Chapter 2: Assessment of the Pacific cod stock in the Gulf of Alaska

Steven Barbeaux, Teresa A'mar, and Wayne Palsson

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Alaska Fisheries Science Center
7600 Sand Point Way NE., Seattle, WA 98115-6349

Executive Summary

Summary of Changes in Assessment Inputs

Relative to last year's assessment, the following changes have been made in the current assessment:

Changes in the input data

1. Federal and state catch data for 2015 were updated and preliminary federal and state catch data for 2016 were included;
2. Commercial federal and state fishery size composition data for 2015 were updated, and preliminary commercial federal and state fishery size composition data for 2016 were included;
3. Size at age (weight and age at length) data for the 2015 GOA bottom trawl survey were included;
4. Survey age composition data from the 2015 GOA bottom trawl survey were included;
5. AFSC longline survey Pacific cod abundance index and length composition data for the GOA were included;
6. Length composition data were aggregated by three gear types, trawl, longline, and pot with no seasons;
7. Length composition data were binned by 1 cm increments from 0.5 to 116.5; and
8. Survey length-at-age data were updated including 2013 and 2015 data.

Changes in the methodology

There was substantial changes in the modeling approach applied in the authors' preferred model for this year. The approach taken with the new model involves a number of simplifications compared to the relatively complex models presented in recent years for GOA Pacific cod. A goal for this year was to disentangle interactions among modeled components, particularly the seasonal fishery selectivities, to ease interpretation. Growth and selectivity treatments were also simplified so that alternative hypotheses could be explored in our models. Another benefit of model simplification was detailing data compilation issues and gaining familiarity with available data. New datasets (the AFSC sablefish longline survey index for Pacific cod along with length composition data from this survey) were also introduced. In the course of developing the model proposed by the authors, over 250 models were built and examined. This document presents a set of models developed and presented in the September Plan Team and October SSC meetings as well as the author's choice for management of this stock. The models presented represent a subset of models deemed to be most informative for discussion and stock management.

- Model 15.3 - Last year's model with the addition of finalized 2015 and preliminary 2016 catch estimates and 2015 NMFS survey age composition data. No new fishery composition data added.
- All proposed models presented were single sex age-based models with length-based selectivity. The models have data from three fisheries (longline, pot, and combined trawl fisheries) with a single season and two survey indices (post-1990 GOA bottom trawl survey and the Auke Bay

Longline survey indices). Length composition data were available for all three fisheries and both indices. Growth was parameterized using the standard three parameter von Bertalanffy growth curve. Recruitment was parameterized as a standard Beverton-holt with steepness fixed at 1.0 and sigma R at 0.44. All selectivities were fit using six parameter double-normal selectivity curves. **The only changes from the September Models 16.6.11, 16.6.20, and 16.7.3 for this iteration were that all three models were updated since September with the 2016 data, the addition of length-at-age data, and modeled to age 20 to provide better estimation of the growth curve**. These three models were analogous to Model configurations 16.10.11, 16.10.20, and Model 16.11.23. We also explored different model tuning alternatives, Model series 16.08.xx and 16.09.xx were not tuned while model Series 16.10.xx and 16.11.xx were tuned using the Francis method.

- Three additional models configurations were developed for this document:
  - Model 16.xx.23 – Same as Model 16.xx.20 with blocked time varying selectivity in both the fisheries and bottom trawl survey data. In addition dome-shaped selectivity was allowed in all fisheries and in the initial bottom trawl survey block. The AFSC longline survey remained asymptotic and fit with a single selectivity curve
  - Model 16.xx.24 – Same as Model 16.xx.23 but with U-shaped natural mortality fit iteratively as per suggestion by Patrick Lynch in the September 2016 Plan Team meeting.
  - Model 16.xx.25 – Same as Model 16.xx.23 but M and Q were fit within the model and dome-shaped selectivity was allowed for all bottom trawl survey years and the AFSC longline survey.

Tuning and data selection series:

Series	Tuning	Sub-27 cm bottom trawl survey composition data
16.08.xx	No	Yes
16.09.xx	No	No
16.10.xx	Francis TA1.8 method	Yes
16.11.xx	Francis TA1.8 method	No

Model configurations:

Models	Natural mortality	Trawl survey catchability	Length-based Selectivity
16.xx.11	M = 0.38	Q = 1.0	Dome-shaped for all but the longline fishery
16.xx.20	M = 0.38	Q = 1.0	Asymptotic for all but the pot fishery
16.xx.23	M = 0.38	Q = 1.0	Blocked time varying selectivity dome-shaped allowed for all but the longline fishery and surveys.
16.xx.24	U-shaped natural mortality	Q = 1.0	Blocked time varying selectivity dome-shaped allowed for all but the longline fishery and surveys.
16.xx.25	Fit with lognormal prior μ=0.38 and σ = 0.1	Fit with uniform prior	Blocked time varying selectivity dome-shaped allowed for all but the longline fishery.

Please note that not all combinations of Series and configurations are presented in this document.

Model 16.08.25 performance in both fit to the available data and retrospective performance was better than any of the other models proposed this year. Therefore Model 16.08.25 was selected as the Authors' preferred method. This will be a substantial change from the 2015 Model, the modeling switches the

overall assumption from a large older cryptic population to a much younger population with higher natural mortality than previous models. Although this change in the model results in a much lower spawning stock biomass and historical total biomass estimates the effect on ABC and OFL were small. Results are summarized below:

Summary of Results

Quantity	As estimated or *specified last* year for:		As estimated or *specified this* year for:	
	2016	2017	2017	2018
M (natural mortality rate)	0.38	0.38	0.47	0.47
Tier	3a	3a	3a	3a
Projected total (age 0+) biomass (t)	518,800	472,800	426,384	428,885
Female spawning biomass (t)				
Projected	165,600	141,800	98,479	90,572
$B_{100\%}$	325,200	325,200	196,776	196,776
$B_{40\%}$	130,000	130,000	78,711	78,711
$B_{35\%}$	113,800	113,800	68,872	68,872
F_{OFL}	0.495	0.495	0.652	0.652
$maxF_{ABC}$	0.407	0.407	0.530	0.530
F_{ABC}	0.407	0.407	0.530	0.530
OFL (t)	116,700	116,700	105,378	94,188
maxABC (t)	98,600	85,200	88,342	79,272
ABC (t)	98,600	85,200	88,342	79,272
Status	As determined *last* year for:		As determined *this* year for:	
	2014	2015	2015	2016
Overfishing	no	n/a	no	n/a
Overfished	n/a	no	n/a	no
Approaching overfished	n/a	no	n/a	no

Area apportionment

In 2012 the ABC for GOA Pacific cod was apportioned among regulatory areas using a Kalman filter approach based on trawl survey biomass estimates. In the 2013 assessment, the random effects model (which is similar to the Kalman filter approach, and was recommended in the Survey Average working group report which was presented to the Plan Team in September 2013) was used; this method was used for the ABC apportionment for 2014. The SSC concurred with this method in December 2013. Using this method with the trawl survey biomass estimates through 2015, the area-apportioned ABCs are:

	Western	Central	Eastern	Total
Random effects area apportionment (percent)	41.08	50.01	8.91	100.00
2017 ABC	36,291	44,180	7,871	88,342
2018 ABC	32,565	39,644	7,063	79,272

Responses to SSC and Plan Team Comments Specific to this Assessment

September 2016 Plan Team

The Plan Team recommended moving forward with the set of models above proposed by the assessment author. The Plan Team also recommended a comparison of the author's preferred model with the 2015 model when applied to a consistent data set (i.e., data used in the 2015 assessment).

- Model 15.3 is last year's model with updated catch and survey information.

The Plan Team further recommended that a model with age-specific natural mortality be evaluated, as it may provide more insight to the "hide them" vs "kill them" modeling approaches.

- Model series 16.xx.24 has age specific natural mortality fixed in the model with ages 2-12 averaged to M=0.38.

The Plan Team recommended comparing time series of mean size in survey data to the observed declines in fishery data.

- They are consistent with the data from the AFSC longline survey data, the trend is not as clear in the bottom trawl survey data.

October 2016 SSC

There were questions whether the treatment of the plus group in the population dynamics (not the plus group for the data), might have a potential interaction with growth estimation in the GOA models. This should be investigated as time permits.

- This was investigated, there were some minor differences in growth estimated between models with age 12+ versus age 20+, although the affects were minor. For all models presented the plus group was changed to 20+ instead of 12+.

Introduction

Pacific cod (*Gadus macrocephalus*) is a transoceanic species, occurring at depths from shoreline to 500 m. The southern limit of the species' distribution is about 34° N latitude, with a northern limit of about 63° N latitude. Pacific cod is distributed widely over Gulf of Alaska (GOA), as well as the eastern Bering Sea (EBS) and the Aleutian Islands (AI) area. Tagging studies (e.g., Shimada and Kimura 1994) have demonstrated significant migration both within and between the EBS, AI, and GOA. Recent research indicates the existence of discrete stocks in the EBS and AI (Canino et al. 2005, Cunningham et al. 2009, Canino et al. 2010, Spies 2012). Pacific cod is not known to exhibit any special life history characteristics that would require it to be assessed or managed differently from other groundfish stocks in the GOA. The Pacific cod stock in the GOA is managed as one stock.

Review of Life History

Pacific cod eggs are demersal and adhesive. Eggs hatch in about 15 to 20 days. Spawning takes place in the sublittoral-bathyal zone (40 to 290 m) near bottom. Eggs sink to the bottom after fertilization and are somewhat adhesive. Optimal temperature for incubation is 3° to 6°C, optimal salinity is 13 to 23 parts per thousand (ppt), and optimal oxygen concentration is from 2 to 3 ppm to saturation. Little is known about the optimal substrate type for egg incubation.

Little is known about the distribution of Pacific cod larvae, which undergo metamorphosis at about 25 to 35 mm. Larvae are epipelagic, occurring primarily in the upper 45 m of the water column shortly after hatching, moving downward in the water column as they grow.

Juveniles occur mostly over the inner continental shelf at depths of 60 to 150 m. Adults occur in depths from the shoreline to 500 m, although occurrence in depths greater than 300 m is fairly rare. Preferred substrate is soft sediment, from mud and clay to sand. Average depth of occurrence tends to vary directly with age for at least the first few years of life, going deeper with age. In the GOA trawl survey, the percentage of fish residing in waters less than 100 m tends to decreases with length. The GOA trawl survey also indicates that fish occupying depths greater than 200 m are typically in the 40-90 cm range.

It is conceivable that mortality rates, both fishing and natural, may vary with age in Pacific cod. In particular, very young fish likely have higher natural mortality rates than older fish (note that this may not be particularly important from the perspective of single-species stock assessment, so long as these higher natural mortality rates do not occur at ages or sizes that are present in substantial numbers in the data). For example, Leslie matrix analysis of a Pacific cod stock occurring off Korea estimated the instantaneous natural mortality rate of 0-year-olds at 9.10 yr^{-1} (Jung et al. 2009). This may be compared to a mean estimate for age 0 Atlantic cod (*Gadus morhua*) in Newfoundland of 4.17% per day, with a 95% confidence interval ranging from about 3.31% to 5.03% (Gregory et al. in prep.); and age 0 Greenland cod (*Gadus ogac*) of 2.12% per day, with a 95% confidence interval ranging from about 1.56% to 2.68% (Robert Gregory and Corey Morris, *pers. commun.*).

Although little is known about the likelihood of age-dependent natural mortality in adult Pacific cod, it has been suggested that Atlantic cod may exhibit increasing natural mortality with age (Greer-Walker 1970).

At least one study (Ueda et al. 2006) indicates that age-2 Pacific cod may congregate more, relative to age-1 Pacific cod, in areas where trawling efficiency is reduced (e.g., areas of rough substrate), causing their selectivity to decrease. Also, Atlantic cod have been shown to dive in response to a passing vessel (Ona and Godø 1990), which may complicate attempts to estimate catchability or selectivity. It is not known whether Pacific cod undertake a similar response.

As noted above, Pacific cod are known to undertake seasonal migrations, the timing and duration of which may be variable (Savin 2008).

Fishery

During the two decades prior to passage of the Magnuson Fishery Conservation and Management Act (MFCMA) in 1976, the fishery for Pacific cod in the GOA was small, averaging around 3,000 t per year. Most of the catch during this period was taken by the foreign fleet, whose catches of Pacific cod were usually incidental to directed fisheries for other species. By 1976, catches had increased to 6,800 t. Catches of Pacific cod since 1991 are shown in Table 2.1; catches prior to that are listed in Thompson et al. (2011). Presently, the Pacific cod stock is exploited by a multiple-gear fishery, including trawl, longline, pot, and jig components. Trawl gear took the largest share of the catch in every year but one from 1991-2002, although pot gear has taken the largest single-gear share of the catch in each year since 2003 (not counting 2016, for which data are not yet complete). Figure 2.1 shows landings by gear since 1977. Table 2.1 shows the catch by jurisdiction and gear type.

The history of acceptable biological catch (ABC) and total allowable catch (TAC) levels is summarized and compared with the time series of aggregate commercial catches in Table 2.2. For the first year of management under the MFCMA (1977), the catch limit for GOA Pacific cod was established at slightly less than the 1976 total reported landings. During the period 1978-1981, catch limits varied between 34,800 and 70,000 t, settling at 60,000 t in 1982. Prior to 1981 these limits were assigned for "fishing years" rather than calendar years. In 1981 the catch limit was raised temporarily to 70,000 t and the fishing year was extended until December 31 to allow for a smooth transition to management based on calendar years, after which the catch limit returned to 60,000 t until 1986, when ABC began to be set on an annual basis. From 1986 (the first year in which an ABC was set) through 1996, TAC averaged about 83% of ABC and catch averaged about 81% of TAC. In 8 of those 11 years, TAC equaled ABC exactly. In 2 of those 11 years (1992 and 1996), catch exceeded TAC.

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

Changes in ABC over time are typically attributable to three factors: 1) changes in resource abundance, 2) changes in management strategy, and 3) changes in the stock assessment model. Assessments conducted prior to 1988 were based on survey biomass alone. From 1988-1993, the assessment was based on stock reduction analysis (Kimura et al. 1984). From 1994-2004, the assessment was conducted using the Stock Synthesis 1 modeling software (Methot 1986, 1990) with length-based data. The assessment was migrated to Stock Synthesis 2 (SS2) in 2005 (Methot 2005b), at which time age-based data began to enter the assessment. Several changes have been made to the model within the SS2 framework (renamed "Stock Synthesis," or SS3, in 2008) each year since then.

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

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

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

> "Amendment 83 allocates the Pacific cod TAC in the Western and Central regulatory areas of the GOA among various gear and operational sectors, and eliminates inshore and offshore allocations in these two regulatory areas. These allocations apply to both annual and seasonal limits of Pacific cod for the applicable sectors. These apportionments are discussed in detail in a subsequent section of this rule. Amendment 83 is intended to reduce competition among sectors and to support stability in the Pacific cod fishery. The final rule implementing Amendment 83 limits access to the Federal Pacific cod TAC fisheries prosecuted in State of Alaska (State) waters adjacent to the Western and Central regulatory areas in the GOA, otherwise known as parallel fisheries. Amendment 83 does not change the existing annual Pacific cod TAC allocation between the inshore and offshore processing components in the Eastern regulatory area of the GOA.
>
> "In the Central GOA, NMFS must allocate the Pacific cod TAC between vessels using jig gear, catcher vessels (CVs) less than 50 feet (15.24 meters) length overall using hook-and-line gear, CVs equal to or greater than 50 feet (15.24 meters) length overall using hook-and-line gear, catcher/processors (C/Ps) using hook-and-line gear, CVs using trawl gear, C/Ps using trawl gear, and vessels using pot gear. In the Western GOA, NMFS must allocate the Pacific cod TAC between vessels using jig gear, CVs using hook-and-line gear, C/Ps using hook-and-line gear, CVs using trawl gear, and vessels using pot gear. Table 3 lists the proposed amounts of these seasonal allowances. For the Pacific cod sector splits and associated management measures to become effective in the GOA at the beginning of the 2012 fishing year, NMFS published a final rule (76 FR 74670, December 1, 2011) and will revise the final 2012 harvest specifications (76 FR 11111, March 1, 2011)."
>
> "NMFS proposes to calculate of the 2012 and 2013 Pacific cod TAC allocations in the following manner. First, the jig sector would receive 1.5 percent of the annual Pacific cod TAC in the Western GOA and 1.0 percent of the annual Pacific cod TAC in the Central GOA, as required by proposed § 679.20(c)(7). The jig sector annual allocation would further be apportioned between the A (60 percent) and B (40 percent) seasons as required by § 679.20(a)(12)(i). Should the jig sector harvest 90 percent or more of its allocation in a given area during the fishing year, then this allocation would increase by one percent in the subsequent fishing year, up to six percent of the annual TAC. NMFS proposes to allocate the remainder of the annual Pacific cod TAC based on gear type, operation type, and vessel length overall in the Western and Central GOA seasonally as required by proposed § 679.20(a)(12)(A) and (B)."

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

Data

This section describes data used in the current assessment (Fig. 2.2). It does not attempt to summarize all available data pertaining to Pacific cod in the GOA.

Data	Source	Type	Years included
Federal and state fishery catch, by gear type	AKFIN	metric tons	1977 – 2016
Federal fishery catch-at-length, by gear type	AKFIN / FMA	number, by cm bin	1977 – 2016
State fishery catch-at-length, by gear type	ADF&G	number, by cm bin	1997 – 2016
GOA NMFS bottom trawl survey biomass and abundance estimates	AFSC	metric tons, numbers	1984 – 2015
AFSC Sablefish Longline survey Pacific cod RPN	AFSC	RPN	1990 – 2016
GOA NMFS bottom trawl survey length composition	AFSC	number, by cm bin	1984 – 2015
GOA NMFS bottom trawl survey age composition	AFSC	number, by age	1987 – 2015
GOA NMFS bottom trawl survey mean length-at-age and conditional age-at-length	AFSC	mean value and number	1987 – 2015
AFSC Sablefish Longline survey Pacific Cod length composition	AFSC	Number, by cm bin	1990 – 2016

Fishery

Catch Biomass

Catches for the period 1991-2015 are shown for the three main gear types in Table 2.1, with the catches for 2016 Oct – Dec estimated given the average fraction of annual catch by gear type for this period in 2015. The fishery was set in three gear type, trawl (all trawl types), longline (longline and jig) and pot. The weight of catch of other commercial species caught in the Pacific cod targeted fisheries for 2012 through 2016 are shown in Table 2.4, and incidental catch of non-commercial species for 2007 – 2016 are shown in Table 2.6. Non-commercial catch of Pacific cod in other activities is shown in Figure 2.7.

