	-	605,701	-	-	-	352,826
1965	-	-	-	602,736	-	-	-	349,048
1966	-	-	-	598,038	-	-	-	348,908
1967	-	-	-	592,543	-	-	-	348,996
1968	-	-	-	584,726	-	-	-	349,062
1969	-	-	-	580,959	-	-	-	348,360
1970	-	-	-	578,849	-	-	-	347,034
1971	-	-	-	578,443	-	-	-	343,660
1972	-	-	-	584,885	-	-	-	339,470
1973	-	-	-	596,640	-	-	-	332,969
1974	-	-	-	610,677	-	-	-	323,169
1975	-	-	-	637,999	-	-	-	319,926
1976	-	-	-	672,817	-	-	-	321,450
1977	1,185,809	1,035,134	1,321,607	728,160	709,072	584,763	819,800	326,259
1978	1,179,987	1,050,017	1,303,286	788,266	701,798	580,682	805,192	331,214
1979	1,191,648	1,070,667	1,303,734	864,701	693,160	585,016	790,907	344,549
1980	1,206,124	1,099,728	1,316,576	933,220	681,874	583,239	772,487	364,973
1981	1,214,391	1,116,962	1,323,760	997,600	670,128	575,441	753,744	390,127
1982	1,216,030	1,127,364	1,325,710	1,038,750	664,222	580,106	738,614	422,499
1983	1,218,072	1,136,226	1,324,954	1,082,360	666,702	594,061	738,704	468,214
1984	1,227,617	1,136,660	1,326,732	1,121,059	674,123	606,580	739,653	522,248
1985	1,250,285	1,161,506	1,337,691	1,170,262	690,971	632,011	756,137	578,714
1986	1,291,542	1,192,545	1,381,942	1,236,385	709,564	660,997	782,794	626,219
1987	1,361,219	1,251,862	1,455,903	1,301,291	719,639	670,149	793,174	658,463
1988	1,433,410	1,300,781	1,529,610	1,363,601	718,191	662,690	787,902	674,266
1989	1,503,995	1,386,865	1,599,736	1,434,007	717,926	658,782	782,385	687,691
1990	1,569,916	1,458,144	1,673,178	1,504,308	730,763	668,928	789,750	711,185
1991	1,625,759	1,526,196	1,729,670	1,576,081	754,625	687,753	810,431	742,038
1992	1,672,310	1,565,103	1,780,304	1,630,626	793,192	724,518	854,879	781,374
1993	1,691,042	1,578,516	1,806,597	1,665,283	841,101	756,962	908,055	818,098
1994	1,693,882	1,570,970	1,811,198	1,682,752	890,289	795,620	961,469	852,823
1995	1,688,417	1,569,126	1,808,874	1,683,335	923,097	843,741	994,504	882,016
1996	1,685,699	1,569,542	1,806,298	1,679,446	947,984	878,929	1,019,209	915,879
1997	1,679,691	1,562,968	1,799,351	1,672,591	960,816	885,603	1,038,234	943,839
1998	1,695,608	1,576,712	1,811,254	1,690,966	971,365	884,728	1,051,414	965,667
1999	1,738,164	1,600,882	1,843,606	1,726,088	972,868	883,330	1,054,852	974,568
2000	1,805,860	1,646,876	1,924,534	1,772,064	961,331	874,983	1,039,611	967,665
2001	1,855,160	1,699,509	1,978,412	1,819,776	944,302	865,488	1,022,505	950,142
2002	1,896,407	1,755,017	2,018,626	1,867,693	939,134	864,124	1,014,588	938,457
2003	1,917,806	1,799,418	2,030,020	1,902,076	943,378	869,071	1,015,812	937,527
2004	1,923,083	1,815,000	2,021,697	1,921,978	957,279	876,324	1,025,947	947,196
2005	1,927,680	1,826,822	2,022,910	1,948,266	1,003,336	904,722	1,073,249	986,013
2006	1,925,555	1,835,332	2,011,877	1,964,145	1,056,786	951,335	1,148,048	1,029,388
2007	1,894,421	1,803,954	1,977,254	1,948,694	1,092,731	996,546	1,193,948	1,063,819
2008	1,855,792	1,764,792	1,934,969	1,913,476	1,104,409	1,021,989	1,187,878	1,089,110
2009	1,794,927	1,706,462	1,874,718	1,853,758	1,093,387	1,029,630	1,152,553	1,096,989
2010	1,728,927	1,642,686	1,809,381	1,784,400	1,078,325	1,022,160	1,129,816	1,098,611
2011	1,665,860	1,582,393	1,742,757	1,720,699	1,061,153	1,004,320	1,113,088	1,096,358
2012	1,600,388	1,528,027	1,668,592	1,652,665	1,034,291	975,996	1,088,071	1,079,482
2013	1,549,393	1,483,923	1,606,965	1,601,706	1,007,665	947,047	1,063,980	1,056,792
2014	1,501,178	1,434,412	1,560,868	1,549,169	970,252	912,748	1,023,186	1,015,375
2015	1,434,161	1,366,310	1,497,826	1,473,237	913,536	858,986	963,898	950,174
2016	1,396,421	1,330,688	1,467,881	1,423,624	870,731	822,005	917,858	900,645
2017	1,356,874	1,287,322	1,439,445	1,375,884	833,635	790,328	877,129	860,961
2018	1,326,485	1,235,694	1,425,689	1,344,062	799,937	759,261	839,837	827,336
2019	1,296,381	1,183,217	1,415,122	1,310,986	779,069	738,528	820,576	805,013
2020	1,325,868	1,212,704	1,439,032	-	756,101	715,559	796,643	-
2021	1,321,076	1,280,534	1,361,618	-	718,325	677,783	758,867	-

Table 7.18: Model estimates of Arrowtooth Flounder age 1 recruitment (x 1,000), from Model 19.0 and 17.1a. Lower 95% and upper 95% credible intervals (CIs) based on MCMC runs. Note 2019 values not presented, as they are not estimable.

Year	Model 19.0 Recruitment	Lower 95% CI	Upper 95% CI	Model 17.0a Recruitment	Lower 95% CI	Upper 95% CI
1961	-	-	-	310,642	196,204	477,959
1962	-	-	-	302,390	160,279	492,846
1963	-	-	-	276,168	166,860	457,328
1964	-	-	-	303,325	156,783	545,814
1965	-	-	-	231,337	127,801	368,942
1966	-	-	-	235,481	120,676	373,933
1967	-	-	-	288,790	152,988	518,535
1968	-	-	-	221,175	131,995	389,211
1969	-	-	-	313,256	135,879	605,418
1970	-	-	-	295,829	144,137	469,995
1971	-	-	-	311,761	173,418	503,492
1972	-	-	-	401,454	240,524	575,022
1973	-	-	-	488,175	298,509	795,508
1974	-	-	-	511,705	307,630	789,565
1975	-	-	-	552,712	248,098	937,660
1976	-	-	-	558,561	338,364	901,874
1977	574,590	321,049	883,943	895,317	568,408	1,280,494
1978	659,474	365,883	1,078,626	881,344	503,052	1,281,449
1979	891,323	591,319	1,322,454	994,076	657,856	1,431,830
1980	710,163	393,634	1,186,470	650,340	440,286	1,028,611
1981	542,279	309,449	886,704	697,317	383,506	1,006,047
1982	485,839	292,689	728,219	366,799	238,193	599,960
1983	550,784	296,875	810,129	693,296	488,442	1,035,713
1984	795,406	504,329	1,143,781	730,939	434,887	1,034,340
1985	892,160	549,898	1,329,164	926,407	694,274	1,221,543
1986	1,054,937	705,343	1,587,319	1,133,766	674,595	1,626,365
1987	1,375,693	729,293	2,055,015	917,912	582,264	1,440,805
1988	1,149,673	632,856	1,752,960	950,881	561,548	1,448,521
1989	990,764	442,840	1,795,018	1,124,137	753,671	1,535,681
1990	909,390	458,999	1,507,426	1,019,085	647,565	1,439,083
1991	978,909	539,785	1,578,320	1,195,623	729,320	1,672,207
1992	954,728	599,837	1,354,129	864,519	486,672	1,402,200
1993	650,420	390,379	988,888	783,478	449,489	1,079,173
1994	639,102	401,275	944,483	680,151	400,327	1,067,019
1995	865,775	460,171	1,250,639	777,811	507,407	1,048,782
1996	855,110	397,169	1,367,529	734,848	386,716	1,095,366
1997	898,101	571,192	1,376,494	870,288	566,751	1,242,948
1998	1,156,435	704,219	1,716,072	1,241,681	764,844	1,673,237
1999	1,412,874	704,377	2,296,384	1,262,566	877,532	1,752,069
2000	1,674,729	992,489	2,427,364	1,345,239	995,419	2,011,275
2001	1,086,958	624,301	1,641,918	1,316,723	673,299	2,259,398
2002	899,760	541,937	1,340,917	1,113,208	643,784	1,778,117
2003	775,216	334,551	1,325,112	908,002	582,720	1,222,524
2004	936,166	373,353	1,523,827	1,024,884	612,789	1,609,592
2005	785,780	520,711	1,185,170	972,052	620,291	1,373,553
2006	954,176	629,576	1,352,568	1,000,744	698,248	1,348,334
2007	594,234	384,668	861,545	668,270	272,126	984,558
2008	656,152	410,721	936,960	507,661	264,762	821,623
2009	453,379	286,103	665,353	415,260	223,397	656,653
2010	470,659	275,754	697,960	439,503	233,613	646,050
2011	633,796	445,120	874,289	702,761	479,555	914,699
2012	683,087	351,737	1,025,604	706,533	517,200	934,894
2013	656,079	365,075	909,086	707,326	351,485	994,702
2014	623,191	360,891	939,104	572,318	339,266	865,981
2015	447,488	259,060	668,038	359,287	162,570	618,616
2016	683,758	294,650	1,075,336	594,991	328,023	891,745
2017	538,768	156,663	1,104,940	558,910	159,901	1,401,489
2018	805,019	276,993	1,734,327	911,074	148,174	2,823,406

Table 7.19: Estimated age 1 recruitment (1,000's) and fishing mortality (F), from Model 19.0, 17.1a, and Model 17.0e.

Year	Model 19.0	Model 17.1a	Model 17.0e	Model 19.0	Model 17.1a	Model 17.0e
Year	Recruitment	Recruitment	Recruitment	F	F	F
1961	-	313,580	320,780	-	0.00	0
1962	-	303,194	312,024	-	0.00	0
1963	-	292,282	300,480	-	0.00	0
1964	-	282,696	290,452	-	0.00	0
1965	-	272,554	280,740	-	0.00	0
1966	-	265,780	273,908	-	0.01	0.01
1967	-	262,494	270,558	-	0.01	0.01
1968	-	269,486	278,044	-	0.01	0
1969	-	287,108	296,148	-	0.00	0
1970	-	315,832	331,904	-	0.01	0.01
1971	-	350,388	387,380	-	0.00	0
1972	-	398,708	475,980	-	0.01	0.01
1973	-	525,598	621,190	-	0.03	0.03
1974	-	684,776	662,024	-	0.02	0.01
1975	-	673,358	582,640	-	0.01	0.01
1976	-	657,818	693,426	-	0.01	0.01
1977	605,128	722,826	763,684	0.01	0.03	0.03
1978	686,990	828,466	877,758	0.01	0.02	0.02
1979	753,254	902,080	967,784	0.01	0.02	0.02
1980	687,738	792,824	877,652	0.01	0.02	0.02
1981	582,398	635,444	735,070	0.01	0.02	0.02
1982	560,350	576,074	680,684	0.01	0.01	0.01
1983	617,130	613,800	697,268	0.01	0.01	0.01
1984	794,548	792,092	884,336	0.01	0.01	0.01
1985	1,104,572	1,097,788	1,170,890	0	0.00	0
1986	1,058,486	1,039,240	988,394	0	0.00	0
1987	1,052,612	1,030,584	1,023,296	0.01	0.01	0.01
1988	1,126,030	1,103,026	1,179,172	0.01	0.01	0.01
1989	1,064,804	1,042,220	1,028,930	0	0.00	0
1990	920,064	896,348	904,012	0.01	0.01	0.01
1991	991,674	971,572	1,047,168	0.01	0.01	0.01
1992	944,714	928,446	944,598	0.02	0.02	0.02
1993	751,434	732,820	750,150	0.02	0.02	0.02
1994	747,804	729,376	800,290	0.03	0.03	0.03
1995	793,886	778,946	829,796	0.02	0.02	0.02
1996	774,846	759,554	823,724	0.02	0.02	0.02
1997	955,058	941,306	1,077,690	0.02	0.02	0.02
1998	1,218,528	1,213,828	1,297,598	0.01	0.01	0.01
1999	1,320,202	1,318,808	1,346,416	0.02	0.02	0.02
2000	1,668,762	1,687,798	1,766,774	0.03	0.03	0.03
2001	1,091,764	1,087,868	1,122,684	0.02	0.02	0.02
2002	981,680	976,518	1,047,078	0.02	0.02	0.02
2003	900,330	892,334	938,466	0.03	0.03	0.03
2004	939,116	934,742	1,013,960	0.02	0.02	0.02
2005	955,116	952,590	1,024,700	0.02	0.02	0.02
2006	891,066	888,554	990,332	0.03	0.03	0.03
2007	652,944	643,126	698,780	0.02	0.02	0.02
2008	625,840	618,024	693,510	0.03	0.03	0.03

2009	468,592	456,456	503,744	0.02	0.02	0.02
2010	456,748	444,652	495,688	0.02	0.02	0.02
2011	589,224	580,876	624,088	0.03	0.03	0.03
2012	695,282	691,348	753,172	0.02	0.02	0.02
2013	705,048	698,294	735,744	0.02	0.02	0.02
2014	569,194	552,782	638,226	0.04	0.04	0.04
2015	489,678	462,282	431,166	0.02	0.02	0.02
2016	612,488	577,588	614,958	0.02	0.02	0.02
2017	606,838	540,608	436,000	0.03	0.03	0.02
2018	1,047,082	863,528	-	0.03	0.03	-
2019	436,000	436,000	-	0.03	0.03	-

Table 7.20: Projections of Arrowtooth Flounder female spawning biomass (FSB), future catch, and fishing mortality rates (F) for seven future harvest scenarios. Estimates of FSB and catch are in metric tons (t) for Model 19.0. Continued on next page.

Scenarios 1 and 2 Maximum ABC harvest permissible			
Year	FSB	Catch	F
2019	779,672	20,575	0.028
2020	756,101	24,186	0.034
2021	718,325	124,358	0.193
2022	611,375	107,778	0.193
2023	535,078	95,812	0.193
2024	485,406	87,854	0.193
2025	449,574	82,906	0.193
2026	424,007	79,827	0.192
2027	411,310	76,837	0.188
2028	407,691	75,790	0.186
2029	408,130	76,178	0.186
2030	410,028	76,821	0.186
2031	411,981	77,465	0.187
2032	413,537	77,951	0.187

Scenario 3, Maximum Tier 3 ABC harvest permissible set at F60			
Year	FSB	Catch	F
2019	779,672	20,575	0.028
2020	756,101	24,186	0.034
2021	726,670	19,934	0.029
2022	704,557	19,530	0.029
2023	692,296	19,296	0.029
2024	691,356	19,289	0.029
2025	693,317	19,482	0.029
2026	696,851	19,788	0.029
2027	706,888	20,136	0.029
2028	721,318	20,541	0.029
2029	736,782	21,027	0.029
2030	752,333	21,479	0.029
2031	767,126	21,894	0.029
2032	780,591	22,262	0.029

Scenario 4 Harvest at average F over past 5 years			
Year	FSB	Catch	F
2019	779,672	20,575	0.028
2020	756,101	24,186	0.034
2021	723,482	61,268	0.091
2022	667,420	57,268	0.091
2023	627,116	54,294	0.091
2024	602,872	52,419	0.091
2025	585,220	51,452	0.091
2026	572,368	51,069	0.091
2027	568,567	51,031	0.091
2028	570,883	51,339	0.091
2029	575,673	51,979	0.091
2030	581,469	52,595	0.091
2031	587,207	53,162	0.091
2032	592,368	53,647	0.091

Scenario 5 No fishing			
Year	FSB	Catch	F
2019	779,672	20,575	0.028
2020	756,101	24,186	0.034
2021	728,158	0	0.000
2022	722,579	0	0.000
2023	725,130	0	0.000
2024	737,522	0	0.000
2025	751,583	0	0.000
2026	766,013	0	0.000
2027	785,903	0	0.000
2028	809,432	0	0.000
2029	833,267	0	0.000
2030	856,701	0	0.000
2031	878,990	0	0.000
2032	899,510	0	0.000

Alternative 6, Determination of whether Arrowtooth Flounder are currently overfished			
Year	FSB	Catch	F
2019	779,672	20,575	0.028
2020	745,563	153,017	0.234
2021	610,919	127,774	0.234
2022	510,593	109,363	0.234
2023	442,953	96,868	0.234
2024	402,171	87,215	0.228
2025	376,041	77,964	0.213
2026	362,436	74,164	0.205
2027	360,962	74,182	0.204
2028	365,165	76,063	0.206
2029	370,361	78,450	0.209
2030	374,761	80,267	0.211
2031	377,743	81,456	0.213
2032	379,529	82,176	0.214

Scenario 7, Determination of whether stock is approaching an overfished condition			
Year	FSB	Catch	F
2019	779,672	20,575	0.028
2020	747,724	128,060	0.193
2021	633,041	110,273	0.193
2022	543,165	115,805	0.234
2023	467,524	101,677	0.234
2024	420,351	92,677	0.234
2025	387,936	82,533	0.220
2026	369,335	76,683	0.209
2027	364,788	75,519	0.206
2028	367,136	76,708	0.207
2029	371,262	78,712	0.209
2030	375,092	80,334	0.211
2031	377,803	81,440	0.213
2032	379,478	82,132	0.214

Figures

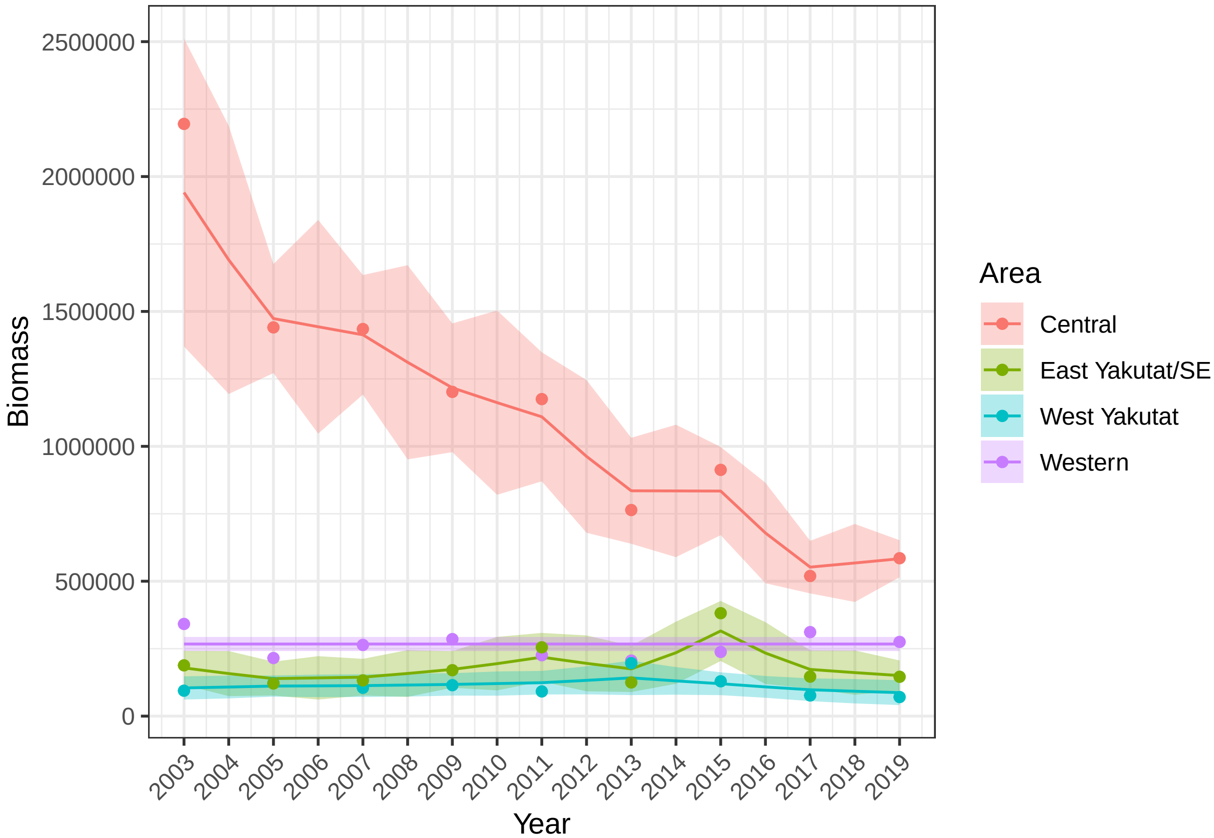


Figure 7.1: Random effects estimates of biomass applied to the four GOA areas among which the catches of Arrowtooth Flounder are apportioned, 2003-2019.

