7. Assessment of the arrowtooth flounder stock in the Gulf of Alaska

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Executive Summary

Changes in the input data

The following new data was included in the model:

1. The 2015 NOAA Resource Assessment and Conservation Engineering (RACE) Gulf of Alaska (GOA) survey biomass and standard error were added to the model.
2. Catch for 2013 was updated and 2014 and 2015 catch (to October 12, 2015) were added.
3. Fishery length data was updated for 2014 and 2015.
4. Fishery length data updated for all years (1977-2015).
5. Survey age data updated for all years (1984-2013).
6. Survey length frequency data was added for 1985, 1986, 1989, years that were not previously in the model, as well as data for 2015.
7. A new length-age transition matrix was created using age length data from 1977-2015.
8. Weight at age was recalculated for males and females, using 1977-2015 age data, by fitting the data to a von Bertalanffy growth curve.
9. Maturity at age was updated based on Stark (2008).

Changes in assessment methodology

In 2013 the joint BSAI and GOA plan teams recommended that the GOA and the Bering Sea and Aleutian Islands (BSAI) arrowtooth flounder models be standardized. In 2014 a new the BSAI ATF model was accepted that incorporated non-parametric estimation of fishery selectivities, similar to the GOA model for fishery likelihoods. Further standardization required that the number of ages be increased for the GOA model; the BSAI model incorporates ages 1-21 while the GOA model has historically used ages 3-15+. This standardization also required updated length at age, for 26 bin sizes, weight at age for 21 ages, and an updated length-age transition matrix.

In September 2015, a new generalized model was presented to the GOA Plan Team, which can be used to run arrowtooth flounder BSAI and GOA stock assessment models. This “generalized model” can incorporate data from any number of surveys and a range of ages. Using the generalized model, the preferred model (referred to as Model 2.1) incorporates ages 1-21+, and estimates selectivity up to age 19, similar to the BSAI assessment model, rather than to age 11 as in the previous GOA model (Models 0 and 1). It also has updated maturity based on the most recent maturity at age work by Stark (2008). Model 0 represents last year’s final model with no new data. Model 1.0 is last year’s model with updated 2015 data. Model 2.2 represents the same model as Model 2.1 (the generalized model) with ages 3-15+ and updated 2015 data. Model 2.3 is similar to Model 2.2 (1-21+) but estimates selectivity parameters up to age 11. The authors recommend Model 2.1 for setting final harvest specifications for 2016 and preliminary harvest specifications for 2017.

Summary of Results

Arrowtooth flounder biomass estimates in the current model are very similar to those estimated in the last assessment in 2013. The generalized model estimates biomass for two additional ages, ages 1 and 2, so age 1+ and 3+ biomass are presented. The model estimates of total (age 1+) biomass increased from a low of 390,626 t in 1970 to a high of 2,109,820 t in 2009 and slight decrease to 2,093,010 t in 2015 (Table 1). Female spawning biomass in 2015 was estimated at 1,221,500 t, a <3% increase from the projected 2015 biomass (fishing at the average 5 year F) of 1,189,120 t from the 2013 assessment. Maturity at age changed slightly in the 2015 assessment, based on new data (Stark 2008). The 2015 ABC using $F_{40\%}$ was 192,921 t. The 2016 and 2017 ABCs using $F_{40\%}$ were estimated at 186,188 t and 189,332 t, and the 2016 and 2017 OFLs were 219,430 t and 196,714 t, estimated using the projection model.

Quantity	As estimated or *specified last* year for: 2015	2016	*As estimated or *recommended this* year for: 2016	2017
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 3+) biomass (t)	1,957,970	1,915,170		
Projected total (age 1+) biomass (t)			2,103,860	2,083,450
Projected Female spawning	1,189,120	1,147,450	1,175,240	1,157,520
$B_{100\%}$	1,155,170	1,155,170	992,272	992,272
$B_{40\%}$	462,067	462,067	396,909	396,909
$B_{35\%}$	404,309	404,309	347,295	347,295
F_{OFL}	0.204	0.204	0.204	0.204
$maxF_{ABC}$	0.172	0.172	0.171	0.171
F_{ABC}	0.172	0.172	0.171	0.171
OFL (t)	226,390	217,522	219,430	196,714
maxABC (t)	192,921	185,352	186,188	189,332
ABC (t)	192,921	185,352	186,188	189,332
Status	As determined *last* year for: 2013	2014	As determined *this* year for: 2014	2015
Overfishing		n/a		n/a
Overfished	n/a		n/a	
Approaching overfished	n/a		n/a	

*Projections are based on estimated catches of 20,324 t for 2015 and 2016.
**Natural mortality rate is 0.35 for males, 0.2 for males.

Arrowtooth flounder is managed as a single stock in the Gulf of Alaska. However, the ABC by management area using $F_{40\%}$ was estimated by calculating the fraction of the survey biomass in each area and applying that fraction to the ABC:

Arrowtooth ABC by INPFC area

	Western	Central	West Yakutat	East Yakutat/SE	Total
2013 survey biomass percent by area	15.94	59.18	19.06	5.82	100
ABC 2014	31,142	115,612	37,232	11,372	195,358
ABC 2015	30,217	112,178	36,126	11,035	189,556
2015 survey biomass percent by area	14.34	54.88	19.14	11.64	100
ABC 2016	26,699	102,180	35,636	21,672	186,188
ABC 2017	27,150	103,905	36,238	22,038	189,332

Responses to SSC and Plan Team Comments on Assessments in General

For this year's final assessments, the Teams recommend that each author of an age-structured assessment use one of several specified model-naming conventions.

Responses to SSC and Plan Team Comments on Assessments in General
The authors use one of the recommended naming conventions in this assessment.

SSC comments specific to arrowtooth flounder assessment

1. The Team recommends that the assessment authors evaluate a range of plus group ages, and start the model at age 1, similar to the BSAI model.
2. In general, for all flatfish assessments, the Team recommends that new maturity information be evaluated and incorporated as appropriate.

Authors' response:

1. The author explored models with ages 1-21+ (Model 2.1 and 2.3) and 3-15+ (Model 0 and Model 2.2). Model 2.1, the generalized model with ages 1-21+, is the preferred model.
2. Maturity was updated with Gulf of Alaska maturity at age estimates from Stark (2008).

Introduction

Arrowtooth flounder (*Atheresthes stomias*) range from central California to the eastern Bering Sea and are currently the most abundant groundfish species in the Gulf of Alaska. Arrowtooth flounder occur from central California to the Bering Sea, in waters from about 20m to 800m, although 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).

In the Gulf of Alaska, arrowtooth flounder are managed as a single stock but the ABC is specified separately for the Western (NMFS area 610), Central (620, 630), West Yakutat (640), and Southeast outside (650).

Historically, arrowtooth flounder has not been targeted as a commercial fishery because the muscle degrades rapidly when heated. However, several recent developments have allowed arrowtooth flounder to become more desirable to commercial markets. Several methods exist to neutralize the enzymes that cause the flesh to degrade, including chilling to near zero or immediate processing and freezing. The arrowtooth flounder currently caught, processed, and sold each year from the Gulf of Alaska are typically sold in Asian markets. They are eaten as less expensive fillets, used raw in sashimi, or used to manufacture surimi (http://alaskafisheries.noaa.gov/newsreleases/2008/arrowtooth120208.htm). "Arrowshimi" is being marketed successfully from arrowtooth flounder. The catches for arrowtooth flounder remain below the ABC; approximately 20,000-30,000 t for the past 10 years.

Trophic studies (Yang 1993, Hollowed, et al. 1995, Hollowed et al. 2000) suggest they are an important component in the dynamics of the Gulf of Alaska benthic ecosystem. 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. 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 was fixed at 0.2 for females and 0.35 for males in the model. 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, 21 year old males have been observed in every survey since that time.

Information concerning stock structure is not currently available.

Fishery

The directed fishery for arrowtooth flounder takes place throughout the GOA, but is primarily in the central GOA (NMFS area 630). Arrowtooth flounder are typically caught with bottom trawl nets. Their area of highest abundance, and catch, is in the central and western GOA (Figure 1). Outside of the directed fishery, they are primarily caught as bycatch in the Other Flatfish fisheries. Substantial amounts of flatfish are discarded overboard in the various trawl target fisheries. Table 2 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% since 2010.

Catch increased gradually since the 1960's when it was first recorded, and has remained approximately 20,000-30,000 t since 2000. Catch remains well below the TAC (Tables 3a, 3b). 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. The highest recorded catch was 34,327 t in 2014. Catch as of October 29, 2015 was 16,964 t, and the projected total for 2015 is 20,324 t. Total allowable catch for 2015 was 14,500 t for the Western GOA, 6,900 t for the W. Yakutat, 75,000 t for the Central GOA, and 6,900 t for the SE outside region (103,300 t total). TAC increased from 43,000 t in 2011 to 103,300 t in 2012-2015 (Table 3b). Specified TAC, ABC, and OFL since the 1990's are shown in Table 3b.

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. The best estimate of annual arrowtooth catch between 1960 and 1993 was calculated by multiplying the proportion of arrowtooth in observer sampled flatfish catches in recent years (nearly 50%) by the reported flatfish catch (1960-1977 from Murai et al. 1981 and 1978-1993 from Wilderbuer and Brown 1993) (Tables 3a, 3b).

The survey biomass estimates used in this assessment are from International Pacific Halibut Commission (IPHC) trawl surveys and NMFS groundfish surveys (Table 4). 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 IPHC surveys did not cover the whole Gulf of Alaska area in one year, but surveyed different regions each year. 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 also did not cover the entire GOA in any one year and were combined to provide total coverage of the survey area. However, sample sizes were lower in the 1970's surveys (403 hauls, Table 4) 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 NMFS triennial surveys (starting in 1984) 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 but none for the 1960's surveys.

In the assessment modeling, the survey catchability coefficient (q) 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.

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 (Brown, unpub.). 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.

Survey abundance estimates were low in the 1960's and 1970's, increasing from about 146,000 t in the early 1970's to about 2,822,830 t in 2003. Survey biomass declined to 1,899,778 t in 2005. Survey biomass has decreased from 1,772,029 t in 2009, to 1,747,339 t in 2011, and 1,659,128 t in 2015. The 2015 estimate is higher than the 2013 estimate of 1,290,727 but lower than the 2001-2011 estimates. The 1984, 1987, 1999, 2005, 2007, 2009 and 2015 surveys covered depths to 1000m, the 1990, 1993, 1996, and 2001 surveys to 500m and the 2003, 2011 and 2013 surveys covered depths to 700m. 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 4). The eastern Gulf biomass was between 14% and 22% of the total biomass for the 1993-1999 surveys.

Effort on CPUE data since 1984 is available from the NMFS GOA trawl survey (Figure 1a-n). CPUE by haul indicates that the highest abundance occurs between about 149 and 156 degrees longitude, to the southwest and to the northeast of Kodiak Island (Figure 1a-n). Results show that CPUE is typically highest in the Chirikof region of the central GOA, NMFS area 620. Between 2011 and 2015, the peak CPUE appears to have shifted east from approximately 155W to 150W.

Data

The model simulates the dynamics of the population and compares the expected values of the population characteristics to those observed from surveys and fishery sampling programs.
The following data sources (and years of availability) were used in the model:

Data component	Years
Fishery catch	1961-2015
IPHC trawl survey biomass and S.E.	1961-1962
NMFS exploratory research trawl survey biomass and S.E.	1973-1976
NMFS trawl survey biomass and S.E.	1984,1987,1990,1993,1996,1999,2001,2003, 2005,2007,2009, 2011, 2013, 2015
Fishery size compositions	1977-1993,1995-2015
NMFS survey size compositions	1975, 1985, 1986, 1989, 2015
NMFS triennial trawl survey age composition data	1984,1987,1990,1993,1996,1999,2001, 2003,2005,2007,2009, 2011, 2013

Sample sizes for the fishery length data were generally at least 1,000 for the 1970s through 1984 (Table 5). Sample sizes were under 800 between 1985-1988 and were not taken in 1989. Fishery length data was updated in the current assessment, and the following years of data were added: 1982, 1983, 1984, 2014, 2015. 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 (Figure 2).

Otoliths from the 1984 to 2013 NMFS trawl surveys have been aged and used in the model. Length composition data from 1975, 1985, 1986, 1989, and 2015 are used in the model since age data are not yet available for 2015 and only length data are available for 1975, 1985, 1986, and 1989. Table 6 documents annual research catches (1977 - 2013) from NMFS longline, trawl, and echo integration trawl (EIT) surveys. Table 7 contains incidental catches from halibut fisheries by area and year (2001-2010).

Survey biomass estimates, standard error, number of hauls, and maximum depth are shown in Table 3. Biomass by area is shown in Table 7. Age and length frequency data from NMFS surveys are shown in Tables 7 and 8, respectively.

Analytic approach

Model Structure

The model structure was developed following Fournier and Archibald's (1982) methods, with many similarities to Methot (1990). We implemented the model using automatic differentiation software developed as a set of libraries under C++ (ADModel Builder). ADModel Builder can estimate a large number of parameters in a non-linear model using automatic differentiation software extended from Greiwank and Corliss (1991) and developed into C++ class libraries. This software provides the derivative calculations needed for finding the objective function via a quasi-Newton function minimization routine (e.g., Press et al. 1992). The model implementation language (ADModel Builder) gives simple and rapid access to these routines and provides the ability to estimate the variance-covariance matrix for all parameters of interest.

Details of the population dynamics and estimation equations, description of variables and likelihood equations are presented in Appendix A (Tables A.1, A.2 and A.3). There were a total of 185 parameters estimated in the model (Table A.4). 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. There were 55 fishing mortality deviates in the model, which were constrained to be small, 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 2014 account for 54 parameters, plus one parameter for the mean recruitment. Survey selectivity was estimated separately for males and females (4 parameters total). The instantaneous natural mortality rate, catchability for the survey and the Von Bertalanffy growth parameters were fixed in the model (Table A.5). 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. Previous models set recruitment at 3 due to poor fitting of the younger ages.

Model 2.1: main features.

1. Generalized model that can incorporate a varying number of surveys and ages. This model can be used for either BSAI or GOA arrowtooth flounder assessments.
2. Ages 1-21+.
3. Updated 2015 age data, survey length frequencies, fishery length frequencies.
4. Fishery length frequency data was updated for all years.
5. Age data from surveys was updated for all years.
6. Updated length-age transition matrix.
7. Updated weight at age for males and females.
8. Selectivity is estimated for the first 19 ages for fishery and survey selectivity, male and female.
9. Updated maturity at age, based on Stark 2008 maturity study.

Model 2.2: main features.

1. The same model as Model 2.1 (generalized model).
2. Ages 3-15+.
3. Updated 2015 age data, survey length frequencies, fishery length frequencies, survey biomass.
4. Selectivity is estimated for the first 11 ages for fishery and survey selectivity, male and female.

Model 2.3: main features.

1. The same model as Model 2.1 (generalized model).
2. Ages 1-21+.
3. Updated 2015 age data, survey length frequencies, fishery length frequencies, survey biomass.
4. Updated length-age transition matrix.
5. Updated weight at age for males and females.
6. Selectivity is estimated for the first 11 ages for fishery and survey selectivity, male and female.

Model 2.4: main features.

1. The same model as Model 2.1 (generalized model).
2. Ages 3-15+.
3. No updated data – can be compared with Model 0.

Model 0: main features.

1. Last year's model that has been used for the past 5+ GOA ATF assessments.
2. Data updated 2013.
3. Ages 3-15+.
4. No change since 2013 assessment.

Model 1.0: main features.

1. Last year's model that has been used for the past 5+ GOA ATF assessments.
2. Updated 2013 age data, survey length frequencies, fishery length frequencies.
3. Fishery length frequency data was not updated for all years.
4. Age data from surveys was not updated for all years.
5. Ages 3-15+.

Parameters Estimated Outside the Assessment Model

Natural mortality, Age of recruitment, and Maximum Age

Natural mortality (M) rates for Gulf of Alaska arrowtooth flounder were estimated using the methods of Alverson and Carney (1975), Pauly (1980), and Hoenig (1983) in the 1988 assessment (Wilderbuer and Brown 1989). The maximum age of arrowtooth flounder otoliths collected in the GOA was a male, at 34 years (Tables 9a, 9b).

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 8.14). 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).

An alternative explanation for the data is that the prevalence of females in the survey and fishery data is the result of lower availability for males. If lower availability is assumed, then the 3+ biomass and ABC will be higher, even though the $F_{40\%}$ and female spawning biomass will remain unchanged. However, if males became unavailable to the gear at a fairly constant rate as they age, the same effect could explain the data. Three pieces of evidence indicate the process is linked to natural mortality rather than catchability. First, the survey and fishery data in both the Bering Sea and GOA have about 70% female in the catches, which also points towards a higher M for males. Second, most of the abundance of arrowtooth flounder from survey data occurs at depths less than 300 meters. The fraction female is fairly constant at about 65% to 74% for depths up to 500 meters. In the deepest areas, covered in the 1999 and 1987 surveys, the proportion female was variable, being about 50% in 1987 and 83% in 1999. The data by depth do not indicate that males in any depth strata are less available than in other depth strata. Third, analysis of arrowtooth flounder age data in the Bering Sea show the same phenomena.

Weight at Length
The weight-length relationship for arrowtooth flounder is, $W = .003915\ L^{3.2232}$, for both sexes combined where weight is in grams and length in centimeters.

Weight at Age
In this assessment, weight at age data from 1977-2015 was fit to a von Bertalanffy growth curve,

$Weight \sim S_{inf} * (1 - e^{-(k*(age - t_0))})$. Parameters for males and females are shown below. Weight at age estimates closely matched previous estimates used in the 2013 model (Figure 3). The plus group estimate of weight at age 21+ was made by taking a weighted average of the estimated number of individuals in each age class 21 and older, up to age 34, the oldest age observed. Weights were based on the number in each age class surviving when natural mortality was applied.

	S_{inf}	K	t_0
Females	5.102e4	4.405e-3	2.250
Males	1378.665	0.1151	1.550

Growth
Growth was estimated from length and age data from 1984 to 2005 surveys. The 2007 and 2009 length-age curves are very close to the 1984-2005 length-age relationship, and while not incorporated into this assessment, are not expected to change the length-age curve. L_{inf} was estimated as 81.9 cm for females and 49.7 cm for males. The length at age 2 (L_2) for both sexes was estimated at 21 cm and k was 0.102 for females and 0.236 for males.

$$L_{age} = L_{\inf} + (L_2 - L_{\inf}) * \exp(-k(age - 2)) .$$

The mean length at age data from the surveys for older females increases from 1984 to the mid-1990's, then decreases in 2005 for females. Younger females look similar by year. Males show similar trends, but to a lesser degree (Tables 9, 11, 12, 13, and Figure 4). Mean length at age is used to construct the age-length transition matrix for fitting length composition data for the fishery and the survey length data. The mean length at age for age 15 females is about 6 cm (about 4 cm for males) lower (in the current assessment model) than the mean length at age for 15 year-olds used in the 2005 assessment model.

Maturity
Maturity through 2013 was based on a maturity-at-length study by Zimmerman (1997). Length at 50% mature 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). Length at 50% mature from survey data in 1992 off Washington was 36.8 cm for females and 28.0 cm for males, with logistic slopes of -0.54 and -0.893 respectively (Rickey 1995). Oregon arrowtooth flounder had length at 50% mature of 44 cm for females and 29 cm for males (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 were found in the northeastern Gulf, off Prince William Sound, off Cape St. Elias, and Icy Bay.

A newer study was conducted in 2008 that examined maturity-at-age, and is considered a better estimate of maturity because it avoids the problem of estimating age at length (Stark 2008). In this study, a sample of 301 fish was made in February 2002 and a separate collection (226 fish) in July 2003, both in 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 *y* intercept was -9.6183. Fish mature at a slightly younger age in the 2008 study compared to the 1997 study (Figure 5).

Likelihood weights and other model structure
Likelihood weights have not changed since the previous full assessment in 2013. Weights used on the likelihood values were 1.0 for the survey length, survey age data and the survey biomass (simply implying that the variances and sample sizes specified for each data component were approximately correct). A weight of 0.25 was used for the fishery length data. The fishery length data is essentially from bycatch and in some years has low sample sizes. A lower weight on the fishery length data allows the model to fit the survey data components better. The estimated length at age relationship is used to convert population age compositions to estimated size compositions. The current model estimated size compositions using a fixed length-age transition matrix estimated from the 1977 through 2015 age data (Tables 9a, 9b). The distribution of lengths within ages was assumed to be normal with cv's estimated from the length at age data of 0.06 for younger ages and 0.10 for older ages. Size bins were 0-9cm, 10-15cm, and 2 cm starting at 16 cm, 3 cm bins from 40 cm to 69cm, one 5 cm bin from 70 cm to 74 cm, then a 75+cm bin. There were 20 age bins from 1-20 by 1 year interval, and ages over 20 accumulated in the last bin, 21+.

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 (see Tables A.1 and A.2).

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. These fishing mortality rates are assumed to be the same for each sex.

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 6). 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.

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 1000.

Results

Model evaluation
A new generalized model was introduced in this stock assessment. The generalized ATF model can be used to run either the GOA or the BSAI stock assessments. The model can accept data from any number of surveys and can accommodate a range of ages. Model 2.4 produced very similar results to the 2013 GOA model (Model 0); for example, the fit to survey biomass is nearly identical (Figure 7), as are the fits to fishery and survey selectivities (Figure 8). The models are not identical, but the generalized model is considered a better model. It provides a lower estimate of survey likelihood; i.e. a better fit to the survey

data. Model 0 contained a plus group age frequency accumulation error. The likelihood components for Model 0 and Model 2.4 are shown in Table 10.

Last year's model was updated with 2015 data from survey ages and lengths, survey estimates of biomass, and fishery length frequencies (Model 1). Model 2.1 and 1.0 estimates of female spawning biomass and total (age 3+) biomass estimates show similar values and trends (Figure 18). Model 1.0 suggests a decline in the population size during the 1990's and a decrease in spawning biomass approximately 1998-2002. Model 2.1 estimates less of a decline during this time period, possibly due to the inclusion of more age and length frequency data.

The generalized model was run with ages 1-21+ and ages 3-15+. The differences in female spawning biomass and total (3+ biomass) are shown in Figure 19. In the 2013 assessment, selectivity was estimated for the first 9 ages, up to age 11. With more ages in the model, it became possible to estimate selectivity for more ages, as in the BSAI assessment. Model 2.1 estimates selectivity for ages 1-19, similar to the BSAI assessment. This resulted in a higher likelihood value, even though it increased the number of parameters to be estimated by 16 (Figure 20). The updated maturity ogive (Stark 2008) did not change the overall estimate of biomass, but it did increase the estimate of female spawning biomass (Figure 21).

Overall, the model fit size and age data well, although there is some overestimation of medium to large female fish, particularly from the survey (Figure 9). This was also an issue with the past few GOA ATF assessments. Fishery length frequency data is not highly weighted because catches of arrowtooth flounder are low compared to their overall abundance. Fits to the size composition data from the fishery are shown in Figure 9 for females and Figure 10 for males. The survey length data for both fits well (Figures 12 and 13). The model also provides a good fit to survey age data for both females and males (Figures 14 and 15). The previous model incorporated ages 3-15+ because of the difficulty fitting the younger ages. Figures 12, 13, 14, and 15 include the fit to the data of ages 3-15+ for the survey length and age data (Model 1.0). The inclusion of ages 1-21+ does not appear to negatively affect the fit to the data.

Both the model and the survey indicate that ATF biomass has been relatively constant since 2009 (Figure 17). Survey estimates of biomass in 2013 suggested a decline in biomass, but the model does not indicate a significant decline in recent years. The 2015 survey estimate of biomass is increased from 2013, and the model fits the data well for that year (Figure 17). Biomass estimates for the current year are similar to 2013 (Figure 18), but the current year provides a smoother fit to the data, likely due to the inclusion of more age data.

Time series results

The female spawning biomass has been consistently increasing throughout the time period in the 2007-2015 assessments (Figure 22). Female spawning biomass in 2015 was estimated at 1,221,500 t, a <3% increase from the projected 2015 biomass (fishing at the average 5 year F) of 1,189,120 t from the 2013 assessment (Table 1). The model estimates of age 1+ biomass increased from a low of 390,626 t in 1970 to a high of 2,109,820 in 2009 and slight decrease to 2,093,010 t in 2015 (Table 1 and Figure 22).

Age 1 recruitment estimates from the MCMC simulation are shown in Figure 23. Recruitment peaked in 2000 at $1.5x10^9$, again in 2005 and 2006 over $1.0x10^9$, and $1.5x10^9$ and $1.4x10^9$ in 2013 and 2014 respectively; however, recent recruits have higher uncertainty than past recruits.

Age frequency data from surveys is available between 1977 and 2013 (Tables 9a and 9b). That data was used to construct the new age length transition matrix used in the model. Only NMFS RACE GOA survey age frequency data was used to construct the age likelihood in the assessment model, years 1984, 1987, 1990, 1993, 1996, 1999, 2001, 2003, 2005, 2007, 2009, 2011, 2013. Length frequency data is available from NMFS GOA surveys since 1975 (Table 11).

Reference fishing mortality rates and yields
Reliable estimates of biomass, $B_{35\%}$, $F_{35\%}$ and $F_{40\%}$, are available for arrowtooth flounder. Given that the current biomass is greater than $B_{40\%}$, arrowtooth flounder 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 $F_{40\%}$.

