Preliminary age structured assessment model of the Pacific cod stock in the Aleutian Islands

Ingrid Spies, Grant G. Thompson, Steve Barbeaux, and James N. Ianelli
Alaska Fisheries Science Center, National Marine Fisheries Service
National Oceanic and Atmospheric Administration
7600 Sand Point Way NE., Seattle, WA 98115-6349
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Harvest specifications for Aleutian Islands (AI) Pacific cod have been based on Tier 5 methodology since the AI and eastern Bering Sea (EBS) stocks were first managed separately in 2014. Several age-structured models of this stock have been explored in assessments from 2012-2016. This document presents an age structured model for the Aleutian Islands Pacific cod stock using complete data through 2018.

Summary of results

The results of the model are presented in the following table. Biomass and catch statistics are in metric tons (t). This is a preliminary model and it was not presented or used last year. The projected age 1+ total biomass for 2019 is 127,751 t. The projected female spawning biomass for 2019 is 34,348 t. The recommended 2019 ABC is 20,331 t based on an $F_{40\%}$ =0.686 harvest level. The 2019 overfishing level is 24,645 t based on a $F_{35\%}$ =0.880 harvest level.

	As estimated or *specified last* year for:		As estimated or *recommended this* year for:	
Quantity	2018	2019	2019	2020
M (natural mortality rate)	-	-	0.4	0.4
Tier	-	-	3b	3b
Projected total (age 1+) biomass (t)	-	-	127,419 t	127,751 t
Projected female spawning biomass (t)	-	-	35,939 t	34,348 t
$B_{100\%}$	-	-	96,132 t	96,132 t
$B_{40\%}$	-	-	38,453 t	38,453 t
$B_{35\%}$	-	-	33,646 t	33,646 t
F_{OFL}	-	-	0.880	0.880
$maxF_{ABC}$	-	-	0.686	0.686
F_{ABC}	-	-	0.686	0.686
OFL	-	-	27,343 t	24,645 t
$maxABC$	-	-	22,620 t	20,331 t
ABC	-	-	22,620 t	20,331 t
Status	2016	2017	2017	2018
Overfishing	-	-	No	n/a
Overfished	-	-	n/a	No
Approaching overfished	-	-	n/a	No

*Projections are based on annual catches of 20,414 t for 2019 and the 2019 ABC for 2020.

Introduction

This document presents a new age-structured model for the assessment of the Pacific cod (*Gadus macrocephalus*) stock in the Aleutian Islands (AI). The most recent age-structured models for Aleutian Islands Pacific cod were presented in the 2016 preliminary (September) stock assessment. The website located at http://tinyurl.com/Pcod-cie-2016 contains final reports from the three reviewers of a recent Center for Independent Experts (CIE) review of the Aleutian Islands Pacific cod assessment.

Aleutian Islands Pacific cod were managed together with the eastern Bering Sea stock through the assessment year 2012. Starting in 2013, the assessment has been based on Tier 5 methodology, although age structured models have been presented from 2012-2016. The Aleutian Islands stock was determined to be distinct from the Bering Sea stock due to genetic, movement, and growth differences, which are summarized briefly here. There is evidence for isolation-by-distance stock structure in Pacific cod (Cunningham et al. 2009, Spies 2012, Drinan et al. 2018). The Bering Sea and Aleutian Islands have been shown to be genetically distinct (Spies 2012). Within the Aleutian Islands there may be some evidence for additional sub-structure at the level of the spawning stock but this remains to be confirmed (Spies 2012).

Tagging studies provide evidence for a closed system of annual migration in Pacific cod to spawning areas in winter return followed by movement to summer feeding areas (Shimada and Kimura 1994; Rand et al. 2014). Fish captured in the same three month period within the same season in different years showed only random movement, but little directional movement. In contrast, strong inter-seasonal movements between fall-winter and winter-spring tag recaptures were observed, as cod moved from feeding to spawning areas. Seasonal migrations outside of spawning season may be triggered by a combination of avoidance of temperature extremes and food availability.

Pacific cod range from the coast of Washington State, U.S.A, including the inland waters of Puget Sound, along the west coast of Canada, the Gulf of Alaska, the Bering Sea, Aleutian Islands, and along the Pacific rim as far as Korea. Pacific cod larvae can survive within a thermal window of 0-8°C (Laurel et al. 2008), and adults are seldom observed in the cold pool, water below 2°C (Stevenson and Lauth 2019). Temperature avoidance in the ocean may be achieved vertically or horizontally (Yang et al. 2019). Coastal stocks may achieve this by moving deeper to avoid warm water, but the bathymetry of the Bering Sea may necessitate long range movement (Shimada and Kimura 1994).

Further information on Pacific cod fishery, survey, and life history are available in the main portion of the 2019 Aleutian Islands stock assessment.

Data

The data used in this preliminary age structured model include fishery catch and size compositions, survey biomass and standard error, and age compositions from survey data. Data sources and years are shown in the following table.

Source	Type	Years
Fishery	Catch biomass	1990-2018*
Fishery	Size composition	1990-2018
AI bottom trawl survey	Biomass estimate	1991, 1994, 1997, 2000, 2002, 2004, 2006, 2010, 2012, 2014, 2016, 2018
AI bottom trawl survey	Age composition	1991, 1994, 1997, 2000, 2002, 2004, 2006, 2010, 2012, 2014, 2016

*Partial catch information for 2019 was available and was extrapolated to estimate the catch for the full year. Catch as of August 23, 2019 was 18,133 t.

Fishery

There are three predominant gear types in the Pacific cod fishery; pot, trawl, and longline (Figure 1). Cod fisheries that operate during the feeding season, typically rely on longline gear, while cod are targeted primarily using trawl nets during spawning season because they aggregate. Pot gear is the least common gear type, and is used throughout the year. Catch data is used in the model by area and gear combined; there is a single catch biomass (Table 1) and vector of length frequencies in each year from the fishery. The number of length observations from catch data by year is shown in Table 2.

Fishery lengths are taken throughout the year by observers (Figure 1).

Survey

The National Marine Fisheries Service (NMFS) conducts biennial daytime summer trawl surveys in the Aleutian Islands. Survey biomass is estimated by extrapolating the weight from individual trawls with the measured path of the trawl area to the total area surveyed. The net used in the Aleutian Islands survey is a high-rise poly-Noreastern 4 seam bottom trawl (27.2 m headrope, 36.8 m footrope) (Nichol et al. 2007). Survey biomass estimates and standard error for Pacific cod are available for the survey years 1991, 1994, 1997, 2000, 2002, 2004, 2006, 2010, 2012, 2014, 2016, and 2018 (Table 3). Aleutian Islands surveys prior to 1991 were not used in the model because they were not standardized to current survey methodology; therefore, data from the 1980, 1983, and 1987 surveys were excluded. Survey data includes NMFS areas 541, 542, and 543. The Aleutian Islands bottom trawl survey does include NMFS areas 518 and 519, but these are part of the Bering Sea management area and were not included in data for this model.

Age data from the survey is available, and was used in the model. The number of aged fish from each year of the survey is shown below.

Year	Number aged
1991	919
1994	1,174
1997	845
2000	828
2002	1,270
2004	775
2006	754
2010	673
2012	598
2014	557
2016	681

Other data used in the assessment:

Length-at-age and weight-at-length were used outside the model to configure a length-age conversion matrix and vonBertalanffy growth curve.

Analytic Approach

General Model Structure

The age-structured statistical model was implemented in the Automatic Differentiation Model Builder (ADMB) framework (Fournier et al. 2012). This framework uses automatic differentiation and allows estimation of highly-parameterized and non-linear models. The age-structured population dynamics model was fit to survey abundance estimates, survey age data, fishery catch, and fishery length composition data. The model was fit to the data by minimizing the objective function, analogous to maximizing the likelihood function. The model implementation language provides the ability to estimate the variance-covariance matrix for all parameters of interest. The model incorporated ages 1-10, where 10 is considered a "plus group" including all ages 10 and above, and estimated selectivity using an increasing logistic equation for the fishery and the survey. 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. A projection model was implemented to generation estimates of spawning stock biomass and reference points into the future. In this model, spawning month was set to February, which is typically the peak of spawning in the Aleutian Islands. As a result, estimates of spawning biomass for 2018 onward from the projection model are slightly lower than the age structured model results because they take into account two months of mortality (January, February).

Model features:

- One fishery, one gear type, one season per year.
- Single sex model, 50% male female ratio.
- Logistic age-based selectivity for both the fishery and survey.
- External estimation of a single growth curve (vonBertalanffy), length at age, weight at age.
- An ageing error matrix for ages 1 through 10.
- All parameters constant over time except for recruitment and fishing mortality.
- Internal estimation of fishing mortality, catchability, and selectivity parameters.
- Recruitment estimated as a mean with normally distributed deviations
- Natural mortality was fixed in the model, and estimated with input from likelihood profiles performed using the model.
- Survey catchability was estimated within the model as a constant multiplier on survey selectivity.

Parameters Estimated Outside the Assessment Model

Maturity

The maturity-at-age is governed by the relationship:

$$Maturity_{age} = \frac{1}{1 + e^{-(A+B*age)}},$$

where A and B are parameters in the relationship.

A study based on a collection of 129 female fish in February, 2003, from the Unimak Pass area, NMFS area 509, found that 50% of female fish become mature at approximately 4.88 years ($L_{50\%}$) and 58.0 cm, A=-4.7143, B=0.9654 (i.e. Tables 2 and 4 in Stark 2007). Several aspects of this study have been called into question; the sample size was low, and the sampling location was not in the Aleutian Islands.

Observers routinely collect maturity at length from Pacific cod. There are 2,098 records from the Aleutian Islands (see table below) during the months January – March since 2008. These were used to estimate a maturity ogive by length using the R package *sizeMat*, which estimates the length of fish at gonad maturity. The size at 50% maturity was estimated as the length at which a randomly chosen specimen has a 50% chance of being mature. Maturity was considered a binomial response varable and variables were fitted to the logistic function above for maturity, and the length at which 50% of cod are mature is $L_{50\%} = -A/B$.

Year	Number of records
2008	1185
2009	35
2010	156
2011	80
2012	151
2013	61
2014	128
2015	78
2016	79
2017	42
2018	26
2019	77

Using this method the parameters were A=-7.881832 and B=0.1464385. This ogive provided maturity at length which was converted to maturity at age using the length age conversion matrix. The resulting ogive had $L_{50\%}$, slightly lower than the Stark (2007) estimate. $L_{50\%}$ was estimated to be 53.8 cm (age 4). Maturity parameters for the Stark (2007) data and the ogive using observer data are shown in Figure 2 and Table 4.

Selectivity

Selectivity for the fishery and the survey were fit (separately) using a two parameter logistic growth curve:

$$Selectivity_{age} = \frac{1}{1 + e^{-(slope*age-a_{50})}},$$

where the two parameters estimated were *slope* and a_{50}.

Length at Age

Pacific cod do not exhibit sexually dimorphic growth; males and females grow at the same rate. Therefore, the model did not distinguish between males and females. Growth was estimated from length and age data from AI surveys from 1991 to 2016. All data used in the model was aged after 2007, as there was a shift in our understanding of the first two checks deposited at early ages in Pacific cod. Prior to 2007 they were thought to be true annuli, but subsequently determined not to be. Length at age is typically adjusted for survey length frequencies for which there is more data and is assumed to be a better representation of the length frequencies in the population than the lengths of the aged fish. Fish were historically collected in length stratified collections and there were 489,000 length observations from surveys 1991-2016. The correction is based on Bayes Theorem, and follows (Dorn 1992). The stratified age collections consist of the probability of length given age $P(Length|Age)$. These are often corrected for the length frequencies in the population by dividing by length frequencies from survey data from the same years,

$$P(Age|Length) = P(Length|Age) * P(Age)/P(Length).$$

A von Bertalanffy individual growth model was applied to the corrected and uncorrected length at age data, using the R package *fishmethods*, resulting in the following parameter estimates.