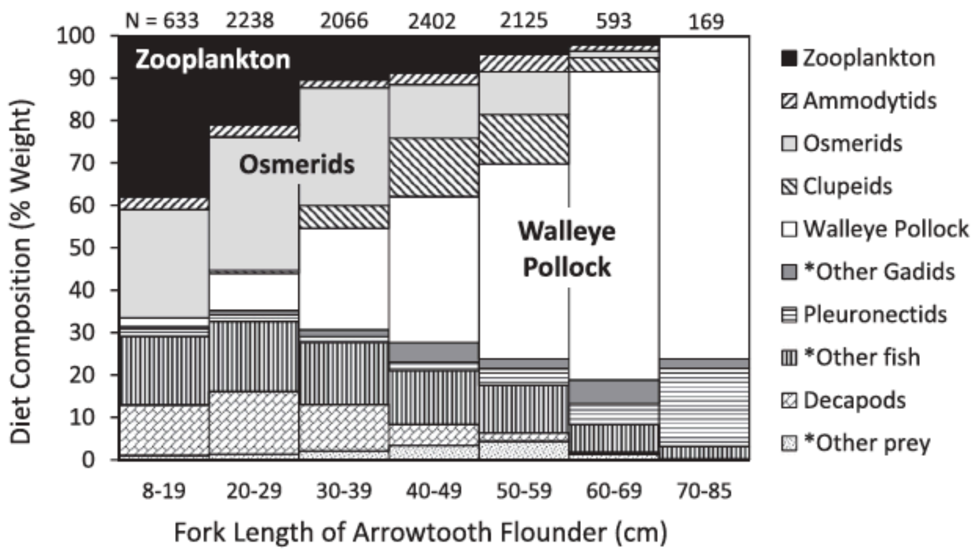


Figure 7.2: Composition of Arrowtooth Flounder diet weight for different size categories of fish, based on stomach content analysis of specimens from groundfish surveys in the Gulf of Alaska.

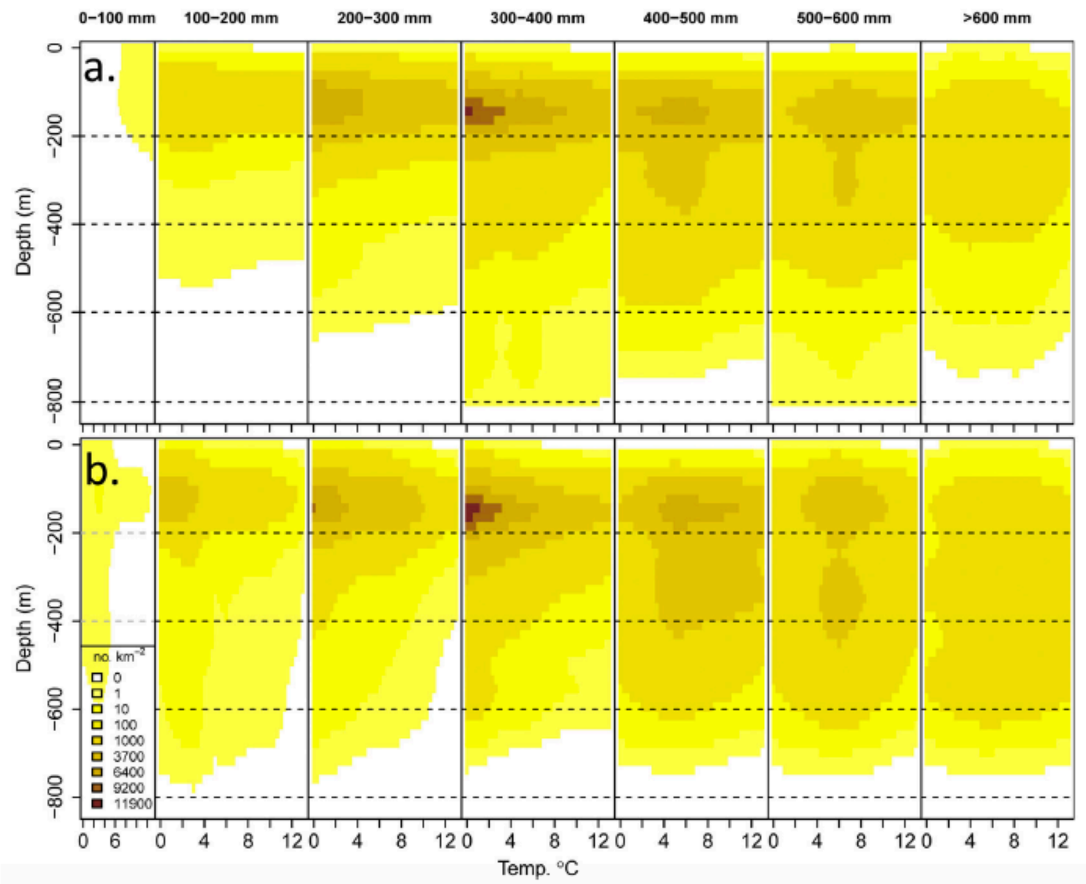
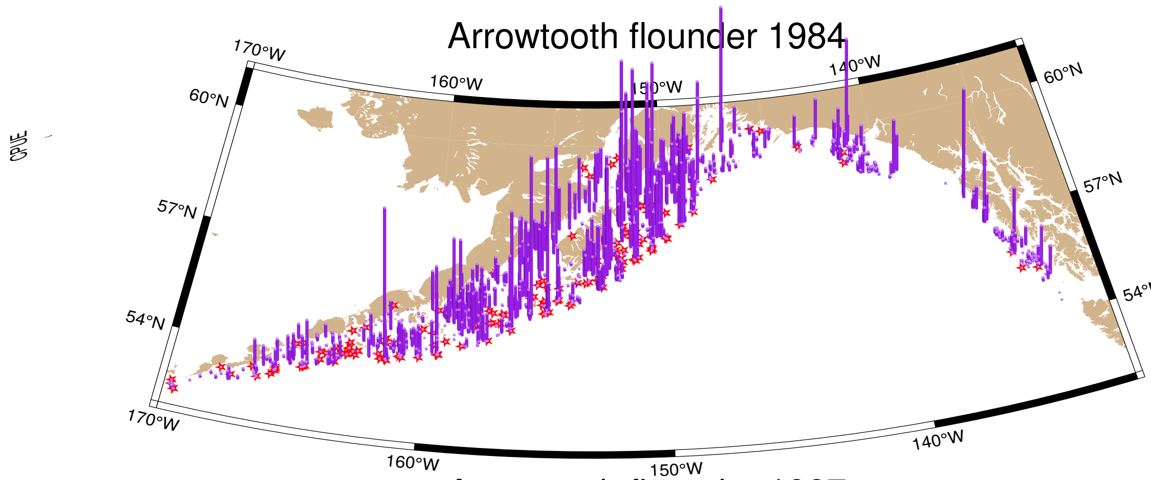
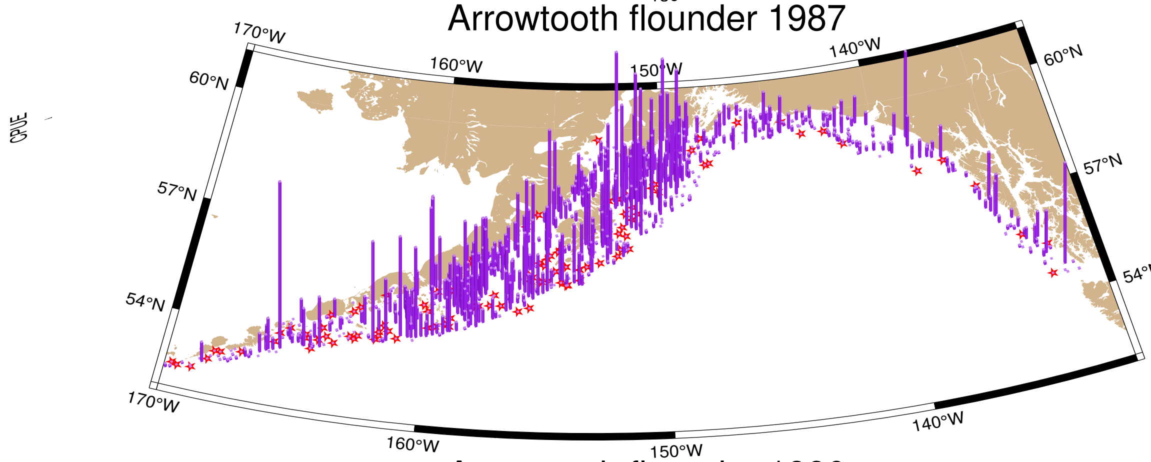
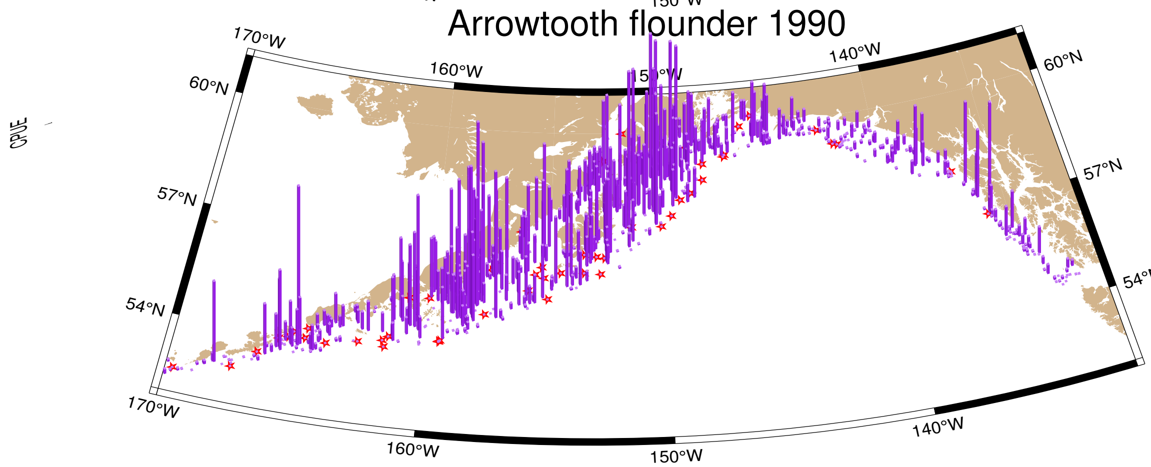
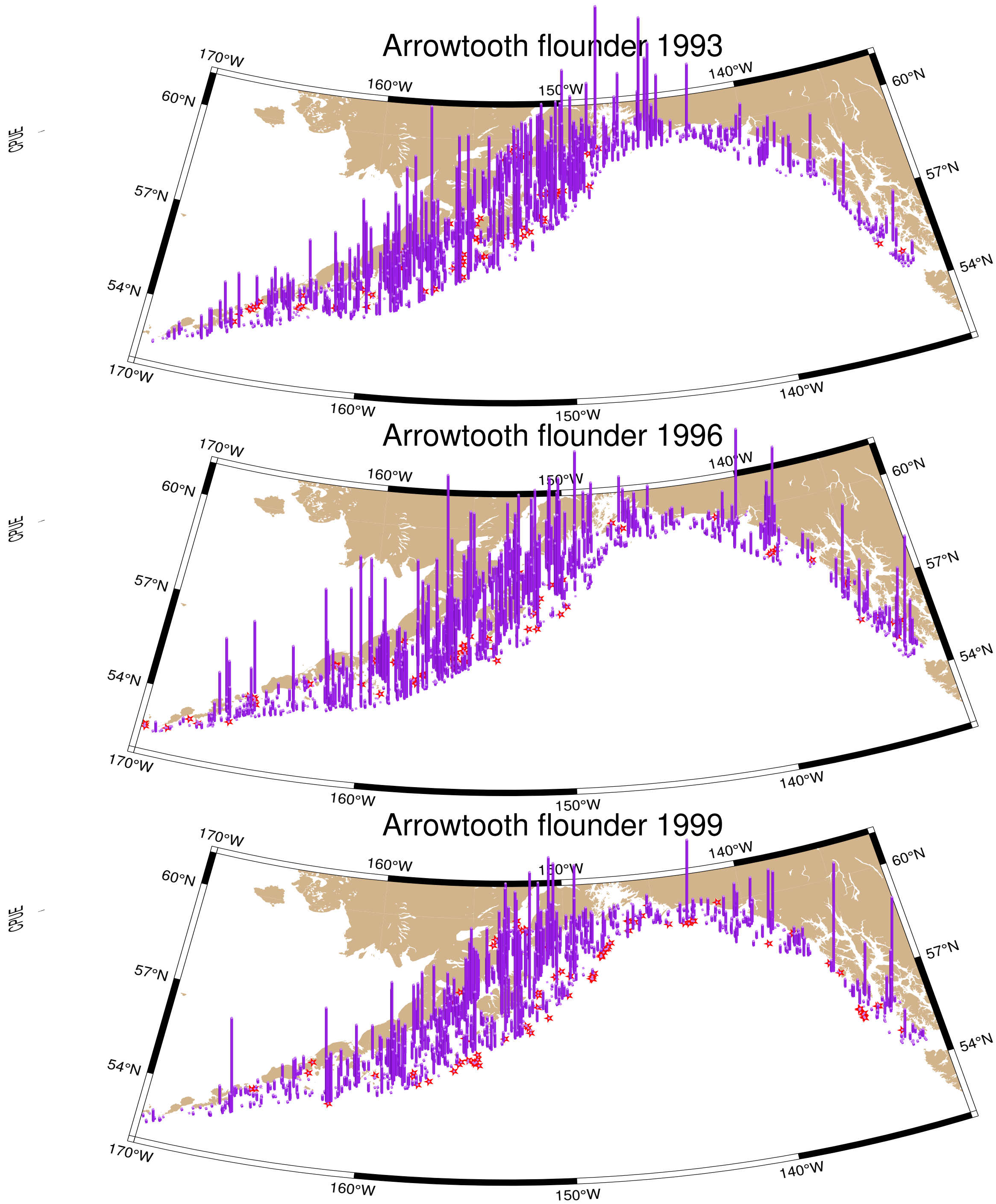


Figure 7.3: Arrowtooth Flounder predicted density,N/km^2 at 56N latitude and 155W longitude from the delta-log gamma model for GOA bottom trawl survey data. Panel a. shows 2001 density using warm years (1984, 1987, 1990, 1993, 2001, 2003, 2005, and 2015) and Panel b. shows density for 2009 using cold years (1996, 1999, 2007, 2009, 2011, and 2013) for seven length bins by bottom depth (m) and bottom temperature (C). Figure from Doyle et al. 2018.


Arrowtooth flounder 1984
CPUE
170°W
160°W
150°W
140°W
60°N
57°N
54°N


Arrowtooth flounder 1987
CPUE
170°W
160°W
150°W
140°W
60°N
57°N
54°N


Arrowtooth flounder 1990
CPUE
170°W
160°W
150°W
140°W
60°N
57°N
54°N


Arrowtooth flounder 1993
CPUE
170°W
160°W
150°W
140°W
60°N
57°N
54°N
Arrowtooth flounder 1996
CPUE
170°W
160°W
150°W
140°W
60°N
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Arrowtooth flounder 1999
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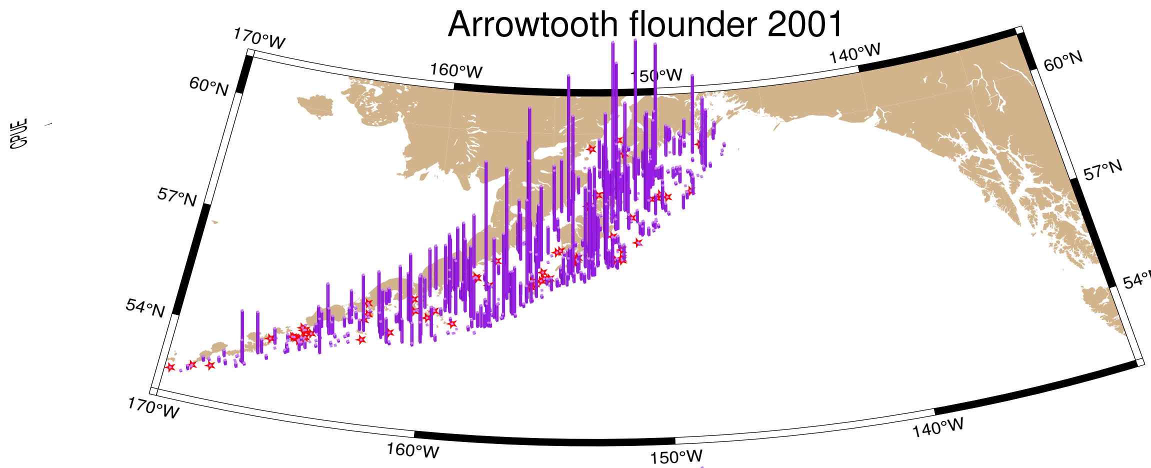
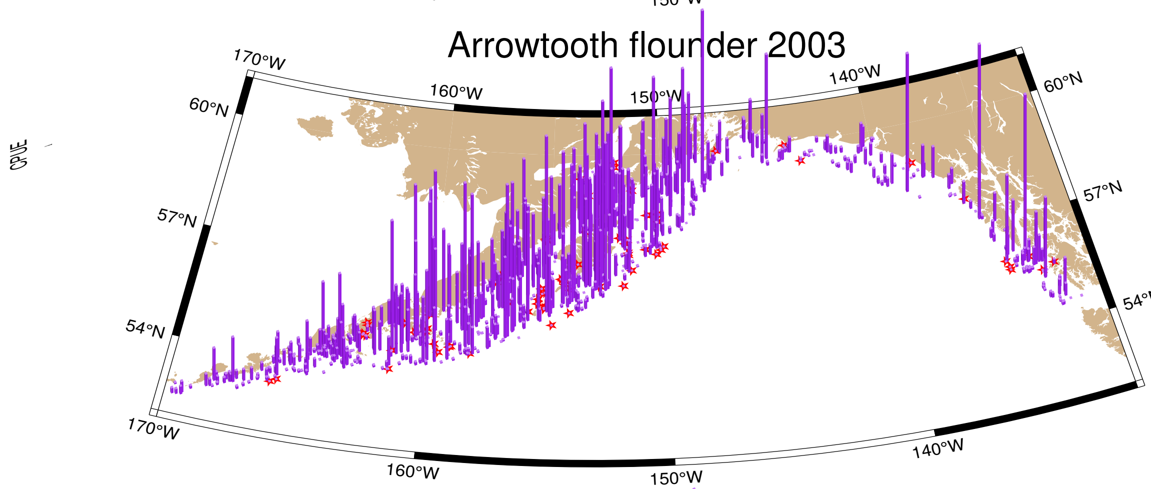
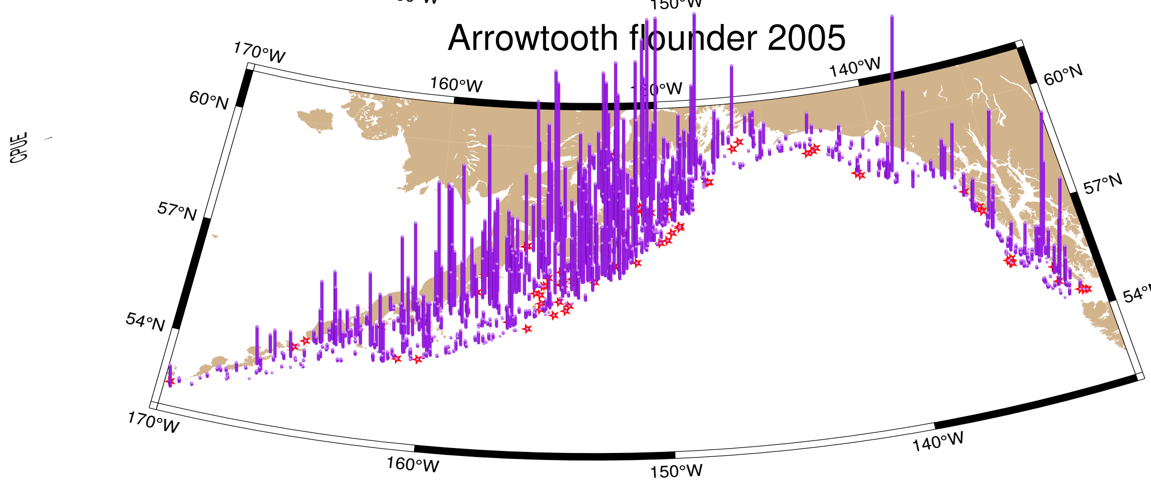
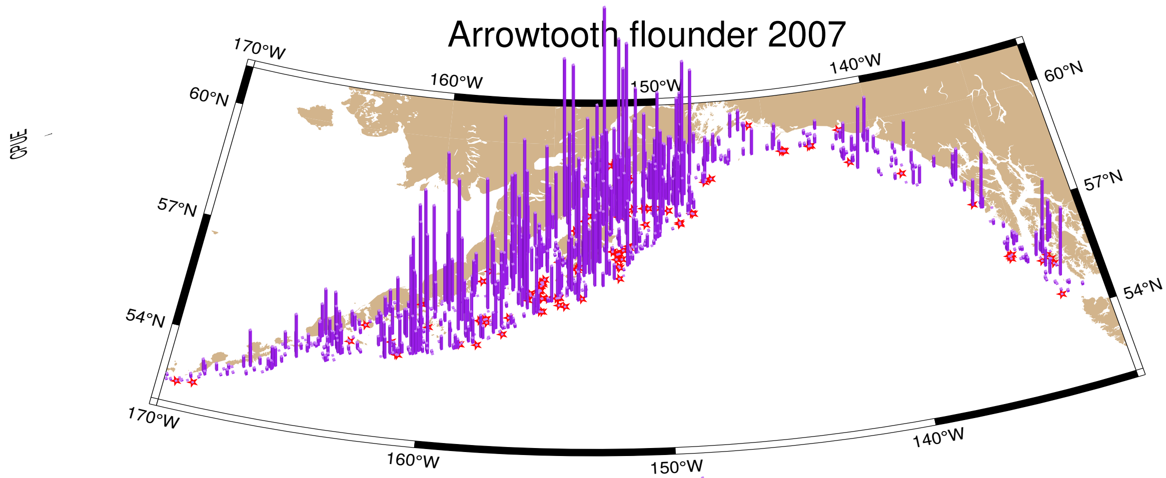
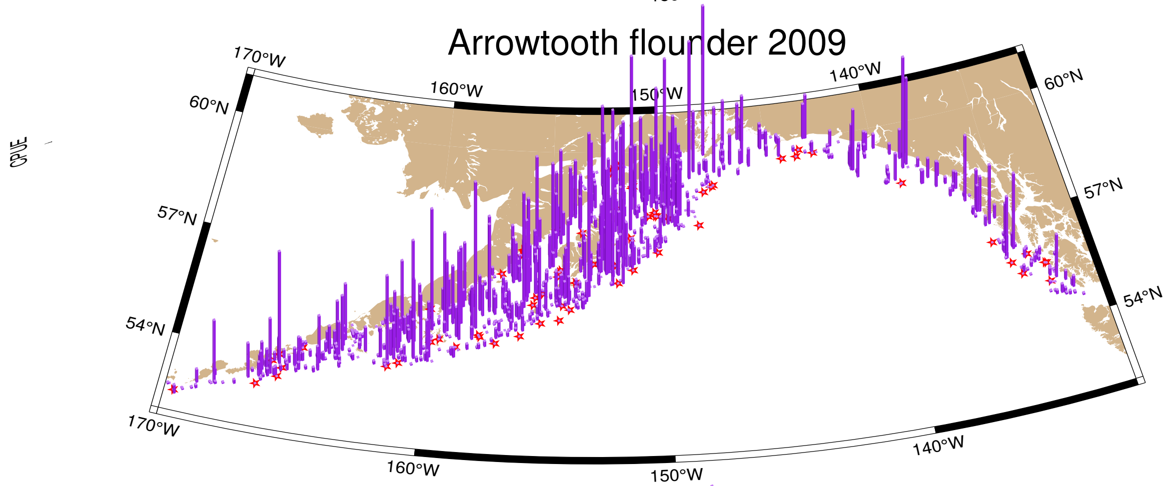
60°N
57°N
54°N