Reference points for the 2015 assessment are summarized in Table 15. ABC for 2016 using $F_{40\%}$ = 0.171 (2013 assessment $F_{40\%}$ = 0.172) was estimated at 186,188 t (2015 ABC was 192,921 t). OFL for 2016 at $F_{35\%}$ = 0.204 (2013 assessment $F_{35\%}$ = 0.204) was estimated at 219,430 t. Model estimates of fishing mortality have been well below target rates (Figure 25). The highest fishing mortality was estimated to be 0.044 in 1973 since 1961 and have ranged from 0.014 to 0.031 from 1995 to 2015 (Table 1).

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 1,199,880 t in 2015. $B_{35\%}$ (equilibrium spawning biomass with fishing at $F_{35\%}$) was estimated at 347,295 t and $B_{40\%}$ was 396,909 t.

Retrospective analysis
A retrospective analysis was performed, in which data was peeled back and spawning bimass was estimated or the years 2007, 2009, 2011, 2013, and 2015. There was no clear pattern that would indicate a bias. Mohn's rho was calculated to be 0.38.

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 2013 numbers at age estimated in the assessment (Table 15). This vector is then projected forward to the beginning of 2014 using the schedules of natural mortality and selectivity described in the assessment and the best available estimate of total (year-end) catch for 2013. 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 1000 times to obtain distributions of possible future stock sizes, fishing mortality rates, and catches. The 2015 total catch (20,324 t) was estimated using the catch as of October 29, 2015 (16,964 t) plus the average November and December catches for 2012-2014 (3,360 t). Catch in 2014 was estimated at 20,324 t as well.

Five of the seven standard scenarios will be used in an Environmental Assessment prepared in conjunction with the final SAFE. These five scenarios, which are designed to provide a range of harvest alternatives that are likely to bracket the final TAC for 2016, are as follows ("*max* F_{ABC}" refers to the maximum permissible value of F_{ABC} under Amendment 56):

Scenario 1: In all future years, F is set equal to *max* F_{ABC}. (Rationale: Historically, TAC has been constrained by ABC, so this scenario provides a likely upper limit on future TACs.)

Scenario 2: In all future years, F is set equal to 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, *F* is set equal to 50% of max F_{ABC}. (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 recent 5 year average *F*. (Rationale: For some stocks, TAC can be well below ABC, and recent average *F* may provide a better indicator of F_{TAC} than F_{ABC}.)

Scenario 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 were estimated using $F_{40\%}$, F equal to the average F from 2011 to 2015 (F=0.021), F equal to one half $F_{40\%}$, and F=0 from 2015 to 2028 (Table 15). Under scenario 6 above, the year 2016 female spawning biomass is 1,160,800 t and the year 2028 spawning biomass is 396,853 t, above the $B_{35\%}$ level of 347,295 t. For scenario 7 above, the year 2028 spawning biomass is 399,500 t, also above $B_{35\%}$. Fishing at $F_{40\%}$, female spawning biomass would still be above $B_{40\%}$ (396,909 t) in year 2028 (454,110 t, Figure 26). Female spawning biomass would be expected to decrease by about 40% over the next 12 years, if fishing continues at the last 5-year average fishing mortality (0.021) (Table 15, Figure 27, scenario 4).

ABC and OFL for 2016 and 2017

ABC for 2016 using $F_{40\%} = 0.171$ was estimated at 186,188 t. The projection model was used to estimate the 2017 ABC using an estimated 2016 catch of 20,324 t (similar to the 2015 estimated total catch) at 189,332 t. In the 2013 update assessment, the 2015 ABC using $F_{40\%} = 0.172$ was estimated at 192,921 t (http://www.afsc.noaa.gov/REFM/Stocks/assessments.htm). An ABC of 186,188 t and an OFL of 219,430 t is recommended for 2016 and an ABC of 189,332 t and an OFL of 196,774 t is recommended for 2017. The stock is not currently being subjected to overfishing, as determined by comparing the complete 2013 and 2014 catch to the specified OFL for that year. The stock is not overfished, and is not approaching a condition of being overfished.

Ecosystem Considerations

See Appendix B.

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 2009 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.

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Tables

Table 1new. Estimated total (age 3+) biomass (t), female spawning biomass (FSB; t) and age 3 recruits (1,000's), and fishing mortality (M), from the current and the 2013 assessment.

Year	3+biomass 2013 assessment	3+biomass 2015 assessment	1+ biomass 2015 assessment	FSB 2013 assessment	FSB 2015 assessment	Recruits 2013 (age 3)	Recruits 2015 (age 3)	2015 Estimated M
1961	370,329	411,714	421,726	204,146	286,489	123,787	84,866	0.002
1962	379,715	404,984	415,135	209,692	277,722	125,733	87,689	0.002
1963	387,133	399,727	409,843	213,512	269,440	122,286	88,936	0.002
1964	394,231	395,480	405,378	216,646	262,314	128,019	88,654	0.002
1965	400,459	391,630	401,810	219,795	256,714	126,930	86,667	0.002
1966	405,499	388,645	399,127	223,165	252,571	123,629	89,139	0.011
1967	407,708	384,814	395,981	225,041	247,901	122,990	91,727	0.01
1968	410,399	383,254	394,160	227,074	244,135	127,253	97,855	0.008
1969	414,747	383,141	393,039	229,620	241,375	134,157	95,661	0.006
1970	421,869	382,286	390,626	232,369	239,584	147,043	86,952	0.009
1971	430,571	377,148	406,022	234,438	238,254	155,514	70,293	0.005
1972	457,236	405,216	424,045	237,093	238,422	254,336	254,312	0.02
1973	497,803	430,311	466,379	237,714	236,487	325,322	162,653	0.044
1974	557,048	477,534	532,107	235,607	231,192	428,190	313,305	0.021
1975	649,390	575,478	606,912	240,520	235,161	539,020	481,054	0.011
1976	718,002	659,277	682,328	253,882	253,472	318,662	276,475	0.011
1977	792,910	716,282	744,378	278,593	285,454	402,080	201,244	0.027
1978	846,051	757,606	788,488	313,336	328,185	330,606	245,705	0.021
1979	890,639	797,594	832,184	361,410	385,082	319,384	270,005	0.017
1980	935,299	841,227	887,070	413,907	437,470	360,684	301,468	0.016
1981	998,827	902,887	948,508	459,686	471,790	502,856	401,555	0.014
1982	1,066,840	972,606	1,009,880	497,580	496,345	506,702	400,727	0.009
1983	1,107,090	1,032,613	1,078,370	530,027	523,650	316,124	325,425	0.011
1984	1,140,760	1,095,104	1,145,360	559,279	555,804	345,846	400,215	0.006
1985	1,195,780	1,167,516	1,227,350	593,828	598,683	503,604	438,956	0.002
1986	1,263,590	1,258,502	1,323,860	635,418	647,268	555,276	523,374	0.002
1987	1,351,500	1,365,064	1,410,050	674,708	693,396	657,518	575,322	0.007
1988	1,421,270	1,437,984	1,487,500	694,776	736,291	583,132	393,448	0.007
1989	1,482,620	1,498,026	1,559,090	715,714	785,333	530,162	432,170	0.003
1990	1,546,350	1,572,318	1,621,360	745,209	846,525	580,394	536,564	0.009
1991	1,583,330	1,621,898	1,667,580	781,945	903,970	473,564	430,062	0.011
1992	1,604,780	1,652,656	1,710,410	824,149	950,486	444,956	398,533	0.016
1993	1,624,790	1,687,160	1,736,810	862,202	982,362	511,232	506,951	0.016
1994	1,625,260	1,709,186	1,746,870	891,949	1,008,600	420,126	436,468	0.023
1995	1,599,820	1,696,099	1,736,300	902,348	1,022,980	386,532	329,712	0.018
1996	1,572,920	1,678,717	1,723,440	909,438	1,034,910	370,584	351,534	0.022
1997	1,549,700	1,659,367	1,700,170	909,872	1,041,290	423,070	392,239	0.016
1998	1,547,510	1,641,716	1,692,380	909,845	1,048,020	509,838	356,057	0.013
1999	1,569,510	1,641,961	1,703,410	906,416	1,046,640	598,568	442,362	0.016
2000	1,616,640	1,663,951	1,725,840	891,009	1,034,220	738,604	538,218	0.025
2001	1,687,350	1,690,399	1,794,460	867,481	1,014,920	857,380	536,344	0.021
2002	1,814,410	1,800,278	1,858,460	856,439	1,005,260	1,073,254	917,591	0.022
2003	1,893,420	1,873,053	1,931,650	856,834	1,006,340	688,878	509,499	0.03
2004	1,930,520	1,914,979	1,970,000	871,288	1,019,770	549,454	513,617	0.015
2005	1,974,370	1,951,748	2,010,430	921,729	1,065,840	592,906	481,475	0.018
2006	2,016,730	1,973,511	2,040,080	986,829	1,124,890	699,976	512,929	0.025
2007	2,053,730	1,995,488	2,073,070	1,049,570	1,172,450	737,986	581,478	0.022
2008	2,108,760	2,043,244	2,090,960	1,094,860	1,198,700	834,996	683,548	0.025
2009	2,112,760	2,046,594	2,109,820	1,116,670	1,206,030	518,210	415,766	0.021
2010	2,102,280	2,058,406	2,098,620	1,134,860	1,214,950	485,818	556,852	0.02
2011	2,065,380	2,035,682	2,070,550	1,156,810	1,231,940	399,078	353,014	0.026
2012	2,013,270	1,975,448	2,028,960	1,177,960	1,245,960	422,986	302,993	0.017
2013	1,994,960	1,940,658	2,033,570	1,200,320	1,256,950	604,414	463,478	0.018
		1,980,403	2,073,910		1,252,250		813,624	0.031
		2,049,775	2,093,010		1,221,500		825,564	0.014

Table 2. Percent of the Gulf of Alaska stock of arrowtooth flounder retained by commercial fishing operations 1991-2015.

Year	Percent retained
1991	10%
1992	2%
1993	6%
1994	2%
1995	12%
1996	24%
1997	18%
1998	15.8%
1999	26.3%
2000	43.2%
2001	33.2%
2002	49.2%
2003	57.3%
2004	56.5%
2005	60.0%
2006	57.8%
2007	59.2%
2008	69.3%
2009	54.1%
2010	72.8%
2011	76.8%
2012	74.3%
2013	71.4%
2014	90.5%
2015[1]	88.8%

[1]Data obtained October 29, 2015. Source: AKFIN database (https://akfinbi.psmfc.org/analytics/).

Table 3a. Catch, ABC, OFL and TAC for arrowtooth flounder in the Gulf of Alaska from 1964 to 1992. Values are in metric tons.

Year	Catch	ABC	OFL	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	303,889	427,220	25,000

Table 3b. Catch, ABC, OFL and TAC for arrowtooth flounder in the Gulf of Alaska from 1993 to October 29, 2015. Values are in metric tons. Arrowtooth flounder ABC was separated from Flatfish ABC after 1990.

Year	Catch	ABC	OFL	TAC
1993	15,559	321,287	451,690	30,000
1994	23,560	236,240	275,930	30,000
1995	18,428	198,130	231,420	35,000
1996	22,583	198,130	231,420	35,000
1997	16,319	197,840	280,800	35,000
1998	12,975	208,337	295,970	35,000
1999	16,207	217,106	308,875	35,000
2000	24,252	145,361	173,915	35,000
2001	19,964	148,151	173,546	38,000
2002	21,231	146,264	171,057	38,000
2003	29,994	155,139	181,394	38,000
2004	15,304	194,900	228,134	38,000
2005	19,770	194,900	228,134	38,000
2006	27,653	177,800	207,700	38,000
2007	25,494	184,008	214,828	43,000
2008	29,293	226,470	266,914	43,000
2009	24,937	221,512	261,022	43,000
2010	24,268	215,882	254,271	43,000
2011	30,903	213,150	251,068	43,000
2012	20,713	212,882	250,100	103,300
2013	18,315	210,451	247,196	103,300
2014	34,327	195,358	229,248	103,300
2015	16,964	189,556	222,160	103,300

Table 4. Biomass estimates and standard errors from bottom trawl surveys, 1961-2015.

Survey	Biomass(t)	Standard Error	No. hauls	Maximum Depth(m)
IPHC 1961-1962	283,799	61,515	1,172	
NMFS groundfish 1973-1976	145,744	33,531	403	
NMFS triennial 1984	1,112,215	71,209	930	1,000
NMFS triennial 1987	931,598	74,673	783	1,000
NMFS triennial 1990	1,907,177	239,150	708	500
NMFS triennial 1993	1,551,657	101,160	776	500
NMFS triennial 1996	1,639,632	114,792	804	500
NMFS triennial 1999	1,262,151	99,329	764	1,000
NMFS 2001	1,621,892*	178,408	489	500
NMFS 2003	2,819,095	372,326	809	700
NMFS 2005	1,899,778	125,788	839	1,000
NMFS 2007	1,939,055	150,059	820	1,000
NMFS 2009	1,772,029	159,402	823	1,000
NMFS 2011	1,747,339	179,801	670	1,000
NMFS 2013	1,290,727	130,348	548	700
NMFS 2015	1,659,128	133,986	772	1,000

Table 5. The number of fisheries length observations taken by fisheries observers, by year. Historical foreign and current domestic data were downloaded for this stock assessment (downloaded October, 2015).

	Number of observations	
Year	Model 2 Updated data	Model 0 data file
1975	121	0
1976	0	0
1977	868	866
1978	5,491	5,491
1979	9,499	6,079
1980	4,500	3,535
1981	2,062	1,908
1982	19,139	0
1983	14,963	0
1984	7,149	7,149
1985	671	668
1986	194	194
1987	763	750
1988	211	211
1989	0	0
1990	217	204
1991	5,892	5,862
1992	198	142
1993	1,223	597
1994	121	0
1995	2,628	720
1996	889	1,045
1997	2,999	1,055
1998	472	263
1999	2,642	2,521
2000	6,351	6,153
2001	6,266	5,740
2002	8,275	6,829
2003	15,052	15,012
2004	4,961	4,076
2005	7,073	5,614
2006	8,413	6,426
2007	10,004	8,143
2008	9,271	9,001
2009	8,406	7,840
2010	7,600	7,084
2011	11,282	9,136
2012	9,583	7,188
2013	8,186	3,328
2014	16,346	0
2015	10,568	0

Table 6. Catches from NMFS research cruises from 1977 to 2013.

Year	Catch (t)	Year	Catch (t)
1977	29.3	1996	154.6
1978	30.6	1997	40.6
1979	38.9	1998	115.6
1980	36.7	1999	101.5
1981	151.5	2000	24.0
1982	90.2	2001	83.9
1983	61.4	2002	11.0
1984	223.9	2003	183.6
1985	149.4	2004	0.0
1986	179.0	2005	124.6
1987	297.4	2006	0.0
1988	22.0	2007	133.0
1989	64.1	2008	0.0
1990	228.1	2009	111.6
1991	27.7	2010	16.2
1992	32.1	2011	101.9
1993	255.4	2012	7.5
1994	36.7	2013	68.4
1995	173.5		

Table 7. Catch (t) of arrowtooth from halibut fisheries by area and year (2001-2010).

	WGOA (610)	CGOA-Shumagin (620)	CGOA-Kodiak/PWS (630)	EGOA-Yakutat (640)	EGOA-Southeast (650)	Southeast Inside (659)	Total
2001	72.4	113.8	158.8	30.5	46.1	140.3	561.9
2002	57.8	131.8	173	30.8	42.1	138.6	574.1
2003	80.2	94.8	56	15.6	23.6	155.4	425.6
2004	120	112.5	92.2	12.9	25.6	202	565.2
2005	125.1	129.4	104.5	16	33.2	207.5	615.7
2006	93.7	102.7	79	25.4	46.3	262.7	609.8
2007	64.1	51.9	144.8	13.4	19.4	165	458.6
2008	64.3	112.1	185.1	29.4	32.9	162.5	586.3
2009	25.4	69.3	158.6	38.3	32.6	114.1	438.3
2010	25.5	73.3	125.3	41	9	39.2	313.3

Table 8. Survey biomass estimates (t) for 1993 to 2015 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	Central	Eastern
1993	212,332	1,117,361	222,015
1996	202,594	1,176,714	260,324
1999	143,374	845,176	273,490
2001	188,100	1,181,848	251,943*
2003	341,620	2,198,829	282,379
2005	215,287	1,441,111	243,381
2007	263,856	1,437,886	237,313
2009	285,427	1,201,756	284,846
2011	225,683	1,175,072	346,584
2013	205,752	763,845	321,130
2015	237,919	910,561	510,649

Table 9a. Female age data from NMFS GOA surveys 1977 through 2013. The numbers are normalized, and add to 1 within each year.

Females	N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1977	1454	0	0	0.02	0.03	0.11	0.13	0.17	0.1	0.12	0.12	0.09	0.05	0.02	0.03	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1978	2659	0	0.02	0.11	0.21	0.17	0.14	0.12	0.07	0.06	0.03	0.02	0.01	0.01	0.01	0.02	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1979	3595	0	0	0.01	0.15	0.08	0.11	0.08	0.13	0.11	0.08	0.08	0.09	0.01	0.02	0.02	0.01	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	593	0	0.09	0.13	0.11	0.17	0.2	0.19	0.07	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	5051	0	0.01	0.07	0.11	0.11	0.15	0.12	0.13	0.08	0.08	0.04	0.04	0.03	0.01	0.01	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1990	1548	0	0.02	0.04	0.05	0.11	0.1	0.07	0.09	0.07	0.05	0.09	0.06	0.04	0.04	0.03	0.02	0.05	0.03	0.01	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0
1991	1021	0	0	0	0.03	0.05	0.14	0.17	0.16	0.19	0.21	0.05	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1993	6071	0	0.02	0.04	0.04	0.05	0.07	0.08	0.08	0.11	0.11	0.06	0.07	0.08	0.05	0.03	0.03	0.04	0.03	0.01	0.01	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	547	0	0	0.02	0.02	0.18	0.21	0.19	0.16	0.12	0.07	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	4121	0	0.02	0.05	0.06	0.07	0.08	0.08	0.09	0.11	0.14	0.08	0.08	0.06	0.05	0.02	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1998	1328	0	0.02	0.06	0.07	0.07	0.06	0.1	0.1	0.16	0.11	0.12	0.12	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1999	4297	0	0.02	0.05	0.06	0.06	0.06	0.06	0.07	0.06	0.06	0.08	0.11	0.08	0.06	0.06	0.03	0.04	0.01	0.02	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0
2001	7180	0	0.03	0.03	0.05	0.05	0.04	0.05	0.04	0.04	0.05	0.06	0.06	0.07	0.11	0.1	0.07	0.06	0.04	0.02	0.01	0.01	0	0.01	0	0	0	0	0	0	0	0	0	0	0
2003	5329	0.01	0.02	0.02	0.05	0.05	0.06	0.05	0.04	0.04	0.04	0.05	0.06	0.07	0.06	0.06	0.08	0.05	0.07	0.04	0.04	0.03	0.01	0	0	0	0	0	0	0	0	0	0	0	0
2004	2464	0.01	0.04	0.07	0.08	0.11	0.1	0.09	0.12	0.1	0.07	0.05	0.09	0.01	0.01	0.01	0.03	0	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0
2005	3456	0	0.02	0.03	0.03	0.07	0.07	0.1	0.07	0.04	0.03	0.08	0.06	0.05	0.04	0.07	0.08	0.03	0.05	0.01	0.03	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0
2007	4231	0	0.03	0.03	0.04	0.04	0.06	0.05	0.07	0.05	0.04	0.04	0.03	0.07	0.04	0.02	0.05	0.09	0.05	0.04	0.04	0.02	0.03	0.04	0.01	0.02	0	0	0	0	0	0	0	0	0
2009	4202	0	0.03	0.03	0.05	0.05	0.05	0.06	0.05	0.05	0.08	0.03	0.05	0.04	0.06	0.04	0.05	0.05	0.03	0.05	0.04	0.02	0.03	0.04	0	0.02	0	0.01	0	0.01	0	0	0	0	0
2010	4648	0	0.02	0.03	0.06	0.1	0.06	0.1	0.06	0.07	0.05	0.06	0.04	0.04	0.04	0.05	0.03	0.02	0.04	0.03	0.03	0.02	0.02	0.01	0	0.02	0.01	0	0	0	0	0	0	0	0
2011	4801	0	0.02	0.03	0.04	0.04	0.05	0.04	0.05	0.05	0.04	0.06	0.07	0.03	0.07	0.04	0.06	0.05	0.04	0.06	0.05	0.02	0.02	0.01	0.01	0.02	0.01	0	0.01	0	0	0	0	0	0
2012	5549	0	0.01	0.03	0.04	0.06	0.11	0.14	0.11	0.14	0.1	0.08	0.05	0.05	0.02	0.02	0.01	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2013	3705	0.01	0.03	0.05	0.04	0.06	0.05	0.05	0.06	0.07	0.04	0.04	0.09	0.07	0.07	0.06	0.04	0.04	0.03	0.03	0.01	0.02	0.02	0.01	0	0.02	0	0	0	0	0	0	0	0	0

Table 9b. Male age data from NMFS GOA surveys 1977 through 2013. The numbers are normalized, and add to 1 within each year.

Males	N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1977	499	0	0	0.01	0.06	0.3	0.32	0.17	0.11	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1978	1570	0	0.04	0.16	0.28	0.21	0.13	0.13	0.04	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1979	1588	0	0.01	0.06	0.3	0.16	0.16	0.16	0.07	0.06	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	468	0	0.08	0.13	0.09	0.25	0.21	0.19	0.03	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	3543	0	0.01	0.13	0.22	0.19	0.15	0.11	0.08	0.04	0.01	0.02	0.01	0.02	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1990	505	0	0.08	0.12	0.16	0.15	0.14	0.12	0.03	0.05	0.04	0.07	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1991	317	0	0	0.04	0.06	0.16	0.21	0.38	0.1	0.06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1993	2418	0	0.06	0.11	0.07	0.11	0.19	0.11	0.1	0.07	0.05	0.03	0.05	0.02	0.01	0.01	0.01	0	0.01	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	235	0	0.02	0.06	0.05	0.11	0.2	0.21	0.31	0	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	1884	0	0.04	0.08	0.09	0.12	0.15	0.09	0.14	0.06	0.05	0.06	0.06	0.01	0.01	0.02	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1998	317	0	0.05	0.26	0.19	0.16	0.06	0.18	0.05	0	0.06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1999	2043	0	0.04	0.09	0.11	0.1	0.07	0.09	0.09	0.06	0.06	0.05	0.08	0.06	0.03	0.04	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2001	2593	0.01	0.09	0.09	0.12	0.11	0.08	0.06	0.07	0.05	0.07	0.05	0.07	0.04	0.03	0.01	0.04	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2003	2113	0.02	0.06	0.06	0.12	0.09	0.1	0.07	0.08	0.03	0.07	0.05	0.06	0.05	0.02	0.05	0.04	0.02	0.01	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2004	675	0.01	0.12	0.14	0.19	0.16	0.14	0.08	0.08	0.03	0	0.02	0	0	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2005	1596	0.01	0.04	0.09	0.07	0.09	0.18	0.08	0.04	0.05	0.08	0.05	0.07	0.04	0.04	0.05	0.01	0.01	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2007	1745	0	0.06	0.08	0.12	0.08	0.08	0.08	0.09	0.04	0.02	0.03	0.03	0.04	0.04	0.03	0.03	0.03	0.01	0.03	0.03	0	0.01	0	0.01	0	0	0	0	0	0	0	0	0	0
2009	1764	0.01	0.06	0.06	0.11	0.1	0.11	0.11	0.05	0.05	0.05	0.04	0.03	0.04	0.02	0.05	0	0	0	0.01	0.02	0.04	0.01	0	0	0	0	0	0	0	0	0	0.02	0	0
2010	2373	0	0.03	0.06	0.08	0.15	0.08	0.11	0.05	0.03	0.03	0.02	0.06	0.02	0.04	0.02	0	0.01	0.02	0.02	0.01	0.03	0.02	0.01	0.01	0.04	0.01	0	0	0	0	0.01	0.01	0	0.03
2011	2268	0.01	0.04	0.07	0.09	0.06	0.1	0.1	0.06	0.04	0.02	0.01	0.06	0.04	0.06	0.02	0.04	0.03	0.01	0.01	0.02	0.03	0.03	0.02	0.01	0.01	0.01	0	0	0	0	0	0	0	0
2012	1982	0	0.02	0.06	0.12	0.11	0.19	0.14	0.16	0.07	0.04	0.04	0.03	0.01	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2013	1796	0.01	0.06	0.1	0.07	0.09	0.06	0.06	0.15	0.05	0.03	0.07	0.03	0.06	0.02	0.02	0.02	0.03	0.01	0.02	0.01	0.01	0.02	0	0	0	0	0	0	0	0	0	0	0	0

Table 10. Likelihood components for Model 2.4 and Model 0.

Likelihood component	Model 2.4	Model 0
Survey	42.3609	44.0099
Fishery lengths	1251.84	1226.11
Survey lengths	64.3628	63.1612
Survey ages	182.044	164.133
Penalty on fishing mortality	33.6675	33.8715
Catch	0.0112175	0.0120077
Recruitment	35.2828	33.552
Female fishery selectivity	2.41959	2.44736
Male fishery selectivity	3.03409	2.9976

Table 11. Length data (cm) from NMFS GOA surveys in 1984 through 2015. The numbers are percentages, where the numbers add to 100 within a year for each sex.