Figure 2.3 shows the distribution of catch from 1990-2014 by gear type. Figure 2.4 maps the distribution of catch by gear type in 2015 and Figure 2.5 maps the distribution of catch by gear in 2016 as of October 17, 2016. Catch locations in 2015 appear consistent with historical locations. Although there appears to be some differences in 2016 this is likely due to the fisheries not yet being concluded.

Catch Size Composition

Fishery size compositions are presently available by gear for at least one gear type in every year from 1977 through the first half of 2015. Size composition data are based on 1-cm bins ranging from 1 to 116 cm. As the maximum percent of fish larger than 110 cm over each year-gear type-season is less than 0.5%, the upper limit of the length bins was set at 116 cm, with the 116-cm bin accounting for all fish 116 cm and larger.

The trawl fishery (Fig. 2.6), longline fishery (Fig. 2.7), and Pot fishery (Fig. 2.8) length composition data are provided in Appendix 2.2 in an Excel spreadsheet.

(http://www.afsc.noaa.gov/REFM/Docs/2016/GOApcod_Appendix2_2.xlsx)

Surveys

NMFS Gulf of Alaska Bottom Trawl Survey

Abundance Estimates

Estimates of total abundance (both in biomass and numbers of fish) obtained from the trawl surveys are shown in Table 2.8 and Fig. 2.9, together with their respective coefficients of variation. The abundance estimates by area are shown in Figure 2.10 and mapped in Figure 2.11. Historically areas 610, 620, and 630

have all vied for the area with the highest biomass. A large increase in abundance and biomass from the 2007 to 2009 survey occurred primarily in area 630.

The highest biomass ever observed by the survey was the 2009 estimate of 752,651 t, and the low point was the preceding (2007) estimate of 233,310 t. The 2009 biomass estimate represented a 223% increase over the 2007 estimate. The 2011 biomass estimate was down 33% from 2009, but still 115% above the 2007 estimate. The 2015 biomass estimate is a significant decrease (50%) from the 2013 estimate (Table 2.8).

In terms of population numbers, the record high was observed in 2009, when the population estimated by the survey included over 573 million fish. The 2005 estimate of 140 million fish was the low point in the time series. The 2009 abundance estimate represented a 199% increase over the 2007 estimate. The 2011 abundance estimate was a decrease of 39% from 2009, but still 81% above the 2007 estimate.

The 2015 total abundance estimate is a significant decrease (42%) from the 2013 estimate. The 2015 abundance estimate for fish 27 cm and larger is also a significant decrease of (29%) from the 2013 estimate; the 27-plus abundance estimates have been decreasing by at least 19% between survey years since 2009 (Fig. 2.9). The 2015 abundance estimate for fish less than 27 cm is a large decrease (84%) from the 2013 estimate. The total, 27-plus, and sub-27 abundance estimates for 2015 are a decrease of at least 56% from the 2009 estimates.

Length Composition

The length composition data from the trawl surveys of the GOA conducted by the Alaska Fisheries Science Center have been partitioned into two length categories: fish smaller than 27 cm (the "sub-27" survey) and fish 27 cm and larger (the "27-plus" survey). The relative length compositions from 1984-2015 are provided for the sub-27 and the 27-plus survey in Appendix 2.2 in an Excel spreadsheet (http://www.afsc.noaa.gov/REFM/Docs/2016/GOApcod_Appendix2_2.xlsx)

and shown in Figure 2.12.

Age Composition

Age compositions from each trawl survey except 1984 are available (note that the sample size for the 1987 was very small, however). The age compositions are shown in Fig. 2.12 and provided in Appendix 2.2 in an Excel spreadsheet. Recent study by Kastelle *et al.* (2017) state that one of the specific reasons for their study was to investigate the apparent mismatch between the mean length at age (from growth-zone based ages) and length-frequency modal sizes in the BSAI Pacific cod stock assessments and to evaluate whether age determination bias could account for the mismatch. Mean lengths at age (either from raw age-length pairs or age-length keys) were reported to be smaller than the modal size at presumed age from length distributions. In general, for the specimens in their study, there was an increased probability of a positive bias in fish at ages 3 and 4 (Kastelle *et al.* 2017; Fig. 6, Table 2); that is, they were over-aged. In effect, this over-ageing created a bias in mean length at age, resulting in smaller estimates of size at a given age. When correcting for ageing bias by reallocating age-length samples in all specimens aged 2–5 in proportion to that seen in the true age distribution, mean size at ages 2–4 did indeed increase (Kastelle *et al.* 2017; Fig. 7). For example, there was an increase of 35 mm and 50 mm for Pacific cod aged 3 and 4, respectively. This correction brings the mean size at corrected age closer to modal sizes in the length compositions. While beyond the scope of their study, they postulate that the use of this correction to adjust the mean size at age data currently included in Pacific cod stock assessments should prove beneficial for rectifying discrepancies between mean length-at-age estimates and length-frequency modes. Although not implemented this year, we will work with the age and growth lab in 2017 to add aging bias to the assessment model.

NMFS bottom trawl survey age composition data are provided in Appendix 2.2 in an Excel spreadsheet. (http://www.afsc.noaa.gov/REFM/Docs/2016/GOApcod_Appendix2_2.xlsx)

AFSC Longline Survey for the Gulf of Alaska

Relative Population Numbers Index and Length Composition

The AFSC longline survey for the Gulf of Alaska survey data on relative Pacific cod abundance were added to this year's models (Table 2.9 and Fig. 2.13). These data included the Relative Population numbers (RPN) of Pacific cod as an index of abundance and Pacific cod length composition data for 1990 through 2015 (Fig 2.14). These data were provided by Dr. Dana Hanselman of the Auke Bay Laboratory and a description of the methods for the AFSC sablefish longline survey and how the datasets were developed can be found in Hanselman et al. (2015) and Echave et al. (2012).

This RPN index mirrors the trend observed in the bottom trawl survey for 1990 through 2015 with a decline in abundance from 1990 through 2008 and a sharp increase in 2009 (Fig. 2.13)

Unlike the bottom trawl survey, the longline survey encounters few small fish (Fig. 2.14). There were no sub-27 cm fish in the longline survey length composition data. The data reveal consistent and steep unimodal distributions with a decreasing trend in mean size since the mid-1990s, matching the trend observed in all three fisheries, but not in the bottom trawl survey. The length composition data for the AFSC longline survey data are provided in Appendix 2.2 in an Excel spreadsheet.

(http://www.afsc.noaa.gov/REFM/Docs/2016/GOApcod_Appendix2_2.xlsx)

Analytic Approach

Model Structure

Model Structures Considered in This Year's Assessment

This year's proposed models are substantially different from previous year's models. To see the history of models used in this assessment refer to A'mar and Pallson (2015). Stock Synthesis version 3.24U (Methot and Wetzel 2013; Methot 2013) was used to run all the model configurations in this analysis.

We include in this year's assessment for comparison the 2015 final model (Model 15.3) with updated 2015 and 2016 catch data as well as 2015 conditional age-at-length data from the bottom trawl survey.

The new models presented in this document were all based on the models presented to the plan team in September 2016 (Appendix 2.1). The approach taken with the new model involves a number of simplifications compared to the relatively complex models presented in recent years for GOA Pacific cod (A'mar and Pallson 2015). A goal for this year was to disentangle interactions among modeled components, particularly the seasonal fishery selectivities, to ease interpretation. Growth and selectivity treatments were also simplified so that alternative hypotheses could be explored in our models. Another benefit of model simplification was detailing data compilation issues and gaining familiarity with available data. New datasets (the AFSC sablefish longline survey index for Pacific cod along with length composition data from this survey) were also introduced. In the course of developing the model proposed by the authors, over 250 models were built and examined. This document presents a set of models developed and presented in the September Plan Team and October SSC meetings as well as the author's choice for management of this stock. The models presented represent a subset of models deemed to be most informative for discussion and stock management.

- All models presented were single sex age-based models with length-based selectivity. The models have data from three fisheries (longline, pot, and combined trawl fisheries) with a single season and two survey indices (post-1990 GOA bottom trawl survey and the Auke Bay Longline survey indices).

Length composition data were available for all three fisheries and both indices. Growth was parameterized using the standard three parameter von Bertalanffy growth curve. Recruitment was parameterized as a standard Beverton-holt with steepness fixed at 1.0 and sigma R at 0.44. All selectivities were fit using six parameter double-normal selectivity curves. The only change from the September Models 16.6.11, 16.6.20, and 16.7.3 for this iteration was that all three models were updated since September with the 2016 data, the addition of length-at-age data, and modeled to age 20 to provide better estimation of the growth curve. These three models were analogous to Model 16.xx.11, Model 16.xx.20, and Model 16.11.20. We also explored different model tuning alternatives, Model series 16.08.xx and 16.09.xx were not tuned while model Series 16.10.xx and 16.11.xx were tuned using the Francis method (Table 2.11).

- Three additional models configurations have been developed for this document:
  - Model 16.xx.23 – Same as Model 16.xx.20 with blocked time varying selectivity in both the fisheries and bottom trawl survey data. In addition dome-shaped selectivity was allowed in all fisheries and in the initial bottom trawl survey block. The AFSC longline survey remained asymptotic and fit with a single selectivity curve
  - Model 16.xx.24 – Same as Model 16.xx.23 but with U-shaped natural mortality fit iteratively as per suggestion by Patrick Lynch in the September 2016 Plan Team meeting.
  - Model 16.xx.25 – Same as Model 16.xx.23 but M and Q were fit within the model and dome-shaped selectivity was allowed for all bottom trawl survey years and the AFSC longline survey.

Tuning and data selection series:

Series	Tuning	Sub-27 cm bottom trawl survey composition data
16.08.xx	No	Yes
16.09.xx	No	No
16.10.xx	Francis TA1.8 method	Yes
16.11.xx	Francis TA1.8 method	No

Model configurations:

Models	Natural mortality	Trawl survey catchability	Selectivity
16.xx.11	M = 0.38	Q = 1.0	Dome-shaped for all but the longline fishery
16.xx.20	M = 0.38	Q = 1.0	Asymptotic for all but the pot fishery
16.xx.23	M = 0.38	Q = 1.0	Blocked time varying selectivity dome-shaped allowed for all but the longline fishery and bottom trawl survey.
16.xx.24	U-shaped natural mortality	Q = 1.0	Blocked time varying selectivity dome-shaped allowed for all but the longline fishery and bottom trawl survey.
16.xx.25	Fit with lognormal prior μ=0.38 and σ = 0.1	Fit with uniform prior	Blocked time varying selectivity dome-shaped allowed for all but the longline fishery.

Time varying selectivity components:

Configuration	Component	Temporal Blocks/Devs.

16.xx.11	Trawl Fishery	Devs. – 1977-2016, σ_{dev} = 0.2
	Longline Fishery	Devs. – 1977-2016, σ_{dev} = 0.2
16.xx.23, 16.xx.24, and 16.xx.25	Longline Fishery	Blocks – 1977-1995, 1996-2005, and 2006-2016
	Trawl Fishery	Blocks – 1977-1995, 1996-2005, and 2006-2016
	Pot Fishery	Blocks – 1977-2012 and 2013-2016
	Bottom trawl survey	Blocks – 1977-1995, 1996-2006, 2007-2016

Parameters Estimated Outside the Assessment Model

Natural Mortality

In the 1993 BSAI Pacific cod assessment (Thompson and Methot 1993), the natural mortality rate *M* was estimated using SS1 at a value of 0.37. All subsequent assessments of the BSAI and GOA Pacific cod stocks (except the 1995 GOA assessment) have used this value for *M*, until the 2007 assessments, at which time the BSAI assessment adopted a value of 0.34 and the GOA assessment adopted a value of 0.38. Both of these were accepted by the respective Plan Teams and the SSC. The new values were based on Equation 7 of Jensen (1996) and ages at 50% maturity reported by (Stark 2007; see "Maturity" subsection below). In response to a request from the SSC, the 2008 BSAI assessment included further discussion and justification for these values.

Published estimates of *M* for Pacific cod are shown below:

Area	Author	Year	Value
Eastern Bering Sea	Low	1974	0.3 - 0.45
Eastern Bering Sea	Wespestad et al.	1982	0.7
Eastern Bering Sea	Bakkala and Wespestad	1985	0.45
Eastern Bering Sea	Thompson and Shimada	1990	0.29
Eastern Bering Sea	Thompson and Methot	1993	0.37
Eastern Bering Sea	Shimada and Kimura	1994	0.96
Eastern Bering Sea	Shi et al.	2007	0.4 - 0.5
Gulf of Alaska	Thompson and Zenger	1993	0.27
Gulf of Alaska	Thompson and Zenger	1995	0.5
British Columbia	Ketchen	1964	0.56-0.63
British Columbia	Fournier	1983	0.65
Korea	Jung et al.	2009	0.82
Japan	Ueda et al.	2004	0.2

For all models, except Model 16.xx.24 and Model 16.xx.25, *M* was set independently at the SSC-approved value of 0.38. For Model 16.xx.25 M was estimated using a lognormal prior with a mean of 0.38 and CV of 0.1. Model 16.xx.24 was exploratory and a U-shaped vector of natural mortality was used. The mean of the values between 2 and 12 were set at $\bar{M}$ = 0.38.

Natural mortality by age use in model configuration 16.xx.24:

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
0.9	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
0.7	0.7	0.8	0.9	0.99	0.99	0.99	0.99	0.99	0.99

Catchability
All of the current model configurations had catchability fixed at 1.0, except for Model 16.xx.25 where catchability is fit with a non-informative prior.

Variability in Estimated Age
Variability in estimated age in SS is based on the standard deviation of estimated age. Weighted least squares regression has been used in the past several assessments to estimate a linear relationship between standard deviation and age. The regression was recomputed in 2011, yielding an estimated intercept of 0.023 and an estimated slope of 0.072 (i.e, the standard deviation of estimated age was modeled as 0.023 + 0.072 × age), which gives a weighted R^2 of 0.88. This regression was retained in the present assessment.

Weight at Length
Parameters governing the weight-at-length were estimated outside the model using all available GOA bottom trawl survey data through 2015, giving the following values:

	Value
α:	5.631×10^{-6}
β:	3.1306
Samples:	7,366

Maturity
A detailed history and evaluation of parameter values used to describe the maturity schedule for GOA Pacific cod was presented in the 2005 assessment (Thompson and Dorn 2005). A length-based maturity schedule was used for many years. The parameter values used for this schedule in the 2005 and 2006 assessments were set on the basis of a study by Stark (2007) at the following values: length at 50% maturity = 50 cm and slope of linearized logistic equation = –0.222. However, in 2007, changes in SS allowed for use of either a length-based or an age-based maturity schedule. Beginning with the 2007 assessment, the accepted model has used an age-based schedule with intercept = 4.3 years and slope = –1.963 (Stark 2007). The use of an age-based rather than a length-based schedule follows a recommendation from the maturity study's author (James Stark, ret., Alaska Fisheries Science Center, personal communication). The age-based parameters were retained in the present assessment.

Parameters Estimated Inside the Assessment Model

Parameters estimated conditionally (i.e., within individual SS runs, based on the data and the parameters estimated independently) in the model include the von Bertalanffy growth parameters, annual recruitment deviations, initial fishing mortality, gear-specific fishery selectivity parameters, and survey selectivity parameters (Table 2.10).

The same functional form (pattern 24 for length-based selectivity, pattern 20 for age-based selectivity) used in Stock Synthesis to define the fishery selectivity schedules in previous year's assessments was used this year for both the fishery and survey. This functional form, the double normal, is constructed from two underlying and rescaled normal distributions, with a horizontal line segment joining the two peaks. This form uses the following six parameters (selectivity parameters are referenced by these numbers in several of the tables in this assessment):

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

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

In this year's models both fishery and survey selectivities were length-based. In last year's model trawl survey selectivities were age-based.

Uniform prior distributions were used for all selectivity parameters, except for *dev* vectors in model configuration 16.xx.11 were constrained by input standard deviations ("sigma") of 0.2.

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

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

Likelihood Components

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

In SS, emphasis factors are specified to determine which likelihood components receive the greatest attention during the parameter estimation process. As in previous assessments, all likelihood components were given an emphasis of 1.0 in the present assessment.

Use of Size and Age Composition Data in Parameter Estimation

Size and age composition data are assumed to be drawn from a multinomial distribution specific to a particular year and gear within the year. In the parameter estimation process, SS weights a given size composition observation (i.e., the size frequency distribution observed in a given year and gear) according to the emphasis associated with the respective likelihood component and the sample size specified for the multinomial distribution from which the data are assumed to be drawn. We set initial sample sizes for the fishery at the number of hauls sampled, for the surveys both size and age composition sample sizes were initially set at 100. For one subset of models Series 16.08.xx and 16.09.xx we did not tune the models. For another set of models, Series 16.10.xx and 16.11.xx, we implemented the Francis TA1.8 method (Francis 2011) for tuning the model and explore the model sensitivity to the length composition sample size as implemented in the R4SS package (Hicks et al. 2016). Model 16.10.20 was tuned over three iterations, until the Francis weights diagnostics neared 1.0 for the length and age composition data. The same weights were used for all Series 16.10.xx and 16.11.xx models.

Results

Model Evaluation

The 2015 final model with data from 2015, and new model configurations are presented. The new models differed in data weighting, which and how the survey data were used, and the number of periods for time-varying survey and fishery selectivity-at-length. The model evaluation criteria included model adherence to biological principles and assumptions, the relative sizes of the likelihood components, and how well the model estimates fit to the survey indices, the survey age composition and conditional age-at-length data,

reasonable curves for fishery and survey selectivity, and retrospective pattern. All models presented adequately estimated the variance-covariance matrix. Model likelihoods and key parameter estimates are provided in Table 2.11 and Table 2.12. Likelihoods by fleet are provided in Table 2.13. It should be noted that not all models can be compared directly using likelihoods or AIC due to differences in data and data weighting. Retrospective results, index RMSE and composition mean effective sample sizes are provided in Table 2.14.