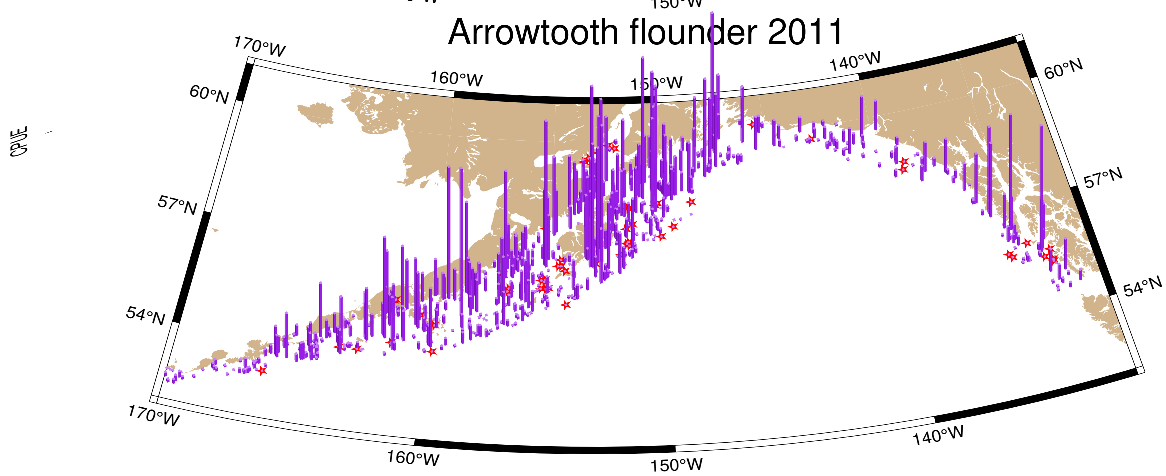

Arrowtooth flounder 2001
CPUE
170°W
160°W
150°W
140°W
60°N
57°N
54°N

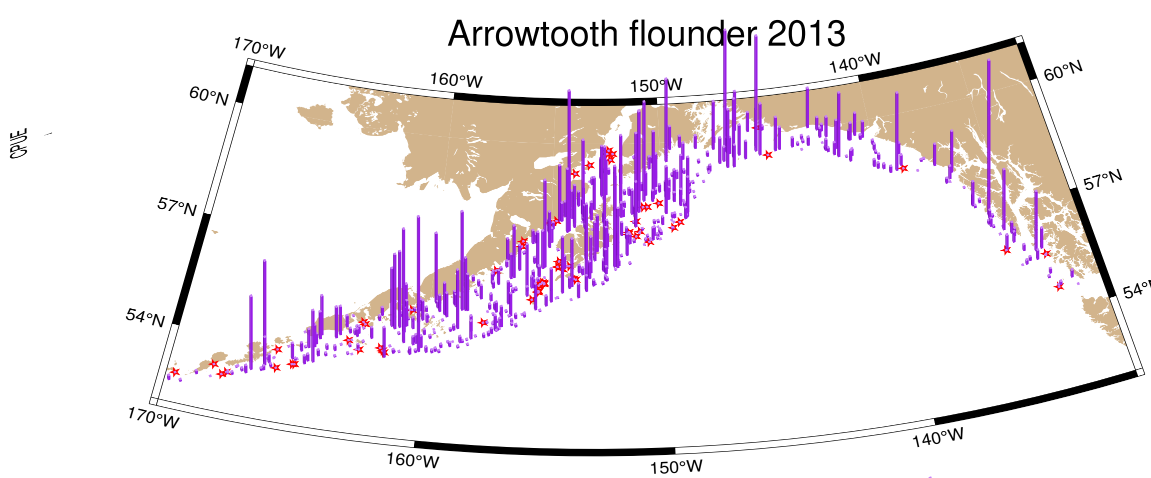

Arrowtooth flounder 2003
CPUE
170°W
160°W
150°W
140°W
60°N
57°N
54°N

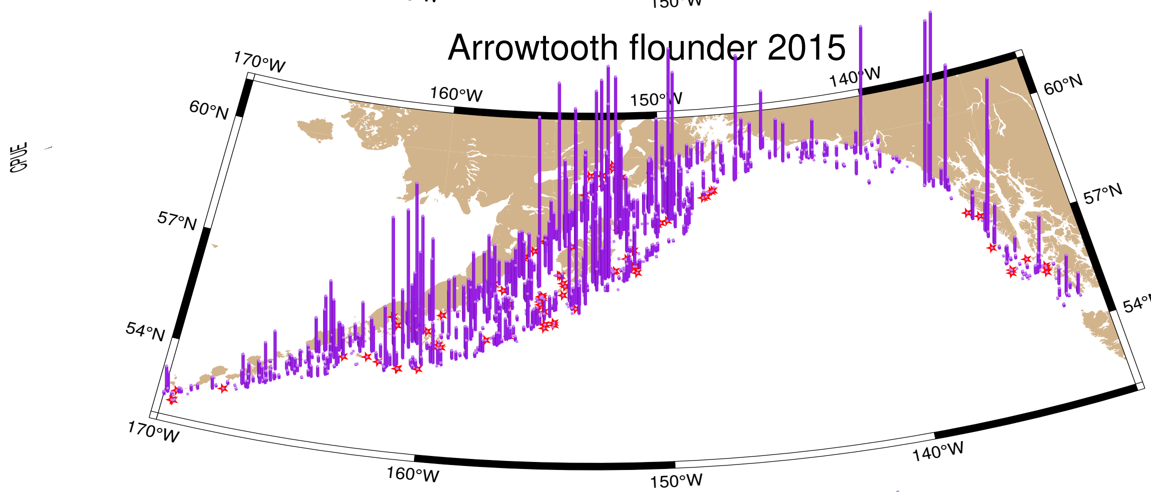

Arrowtooth flounder 2005
CPUE
170°W
160°W
150°W
140°W
60°N
57°N
54°N

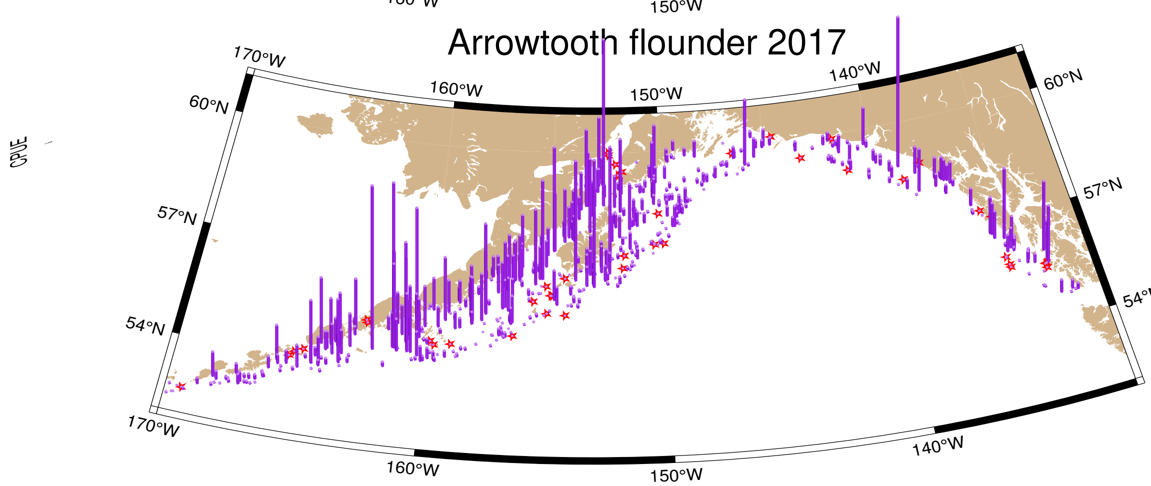

Arrowtooth flounder 2007
CPUE
170°W
160°W
150°W
140°W
60°N
57°N
54°N


Arrowtooth flounder 2009
CPUE
170°W
160°W
150°W
140°W
60°N
57°N
54°N


Arrowtooth flounder 2011
CPUE
170°W
160°W
150°W
140°W
60°N
57°N
54°N


Arrowtooth flounder 2013
CPUE
170°W
160°W
150°W
140°W
60°N
57°N
54°N


Arrowtooth flounder 2015
CPUE
170°W
160°W
150°W
140°W
60°N
57°N
54°N


Arrowtooth flounder 2017
CPUE
170°W
160°W
150°W
140°W
60°N
57°N
54°N

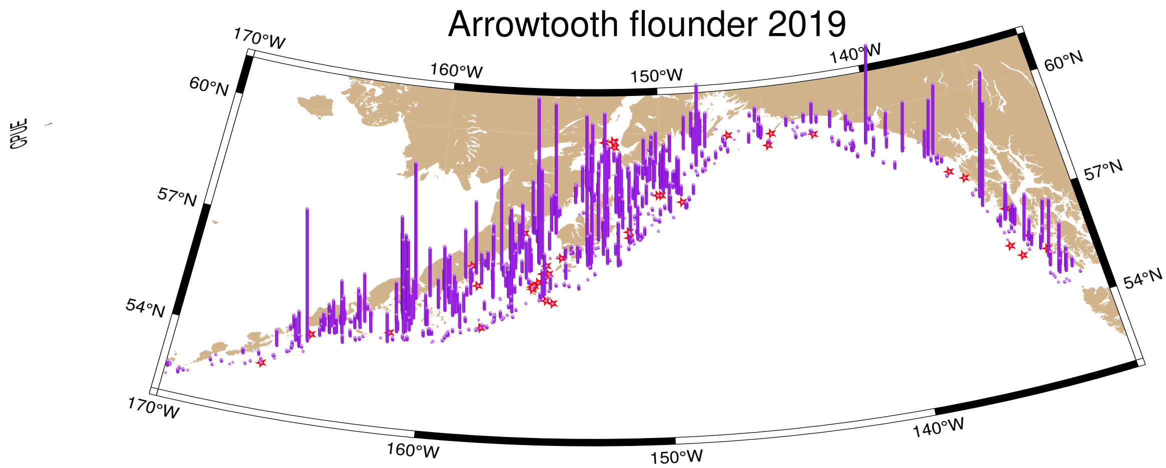


Figure 7.4: Arrowtooth Flounder 2013 survey cpue by tow

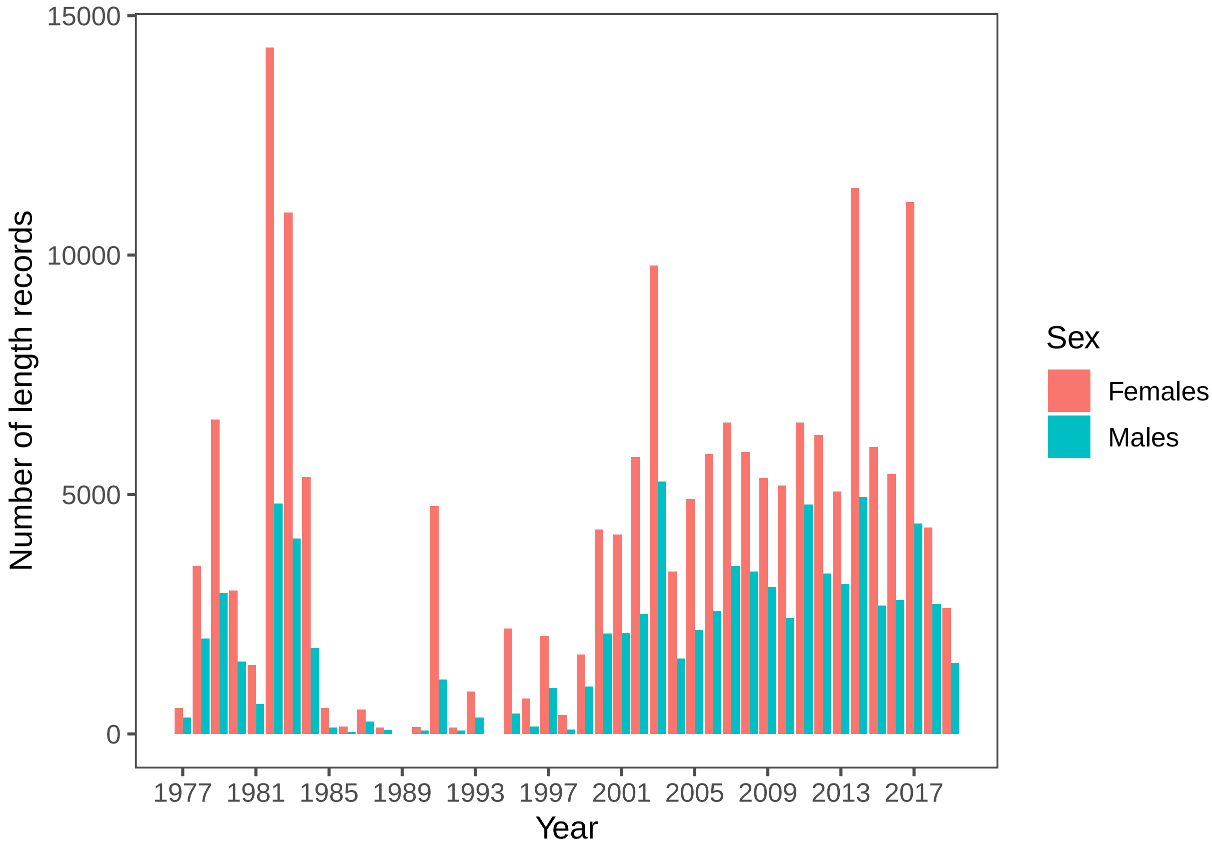


Figure 7.5: Fishery length frequency data used in this assessment, by sex.

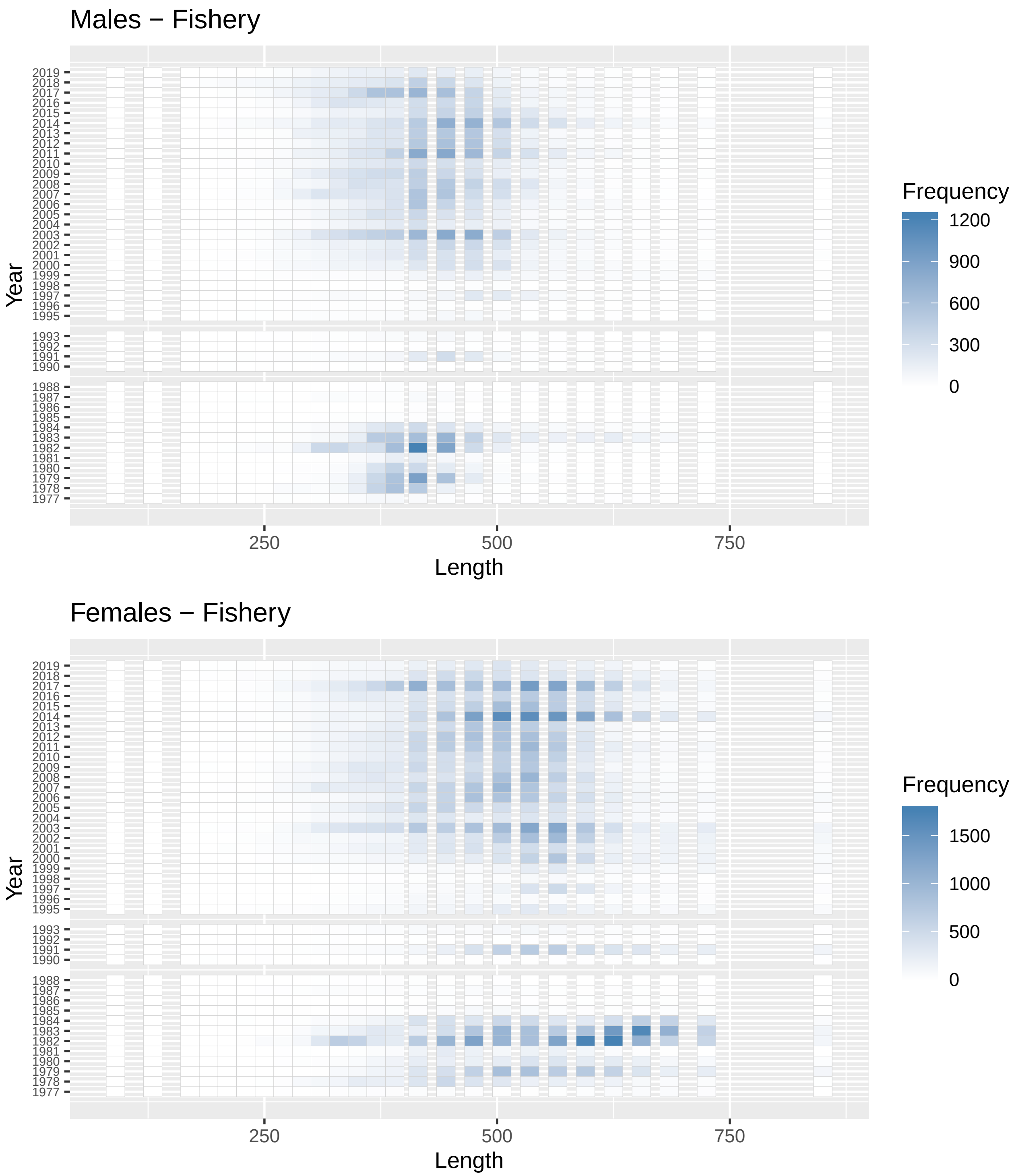


Figure 7.6: Length frequency composition for fishery length data, males above, females below.

Figure 7.7: Length frequency composition for survey data, males above, females below. Note that only length composition data from 1985, 1986, 1989, and 2019 were used in Model 19.0 since age data were not yet available for 2019 and only length data are available for 1985, 1986, and 1989. Numbers in legend represent percentages in each length bin by year.