Input data	S_{inf}	K	t_0
Corrected Length at age	106.3310	0.18587	-0.07247
Uncorrected length at age	124.93646	0.15883	-0.09981

The growth curve was fit to the vonBertalanffy growth equation:

$$Length_{age} = S_{inf}(1 - e^{-(K(age-t_0))}).$$

The correction downweights lengths for which there are fewer observations in the population as a whole, and there are typically the fewest length observations at very large and very small sizes. The correction operates under the assumption that the survey length frequencies are representative of the Aleutian Islands population as a whole. However, this may not be the case, as larger fish are observed in the fishery than the survey (Figure 3). For example the largest fish recorded in the fishery was 143 cm, while the largest fish from the survey was 116 cm. Correcting for survey length frequencies reduced the expected length at age in the population as compared to lengths of aged fish from a stratified collection (Figure 4). When the correction was implemented, the asymptotic size S_{inf} was was 106 cm, but without the correction, S_{inf} was 124 cm (Figure 5). Therefore, the growth curve and the length at age conversion matrix were calculated without correcting for survey length frequencies.

A length-age conversion matrix was compiled using average length-at-age based on the uncorrected lengths at age shown above. The coefficient of variation (CV) typically decreases with age. The CV of length at age was fitted using linear regression (Figure 6), with the parameters shown in the figure. When a monotonically decreasing CV is converted to variance, it becomes inversely dome shaped, with lower variance at middle ages (Figure 7).

The length-age conversion matrix was generated by simulating $10x10^6$ data points for mean length at ages 1-10+ based on estimates of mean length at age and variance at each age. The simulations were generated from a normal distribution, with the mean length at age determined by the von Bertalanffy parameters fit to the length-age data and the variance for length at age determined by the parameters of the linear models (Figure 5). The length-age conversion matrix is shown in Figure 7, and mean length at age is compared with raw data in Figure 5 (red line).

Length at age was converted to weight at age with the weight-at-length relationship described in the next section.

Weight-at-length The weight-length relationship for Aleutian Islands Pacific cod was evaluated to be:

$$Weight_{age} = 1.284x10^{-6} * Length_{age}^{3.319},$$

for both sexes combined, where weight is in kilograms and length in millimeters (Figure 8). Analysis was performed using nonlinear least squares fit to all weight and length data, 9,213 individuals. The nonlinear least squares (nls) method was implemented from the R package *stats* R Core Team (2019).

Natural mortality

A natural mortality esimate of 0.36 been used in the most recent Aleutian Islands Pacific cod assessment, as well as the BSAI cod assessment (Thompson et al. 2018). For the Gulf of Alaska, a natural mortality of 0.49 was used in the most recent assessment (Barbeaux et al. 2018). In this assessment a likelihood profile was performed on natural mortality values from 0.1 to 0.9.

The natural mortality likelihood profile showed some contrast in the results; the fishery length likelihood indicated that the lowest likelihood occurred at $M = 0.3$, whereas the other likelihood components (survey age, survey biomass, and recruitment) were minimized at $M = 0.8$ (Table 5). However, these likelihoods decreased quickly until $M = 0.3$ and remained shallow thereafter (Figure 9). To balance the different likelihood components and consider the values for M used in other assessments, the value $M = 0.4$ was selected. This value of M was fixed in the model.

Catchability

Literature and previous studies can inform choices for catchability. Somerton (2004) found no evidence for herding in Pacific cod. This experiment took place using the 83-112 Eastern Trawl trawl net in the eastern Bering Sea and the Poly Noreastern trawl net in the Bering Sea (Somerton et al. 2004). Another study estimated that 47.3% of cod in the water column to be available to the trawl used on the eastern Bering Sea trawl survey and 91.6% are available to the trawl used on the Gulf of Alaska and Aleutian Islands surveys (Nichol et al. 2007). This study was based on results showing that 95% of cod were found within 10 m of the seafloor, based on 286 archival tagged cod off Kodiak Island in the Gulf of Alaska and off Unimak Pass in the eastern Bering Sea, Alaska (Nichol et al. 2007).

Survey catchability (q) was estimated within the model as a constant multiplier on the survey selectivity. Fishery catchability was assumed to be 1.

Parameters Estimated Inside the Assessment Model

Survey Catchability

Survey catchability was estimated within the model as a multiplier on survey selectivity.

Results

Model Evaluation

The Aleutian Islands stock of Pacific cod was managed jointly with the eastern Bering Sea stock through 2012. An age structured model for AI cod was first presented to the SSC in 2012 and age structured models were presented in 2013-2015. The development of these models is presented in the Appendix.

The initial age structured model presented by Grant Thompson in 2012 included:

- a single season,
- one fishery,
- AI-specific weight-length parameters,
- 1 cm length bins to 150cm,
- forced asymptotic fishery selectivity,
- fishery selectivity constant over time,
- survey samples age 1 fish at true age 1.5,
- ageing bias not estimated,
- q (catchability) tuned to match value from archival tagging data relevant to GOA/AI survey net.

In 2013 the SSC supported a model with the development of two models 1. fixed M fixed and q fixed at 1 and freely estimated selectivity. 2. M fixed, q estimated with a prior, and asymptotic survey selectivity.

In 2014 the Plan Team recommended only data from 1991 onward.

In 2015 the Plan Team did not consider any of the age structured models credible but encouraged further work on an age-structured model.

The model presented here is very similar to previously developed models, with the following differences:

- logistic fishery (and survey) selectivity,
- fishery (and survey) selectivity constant over time,
- ageing bias was estimated,
- survey q freely estimated (with a prior) and fishery q fixed at 1.

The model contained a total of 65 parameters.

Catchability	Mean log recruitment	Log avg. fmort.	Selectivity	Fishing mortality	Recruitment	Total
1	1	1	4	29	29	65

Likelihood values for survey age composition, survey biomass, fishery length composition and recruitment are presented below.

Likelihood Component	Value
Recruitment	5.695
Survey age	105.412
Survey biomass	16.138

Likelihood Component	Value
Catch	0.002
Fishery length	41.82
Total	169.066

Final parameter estimates generated within the model are listed in Table 6, with confidence bounds. Selectivity for the fishery and the survey are shown in Figure 10.

Retrospective analysis

A retrospective analysis was performed extending back 10 years to evaluate the model, with data from 2008-2018. Data was sequentially removed for years in which Aleutian Islands surveys were conducted; 2018, 2016, 2014, 2012, 2010, and 2008. For example, the 2016 run was created by dropping all data except through 2016, the 2014 run included all data through 2014, etc. The spawning biomass estimates and error bars showed a positive retrospective bias for all retrospective runs except for 2008 which had a negative retrospective bias (Figure 11). Relative differences in spawning biomass were positive except for 2008 which was negative (Figure 12). The value for Rho is 0.1040051.

There are no guidelines regarding how large Rho (absolute value) should be before an assessment is declared to exhibit an important retrospective bias. However, 0.1040051 is in the range of values exhibited by many other Alaska groundfish species. The positive retrospective bias indicates that the model may be slightly overestimating spawning biomass for the current year.

Time Series Results

Total biomass (defined as age 1 and older) declined from approximately 190,000 t in 1990 to a low of 89,787 t in 2013 (Figure 13). Since 2013, the biomass has increased to an estimate of 127,419 t (Table 7). Female spawning biomass has followed a similar trajectory, with a peak of 74,687 t in 1992, declining to 26,659 t in 2011, and then increasing to its current level of 35,939 t in 2018. The phase plan plot (Figure 14) shows that spawning biomass was above $B_{40\%}$ from 1990 until approximately 2007. From 2007-2012, fishing was above F_{abc} but declined starting in 2013. Spawning biomass fell below $B_{35\%}$ from 2009-2016. Since 2016, biomass has been above $B_{35\%}$. Estimates of total biomass, female spawning biomass, and recruitment with 95% MCMC credible intervals are presented in Figure 15 and Table 8.

Harvest Recommendations

The Aleutian Islands Pacific cod stock is above $B_{35\%}$, and projections indicate it will remain above or near $B_{35\%}$ in 2019 and 2020. The 2018 biomass is 127,419 t and the spawning biomass is 35,939 t. The reference fishing mortality rate for Aleutian Islands Pacific cod is determined by the amount of reliable population information available (Amendment 56 of the Fishery Management Plan for the groundfish fishery of the Bering Sea/Aleutian Islands), and this model used Tier 3b methodology. Equilibrium female spawning biomass was calculated by applying the female spawning biomass per recruit resulting from a constant $F_{40\%}$ harvest to an estimate of average equilibrium recruitment. Year classes spawned in 1990-2014 were used to calculate the average equilibrium recruitment. This results in an estimate of $B_{40\%}$ = 35,939 t for 2019. Projected 2019 female spawning biomass is compared to $B_{40\%}$ to determine the Tier level. The stock assessment model estimates the 2020 level of female spawning biomass at 34,348 t. Since reliable estimates of B, $B_{40\%}$, $F_{40\%}$, and $F_{35\%}$ exist and $B > B_{35\%}$ (35,939 > 33,646), Aleutian Islands Pacific cod reference fishing mortality is defined in Tier 3b. For 2018 the recommended $F_{ABC} = F_{40\%} = 0.686$ and $F_{OFL} = F_{35\%} = 0.880$.

The 2018 catch was 20,414 t and the 2018 catch through August 23, 2019 was 18,133 t. The total catch in 2019 was estimated to be the same as in 2018.

The stock is being not subjected to overfishing, not overfished, and not approaching a condition of being overfished.

Acknowledgements

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Tables

Table 1: Fishery catch in metric tons by year, 1990-2018.

Year	Catch (t)
1990	7,541
1991	9,798
1992	43,068
1993	34,205
1994	21,539
1995	16,534
1996	31,609
1997	25,164
1998	34,726
1999	28,130
2000	39,685
2001	34,207
2002	30,801
2003	32,457
2004	28,873
2005	22,694
2006	24,211
2007	34,355
2008	31,229
2009	28,582
2010	29,006
2011	10,889
2012	18,220
2013	13,606
2014	10,605
2015	9,217
2016	13,245
2017	15,204
2018	20,414

Table 2: The number of length observations available for the fishery length composition data, by year.

Year	Number of Lengths
1990	1,913
1991	10,769
1992	55,018
1993	26,912
1994	17,393
1995	18,450
1996	24,804
1997	13,821
1998	49,185
1999	29,412
2000	46,165
2001	50,997
2002	20,197
2003	20,546
2004	21,190
2005	18,267
2006	17,742
2007	24,269
2008	23,179
2009	19,429
2010	30,120
2011	7,732
2012	10,260
2013	7,677
2014	3,750
2015	7,992
2016	6,137
2017	9,943
2018	10,820

Table 3: Aleutian Islands bottom trawl survey biomass estimates and standard error for Pacific cod, for all years used in the model.