Comparing and Contrasting Model Configurations

The 2015 Model 15.3 estimates were substantially different from the new models presented this year. The likelihood components and how these data were fit are too different to compare directly using likelihoods. The results from the GOA Pacific cod stock assessment has been particularly volatile with a wide-array of models presented over the past 16 years (A'mar and Palsson 2015). The 2015 Model 15.3 was well fit to the data, however results of this assessment model were suspect in comparison with previous model efforts and anecdotal evidence suggesting GOA Pacific cod were not as abundant pre-1987 as the model suggests. The female spawning biomass for 1977-1987 from the 2014 and 2015 models were more than double previous model results (Fig. 2.15).

Model 15.3

Overall biomass estimated in Model 15.3 appear to be inflated, particularly for older fish. Model 15.3 had total biomass estimates for surveyed years 1990 – 2015 that were on average 3.15 times the bottom trawl survey estimates. Among all of the 2016 alternative models the model total biomass estimates were on average for 1990 - 2015 between 0.996 (Model 16.10.24) and 1.57 times (Model 16.10.11) the bottom trawl survey estimates. Catchability in Model 15.3 was fixed at 1.00 and M was fixed at 0.38, the model selectivity was highly dome-shaped for all components except a single trawl fishery season. The non-parametric selectivity used to fit the AFSC bottom trawl survey age composition data was peaked for some blocks. The model therefore mostly ignored the fit to the one fishery set as asymptotic. The peaked selectivity then allowed the model to fit very large abundances on either side of the peaks. In Model 15.3, 32% of the total biomass (43% of the spawning biomass) was estimated to be 8 years old or older, where survey selectivity was estimated at ≤ 0.06, suggesting a large cryptic portion of the spawning biomass (Fig 2.16). Model 16.10.11, the model most similar to Model 15.3 with dome-shaped selectivity for the survey and fixed M = 0.38 and Q = 1.0, estimated 28% of the total biomass and 40% of the spawning biomass at age 8 or older. For the remaining proposed models the percentage of total biomass at age 8 or older ranged from 11.4% (Model 16.10.20 and Model 16.11.20) to 19.1% (Model16.10.24).

Models 16.xx.11

Among the 2016 alternative models model configuration 16.xx.11 was most similar to Model 15.3 in model form and results with fixed M and Q and dome-shaped selectivity on the survey. However, model configuration 16.xx.11 has much less weight on the size and age composition data and does not include a bias adjustment for the age data. Besides overall magnitude of the biomass estimates the 16.xx.11 models all estimate a large 2011-2012 year class which is near the mean in Model 15.3. Note that the 2015 and 2016 fisheries data were not updated or included in the re-run of the 2015 model for this year, the model therefore did not have some of the information available to the alternative models which corroborates the large 2012 year class observed in the 2015 survey data. All of the alternative models estimated 2012 to be well above average, however Model 16.10.11 has the largest deviation from mean recruitment. Although both Model 15.3 and Models with configuration 16.xx.11 fit the available data well, an assumption of a large cryptic older population in the Gulf of Alaska given the extent of both the AFSC longline survey and bottom trawl survey, as well as all three fisheries appears implausible. Even though Models 16.xx.11 estimates a smaller population than Model 15.3 it still assumes a large portion of the spawning biomass was cryptic with over 11% in ages 12 and older and 40% in ages 8 and older.

Models16.xx.20

Model configuration 16.xx.20 was the most basic model with Q fixed at 1.0, M fixed at 0.38, and survey selectivity forced to be asymptotic and non-time varying for all components. Model 16.10.20 was the only model run of the 16.xx.20 configuration completed as the model configuration was not well fit and resulted in low total biomass and spawning biomass estimates, in the order of 112% of the NMFS survey. For evaluation purposes Model 16.10.20 will be compared with other Model 16.10.xx series models. Model 16.10.20 had the worst overall fit of all the 16.10.xx series models. The only components that were better fit were the AFSC longline survey index over Model 16.10.23 (log likelihood -1.2 vs. -0.86) and the AFSC longline length composition data which had a lower likelihood than both Model 16.10.23 and Model 16.10.24 (109.52 – M16.10.20, 110.6 – M16.10.23, and 111.7 – M16.10.24). The retrospective was substantially improved over Model 16.10.11 (Table 2.14). However model fit to the early trawl and longline fishery data remained poor, as well as the fit to the 2014 - 2016 pot fishery length composition data. The pot fishery length composition data had a sharp decline in mean length post-2013 that wasn't matched in the Model 16.10.20 predictions. Model 16.10.20 fit to the pre-1993 trawl survey length composition data tended to underestimate average length. Similarly the fit to the NMFS trawl survey age-composition data tended to underestimate the mean age of fish in the earlier survey years. It is likely that selectivity in this survey changed in 1995 when the survey changed from 30-minute tow durations to 15-minute tow durations.

Models 16.xx.23

Model configuration 16.xx.23 added time-varying selectivity to all three fisheries and the bottom trawl survey in recognition of the weakness in the 16.xx.20 configuration. Model 16.xx.23 had an additional 26 parameters allowing time blocked selectivity for the trawl and longline fisheries, and the AFSC bottom trawl survey. Adding blocked-time varying selectivity to the model configuration with these three series resulted in an overall improvements in the model fit (Table 2.11 and Table 2.12). These additional parameters improved model fit by 199, 39.4, and 102.3 likelihood points and 345, 27, and 152.7 AIC points for model series 16.09.xx, 16.10.xx, and 16.11.xx, respectively (Table 2.13). We did not run Model 16.08.20. The AFSC longline survey index and length composition data and the bottom trawl age composition data were the only component fits that were slightly degraded. The main improvement in the model were in fits to the 1977-1989 longline and trawl fishery length composition data, the post-2013 pot fishery length composition data, and the trawl survey index and length composition data (Table 2.xx). In addition Model 16.xx.23 configurations that included the sub-27 cm fish in survey data (Series 16.08.23 and 16.10.23) resulted in the best retrospective of all models evaluated (Table 2.14). Conversely, model series without the sub-27 cm fish in the survey data (Models 16.09.23 and 16.11.23) resulted in the poor retrospective patterns. In general Models 16.xx.23 tended to under-estimated the larger fish (> 60 cm) in the survey length composition data. All 16.xx.23 Model configuration biomass estimates were lower than their 16.xx.20 and 16.xx.11 series counterpart estimates.

Models 16.xx.24

Model 16.10.24 was meant as exploratory and to satisfy a request by Dr. Patrick Lynch for a U-shaped natural mortality with senescence in older cod. The parameterization used in this model was guesswork, there wasn't enough time to thoroughly research this item. In this run we set M to 0.9 for age 1 and 0.99 for all ages greater than 12. In preliminary models M was averaged to 0.38 for ages 2-12, however as with other models better fits were obtained with higher average M. Model fits to the size and age composition data with M averaged at 0.38 were comparable to fits from Model 16.10.23. However there was a noticeable improvement of the fit to the longline survey index and degradation of the fit to the bottom trawl survey index. Retrospective patterns were also similar to Model 16.10.23. The distribution of fish by age in the population was different. The U-shaped natural mortality allowed the population to have a high peak in biomass at ages 5-6, similar to Model 16.10.23, but had a larger proportion of older fish up to age 11. After age-11 the population quickly declined as expected with high mortality at these older ages. Spawning stock biomass estimates were near Model 16.10.23, however Female $SSB_{100\%}$ for this model was substantially

lower as were total biomass estimates with essentially no cryptic population over age 12. Before this type of parameterization could be used for management we would need more evidence that this stock exhibits senescence, no such studies have yet been undertaken.

Model 16.xx.25

The 16.xx.25 configuration models were similar to Model 16.6.22 presented in September (Appendix 2.1) with both natural mortality and catchability fit in the model, as well as dome-shaped selectivity on both surveys and fisheries. For this model configuration we only ran Model 16.08.25 and Model 16.10.25. Natural mortality was estimated at 0.47 for Model 16.08.25 and 0.50 for Model 16.10.25, well above the current estimate accepted by the SSC, but within the bounds of estimates made in other studies (see above). Catchability was estimated at 1.770 and 1.679 in Model 16.08.25 and Model 16.10.25, suggesting the NMFS bottom trawl survey overestimates fish abundance at the lengths of peak selectivity. Selectivity in the two surveys were estimated to be dome-shaped, however the estimates for the NMFS bottom trawl survey selectivity were higher at older ages and less peaked than those fit in Model 15.3 and Model 16.xx.11. Allowing M and Q to be estimated within the model and allowing dome-shaped selectivity in the NMFS bottom trawl survey substantially improved the fit to all model components resulting in the best fit of all models presented (Table 2.11 and Table 2.12). Only Model 16.10.11 fits any components better than Model 16.10.25 with a smaller likelihood on the trawl fishery size composition data (27.25 vs. 39.30), but at the expense in Model 16.10.11 of an additional 104 parameters/devs. allowing time varying selectivity for the entire trawl fishery time series.

Retrospective analysis results were mixed for the 16.xx.25 configuration with a relatively good retrospective results for Model 16.08.25 and relatively poor retrospective results for Model 16.10.25 in comparison with other models evaluated (Table 2.14). In Model 16.10.25 M and Q estimates were sensitive to fluctuations in the bottom trawl survey index values over time (Fig. 2.17). Model 16.10.25 used Francis TA1.8 tuned multinomial sample size corrections that greatly reduced the weight given to the composition data in comparison to index values. This increase in weight on the indices caused the model to shift Q and M in response to variability in these indices. In Model 16.08.25, which had more weight given to the composition data, M and Q were better estimated and did not change as severely with the addition of new data.

Comparing Configurations With and Without Sub-27 cm in the Length and Age Composition Data

As noted in previous assessments (Amar and Pallson 2015), high numbers of small Pacific cod in the NMFS bottom trawl survey doesn't always equate to a substantial increase in abundance at larger sizes in later surveys and on occasion higher than average year classes that exist in later surveys haven't always occurred as numerous small fish in earlier surveys. The 10-20cm fish in 1996 and 2009 were the dominant peaks in abundance, however in later surveys their abundances although substantial were not at the expected magnitude the earlier data would have suggested.

Model series 16.08.xx and 16.10.xx retained sub-27 cm fish in the NMFS bottom trawl survey data and model series 16.09.xx and 16.11.xx did not. The removal of these small fish from the survey data were meant to reduce the probability of falsely identifying a large year class without their occurrence as larger fish in later surveys. Model 16.11.20 was the same configuration as Model 16.10.20 and Model 16.11.23 had the same configuration as Model 16.10.23. Because the underlying data for the two model series has changed direct comparisons using likelihoods or AIC were not possible. The main change between the 16.10.xx and 16.11.xx series was that even though the 2012 year class remained above average both of the 16.11.xx models reduced the magnitude of the 2012 year class from the Model 16.10.xx estimates (Fig. 2.17). The overall shape of the distribution of biomass by age remained the same between the 16.10.xx and 16.11.xx models (Fig. 2.16). Fit to the fishery length composition data remained comparable. Model 16.11.03 had a slightly degraded fit to the fishery length composition data from Model 16.10.20 (<+5 likelihood points) and Model 16.11.23 showed some small improvement (< -4 likelihood points). In both models the fit to longline survey index were improved and length composition data degraded from their

16.10.xx series counterparts (Table 2.13). For both 16.11.xx series models the survey mean length was consistently underestimated. Residuals for the length composition in both series 16.11.xx models show poor fits to 1996, 2005, 2007, 2009, and 2013 data where the peak abundance of large fish were missed. However although the 16.10.xx series models do a better job of characterizing the mean lengths of these data, the data were not fit well for these years either. Both model series underestimate the larger fish (40-70 cm) in these years. It is possible that there was either a vessel effect or environmental effect that changed selectivity and or Q among years that isn't accounted for in either of these model configurations. Future models should explore environmental covariates that could be used to adjust either Q or selectivity of the survey across years.

Retrospective analysis for the 16.11.xx models reveal that these models had consistently worse current year bias as measured by the Mohn's ρ than their 16.10.xx counterparts, while their overall retrospective bias, as measured by the Woods Hole ρ and retrospective RMSE, were approximately the same. Model 16.11.20 and Model 16.11.23 had Mohn's ρ values of 0.220 and 0.114 somewhat higher than Model16.10.20 at 0.138 and Model 16.10.23 at 0.063, Woods Hole values were -0.032 and -0.042 and retrospective RMSE values were 0.091 and 0.093.

Model tuning in the 2016 alternative models

The 16.08.xx and 16.09.xx series of models were not tuned and Series 16.10.xx and 16.11.xx were tuned using the Francis TA1.8 method. There are no quantitative means to compare and contrast these sets of models currently available, assessment of the two approaches was therefore somewhat subjective. Here we use model configuration 16.xx.25 to compare model results. In general the Francis method resulted in down-weighting length and size composition data sample sizes for all components (Table 2.13), in general degrading the fit to fishery and survey composition data (Fig. 2.18) while marginally improving fit to the survey indices (Table 2.11. Table 2.12 and Fig. 2.19). The harmonic mean of the effective N decreased for four of the five length composition data sets with tuning, due to poorer fits in the tuned models. The only exception was the fit to the AFSC longline length composition data which saw a small (< 0.3 EffN) improvement with tuning. The RMSE of the indices decreased with tuning indicating an improvement in fit to both of the indices for both tuned models. Although there was some improvement to the fit to the indices with tuning it was relatively minor while the decrease in fit to the length composition data was notable (Fig. 2.18).

Results for the tuned models show less variability in recruitment (Table 2.14 and Fig. 2.17) than the un-tuned model. The magnitude of the 1977 year-class was particularly affected by Francis tuning (Fig. 2.21 and Fig. 2.22) as it was moved from the highest recruitment deviation in the un-tuned models to near average in the tuned models (Table 2.15 and Table 2.16). The model 16.10.25 estimate of M was slightly higher (0.50 vs 0.47) resulting in higher overall recruitments (Fig. 2.17). Where M was fixed as in the M16.xx.23 series recruitments were lower in the tuned models on average (Table 2.15). The 2012 year class remains higher than average in both model runs. In all models the 2011 year class remains high and within 50 million fish. Although the magnitude of biomass and abundance estimates differ between models, the un-tuned model results were most similar to pre-2014 GOA Pacific cod models (Fig. 2.24) in the biomass trends.

Retrospective analysis showed a substantial increase in retrospective bias in the tuned model for Model 16.10.25 (Fig. 2.20 and Fig. 2.21). In the tuned model M varied substantially as data were removed from the model. In the un-tuned model where the size composition data had larger weight M and Q remained relatively stable (Fig. 2.22 and Fig. 2.23). In other models of series 16.08.xx and 16.10.xx where M and Q were fixed, the retrospective analysis resulted in little difference between the un-tuned and tuned models.

The benefit of tuning the model using the Francis method was simply placing more weight on the indices in the model. However the Francis TA1.8 method appears to over-weight the indices to a point where signal in the composition data was lost.

Selection of Final Model

Comparing likelihoods or AIC between Model 15.3 and the proposed 2016 models was not appropriate since data and data weights differ substantially. Here model results show that Model 15.3 estimated the total biomass of Pacific cod to be 310% higher on average than the NMFS bottom trawl survey total biomass estimates (Fig. 2.24). The model assumptions of steeply-sided selectivity on the AFSC survey age composition data allow the model to greatly inflate the population on either side of the selectivity peak and therefore inflate the overall abundance estimates. In this model 42% of the spawning biomass was assumed to exist outside of the survey and a substantial portion of the population was at ages never observed in the surveys or fisheries. This result in itself suggests this model was not appropriate for management. Likelihood and AIC comparisons between model series with and without sub-27 cm fish could not be conducted because data differ between the two series. Results from model runs from these series show that retrospectives patterns were negatively impacted with the removal of the sub-27 cm fish. Otherwise results were similar between comparable series with and without sub-27cm fish. Recruitment variability, which the removal of the sub-27 cm fish was to help stabilize, remained nearly identical.

Within each of model series the 16.xx.25 configuration models were the best fit. Models 16.08.25 and Model 16.10.25 which retain the sub-27 cm fish have similar results. Parameter estimates differ in that Model 16.08.25 estimates M at 0.47 with a CV of 0.06 while Model 16.10.25 M was estimated at 0.50 with a CV of 0.09. Catchability also differ between the models with a higher Q in Model 16.08.25 than Model 16.10.25 (Q=1.77, CV= 0.05 vs Q = 1.67, CV= 0.08). Growth also differed between models with faster and higher asymptotic growth in Model 16.08.25 (Fig. 2.25, Table 2.12 and Table 2.26) and different selectivity with less domed selectivity for the fishery and survey composition data (Fig. 2.20). Overall fits to the data differ in that Model 16.08.25 fits length and age composition data marginally better than Model 16.10.25 based on effective sample number, while Model 16.10.25 fits the survey indices marginally better based on RMSE. In addition due to lower natural mortality in Model 16.10.25 the model had selectivity curves that were pushed to the right instead of dome-shaped. This along with slower and lower asymptotic growth, lower Q but higher M caused F_{MSY} to be above 1.0. Further there were substantial differences between the models in the retrospective analysis. Model 16.08.25 had much better retrospective patterns in both spawning biomass and recruitment. Estimates of M and Q were less variable both in the asymptotic model parameter estimates and in the retrospective analyses (Fig. 2.22 and Fig. 2.23).

Asymptotic variance estimates:

	Catchability (Q) St. Dev.	**Natural mortality (M) St. Dev.**
Model 16.08.25	0.094	0.026
Model 16.10.25	0.134	0.047

Retrospective indices:

	Female spawning biomass			**Recruitment age-0**		
	Mohn's σ	Woods Hole ρ	RMSE	Mohn's σ	Woods Hole ρ	RMSE
Model 16.08.25	0.09	0.03	0.10	0.23	0.18	0.32
Model 16.10.25	0.29	0.13	0.19	0.70	0.74	0.62

For these reasons the Author's choice for management of the Gulf of Alaska Pacific cod is Model 16.08.25.