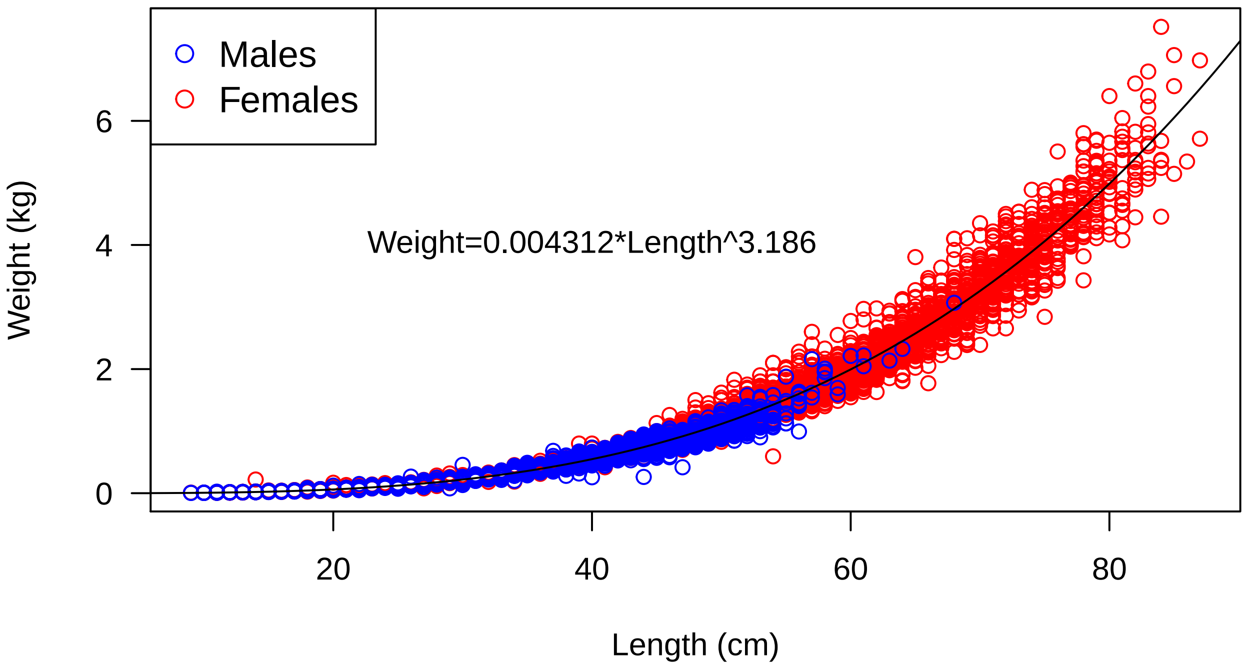


Figure 7.8: Length-weight relationship of Arrowtooth Flounder. Males and females grow at the same trajectory. The fit to weight-at-length is shown as a black line. Data from GOA surveys 1984-2013.

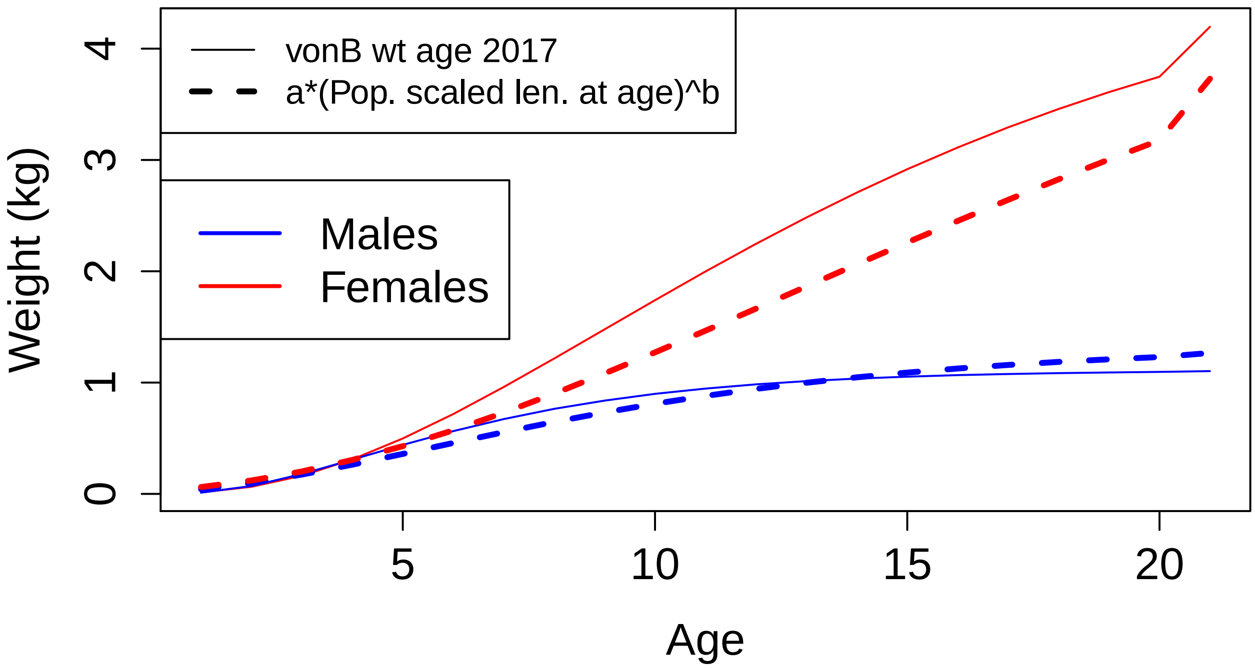


Figure 7.9: Weight at age used in the model is based on length at age corrected by survey length frequencies. Weight at age of females determined by this method is slightly lower than weight at age determined by a weight-at-age vonBertalanffy relationship determined from the stratified age collection. Differences in male weight at age were not as significant as differences in female weight at age.

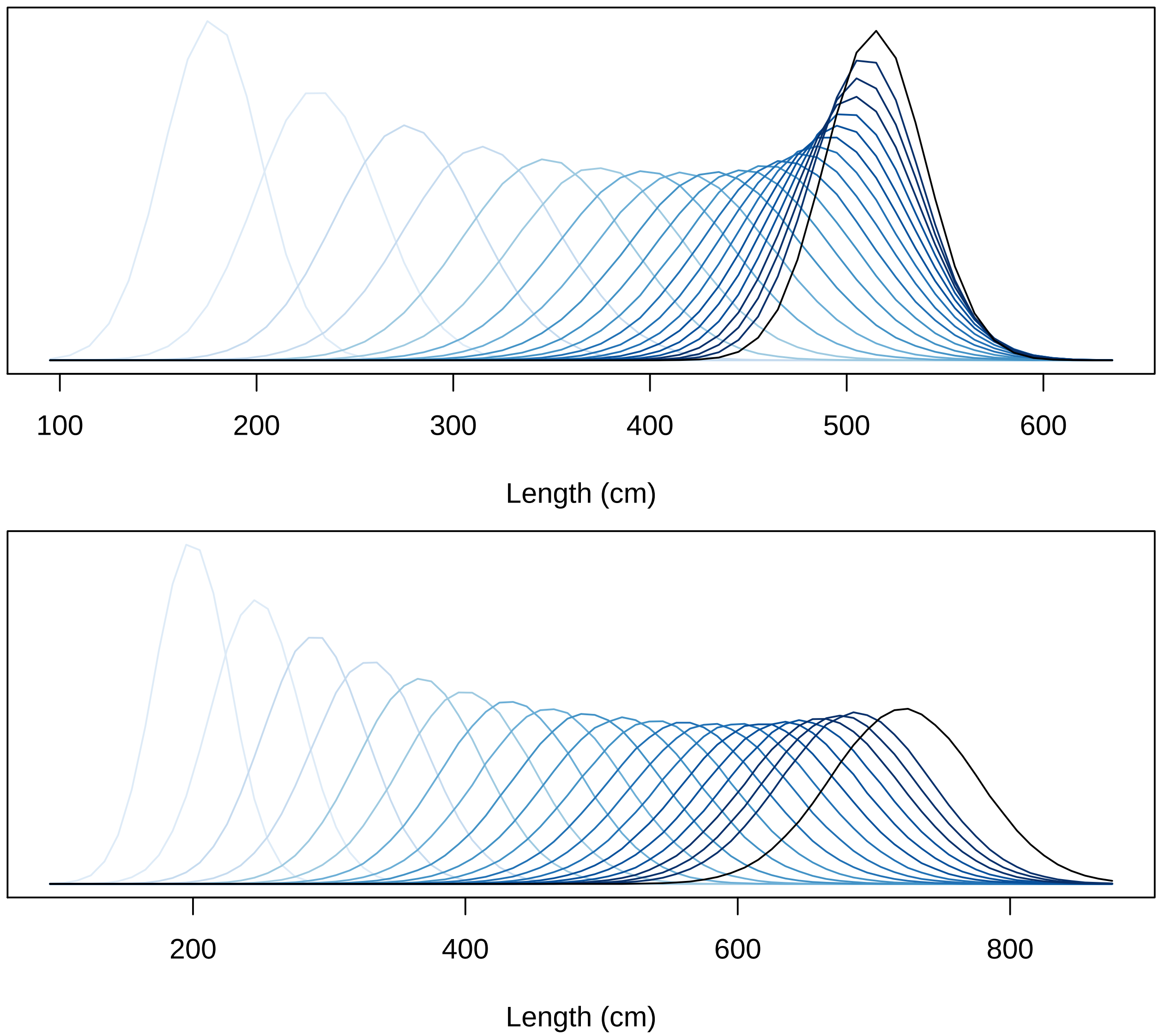


Figure 7.10: Visual representation of the length age conversion matrix used in the model, males above, females below.

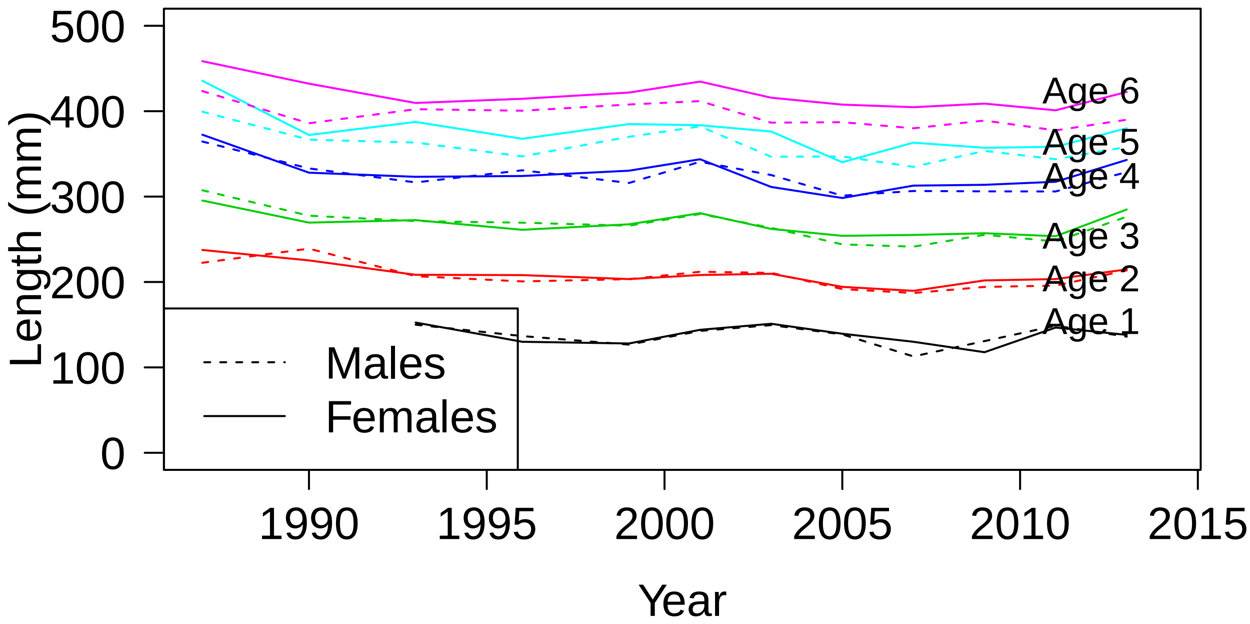


Figure 7.11: Growth differences among males and females start to appear around age 6. Age at 50% maturity is age 7 in females, and is 20% in age 6 fish.

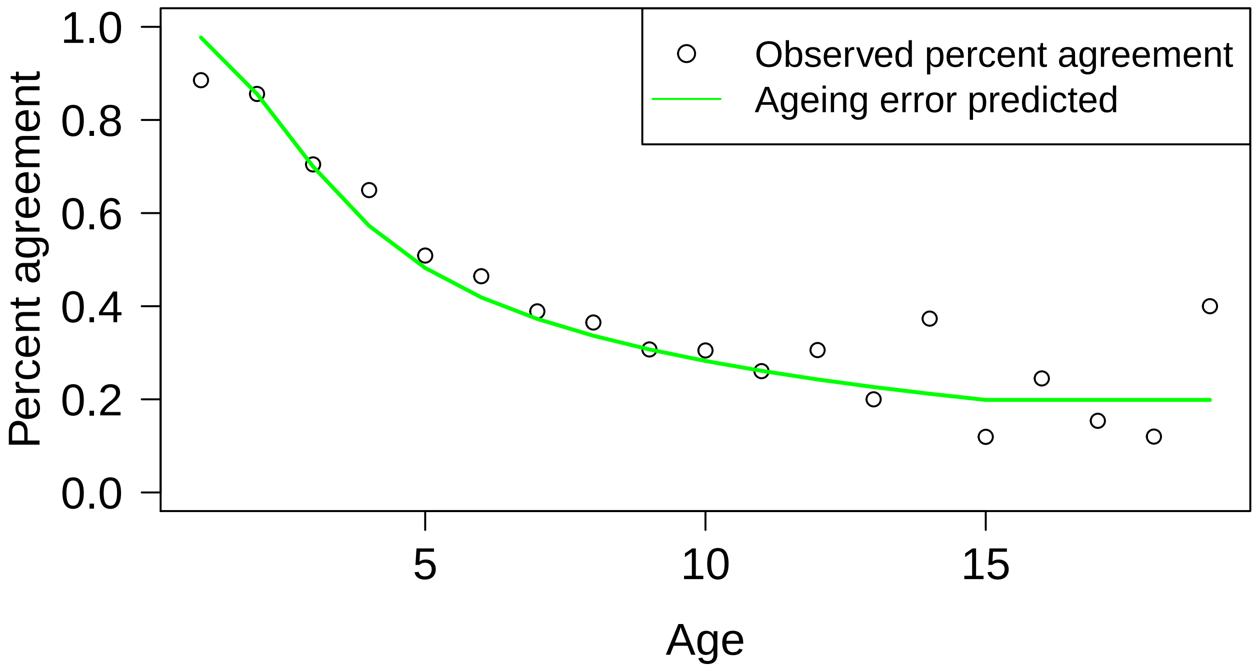


Figure 7.12: Trends in percent agreement in reader-tester evaluations for Arrowtooth Flounder aged by two readers, sample size 3,173.

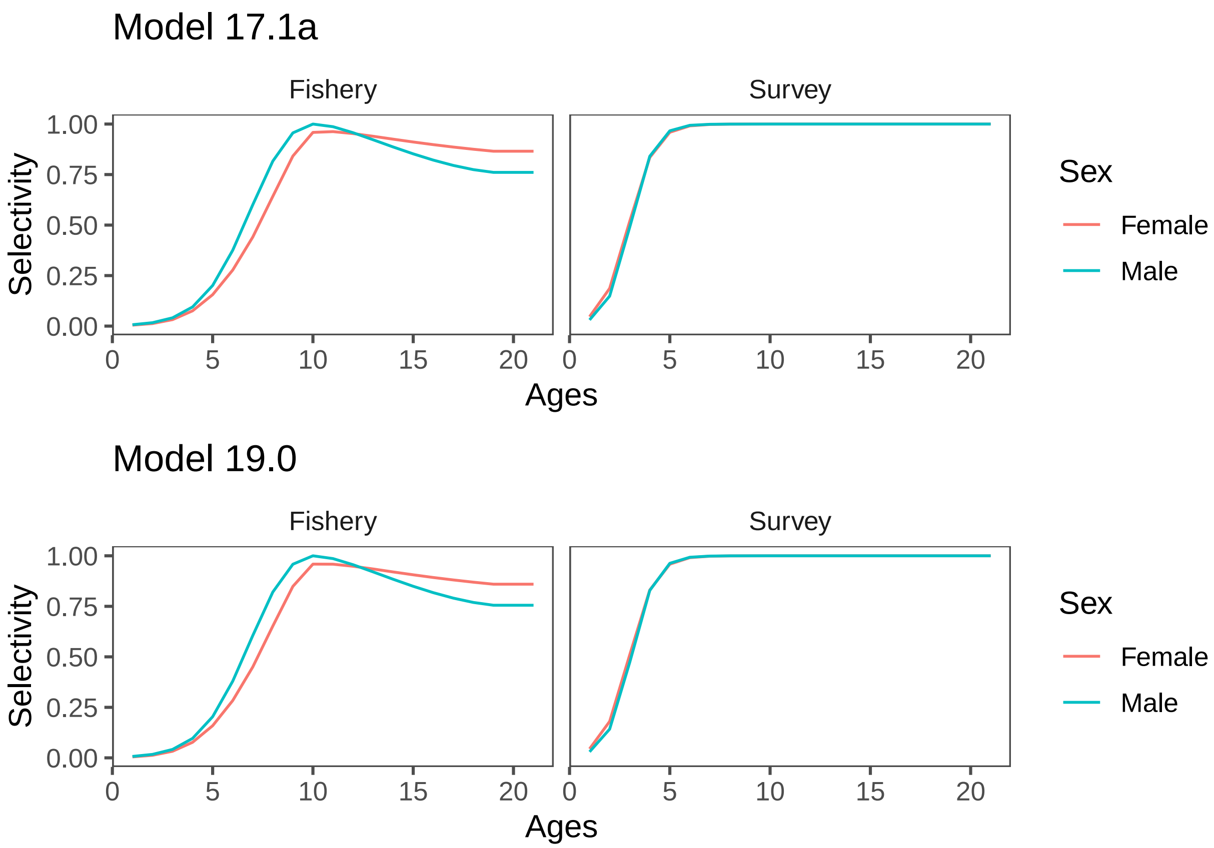


Figure 7.13: Selectivities for fishery and survey estimated by Model 17.1a and Model 19.0.

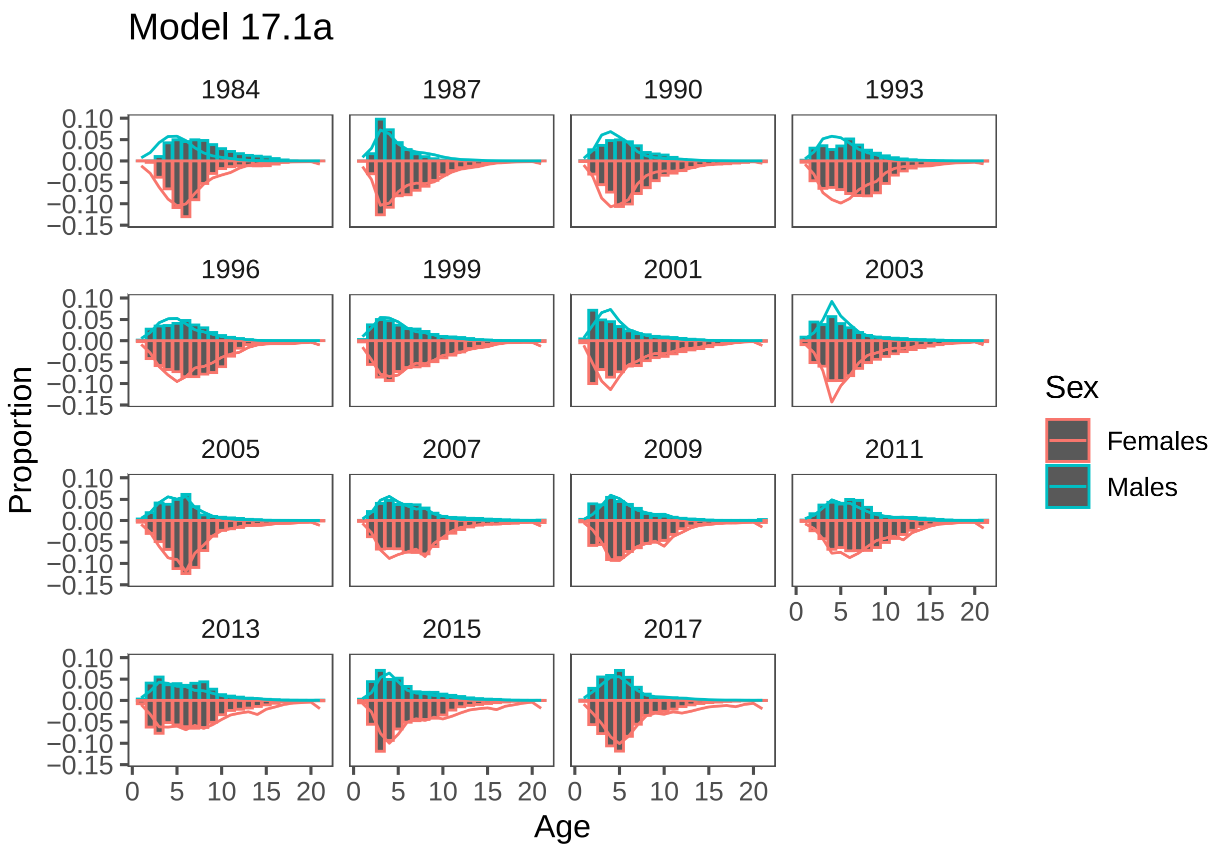


Figure 7.14: Survey age frequency fit to model, males above, females below, solid line is predicted, for Model 17.1a.