Female	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	0.12	0.23	0.53	1.19	1.62	2.12	2.36	3.17	4.73	4.26	4.72	5.45	7.03	13.25	11.28	7.60	6.73	5.38	3.99	3.32	3.21	3.43	2.70	1.38	0.21
1985	0.00	0.30	0.03	0.51	1.89	2.59	1.58	1.01	1.69	3.18	3.18	4.04	4.81	5.25	9.45	13.59	12.29	7.35	6.06	4.26	3.53	3.14	3.56	3.75	2.58	0.36
1986	0.00	0.00	0.00	0.00	0.13	0.67	1.33	3.47	4.00	6.93	9.07	9.33	7.73	6.27	7.47	9.33	7.07	9.73	5.33	2.00	1.33	2.13	3.07	2.00	1.33	0.27
1987	0.00	0.03	0.12	0.42	1.30	1.56	1.57	2.88	5.84	5.91	4.94	5.50	5.78	5.09	6.92	7.96	10.15	11.36	7.99	3.91	2.26	2.01	1.89	2.39	1.86	0.36
1989	0.00	0.08	0.21	0.53	1.12	2.08	2.59	2.56	3.02	3.04	3.73	4.14	4.86	5.97	11.15	10.53	8.80	10.18	9.39	7.17	3.84	1.74	1.15	0.61	0.93	0.56
1990	0.00	0.13	0.21	0.86	1.62	2.10	2.87	3.44	4.08	5.05	4.72	4.81	5.27	5.55	9.36	9.53	8.92	7.75	7.49	5.92	3.64	2.17	1.36	0.90	1.44	0.80
1993	0.00	0.14	0.28	1.29	2.50	2.85	2.77	2.88	3.15	3.49	3.59	3.93	3.98	4.41	7.35	8.16	8.75	10.17	10.84	8.16	4.40	2.42	1.59	1.23	1.11	0.56
1996	0.01	0.21	0.57	1.89	3.37	4.38	3.39	2.52	2.82	3.41	3.51	3.71	4.32	4.74	7.45	7.35	7.37	9.47	10.94	7.69	3.99	2.36	1.60	1.10	1.26	0.60
1999	0.02	0.21	0.54	2.57	4.11	3.29	2.82	4.08	4.70	4.62	4.60	4.83	4.72	4.25	5.77	5.23	6.20	7.40	8.98	8.55	5.17	2.90	1.78	1.25	0.95	0.44
2001	0.02	0.18	0.55	3.04	7.10	8.20	4.74	2.90	3.53	4.24	4.08	3.90	4.22	4.06	6.08	6.33	6.28	6.32	6.37	5.95	4.38	2.61	1.73	1.32	1.36	0.53
2003	0.01	0.59	0.81	2.29	5.06	5.14	4.43	4.53	5.24	6.07	6.46	6.33	6.25	5.02	5.67	4.97	4.75	5.53	6.39	5.79	3.66	2.07	1.00	0.66	0.83	0.45
2005	0.01	0.57	0.75	1.43	2.23	2.39	3.25	4.22	4.72	4.66	5.00	5.58	5.97	6.56	9.65	8.60	7.45	6.24	6.06	5.50	3.90	2.23	1.23	0.72	0.70	0.40
2007	0.02	0.13	0.64	2.85	4.95	3.79	3.02	4.04	5.15	5.07	3.98	3.30	3.20	3.64	6.05	6.94	9.00	11.49	9.22	5.45	3.34	1.96	1.10	0.71	0.55	0.40
2009	0.01	0.24	0.77	3.66	4.99	3.64	2.97	4.02	5.20	5.46	4.83	4.59	4.42	4.53	5.84	4.96	5.72	9.39	11.03	6.57	3.31	1.65	0.89	0.55	0.51	0.25
2011	0.02	0.19	0.17	0.58	1.85	2.91	2.84	2.64	3.58	4.24	4.10	4.65	5.16	5.24	8.38	8.18	8.52	9.28	10.52	7.97	4.34	2.00	1.08	0.65	0.64	0.26
2013	0.04	0.68	0.30	0.69	2.40	4.68	5.05	3.36	3.35	3.69	3.50	2.77	3.11	3.54	6.72	7.96	10.59	11.95	9.98	7.70	4.39	1.80	0.74	0.38	0.43	0.22
2015	0.01	0.24	0.33	0.57	1.68	3.61	4.72	6.11	7.18	8.76	7.18	4.63	3.87	3.72	4.99	5.16	6.76	8.91	9.32	6.40	3.38	1.33	0.59	0.27	0.20	0.08
Male	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	0.38	0.49	1.37	2.43	3.45	4.09	5.18	7.22	8.39	7.70	8.55	11.98	13.84	14.03	6.23	2.39	1.07	0.37	0.24	0.16	0.12	0.16	0.13	0.03	0.02
1985	0.00	0.40	0.02	0.80	4.52	5.58	2.80	2.18	4.81	8.03	10.48	11.59	11.01	11.68	14.45	7.52	3.11	0.62	0.20	0.07	0.07	0.04	0.04	0.00	0.00	0.00
1986	0.00	0.22	0.22	0.00	0.65	2.17	3.04	4.12	4.99	18.66	16.27	10.85	11.93	7.81	9.11	5.21	2.82	1.52	0.22	0.00	0.00	0.00	0.22	0.00	0.00	0.00
1987	0.00	0.19	0.26	0.85	1.85	2.48	2.61	5.17	9.69	9.29	9.49	11.47	9.46	8.96	13.20	9.48	3.54	1.10	0.44	0.20	0.11	0.04	0.06	0.03	0.01	0.01
1989	0.00	0.10	0.40	0.64	0.94	2.38	3.32	3.85	4.49	4.82	5.73	5.43	6.13	10.21	22.84	17.82	8.67	1.84	0.30	0.03	0.03	0.00	0.00	0.00	0.00	0.03
1990	0.00	0.20	0.31	1.35	2.53	2.62	3.75	4.81	5.95	7.18	7.21	7.47	7.79	8.79	16.12	14.41	6.89	1.74	0.51	0.17	0.05	0.05	0.04	0.04	0.01	0.00
1993	0.00	0.23	0.57	2.42	3.85	3.63	3.31	4.19	4.59	4.73	5.06	5.37	6.41	7.80	15.83	16.61	11.29	3.10	0.53	0.21	0.12	0.05	0.06	0.03	0.02	0.00
1996	0.01	0.57	0.99	2.68	5.64	6.07	4.35	3.18	3.67	4.52	5.14	5.41	5.94	6.83	11.99	16.26	11.72	3.94	0.72	0.13	0.11	0.08	0.02	0.02	0.01	0.00
1999	0.05	0.50	1.05	4.33	6.51	4.81	4.11	5.57	6.11	5.70	5.79	5.99	5.74	5.84	9.85	11.93	10.58	4.45	0.77	0.16	0.10	0.02	0.01	0.02	0.01	0.01
2001	0.02	0.40	1.01	5.59	11.92	10.80	5.67	4.34	5.62	5.72	5.37	5.19	5.42	4.74	8.93	8.31	6.73	3.66	0.53	0.02	0.01	0.00	0.00	0.00	0.00	0.00
2003	0.00	1.47	1.15	3.83	7.18	7.49	5.67	5.34	6.81	8.04	8.45	8.01	7.33	5.58	8.37	7.45	4.86	2.18	0.57	0.13	0.04	0.00	0.03	0.00	0.01	0.00
2005	0.02	1.29	1.64	2.71	4.00	4.27	5.54	6.39	6.34	6.08	6.34	6.69	8.39	9.80	14.09	8.56	4.69	2.22	0.67	0.15	0.06	0.04	0.00	0.02	0.01	0.00
2007	0.02	0.22	1.15	4.34	7.04	4.82	4.28	6.17	7.31	6.67	4.74	3.86	4.28	6.39	16.16	14.15	5.43	2.07	0.70	0.12	0.03	0.04	0.02	0.02	0.00	0.00
2009	0.03	0.52	1.60	5.82	6.60	5.16	3.94	5.44	6.70	6.42	5.42	5.26	5.89	6.26	12.29	13.35	6.30	2.23	0.58	0.13	0.02	0.01	0.01	0.00	0.01	0.00
2011	0.01	0.32	0.60	1.14	3.47	4.90	4.03	4.51	6.28	5.82	5.64	6.16	6.96	8.02	15.40	15.15	8.19	2.63	0.61	0.11	0.03	0.01	0.00	0.01	0.01	0.00
2013	0.02	0.48	0.34	1.13	4.11	6.10	5.27	4.71	5.21	5.42	4.05	4.17	5.68	7.20	15.31	17.01	9.48	3.51	0.59	0.15	0.03	0.02	0.01	0.01	0.00	0.00
2015	0.01	0.26	0.42	0.79	2.74	4.46	6.55	7.81	9.68	9.72	5.87	4.86	5.56	5.76	10.75	12.87	8.24	2.95	0.54	0.12	0.02	0.01	0.00	0.01	0.00	0.00

Table 12. Mean length (cm) at age for female arrowtooth flounder from 1977 through 2013.

Females	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
1977			31	34	36	42	43	50	52	56	60	59	61	66	64														
1978	26	24	29	33	37	42	44	47	48	53	55	58	61	62	64	76													
1979		15	32	38	41	45	47	50	53	55	58	61	59	62	65	72	62		80										
1982		21	29	33	36	39	44	49	55																				
1987		24	30	37	43	46	49	51	53	57	59	62	66	65	66	68	70												
1990		23	27	33	37	43	45	49	53	57	59	61	61	66	57	61	74	73	63		70								
1991				38	42	46	52	58	63	67	72	69																	
1993	15	21	27	32	38	40	46	49	54	60	60	63	67	68	69	71	72	75	78	73	81		79						
1994		15	25	35	37	42	46	50	55	59	63																		
1996	14	21	27	33	37	41	46	49	55	58	62	67	67	72	74	72		81		82									
1998	15	18	26	34	41	43	49	52	58	58	64	67	72																
1999	13	20	27	33	39	42	47	51	54	56	60	63	66	66	69	68	70	75	75		54	82							
2001	14	21	28	34	38	44	47	48	53	55	60	61	64	66	68	70	71	76	75	73	81		78						
2003	15	21	26	31	38	42	46	49	53	54	58	62	65	66	65	67	73	72	73	73	72	79		80	78				
2004	13	20	28	36	40	46	49	54	56	60	65	65	68	72	65	68					84								
2005	14	19	25	30	34	41	45	49	55	57	60	61	63	64	66	68	69	72	74	74		87							
2007	13	19	26	31	36	41	44	49	51	53	57	58	63	65	71	63	68	70	66	71	75	71	79	76	75				
2009	12	20	26	31	36	41	47	49	51	53	54	60	63	67	64	64	66	67	71	72	71	71	71		68		84		78
2010	11	17	24	31	37	43	47	51	55	57	61	64	64	66	68	69	75	72	73	74	76	78	82		80	85			
2011	15	20	25	32	36	40	44	46	51	54	57	59	64	64	69	70	68	70	69	72	68	72	76	76	82	83		80	
2012	10	17	24	30	35	41	46	52	53	57	58	63	66	66	70	65	70	73	76	66						74			
2013	14	22	29	34	38	42	46	50	52	56	59	60	63	60	62	69	65	69	68	74	70	74	78		77				

Table 13. Mean length (cm) at age for male arrowtooth flounder from 1977 through 2013.

Males	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1977			31	35	36	39	40	42	47																									
1978		25	30	33	37	41	42	43	44																									
1979		23	32	36	39	41	43	44	46	42																								
1982	13	21	28	32	35	40	42	47	49																									
1987		22	31	36	40	42	44	44	46	50	46	44	48	47																				
1990		24	28	33	37	39	41	44	44	46	47			51																				
1991			35	36	41	45	45	50	48																									
1993	15	21	26	31	35	40	42	46	47	49	47	51	48	40	48	47		52		48														
1994		18	24	31	37	41	44	43		48																								
1996	14	20	28	33	36	40	44	45	48	48	50	54	52	51	52		51																	
1998		17	26	35	40	40	45	47		52																								
1999	13	20	27	32	37	41	42	45	47	49	48	48	51	52	51		48																	
2001	14	21	28	34	38	41	43	45	47	48	48	49	51	52	50	52	52																	
2003	15	21	26	33	35	39	43	47	46	48	48	48	49	53	50	51	51	63	55															
2004	13	20	27	33	38	41	43	46	51		67						53																	
2005	14	19	24	30	35	39	42	44	46	49	48	48	49	51	51	50	51	53																
2007	11	19	24	31	34	38	41	44	43	44	46	45	48	50	47	49	54	53	52	51		52		55										
2009	13	19	26	31	35	39	41	42	46	44	46	47	47	50	52				53	49	51	54										56		
2010	10	18	24	30	34	40	43	44	48	46	47	49	45	48	55		57	55	57	56	58	56	51	58	59	61					65	57		64
2011	15	20	25	31	34	38	41	44	46	46	47	50	48	48	49	50	50	53	50	50	53	54	53	54	54	54								
2012		17	24	30	36	38	41	46	46	46	48	50	49	48																				
2013	14	21	28	33	36	39	43	44	45	46	47	48	50	50	49	51	49	60	52	56	52	51												

Table 14. Summary of results of arrowtooth flounder assessment in the Gulf of Alaska.

Natural Mortality		0.2 females 0.35 males
Age of full (95%) fishery selection		9 females, 9 males
Reference fishing mortalities		
	F_{OFL}	0.204
	F_{ABC}	0.171
Biomass at MSY		N/A
Equilibrium unfished Female Spawning biomass		992,272
$B_{40\%}$ Female Spawning biomass fishing at $F_{40\%}$		396,909
$B_{35\%}$ Female Spawning biomass fishing at $F_{35\%}$		347,295
2016 ABC		186,188
2016 OFL		219,430
Projected 2016 biomass		
	Total(age 3+)	2,103,860
	Spawning	1,175,240

Table 15. Projections of arrowtooth flounder female spawning biomass (1,000s t), future catch (1,000s t) and full selection fishing mortality rates for seven future harvest scenarios.

Scenarios 1 and 2
Maximum ABC harvest permissible

Year	Female spawning biomass	catch	F
2013	1,199,880	20,324	0.018
2014	1,163,340	186,181	0.171
2015	1,029,570	170,578	0.171
2016	951,349	157,035	0.171
2017	898,809	144,369	0.171
2018	833,283	132,976	0.171
2019	744,737	120,922	0.171
2020	662,708	109,282	0.171
2021	600,138	100,469	0.171
2022	553,920	94,515	0.171
2023	519,222	90,152	0.171
2024	492,879	86,699	0.170
2025	471,038	83,667	0.169
2026	454,110	81,226	0.167

Scenario 3
1/2 Maximum ABC harvest permissible

Year	Female spawning biomass	catch	F
2013	1,199,880	20,324	0.018
2014	1,170,170	93,089	0.083
2015	1,111,940	23,612	0.021
2016	1,141,380	23,888	0.021
2017	1,185,460	23,994	0.021
2018	1,204,850	24,004	0.021
2019	1,180,180	23,506	0.021
2020	1,141,210	22,579	0.021
2021	1,105,230	21,686	0.021
2022	1,074,620	21,003	0.021
2023	1,048,470	20,451	0.021
2024	1,026,180	20,004	0.021
2025	1,002,980	19,605	0.021
2026	983,210	19,279	0.021

Scenario 4
Harvest at average F over the past 5 years

Year	Female spawning biomass	catch	F
2015	1,199,880	20,324	0.018
2016	1,173,600	44,227	0.039
2017	1,145,350	95,776	0.085
2018	1,118,220	92,443	0.085
2019	1,107,970	88,802	0.085
2020	1,075,920	85,159	0.085
2021	1,007,730	80,216	0.085
2022	934,873	74,527	0.085
2023	873,791	69,726	0.085
2024	824,821	66,211	0.085
2025	785,281	63,494	0.085
2026	753,226	61,367	0.085
2027	724,124	59,598	0.085
2028	700,126	58,184	0.085

Scenario 5
No fishing

Year	Female spawning biomass	catch	F
2015	1,199,880	0	0.018
2016	1,176,620	0	0
2017	1,186,440	0	0
2018	1,231,400	0	0
2019	1,290,240	0	0
2020	1,323,080	0	0
2021	1,308,800	0	0
2022	1,277,500	0	0
2023	1,246,810	0	0
2024	1,219,750	0	0
2025	1,195,940	0	0
2026	1,175,180	0	0
2027	1,152,080	0	0
2028	1,132,280	0	0

Table 15. (continued).

Scenario 6
Determination of whether arrowtooth flounder are currently overfished
B35=347,295

Year	Female spawning biomass	catch	F
2015	1,199,880	20,324	0.018
2016	1,160,800	219,430	0.204
2017	1,002,000	196,714	0.204
2018	905,825	177,686	0.204
2019	839,605	160,524	0.204
2020	764,214	145,541	0.204
2021	670,732	130,610	0.204
2022	587,675	116,915	0.204
2023	526,382	106,927	0.204
2024	482,440	100,321	0.203
2025	450,417	94,715	0.201
2026	427,368	89,949	0.196
2027	409,625	86,218	0.192
2028	396,853	83,452	0.189

Scenario 7
Determination of whether arrowtooth flounder are approaching an overfished condition
B35=347,295

Year	Female spawning biomass	catch	F
2015	1,199,880	20,324	0.018
2016	1,163,340	186,180	0.171
2017	1,029,570	170,578	0.171
2018	949,366	185,149	0.204
2019	875,773	166,422	0.204
2020	793,458	150,110	0.204
2021	693,504	134,024	0.204
2022	605,064	119,406	0.204
2023	539,553	108,730	0.204
2024	492,395	101,662	0.204
2025	457,907	95,947	0.201
2026	432,837	90,948	0.197
2027	413,473	86,960	0.193
2028	399,500	83,971	0.189

Figures

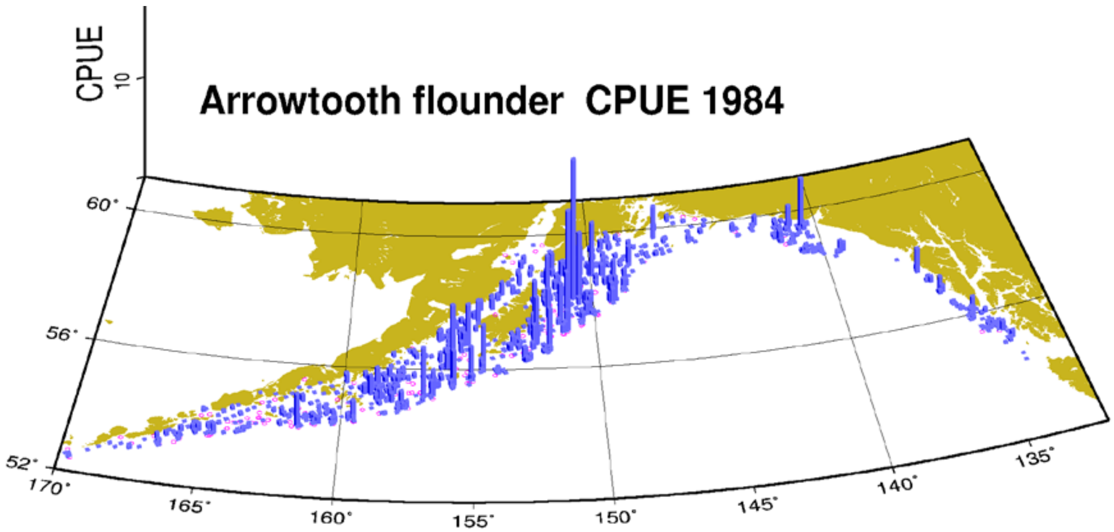

Figure 1a. Arrowtooth flounder 1984 survey cpue by tow.

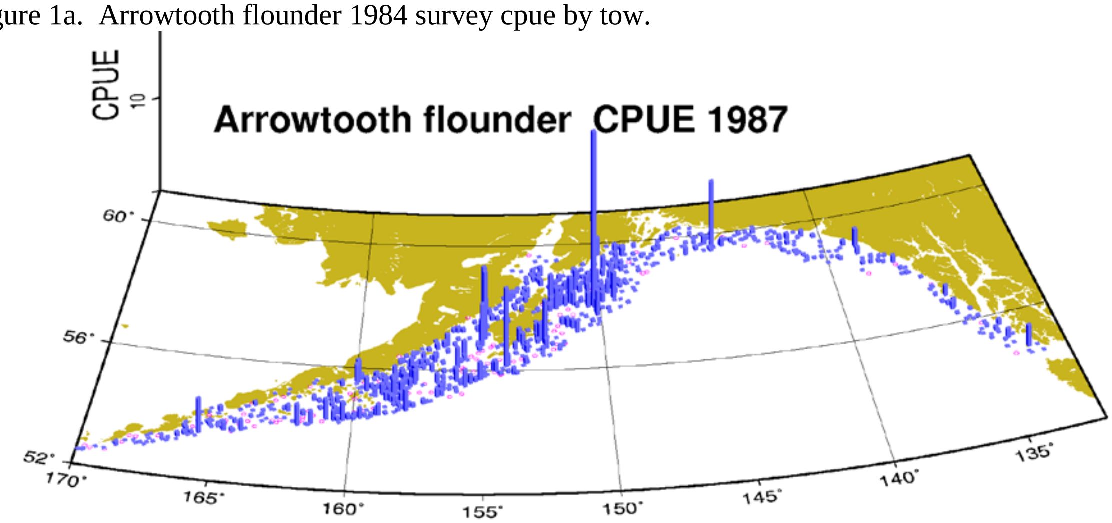

Figure 1b. Arrowtooth flounder 1987 survey cpue by tow.

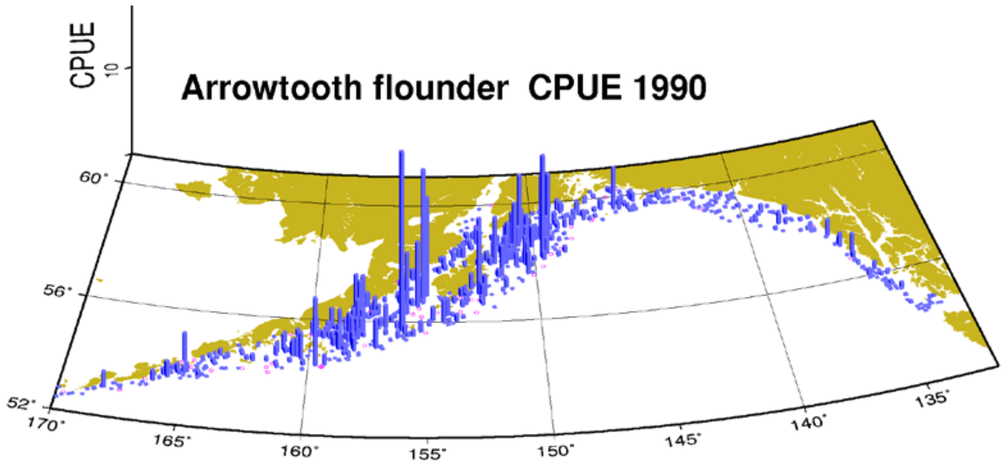

Figure 1c. Arrowtooth flounder 1990 survey cpue by tow.

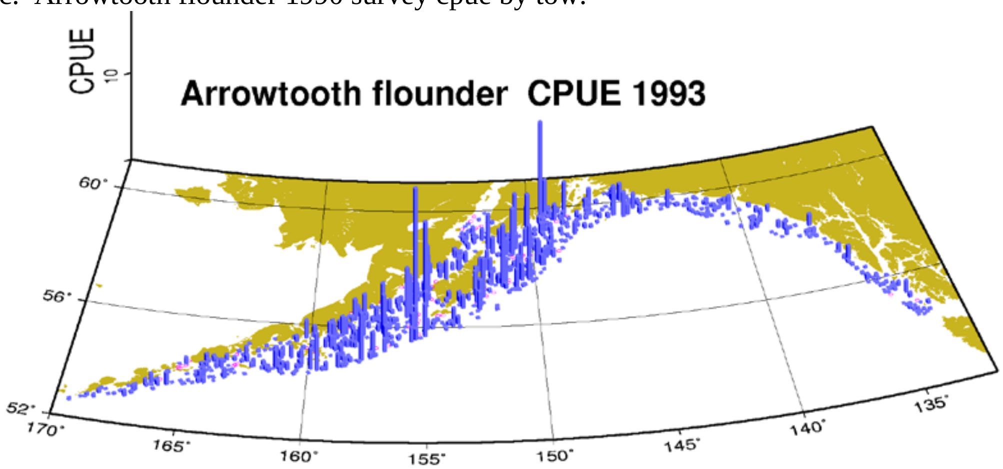

Figure 1d. Arrowtooth flounder 1993 survey cpue by tow.