Model 16.08.25 diagnostics and Suggestions for Future Improvement

Survey Indices

Model 16.08.25 fit to the NMFS bottom trawl survey was within error bounds of the survey estimates for all but the 2009 and 2015 survey (Fig. 2.27). Given the available length and age composition data, the model was not able to increase abundance enough between 2007 and 2009 to match the large increase in abundance between these two surveys. The 2015 NMFS bottom trawl survey estimate was lower than the model expected given the large 2011-2013 recruitments observed in the length composition data and trend observed in the AFSC longline survey.

Model 16.08.25 fits the AFSC longline index well (Fig. 2.27), but like the fit to the NMFS bottom trawl survey index, has difficulty fitting the large increase in abundance between 2008 and 2009, underestimating the 2009-2011 RPN, outside the survey error bounds.

An issue that should be better addressed is that Pacific cod have been found to change distribution with water temperature (Fig.2.28 and Fig. 2.29) with larger cod moving to shallower depths in the cold years and deeper depths in the warm years. 2009 was a very cold year and may have made cod more available to the survey as they moved further onto the shelf while 2015 was very warm and may have resulted in cod being less available to the survey as they moved down the shelf. Future models should examine the effects of temperature on selectivity and catchability. Preliminary model runs with bottom temperature affecting these two factors have shown promise, but were not presented in this year's alternatives.

Length Composition

Selectivities in Model 16.08.25 were dome-shaped, except for the 1990-2016 longline fisheries and 2013-2016 trawl fisheries (Fig. 2.9). Overall model predictions of the length compositions closely match the data for all components (Fig. 2.30). For the trawl fishery the model predictions (Fig. 2.31) although matching the mean length well, tended to underestimate the high peaks of the distributions and overestimate either side of the peaks. Predictions of the longline fishery length composition (Fig. 2.32) were well fit but similarly underestimated the high peaks of the distributions and overestimated either side of the peaks, but in matched the mean length very well. Predictions of the pot fishery length composition (Fig. 2.34) were also very well fit, again, like the trawl and longline fisheries the high peaks of the distributions were underestimated and either side of the peaks were overestimated. The mean length for the pot fishery data were well matched for all but the 2016 fishery. The final 2013-2016 pot fishery length composition (Fig. 2.34) show a steep decline in mean length that couldn't be matched exactly using the blocked time varying selectivity applied in this model. For the fishery length composition, there really is no need for improvement, residuals were small even for the minimal discrepancies noted above for the peak modes.

Model 16.08.25 matched the NMFS bottom trawl survey length composition data mean lengths well (Fig. 2.35), however small fish (sub-27 cm) fish high modes although identified were not always matched in magnitude. The sub-27cm modes in 1996, 2007, and 2009 were estimated lower than observed while a predicted mode for sub-27cm fish in 2011 was not observed in the data. A few peak modes were underestimated, but in general the larger fish were well predicted by the model. Removing the sub-27cm fish improves the fit to the model, but has detrimental effects on the stability of the overall model. Although they fit the data very well non-parametric selectivity curves, as implemented in SS3, with fixed catchability, no sub-27 cm fish and on age-composition as in Model 15.3 appeared to have over-inflated abundance as the selectivity curves were extremely peaked with sharp declines on either side of the modes. Non-parametric selectivity curves should be further explored in fitting the NMFS bottom trawl survey length composition data with the sub-27cm fish.

Although the selectivity for Model 16.08.25 Auke Bay Laboratory length composition data (2.36) were not time varying, the predictions matched the data well. The predictions for 2015 was the only prediction that didn't fit within the 95% confidence bounds of the mean length. No improvement to the fits to the

AFSC longline survey length composition data are needed as the fits appear to be very close with no patterns in the residuals.

Age Composition and Length-at-Age
Even though the shelf survey age composition data were fit using the length composition selectivity (Fig. 2.32) in Model 16.08.25, age composition predictions matched the data well (Fig. 2.37). Mean age predictions all fell within the confidence bounds of the data (Fig. 2.37).

Model 16.08.25 has non-time varying growth (Fig. 2.38). Fits to the length-at-age data are within the error bounds for most ages (Fig. 2.39), however there appears to be some inter-annual variability that was not captured in this model. For instance Pacific cod in 1990 and 2015 were predicted in Model 16.08.25 to be larger at age than the data show for the oldest fish, while 2005 the opposite was true. This may be improved with annually varying growth, however data for pre-1990 data are not available, and therefore modeling inter-annual variability prior to 1990 is not possible.

Mean length and weight at age from Model 16.08.25 are provided in Table 2.19.

Time Series Results

Definitions
The biomass estimates presented here will be defined in two ways: 1) total biomass was defined as age 0+ biomass, consisting of the biomass of all fish aged 0 years or greater in a given year; and 2) spawning biomass was defined as the biomass of all spawning females in a given year. The recruitment estimates presented here was defined as numbers of age-0 fish in a given year. All results presented are from Model 16.08.25.

Biomass
Estimates of total biomass were on average 136% higher than the NMFS bottom trawl survey total biomass estimates. Total biomass estimates show a long decline from their peak of 621,265 t in 1987 (Fig. 2.40) to 226,330 in 2007 and then an increase to 373,364 t from 2007 to 2016. The 2017 and 2018 total biomass is expected to decline. Spawning biomass (Table 2.18) shows a similar trend of decline since the late 1980s with a peak in 1985 at 214,060 t to its lowest level of 51,225 t in 2008 and a continued increase through 2016 to 91,210 t. Projections within the model shows an increase in spawning biomass as the large 2012 and 2013 year classes mature, but then decrease starting in 2018 due to poor recruitment since 2014(Table 2.15). Numbers at age and length are provided in Appendix 2.2 and shown in Figure 2.41.

(http://www.afsc.noaa.gov/REFM/Docs/2016/GOApcod_Appendix2_2.xlsx)

Recruitment and Numbers at Age
The recruitment predictions in Model 16.08.25 (Table 2.16, Fig. 2.42 and Fig. 2.43) show large 1977 and 2012 recruitments with more than 1 billion age-0 fish for each (1.5 billion for 1977 and 1.0 billon for 2012) although uncertainty on the 1977 recruitment estimate was large (σ = 0.456). Large recruitments (<0.7 billion age-o) were also estimated for 1979, 1980, 1984, 1985, 1989, and 2011. Between 1990 and 2010 the average recruitment was estimated at 0.448 billion, 38% lower than the 1977-1989 mean recruitment of 0.725 billion and 20% lower than the 1977-2015 mean recruitment of 0.562 billion.

Fishing Mortality
Fishing mortality appears to have increased steadily with the decline in abundance from 1990 through a peak in 2010 in all models (Table 2.20 and Fig. 2.44). This period saw both a decline in recruitment paired with increases in catch. The largest increase in catch has been in the pot fishery, which also shows the largest increase in continuous F (Fig. 2.45). The phase plane plot (Fig. 2.46) shows that F was estimated to have been above $F_{35\%}$ for the years between 2007 and 2012 and again in 2014 and 2015 and biomass was below $B_{35\%}$ between 2008 and 2011.

Retrospective analysis

Estimates of spawning biomass for Model 16.08.25 with an ending year of 2006 through 2016 are not consistently biased from 1984 through 2000, have a consistent negative adjustment from 2009-2013 and an positive adjustment post-2013 as more data are included (Fig. 2.20). Relative differences in estimates of spawning biomass and recruitment show the same pattern for the more recent years.

Harvest Recommendations

Amendment 56 Reference Points

Amendment 56 to the GOA Groundfish Fishery Management Plan (FMP) defines the "overfishing level" (OFL), the fishing mortality rate used to set OFL (F_{OFL}), the maximum permissible ABC, and the fishing mortality rate used to set the maximum permissible ABC. The fishing mortality rate used to set ABC (F_{ABC}) may be less than this maximum permissible level, but not greater. Because reliable estimates of reference points related to maximum sustainable yield (MSY) are currently not available but reliable estimates of reference points related to spawning per recruit are available, Pacific cod in the GOA have generally been managed under Tier 3 of Amendment 56. Tier 3 uses the following reference points: $B_{40\%}$, equal to 40% of the equilibrium spawning biomass that would be obtained in the absence of fishing; $F_{35\%}$, equal to the fishing mortality rate that reduces the equilibrium level of spawning per recruit to 35% of the level that would be obtained in the absence of fishing; and $F_{40\%}$, equal to the fishing mortality rate that reduces the equilibrium level of spawning per recruit to 40% of the level that would be obtained in the absence of fishing. The following formulae apply under Tier 3:

3a) Stock status: $B/B_{40\%} > 1$

$F_{OFL} = F_{35\%}$

$F_{ABC} \leq F_{40\%}$

3b) Stock status: $0.05 < B/B_{40\%} \leq 1$

$F_{OFL} = F_{35\%} \times (B/B_{40\%} - 0.05) \times 1/0.95$

$F_{ABC} \leq F_{40\%} \times (B/B_{40\%} - 0.05) \times 1/0.95$

3c) Stock status: $B/B_{40\%} \leq 0.05$

$F_{OFL} = 0$

$F_{ABC} = 0$

Other useful biomass reference points which can be calculated using this assumption are $B_{100\%}$ and $B_{35\%}$, defined analogously to $B_{40\%}$. These reference points are estimated as follows, based on this year's model, Model 16.08.25:

Reference point:	$B_{35\%}$	$B_{40\%}$	$B_{100\%}$
Spawning biomass:	68,872 t	78,711 t	196,776 t

For a stock exploited by multiple gear types, estimation of $F_{35\%}$ and $F_{40\%}$ requires an assumption regarding the apportionment of fishing mortality among those gear types. For this assessment, the apportionment was based on this year's model's estimates of fishing mortality by gear for the five most recent complete years of data (2010-2015). The average fishing mortality rates for implied that total fishing mortality was divided among the three main gear types according to the following percentages: trawl 30%, longline 20%, and pot 50%. This apportionment results in estimates of $F_{35\%}$ and $F_{40\%}$ equal to 0.652 and 0.530, respectively.

Specification of OFL and Maximum Permissible ABC

Spawning biomass for 2017 is estimated by this year's model to be 98,479 t. This is above the $B_{40\%}$ value of 78,711 t, thereby placing Pacific cod in sub-tier "a" of Tier 3. Given this, the model estimates OFL, maximum permissible ABC, and the associated fishing mortality rates for 2017 and 2018 as follows (2018 values are predicated on the assumption that 2017 catch will equal 2017 maximum permissible ABC):

Units	Year	Overfishing Level (OFL)	Maximum Permissible ABC
Harvest amount	2016	105,378 t	88,342 t
Harvest amount	2017	94,188 t	79,272 t
Fishing mortality rate	2016	0.652	0.530
Fishing mortality rate	2017	0.652	0.530

The age 0+ biomass projections for 2017 and 2018 from this year's model are 428,885 t and 400,755 t, respectively.

ABC Recommendation

Since 2008 the GOA Plan Team and SSC recommended setting the ABC at the maximum permissible level under Tier 3. Biological reference points from GOA Pacific cod SAFE documents for years 2001 – 2016 are provided in Table 2.21.

Following this practice, this year's ABC recommendations for 2017 and 2018 are at their respective maximum permissible levels of 88,342 t and 79,272 t.

Area Allocation of Harvests

For the past several years, ABC has been allocated among regulatory areas on the basis of the three most recent surveys. The previous proportions based on the 2009-2013 surveys were 33% Western, 64% Central, and 3% Eastern. In the 2013 assessment, the random effects model was used for the 2014 ABC apportionment. Using this method with the trawl survey biomass estimates through 2015, the area-apportioned ABCs are:

	Western	Central	Eastern	Total
Random effects area apportionment (percent)	41.08	50.01	8.91	100.00
2017 ABC	36,291	44,180	7,871	88,342
2018 ABC	32,565	39,644	7,063	79,272

Standard Harvest and Recruitment Scenarios and Projection Methodology

A standard set of projections for population status under alternatives were conducted to comply with Amendment 56 of the FMP. 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 2015 numbers at age estimated in the assessment. This vector is then projected forward to the beginning of 2016 using the schedules of natural mortality and selectivity described in the assessment and the best available estimate of total (year-end) catch for 2016 (here assumed to be 70,494 t). In each subsequent year, the fishing mortality rate is prescribed based on the spawning biomass in that year and the respective harvest scenario. In each year, recruitment is drawn from an inverse Gaussian distribution whose parameters consist of maximum likelihood estimates determined from recruitments estimated in the assessment. Spawning biomass is computed in each year based on the time of peak spawning and the maturity and weight schedules described in the assessment. Total catch is assumed to equal the catch associated with the respective harvest scenario in all years. This projection scheme is run 1,000 times to obtain distributions of possible future stock sizes, fishing mortality rates, and catches.

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 2017, are as follow ("*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 the author's recommend level. Due to current conditions of strong recruitment and a projected increasing biomass, the recommendation is set equal to the maximum permissible ABC.

Scenario 3: In all future years, *F* is set equal to the 2010-2015 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 4: In all future years, *F* is set equal to the $F_{75\%}$. (Rationale: This scenario was developed by the NMFS Regional Office based on public feedback on alternatives.

Scenario 5: In all future years, *F* is set equal to zero. (Rationale: In extreme cases, TAC may be set at a level close to zero.)

Two other scenarios are needed to satisfy the MSFCMA′s requirement to determine whether a stock is currently in an overfished condition or is approaching an overfished condition. These two scenarios are as follows (for Tier 3 stocks, the MSY level is defined as $B_{35\%}$):

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 half of its B_{MSY} level in 2016 and above its B_{MSY} level in 2026 under this scenario, then the stock is not overfished.)

Scenario 7: In 2017 and 2018, F is set equal to max FABC, and in all subsequent years, F is set equal to FOFL. (Rationale: This scenario determines whether a stock is approaching an overfished condition. If the stock is 1) above its MSY level in 2018 or 2) above 1/2 of its MSY level in 2018 and expected to be above its MSY level in 2028 under this scenario, then the stock is not approaching an overfished condition.)

Scenarios 1 through 7 were projected 13 years from 2016 (Table 2.22). Fishing at the maximum permissible rate indicate that the spawning stock (Fig. 2.47) would likely drop below $SSB_{35\%}$ in 2019 (scenario 6) and 2020 (in scenario 7) due to poor recruitment post-2013, but then recover to $SSB_{35\%}$ under mean recruitment by 2021.

Our projection model run under these conditions indicates that for Scenario 6, the GOA Pacific cod stock is not overfished based on the first criterion (year 2016 spawning biomass estimated at 80,472 t relative to $B_{35\%}$ = 68,872 t) and will be above its MSY value in 2026 at 73,601 t.

Projections 7 with fishing at the OFL after 2018 results in an expected spawning biomass of 73,965 t by 2028. These projections illustrate the impact of the 2011-2013 high recruitments observed in the surveys and fishery data and then drop in recruitment in 2014 and 2015. For example, under all scenarios, the spawning biomass is expected to continue increasing through 2019 and then drops due to the low recruitments post-2013 and decreasing influence of the 2011-2013 year classes and then levels off as the projection relies on mean recruitment.

Under Scenarios 6 (Fig. 2.47) and 7 of the 2016 Model 16.08.25 the projected spawning biomass for Gulf of Alaska Pacific cod is not currently overfished, nor is it approaching an overfished status.

Ecosystem Considerations

Ecosystem Effects on the Stock

A primary ecosystem phenomenon affecting the Pacific cod stock seems to be the occurrence of periodic "regime shifts," in which central tendencies of key variables in the physical environment change on a scale spanning several years to a few decades (Boldt (ed.), 2005). One well-documented example of such a regime shift occurred in 1977, and shifts occurring in 1989 and 1999 have also been suggested (e.g., Hare and Mantua 2000). Establishing a link between environment and recruitment within a particular regime is more difficult. In the 2004 assessment (Thompson et al. 2004), for example, the correlations between age 1 recruits spawned since 1977 and monthly values of the Pacific Decadal Oscillation (Mantua et al. 1997) were computed and found to be very weak.

The prey and predators of Pacific cod have been described or reviewed by Albers and Anderson (1985), Livingston (1989, 1991), Lang et al. (2003), Westrheim (1996), and Yang (2004). The composition of Pacific cod prey varies to some extent by time and area. In terms of percent occurrence, some of the most important items in the diet of Pacific cod in the BSAI and GOA have been polychaetes, amphipods, and crangonid shrimp. In terms of numbers of individual organisms consumed, some of the most important dietary items have been euphausids, miscellaneous fishes, and amphipods. In terms of weight of organisms consumed, some of the most important dietary items have been walleye pollock, fishery offal, yellowfin sole, and crustaceans. Small Pacific cod feed mostly on invertebrates, while large Pacific cod are mainly piscivorous. Predators of Pacific cod include Pacific cod, halibut, salmon shark, northern fur seals, Steller sea lions, harbor porpoises, various whale species, and tufted puffin. Major trends in the most important prey or predator species could be expected to affect the dynamics of Pacific cod to some extent.

Fishery Effects on the Ecosystem

Potentially, fisheries for Pacific cod can have effects on other species in the ecosystem through a variety of mechanisms, for example by relieving predation pressure on shared prey species (i.e., species which serve as prey for both Pacific cod and other species), by reducing prey availability for predators of Pacific cod, by altering habitat, by imposing bycatch mortality, or by "ghost fishing" caused by lost fishing gear.

Incidental Catch of Nontarget Species

Incidental catches of nontarget species in each year 2007-2016 are shown Table 2.6. In terms of average catch over the time series, only sea stars account for more than 250 t per year.

Steller Sea Lions

Sinclair and Zeppelin (2002) showed that Pacific cod was one of the four most important prey items of Steller sea lions in terms of frequency of occurrence averaged over years, seasons, and sites, and was especially important in winter. Pitcher (1981) and Calkins (1998) also showed Pacific cod to be an important winter prey item in the GOA and BSAI, respectively. Furthermore, the size ranges of Pacific cod harvested by the fisheries and consumed by Steller sea lions overlap, and the fishery operates to some extent in the same geographic areas used by Steller sea lion as foraging grounds (Livingston (ed.), 2002).

The Fisheries Interaction Team of the Alaska Fisheries Science Center has been engaged in research to determine the effectiveness of recent management measures designed to mitigate the impacts of the Pacific cod fisheries (among others) on Steller sea lions. Results from studies conducted in 2002-2003 were summarized by Conners et al. (2004). These studies included a tagging feasibility study, which may evolve into an ongoing research effort capable of providing information on the extent and rate to which Pacific cod move in and out of various portions of Steller sea lion critical habitat. Nearly 6,000 cod with spaghetti tags were released, of which approximately 1,000 had been returned as of September 2003.