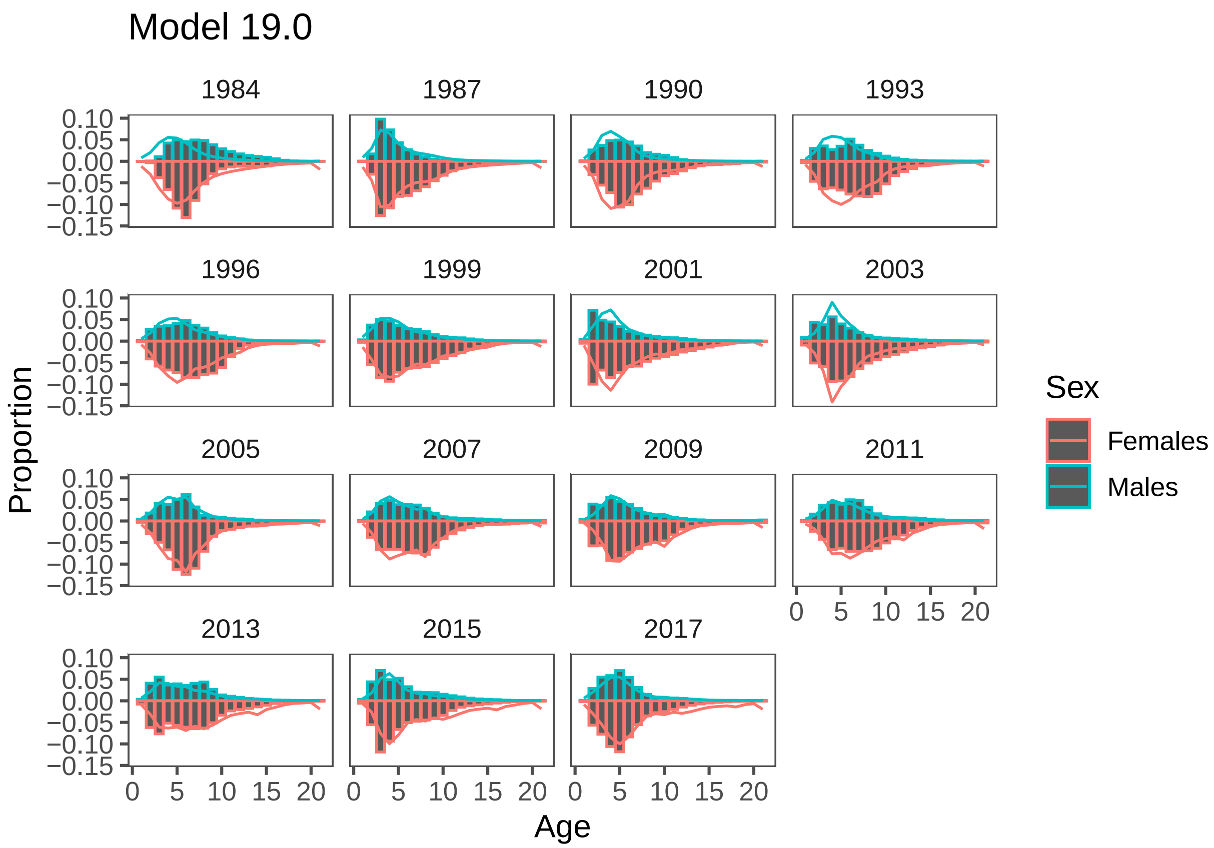


Figure 7.15: Survey age frequency fit to model, males above, females below, solid line is predicted, for Model 19.0.

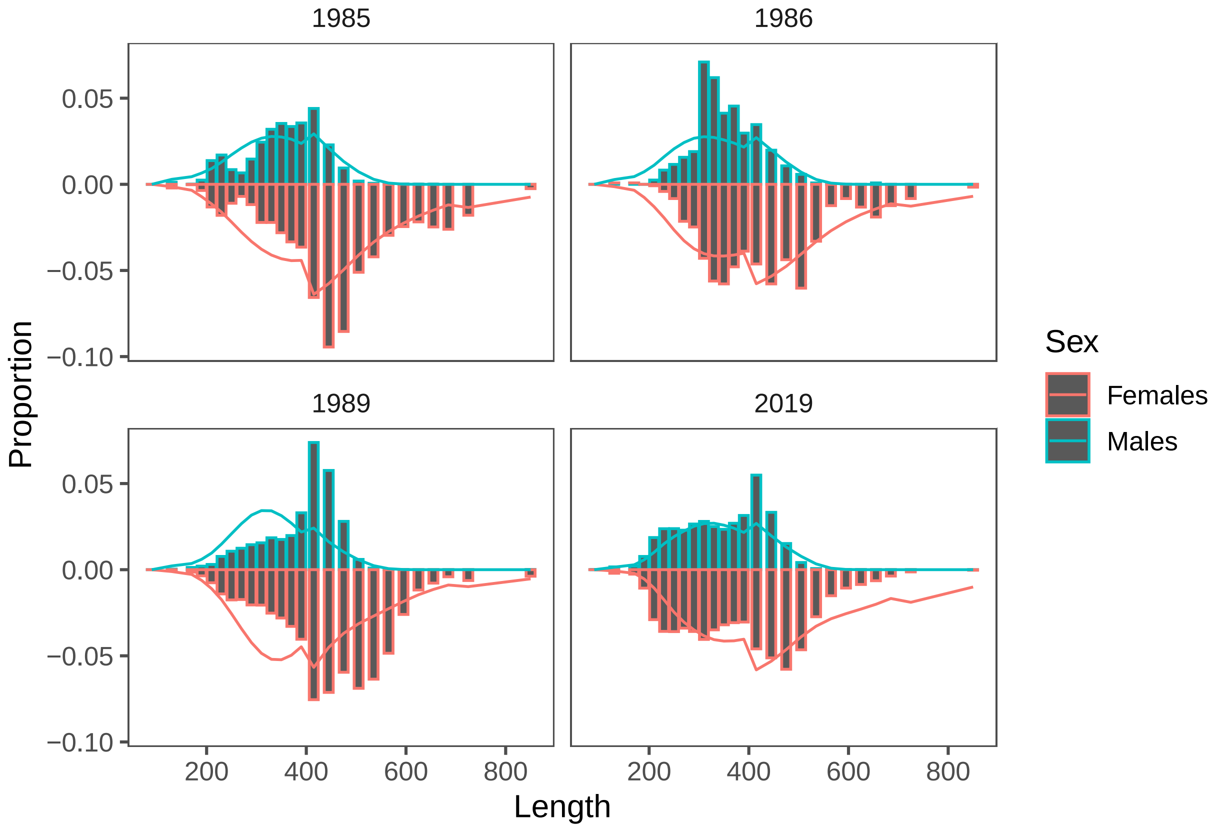


Figure 7.16: Survey length frequency fit to model, males above, females below, solid line is predicted.

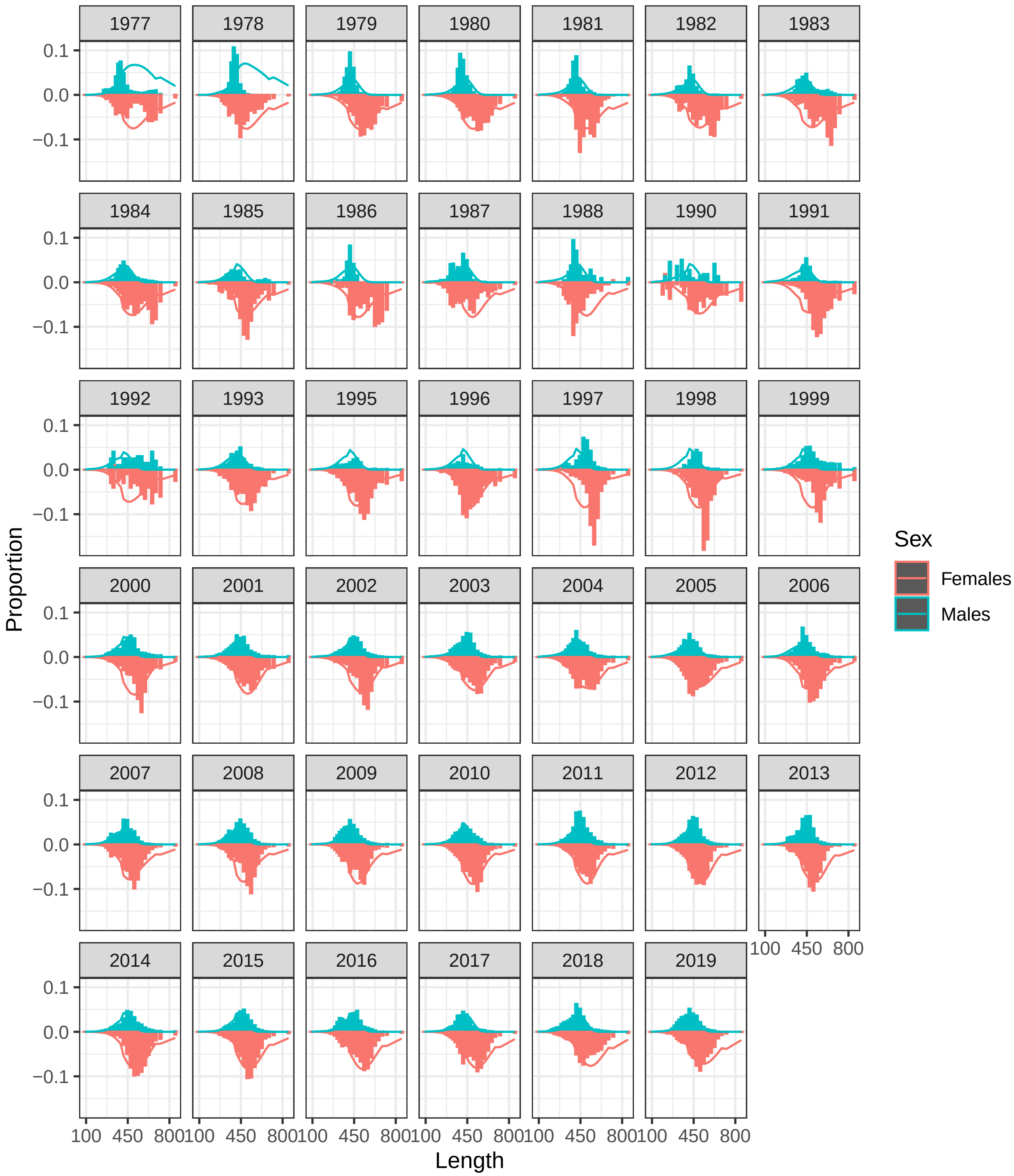


Figure 7.17: Fit to the male and female fishery length composition data for Model 19.0, solid line is predicted.

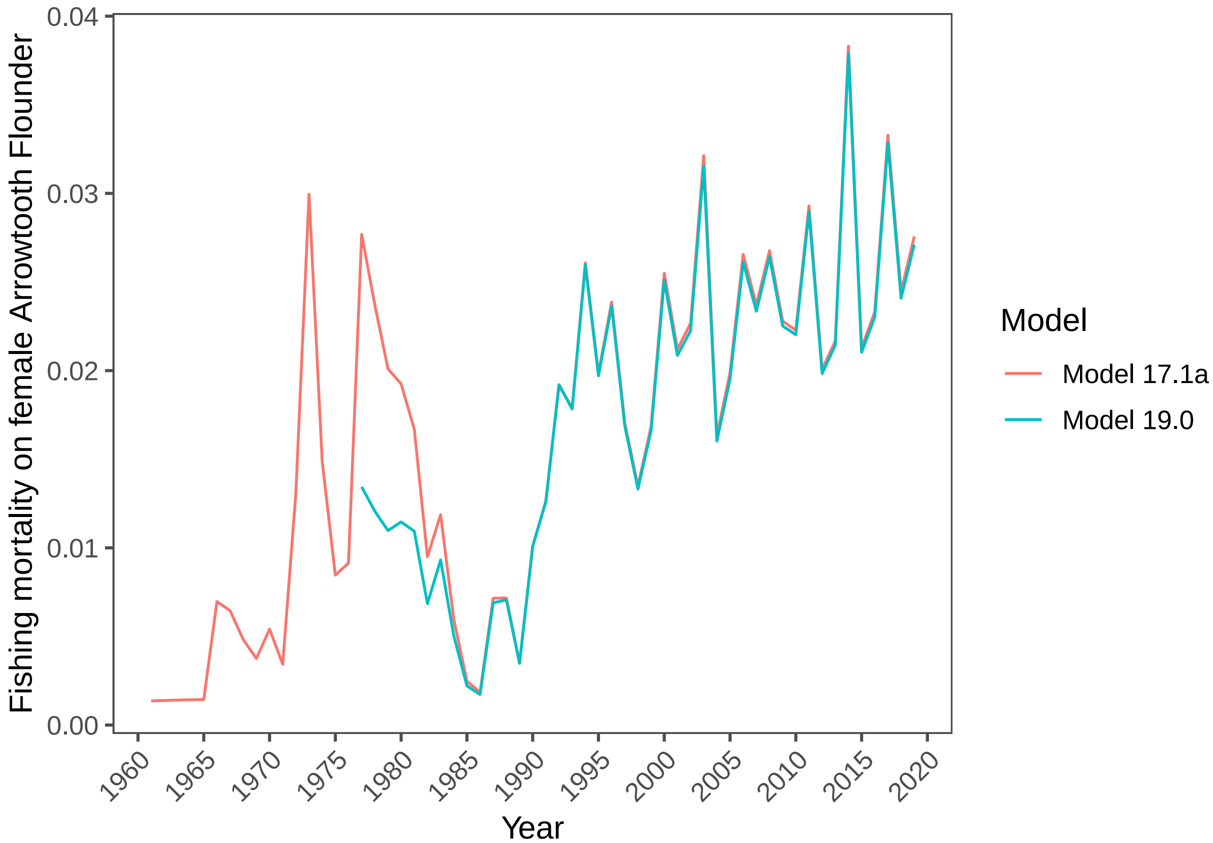


Figure 7.18: Natural mortality estimated by the Model 17.1a and 19.0, 1961-2019.

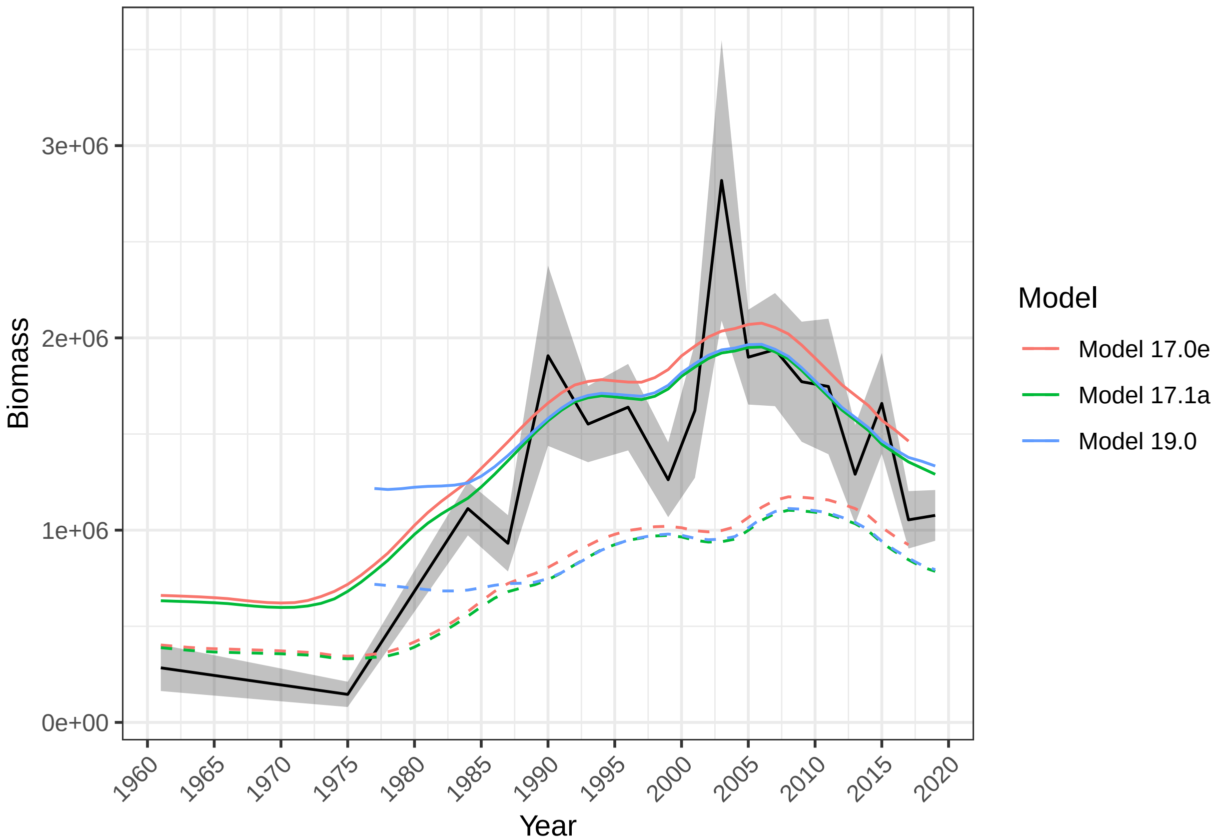


Figure 7.19: Predicted and observed survey biomass, 1961-2019 for Models 17.0e, 17.1a, and 19.0. Dotted lines show model estimates for female spawning biomass over the time series.

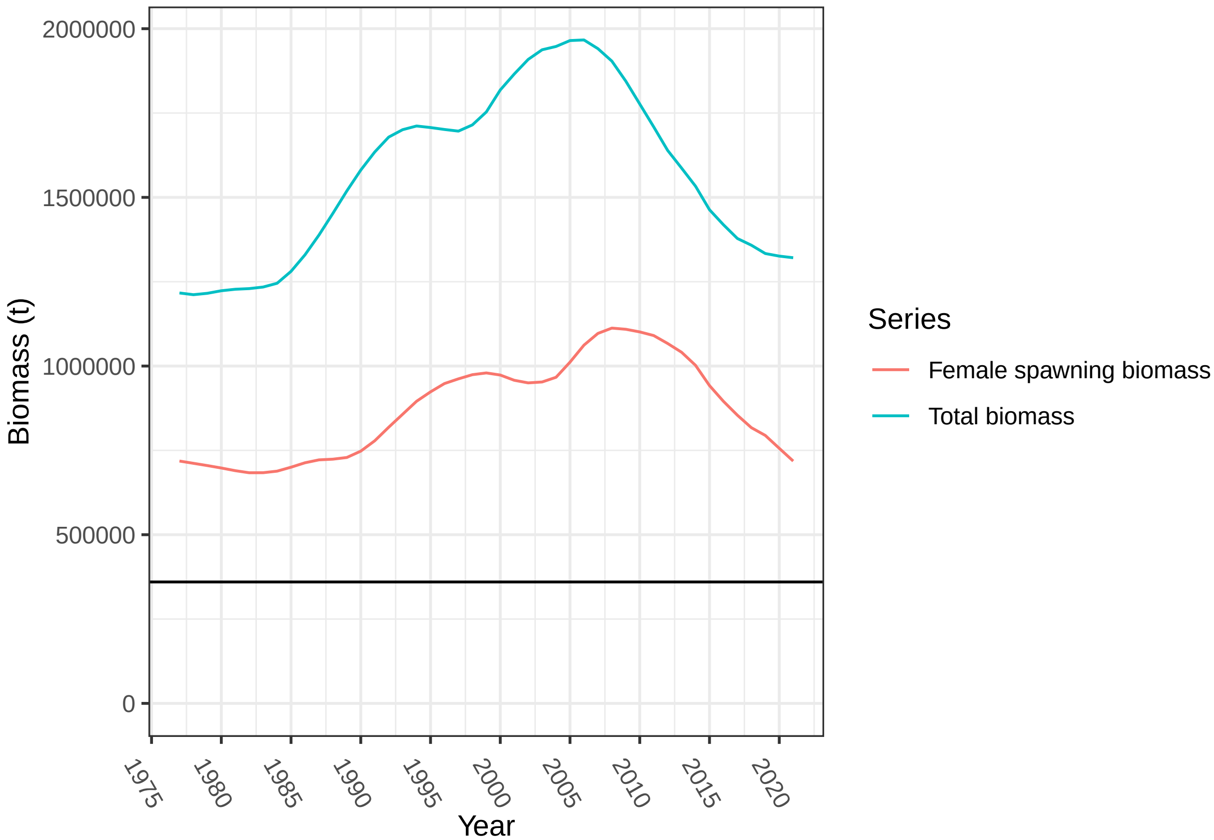


Figure 7.20: Predicted female spawning biomass and total biomass (age 1+) for Model 19.0, 1977-2021. Values for 2020 and 2021 were estimated using the projecion model. Horizontal line is B35%.