Year	Biomass (t)	Standard error
1991	180,170	16,302
1994	153,416	31,676
1997	72,848	9,790
2000	126,870	23,494
2002	73,551	12,051
2004	82,218	16,443
2006	84,861	24,406
2010	55,825	10,550
2012	58,910	8,733
2014	73,608	13,798
2016	84,409	15,500
2018	81,272	12,894

Table 4: Maturity at age ogives based on Stark (2007) and observer maturity at length data.

Age	Stark 2007	Observer data
1	0.0230021	0.0029246
2	0.0582223	0.0410585
3	0.1396620	0.2098209
4	0.2988668	0.5126784
5	0.5281452	0.7861340
6	0.7461343	0.9230804
7	0.8852892	0.9729864
8	0.9529746	0.9893226
9	0.9815542	0.9948935
10	0.9928941	0.9974016

Table 5: Likelihood values for recruitment, survey age, survey biomass, fishery lengths likelihood components for various values of natural mortality, M. The total includes all likelihood components except the fishery.

Natural Mortality	Recruitment	Survey Age	Survey Biomass	Fishery	Total (excluding Fishery)
0.11	11.77	125.30	50.89	118.09	187.95
0.12	11.24	124.32	47.56	115.99	183.12
0.13	10.75	123.33	44.40	113.95	178.48
0.14	10.30	122.32	41.40	111.98	174.01
0.16	9.47	120.27	35.92	108.26	165.66
0.17	9.11	119.23	33.44	106.52	161.78
0.18	8.77	118.19	31.15	104.86	158.11
0.27	6.93	109.69	19.19	93.92	135.81
0.28	6.84	108.97	18.85	93.16	134.67
0.29	6.77	108.33	18.71	92.51	133.82
0.34	6.35	107.13	17.57	109.34	131.05
0.35	6.23	107.11	17.32	111.66	130.66
0.37	5.99	107.12	16.81	114.89	129.92
0.39	5.79	107.12	16.32	119.17	129.22
0.40	5.70	107.11	16.08	121.82	128.88
0.41	5.62	107.09	15.85	124.89	128.56
0.42	5.54	107.06	15.63	128.44	128.23
0.44	5.42	107.00	15.20	137.32	127.62
0.45	5.37	106.95	15.00	142.87	127.32
0.46	5.32	106.91	14.80	149.31	127.03
0.47	5.28	106.86	14.61	156.79	126.75
0.48	5.25	106.80	14.43	165.47	126.48
0.49	5.22	106.74	14.25	175.49	126.21
0.50	5.20	106.68	14.08	187.03	125.96
0.51	5.18	106.61	13.92	200.25	125.71
0.52	5.16	106.54	13.77	215.30	125.47
0.53	5.15	106.47	13.62	232.28	125.24
0.54	5.14	106.40	13.49	251.26	125.02
0.55	5.13	106.33	13.36	272.28	124.82
0.56	5.12	106.26	13.23	295.29	124.62
0.57	5.12	106.19	13.12	320.23	124.43
0.58	5.12	106.12	13.01	346.96	124.25
0.59	5.11	106.06	12.91	375.34	124.08
0.60	5.11	106.00	12.81	405.17	123.92
0.61	5.11	105.94	12.72	436.24	123.78
0.62	5.11	105.89	12.64	468.34	123.64
0.63	5.11	105.84	12.56	501.22	123.52
0.64	5.11	105.80	12.49	534.62	123.40
0.65	5.11	105.76	12.42	568.23	123.29
0.66	5.11	105.73	12.35	601.67	123.19
0.67	5.11	105.71	12.29	634.48	123.10
0.68	5.09	105.69	12.22	666.30	122.99
0.69	5.02	105.47	12.14	685.62	122.63
0.70	5.02	105.27	12.11	711.52	122.40
0.71	5.03	105.08	12.07	736.84	122.18
0.72	5.03	104.91	12.04	761.66	121.98
0.73	5.04	104.76	12.01	786.05	121.81
0.74	5.05	104.62	11.98	810.06	121.66
0.75	5.07	104.50	11.96	833.73	121.53
0.76	5.08	104.41	11.93	857.09	121.42

0.78	5.12	104.27	11.89	902.96	121.27
0.79	5.14	104.23	11.87	925.50	121.23
0.80	5.16	104.20	11.85	947.80	121.21
0.82	5.21	104.22	11.81	991.71	121.25
0.83	5.24	104.26	11.80	1013.35	121.30
0.84	5.27	104.32	11.78	1034.80	121.38
0.85	5.31	104.40	11.77	1056.06	121.48
0.86	5.34	104.50	11.76	1077.15	121.60
0.87	5.38	104.62	11.75	1098.08	121.75
0.88	5.42	104.76	11.73	1118.85	121.91
0.89	5.46	104.92	11.72	1139.48	122.10
0.90	5.50	105.10	11.71	1159.98	122.32

Table 6: Parameter values and their 95% confidence intervals, estimated within the model. Parameters include catchability (q), the mean log(recruitment), the log of the average fishing mortality, and two selectivity parameters for the fishery and the survey, *slope* and a_{50}.

	Value	Lower Confidence Interval	Upper Confidence Interval
Catchability	0.91940	0.6557800	1.1830200
Mean log recruitment	10.54000	10.4444735	10.6355265
Log average fishing mortality	-0.65799	-0.9780776	-0.3379024
Survey selectivity slope	1.13220	0.9956213	1.2687787
Survey selectivity a50	3.52110	3.0692612	3.9729388
Fishery selectivity slope	1.33620	0.4394020	2.2329980
Fishery selectivity a50	5.22230	4.3312448	6.1133552

Table 7: Model estimates for total biomass (metric tons, age 1+), recruitment (number of age 1 individuals), and spawning biomass (t), 1990-2018.

Year	Biomass (t)	Spawning biomass (t)	Recruitment
1990	190,205	60,707	79,270
1991	209,867	67,951	23,036
1992	218,979	74,689	30,172
1993	186,417	64,527	38,462
1994	168,715	57,730	82,125
1995	172,764	54,708	37,987
1996	183,131	55,262	70,739
1997	183,093	52,074	75,753
1998	195,588	55,692	43,510
1999	192,215	55,593	42,373
2000	193,970	59,813	68,864
2001	185,234	56,154	68,096
2002	183,253	53,048	37,759
2003	179,967	53,109	28,674
2004	168,822	53,777	32,757
2005	156,032	53,478	19,606
2006	146,542	51,699	54,522
2007	139,239	46,115	46,361
2008	124,898	35,632	38,374
2009	115,598	30,187	28,401
2010	106,658	29,132	18,762
2011	91,274	26,659	22,059
2012	94,774	30,740	26,142
2013	89,782	28,451	41,069
2014	93,506	27,439	35,304
2015	102,875	28,884	39,213
2016	114,833	33,052	28,541
2017	121,399	36,627	38,028
2018	126,451	39,177	43,607

Table 8: MCMC posterior estimates of female spawning biomass, FSB, (t), total biomass, (t), and recruitment (number of age 1 individuals). Mean values with 95% MCMC credible intervals are presented. Lower 95% credible intervals (LCI) and upper 95% credible intervals (UCI) are shown to the right of the statistic they refer to. The 2019 and 2020 values come from the project model, and confidence intervals were estimated from the variance of the 2018 values.

Year	FSB	LCI	UCI	Tot. biomass	LCI	UCI	Recruitment	LCI	UCI
1990	63,991	53,869	75,750	198,382	175,561	225,317	80,025	67,791	93,186
1991	71,224	62,062	82,036	217,601	195,684	243,471	23,304	17,393	29,973
1992	77,799	68,814	88,280	226,102	204,519	250,899	30,500	23,357	38,497
1993	67,399	58,715	77,399	193,097	172,516	216,640	38,931	30,766	47,789
1994	60,466	51,844	70,206	175,151	155,223	197,882	83,099	71,361	95,977
1995	57,342	48,986	66,722	178,986	159,782	200,367	38,043	29,583	47,324
1996	57,743	49,889	66,619	188,964	170,837	208,901	71,114	60,100	83,188
1997	54,380	47,164	62,386	188,606	171,872	207,002	76,036	64,986	87,836
1998	57,955	50,902	65,662	200,957	184,715	218,780	43,585	35,480	52,422
1999	57,838	50,966	65,456	197,494	181,573	215,024	42,435	34,882	50,633
2000	62,025	55,342	69,390	199,075	183,559	216,337	68,940	59,752	78,854
2001	58,380	51,735	65,700	190,369	174,933	207,747	68,379	58,826	78,631
2002	55,243	48,750	62,487	188,258	173,019	205,211	37,881	30,920	45,295
2003	55,166	48,902	62,282	184,698	169,545	201,443	28,714	22,356	35,748
2004	55,706	49,506	62,643	173,304	158,016	189,962	32,388	25,284	40,067
2005	55,411	48,901	62,511	160,286	145,090	176,209	19,338	13,403	26,279
2006	53,581	46,965	60,586	150,361	136,243	164,854	54,193	44,597	64,905
2007	47,780	41,573	54,207	142,425	130,815	154,743	46,107	38,100	55,157
2008	37,034	31,861	42,338	127,585	118,365	137,834	38,494	32,303	45,417
2009	31,312	27,520	35,424	117,956	109,398	127,730	28,666	23,467	34,356
2010	30,118	26,863	33,818	109,152	100,089	119,796	18,989	14,937	23,428
2011	27,731	24,143	32,070	94,155	84,211	106,141	22,392	17,727	27,742
2012	31,965	27,784	37,027	97,857	86,884	111,173	26,508	20,985	32,911
2013	29,739	25,232	35,253	93,007	80,741	107,772	41,678	33,014	51,508
2014	28,759	23,978	34,589	96,831	82,775	113,468	35,448	26,921	45,660
2015	30,216	24,883	36,527	106,195	89,792	125,502	39,511	27,279	54,196
2016	34,388	28,256	41,589	118,159	98,853	140,644	29,500	16,587	45,747
2017	37,961	30,590	46,412	125,952	103,419	151,886	51,312	11,730	128,494
2018	40,642	31,906	50,793	134,435	105,462	170,391	43,803	41,925	45,842
2019	35,939	27,203	25612	127,419	98,446	98,778	-	-	-
2020	34,348	44,675	43084	127,751	156,392	225,317	-	-	-

Figures

Figure 1: Proportion of fishery lengths taken by month for each gear type, with year of the month listed as a number from 1 (January) to 12 (December).