Seabirds
The following is a summary of information provided by Livingston (ed., 2002): In both the BSAI and GOA, the northern fulmar (*Fulmarus glacialis*) comprises the majority of seabird bycatch, which occurs primarily in the longline fisheries, including the hook and line fishery for Pacific cod Shearwater (*Puffinus* spp.) distribution overlaps with the Pacific cod longline fishery in the Bering Sea, and with trawl fisheries in general in both the Bering Sea and GOA. Black-footed albatross (*Phoebastria nigripes*) is taken in much greater numbers in the GOA longline fisheries than the Bering Sea longline fisheries, but is not taken in the trawl fisheries. The distribution of Laysan albatross (*Phoebastria immutabilis*) appears to overlap with the longline fisheries in the central and western Aleutians. The distribution of short-tailed albatross (*Phoebastria albatrus*) also overlaps with the Pacific cod longline fishery along the Aleutian chain, although the majority of the bycatch has taken place along the northern portion of the Bering Sea shelf edge (in contrast, only two takes have been recorded in the GOA). Some success has been obtained in devising measures to mitigate fishery-seabird interactions. For example, on vessels larger than 60 ft. LOA, paired streamer lines of specified performance and material standards have been found to reduce seabird incidental take significantly.

Fishery Usage of Habitat
The following is a summary of information provided by Livingston (ed., 2002): The longline and trawl fisheries for Pacific cod each comprise an important component of the combined fisheries associated with the respective gear type in each of the three major management regions (BS, AI, and GOA). Looking at each gear type in each region as a whole (i.e., aggregating across all target species) during the period 1998-2001, the total number of observed sets was as follows:

Gear	BS	AI	GOA
Trawl	240,347	43,585	68,436
Longline	65,286	13,462	7,139

In the BS, both longline and trawl effort was concentrated north of False Pass (Unimak Island) and along the shelf edge represented by the boundary of areas 513, 517 (in addition, longline effort was concentrated along the shelf edge represented by the boundary of areas 521-533). In the AI, both longline and trawl effort were dispersed over a wide area along the shelf edge. The catcher vessel longline fishery in the AI occurred primarily over mud bottoms. Longline catcher-processors in the AI tended to fish more over rocky bottoms. In the GOA, fishing effort was also dispersed over a wide area along the shelf, though pockets of trawl effort were located near Chirikof, Cape Barnabus, Cape Chiniak and Marmot Flats. The GOA longline fishery for Pacific cod generally took place over gravel, cobble, mud, sand, and rocky bottoms, in depths of 25 fathoms to 140 fathoms.

Impacts of the Pacific cod fisheries on essential fish habitat were further analyzed in an environmental impact statement by NMFS (2005).

Gulf of Alaska Pacific cod economics
Appendix 2.3 includes an exploration of economic performance of the GOA Pacific cod fisheries by Dr. Ben Fissel.

Data Gaps and Research Priorities

Understanding of the above ecosystem considerations would be improved if future research were directed toward closing certain data gaps. Such research would have several foci, including the following: 1) ecology of the Pacific cod stock, including spatial dynamics, trophic and other interspecific relationships, and the relationship between climate and recruitment; 2) behavior of the Pacific cod fishery, including spatial dynamics; 3) determinants of trawl survey catchability and selectivity and relationship with environmental

covariates; 4) age determination and effects of aging error and bias on model parameters including natural mortality; 5) ecology of species taken as bycatch in the Pacific cod fisheries, including estimation of biomass, carrying capacity, and resilience; and 6) ecology of species that interact with Pacific cod, including estimation of biomass, carrying capacity, and resilience.

Literature Cited

Albers, W. D., and P. J. Anderson. 1985. Diet of Pacific cod, *Gadus macrocephalus*, and predation on the northern pink shrimp, *Pandalus borealis*, in Pavlof Bay, Alaska. Fish. Bull., U.S. 83:601-610.

A'mar, T. and W. Pallson 2015. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 173-296. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501

A'mar, T., Thompson, G., Martin, M., and W. Palsson. 2012. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 183-322. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501

Bakkala, R. G., and V. G. Wespestad. 1985. Pacific cod. *In* R. G. Bakkala and L. L. Low (editors), Condition of groundfish resources of the eastern Bering Sea and Aleutian Islands region in 1984, p. 37-49. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-83.

Boldt, J. (editor). 2005. Ecosystem Considerations for 2006. North Pacific Fishery Management Council, 605 West 4th Ave., Suite 306, Anchorage, AK 99501.

Calkins, D. G. 1998. Prey of Steller sea lions in the Bering Sea. Biosphere Conservation 1:33-44.

Fournier, D. 1983. An analysis of the Hecate Strait Pacific cod fishery using an age-structured model incorporating density-dependent effects. Can. J. Fish. Aquat. Sci. 40:1233-1243.

Fournier, D., and C. P. Archibald. 1982. A general theory for analyzing catch at age data. Can. J. Fish. Aquat. Sci. 38:1195-1207.

Fournier, D.A., H. J. Skaug, J. Ancheta, J. Ianelli, A. Magnusson, M. N. Maunder, A. Nielsen, and J. Sibert. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optim. Methods Softw. 27:233-249.

Greer-Walker, M. 1970. Growth and development of the skeletal muscle fibres of the cod (*Gadus morhua L.*). Journal du Conseil 33:228-244.

Gregory, R. S., C. Morris, and B. Newton. In review. Relative strength of the 2007 and 2008 year-classes, from nearshore surveys of demersal age 0 Atlantic cod in Newman Sound, Bonavista Bay. Can. Sci. Advis. Sec. Res. Doc. series./xxx.

Hare, S. R., and N. J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47:103-146.

Hiatt, T., R. Felthoven, M. Dalton, B. Garber-Yonts, A. Haynie, K. Herrmann, D. Lew, J. Sepez, C. Seung, L. Sievanen, and the staff of Northern Economics. 2007. Stock Assessment and Fishery Evaluation Report for the Groundfish Fisheries of the Gulf of Alaska and Bering Sea/Aleutian Islands Area: Economic Status of the Groundfish Fisheries off Alaska, 2006. Economic and Social Sciences Research Program, Resource Ecology and Fisheries Management Division, Alaska Fisheries Science Center, NMFS, NOAA, 7600 Sand Point Way N.E., Seattle, Washington 98115-6349. 353 p.

Jung, S., I. Choi, H. Jin, D.-w. Lee, H.-k. Cha, Y. Kim, and J.-y. Lee. 2009. Size-dependent mortality formulation for isochronal fish species based on their fecundity: an example of Pacific cod (*Gadus macrocephalus*) in the eastern coastal areas of Korea. Fisheries Research 97:77-85.

Ketchen, K.S. 1964. Preliminary results of studies on a growth and mortality of Pacific cod (*Gadus macrocephalus*) in Hecate Strait, British Columbia. J. Fish. Res. Bd. Canada 21:1051-1067.

Lang, G. M., C. W. Derrah, and P. A. Livingston. 2003. Groundfish food habits and predation on commercially important prey species in the Eastern Bering Sea from 1993 through 1996. Alaska Fisheries Science Center Processed Report 2003-04. Alaska Fisheries Science Center, 7600 Sand Point Way NE., Seattle, WA 98115-6349. 351 p.

Livingston, P. A. 1989. Interannual trends in Pacific cod, Gadus macrocephalus, predation on three commercially important crab species in the eastern Bering Sea. Fish. Bull., U.S. 87:807-827.

Livingston, P. A. 1991. Pacific cod. *In* P. A. Livingston (editor), Groundfish food habits and predation on commercially important prey species in the eastern Bering Sea from 1984 to 1986, p. 31-88. U.S. Dept. Commer, NOAA Tech. Memo. NMFS F/NWC-207.

Livingston, P. A. (editor). 2003. Ecosystem Considerations for 2003. North Pacific Fishery Management Council, 605 West 4th Ave., Suite 306, Anchorage, AK 99501.

Low, L. L. 1974. A study of four major groundfish fisheries of the Bering Sea. Ph.D. Thesis, Univ. Washington, Seattle, WA. 240 p.

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., & Francis, R. C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78, 1069-1079.

Methot, R. D. 1986. Synthetic estimates of historical abundance and mortality for northern anchovy, *Engraulis mordax*. NMFS, Southwest Fish. Cent., Admin. Rep. LJ 86-29, La Jolla, CA.

Methot, R. D. 1990. Synthesis model: An adaptable framework for analysis of diverse stock assessment data. Int. N. Pac. Fish. Comm. Bull. 50:259-277.

Methot, R. D. 1998. Application of stock synthesis to NRC test data sets. *In* V. R. Restrepo (editor), Analyses of simulated data sets in support of the NRC study on stock assessment methods, p. 59-80. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-F/SPO-30.

Methot, R. D. 2000. Technical description of the stock synthesis assessment program. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-NWFSC-43, 46 p.

Methot, R. D. 2005a. Technical description of the Stock Synthesis II Assessment Program. Unpubl. manuscr. National Marine Fisheries Service, Northwest Fisheries Science Center, 2725 Montlake Blvd. East, Seattle, WA 98112-2097. 54 p.

Methot, R. D. 2005b. User manual for the assessment program Strock Synthesis 2 (SS2), Model Version 1.19. National Marine Fisheries Service, Northwest Fisheries Science Center, 2725 Montlake Blvd. East, Seattle, WA 98112-2097. 47 p.

Methot, R. D. 2007. User manual for the integrated analysis program Stock Synthesis 2 (SS2), Model Version 2.00c. National Marine Fisheries Service, Northwest Fisheries Science Center, 2725 Montlake Blvd. East, Seattle, WA 98112-2097. 47 p.

Methot, R. D. 2013. User Manual for Stock Synthesis, Model Version 3.24q. Unpublished manuscript. 150 p.

Methot, R. D., and Wetzell, C. R. 2013. Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. Fish. Rsch. 142:86-99.

National Marine Fisheries Service (NMFS). 2005. Final environmental impact statement for essential fish habitat identification and conservation in Alaska. National Marine Fisheries Service, Alaska Region. P.O. Box 21668, Juneau, AK 99802-1668.

Nichol, D. G., T. Honkalehto, and G. G. Thompson. 2007. Proximity of Pacific cod to the sea floor: Using archival tags to estimate fish availability to research bottom trawls. *Fisheries Research* 86:129-135.

Ona, E., and O. R. Godø. 1990. Fish reaction to trawling noise: the significance for trawl sampling. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer 189: 159–166.

Pitcher, K. W. 1981. Prey of Steller sea lion, *Eumetopias jubatus*, in the Gulf of Alaska. Fishery Bulletin 79:467-472.

Savin, A. B. 2008. Seasonal distribution and Migrations of Pacific cod *Gadus macrocephalus* (Gadidae) in Anadyr Bay and adjacent waters. Journal of Ichythyology 48:610-621.

Shimada, A. M., and D. K. Kimura. 1994. Seasonal movements of Pacific cod (*Gadus macrocephalus*) in the eastern Bering Sea and adjacent waters based on tag-recapture data. U.S. Natl. Mar. Fish. Serv., Fish. Bull. 92:800-816.

Sinclair, E.S. and T. K. Zeppelin. 2002. Seasonal and spatial differences in diet in the western stock of Steller sea lions (*Eumetopias jubatus*). Journal of Mammalogy 83(4).

Spies I. 2012. Landscape genetics reveals population subdivision in Bering Sea and Aleutian Islands Pacific cod. *Transactions of the American Fisheries Society* 141:1557-1573.

Stark, J. W. 2007. Geographic and seasonal variations in maturation and growth of female Pacific cod (*Gadus macrocephalus*) in the Gulf of Alaska and Bering Sea. Fish. Bull. 105:396–407.

Thompson, G., T. A'mar, and W. Palsson. 2011. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 161-306. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501

Thompson, G. G., and M. E. Conners. 2007. Report of the Pacific cod technical workshop held at the Alaska Fisheries Science Center, April 24-25, 2007. Unpubl. manuscr., Alaska Fisheries Science Center, Resource Ecology and Fisheries Management Division, 7600 Sand Point Way NE., Seattle, WA 98115-6349. 56 p.

Thompson, G. G., and M. W. Dorn. 2005. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 155-244. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G., M. Dorn, and D. Nichol. 2006. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 147-220. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G., J. Ianelli, M. Dorn, D. Nichol, S. Gaichas, and K. Aydin. 2007a. Assessment of the Pacific cod stock in the Eastern Bering Sea and Aleutian Islands Area. *In* Plan Team for Groundfish Fisheries of the Bering Sea/Aleutian Islands (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands regions, p. 209-327. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G., J. Ianelli, M. Dorn, and M. Wilkins. 2007b. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 169-194. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G., J. Ianelli, M. Dorn, and M. Wilkins. 2009. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 165-352. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G., J. Ianelli, M. Dorn, and M. Wilkins. 2010. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 157-328. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G. G., and R. D. Methot. 1993. Pacific cod. *In* Plan Team for Groundfish Fisheries of the Bering Sea/Aleutian Islands (editor), Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands region as projected for 1994, chapter 2. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G. G., and A. M. Shimada. 1990. Pacific cod. *In* L. L. Low and R. E. Narita (editors), Condition of groundfish resources of the eastern Bering Sea-Aleutian Islands region as assessed in 1988, p. 44-66. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-178.

Thompson, G. G, and H. H. Zenger. 1993. Pacific cod. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (editor), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska as projected for 1994, chapter 2. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G. G, and H. H. Zenger. 1994. Pacific cod. *In* Plan Team for Groundfish Fisheries of the Gulf of Alaska (editor), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska as projected for 1995, chapter 2. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G. G., and H. H. Zenger. 1995. Pacific cod. *In* Plan Team for the Groundfish Fisheries of the Gulf of Alaska (editor), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska as projected for 1996, chapter 2. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G. G., H. H. Zenger, and M. K. Dorn. 2002. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for the Groundfish Fisheries of the Gulf of Alaska (compiler), Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Gulf of Alaska p. 89-167. North Pacific Fishery Management Council, 605 West 4th Ave., Suite 306, Anchorage, AK 99501.

Thompson, G. G., H. H. Zenger, and M. K. Dorn. 2004. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Plan Team for the Groundfish Fisheries of the Gulf of Alaska (compiler), Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Gulf of Alaska p. 131-232. North Pacific Fishery Management Council, 605 West 4th Ave., Suite 306, Anchorage, AK 99501.

Ueda, Y., Y. Narimatsu, T. Hattori, M. Ito, D. Kitagawa, N. Tomikawa, and T. Matsuishi. 2006. Fishing efficiency estimated based on the abundance from virtual population analysis and bottom-trawl surveys of Pacific cod (Gadus macrocephalus) in the waters off the Pacific coast of northern Honshu, Japan. Nippon Suisan Gakkaishi 72:201-209.

Wespestad, V., R. Bakkala, and J. June. 1982. Current abundance of Pacific cod (*Gadus macrocephalus*) in the eastern Bering Sea and expected abundance in 1982-1986. NOAA Tech. Memo. NMFS F/NWC-25, 26 p.

Westrheim, S. J. 1996. On the Pacific cod (*Gadus macrocephalus*) in British Columbia waters, and a comparison with Pacific cod elsewhere, and Atlantic cod (*G. morhua*). Can. Tech. Rep. Fish. Aquat. Sci. 2092. 390 p.

Yang, M-S. 2004. Diet changes of Pacific cod (Gadus macrocephalus) in Pavlof Bay associated with climate changes in the Gulf of Alaska between 1980 and 1995. U.S. Natl. Mar. Fish. Serv., Fish. Bull. 102:400-405.

Tables

Table 2.1. Catch (t) for 1991 through 2016 by jurisdiction and gear type (as of 2016-10-28)

	Federal					State				
Year	Trawl	Longline	Pot	Other	Subtotal	Longline	Pot	Other	Subtotal	Total
1991	58,093	7,656	10,464	115	76,328	0	0	0	0	76,328
1992	54,593	15,675	10,154	325	80,747	0	0	0	0	80,747
1993	37,806	8,963	9,708	11	56,488	0	0	0	0	56,488
1994	31,447	6,778	9,161	100	47,485	0	0	0	0	47,485
1995	41,875	10,978	16,055	77	68,985	0	0	0	0	68,985
1996	45,991	10,196	12,040	53	68,280	0	0	0	0	68,280
1997	48,406	10,978	9,065	26	68,476	0	7,224	1,319	8,542	77,018
1998	41,570	10,012	10,510	29	62,121	0	9,088	1,316	10,404	72,525
1999	37,167	12,363	19,015	70	68,614	0	12,075	1,096	13,171	81,785
2000	25,443	11,660	17,351	54	54,508	0	10,388	1,643	12,031	66,560
2001	24,383	9,910	7,171	155	41,619	0	7,836	2,084	9,920	51,542
2002	19,810	14,666	7,694	176	42,345	0	10,423	1,714	12,137	54,483
2003	18,884	9,470	12,761	161	41,276		7,943	3,241	11,185	52,461
2004	17,512	10,325	14,965	400	43,202		10,602	2,765	13,367	56,569
2005	14,549	5,731	14,749	203	35,232		9,634	2,673	12,306	47,538
2006	13,132	10,236	14,540	118	38,025		9,135	662	9,796	47,822
2007	14,775	11,514	13,573	44	39,906		11,308	681	11,988	51,895
2008	20,293	12,078	11,229	63	43,664		13,438	1,564	15,002	58,666
2009	13,976	13,885	11,951	206	40,017	196	9,919	2,500	12,616	52,633
2010	21,764	16,493	20,114	429	58,801	174	14,603	4,045	18,822	77,623
2011	16,452	16,372	29,231	722	62,777	306	16,675	4,627	21,608	84,385
2012	20,070	14,319	21,237	722	56,348	295	15,939	4,612	20,846	77,195
2013	21,700	12,575	17,011	475	51,761	176	14,153	1,303	15,633	67,394
2014	26,794	14,410	19,956	1,046	62,206	198	18,445	2,838	21,481	83,687
2015	22,260	11,942	20,650	409	55,261	3	19,717	2,790	22,510	77,771
2016	15,018	7,190	15,730	319	38,256	129	18,765	1,696	20,590	58,846

Table 2.2 History of Pacific cod catch (t, includes catch from State waters), Federal TAC (does not include State guideline harvest level), ABC, and OFL. ABC was not used in management of GOA groundfish prior to 1986. Catch for 2015 is current through 2015-10-19. The values in the column labeled "TAC" correspond to "optimum yield" for the years 1980-1986, "target quota" for the year 1987, and true TAC for the years 1988-present. The ABC value listed for 1987 is the upper bound of the range. Source: NPFMC staff.