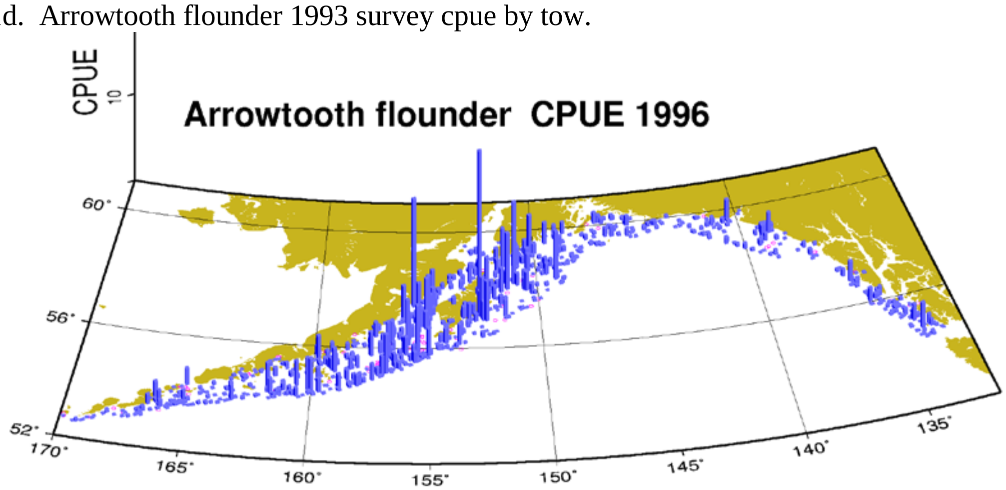

Figure 1e. Arrowtooth flounder 1996 survey cpue by tow.

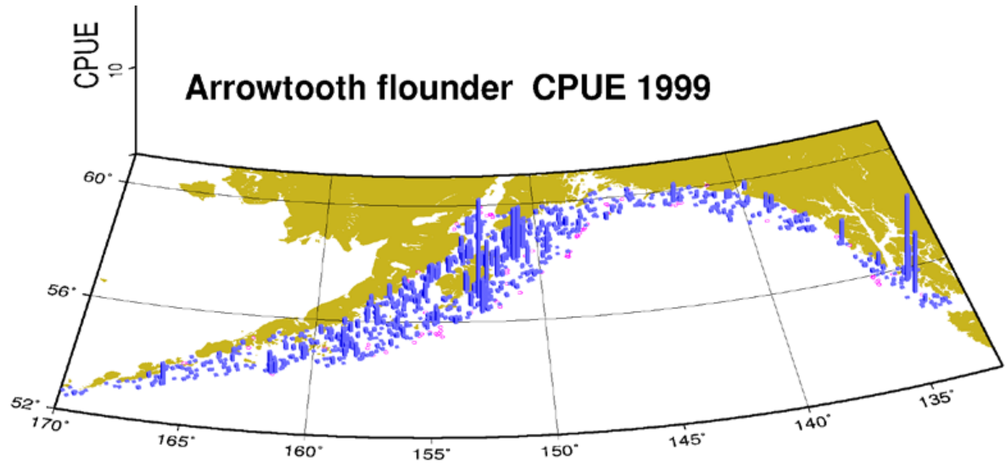

Figure 1f. Arrowtooth flounder 1999 survey cpue by tow.

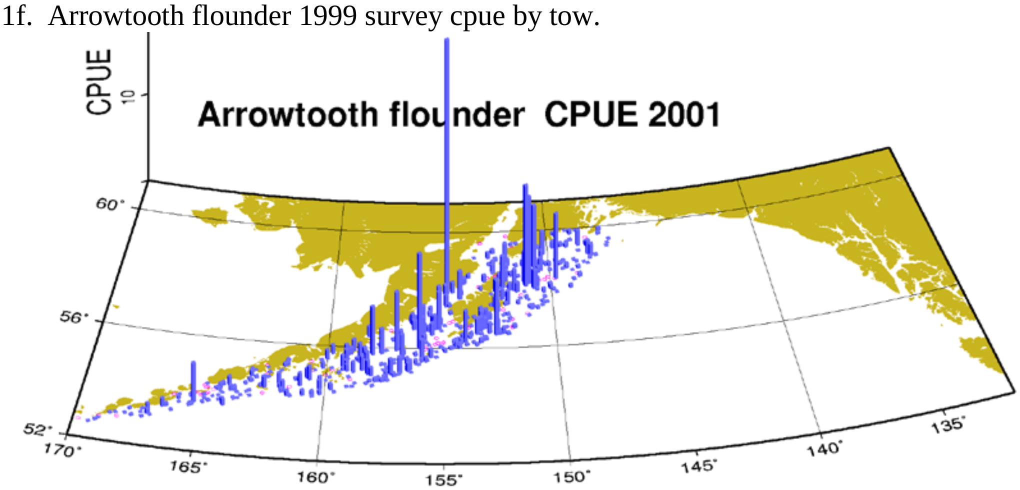

Figure 1g. Arrowtooth flounder 2001 survey cpue by tow.

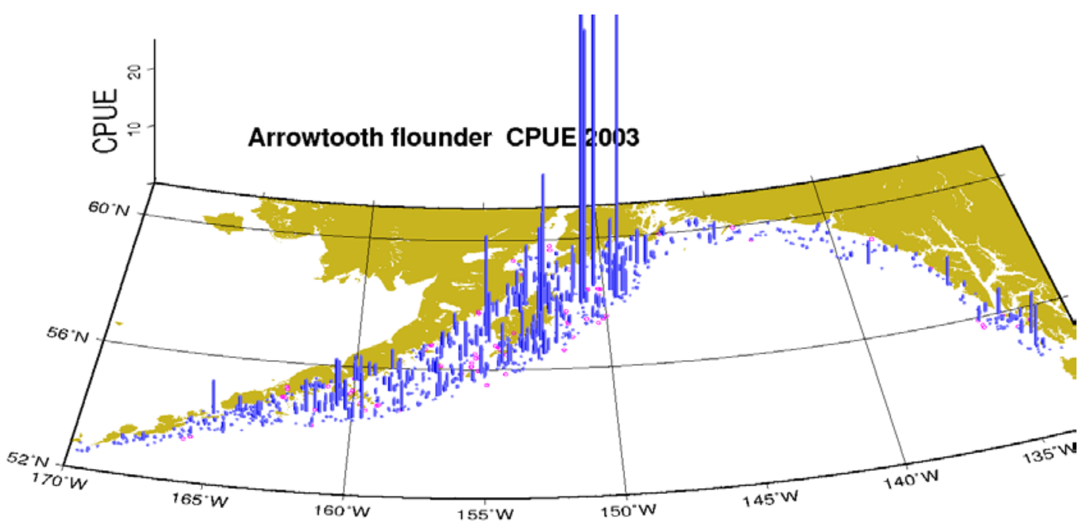

Figure 1h. Arrowtooth flounder 2003 survey cpue by tow.

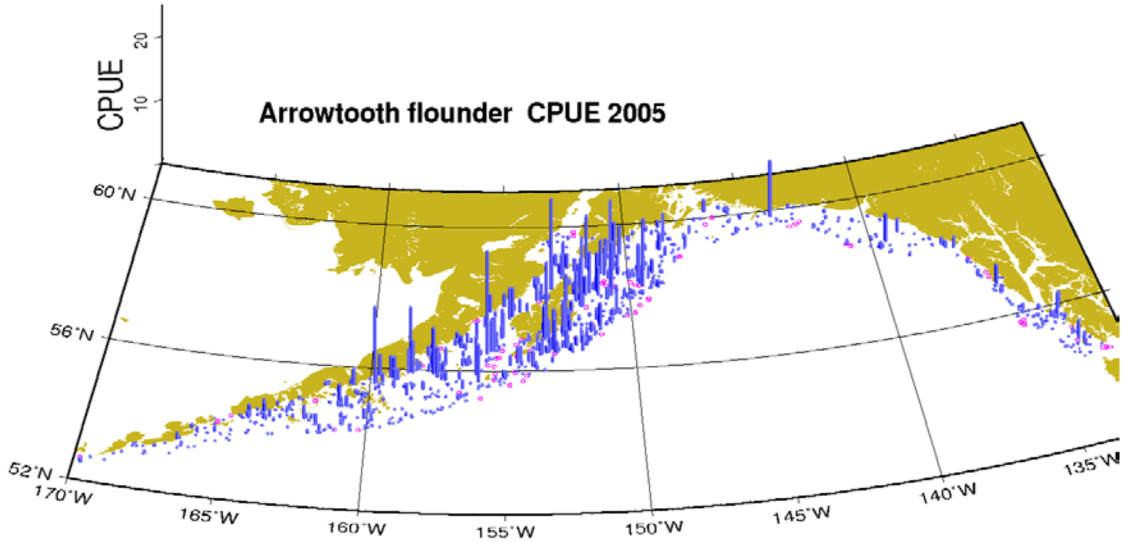

Figure 1i. Arrowtooth flounder 2005 survey cpue by tow.

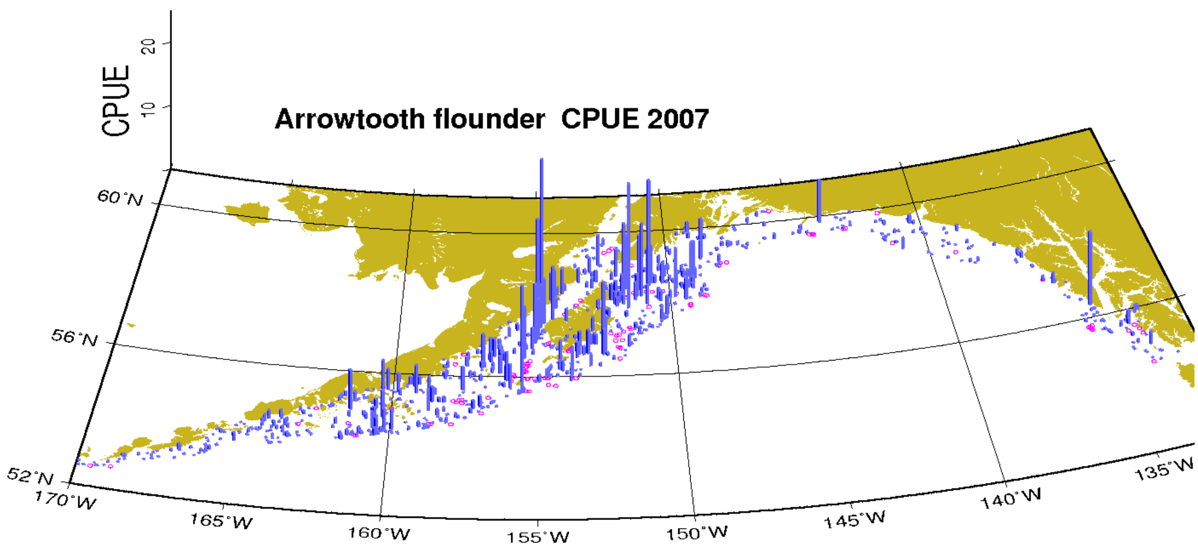

Figure 1j. Arrowtooth flounder 2007 survey cpue by tow.

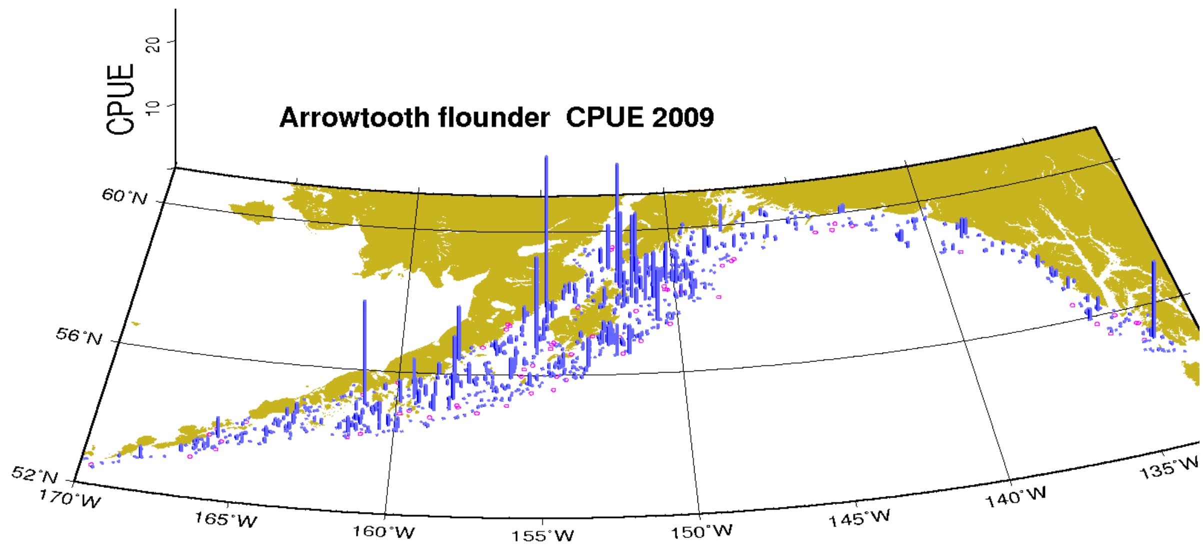

Figure 1k. Arrowtooth flounder 2009 survey cpue by tow.

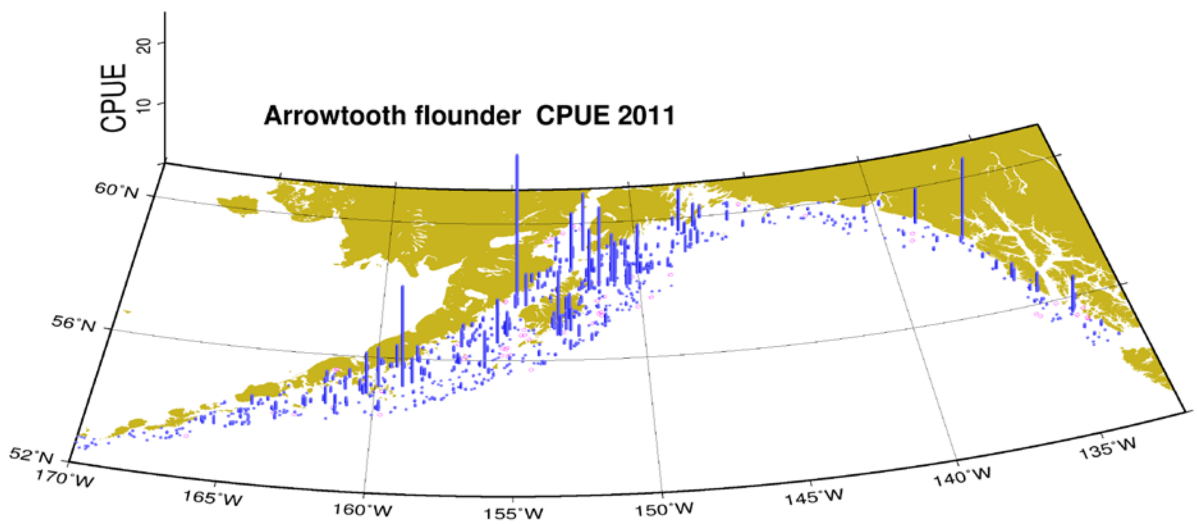

Figure 1l. Arrowtooth flounder 2011 survey cpue by tow.

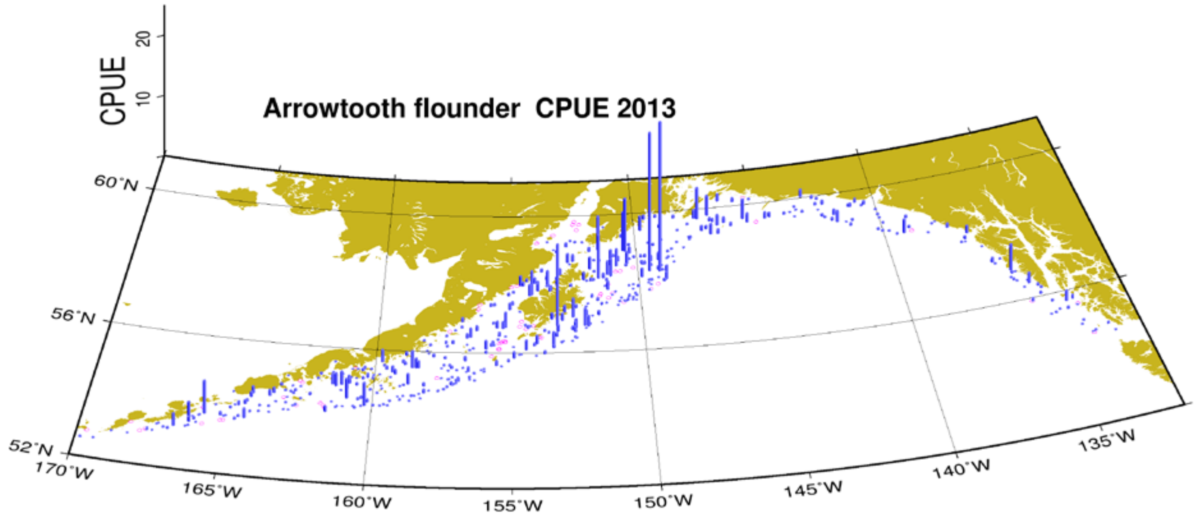

Figure 1m. Arrowtooth flounder 2013 survey cpue by tow.

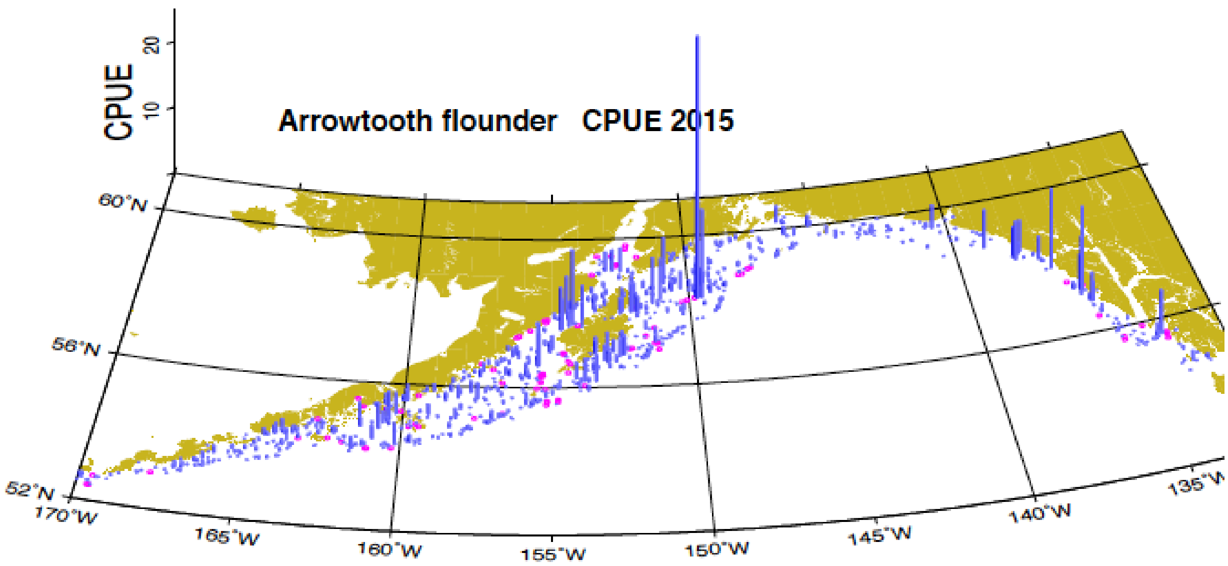

Figure 1n. Arrowtooth flounder 2015 survey cpue by tow.

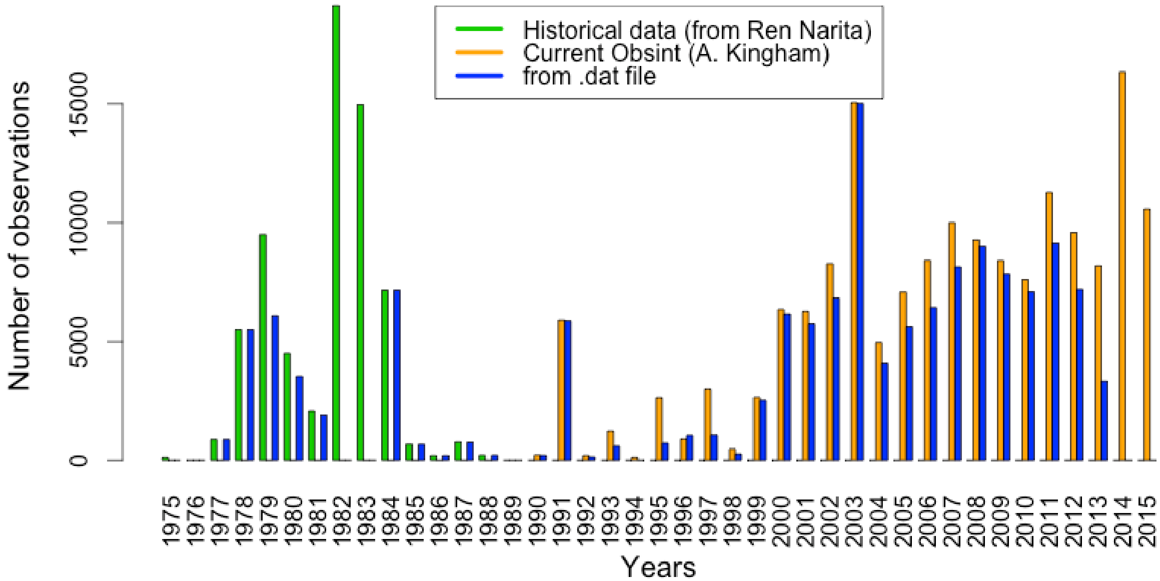

Figure 2. Length frequency data was re-downloaded for the 2015 assessment, green bars for historical data, prior to 1990 and yellow bars for 1990 and later. Blue bars show the number of length frequency observations for the 2013 assessment.

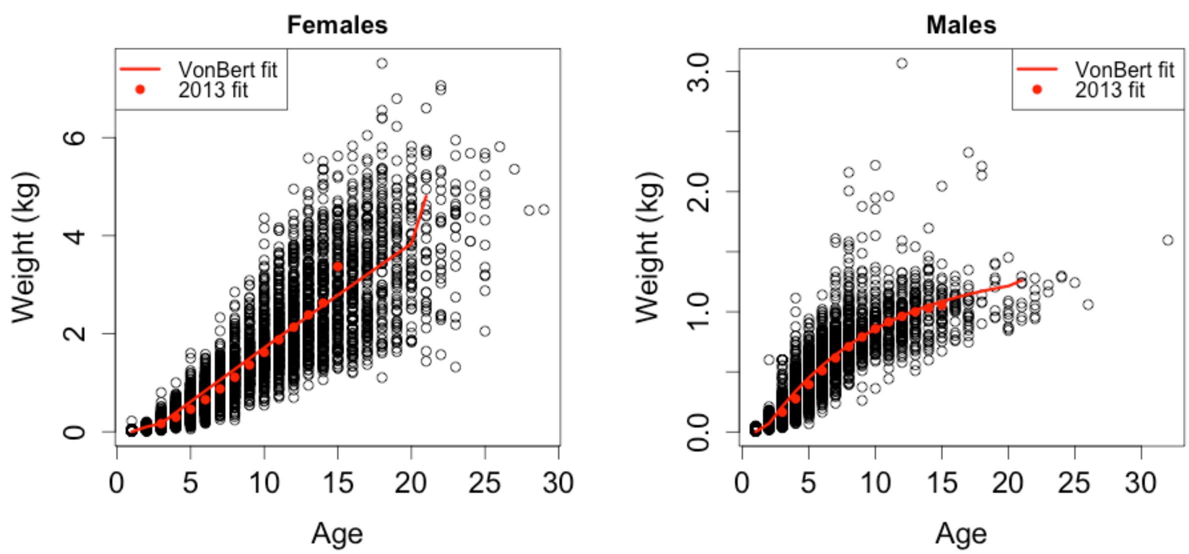

Figure 3. Weight at age data for female (left panel) and male (right panel) arrowtooth flounder in the Gulf of Alaska. The von Bertalanffy curve fit to the data is shown as a solid red line. Dots represent the previous estimate of weight at age, from the 2013 model.