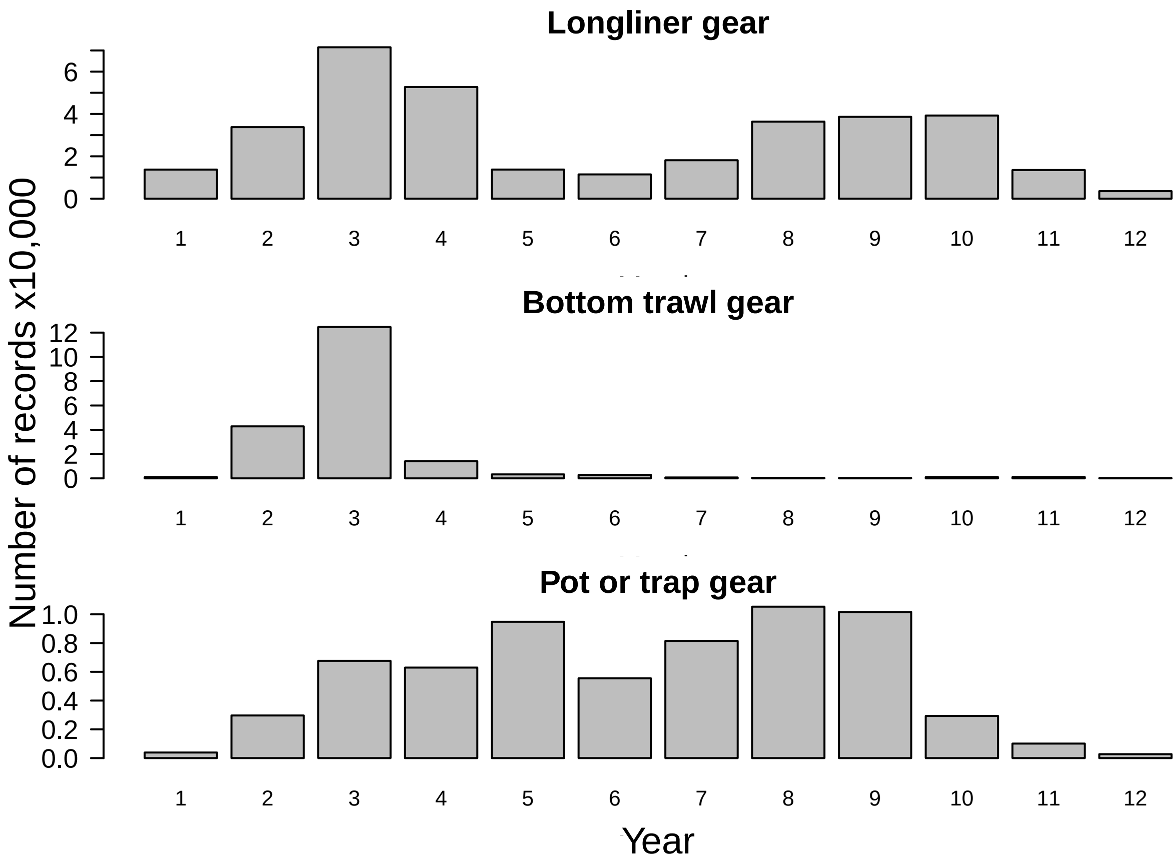


Figure 2: Proportion mature by age, as measured using Stark (2007) parameters and observer maturity at length data.

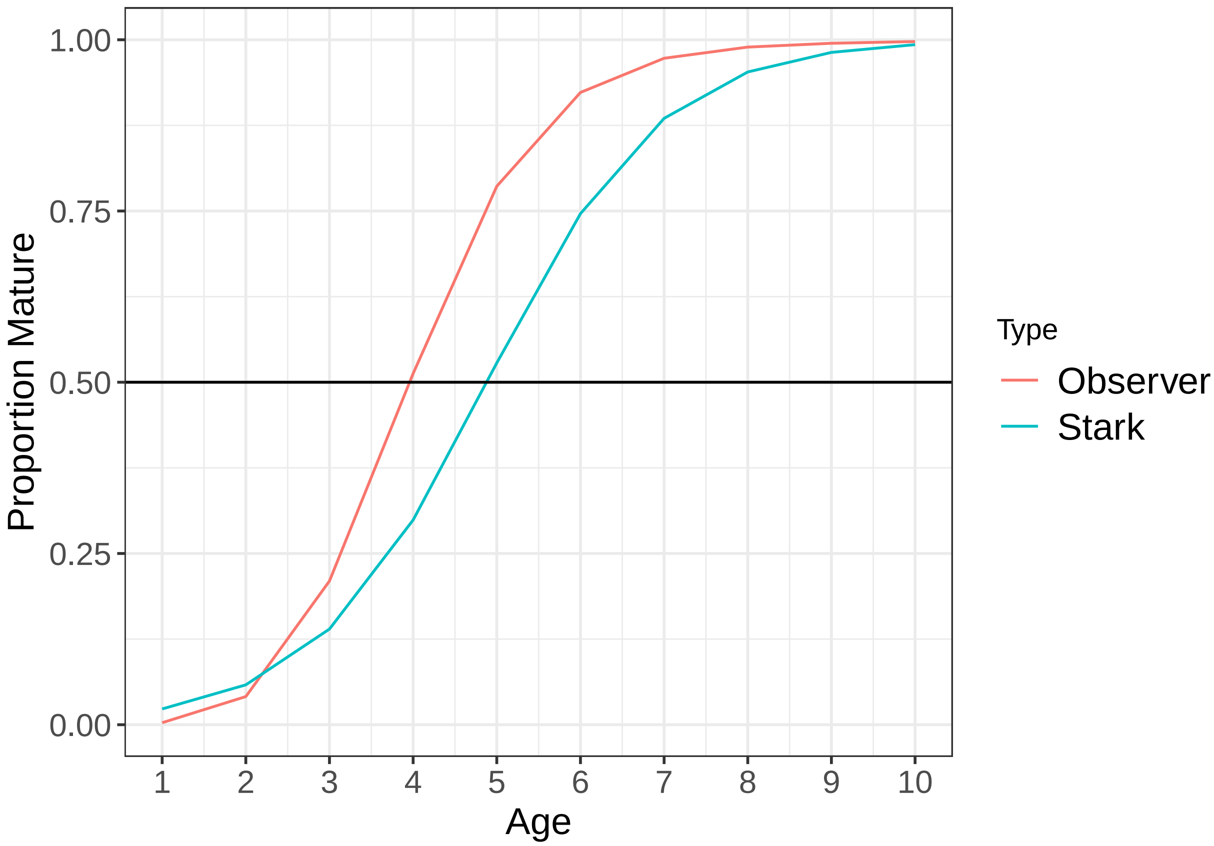


Figure 3: Length frequencies for Pacific cod caught in the Aleutian Islands by the fishery (1990-2018) and the survey, 1991-2018.

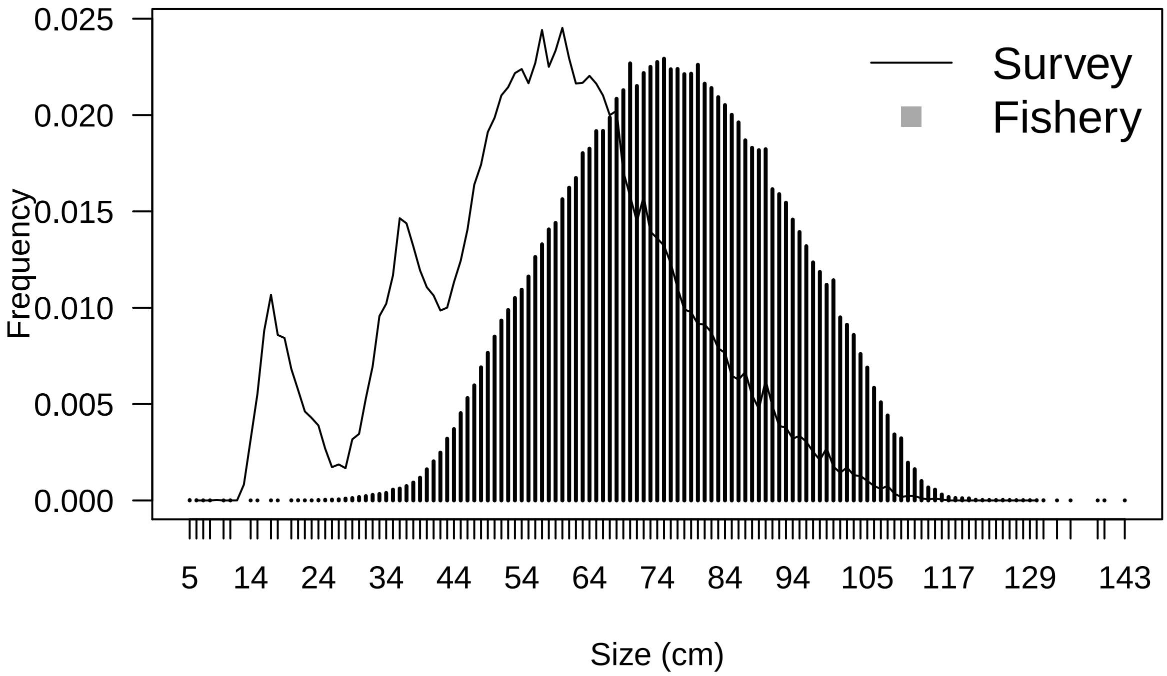


Figure 4: Length frequency by age of cod collected from surveys from 1990-2018.