Year	Catch	TAC	ABC	OFL
1980	35,345	60,000	-	-
1981	36,131	70,000	-	-
1982	29,465	60,000	-	-
1983	36,540	60,000	-	-
1984	23,898	60,000	-	-
1985	14,428	60,000		-
1986	25,012	75,000	136,000	-
1987	32,939	50,000	125,000	-
1988	33,802	80,000	99,000	-
1989	43,293	71,200	71,200	-
1990	72,517	90,000	90,000	-
1991	76,301	77,900	77,900	-
1992	80,073	63,500	63,500	87,600
1993	55,709	56,700	56,700	78,100
1994	46,649	50,400	50,400	71,100
1995	68,085	69,200	69,200	126,000
1996	68,064	65,000	65,000	88,000
1997	67,840	69,115	81,500	180,000
1998	61,520	66,060	77,900	141,000
1999	67,928	67,835	84,400	134,000
2000	54,266	59,800	76,400	102,000
2001	41,533	52,110	67,800	91,200
2002	42,307	44,230	57,600	77,100
2003	52,461	40,540	52,800	70,100
2004	56,569	48,033	62,810	102,000
2005	47,538	44,433	58,100	86,200
2006	47,822	52,264	68,859	95,500
2007	51,895	52,264	68,859	97,600
2008	58,666	50,269	64,493	88,660
2009	52,633	41,807	55,300	66,000
2010	77,623	59,563	79,100	94,100
2011	84,385	65,100	86,800	102,600
2012	77,195	65,700	87,600	104,000
2013	67,394	60,600	80,800	97,200
2014	83,687	64.738	88,500	107,300
2015	77,771	75,202	102,850	140,300
2016*	58,846	71,925	98,600	116,700

*As of 10/28/2016

Table 2.3. History of GOA Pacific cod allocations by regulatory area (in percent)

Year(s)	Western	Central	Eastern
1977-1985	28	56	16
1986	40	44	16
1987	27	56	17
1988-1989	19	73	8
1990	33	66	1
1991	33	62	5
1992	37	61	2
1993-1994	33	62	5
1995-1996	29	66	5
1997-1999	35	63	2
2000-2001	36	57	7
2002	39	55	6
2002	38	56	6
2003	39	55	6
2003	38	56	6
2004	36	57	7
2004	35.3	56.5	8.2
2005	36	57	7
2005	35.3	56.5	8.2
2006	39	55	6
2006	38.54	54.35	7.11
2007	39	55	6
2007	38.54	54.35	7.11
2008	39	57	4
2008	38.69	56.55	4.76
2009	39	57	4
2009	38.69	56.55	4.76
2010	35	62	3
2010	34.86	61.75	3.39
2011	35	62	3
2011	35	62	3
2012	35	62	3
2012	32	65	3
2013	38	60	3
2014	37	60	3
2015	38	60	3
2016	41	50	9

Table 2.4 Estimated retained-and discarded GOA Pacific cod from federal waters (source: AKFIN; *as of 2016-10-28)

Year	Discarded	Retained	Grand Total
1991	1,429	74,899	76,328
1992	3,873	76,199	80,073
1993	5,844	49,865	55,709
1994	3,109	43,540	46,649
1995	3,525	64,560	68,085
1996	7,534	60,530	68,064
1997	4,783	63,057	67,840
1998	1,709	59,811	61,520
1999	1,617	66,311	67,928
2000	1,362	52,904	54,266
2001	1,901	39,632	41,533
2002	3,713	38,594	42,307
2003	2,414	50,047	52,461
2004	1,265	55,304	56,569
2005	1,039	46,499	47,538
2006	1,835	45,986	47,822
2007	1,438	50,456	51,895
2008	3,299	55,367	58,666
2009	3,877	48,756	52,633
2010	2,833	74,790	77,623
2011	2,048	82,336	84,385
2012	962	76,233	77,195
2013	4,480	62,914	67,394
2014	5,177	78,511	83,687
2015	1,672	76,098	77,771
2016*	798	58,048	58,846

Table 2.5 – Groundfish bycatch, discarded and retained, for 2012 – 2016 for GOA Pacific cod as target species (AKFIN; as of 2016-10-28)

	2012		2013		2014		2015		2016	
	D	R	D	R	D	R	D	R		
Arrowtooth Flounder	330.0	498.9	862.8	575.9	817.7	499.2	447.6	659.4	602.8	793.9
Atka Mackerel	12.4	1.9	21.4	0.1	7.4	0.3	146.1	10.6	27.7	7.8
Flathead Sole	51.8	157.5	248.3	178.5	119.3	180.4	97.5	241.4	76.1	244.0
GOA Deep Water Flatfish	0.3	3.1	18.4	5.6	0.9	9.1	25.4	14.9	21.8	3.6
GOA Demersal Shelf Rockfish						0.0				
GOA Dusky Rockfish	23.1	9.4	17.5	6.4	10.1	39.2	11.0	16.4	50.9	19.0
GOA Rex Sole	27.8	109.9	17.5	95.1	12.0	72.7	7.9	112.8	22.9	146.7
GOA Rougheye Rockfish	0.4	3.2	0.4	1.1	1.2	3.0	0.1	3.4	0.8	1.9
GOA Shallow Water Flatfish	125.0	686.4	173.5	792.0	320.8	595.0	297.9	714.9	178.5	535.0
GOA Shortraker Rockfish	2.0	1.6	1.3	2.8	3.0	1.3	0.2	2.8	0.8	1.0
GOA Skate, Big	81.1	654.0	211.6	399.4	659.8	179.9	568.7	202.8	355.0	248.4
GOA Skate, Longnose	9.3	297.3	82.3	265.9	93.6	321.1	147.7	465.1	308.0	151.5
GOA Skate, Other	566.4	119.2	794.4	11.0	876.5	58.9	994.3	81.4	821.0	68.5
GOA Thornyhead Rockfish	0.3	2.6	4.7	3.2	2.6	16.1	4.9	4.2	1.6	8.5
Halibut			0.0	25.6	4.9	29.9	28.1	35.0	5.4	15.4
Northern Rockfish	26.8	24.0	48.1	61.9	12.7	58.7	12.1	35.1	74.1	16.8
Octopus	134.9	273.1	108.5	211.7	673.2	511.0	524.9	376.2	139.8	141.0
Other Rockfish	6.9	29.4	27.5	19.3	28.0	16.5	21.2	47.8	32.6	33.2
Pacific Ocean Perch	7.5	45.9	7.0	5.3	0.4	14.4	104.1	62.2	1344.6	15.5
Pollock	698.6	967.8	104.7	749.7	86.9	1422.4	108.4	1002.4	54.5	327.8
Sablefish	0.4	23.1	30.8	15.5	11.6	44.8	39.2	35.9	80.6	31.8
Sculpin	406.5	42.2	472.7	4.7	534.4	6.9	628.6	3.5	789.2	11.4
Shark	18.7	0.6	59.3	0.1	376.7	0.5	129.0	0.3	410.2	0.2
Squid		0.0	0.1	0.8		0.0	0.2	1.2	0.0	0.6
Grand Total	2530.1	3951.1	3312.8	3431.6	4653.6	4081.3	4345.2	4129.5	5398.8	2823.3

Table 2.6 - Incidental catch (t or birds by number) of non-target species groups by GOA Pacific cod fisheries, 2012-2016 (as of 2016-10-28).

	2012	2013	2014	2015	2016
Benthic urochordata	0.0		0.1	3.7	
Birds				50	56
Bivalves	1.6	1.5	1.5	1.3	0.6
Brittle star unidentified	0.0	0.1	0.0	0.0	0.0
Corals Bryozoans - Unidentified	3.9	0.0	1.3	0.3	0.3
Corals Bryozoans - Red Tree Coral			0.1	0.0	
Dark Rockfish	1.4	1.0	1.7	5.0	1.0
Eelpouts	0.2	0.1	0.1	0.3	
Eulachon	0.0		0.2	0.0	
Giant Grenadier	168.7	78.7	170.9	101.2	8.1
Greenlings	1.8	1.1	1.3	2.5	3.7
Hermit crab unidentified	0.7	1.8	0.4	2.7	0.3
Invertebrate unidentified	4.2	0.3	0.4	0.2	0.1
Misc crabs	2.2	2.8	2.8	0.9	0.9
Misc crustaceans	0.5	0.0	0.0	0.1	
Misc fish	215.3	99.7	127.9	101.2	154.3
Misc inverts (worms etc)				0.0	
Other osmerids					0.0
Pacific Sand lance			0.0		
Pandalid shrimp				0.0	0.0
Polychaete unidentified		0.0			
Sculpins	620.9	614.9	758.1	797.8	807.6
Scypho jellies	0.5	1.6	1.1	4.0	7.8
Sea anemone unidentified	5.6	6.1	5.2	5.1	17.1
Sea pens whips	0.8	2.0	2.6	1.6	0.4
Sea star	442.6	531.4	829.7	1161.4	851.1
Snails	3.5	2.4	22.8	11.4	14.5
Sponge unidentified	0.3	0.4	0.3	1.2	0.4
Stichaeidae		0.1			
urchins dollars cucumbers	3.4	1.2	1.4	4.1	1.7

Table 2.7 – Noncommercial fishery catch (in kg); total source amounts less than 1 mt were omitted (AFSC for GOA bottom trawl survey values; AKFIN for other values, as of 2016-10-28)

Source	2007	2008	2009	2010	2011	2012	2013	2014	2015
Annual Longline Survey	17,330	16,708	30,987	33,224	27,069	30,505	22,734	33,370	39,824
Bait for Crab Fishery							16,444	7,348	1,616
Golden King Crab Pot Survey						12			
Gulf of Alaska Bottom Trawl Survey					29,393		26,221		18,945
IPHC Annual Longline Survey				142,300	124,356	85,595	123,197	138,091	77,044
Large-Mesh Trawl Survey	1,026	207	958	11,702	17,015	20,500	18,577	13,090	8,072
Salmon EFP 13-01							2,647	8,316	
Scallop Dredge Survey			14				8		0
Shelikof Acoustic Survey				14					
Shelikof and Chirikof EIT						4			
Shumagin and Sanak EIT						583			
Shumigans Acoustic Survey				1,030					
Small-Mesh Trawl Survey	113			1,887	1,654	2,662	1,678	1,424	1,412
Sport Fishery				113,660	155,527	143,762	131,133	199,263	183,813
Spot Shrimp Survey	3				3			12	10
Structure of Gulf of Alaska Forage Fish Communities				136					
Western Gulf of Alaska Pollock Acoustic Cooperative Survey				59					
Total	18,472	16,916	31,959	304,011	355,017	283,622	342,639	400,913	330,736

Table 2.8 – Pacific cod abundance measured in biomass (t) and numbers of fish (1000s), as assessed by the GOA bottom trawl survey. Point estimates are shown along with coefficients of variation. The two right-hand sections show the total abundance divided into fish 27 cm or larger and fish smaller than 27 cm (totals are different in the first four years due to exclusion of tows with no length data from the strata extrapolations).

	All lengths				27-plus		Sub-27cm	
Year	Biomass(t)	CV	Abundance	CV	Abundance	CV	Abundance	CV
1984	550,971	0.096	320,525	0.102	275,167	0.114	19,526	0.596
1987	394,987	0.085	247,020	0.121	197,022	0.152	5,127	0.239
1990	416,788	0.100	212,132	0.135	180,108	0.158	14,049	0.261
1993	409,848	0.117	231,963	0.124	204,101	0.137	16,928	0.237
1996	538,154	0.131	319,068	0.140	233,959	0.113	84,382	0.373
1999	306,413	0.083	166,584	0.074	156,185	0.077	9,548	0.176
2001	257,614	0.133	158,424	0.118	136,970	0.133	21,354	0.175
2003	297,402	0.098	159,749	0.085	154,181	0.088	5,799	0.150
2005	308,175	0.170	139,895	0.135	127,324	0.144	12,571	0.247
2007	232,035	0.091	192,306	0.114	134,035	0.107	58,118	0.267
2009	752,651	0.195	573,469	0.185	422,330	0.153	151,139	0.494
2011	500,975	0.089	348,060	0.116	339,385	0.117	8,650	0.222
2013	506,362	0.097	337,992	0.099	257,315	0.091	80,677	0.288
2015	253,694	0.069	196,334	0.079	183,071	0.083	13,131	0.216

Table 2.9 – ABL Longline Relative Population Numbers (RPNs) and CVs for Pacific cod.

Year	RPN	CV	Year	RPN	CV
1990	116,398	0.139	2007	34,992	0.140
1991	110,036	0.141	2008	26,881	0.228
1992	136,311	0.087	2009	68,391	0.138
1993	153,894	0.114	2010	86,722	0.138
1994	96,532	0.094	2011	93,732	0.141
1995	120,700	0.100	2012	63,749	0.148
1996	84,530	0.141	2013	48,534	0.162
1997	104,610	0.169	2014	69,653	0.143
1998	125,846	0.115	2015	88,410	0.160
1999	91,407	0.113	2016	83,887	0.172
2000	54,310	0.145			
2001	33,841	0.181			
2002	51,900	0.170			
2003	59,952	0.150			
2004	53,108	0.118			
2005	29,864	0.214			
2006	34,316	0.197			

Table 2.10 – Number of parameters by category for model configurations presented.

	M15.3	**M16.xx.11**	**M16.xx.20**	**M16.xx.23&24**	**M16.xx.25**
Recruitment					
Early Rec. Devs (1962-1977)	16	16	16	16	16
Main Rec. Devs (1977-2013)	36	36	36	36	36
Late Rec. Devs (2014-2016)	3	3	3	3	3
Future Rec. Devs. (2017-2021)	5	5	5	5	5
R_0	1	1	1	1	1
R_1 offset	1	1	1	1	1
Natural mortality					1
Growth	5	5	5	5	5
Catchability	1				
Q_{trawl}					1
Q_{trawl} env. offset	1				
Initial F	1	2	2	2	2
Selectivity					
Trawl Survey	48	6	4	9	18
Longline survey		5	3	3	5
Trawl Fishery	52	5 +160 dev	3	11	13
Longline Fishery	56	3 + 78 dev	3	9	11
Pot Fishery	44	5	3	10	8
Total	270	331	85	111	126

Table 2.11 – Variance adjustment to input values for Model Series 16.10.xx and 16.11.xx based on the Francis TA1.8 method (Francis 2011).

Sector	**Length Composition**	**Age Composition**
Trawl Fishery	0.091	
Longline Fishery	0.069	
Pot Fishery	0.177	
GOA bottom trawl survey	0.383	0.185
ABL longline survey	0.588	

Table 2.12 – Model fit statistics and results for Model 15.3, M.16.08.xx, and M16.09.xx series models. Note that likelihoods between model series are not completely comparable.

		M15.3	M16.08.23	M16.08.25	M16.09.20	M16.09.23
AIC		2,412	4,111	3,783	4,199	3,853
Likelihoods						
	Total	935.8	1944.4	1765.4	2014.3	1815.6
	Survey	-15.3	31.6	0.0	100.1	53.9
	Length Composition	542.7	1308.6	1213.3	1327.7	1192.8
	Age Composition	439.1	579.6	557.9	562.8	575.5
	Recruitment	-30.9	23.6	-7.6	23.6	-6.9
	Parameter priors	0.0	0.0	0.5	0.0	0.0
	Parameter Devs.	0.0	0.0	0.0	0.0	0.0
Parameters						
	R_0 billions	0.37	0.25	0.55	0.26	0.29
	Steepness	1.00	1.00	1.00	1.00	1.00
	Natural Mortality	0.38	0.38	0.47	0.38	0.38
	q_{Shelf}	1.00	1.00	1.77	1.00	1.00
	L_{min}	44.30	5.31	5.97	9.31	41.10
	L_{max}	98.56	104.44	120.88	103.30	97.11
	Von Bert K	0.17	0.15	0.12	0.14	0.17
Results						
Model						
	SSB_{1978} (t)	488,530	93,013	143,662	29,445	119,753
Projection						
	$SSB_{100\%}$ (t)	347,806	203,433	196,776	180,529	205,543
	SSB_{2016} (t)	200,144	89,895	91,198	90,291	87,408
	$SSB_{2016\%}$	0.58	0.44	0.46	0.50	0.43
	SSB_{2017}(t)	178,024	102,484	98,479	97,551	97,551
	$SSB_{2017\%}$	0.51	0.50	0.50	0.54	0.47
	$F_{35\%}$	0.39	0.50	0.65	1.09	0.47
	$F_{40\%}$	0.33	0.41	0.53	0.85	0.38
2017						
	ABC (t)	97,082	73,675	88,342	80,219	73,429
	F_{ABC}	0.33	0.41	0.53	0.85	0.38
	OFL (t)	112,820	88,099	105,378	98,905	87,572
	F_{OFL}	0.39	0.50	0.65	1.09	0.47
2018						
	ABC (t)	90,217	72,646	79,272	83,576	73,766
	F_{ABC}	0.33	0.41	0.53	0.85	0.38
	OFL (t)	104,833	86,570	94,188	102,481	87,757
	F_{OFL}	0.39	0.50	0.65	1.09	0.47

Table 2.13 – Model fit statistics and results for M.16.10.xx and M16.11.xx series models. Note that likelihoods between model series are not completely comparable and Model 16.10.11 L_{max} (Shaded red) was at its bound.