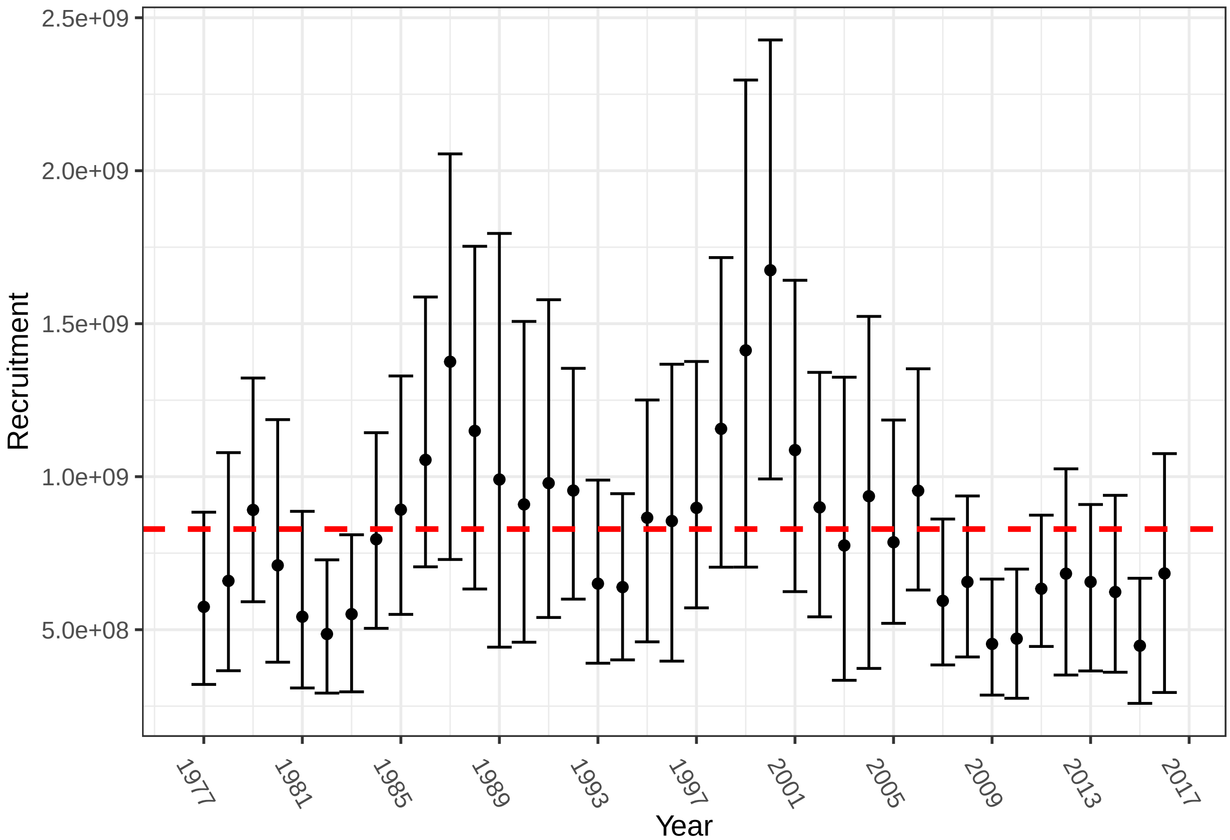


Figure 7.21: Age 1 estimated recruitments (male plus female) in numbers from 1977 to 2016. Data shown only through 2016 because recent recruitment estimates are not reliable as 50% maturity in Arrowtooth Flounder is estimated at age 7. with approximate 5% and 95% credible intervals. Data was generated using 1e+06 MCMC iterations, and thinning every 100 iterations. The horizontal line represents the average recruitment over this period. The dashed horizontal line indicates mean recruitment from 1977-2015, 8.252e+08.

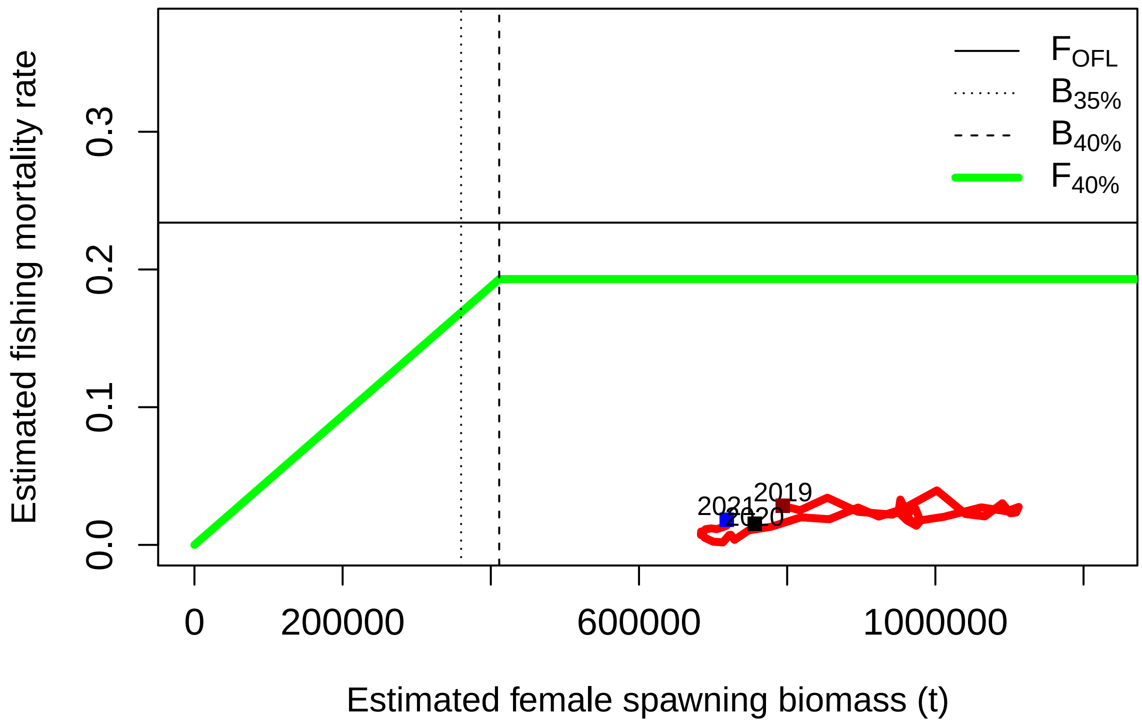


Figure 7.22: Fishing mortality rate and female spawning biomass from 1977 to 2019 compared to the F35% and F40% control rules. Vertical lines are B35% and B40%.

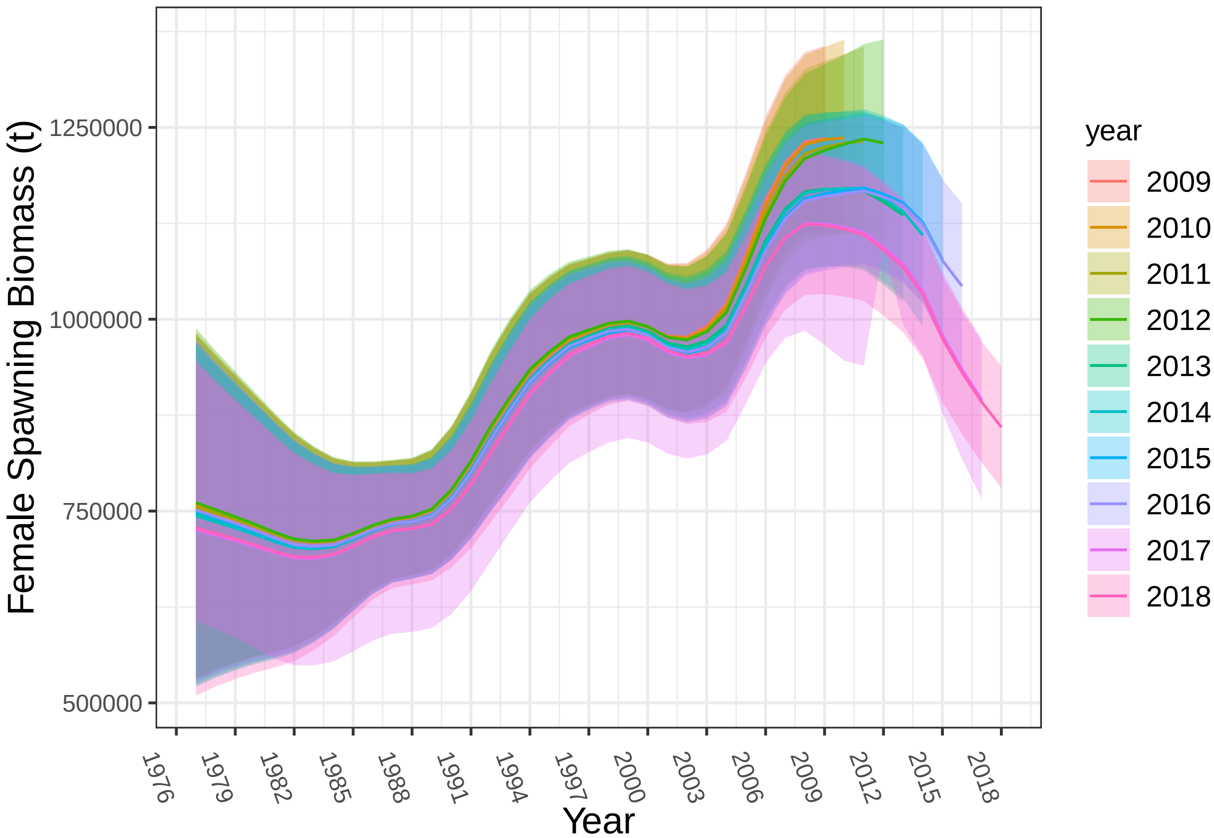


Figure 7.23: Retrospective plot of female spawning biomass. The preferred model from 1977 with data through 2019 is shown, and data was sequentially removed through 2009.

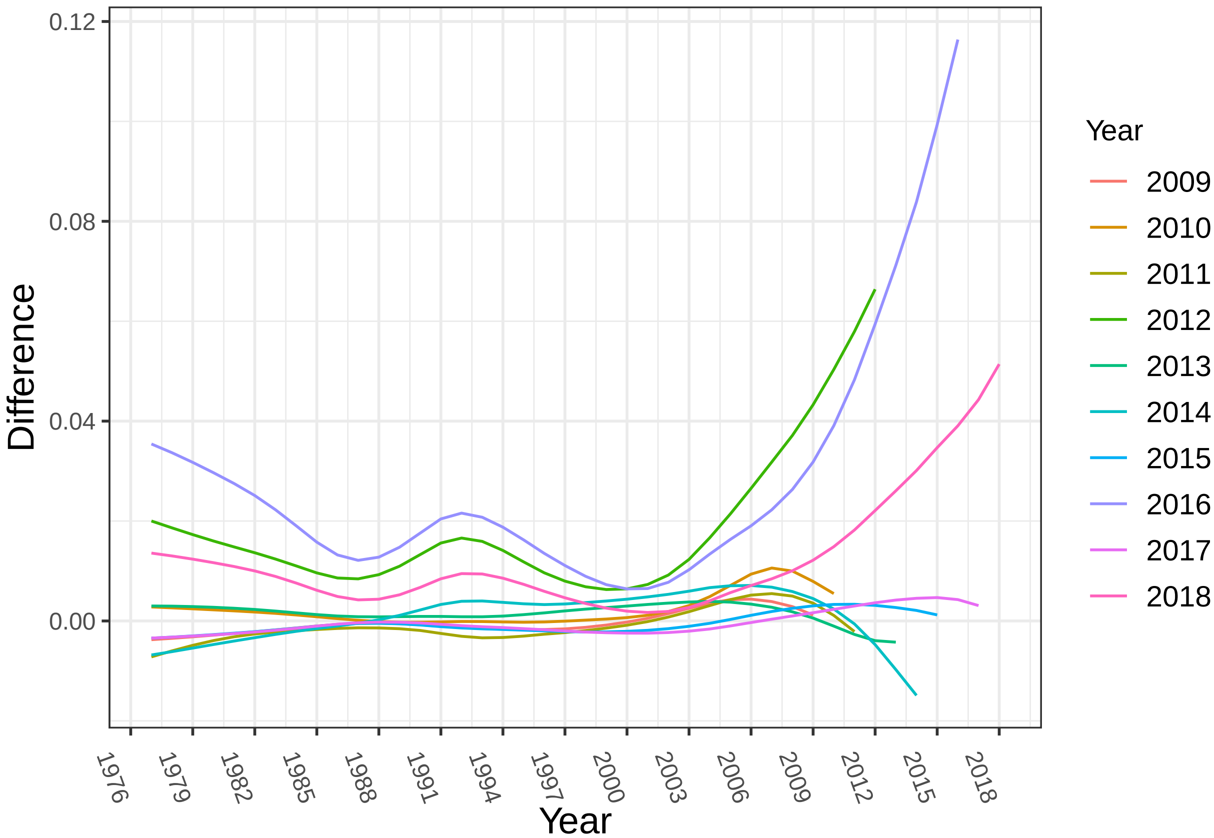


Figure 7.24: Relative differences in estimates of spawning biomass between the preferred 2019 model and the retrospective model run from 1977 through 2019 for retrospective runs for years 2018 through 2009.

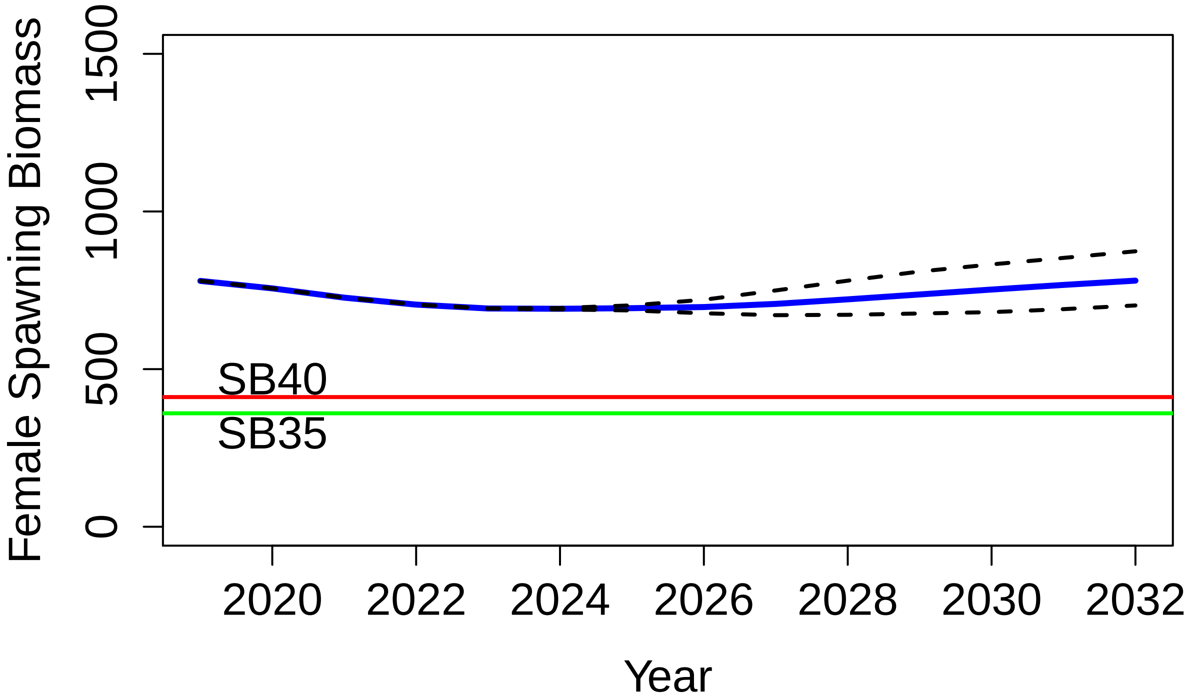


Figure 7.25: Projected female spawning biomass for 2019 to 2032 (blue line), with 5% and 95% confidence intervals, and fishing at the 5-year (2014-2018) average fishing mortality rate, F= 0.029 .

Appendix A

Table A1. Removals (kg) of Arrowtooth Flounder from the Gulf of Alaska (GOA) from sources other than those that are included in the Alaska Region's official estimate of catch, 1990-2019. Source NMFS Alaska Region: Sourced by the AKR.V_NONCOMMERCIAL_FISHERY_CATCH table, October 17, 2019. Abbreviations: IPHC (International Pacific Halibut Commission), ADFG (Alaska Department of Fish and Gam), NMFS (National Marine Fisheries Service).

	ADFG	IPHC	NMFS	Total
1990	0	0	21,922	21,922
1991	63	0	21,448	21,512
1992	0	0	23,599	23,599
1993	79	0	31,992	32,072
1994	0	0	22,509	22,509
1995	0	0	38,913	38,913
1996	0	0	25,801	25,801
1997	0	0	26,996	26,996
1998	4,738	0	33,280	38,018
1999	16,905	0	41,084	57,989
2000	8,262	0	35,666	43,927
2001	13,567	0	26,038	39,605
2002	5,019	0	16,485	21,504
2003	15,835	0	13,789	29,624
2004	5,758	0	13,126	18,884
2005	15,754	0	11,228	26,982
2006	5,748	0	16,637	22,385
2007	8,956	0	17,063	26,019
2008	843	0	16,161	17,004
2009	6,685	0	14,919	21,604
2010	106,283	11,047	16,230	133,560
2011	94,651	8,110	101,888	204,649
2012	82,785	8,422	7,461	98,669
2013	47,220	6,060	76,994	130,274
2014	65,577	9,197	16,853	91,627
2015	117,947	5,535	117,703	241,184
2016	76,752	4,310	6,961	88,024
2017	72,073	2,145	49,632	123,849
Total	771,499	54,826	862,378	1,688,703

Appendix B Ecosystem Considerations

Arrowtooth Flounder are important predators of other groundfish in Alaskan ecosystems. In this section, we give an overview of diet data and ecosystem model results for Arrowtooth Flounder in the Gulf of Alaska (GOA). While Arrowtooth Flounder are present in the Aleutian Islands (AI) and Eastern Bering Sea (EBS or BS in figures), the density of Arrowtooth Flounder as measured in survey-estimated tons per square kilometer is by far the greatest in the GOA (Fig. B.1, left). Although the density of arrowtooth differs between ecosystems, the relative effects of fishing and predation mortality as estimated within food web models constructed for each ecosystem (Aydin et al. in press) are similar between the AI, EBS, and GOA. Here, sources of mortality are compared against the total production of arrowtooth as estimated in the BSAI and GOA arrowtooth stock assessment models (see Background, "Production rates," for detailed methods). The "unknown" mortality in Figure B.1 (right) represents the difference between the stock assessment estimated arrowtooth production and the known sources of fishing and predation mortality. Nearly half of arrowtooth production as estimated by the stock assessment appears to be "unused" in the AI and GOA, which is consistent with results for other predator species such as Pacific cod and halibut. In the EBS, considerably more mortality is accounted for; please see the discussion of arrowtooth mortality rates in the EBS in the BSAI arrowtooth assessment (Wilderbuer et al. 2007). Of the accounted sources of mortality, fishing mortality is generally lower for Arrowtooth Flounder than predation mortality in all three ecosystems (Fig. B.1, right). This is consistent with the currently low fishing effort directed at this species.

To explore ecosystem relationships of Arrowtooth Flounder in more detail, we first examine the diet data collected for arrowtooth. Diet data are collected aboard NMFS bottom trawl surveys in the GOA during the summer (May – August); this comparison uses diet data collected in the early 1990s. In the GOA a total of 1704 arrowtooth stomachs were collected between the 1990 and 1993 bottom trawl surveys (n=654 and 1050, respectively) and used in this analysis and to build the GOA food web model. The diet compositions reported here reflect the size and spatial distribution of arrowtooth in each survey (see Appendix A, "Diet calculations" for detailed methods). While the diet compositions summarized here most accurately reflect early 1990's conditions in the GOA, we also examine changes in arrowtooth diets over time below.

Arrowtooth Flounder have a varied diet comprised of zooplankton, fish, and benthic invertebrates as both juveniles (0-20 cm TL fish) and adults (>20 cm TL; Fig. B.2). Capelin, euphausiids, adult and juvenile pollock, Pandalid shrimp, herring, and other forage fish comprise the majority of adult Arrowtooth Flounder diet, but none of these prey account for more than 22% of diet. As juveniles, arrowtooth prey mainly on euphausiids, which make up nearly 60% of diet, followed by capelin at 24% (Fig. B.2). When the uncertainty in food web model parameters is included (see Aydin et al in press for Ecosense methods), we estimate fairly high annual consumption of these prey by Arrowtooth Flounder. For example, estimated consumption of all forage fish (capelin, sandlance, eulachon, etc.) by adult arrowtooth ranges from 300,000 to 1.2 million metric tons, and estimated consumption of pollock by adult arrowtooth ranges from 400,000 to 800,000 metric tons annually (Fig. B.3, upper panel). Consumption of euphausiids by adult arrowtooth is estimated to range from 100,000 to 800,000 tons annually, with another 60,000 to 490,000 tons consumed annually by juvenile Arrowtooth Flounder (Fig. B.3, upper and lower).