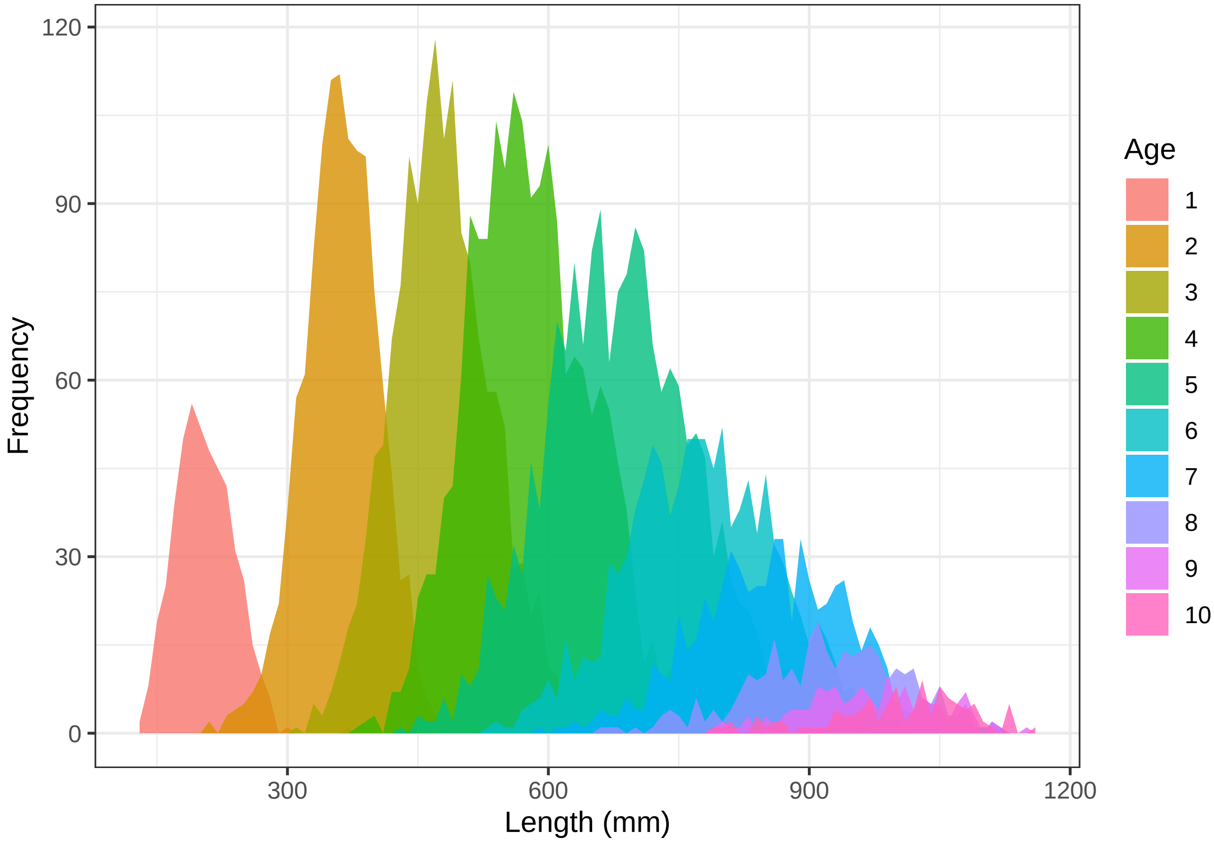
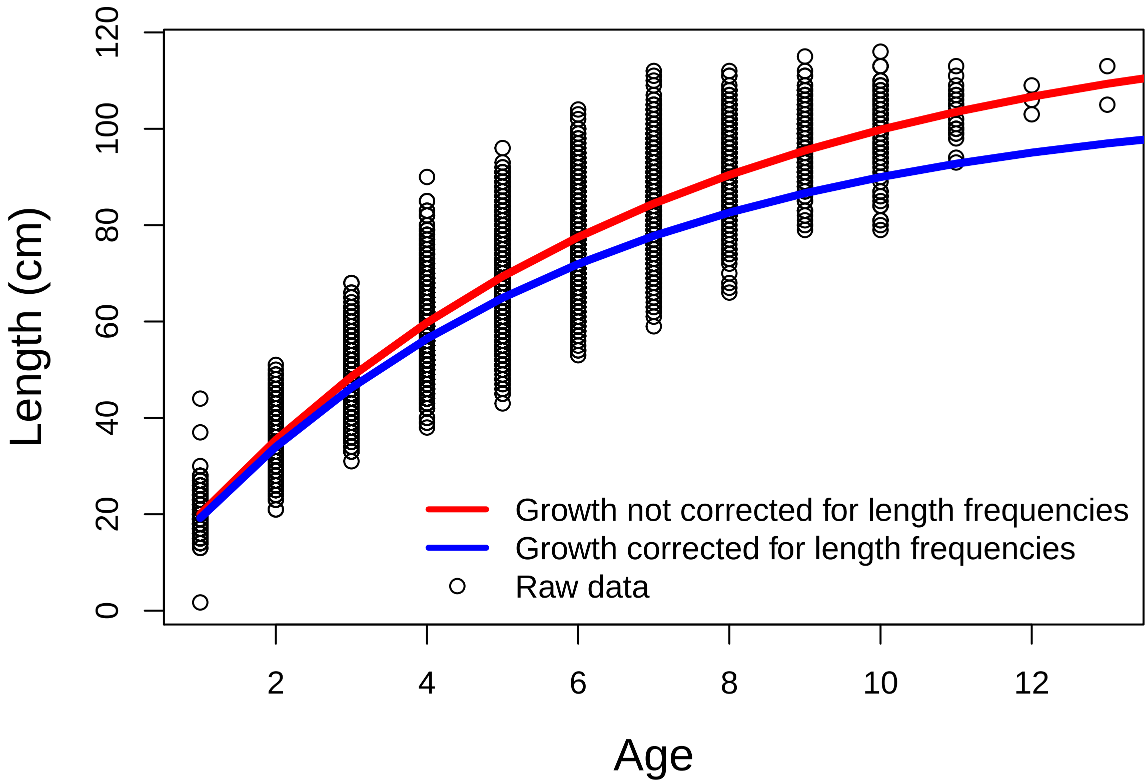
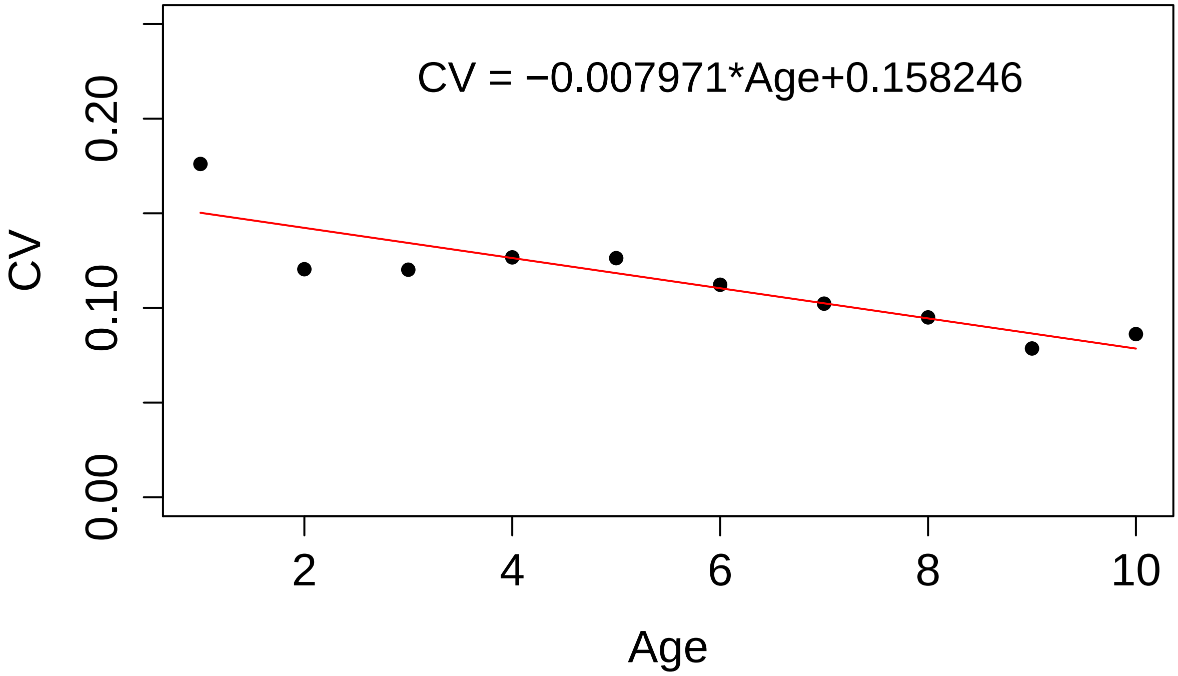


Figure 5: Raw lengths at age and vonBertalanffy growth curves, corrected vs. not corrected for population length frequencies.



312 Figure 6: Coefficient of variation (CV) fitted to age, based on raw data (black points.



313

Figure 7: Length age conversion matrix for Aleutian Islands Pacific cod, ages 1-10, where 10 represents ages 10 and higher.

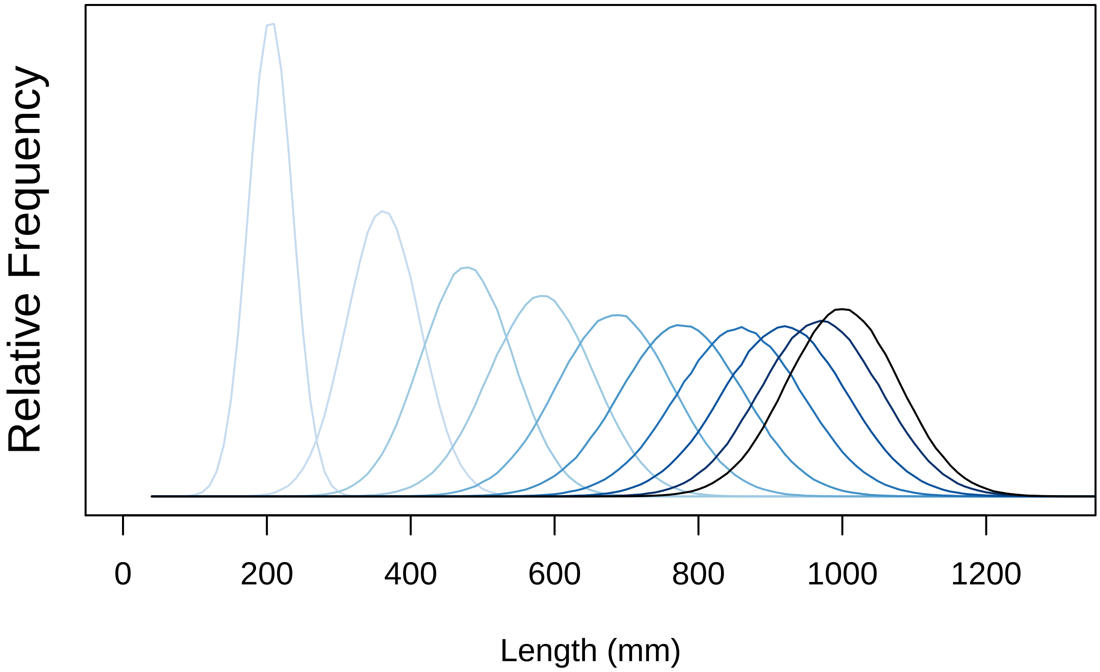


Figure 8: Length-weight relationship for Aleutian Islands Pacific cod, males and females combined. The fit to weight-at-length is shown as a black line. Data is from surveys 1990-2018.

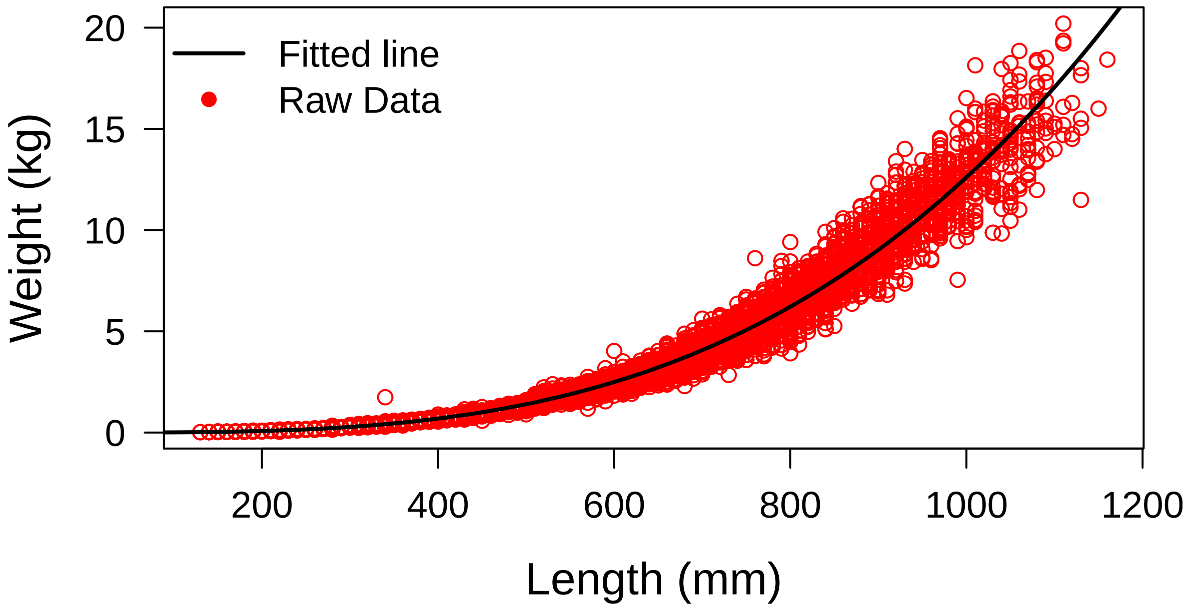


Figure 9: Likelihood profile for natural mortality, showing age, fishery length, recruitment, survey biomass likelihood components. The total likelihood does not include the fishery likelihood component.