	M16.10.11	M16.10.20	M16.10.23	M16.10.24	M16.10.25	M16.11.20	M16.11.23
AIC	2,051	1,667	1,640	1,626	1,590	1,724	1,571
Likelihoods							
Total	694.4	748.3	709.0	702.2	668.9	777.0	674.7
Survey	-3.3	13.9	5.2	6.8	-13.7	27.1	1.4
Length Composition	282.8	330.5	302.4	306.0	282.3	345.6	276.7
Age Composition	421.3	408.9	414.3	405.9	413.7	411.5	410.7
Recruitment	-11.9	-5.0	-13.5	-16.7	-14.5	-7.2	-14.1
Parameter priors	0.0	0.0	0.0	0.0	1.1	0.0	0.0
Parameter Devs.	5.6	0.0	0.0	0.0	0.0	0.0	0.0
Parameters							
R_0 billions	0.31	0.25	0.26	0.33	0.63	0.26	0.27
Steepness	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Natural Mortality	0.38	0.38	0.38	NA	0.50	0.38	0.38
q_{Shelf}	1.00	1.00	1.00	1.00	1.68	1.00	1.00
L_{min}	6.46	4.66	4.69	3.97	3.75	7.01	41.315
L_{max}	130.00	96.33	96.14	92.49	90.02	91.11	85.97
Von Bert K	0.11	0.17	0.17	0.19	0.19	0.18	0.21
Results							
Model							
SSB_{1978} (t)	154,791	53,816	99,324	84,401	103,080	56,123	102,538
Projection							
$SSB_{100\%}$ (t)	265,855	182,569	177,491	99,205	156,014	180,529	176,007
SSB_{2016} (t)	113,218	84,441	77,568	74,260	87,626	90,291	83,819
$SSB_{2016\%}$	0.43	0.46	0.44	0.75	0.56	0.50	0.48
SSB_{2017}(t)	131,866	102,376	83,588	82,896	89,514	79,394	79,394
$SSB_{2017\%}$	0.50	0.56	0.47	0.84	0.57	0.44	0.45
$F_{35\%}$	0.54	1.03	0.66	0.61	1.16	1.09	0.59
$F_{40\%}$	0.45	0.80	0.53	0.50	0.92	0.85	0.48
2017							
ABC (t)	89,349	77,558	63,475	63,769	102,837	80,219	64,064
F_{ABC}	0.45	0.80	0.53	0.50	0.92	0.85	0.48
OFL (t)	106,303	96,445	76,895	75,610	123,819	98,905	76,347
F_{OFL}	0.54	1.03	0.66	0.61	1.16	1.09	0.59
2018							
ABC (t)	94,577	88,735	65,252	65,956	88,722	83,576	62,677
F_{ABC}	0.45	0.80	0.53	0.50	0.92	0.85	0.48
OFL (t)	112,144	109,409	78,715	77,906	106,331	102,481	74,608
F_{OFL}	0.54	1.03	0.66	0.61	1.16	1.09	0.59

Table 2.14 – Likelihood components by fleet for all proposed models.

Model	Label	ALL	FshTrawl	FshLL	FshPot	Srv	LLSrv
Model16.08.23	Age_like	579.6				579.6	
Model16.08.25	Age_like	399.5				399.5	
Model16.09.20	Age_like	562.8				562.8	
Model16.09.23	Age_like	575.5				575.5	
Model16.10.11	Age_like	427.7				427.7	
Model16.10.20	Age_like	408.9				408.9	
Model16.10.23	Age_like	414.3				414.3	
Model16.10.24	Age_like	405.9				405.9	
Model16.10.25	Age_like	413.7				413.7	
Model16.11.20	Age_like	411.5				411.5	
Model16.11.23	Age_like	410.7				410.7	
Model16.08.23	Catch_like	2.24E-09	6.63E-10	7.69E-10	8.05E-10		
Model16.08.25	Catch_like	4.96E-10	1.46E-10	1.72E-10	1.79E-10		
Model16.09.20	Catch_like	1.17E-09	3.32E-10	4.15E-10	4.23E-10		
Model16.09.23	Catch_like	3.86E-10	1.13E-10	1.33E-10	1.40E-10		
Model16.10.11	Catch_like	3.40E-12	8.40E-13	1.25E-12	1.30E-12		
Model16.10.20	Catch_like	5.33E-09	1.58E-09	1.86E-09	1.90E-09		
Model16.10.23	Catch_like	7.21E-09	2.14E-09	2.57E-09	2.49E-09		
Model16.10.24	Catch_like	1.13E-08	3.37E-09	3.92E-09	3.99E-09		
Model16.10.25	Catch_like	5.99E-11	1.76E-11	2.17E-11	2.06E-11		
Model16.11.20	Catch_like	5.72E-10	1.68E-10	1.99E-10	2.05E-10		
Model16.11.23	Catch_like	6.45E-10	1.89E-10	2.31E-10	2.25E-10		
Model16.08.23	Length_like	1,308.6	411.4	281.8	208.0	183.1	224.2
Model16.08.25	Length_like	1,213.3	414.3	261.7	210.4	151.2	175.5
Model16.09.20	Length_like	1,327.7	472.0	332.2	195.2	108.2	220.1
Model16.09.23	Length_like	1,192.8	397.9	266.2	188.1	120.0	220.6
Model16.10.11	Length_like	282.8	27.3	27.1	48.3	76.0	104.2
Model16.10.20	Length_like	330.5	53.0	38.3	46.2	83.4	109.5
Model16.10.23	Length_like	302.4	42.5	32.1	38.5	78.8	110.6
Model16.10.24	Length_like	306.0	43.9	31.4	38.6	80.4	111.7
Model16.10.25	Length_like	282.3	43.9	32.8	39.9	62.1	103.6
Model16.11.20	Length_like	345.6	58.3	37.8	49.5	60.9	139.1
Model16.11.23	Length_like	276.7	42.5	32.3	34.8	52.5	114.6
Model16.08.23	Surv_like	31.6				25.9	5.7
Model16.08.25	Surv_like	0.0				-5.4	5.4
Model16.09.20	Surv_like	100.1				92.7	7.5
Model16.09.23	Surv_like	2.7				8.3	-5.6
Model16.10.11	Surv_like	-3.3				8.5	-11.8
Model16.10.20	Surv_like	13.9				15.5	-1.5
Model16.10.23	Surv_like	5.2				6.4	-1.2
Model16.10.24	Surv_like	6.8				9.2	-2.4
Model16.10.25	Surv_like	-13.7				-8.9	-4.8
Model16.11.20	Surv_like	27.1				31.3	-4.3
Model16.11.23	Surv_like	1.4				7.4	-6.1

Table 2.15 – Retrospective analysis, index RMSE, harmonic mean effective N for length and age compositions, and recruitment variability for assessed models.

	M16.08.23	M16.08.25	M16.09.20	M16.09.23	M16.10.11	M16.10.20	M16.10.23	M16.10.24	M16.10.25	M16.11.20	M16.11.23
Retrospective											
Female spawning biomass											
Mohn's ρ	0.05	0.09	0.31	0.23	0.50	0.14	0.06	0.08	0.29	0.22	0.11
Woods Hole ρ	-0.05	0.03	-0.03	-0.04	0.23	-0.03	-0.02	-0.04	0.13	-0.03	-0.04
RMSE	0.10	0.11	0.10	0.15	0.25	0.07	0.05	0.08	0.19	0.09	0.09
Recruitment (age -0)											
Mohn's ρ	-0.14	0.23	-0.27	-0.15	-0.01	-0.23	-0.15	-0.13	0.70	-0.25	-0.19
Woods Hole ρ	-0.003	0.18	0.03	0.03	0.17	0.01	-0.003	-0.01	0.74	0.01	-0.02
RMSE	0.16	0.33	0.21	0.19	0.24	0.15	0.13	0.13	0.62	0.16	0.14
Index RMSE											
Shelf	0.54	0.32	0.52	0.42	0.46	0.50	0.44	0.46	0.29	0.38	0.29
ABL Longline	0.32	0.31	0.32	0.31	0.27	0.30	0.30	0.30	0.29	0.29	0.28
Size Comp											
Har. Mean EffN											
Trawl	274.8	276.5	219.4	267.0	289.0	173.9	255.4	259.4	262.5	172.0	248.4
Longline	460.0	475.0	377.1	464.8	451.3	272.4	323.4	343.0	327.0	276.0	307.4
Pot	664.1	649.0	635.6	728.0	435.3	487.3	650.5	659.5	648.0	578.7	727.6
Trawl Survey	276.7	352.9	305.5	291.6	244.2	222.2	238.6	232.8	341.6	240.3	241.4
ABL Longline	257.5	307.7	268.4	259.9	307.2	297.5	290.9	286.7	309.1	289.3	276.8
*Mean input N*Adjustment*											
Trawl	153.3	153.3	152.1	152.1	14.0	14.0	14.0	14.0	14.0	14.7	13.9
Longline	157.1	157.1	155.9	155.9	10.9	10.9	10.9	10.9	10.9	11.3	10.8
Pot	181.0	181.0	180.3	180.3	32.1	32.1	32.1	32.1	32.1	39.9	32.0
Trawl Survey	100.0	100.0	100.0	100.0	38.3	38.3	38.3	38.3	38.3	45.0	38.3
ABL Longline	100.0	100.0	100.0	100.0	58.8	58.8	58.8	58.8	58.8	73.9	58.8
Age Comp											
Trawl Survey	3.47	3.50	3.17	3.24	3.61	3.58	3.55	3.53	3.53	3.15	3.27
Mean input N											
Trawl Survey	2.58	2.58	2.84	2.84	1.21	1.21	1.21	1.21	1.21	1.31	1.23
Rec. Var. (1977-2015)											
Std.dev(ln(No. Age 1))	0.38	0.41	0.42	0.38	0.36	0.38	0.33	0.34	0.33	0.36	0.33

Table 2.16 – Age-0 recruitment and standard deviation of age-0 recruits by year for last year's model, Model 15.3, Model 16.08.25 and Model 16.10.25. Highlighted are the 1977 and 2012 year classes.

	Last Year's Model		M15.3		M16.08.25		M16.10.25	
Year	**Age-0 x 10^9**	**Stdev**	**Age-0 x 10^9**	**Stdev**	**Age-0 x 10^9**	**Stdev**	**Age-0 x 10^9**	**Stdev**
1977	1.014	0.174	1.014	0.175	1.560	0.456	0.742	0.391
1978	0.232	0.059	0.231	0.059	0.473	0.178	0.478	0.250
1979	0.356	0.062	0.360	0.062	0.729	0.233	0.471	0.242
1980	0.370	0.061	0.375	0.062	0.801	0.235	0.583	0.287
1981	0.355	0.066	0.360	0.067	0.480	0.147	0.696	0.327
1982	0.360	0.073	0.366	0.074	0.554	0.168	0.690	0.317
1983	0.275	0.070	0.278	0.071	0.628	0.179	0.699	0.310
1984	0.452	0.095	0.459	0.097	0.912	0.224	0.940	0.394
1985	0.374	0.070	0.377	0.071	0.735	0.174	0.891	0.360
1986	0.265	0.050	0.269	0.051	0.562	0.133	0.688	0.274
1987	0.487	0.062	0.493	0.063	0.692	0.156	0.861	0.336
1988	0.311	0.049	0.315	0.050	0.573	0.132	0.711	0.286
1989	0.535	0.071	0.542	0.072	0.726	0.162	0.907	0.354
1990	0.442	0.059	0.446	0.060	0.668	0.148	0.842	0.333
1991	0.351	0.047	0.353	0.047	0.491	0.110	0.631	0.253
1992	0.362	0.050	0.366	0.051	0.429	0.094	0.598	0.233
1993	0.370	0.044	0.373	0.045	0.409	0.087	0.552	0.213
1994	0.379	0.044	0.382	0.045	0.421	0.088	0.563	0.215
1995	0.374	0.041	0.377	0.041	0.502	0.101	0.588	0.218
1996	0.266	0.031	0.267	0.031	0.351	0.073	0.361	0.136
1997	0.255	0.032	0.258	0.032	0.320	0.066	0.365	0.136
1998	0.300	0.032	0.303	0.032	0.392	0.079	0.463	0.167
1999	0.360	0.041	0.364	0.041	0.542	0.105	0.619	0.220
2000	0.324	0.035	0.325	0.035	0.446	0.085	0.530	0.185
2001	0.208	0.030	0.209	0.030	0.232	0.048	0.324	0.116
2002	0.201	0.026	0.202	0.026	0.265	0.052	0.298	0.104
2003	0.218	0.028	0.218	0.028	0.255	0.049	0.291	0.103
2004	0.227	0.026	0.229	0.026	0.389	0.072	0.489	0.167
2005	0.432	0.046	0.426	0.045	0.591	0.108	0.761	0.259
2006	0.442	0.044	0.439	0.044	0.668	0.121	0.836	0.284
2007	0.530	0.059	0.515	0.057	0.531	0.104	0.621	0.223
2008	0.496	0.048	0.478	0.045	0.754	0.142	0.780	0.270
2009	0.320	0.039	0.296	0.036	0.348	0.071	0.400	0.145
2010	0.231	0.029	0.211	0.025	0.401	0.080	0.533	0.187
2011	0.381	0.056	0.334	0.042	0.752	0.153	0.782	0.281
2012	0.317	0.051	0.354	0.041	1.099	0.235	1.200	0.437
2013	0.231	0.072	0.374	0.083	0.570	0.148	0.604	0.263
2014	0.309	0.121	0.286	0.109	0.261	0.078	0.411	0.184
2015	0.357	0.147	0.358	0.148	0.416	0.186	0.603	0.342
2016			0.366	0.151	0.546	0.269	0.628	0.360
Mean 1977-2015	0.361		0.364		0.562		0.626	
Stdev(Ln(x))		0.318		0.314		0.407		0.332

Table 2.17 – Age-0 recruitment and standard deviation of age-0 recruits by year for model series 16.xx.23. Highlighted are the 1977 and 2012 year classes.

	M16.08.23		M16.09.23		M16.10.23		M16.11.23	
Year	**Age-0x10^9**	**St.dev.**	**Age-0x10^9**	**Stdev**	**Age-0x10^9**	**St.dev.**	**Age-0x10^9**	**St.dev.**
1977	0.6192	0.0813	0.7705	0.1014	0.2535	0.0785	0.2682	0.0822
1978	0.1732	0.0468	0.2018	0.0552	0.1742	0.0560	0.1826	0.0592
1979	0.2730	0.0474	0.2954	0.0542	0.1779	0.0527	0.1815	0.0549
1980	0.3057	0.0421	0.3502	0.0489	0.2031	0.0518	0.2178	0.0563
1981	0.1882	0.0309	0.2258	0.0354	0.2274	0.0502	0.2464	0.0549
1982	0.2235	0.0334	0.2325	0.0361	0.2479	0.0520	0.2630	0.0573
1983	0.2628	0.0407	0.2805	0.0473	0.2590	0.0550	0.2895	0.0643
1984	0.4232	0.0477	0.4362	0.0582	0.3665	0.0643	0.3765	0.0713
1985	0.3803	0.0388	0.4250	0.0508	0.3858	0.0607	0.4254	0.0706
1986	0.2759	0.0286	0.2841	0.0375	0.2889	0.0474	0.3065	0.0548
1987	0.3350	0.0275	0.3382	0.0331	0.3502	0.0467	0.3637	0.0526
1988	0.2929	0.0271	0.3132	0.0324	0.2990	0.0441	0.3388	0.0524
1989	0.3741	0.0292	0.4087	0.0342	0.3741	0.0477	0.3980	0.0540
1990	0.3325	0.0268	0.3473	0.0302	0.3417	0.0447	0.3616	0.0494
1991	0.2500	0.0226	0.2776	0.0257	0.2570	0.0373	0.2927	0.0435
1992	0.2147	0.0192	0.2133	0.0209	0.2376	0.0326	0.2438	0.0359
1993	0.2078	0.0178	0.2086	0.0189	0.2234	0.0307	0.2345	0.0331
1994	0.2278	0.0177	0.2452	0.0197	0.2489	0.0310	0.2600	0.0343
1995	0.2714	0.0175	0.2577	0.0186	0.2549	0.0281	0.2510	0.0302
1996	0.1832	0.0147	0.1977	0.0150	0.1586	0.0214	0.1687	0.0223
1997	0.1693	0.0135	0.1804	0.0134	0.1638	0.0214	0.1727	0.0223
1998	0.2143	0.0150	0.2164	0.0147	0.2074	0.0248	0.1997	0.0249
1999	0.2974	0.0174	0.3048	0.0176	0.2773	0.0290	0.2877	0.0303
2000	0.2427	0.0152	0.2459	0.0162	0.2350	0.0260	0.2336	0.0275
2001	0.1240	0.0121	0.1296	0.0127	0.1473	0.0208	0.1532	0.0221
2002	0.1452	0.0124	0.1394	0.0128	0.1360	0.0188	0.1341	0.0194
2003	0.1488	0.0132	0.1518	0.0135	0.1391	0.0204	0.1351	0.0205
2004	0.2194	0.0161	0.2175	0.0162	0.2300	0.0279	0.2283	0.0273
2005	0.3482	0.0206	0.3767	0.0214	0.3672	0.0374	0.3959	0.0412
2006	0.3779	0.0217	0.3530	0.0224	0.3807	0.0377	0.3876	0.0424
2007	0.3097	0.0229	0.3597	0.0240	0.2991	0.0368	0.3506	0.0427
2008	0.4269	0.0247	0.3883	0.0246	0.3591	0.0372	0.3626	0.0404
2009	0.2023	0.0186	0.2137	0.0183	0.1966	0.0298	0.2235	0.0332
2010	0.2261	0.0208	0.2149	0.0194	0.2633	0.0372	0.2804	0.0382
2011	0.4813	0.0393	0.4619	0.0370	0.4258	0.0587	0.4317	0.0574
2012	0.6577	0.0664	0.5738	0.0577	0.5561	0.0838	0.3956	0.0573
2013	0.3646	0.0617	0.4181	0.0727	0.2902	0.0767	0.2880	0.0773
2014	0.1550	0.0357	0.2164	0.0830	0.1903	0.0558	0.2540	0.1081
2015	0.1986	0.0801	0.2870	0.1281	0.2492	0.1093	0.2741	0.1225
2016	0.2467	0.1101	0.2870	0.1281	0.2615	0.1168	0.2740	0.1225
Mean 1977-2015	0.2852		0.3015		0.2678		0.2784	
Stdev(ln(age-0))	0.3874		0.3780		0.3273		0.3168	

Table 2.18 – Estimated female spawning biomass (t) from the 2015 assessment and this year's assessment from Models 15.3 and 16.08.25