Using diet data for all predators of Arrowtooth Flounder and consumption estimates for those predators, as well as fishery catch data, we next estimate the sources of arrowtooth mortality in the GOA (see detailed methods in Background section). As described above, sources of mortality are compared against the total production of arrowtooth as estimated in the GOA stock assessment model for the early 1990s. There are few sources of mortality for Arrowtooth Flounder in the GOA as both adults and juveniles, as indicated by the large proportion of unexplained mortality (76% for adults, 88% for juveniles) in Figure B.4. Predators explain more mortality than fisheries for Arrowtooth Flounder (at least in this model based on early 1990s data where the fishery for Arrowtooth Flounder was extremely limited). Pacific halibut, Steller sea lions, and Pacific cod together explain about 10% of adult arrowtooth mortality, while the flatfish trawl fishery accounts for 2% (Fig. B.4, upper panel). Juvenile Arrowtooth Flounder mortality is caused by adult Arrowtooth Flounder, and both adult and juvenile pollock in the GOA, but the total of these mortality sources is less than 7% of juvenile arrowtooth production (Fig. B.4, lower panel). The total tonnage consumed by predators of Arrowtooth Flounder is low relative to their biomass for both adults and juveniles: the most important predators of arrowtooth, pinnipeds and halibut, are each estimated to consume between 13,000 and 30,000 or

20,000 tons of arrowtooth annually, respectively (Fig. B.5, upper panel). Adult Arrowtooth Flounder are estimated to consume 4,000 to 12,000 tons of juvenile Arrowtooth Flounder annually, with pollock consuming nearly the same small amount (Fig. B.5, lower panel). Few mortality sources for Arrowtooth Flounder are consistent with an increasing population, which has been observed in the Gulf of Alaska since the 1960s.

After comparing the different diet compositions and mortality sources of Arrowtooth Flounder, we shift focus slightly to view them within the context of the larger GOA food webs (Fig. B.6). Arrowtooth Flounder occupy a relatively high trophic level in the GOA, and represent the highest biomass single species group at that high trophic level. The green boxes represent direct prey of arrowtooth, the dark blue boxes the direct predators of arrowtooth, and light blue boxes represent groups that are both predators and prey of arrowtooth. Visually, it is apparent that arrowtooth's direct trophic relationships in each ecosystem include a majority of species groups. In the GOA, the significant predators of arrowtooth (blue boxes joined by blue lines) include the halibut, sea lions, sharks, and fisheries. Significant prey of arrowtooth (green boxes joined by green lines) include several fish groups, Euphausiids, and Pandalid shrimp. The most interesting interaction may be with pollock, which are both prey of adult arrowtooth, and predators on juvenile arrowtooth. This situation is also observed in the EBS, but there the biomass of pollock overwhelms that of arrowtooth so the impact of this interaction on the two populations is very different between ecosystems. We next use the diet and mortality results integrated with information on uncertainty in the food web using the Sense routines (Aydin et al. in press) and a perturbation analysis with each model food web to explore the ecosystem relationships of Arrowtooth Flounder further. Two questions are important in determining the ecosystem role of Arrowtooth Flounder: which species groups are arrowtooth important to, and which species groups are important to arrowtooth? First, the importance of arrowtooth to other groups within the GOA ecosystem was assessed using a model simulation analysis where arrowtooth survival was decreased (mortality was increased) by a small amount, 10%, over 30 years to determine the potential effects on other living groups. This analysis also incorporated the uncertainty in model parameters using the Sense routines, resulting in ranges of possible outcomes which are portrayed as 50% confidence intervals (boxes in Figure B.7) and 95% confidence intervals (error bars in Figure B.7). Species showing the largest median changes from baseline conditions are presented in descending order from left to right. Therefore, the largest change resulting from a 10% decrease in arrowtooth survival is a highly uncertain increase in herring biomass, and an accompanying increase in herring catches in the fishery (Fig. B.7). A more certain outcome of the perturbation is the expected direct effect, a decrease in adult arrowtooth biomass, which has a smaller median change than the herring change. Similarly, sleeper sharks decrease with some certainty, while sablefish and pollock are predicted to increase but with nearly as much uncertainty as herring. In general, the effects of a small change in arrowtooth survival result in a large amount of uncertainty in the ecosystem, with potentially large effects on multiple species due to arrowtooth's ecosystem interactions.

To determine which groups were most important to arrowtooth in each ecosystem, we conducted the inverse of the analysis presented above. In this simulation, each species group in the ecosystem had survival reduced by 10% and the system was allowed to adjust over 30 years. The strongest median effects on GOA arrowtooth are presented in Figure B.8. Here the largest impacts on arrowtooth biomass are the direct effects through changes in arrowtooth survival and juvenile arrowtooth survival, but the next largest impacts are more interesting ecologically. Arrowtooth biomass appears strongly influenced by changes in bottom up production, with decreases in survival for large and small phytoplankton and euphausiids having similar biomass effects as direct effects from arrowtooth and juvenile arrowtooth (Fig. B.8). While euphausiids are direct prey of arrowtooth, phytoplankton are not. Smaller effects on arrowtooth biomass are seen due to decreased survival of capelin (direct prey), but these are uncertain compared with those due to phytoplankton and euphausiids. There are more unequivocal bottom up effects related to Arrowtooth Flounder in these simulations than top down effects of arrowtooth on other species.

Finally, we summarize the available food habits collections for Arrowtooth Flounder in the GOA in Table 1, and make preliminary consumption estimates from this data in Figures B.9 and B.10 for juvenile and adult arrowtooth. In general, while changes in the amount of consumption have been noted, the arrowtooth diet remains diverse and focused on euphausiids, pollock, capelin, and other fish throughout the time series (Fig. B.9). Further analysis of this data will be presented in an upcoming assessment.

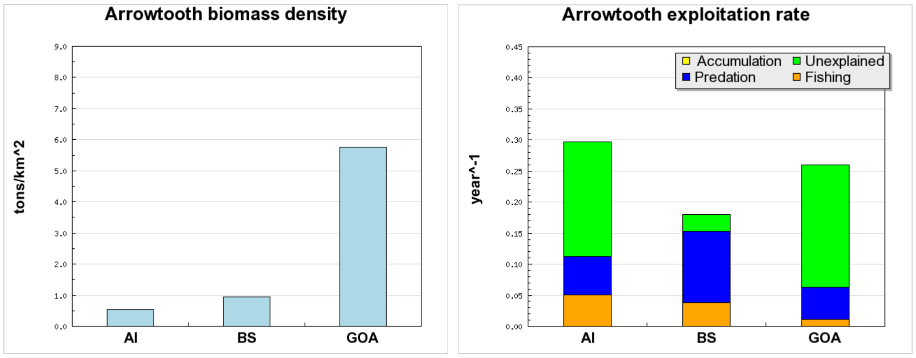


Figure B.1. Comparative biomass density (left) and mortality sources (right) for Arrowtooth flounder in the AI, EBS, and GOA ecosystems. Biomass density (left) is the average biomass from early 1990s NMFS bottom trawl surveys divided by the total area surveyed. Total arrowtooth production (right) is derived from stock assessments for the early 1990's, and partitioned according to fishery catch data and predation mortality estimated from cod predator diet data (Aydin et al. in press). See Background section for detailed methods.

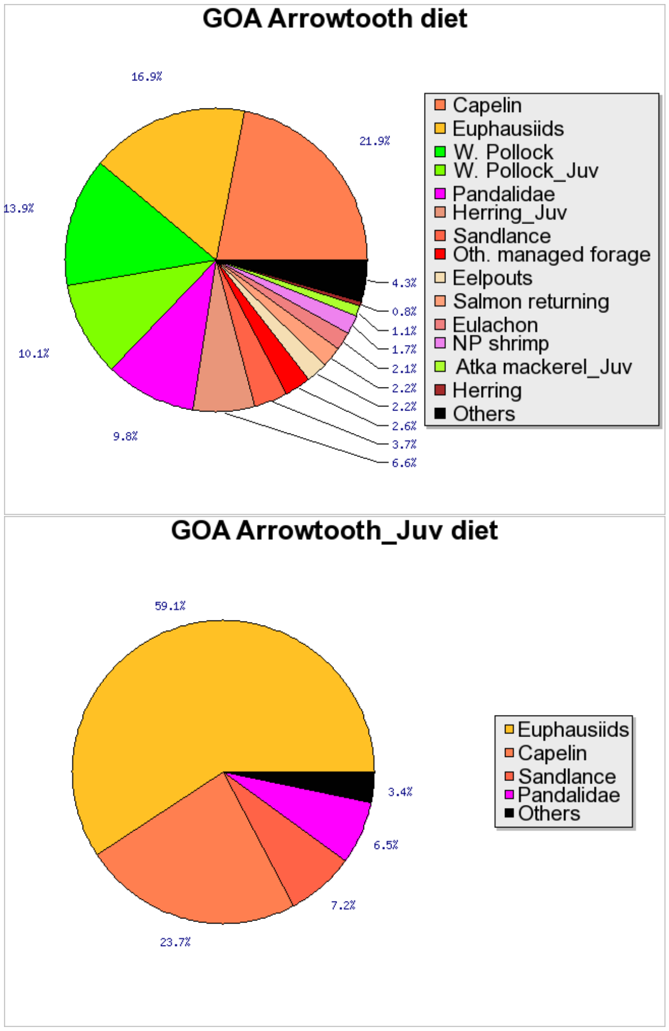


Figure B.2. Arrowtooth flounder diet compositions for the GOA ecosystem, for adults > 20cm (top) and juveniles 0-20 cm in length (bottom). Diets are estimated from stomach collections taken aboard NMFS bottom trawl surveys in 1990-1993. See Background section for detailed methods.

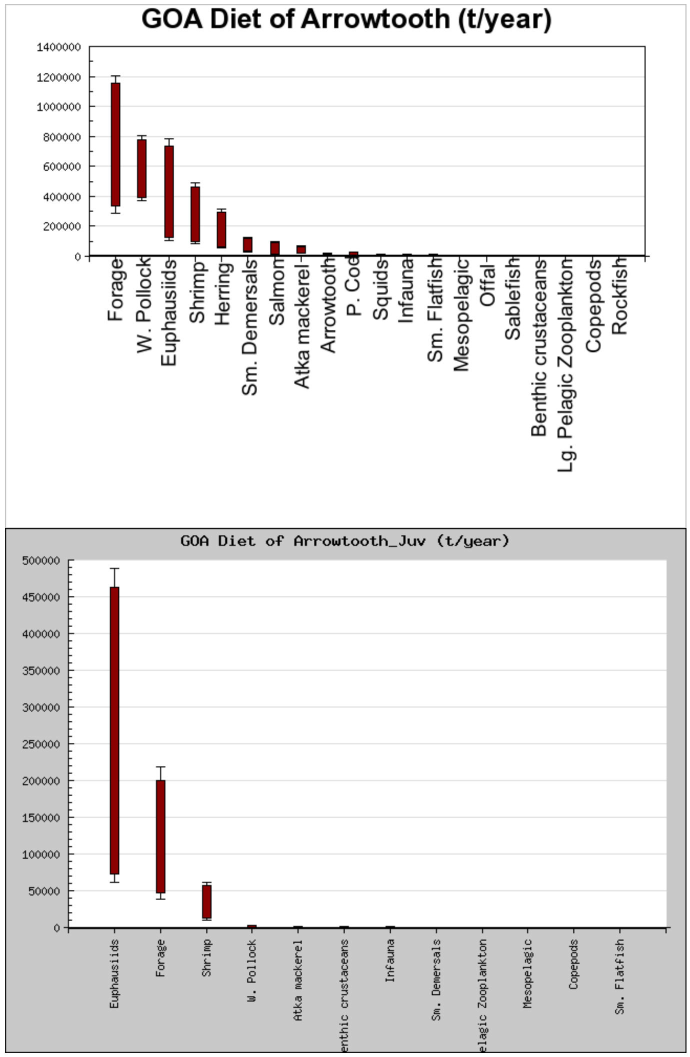
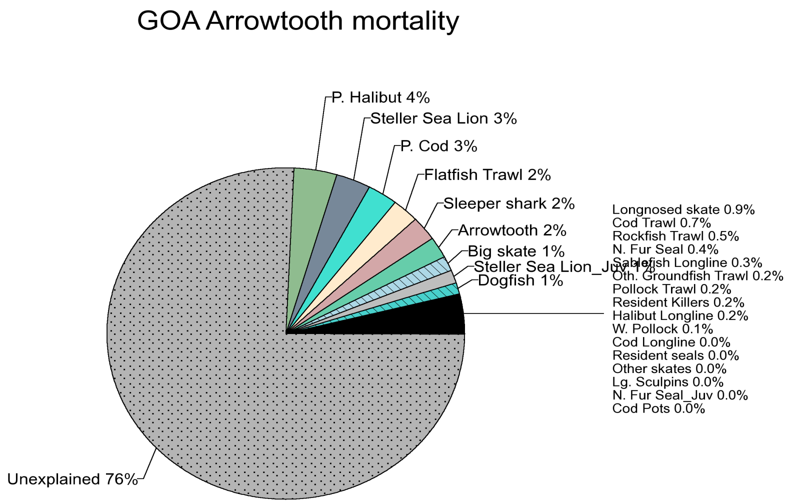


Figure B.3. Estimated annual tons of each prey type consumed by GOA Arrowtooth flounder adults >20 cm (top) and juveniles 0-20 cm (bottom), based on diets in Fig. B.2. “Forage” is all forage fish together, including capelin, sand lance, eulachon, and other managed forage.



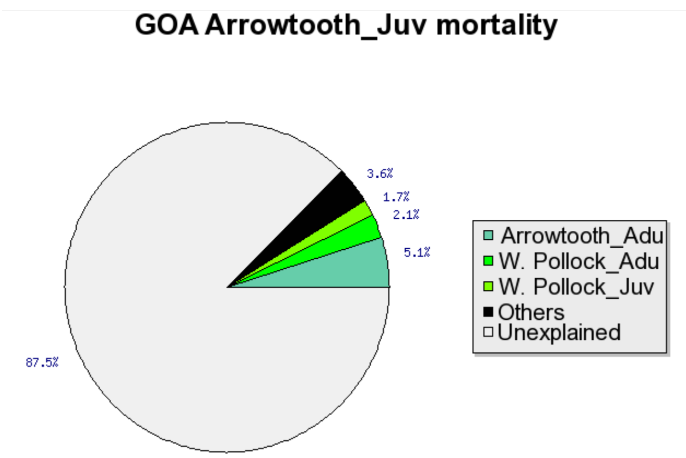


Figure B.4. Arrowtooth flounder mortality sources for the GOA ecosystem, for adults > 20cm (top) and juveniles 0-20 cm in length (bottom). Mortality sources reflect arrowtooth flounder predator diets estimated from stomach collections taken aboard NMFS bottom trawl surveys in 1990-1993, arrowtooth predator consumption rates estimated from stock assessments and other studies, and catch of arrowtooth by all fisheries in the same time periods (Aydin et al. in press). See Background section for detailed methods.

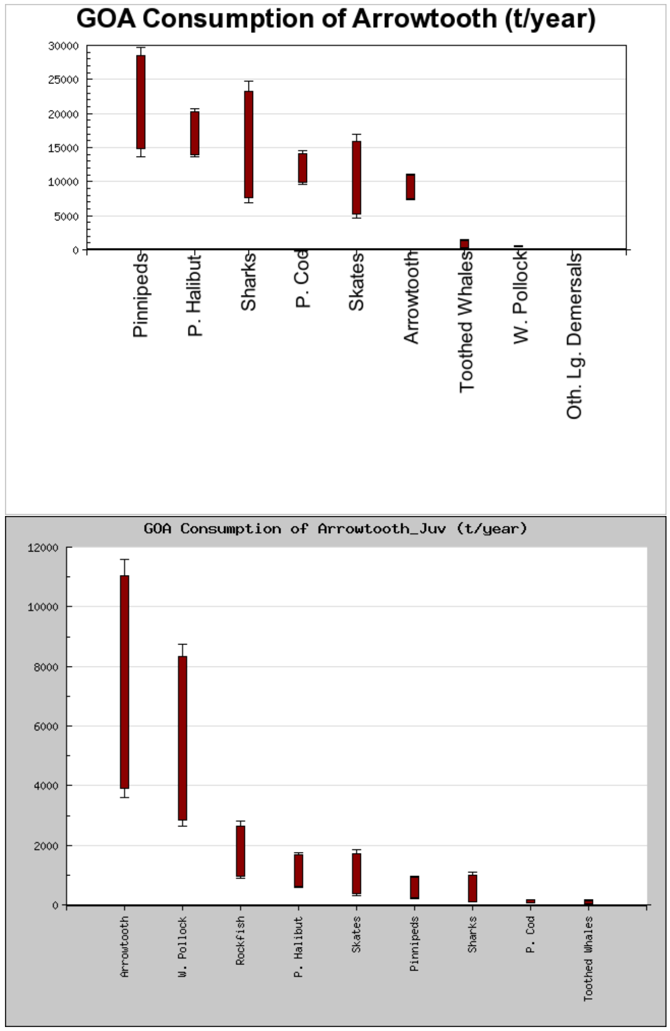


Figure B.5. Estimated annual tons of arrowtooth flounder consumed by predators in the GOA. Consumption of adult arrowtooth 20 cm (top) and juveniles 0-20 cm (bottom), based on mortality estimates in Fig. B.4. “Forage” is all forage fish together, including capelin, sand lance, eulachon, and other managed forage.

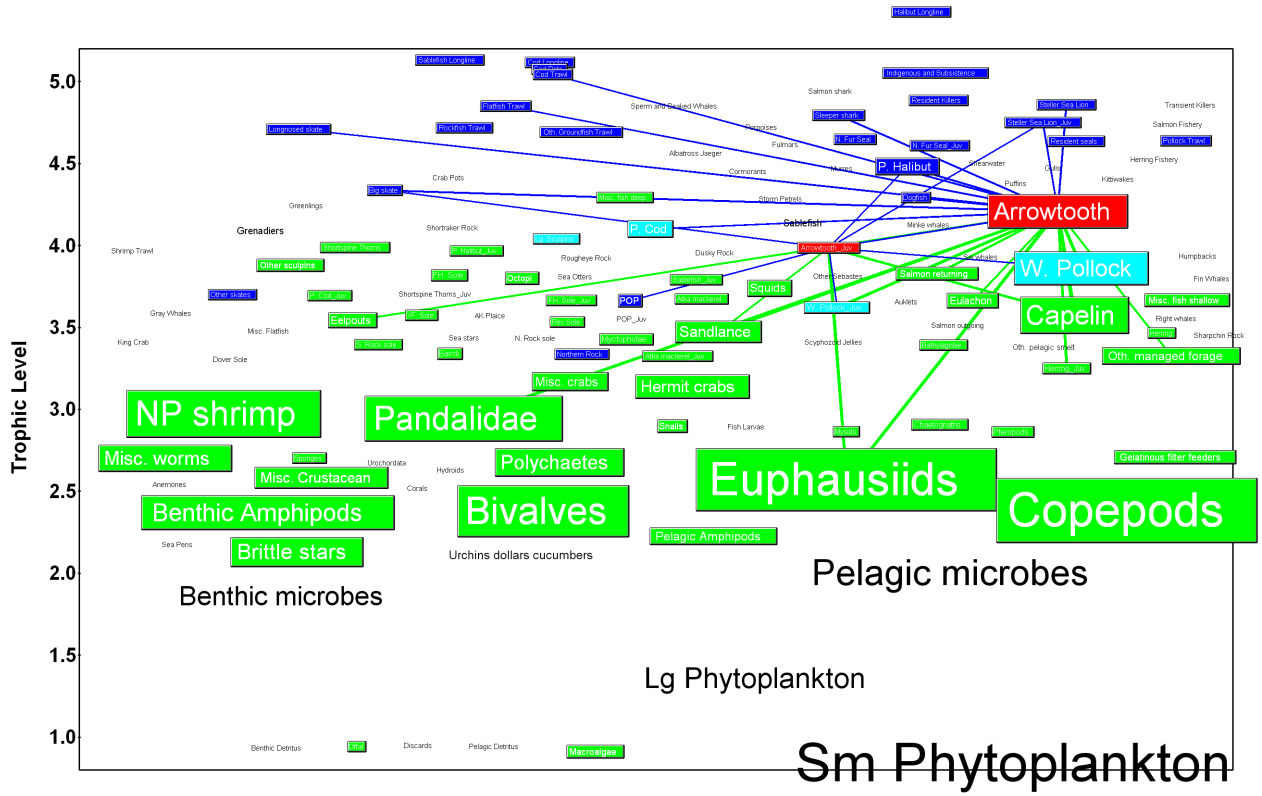


Figure B.6. Adult and juvenile arrowtooth flounder in the GOA food web. Box size is proportional to biomass, and lines between boxes represent the most significant energy flows. Predators of arrowtooth are dark blue, prey of arrowtooth are green, and species that are both predators and prey of arrowtooth are light blue.