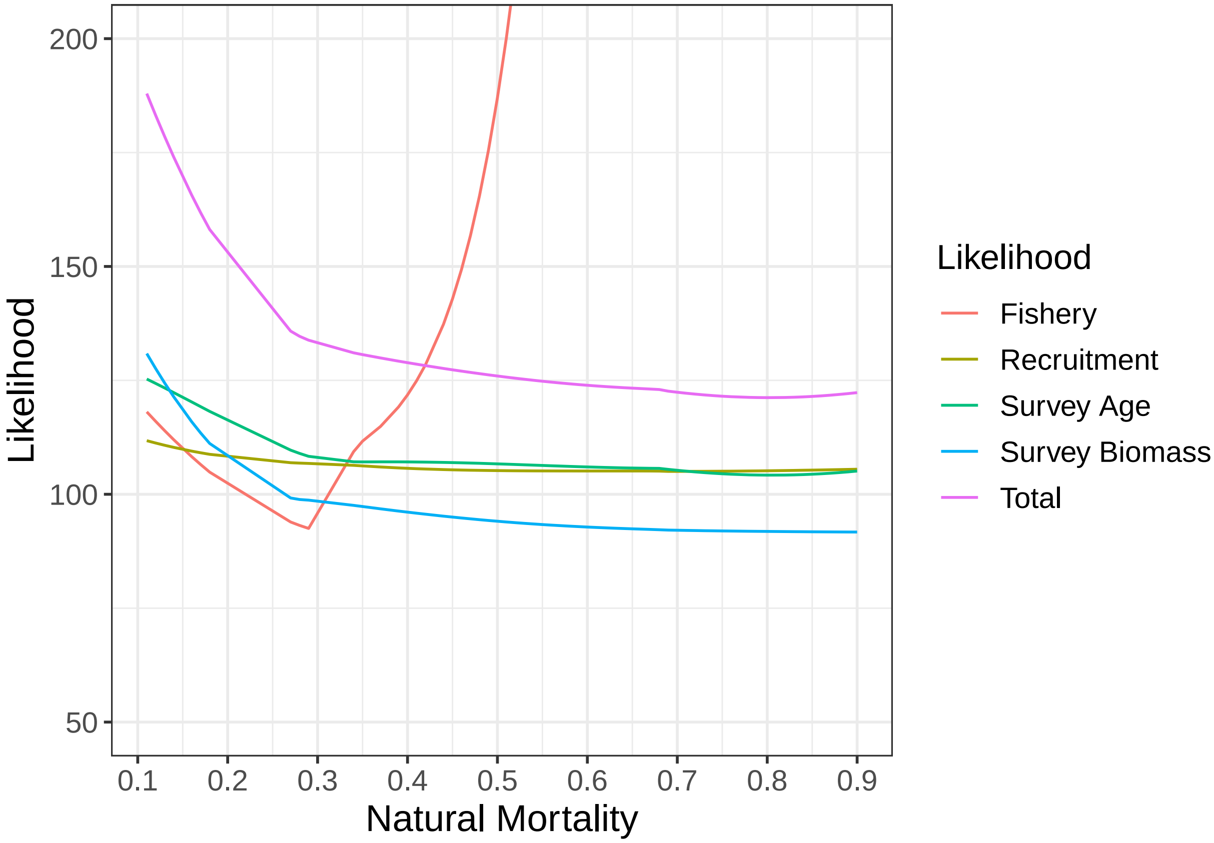
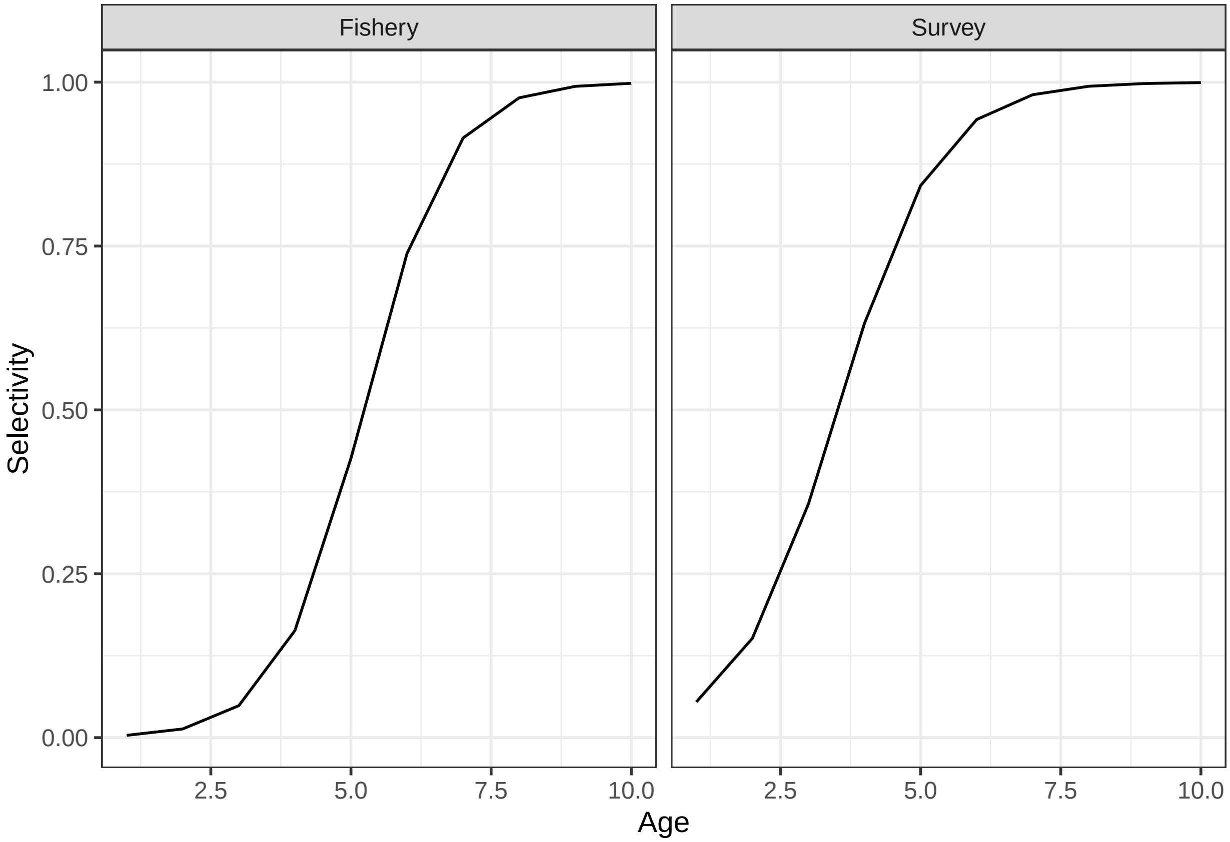


Figure 10: Model estimates for selectivity for the survey and the fishery.



325 Figure 11: Retrospective plot of female spawning biomass. The model with data through 2018 is the longest
326 time series. Retrospective runs were obtained by removing two years of data at a time through 2008.

327

Figure 12: Relative differences in estimates of spawning biomass between the 2018 model and the retrospective model run for years 2016 through 2008.

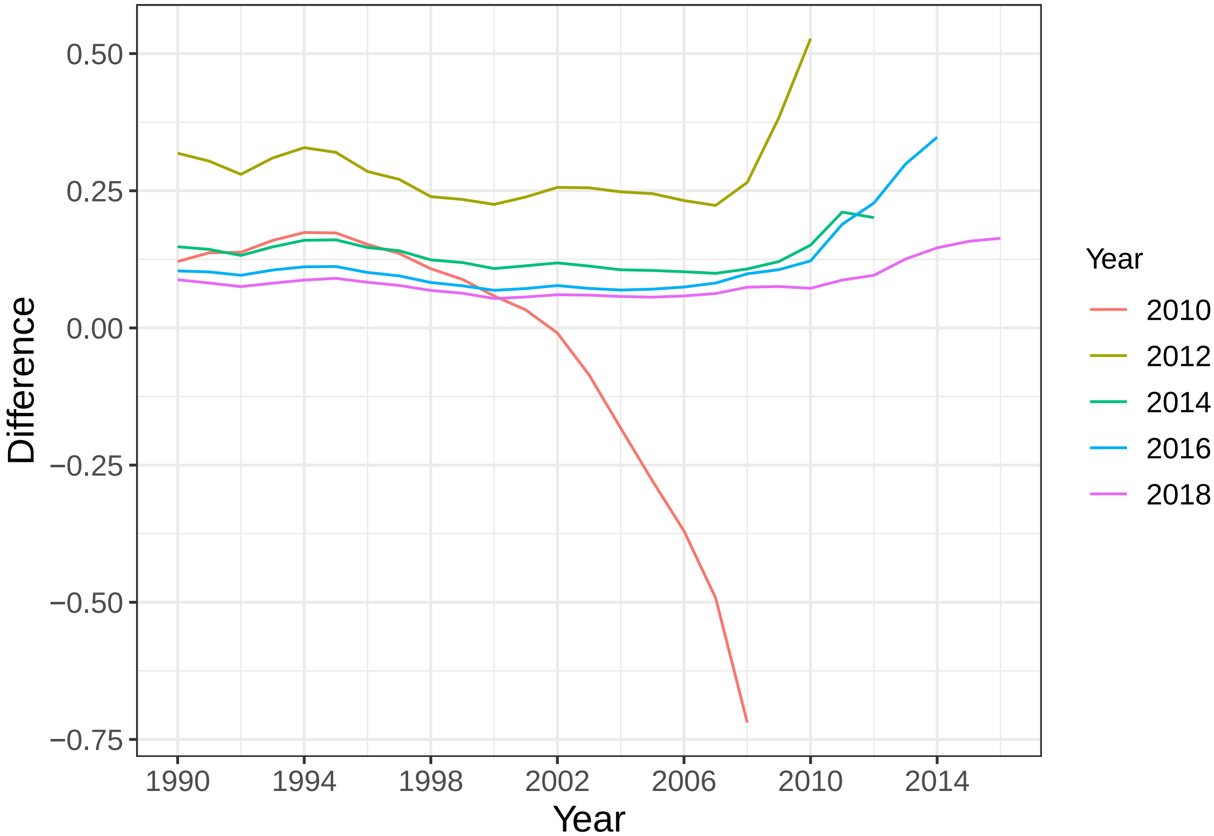


Figure 13: Model estimates for total (age 1+) biomass and female spawning biomass from 1990-2018, plus projection model estimates for 2019. Reference points SB40% and SB35% are shown as horizontal lines.