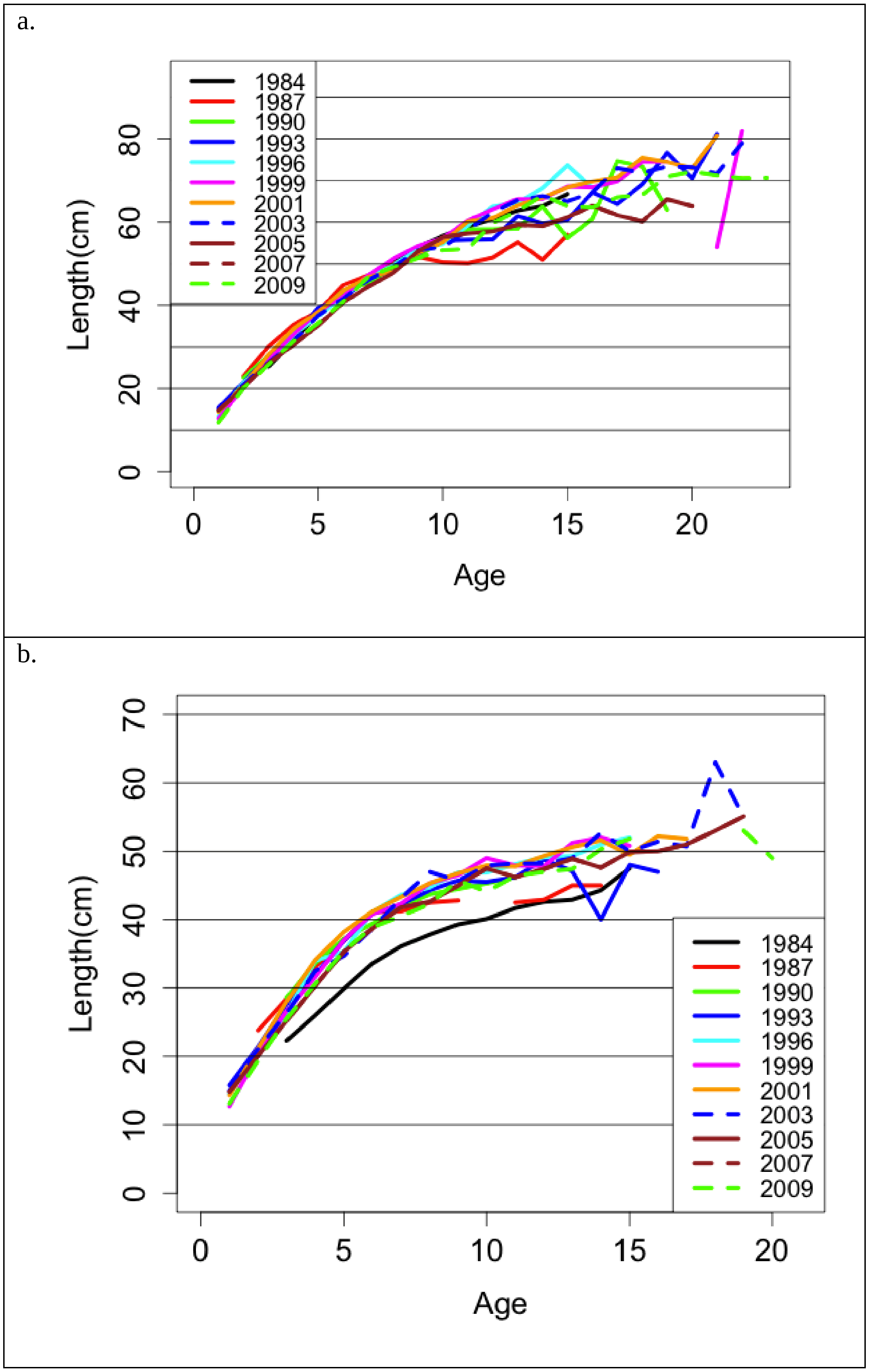

Figure 4. Mean length at age for female (a) and male (b) arrowtooth flounder from survey data 1984 to 2009.[will update this figure]

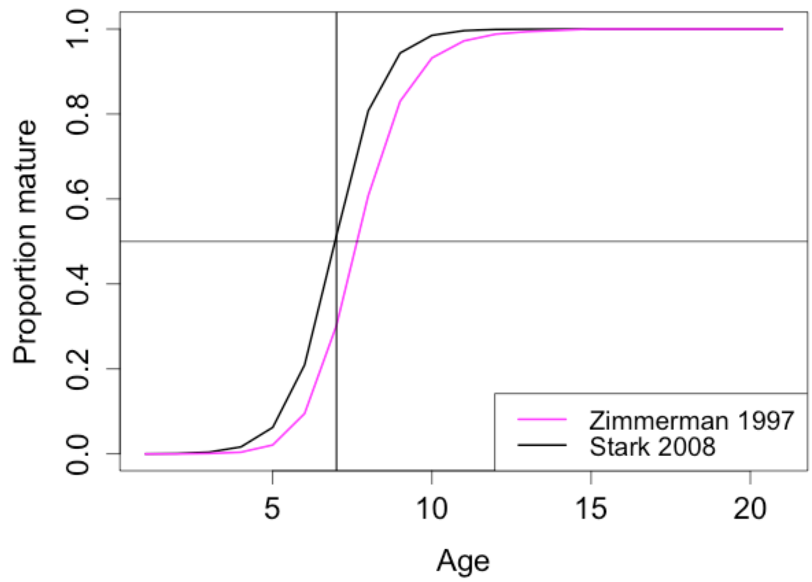

Figure 5. Maturity ogive used in the previous assessment (Zimmerman, 1997), and the maturity estimate used in the current assessment (Stark, 2008).

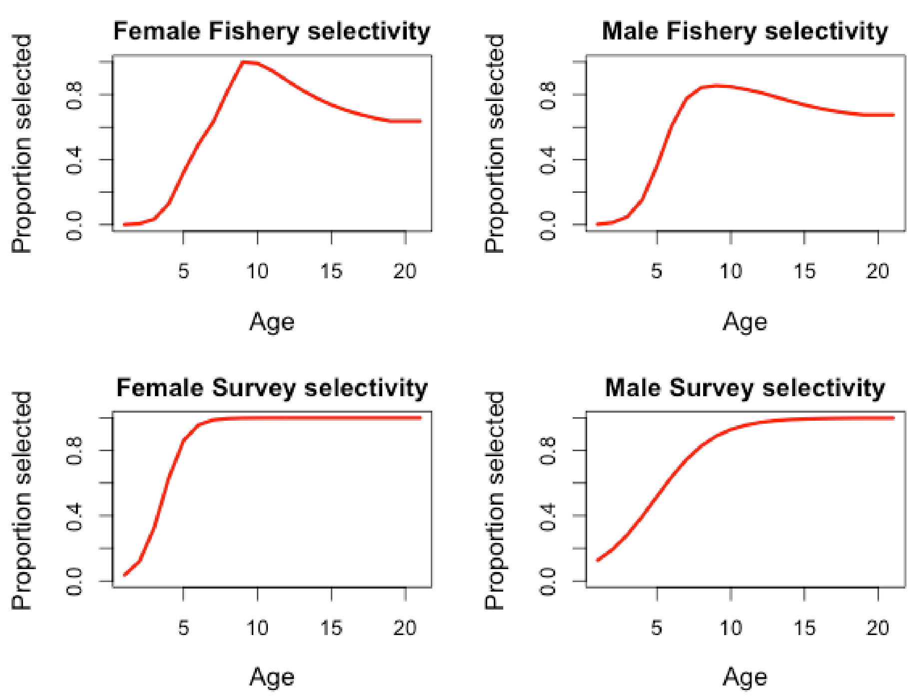

Figure 6. Male and female selectivities for the fishery and survey.

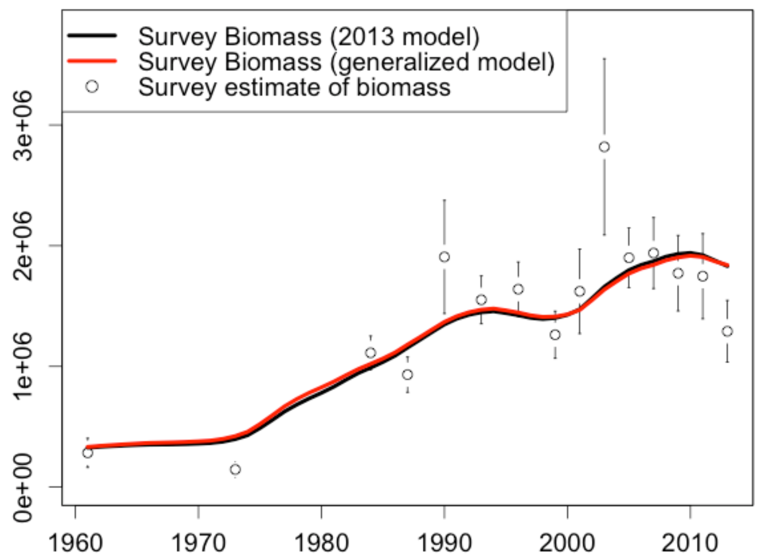

Figure 7. Predicted survey biomass estimated by the generalized model (red line) and the 2013 model (black line), compared with survey estimates of biomass and 95% confidence intervals.

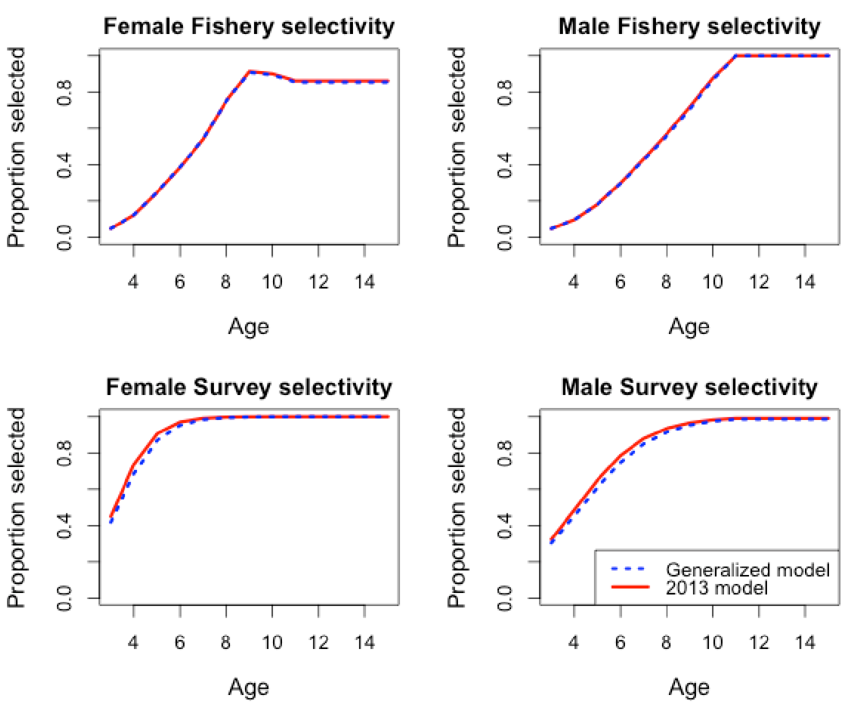

Figure 8. Comparison of male and female survey and fishery selectivites, estimated by the generalized model (blue dotted lines) and the 2013 model (red lines). These are not the selectivities used in the 2015 model, and are presented solely for the purpose of comparing the generalized model with the 2013 model.

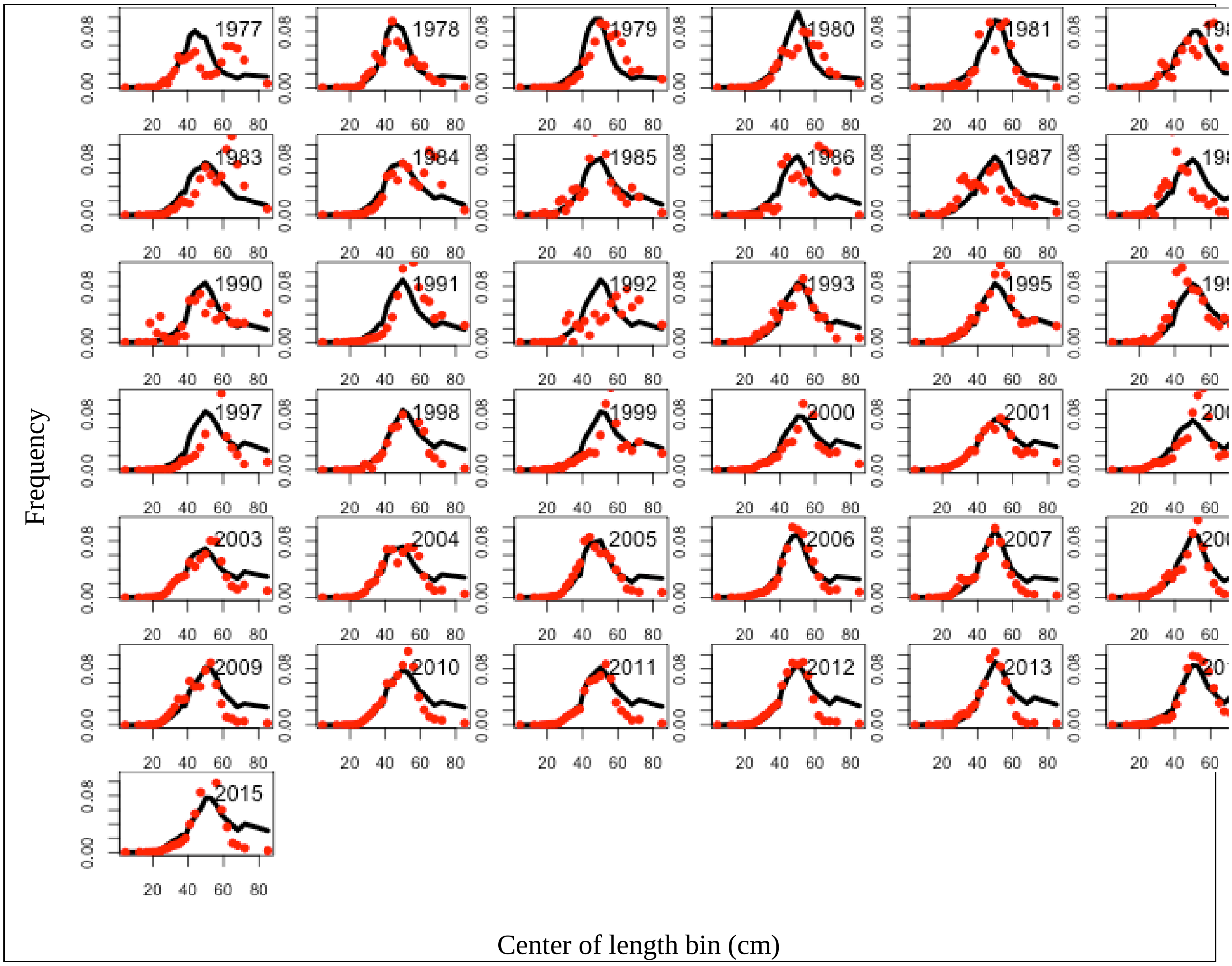

Figure 9. Fit to the female fishery length composition data, 1977-2015. Solid line is predicted.

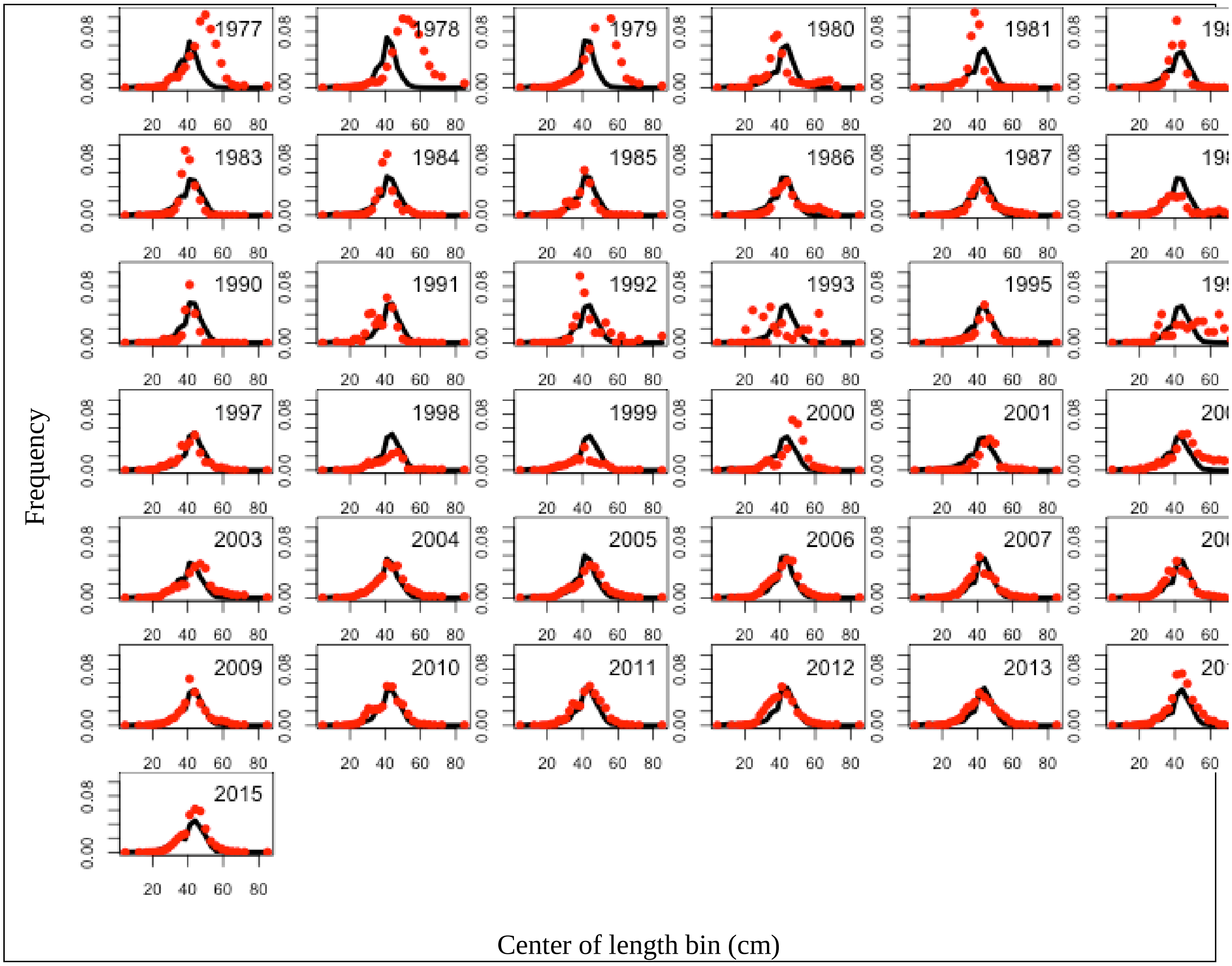

Figure 10. Fit to the male fishery length composition data, 1977-2015. Solid line is predicted.

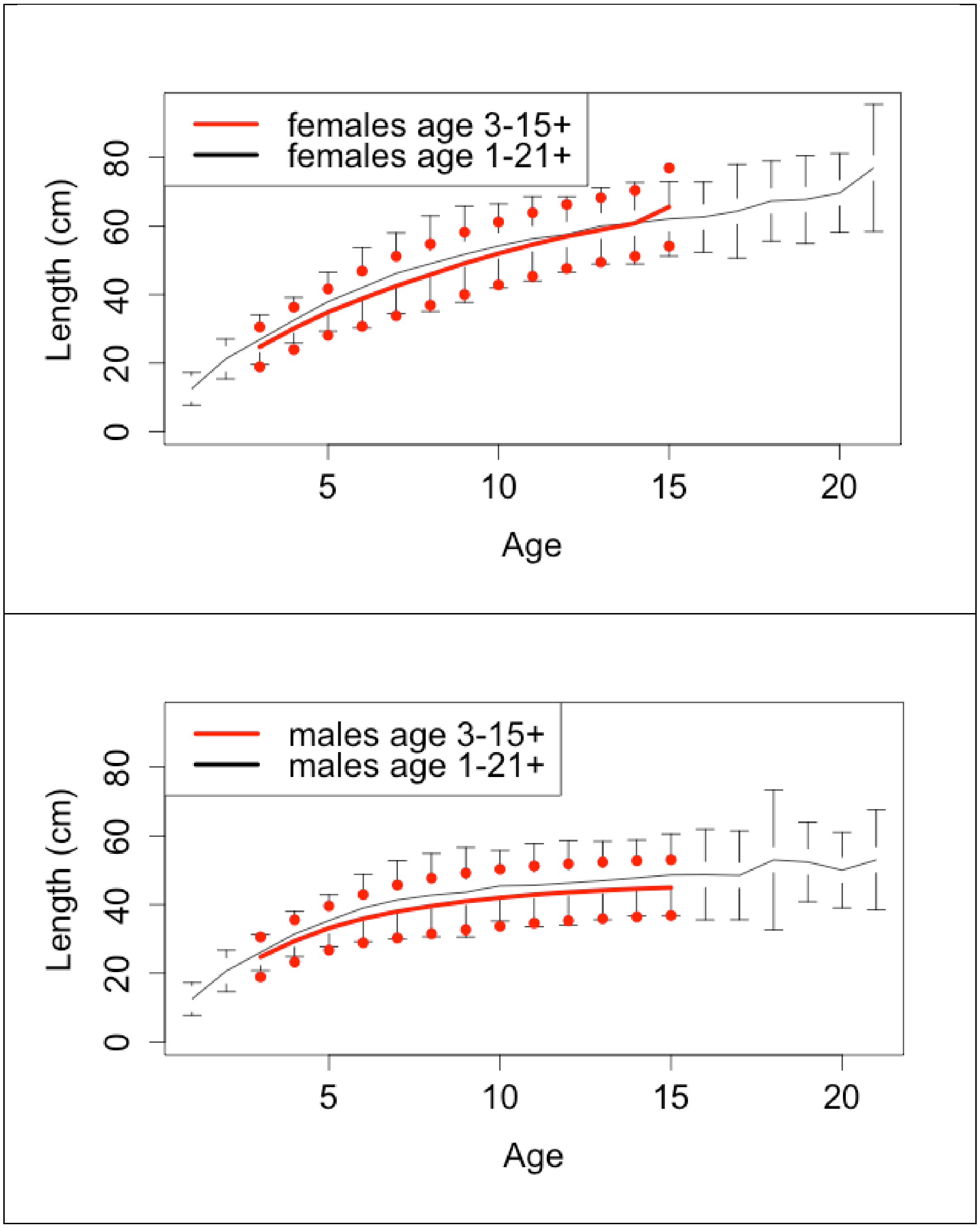

Figure 11. Mean length at age estimated from the 1984 through 2005 survey combined used to estimate the 3-15+ length-age transition matrix, compared to the 1-21+ mean length at age used in the 2015 assessment model.

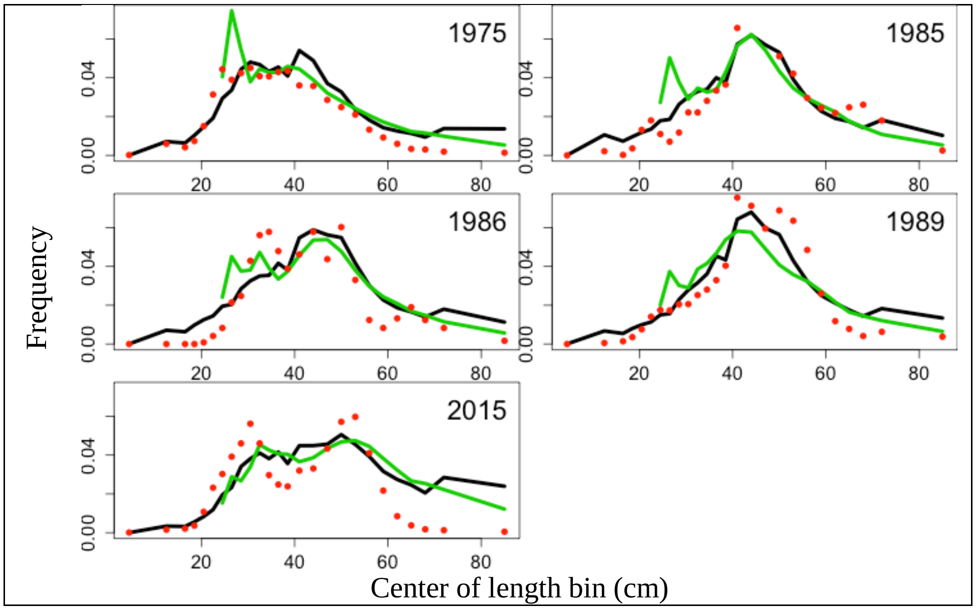

Figure 12. Fit to the female survey length data for 1975, 1985, 1986, 1989, and 2015. Solid line is predicted for Model 2.1, green line is predicted for Model 1.0.

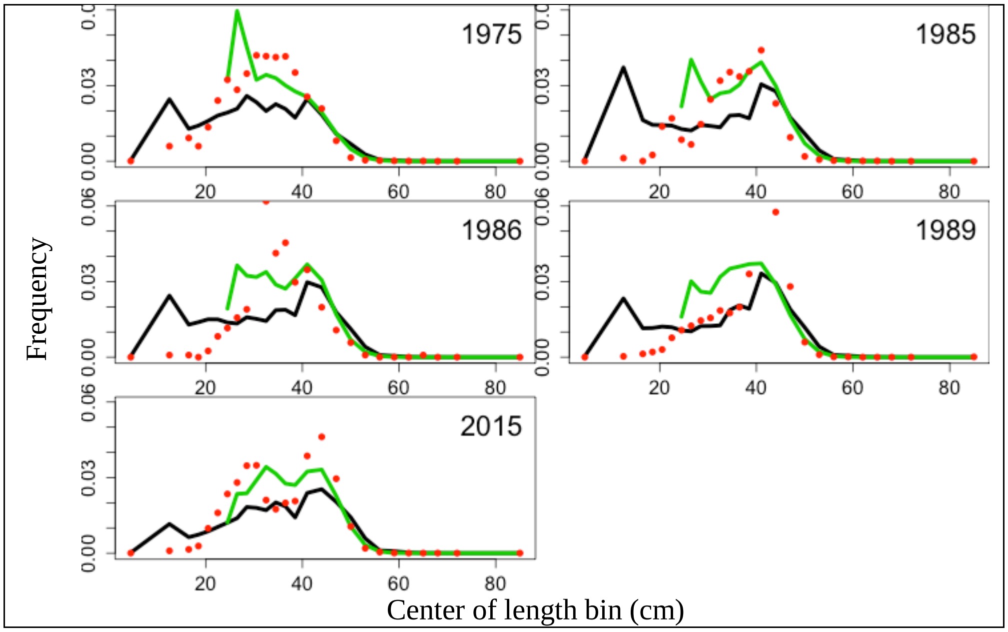

Figure 13. Fit to the male survey length data for 1975, 1985, 1986, 1989, and 2015. Solid line is predicted for Model 2.1, green line is predicted for Model 1.0.