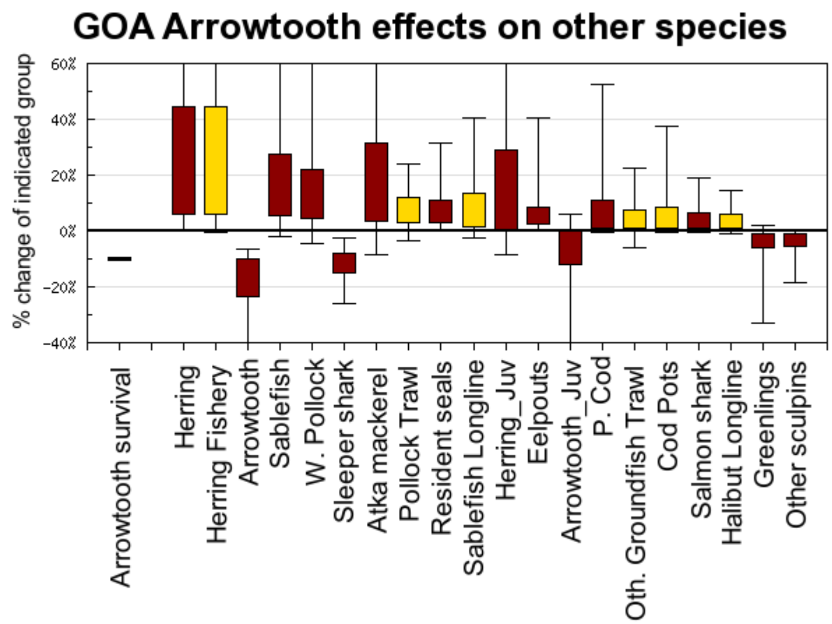


Figure B.7. Effect of changing arrowtooth > 20 cm survival on fishery catch (yellow) and biomass of other species (dark red) in the GOA, from a simulation analysis where arrowtooth survival was decreased by 10% and the rest of the ecosystem adjusted to this decrease for 30 years. Boxes show resulting percent change in the biomass of each species on the x axis after 30 years for 50% of feasible ecosystems, error bars show results for 95% of feasible ecosystems (see Aydin et al. in press for detailed Sense methods).

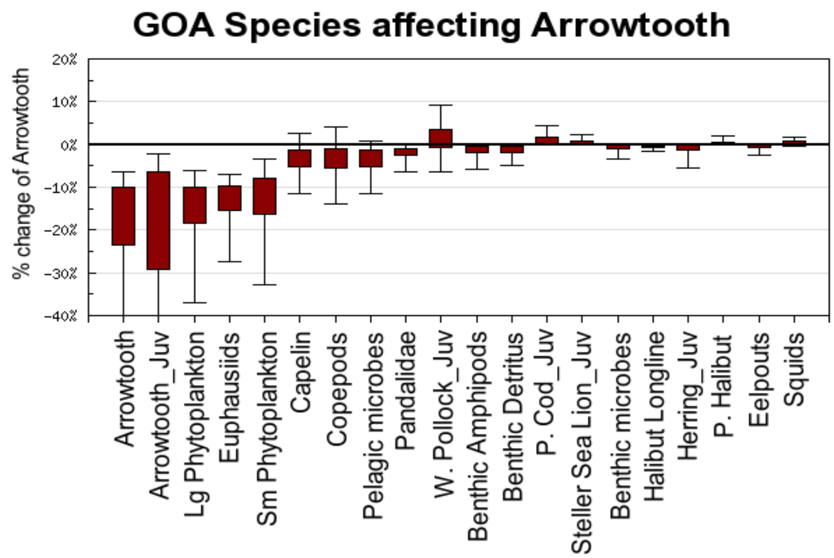


Figure B.8. Effect of reducing fisheries catch (yellow) and other species survival (dark red) on arrowtooth > 20 cm biomass, from a simulation analysis where survival of each X axis species group was decreased by 10% and the rest of the ecosystem adjusted to this decrease for 30 years. Boxes show resulting percent change in the biomass of adult arrowtooth after 30 years for 50% of feasible ecosystems, error bars show results for 95% of feasible ecosystems (see Aydin et al. in press for detailed Sense methods).

Figure B.9. Juvenile (<20 cm) arrowtooth estimated consumption of prey by survey year in the GOA.

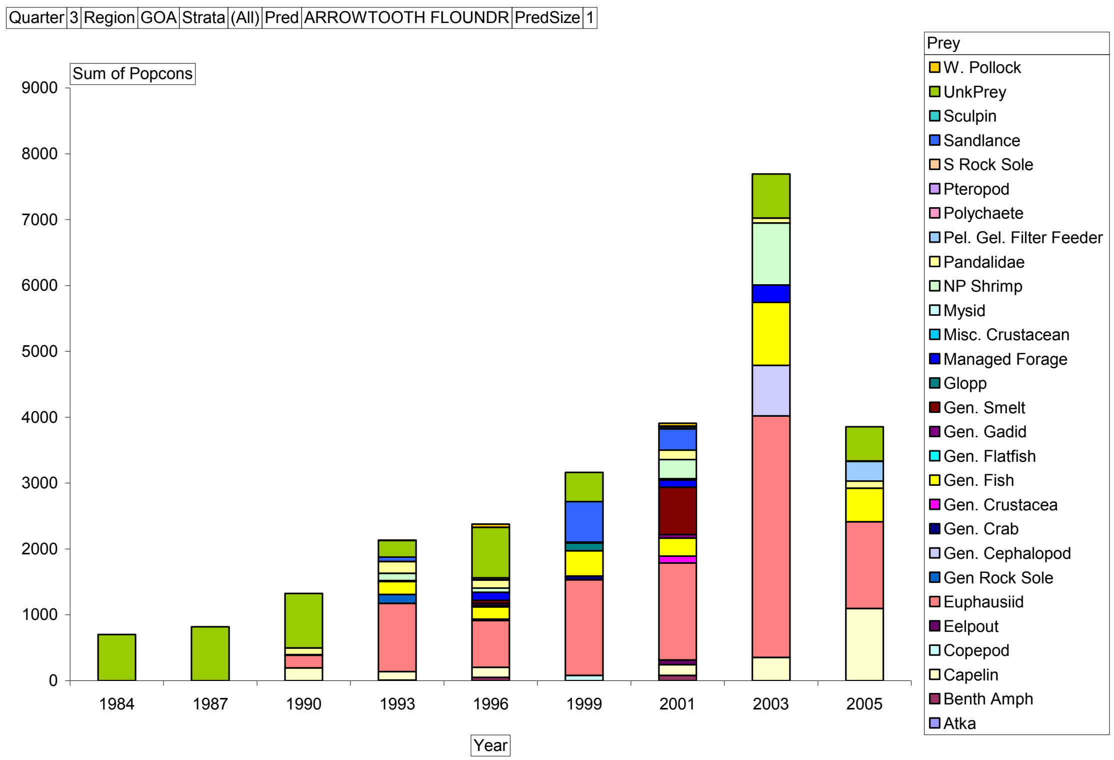


Figure B.9. Juvenile (<20 cm) arrowtooth estimated consumption of prey by survey year in the GOA.

Following Page: Table B.1 of sample sizes for GOA Arrowtooth Flounder stomach collections. Season 3 is May-September and Season 1 is the rest of the year (October-April). HAULCOUNT is the number of hauls sampled in a given regional stratum/arrowtooth size cell. PREDCOUNT is the number of arrowtooth stomachs in the same cell. When we calculate diets, our sample unit is the haul, not the individual fish; all fish collected in a given haul have diets combined based on the assumption that foraging in a given area will be sampling the same prey field. (This assumption may not be correct if fish move very far and digest very slowly). See the full diet calculations in Background section. Regional strata include area and depth: West is NMFS area 610, Central is 620-630, East is 640, and Southeast is 650. Shelf is waters 0-200 m, slope is offshore waters 200 m -1000 m (although not all surveys went that deep), and gully is inshore waters ranging from 100-500 m (gullies are defined according to GOA survey strata). NA did not map to these strata (may have taken samples for diet from "bad" trawl survey hauls that did not go into official biomass estimates). Divisions under each region are three arrowtooth size classes: 0 cm to 19.9 cm, 20 cm to 39.9 cm, and 40 cm and up. Therefore, the first size class represents our juveniles in the ecosystem model, and the second and third size classes are combined to give us our "adult" group of fish 20 cm and larger. Note that 2007 samples are not yet complete, there are still buckets to be analyzed for this past summer so these numbers will increase.

Year	Season	Data	Westshelf			Westgully			Westslope			Centralshelf			Centralgully			Centralslope			Eastshelf			Eastgully			Eastslope			Southeastshelf			Southeastgully			NA		
			1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1985	1	HAULCOUNT									1																											
		PREDCOUNT									2																											
1986	1	HAULCOUNT		1	2																																	
		PREDCOUNT		3	10																																	
1987	1	HAULCOUNT		2	2					1	2																											
		PREDCOUNT		5	9					2	7																											
	3	HAULCOUNT											4	7		2	3																					
		PREDCOUNT											11	28		2	9																					
1990	3	HAULCOUNT		2	1		2	1				3	34	35	2	27	29		1	2		2	2						1									
		PREDCOUNT		8	11		10	5				4	150	212	7	80	131		1	5		14	10						6									
1991	3	HAULCOUNT												3						2																		
		PREDCOUNT												12						6																		
1992	1	HAULCOUNT												1		2	3																					
		PREDCOUNT												6		2	10																					
1993	3	HAULCOUNT	5	12	10		3	3				12	36	45	12	34	46			5	2	7	8															
		PREDCOUNT	16	52	32		6	6				44	146	253	22	158	228			14	16	22	35															
1994	1	HAULCOUNT												1		1	7																					
		PREDCOUNT												2		5	22																					
1995	1	HAULCOUNT		1	1								1				2																					
		PREDCOUNT		4	1								1				11																					
	3	HAULCOUNT	1	8	7		1	1					3	3																								
		PREDCOUNT	1	35	14		1	5					16	15																								
1996	1	HAULCOUNT												1		1	3																					
		PREDCOUNT												1		1	19																					
	3	HAULCOUNT	21	48	38	2	10	10	1	1	9	16	67	88	3	34	52		1	11			1															
		PREDCOUNT	36	177	150	3	33	35	1	1	23	32	256	429	3	100	308		1	25			2															
1997	1	HAULCOUNT																																			2	10
		PREDCOUNT																																			2	31
1998	1	HAULCOUNT										1	9	7	2	7	7																					
		PREDCOUNT										4	44	51	9	32	19																					
	3	HAULCOUNT										4	8	9		4	4																					
		PREDCOUNT										26	31	43		15	17																					
1999	1	HAULCOUNT										8	14	13	5	5	6																					
		PREDCOUNT										21	56	55	7	24	28																					
	3	HAULCOUNT	5	9	10	2	3	3			2	8	34	33	1	23	25			4																		
		PREDCOUNT	18	26	27	3	21	6			3	8	138	146	1	70	100			9																		
2000	1	HAULCOUNT																																			1	3
		PREDCOUNT																																			1	3
	3	HAULCOUNT																																				1
		PREDCOUNT																																				2
2001	1	HAULCOUNT																																		14	28	30
		PREDCOUNT																																		33	102	103
	3	HAULCOUNT	11	20	14	1	5	4		1	2	24	58	48	11	26	27		3	8																		8
		PREDCOUNT	78	98	59	3	30	22		2	4	56	354	292	20	166	144		4	31																		28
2002	1	HAULCOUNT																																				1
		PREDCOUNT																																				3
	3	HAULCOUNT																																				2
		PREDCOUNT																																				4
2003	1	HAULCOUNT																																				3
		PREDCOUNT																																				5
	3	HAULCOUNT	5	11	12							5	16	16		1	1				2	5	5			1					3	3					5	8
		PREDCOUNT	8	73	65							9	139	91		8	5				3	25	8			6					12	5					11	20
2004	1	HAULCOUNT																													2	2					1	7
		PREDCOUNT																													2	4					2	11
	3	HAULCOUNT																													1	2					1	8
		PREDCOUNT																													1	4					1	24
2005	3	HAULCOUNT	3	7	6		1	2		1	1	2	6	15		6	8			6	2	5	10		1			1		1	4	5			3			
		PREDCOUNT	5	13	10		2	2		2	1	7	16	40		21	24			8	2	16	26		3			7		1	7	13			8			
2007	3	HAULCOUNT	3	9	11		2			1	1	2	13	17		10	11				1	6	7			1					1	1		1	1			
		PREDCOUNT	12	27	33		2			1	1	2	31	47		17	19				1	7	14			3					5	7		1	1			

BACKGROUND INFO ON MODEL PARAMETERS: REPRINTED FROM Aydin, et al., TECH MEMO

Arrowtooth Flounder (*Atherestes stomias*) are relatively large, piscivorous flatfish in the family Pleuronectidae (right-eyed flounders) which range from Kamchatka, Russia in the Bering Sea through the Gulf of Alaska to Santa Barbara, CA on the U.S. west coast. It is found in benthic habitats from less than 10m to over 1000 m depth (Love et al. 2005). During the early 2000's Arrowtooth Flounder were the most abundant groundfish in the GOA (Turnock et al. 2003). They exhibit differential growth by sex, with females reaching a maximum size of 1 m and age of 23, and males growing to 54 cm and 20 years. Females reach 50% maturity at 47 cm in the GOA, and display exponentially increasing fecundity with length, with large females producing over 2 million eggs annually (Zimmerman 1997). Until recently, Arrowtooth Flounder were not a desirable commercial species because their flesh quality was considered poor; however recently developed processing techniques have allowed a moderate commercial fishery to develop around Kodiak Island (AFSC website http://www.afsc.noaa.gov/species/Arrowtooth_flounder.php).

Adult Arrowtooth Flounder

In the EBS model, adult arrowtooth biomass is the NMFS bottom trawl survey estimate from 1991. GOA adult biomass is the average of 1990 and 1993 GOA NMFS bottom trawl survey estimates. In the AI biomass is the average of 1991 and 1994 estimates from the AI bottom trawl survey. The biomass was proportioned across the subareas according to survey estimates in each one.

In the EBS, the P/B ratio of 0.18 was estimated from the 1991 age structure in the EBS arrowtooth/Kamchatka flounder stock assessment (Wilderbuer and Sample 2003), and weight at age data collected on NMFS bottom trawl surveys for the EBS (see Appendix B for methods). The EBS Q/B ratio of 1.16 was estimated using weight at age data fit a generalized von Bertalanffy growth function (Essington et al. 2001) and scaled to the 1991 age structure from the EBS stock assessment. The GOA P/B ratio of 0.26 and Q/B ratio of 1.44 were estimated using the same methods as in the EBS from the 1990-1993 age structure in the GOA Arrowtooth Flounder stock assessment (Turnock et al. 2003) and weight at age data collected on NMFS bottom trawl surveys. Values for the AI P/B and Q/B ratios of 0.297 and 2.61 were estimated using the age structure for 1991 in the BSAI stock assessment for arrowtooth/ Kamchatka flounder (Wilderbuer and Sample 2003), and weight at age data collected on NMFS bottom trawl surveys for the Gulf of Alaska.

Adult arrowtooth diet composition was estimated from food habits collections made during bottom trawl surveys in each ecosystem. The EBS diet was derived from 1991 collections, the GOA diet was derived from the 1990 and 1993 bottom trawl surveys of the GOA, and in the AI it comes from stomachs collected in 1991 and 1994 as part of the bottom trawl surveys.

The adult arrowtooth biomass data pedigree was 2 for the EBS and AI models (data is a direct estimate from surveys in AI and EBS but the assessment is conducted for the combined area), and 1 for the GOA model (direct estimate from surveys which agrees with the GOA assessment). P/B and Q/B parameters were rated differently by system: 3 in the GOA model (proxy with known and consistent bias), 4 in the EBS model (proxy for combined BSAI with some species mixing), and 5 in the AI model (proxy for combined BSAI with some species mixing plus weight at age from adjacent area). Diet composition data rated 1 in all systems (data established and substantial,with resolution on multiple spatial scales).

Arrowtooth Flounder adults have a significantly higher density in the GOA (5.7 t/km2) than in either the EBS or AI (<1 t/km2). They are preyed upon by pollock, Alaska skates and sleeper sharks which jointly account for 60% of the total mortality in the EBS, but have relatively few predators in the AI; sleeper sharks are the only significant ones (16% of total mortality). In the GOA, there are no major predators on arrowtooth, as sleeper sharks, cod, pollock and cannibalism barely account for 11% of the total mortality. The fisheries in aggregate cause 15%-17% of the mortality in the EBS and AI respectively, while only 4% in the GOA. In all three systems adult Arrowtooth Flounder eat primarily pelagic prey. In the GOA they eat mostly capelin (22% of diet) and euphausiids (17%), followed by adult pollock (14%), and juvenile pollock (10%). In the EBS, Arrowtooth Flounder eat primarily juvenile pollock (47% of diet), followed by adult pollock (20%) and euphausiids (10%). In the AI, arrowtooth mostly prey on myctophids (27%), juvenile Atka mackerel (16%), and pandalid shrimp (16%).

Juvenile Arrowtooth Flounder

In all three models, juveniles were defined as fish less than 20 cm in length, which roughly corresponds to 0 through 1 year old arrowtooth. In the AI, juvenile arrowtooth biomass is based on an EE of 0.8. In the EBS and GOA models, initial attempts at estimating juvenile biomass using top-down methods were not successful because there are apparently few predators of juvenile Arrowtooth Flounder in either ecosystem. Therefore, in the EBS juvenile Arrowtooth Flounder biomass in each model stratum was assumed to be 10% of adult arrowtooth biomass in that stratum. In the GOA, we estimated juvenile arrowtooth mortality to be 0.5, a rate comparable to those estimated by MSVPA model runs in the EBS (Jurado-Molina 2001). This mortality rate was used to estimate juvenile biomass given the numbers and weight at age estimated for those years. In the EBS, the P/B ratio of 1.58 was estimated by the same methods as described above for adults. In the GOA, the estimated juvenile mortality rate of 0.5 was used to estimate the P/B ratio to 0.90 for 1990-1993 based on stock assessment age structure. The juvenile arrowtooth P/B in the AI was estimated using the same method as that described above for adults, resulting in a value of 1.01. In all three ecosystems, Q/B ratios were estimated by the same method and using the same information as for adults. The EBS juvenile arrowtooth Q/B was therefore 3.31, the GOA juvenile arrowtooth Q/B was 2.45, and the AI Q/B ratio was 3.77.

Juvenile Arrowtooth Flounder diet composition was estimated from food habits collections made during bottom trawl surveys in each ecosystem. The EBS diet was derived from 1991 collections, the GOA diet was derived from the 1990 and 1993 bottom trawl surveys of the GOA, and in the AI it comes from stomachs collected in 1991 and 1994 as part of the bottom trawl surveys.

The juvenile arrowtooth biomass data pedigree was 8 for the EBS and AI models (no estimate available, top down balance), and 4 for the GOA (proxy with limited confidence). P/B and Q/B parameters were rated differently by system: 4 in the GOA model (proxy with limited confidence), 5 in the EBS model (downgraded from adult rating of 4), and 6 in the AI model (downgraded from adult rating of 5). Diet composition data rated 1 in all systems (data established and substantial, with resolution on multiple spatial scales).

Arrowtooth Flounder juveniles have a low fraction of total mortality due to predation in the EBS and GOA, so the assumption of an EE=0.8 in the AI model to top down balance this group might be re-examined in revisions to that model. The major source of mortality in the EBS and GOA are adult arrowtooth (3-5%, respectively), but they are preyed upon mostly by Pacific cod (20%) in the AI. Juvenile Arrowtooth Flounder appear to eat from different sections of the food web in each system. They eat primarily benthic invertebrates (pandalids and benthic amphipods) in the AI, show approximately equal feeding from benthic and pelagic groups (non pandalids and juvenile pollock) in the EBS, but feed predominantly on pelagic euphausiids and capelin in the GOA.

[NOTE: Parameter estimation methods below are reprinted from tech memo]

Fish Production rates

Production/biomass (P/B) and consumption/biomass (Q/B) for a given population depend heavily on the age structure, and thus mortality rate of that population. For a population with an equilibrium age structure, assuming exponential mortality and Von Bertalanffy growth, P/B is in fact equal to total mortality Z (Allen 1971) and Q/B is equal to (Z+3K)/A, where K is Von Bertalanffy's K, and A is a scaling factor for indigestible proportions of prey (Aydin 2004). If a population is not in equilibrium, P/B may differ substantially from Z although it will still be a function of mortality.

For the Bering Sea, Aleutian Islands, and Gulf of Alaska ECOPATH models, P/B and Q/B values depend on available mortality rates, which were taken from estimates or literature values used in single-species models of the region. It is noted that the single-species model assumptions of constant natural mortality are violated by definition in multispecies modeling; therefore, these estimates should be seen as “priors” to be input into the ECOPATH balancing procedures or other parameter-fitting (e.g. Bayesian) techniques.

Several methods were used to calculate P/B, depending on the level of data available. Proceeding from most data to least data, the following methods were used:

1. If a population is not in equilibrium, total production P for a given age class over the course of a year can be approximated as (Nat · deltaWat), where Nat is the number of fish of a given age class in a given

year, exponentially averaged to account for mortality throughout the year, and deltaWat is the change in body weight of that age class over that year. For a particular stock, if weight-at-age data existed for multiple years, and stock-assessment reconstructed numbers-at-age were also available, production was calculated by summing this equation over all assessed age classes. Walleye pollock P/B for both the EBS and GOA were calculated using this method: examining the components of this sum over the years showed that numbers-at-age variation was responsible for considerably more variability in overall P/B than was weight-at-age variation.

2. If stock assessment numbers-at-age were available, but a time series of weight-at-age was not available and some weight-at-age data was available, the equation in (1), above, was used, however, the change in body weight over time was estimated using fits to the generalized Von Bertalanffy equations described in the consumption section, below.
3. If no stock assessment of numbers-at-age was available, the population was assumed to be in equilibrium, so that P/B was taken to equal Z. In cases for many nontarget species, estimates of Z were not available so estimates of M were taken from conspecifics with little assumed fishing mortality for this particular calculation.

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