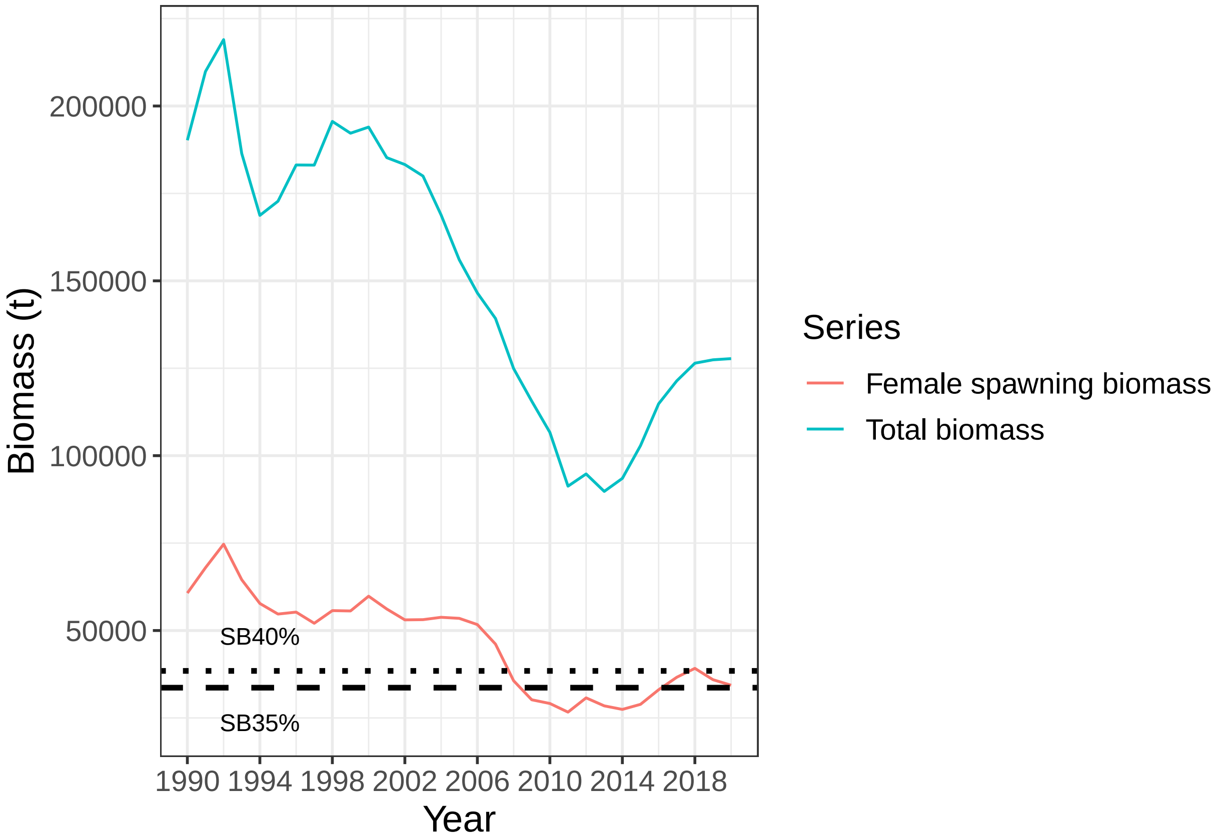


Figure 14: Phase plane diagram showing the time-series of stock assessment model estimates of female spawning biomass relative to the harvest control rule, with assessment model results for 1990-2018 and projection model results for 2019 (black square) and 2020 (blue square).

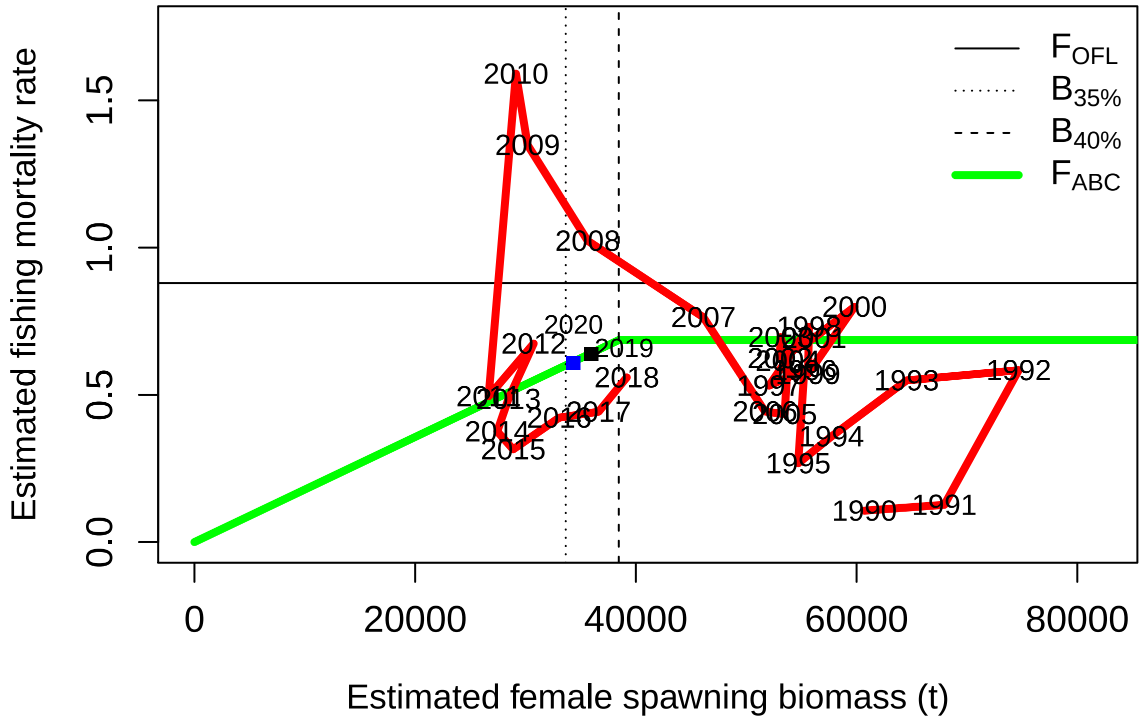
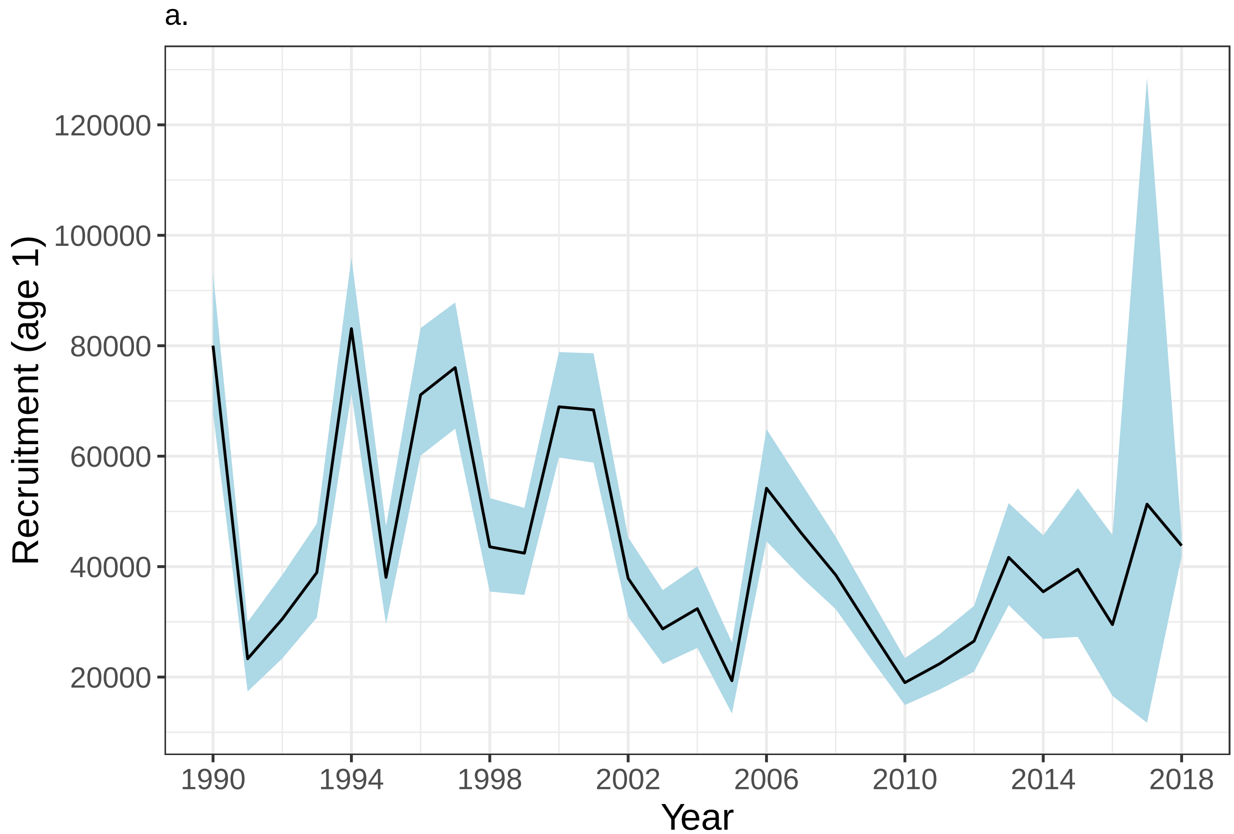
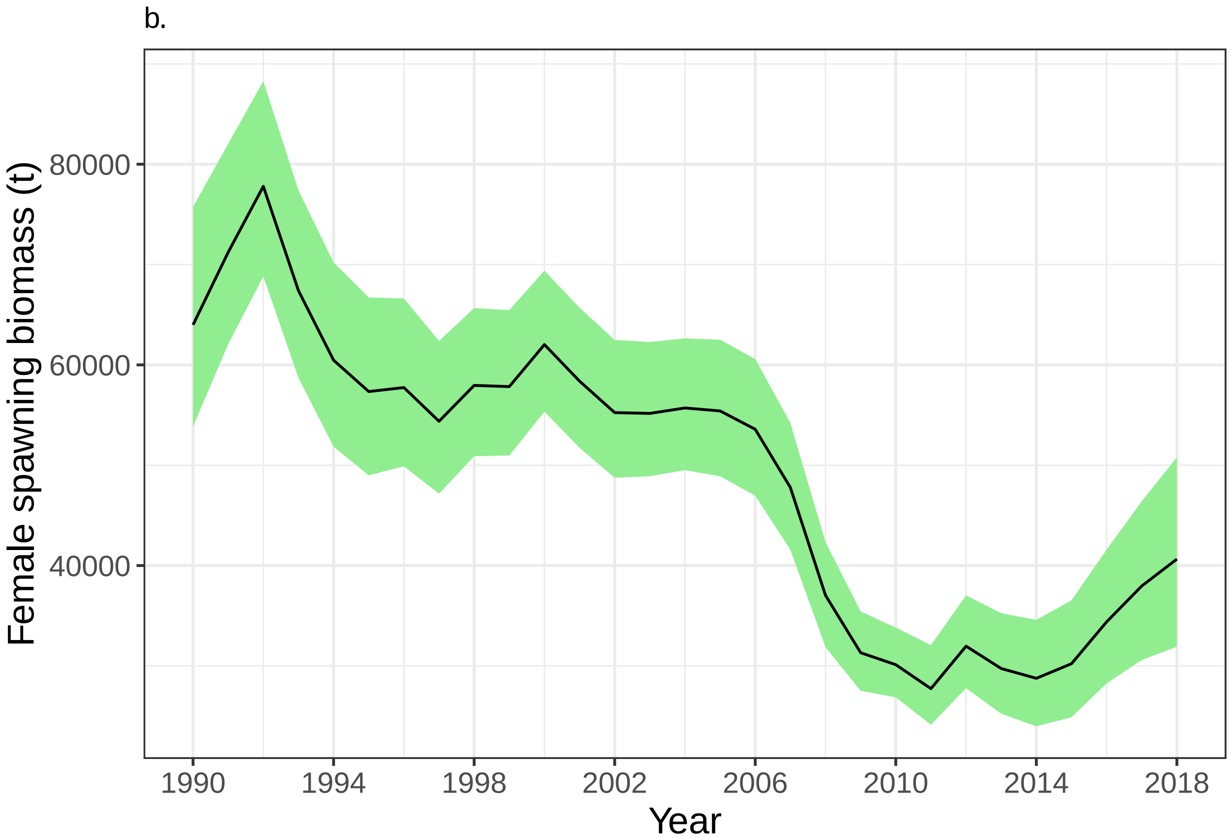
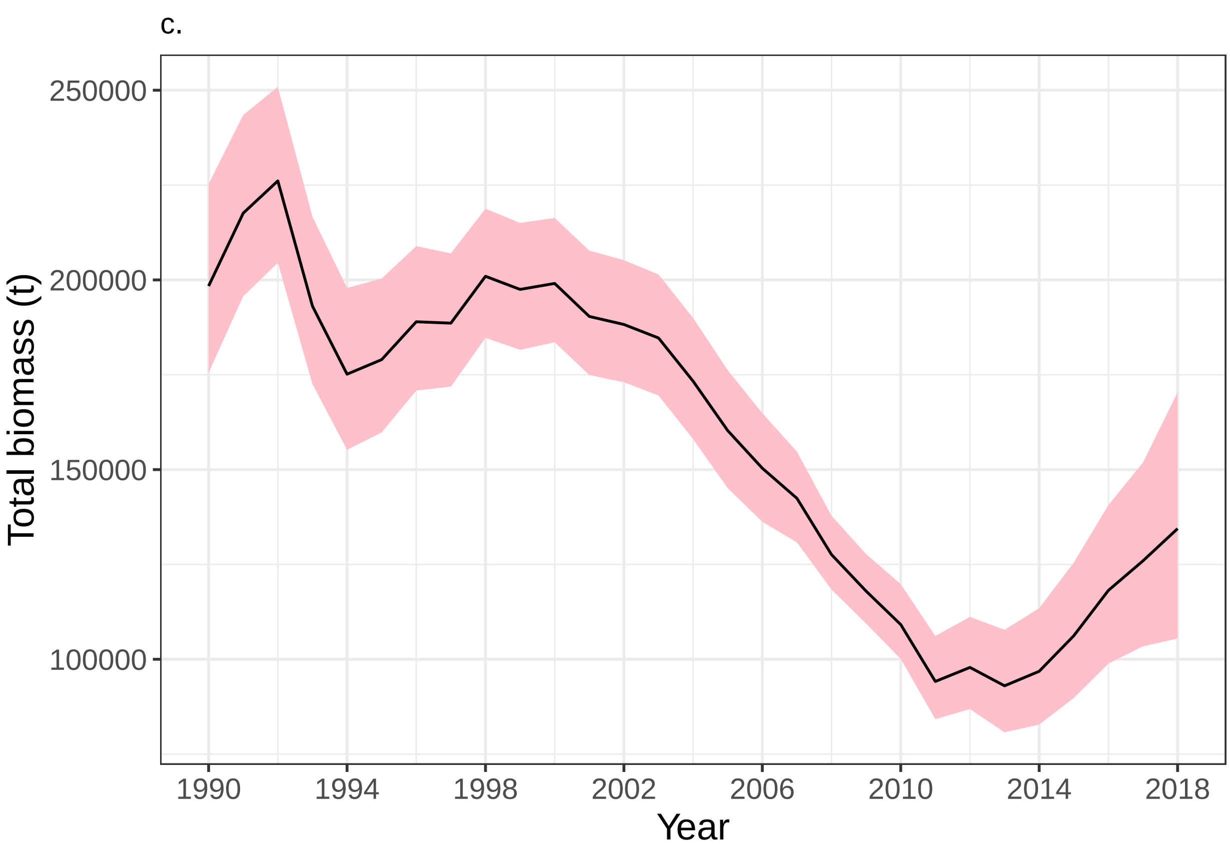