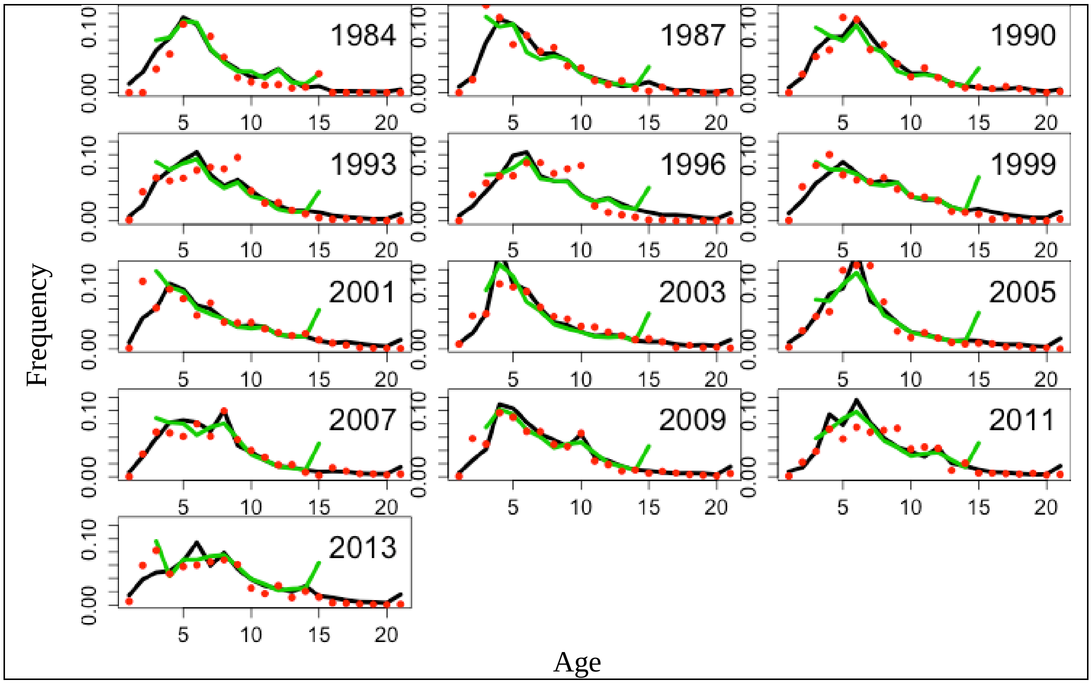

Figure 14. Fit to the female survey age data. The last age group is 21+. Solid line is predicted for Model 2.1, green line is predicted for Model 1.0.

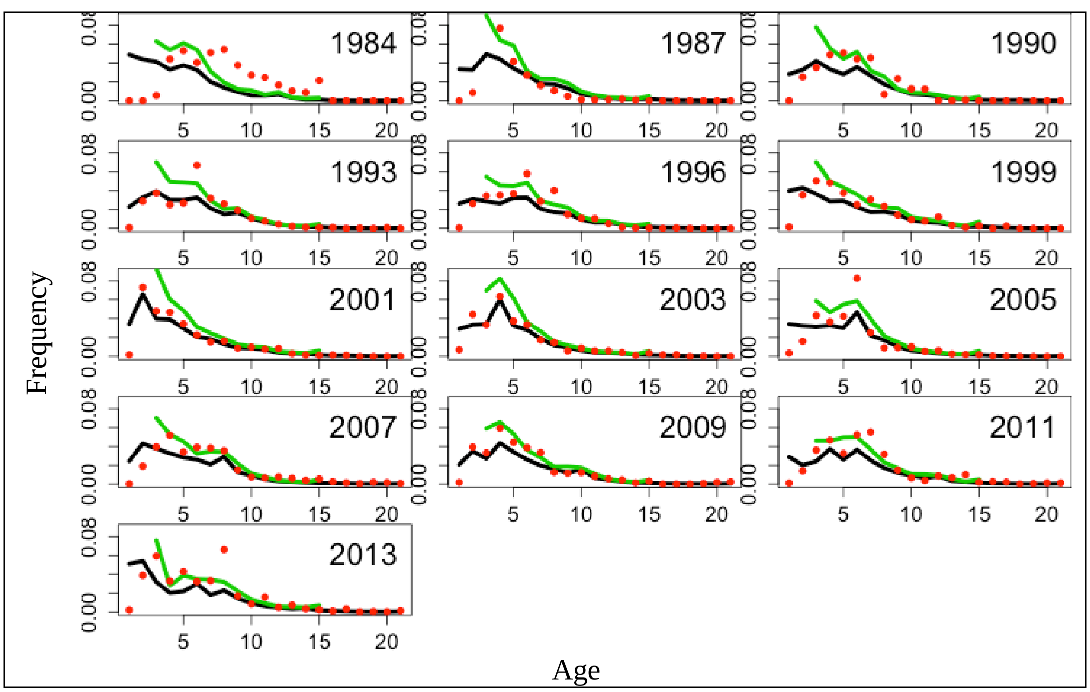

Figure 15. Fit to the male survey age data. The last age group is 21+. Solid line is predicted for Model 2.1, green line is predicted for Model 1.0.

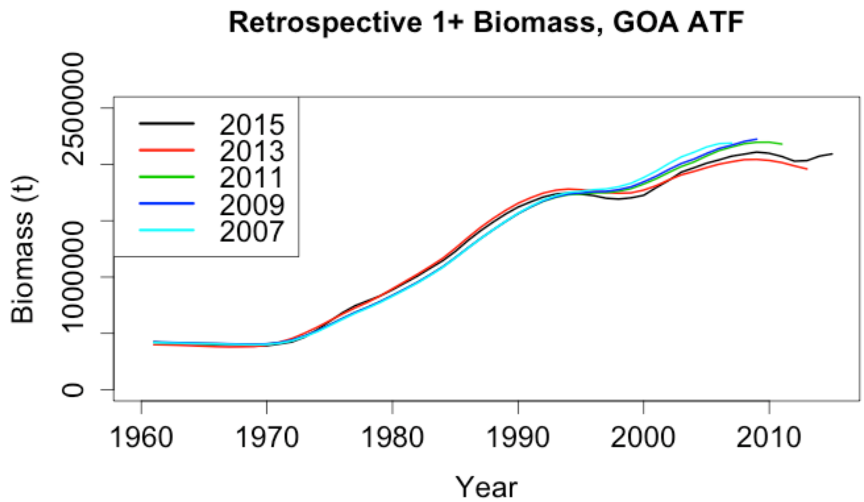

Figure 16. Estimates for total (age 1+) biomass and female spawning biomass from the 2007, 2009, 2011, 2013, and 2015 assessments.

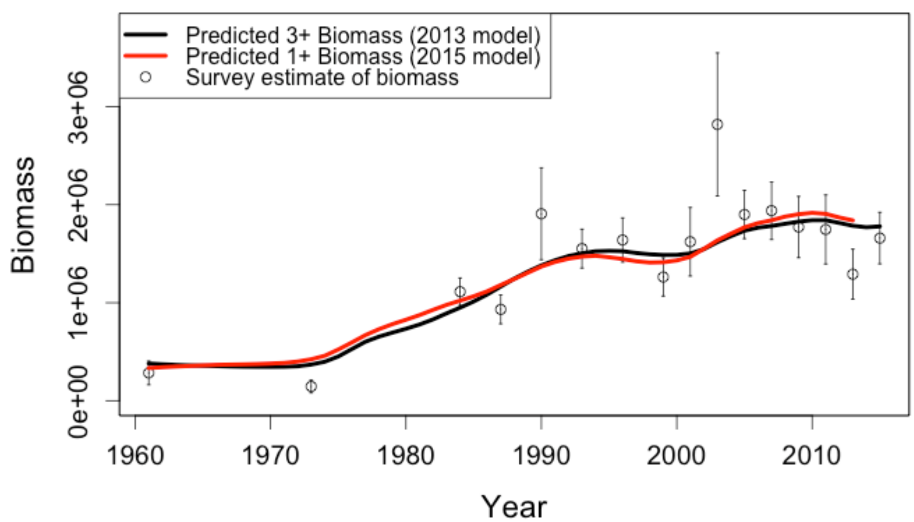

Figure 17. Fit to survey biomass estimates with approximate 95% confidence intervals for the observed survey 3+ biomass estimates 1961 to 2015.

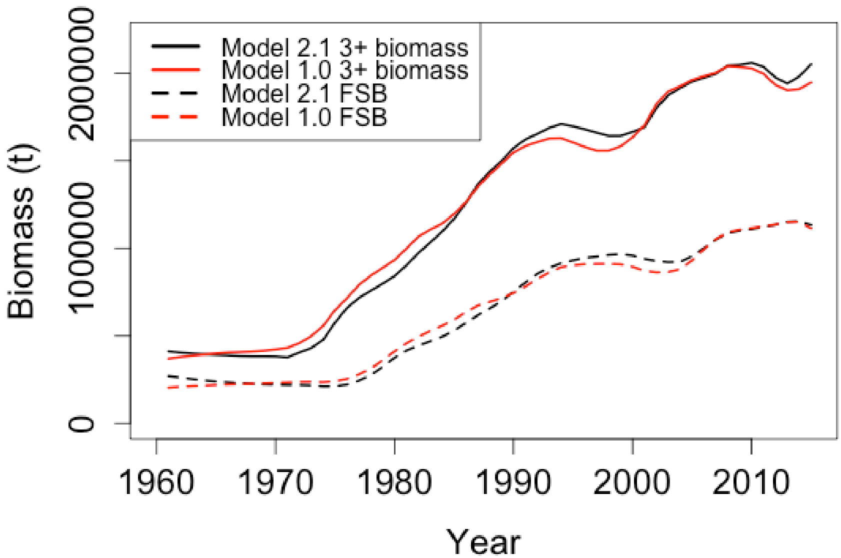

Figure 18. Comparison of Model 2.1 and Model 1.0 estimate of total 3+ biomass and female spawning biomass (FSB).

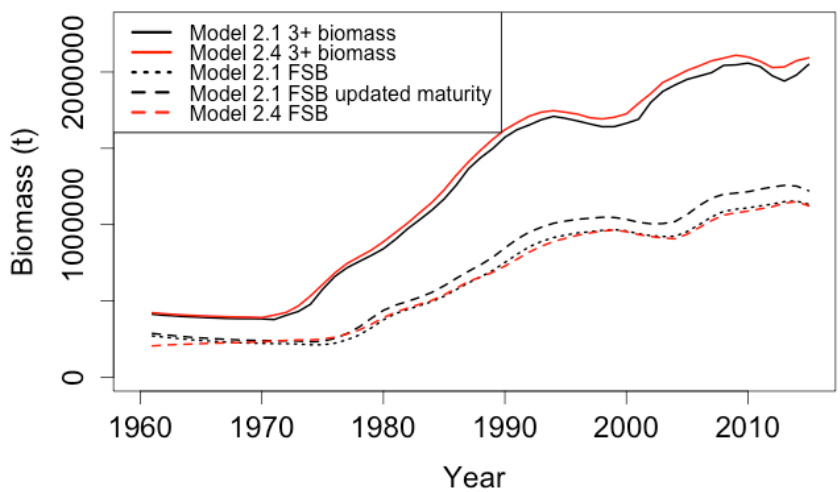

Figure 19. Female spawning biomass (FSB; broken lines) and total (3+ biomass; solid lines) for the generalized model run with ages 1-21+ (Model 2.1, black lines) and with ages 3-15+ (Model 2.4, red lines). The black dashed line is female spawning biomass Model 2.1 run with updated maturity (Stark 2008).

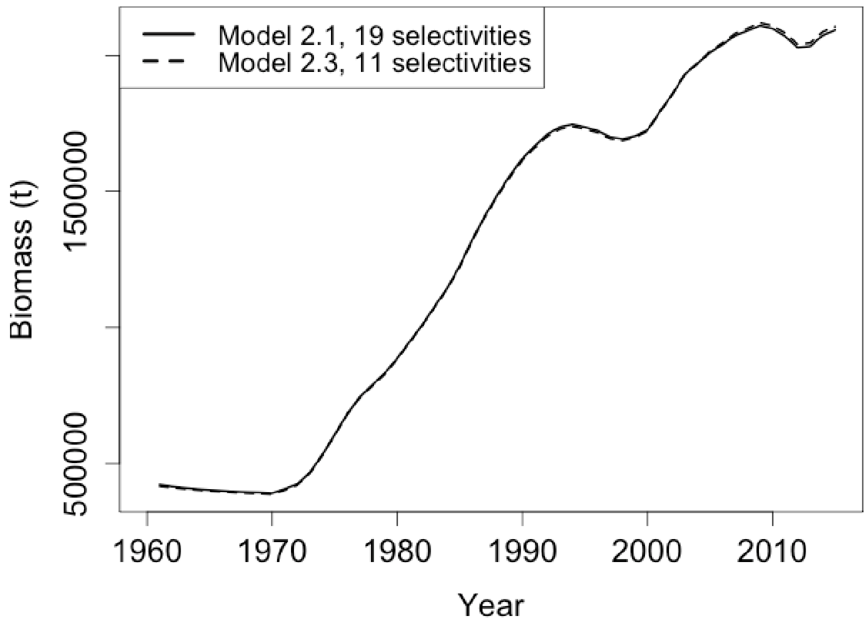

Figure 20. The difference in total (1+) biomass when selectivity is estimated up to age 19 (Model 2.1), vs. up to age 11 (Model 2.3) in the generalized model.

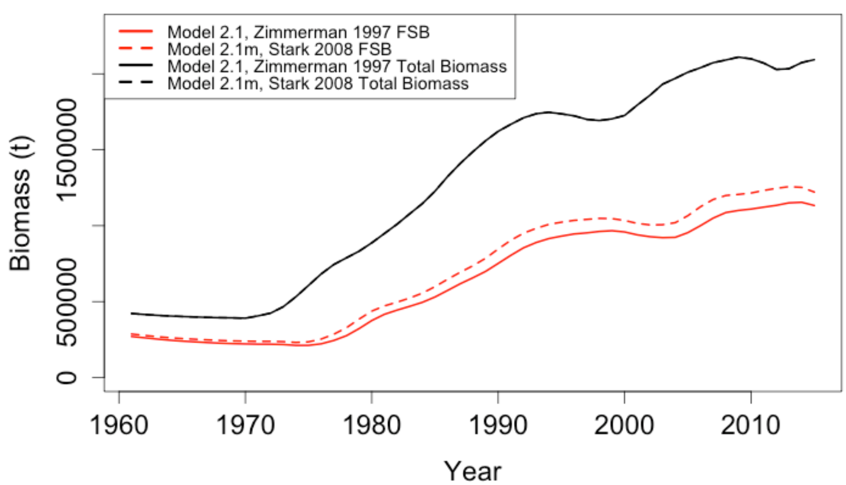

Figure 21. Biomass (black lines) and female spawning biomass (red lines), estimated with Model 2.1 for the newer maturity estimate (Stark 2008, dotted lines) and the Zimmerman (1997) estimate (solid lines).

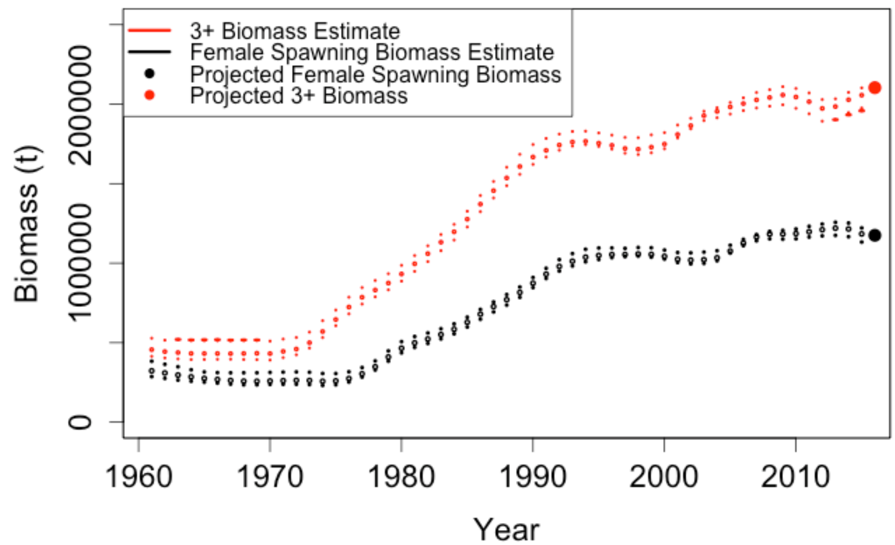

Figure 22. Median age 3+ biomass and female spawning biomass from 1961 to 2015, based on 10^6 mcmc iterations of the assessment model, thinning every 100. Error bars are 5% and 95% credible intervals. Projected female spawning under the current 5-year average fishing mortality rate is also shown

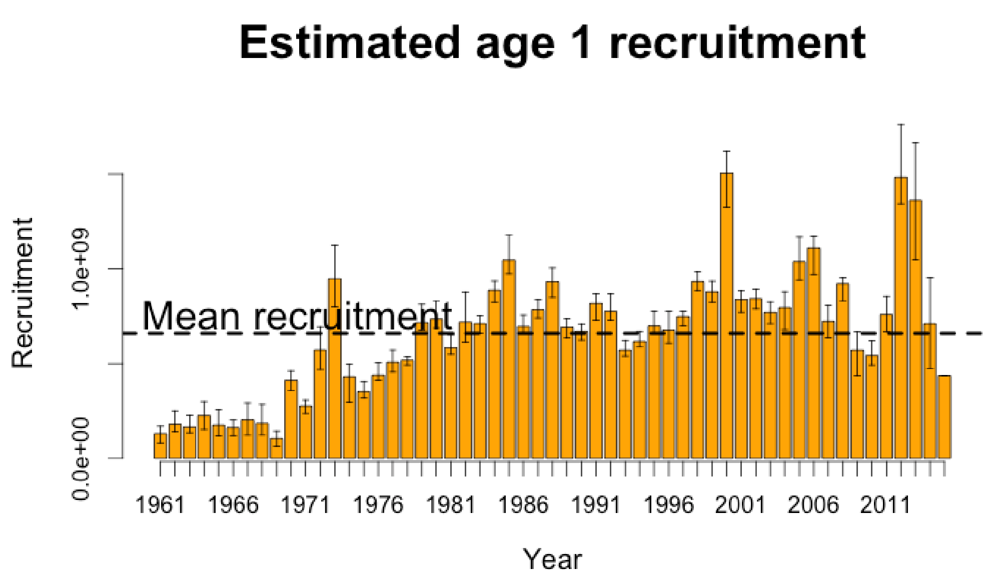

Figure 23. Age 1 estimated recruitments (male plus female) in numbers from 1961 to 2015, with approximate 5% and 95% credible intervals. Data was generated using out of 10^6 mcmc iterations, thinning every 100 iterations. The horizontal line represents the average recruitment over this time period.

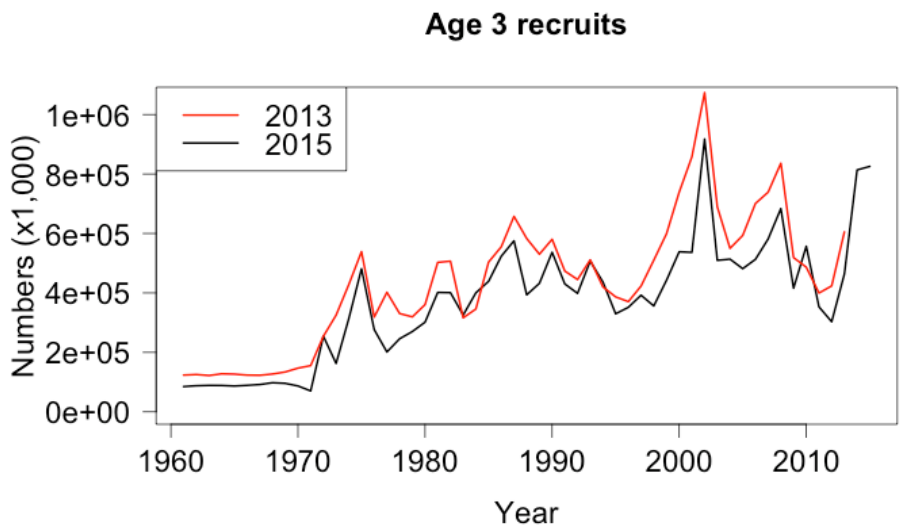

Figure 24. Age 3 recruitment estimates from 2013 and 2015 models.

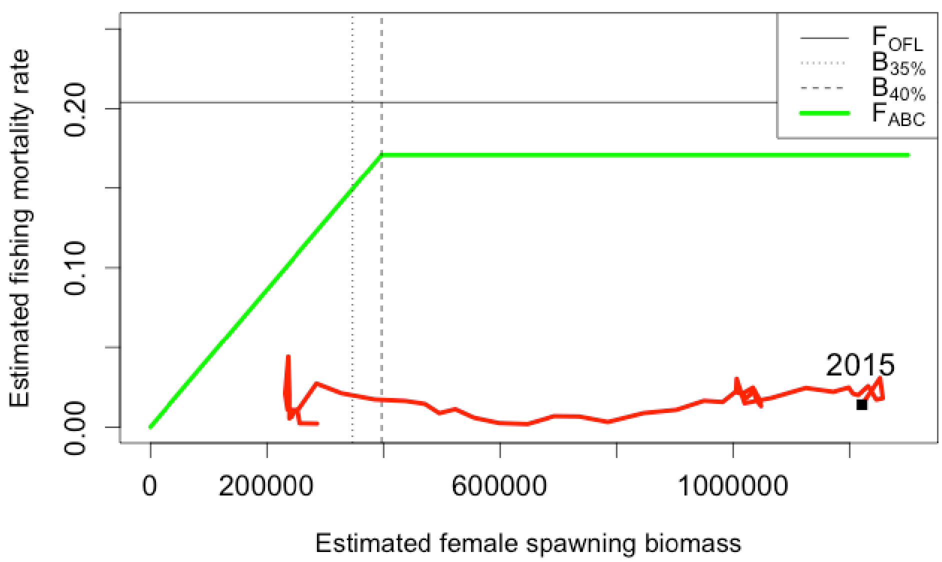

Figure 25. Fishing mortality rate and female spawning biomass from 1961 to 2015 compared to the $F_{35\%}$ and $F_{40\%}$ control rules. Vertical lines are $B_{35\%}$ and $B_{40\%}$.

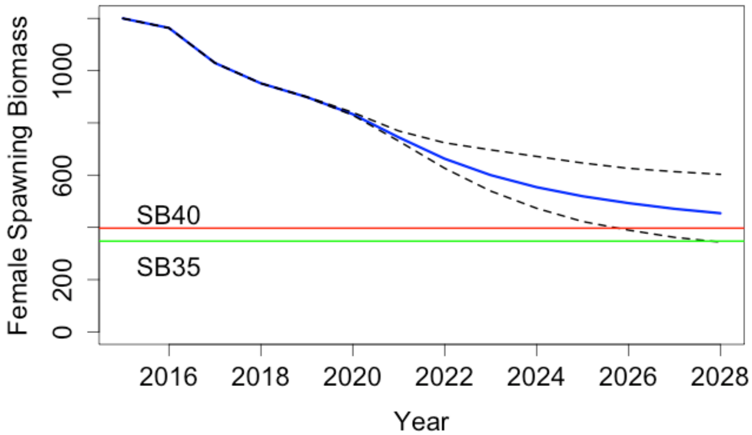

Figure 26. Projected female spawning biomass for 2013 to 2026 (blue line), with 5% and 95% confidence intervals, fishing at the maximum FABC=F40%.

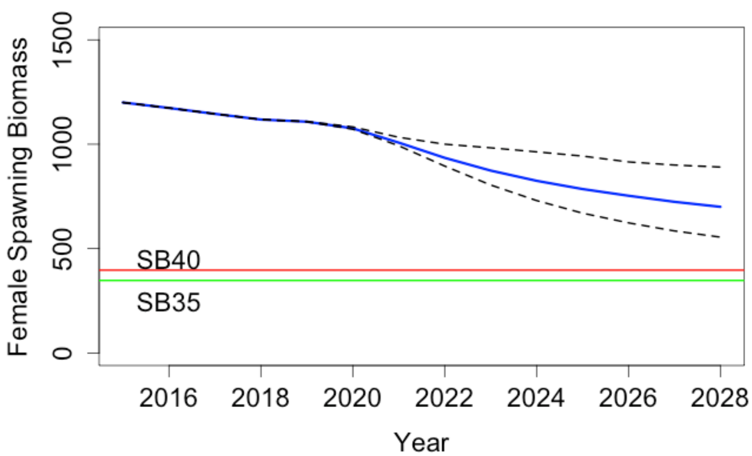

Figure 27. Projected female spawning biomass for 2015 to 2028 (blue line), with 5% and 95% confidence intervals, and fishing at the 5-year average F.

Appendix A.

Table A.1. Model equations describing the populations dynamics.

$N_{t,1} = R_t = R_0 e^{\tau_t}$	$\tau_t \sim N(0, \sigma_R^2)$	Recruitment
$C_{t,a} = \frac{F_{t,a}}{Z_{t,a}}(1 - e^{-Z_{t,a}})N_{t,a}$	$1 \le t \le T$ $1 \le a \le A$	Catch
$N_{t+1,a+1} = N_{t,a} e^{-Z_{t,a}}$	$1 < t \le T$ $1 \le a < A$	Numbers at age
$FSB_t = \sum_{a=1}^{A} w_a \phi_a N_{t,a}$		Female spawning biomass
$N_{t+1,A} = N_{t,A-1} e^{-Z_{t,A-1}} + N_{t,A} e^{-Z_{t,A}}$	$1 < t \le T$	Numbers in “plus” group
$Z_{t,a} = F_{t,a} + M$		Total Mortality
$C_t = \sum_{a=1}^{A} C_{t,a}$		Total Catch in numbers
$p_{t,a} = C_{t,a} / C$		proportion at age in the catch
$Y_t = \sum_{a=1}^{A} w_{t,a} C_{t,a}$		Yield
$F_{t,a} = s_{t,a} E_t e^{\varepsilon_t}$	$\varepsilon_t \sim N(0, \sigma_R^2)$	Fishing mortality
S_a for a = 3 to 12		Fishery selectivity – smooth monotonically increasing
S_a for a = 3 to 12		selectivity –ascending logistic for survey
$SB_t = Q \sum_{a=1}^{A} w_a s_{t,a}^{s} N_{t,a}$		survey biomass, Q = 1.

Table A.2. Likelihood components.

$\sum_{t=1}^{T}\left[\log(C_{t,obs}) - \log(C_{t,pred})\right]^2$	Catch using a lognormal distribution.
$\sum_{t=1}^{T}\sum_{a=1}^{A} nsamp_t * p_{obs,t,a}\log(p_{pred,t,a})$ - offset	age and length compositions using a multinomial distribution. Nsamp is the observed sample size. Offset is a constant term based on the multinomial distribution.
offset = $\sum_{t=1}^{T}\sum_{a=1}^{A} nsamp_t * p_{obs,t,a}\log(p_{obs,t,a})$	the offset constant is calculated from the observed proportions and the sample sizes.
$\sum_{t=1}^{ts}\left[\frac{\log\left[\frac{SB_{obs,t}}{SB_{pred,t}}\right]}{sqrt(2) * s.d.(\log(SB_{obs,t}))}\right]^2$	survey biomass using a lognormal distribution, ts is the number of years of surveys.
$\sum_{t=1}^{T}(\tau_t)^2$	Recruitment, where $\tau_t \sim N(0,\sigma_R^2)$
$\sum_{a=3}^{15}(diff(diff(s_a)))^2$	Smooth selectivities. The sum of the squared second differences.

Table A.3. List of variables and their definitions used in the model.

Variable	Definition
T	number of years in the model(t=1 is 1961 and t=T is the end year of the model
A	number of age classes (A =21, corresponding to ages 1(a=1) to 21+)
w_a	mean body weight(kg) of fish in age group a.
ϕ_a	proportion mature at age a
R_t	age 1 recruitment in year t
R_0	geometric mean value of age 1 recruitment
τ_t	recruitment deviation in year t
$N_{t,a}$	number of fish age a in year t
$C_{t,a}$	catch number of age group a in year t
$p_{t,a}$	proportion of the total catch in year t that is in age group a
C_t	Total catch in year t
Y_t	total yield(tons) in year t
$F_{t,a}$	instantaneous fishing mortality rate for age group a in year t
M	Instantaneous natural mortality rate
E_t	average fishing mortality in year t
ε_t	deviations in fishing mortality rate in year t
$Z_{t,a}$	Instantaneous total mortality for age group a in year t
s_a	selectivity for age group a

Table A.4. Estimated parameters for the ADmodel builder model. There were 185 total parameters estimated in the model.

Parameter	N	Description
$\log(R_0)$	1	log of the geometric mean value of age 1 recruitment
τ_t 1961 $\leq t \leq$ 2015-1,	54	Recruitment deviation in year t (not estimated in final year)
Recruitment deviations for the initial age composition	21	Recruitment deviation for initial age composition
$\log(f_0)$	1	log of geometric mean value of fishing mortality
ε_t 1961 $\leq t \leq$ 2015	55	deviations in fishing mortality rate in year t
Slope and a50% selectivity parameters	8	Slope and a50% 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
$F_{40\%}$, $F_{30\%}$, $F_{35\%}$	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 A.5. Fixed parameters in the ADmodel builder model.

Parameter	Description
M = 0.2 females , M=0.35 males	Natural mortality
Q = 1.0	Survey catchability
Weight at age for males and females.	von Bertalanffy growth parameters estimated from the 1977-2015 survey weight and age data.

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 Appendix A, “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 Appendix A). 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.

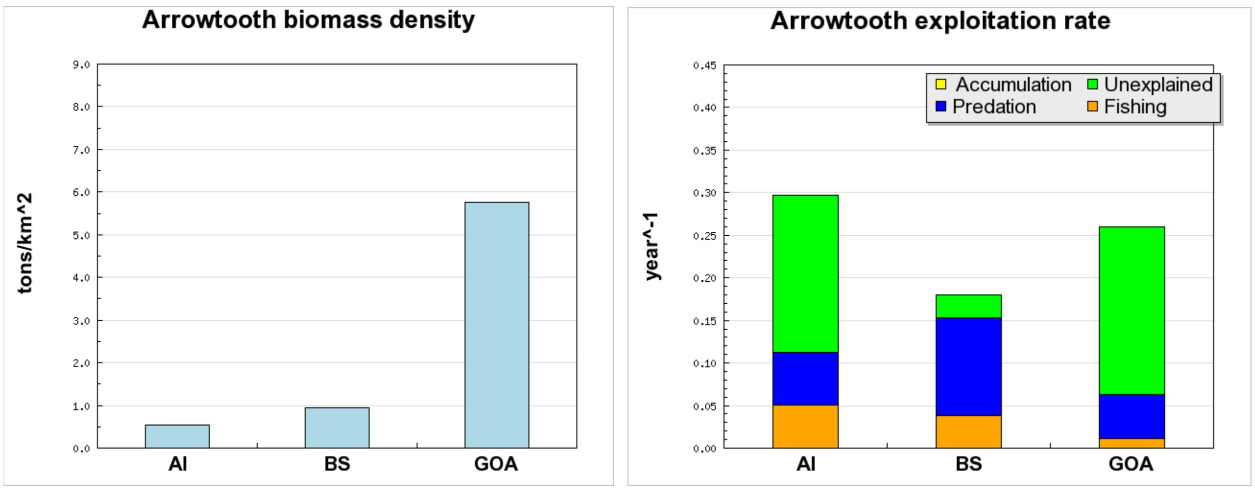

Figure B.1. Comparative biomass density (left) and mortality sources (right) for Arrowtooth flounder in the AI, EBS, and GOA ecosystems. Biomass density (left) is the average biomass from early 1990s NMFS bottom trawl surveys divided by the total area surveyed. Total arrowtooth production (right) is 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 Appendix A for detailed methods.

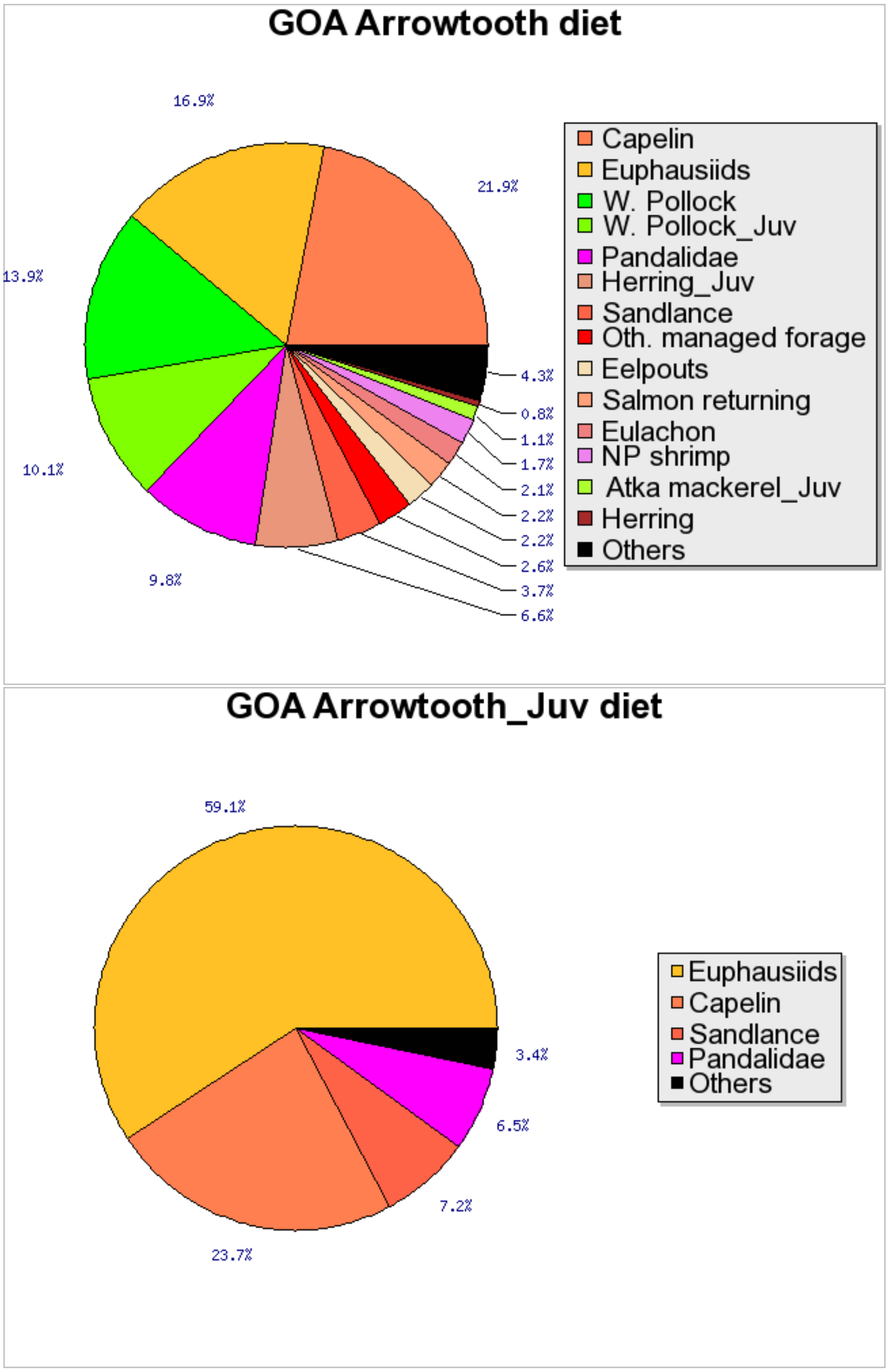

Figure B.2. Arrowtooth flounder diet compositions for the GOA ecosystem, for adults > 20cm (top) and juveniles 0-20 cm in length (bottom). Diets are estimated from stomach collections taken aboard NMFS bottom trawl surveys in 1990-1993. See Appendix A for detailed methods.

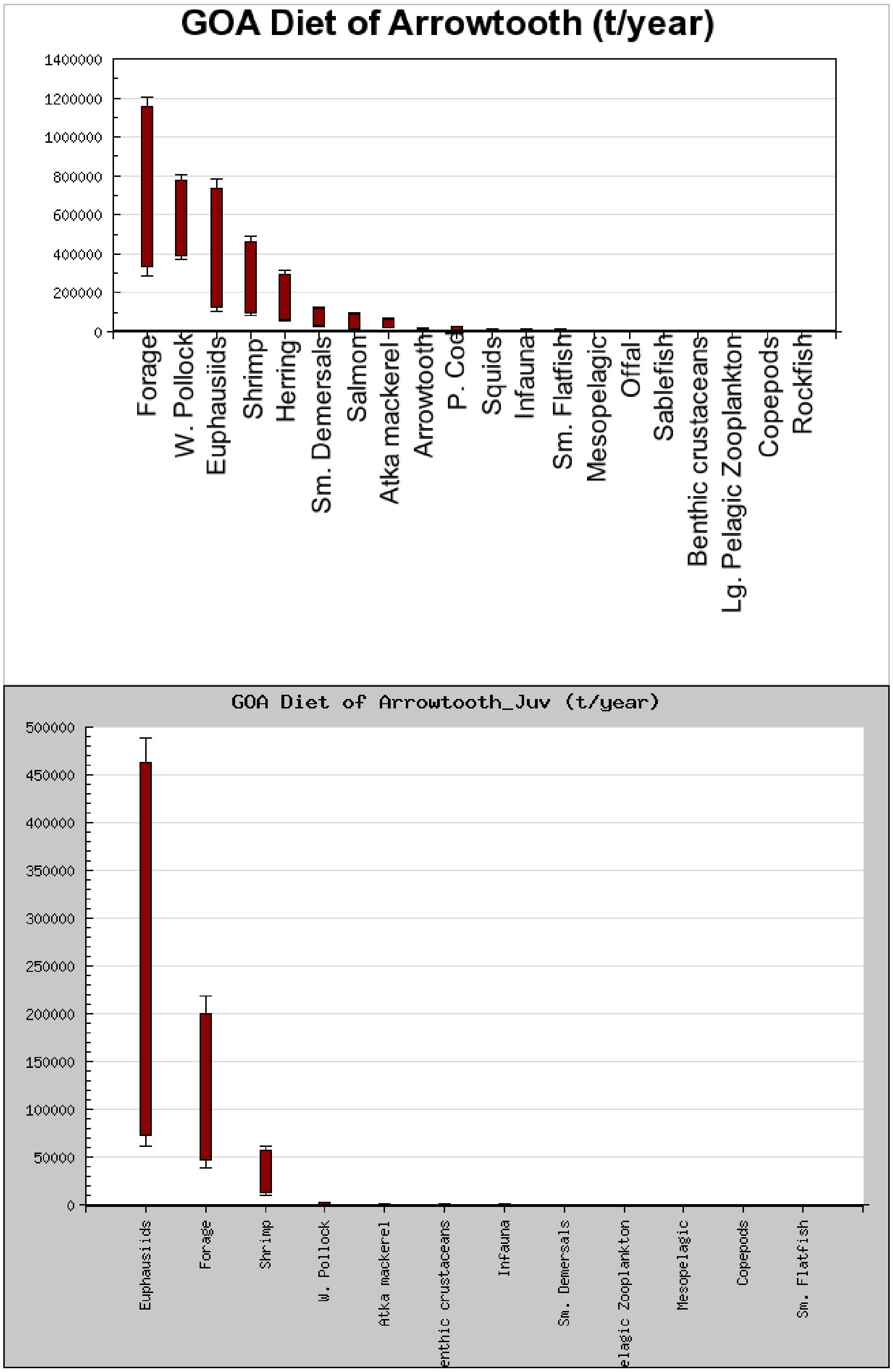

Figure B.3. Estimated annual tons of each prey type consumed by GOA Arrowtooth flounder adults >20 cm (top) and juveniles 0-20 cm (bottom), based on diets in Fig. B.2. “Forage” is all forage fish together, including capelin, sand lance, eulachon, and other managed forage.

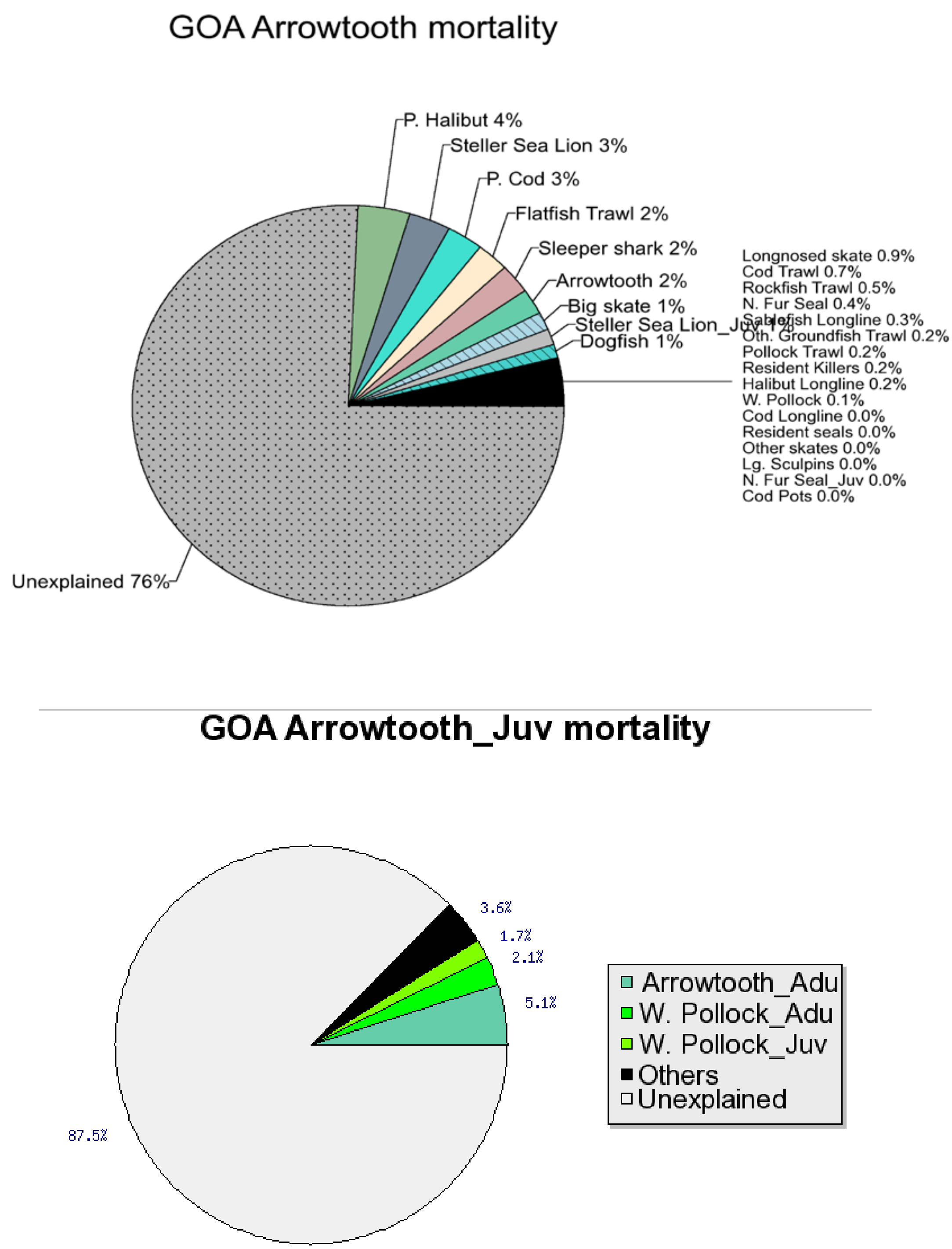

Figure B.4. Arrowtooth flounder mortality sources for the GOA ecosystem, for adults > 20cm (top) and juveniles 0-20 cm in length (bottom). Mortality sources reflect arrowtooth flounder predator diets estimated from stomach collections taken aboard NMFS bottom trawl surveys in 1990-1993, arrowtooth predator 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 Appendix A for detailed methods.

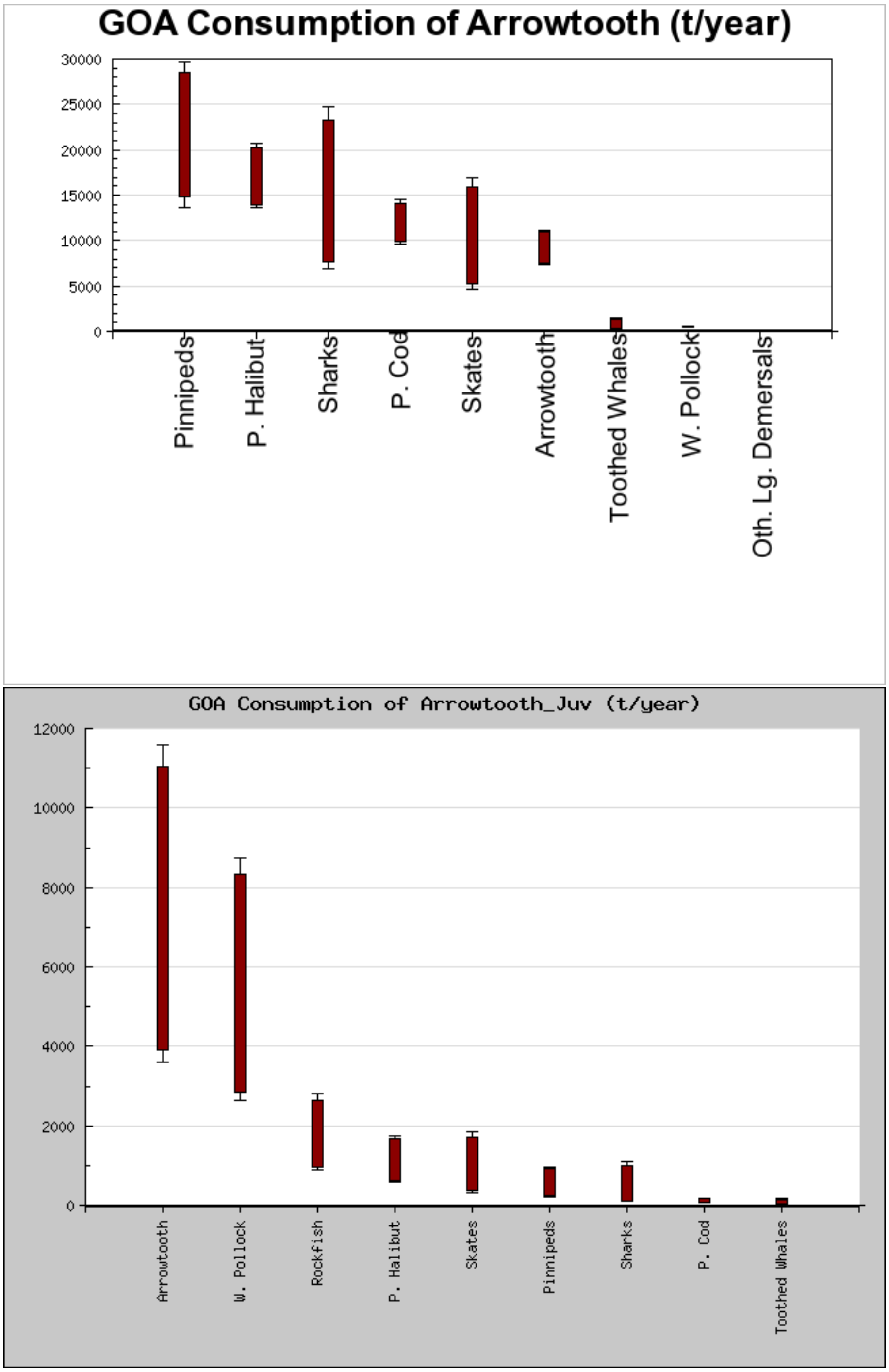

Figure B.5. Estimated annual tons of arrowtooth flounder consumed by predators in the GOA. Consumption of adult arrowtooth 20 cm (top) and juveniles 0-20 cm (bottom), based on mortality estimates in Fig. B.4. “Forage” is all forage fish together, including capelin, sand lance, eulachon, and other managed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