Figure 15: Mean and 95% credible intervals for age 1 recruitment (panel a.), female spawning biomass (t) (Panel b.), and total biomass (t) (Panel c.).




b.
Female spawning biomass (t)
80000
60000
40000
1990
1994
1998
2002
2006
2010
2014
2018
Year


c.
Total biomass (t)
250000
200000
150000
100000
1990
1994
1998
2002
2006
2010
2014
2018
Year

Appendix (copied from the 2016 Aleutian Islands Pacific cod council review draft by Grant Thompson)

APPENDIX 2A.3: HISTORY OF PREVIOUS AI PACIFIC COD MODEL STRUCTURES DEVELOPED UNDER STOCK SYNTHESIS

For 2013 and beyond, the SSC's accepted model from the final assessment is shown in italics.

Pre-2011

The AI Pacific cod stock was managed jointly with the EBS stock, with a single OFL and ABC. Prior to the 2004 assessment, results from the EBS model were inflated into BSAI-wide equivalents based on simple ratios of survey biomasses from the two regions. Beginning with the 2004 assessment, the simple ratios were replaced by a random-walk Kalman filter.

2011

Preliminary assessment

A Tier 5 model based on the same Kalman filter approach that had been used to inflate EBS model results into BSAI-wide equivalents since 2004 was applied to the AI stock as a stand-alone model.

Final assessment

Because no new survey data had become available since the preliminary assessment, the Tier 5 Kalman filter model was not updated. The SSC did not accept the Tier 5 Kalman filter model, so the AI stock continued to be managed jointly with the EBS stock.

2012

Preliminary assessment

Two models were included: Model 1 was similar to the final 2011 EBS model except: *Only one season* Only one fishery *AI-specific weight-length parameters used* Length bins (1 cm each) extended out to 150 cm instead of 120 cm *Fishery selectivity forced asymptotic* Fishery selectivity constant over time *Survey samples age 1 fish at true age 1.5* Ageing bias not estimated (no age data available) *Q tuned to match the value from the archival tagging data relevant to the GOA/AI survey net

Model 2 was identical to Model 1 except with time-varying L1 and Linf Six other models considered in a factorial design in order to determine which growth parameters would be time-varying in Model 2, but only partial results presented.

The SSC gave notice that it would not accept any model for this stock prior to the 2013 assessment.

Final assessment

Four models were included: Model 1 was identical to Model 1 from the preliminary assessment Model 2 was identical to Model 2 from the preliminary assessment Model 3 was identical to Model 1 except that input N values were multiplied by 1/3 Model 4 was identical to Model 1 except: *Survey data from years prior to 1991 were omitted* Q was allowed to vary randomly around a base value *Survey selectivity was forced asymptotic* Fishery selectivity was allowed to be domed *Input N values for sizecomp data were estimated iteratively by setting the root-mean-squared-standardized-residual of the survey abundance time series equal to unity* All fishery selectivity parameters except initial_selectivity and the ascending_width survey selectivity parameters were allowed (initially) to vary randomly, with the input standard deviations estimated iteratively by matching the respective standard deviations of the estimated devs *Input standard deviation for log-scale recruitment devs was estimated internally (i.e., as a free parameter)

None of the models was accepted by the SSC, so the AI stock continued to be managed jointly with the EBS stock.

2013 Preliminary assessment Three models were included:

Model 1 was identical to Model 1 from the 2012 assessment except: *Fishery selectivity was not forced asymptotic* Selectivity was estimated as a random walk with respect to age instead of the double normal, with normal priors tuned so that the prior mean is consistent with logistic selectivity and the prior standard deviation is consistent with apparent departures from logistic selectivity *Potentially, length and age composition input sample sizes could be tuned so that the harmonic mean effective sample size is at least as large as the arithmetic mean input sample size (if it turned out that the initial average N of 300 already satisfied this criterion, no tuning was done)* Potentially, each selectivity parameter could be time-varying with annual additive devs, where the sigma term is tuned to match the standard deviation of the estimated devs (if this tuning resulted in a sigma that was essentially equal to zero, time variability was turned off)

Model 2 was identical to Model 1 except that Q was estimated with an informative prior developed from a meta-analysis of other AI assessments

Model 3 was identical to Model 1 except that both M and Q were estimated freely

Final assessment

Four models were included:

Tier 3 Model 1 was identical to Model 1 from the preliminary assessment, except with Q fixed at 1.0

Tier 3 Model 2 was identical to Tier 3 Model 1 except: *Q was estimated with the same prior as in Model 2 from the preliminary assessment* Survey selectivity was forced asymptotic

Tier 5 Model 1 was the Kalman filter model that had been used since 2004 to estimate the expansion factor for converting results from the EBS model into BSAI equivalents

Tier 5 Model 2 was the random effects model recommended by the Survey Averaging Working Group

2014

Preliminary assessment Three models were included:

Model 1 was identical to Model 2 from the final 2013 assessment, except that survey selectivity was not forced to be asymptotic, each selectivity was allowed (potentially) to vary with time, a normal prior distribution for each selectivity parameter was tuned using the same method as Model 6 from the preliminary assessment 2014 EBS assessment, prior distributions and standard deviations for the annual selectivity deviations were estimated iteratively, and the 1976-1977 "recruitment offset" parameter was fixed at zero

Model 2 was identical to Model 1, except that the recruitment offset was estimated freely

Model 3 was identical to Model 2, except that survey selectivity first-differences were forced to equal zero after the age at which survey selectivity peaked in Model 2, and the lower bound on survey selectivity first-differences at all earlier ages was set at 0 (the combination of these two changes forced survey selectivity to increase monotonically until the age at which it peaked in Model 2, after which survey selectivity was constant at unity)

Final assessment Three models were included:

Model 1 was identical to Tier 5 Model 2 from the final 2013 assessment

Model 2 was identical to Model 1 from the preliminary assessment

Model 3 was identical to Model 1 from the preliminary assessment, except that the prior distributions for survey selectivity parameters were tightened so that the resulting selectivity curve was less dome-shaped

2015

Preliminary assessment New features or methods examined in the preliminary assessment included the following (these were based on experience with the preliminary assessment of the EBS Pacific cod stock):

1. The standard deviation of log-scale age 0 recruitment (σR) was estimated iteratively instead of being estimated internally.
2. Richards growth was assumed instead of von Bertalanffy growth (a special case of Richards).
3. 20 age groups were estimated in the initial numbers-at-age vector instead of 10.
4. Survey catchability was allowed to vary annually if the root-mean-squared-standardized residual exceeded unity (this resulted in time-varying Q for Model 5 but not for Model 3).
5. Selectivity at ages 8+ was constrained to equal selectivity at age 7 for the fishery, and selectivity at ages 9+ was constrained to equal selectivity at age 8 for the survey.
6. A superfluous selectivity parameter was fixed at the mean of the prior (in Models 3 and 4, the estimate of this parameter automatically went to the mean of the prior).
7. Composition data were given a weight of unity if the harmonic mean of the effective sample size was greater than the mean input sample size of 300; otherwise, composition data were weighted by tuning the mean input sample size to the harmonic mean of the effective sample size.
8. All iterative tunings were conducted simultaneously rather than sequentially.
9. The method of Thompson (in prep.) was used for iterative tuning of the sigma parameters for selectivity and recruitment.
10. Iterative tuning of the sigma parameter for time-varying catchability involved adjusting sigma until the root-mean-squared-standardized-residual for survey abundance equaled unity.

Four of the models spanned a 2×2 factorial design. The factors were:

The new features or methods listed above (use or not use) Historic fishery time series data from 1977-1990 (use or not use)

Five models were included in all (there was no model numbered "1," per SSC request):

Model 0 was identical to Model 1 from the final 2014 assessment (Tier 5 random effects) Model 2 used the new features/methods; did not use the historic fishery data *Model 3 not use the new features/methods; did use the historic fishery data* Model 4 did not use the new features/methods; did not use the historic fishery data *Model 5 used the new features/methods; did not use the historic fishery data

Note that Model 4 was identical to Model 2 from the 2014 final assessment

Final assessment

Three models were included: *Model 13.4 (new name for the Tier 5 random effects model)

*Model 15.6 was also a random effects model, but with the IPHC longline survey CPUE added as a second time series

*Model 15.7 was the same as Model 3 from the preliminary assessment (now renamed Model 15.3), but with both fishery and survey selectivity held constant (with respect to age) above age 8, as opposed to being free at all ages (1-20) in Model 15.3

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