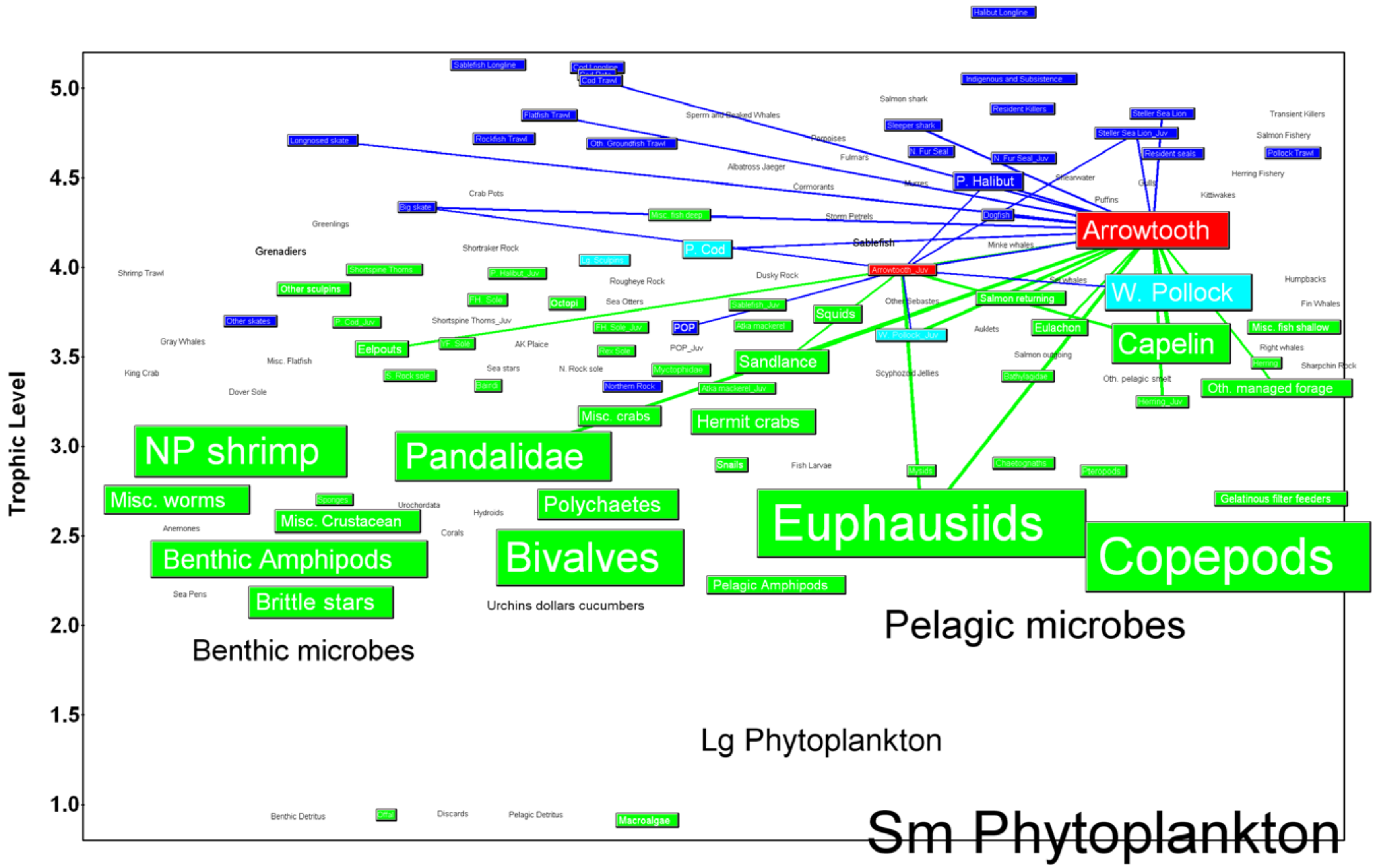

Figure B.6. Adult and juvenile arrowtooth flounder in the GOA food web. Box size is proportional to biomass, and lines between boxes represent the most significant energy flows. Predators of arrowtooth are dark blue, prey of arrowtooth are green, and species that are both predators and prey of arrowtooth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

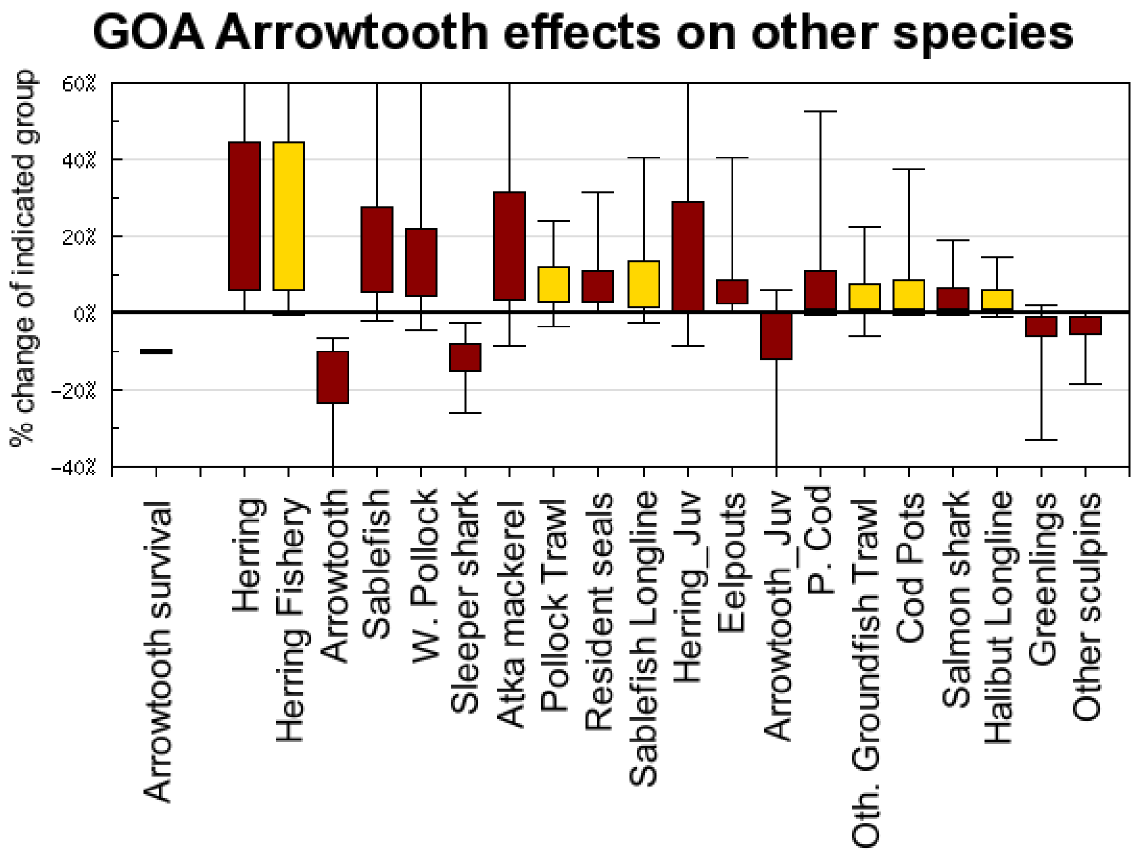

Figure B.7. Effect of changing arrowtooth > 20 cm survival on fishery catch (yellow) and biomass of other species (dark red) in the GOA, from a simulation analysis where arrowtooth survival was decreased by 10% and the rest of the ecosystem adjusted to this decrease for 30 years. Boxes show resulting 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).

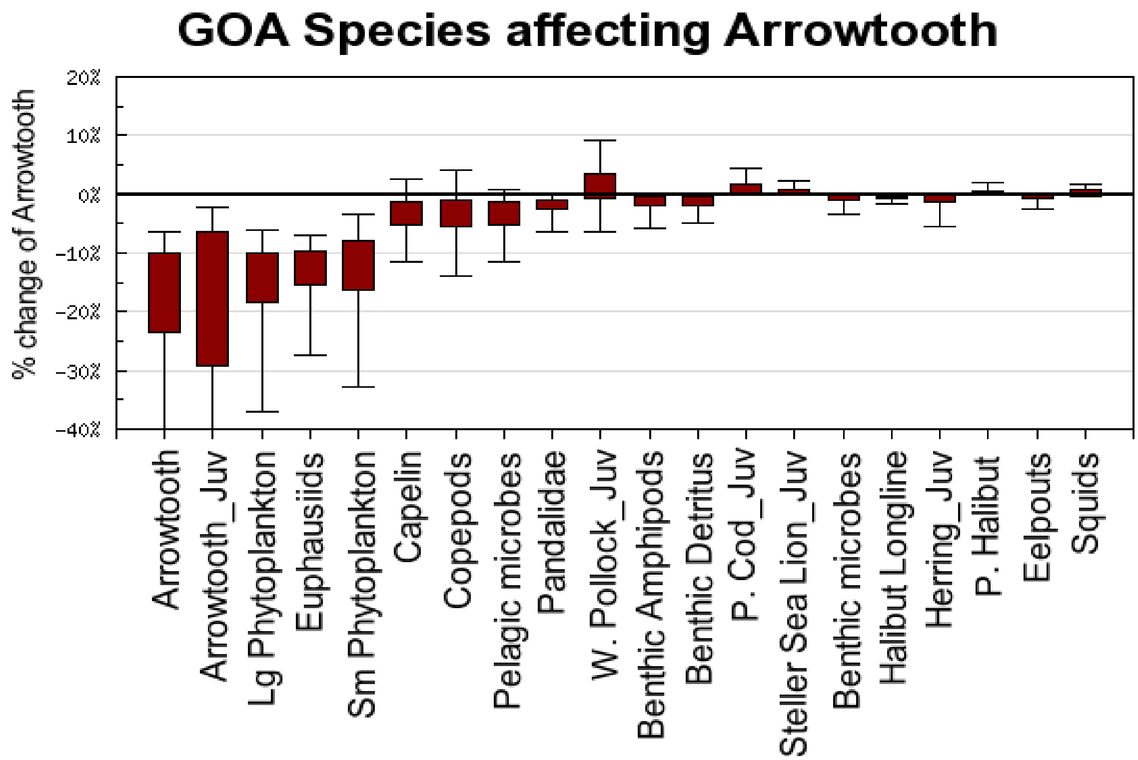

Figure B.8. Effect of reducing fisheries catch (yellow) and other species survival (dark red) on arrowtooth > 20 cm biomass, from a simulation analysis where survival of each X axis species group was decreased by 10% and the rest of the ecosystem adjusted to this decrease for 30 years. Boxes show resulting 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).

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 calc appendix in this doc. 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, and I'm still figuring out why (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.

			Westshelf			Westgully			Westslope			Centralshelf			Centralgully			Centralslope			Eastshelf			Eastgully			Eastslope			Southeastshelf			Southeastgully			NA		
Year	**Season**	**Data**	**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			

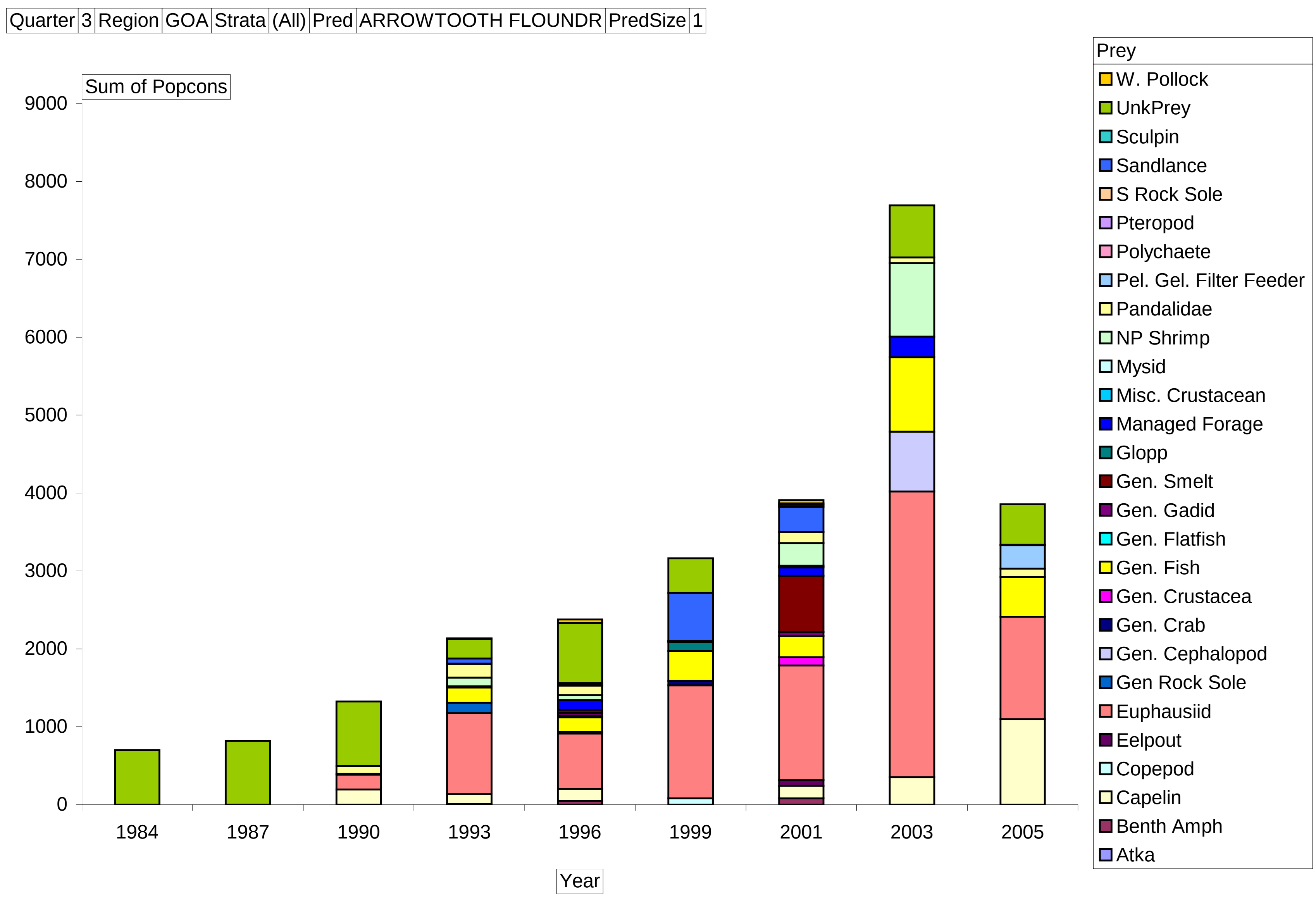

Figure B.9. Juvenile (<20 cm) arrowtooth estimated consumption of prey by survey year in the GOA.

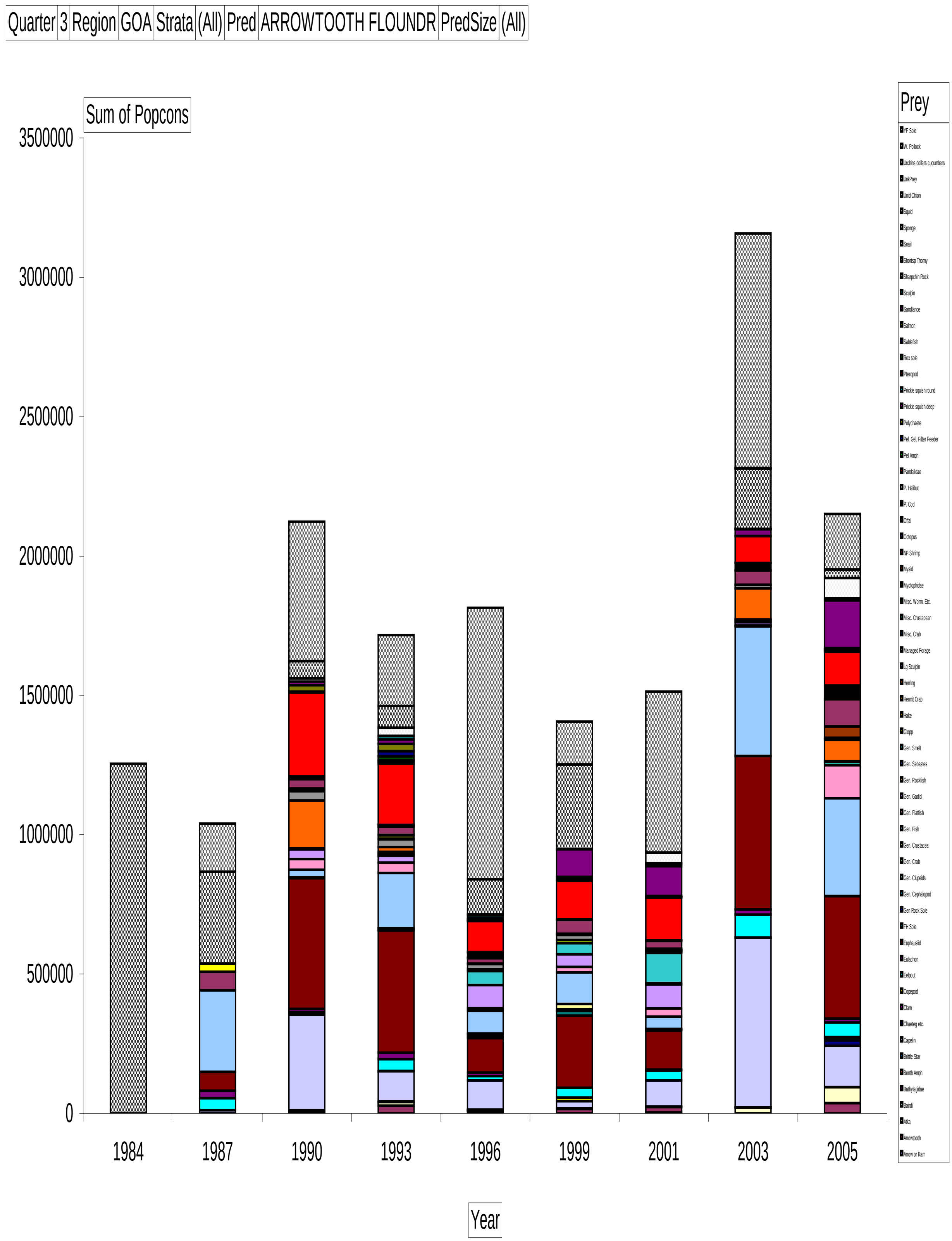

Figure B.10. Adult (20+ cm) arrowtooth estimated consumption of prey by survey year in the GOA.

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). Arrowtooth flounder are currently the most abundant groundfish in the GOA (Turnock et al. 2003a). 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. 2003a) 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/km^2) than in either the EBS or AI (<1 t/km^2). 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 ($N_{at} \cdot \Delta W_{at}$), where N_{at} is the number of fish of a given age class in a given year, exponentially averaged to account for mortality throughout the year, and ΔW_{at} 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.

Fish Consumption rates

There are multiple methods for estimating the consumption rates (Q/B, consumption per unit biomass) for fish. Four methods were considered in the construction of these models: bioenergetics models (based on laboratory and field experiments), allometric fitting to weight-at-age data (e.g. Essington et al. 2001), evacuation rate calculation from field stomach contents data (e.g. MAXIMS, Jarre et al. 1991) and empirical methods based on morphological characteristics (Pauly 1986). One goal in selecting methods was to choose options which could be used consistently in all three ecosystem models and thus provide reasonable bases for comparison.

It was determined that insufficient data existed for the application of bioenergetics models or evacuation rate calculations; while models existed for a very limited number species, input data such as foraging rates and water temperature specific to the Alaska region were not consistently available, and lack of these data could result in extremely broad error ranges or bias in estimates. Pauly's (1986) empirical methods have an order-of-magnitude error range and thus were considered as a worst-case solution only.

While bioenergetics data was limited, weight-at-age data existed for many species throughout the region: the method of fitting the generalized Von Bertalanffy growth equations to these data (Essington et al. 2001) was thus selected. (The solution for Q/B given above, (Z+3K)/A, is a solution for a specialized case of the equations, as described below).

The generalized Von Bertalanffy growth equation assumes that both consumption and respiration scale allometrically with body weight, and change in body weight over time (dW/dT) is calculated as follows (Paloheimo and Dickie 1965):

$$\frac{dW_t}{dt} = H \cdot W_t^d - k \cdot W_t^n \qquad (1)$$

Here, W_t is body mass, t is the age of the fish (in years), and H, d, k, and n are allometric parameters. The term $H \cdot W_t^d$ is an allometric term for "useable" consumption over a year, in other words, the consumption (in wet weight) by the predator after indigestible portions of the prey have been removed and assuming constant caloric density between predator and prey. Total consumption (Q) is calculated as $(1/A) \cdot H \cdot W_t^d$, where A is a scaling fraction between predator and prey wet weights that accounts for indigestible portions of the prey and differences in caloric density. The term $k \cdot W_t^n$ is an allometric term for the amount of biomass lost yearly as respiration.

Based on an analysis performed across a range of fish species, Essington et al. (2001) suggested that it is reasonable to assume that the respiration exponent n is equal to 1 (respiration linearly proportional to body weight). In this case, the differential equation above can be integrated to give the following solution for weight-at-age:

$$W_t = W_\infty \cdot \left(1 - e^{-k(1-d)(t-t_0)}\right)^{\frac{1}{1-d}} \qquad (2)$$

Where W_∞ (asymptotic body mass) is equal to $(H/k)^{\frac{1}{1-d}}$, and t_0 is the weight of the organism at time=0. If the consumption exponent d is set equal to 2/3, this equation simplifies into the "specialized" von Bertalanffy length-at-age equation most used in fisheries management, with the "traditional" von Bertalanffy K parameter being equal to the k parameter from the above equations divided by 3.

From measurements of body weight and age, equation 2 can be used to fit four parameters (W_∞, d, k, and t_0) and the relationship between W_∞ and the H, k, and d parameters can then be used to determine the consumption rate $H \cdot W_t^d$ for any given age class of fish. For these calculations, weight-at-age data available and specific to the modeled regions were fit by minimizing the difference between log(observed) and log(predicted) body weights as calculated by minimizing negative log likelihood: observation error was assumed to be in weight but not aging. A process-error model was also examined but did not give significantly different results.

Initial fitting of 4-parameter models showed, in many cases, poor convergence to unique minima and shallow sum-of-squares surfaces: the fits suffered especially from lack of data at the younger age classes that would allow fitting to body weights near t=0 or during juvenile, rapidly growing life stages. To counter this, the following multiple models were tested for goodness-of-fit:

1. All four parameters estimated by minimization;
2. d fixed at 2/3 (specialized von Bertalanffy assumption)
3. d fixed at 0.8 (median value based on metaanalysis by Essington et al. 2001).
4. t_0 fixed at 0.
5. d fixed at 2/3 with t_0 fixed at 0, and d fixed at 0.8 with t_0 fixed at 0.

The multiple models were evaluated using Aikeike's Information Criterion, AIC (Anderson and Burnham 2002). In general, the different methods resulted in a twofold range of consumption rate estimates; consistently, model #3, d fixed at 0.8 while the other three parameters were free, gave the most consistently good results using the AIC. In some cases model #1 was marginally better, but in some cases, model #1 failed to converge. The poorest fits were almost always obtained by assuming that d was fixed at 2/3.

To obtain absolute consumption (*Q*) for a given age class, the additional parameter *A* is required to account for indigestible and otherwise unassimilated portions of prey. We noted that the range of indigestible percentage for a wide range of North Pacific zooplankton and fish summarized in Davis (2003) was between 5-30%, with major zooplankton (copepods and euphasiids), as well as many forage fish, having a narrower range of indigestible percentages, generally between 10-20%. Further, bioenergetics models, for example for walleye pollock (Buckley and Livingston 1994), indicate that nitrogenous waste (excretion) and egestion resulted in an additional 20-30% loss of consumed biomass. As specific bioenergetics models were not available for most species, we made a uniform assumption of a total non-respirative loss of 40% (from a range of 25-60%) for all fish species, with a corresponding *A* value of 0.6.

Finally, consumption for a given age class was scaled to population-level consumption using the available numbers-at-age data from stock assessments, or using mortality rates and the assumption of an equilibrium age structure in cases where numbers-at-age reconstructions were not available.

Diet queries for fish

The most central parameter set for food web models are the diet composition matrices, obtainable through stomach sampling or other analyses. In particular, the elaboration of our food web models with respect to fished species depends heavily on the analysis of 250,000+ stomachs collected by the Resource Ecology and Ecosystem Management (REEM) program. Continuation of this collection will allow for a regular update and improvement of these models. Due to the high resolution and coverage of this diet data, we were able to model functional groups at a relatively high resolution: over 120 functional groups are specifically and separately accounted with survey strata-level resolution (rough depth and location), with specific juvenile and adult accounting for several of the commercial groundfish, crab, and pinniped species. Diets estimated directly from stomach samples collected in the same area that a model covers are considered “direct”.

The diet composition for a species is calculated from stomach sampling beginning at the level of the individual survey haul (1), combining across hauls within a survey stratum (2), weighting stratum diet compositions by stratum biomass (3), and finally combining across predator size classes by weighting according to size-specific ration (consumption rate) estimates and biomass from stock assessment estimated age structure (4). Consumption rate calculations are described in detail above.

Notation:

DC = diet composition
W = weight in stomach
n = prey
p = predator
s = predator size class
h = survey haul
r = survey stratum
B = biomass estimate
v = survey
a = assessment
R = Q/B = ration estimate

Diet composition (DC) of prey n in predator p of size s in haul h is the total weight of prey n in all of the stomachs of predator p of size s in the haul divided by the sum over all prey in all of the stomachs for that predator size class in that haul:

$$DC_{n,p,s,h} = W_{n,p,s,h} \Big/ \sum_n W_{n,p,s,h} \qquad (1)$$

Diet composition of prey n in predator p of size s in survey stratum r is the average of the diet compositions across hauls within that stratum:

$$DC_{n,p,s,r} = \sum_h DC_{n,p,s,h} \Big/ h \qquad (2)$$

Diet composition of prey n in predator p of size s for the entire area t is the sum over all strata of the diet composition in stratum r weighted by the survey biomass proportion of predator p of size s in stratum r:

$$DC_{n,p,s,t} = \sum_r DC_{n,p,s,r} * B^v_{p,s,r} \Big/ \sum_r B^v_{p,s,r} \qquad (3)$$

Diet composition of prey n in predator p for the entire area t is the sum over all predator sizes of the diet composition for predator p of size s as weighted by the relative stock assessment biomass of predator size s times the ration of predator p of size s:

$$DC_{n,p,t} = \sum_s DC_{n,p,s,t} * B^a_{p,s} * R_{p,s} \Big/ \sum_s B^a_{p,s} * R_{p,s} \qquad (4)$$

Diets for fish and shellfish not included in the REEM database were taken from published literature sources or the nearest survey samples. For example, diets estimated from stomachs collected in the EBS may be used as surrogates in the AI and GOA if these last systems lack specific diet information. However these diets would be considered “general” for the AI and GOA in the sense that they are not from stomach samples taken as part of the REEM program and are neither weighted by depth nor location (but they would be for the EBS); in these cases prey items were assigned fixed percentages.

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