	Last Year's Model		Model15.3		Model 16.08.25	
	Sp.Bio	St.dev	Sp.Bio	St.dev	Sp.Bio	St.dev
1977	449,277	91,438	455,060	91,995	132,285	30,821
1978	483,965	96,177	488,530	96,325	143,660	31,718
1979	474,895	92,067	478,725	91,985	140,575	30,038
1980	459,504	85,451	463,585	85,405	140,510	28,713
1981	475,040	82,750	479,410	82,755	160,675	31,350
1982	493,067	80,319	496,590	80,200	195,575	35,342
1983	467,587	72,914	470,290	72,720	208,360	35,003
1984	428,067	63,905	430,520	63,755	210,755	33,449
1985	399,136	55,378	401,645	55,350	214,060	31,229
1986	376,380	48,032	379,045	48,144	211,320	27,717
1987	354,220	42,404	357,035	42,594	203,960	24,308
1988	331,807	38,100	334,755	38,302	202,310	21,719
1989	320,414	35,217	323,435	35,412	208,230	19,750
1990	300,556	32,543	303,490	32,728	204,735	17,454
1991	277,791	30,240	280,790	30,430	184,630	15,274
1992	261,240	29,232	264,395	29,436	167,680	13,742
1993	257,833	28,811	261,115	29,014	153,455	12,756
1994	269,945	29,044	273,235	29,221	154,515	12,172
1995	280,725	28,352	283,780	28,487	155,935	11,135
1996	271,803	26,591	274,575	26,690	140,470	9,572
1997	261,124	24,797	263,730	24,878	121,770	8,053
1998	246,415	23,056	248,850	23,120	104,710	6,952
1999	239,692	21,664	241,930	21,709	94,670	6,373
2000	222,655	20,222	224,620	20,253	84,750	6,031
2001	213,974	18,660	215,690	18,682	77,685	5,553
2002	204,412	17,460	206,060	17,478	75,600	5,140
2003	197,263	16,798	198,945	16,812	78,190	5,022
2004	197,748	16,669	199,380	16,683	80,825	4,965
2005	193,289	16,271	194,675	16,275	76,535	4,462
2006	179,638	15,455	180,805	15,452	67,700	3,660
2007	166,316	14,308	167,260	14,296	57,805	3,040
2008	152,734	13,268	153,420	13,247	51,225	2,876
2009	152,479	12,880	152,680	12,837	53,605	3,357
2010	168,483	13,963	167,630	13,858	69,070	4,222
2011	189,732	15,923	187,305	15,740	77,630	5,057
2012	213,863	18,412	208,835	18,075	81,330	5,957
2013	230,967	19,805	222,770	19,286	85,110	6,543
2014	223,789	19,519	212,275	18,790	81,115	6,412
2015	202,714	18,216	188,180	17,155	75,485	7,088
2016	***186,487***		178,635	15,991	91,210	10,037
2017			**178,024**		**98,479**	

Table 2.19 – Estimated beginning year weight and length at age from Model 16.08.25.

Age	Weight (kg)	Length (cm)	Age	Weight (kg)	Length (cm)
0	0.000	0.5	11	7.173	88.3
1	0.020	12.7	12	8.146	92.0
2	0.145	24.9	13	9.080	95.3
3	0.437	35.8	14	9.963	98.2
4	0.910	45.4	15	10.784	100.7
5	1.551	53.9	16	11.538	103.0
6	2.331	61.5	17	12.218	105.0
7	3.216	68.2	18	12.825	106.8
8	4.171	74.2	19	13.359	108.4
9	5.166	79.5	20	14.525	112.2
10	6.174	84.2			

Table 2.20 – Estimated fishing mortality in Apical F and Total exploitation for Model 16.08.25.

	Sum Apical F				**Sum Apical F**		
Year	F	σ	**Total Exploitation**	**Year**	F	σ	**Total Exploitation**
1977	0.009	0.002	0.006	2001	0.428	0.033	0.177
1978	0.049	0.011	0.034	2002	0.449	0.033	0.169
1979	0.061	0.013	0.039	2003	0.586	0.040	0.201
1980	0.136	0.029	0.070	2004	0.625	0.041	0.234
1981	0.113	0.023	0.068	2005	0.535	0.033	0.221
1982	0.080	0.015	0.053	2006	0.609	0.036	0.248
1983	0.095	0.016	0.063	2007	0.833	0.051	0.281
1984	0.061	0.010	0.042	2008	1.149	0.078	0.289
1985	0.037	0.005	0.026	2009	0.965	0.067	0.223
1986	0.067	0.009	0.045	2010	1.139	0.079	0.291
1987	0.091	0.011	0.057	2011	1.097	0.081	0.285
1988	0.091	0.011	0.058	2012	0.908	0.074	0.275
1989	0.113	0.013	0.076	2013	0.541	0.054	0.256
1990	0.265	0.023	0.131	2014	0.742	0.077	0.296
1991	0.315	0.027	0.150	2015	0.704	0.081	0.233
1992	0.371	0.032	0.167				
1993	0.278	0.024	0.122				
1994	0.230	0.018	0.106				
1995	0.343	0.025	0.162				
1996	0.377	0.027	0.180				
1997	0.437	0.031	0.202				
1998	0.471	0.034	0.199				
1999	0.616	0.046	0.241				
2000	0.547	0.042	0.219				

Table 2.21 – Biological reference points from GOA Pacific cod SAFE documents for years 2001 – 2016

Year	$SB_{100\%}$	$SB_{40\%}$	$F_{40\%}$	SB_{y+1}	ABC_{y+1}
2001	212,000	85,000	0.41	82,000	57,600
2002	226,000	90,300	0.35	88,300	52,800
2003	222,000	88,900	0.34	103,000	62,810
2004	211,000	84,400	0.31	91,700	58,100
2005	329,000	132,000	0.56	165,000	68,859
2006	259,000	103,000	0.46	136,000	68,859
2007	302,000	121,000	0.49	108,000	66,493
2008	255,500	102,200	0.52	88,000	55,300
2009	291,500	116,600	0.49	117,600	79,100
2010	256,300	102,500	0.42	124,100	86,800
2011	261,000	104,000	0.44	121,000	87,600
2012	234,800	93,900	0.49	111,000	80,800
2013	227,800	91,100	0.54	120,100	88,500
2014	316,500	126,600	0.50	155,400	102,850
2015	325,200	130,000	0.41	116,600	98,600
2016	*196,776*	*78,711*	*0.53*	*105,378*	*88,342*

Table 2.22 – Results for the projection scenarios from Model 16.08.25. Female spawning stock biomass (SSB) SSB, fishing mortality (F), and catch for the 7 projection scenarios.

SSB	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
2016	80,472	80,472	80,472	80,472	80,472	80,472	80,472
2017	98,479	98,479	101,429	102,829	104,191	97,204	98,479
2018	90,572	90,572	108,298	117,874	127,982	83,837	90,572
2019	74,065	74,065	100,362	116,754	135,619	65,792	73,125
2020	69,256	69,256	96,923	117,209	142,523	63,030	65,148
2021	73,901	73,901	100,950	123,484	153,370	68,395	68,852
2022	78,351	78,351	106,455	130,861	164,506	72,370	72,381
2023	80,692	80,692	110,731	136,916	173,934	73,921	73,876
2024	81,424	81,424	113,352	141,116	181,119	74,088	74,061
2025	81,334	81,334	114,615	143,634	186,125	73,723	73,712
2026	81,276	81,276	115,376	145,299	189,732	73,601	73,597
2027	81,376	81,376	115,964	146,511	192,406	73,709	73,708
2028	81,622	81,622	116,531	147,514	194,491	73,965	73,965
2029	81,721	81,721	116,866	148,170	195,958	74,031	74,031
F							
2016	0.49	0.49	0.49	0.49	0.49	0.49	0.49
2017	0.53	0.53	0.25	0.12	0.00	0.65	0.53
2018	0.53	0.53	0.25	0.12	0.00	0.65	0.53
2019	0.50	0.50	0.25	0.12	0.00	0.54	0.60
2020	0.46	0.46	0.25	0.12	0.00	0.52	0.53
2021	0.48	0.48	0.25	0.12	0.00	0.55	0.56
2022	0.49	0.49	0.25	0.12	0.00	0.58	0.58
2023	0.50	0.50	0.25	0.12	0.00	0.59	0.59
2024	0.50	0.50	0.25	0.12	0.00	0.59	0.59
2025	0.50	0.50	0.25	0.12	0.00	0.59	0.59
2026	0.50	0.50	0.25	0.12	0.00	0.59	0.59
2027	0.50	0.50	0.25	0.12	0.00	0.59	0.59
2028	0.50	0.50	0.25	0.12	0.00	0.59	0.59
2029	0.50	0.50	0.25	0.12	0.00	0.59	0.59
Catch							
2016	70,494	70,494	70,494	70,494	70,494	70,494	70,494
2017	88,342	88,342	45,318	22,988	0	105,378	88,342
2018	79,272	79,272	47,185	25,717	0	88,779	79,272
2019	61,610	61,610	43,388	25,139	0	59,651	72,612
2020	54,899	54,899	41,751	24,906	0	56,129	59,469
2021	61,334	61,334	43,528	26,107	0	65,778	66,371
2022	66,763	66,763	46,080	27,726	0	72,298	72,235
2023	69,532	69,532	47,938	29,013	0	74,749	74,650
2024	70,161	70,161	48,942	29,818	0	74,869	74,820
2025	70,058	70,058	49,376	30,259	0	74,341	74,323
2026	69,999	69,999	49,614	30,527	0	74,149	74,144
2027	70,164	70,164	49,824	30,731	0	74,303	74,302
2028	70,350	70,350	50,037	30,908	0	74,601	74,601
2029	70,342	70,342	50,125	31,006	0	74,595	74,595

Figures

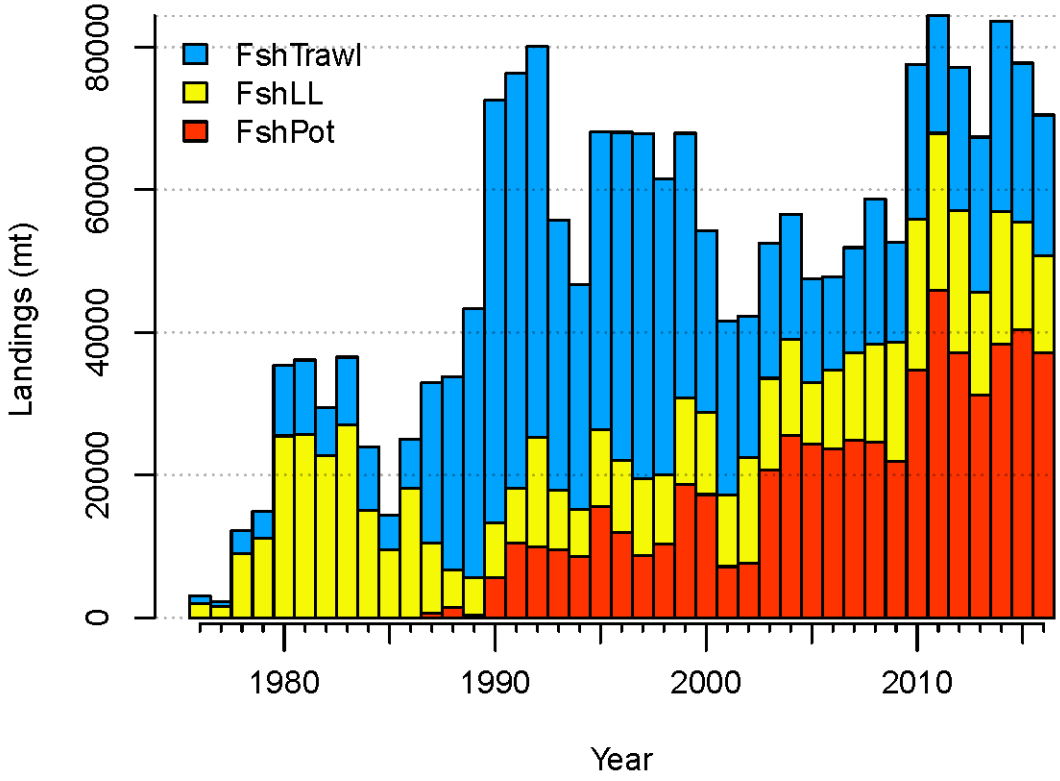


Figure 2.1 – Gulf of Alaska Pacific cod catch from 1977-2016. Note that 2016 catch was estimated.

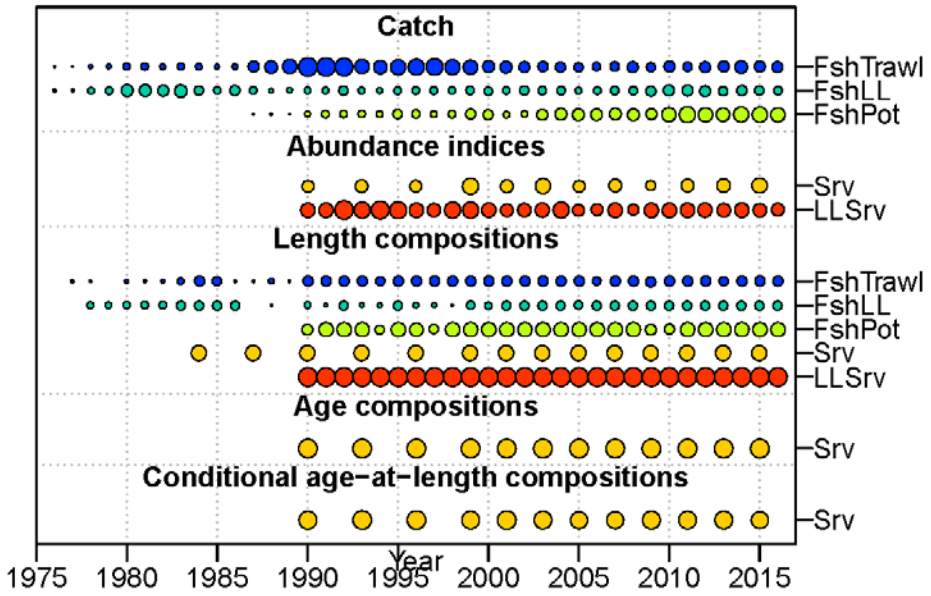


Figure 2.2 – Data used in the alternative 2016 models.

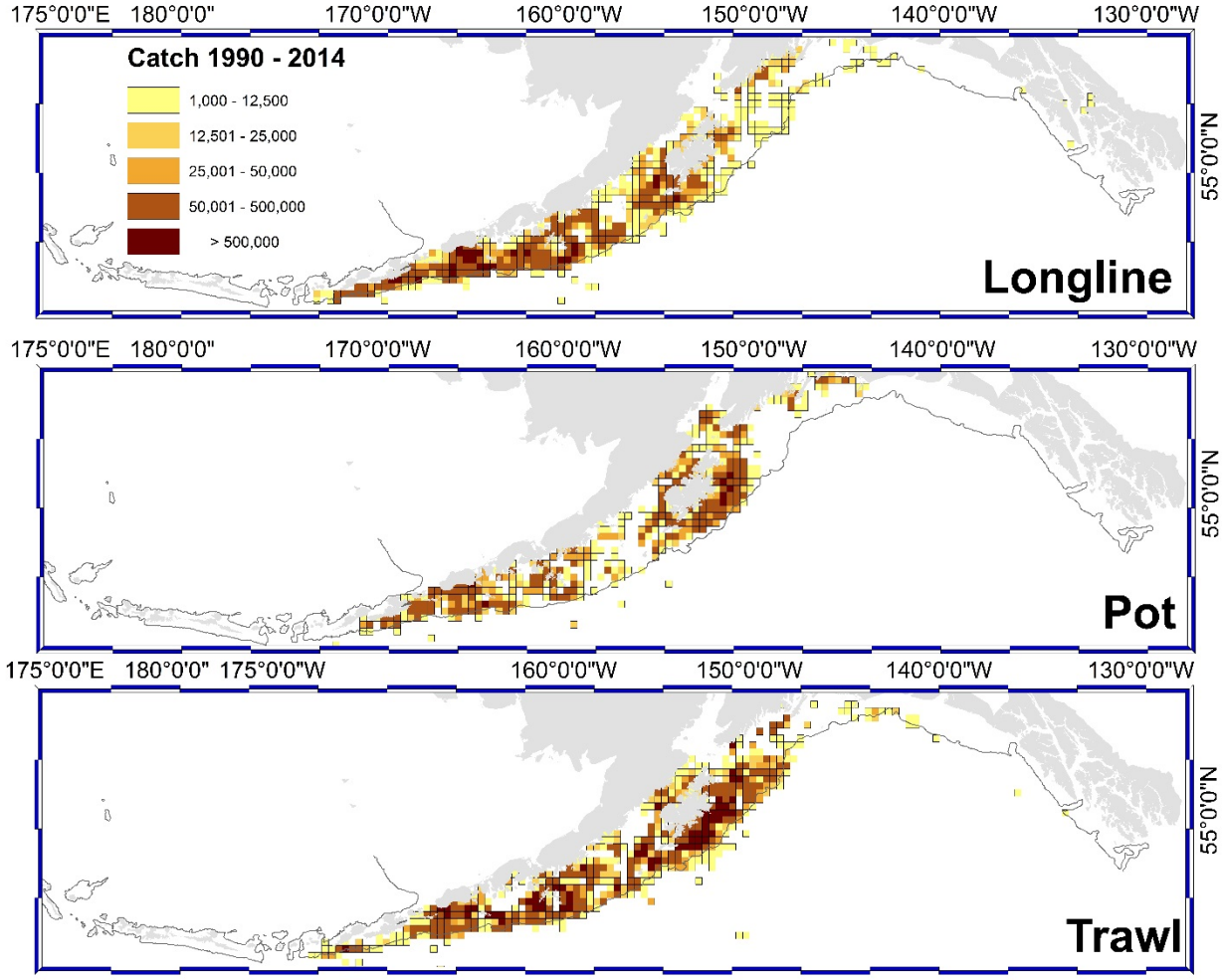


Figure 2.3 – Commercial catch of Pacific cod in the Gulf of Alaska by 20km^2 grid for 1990-2014.

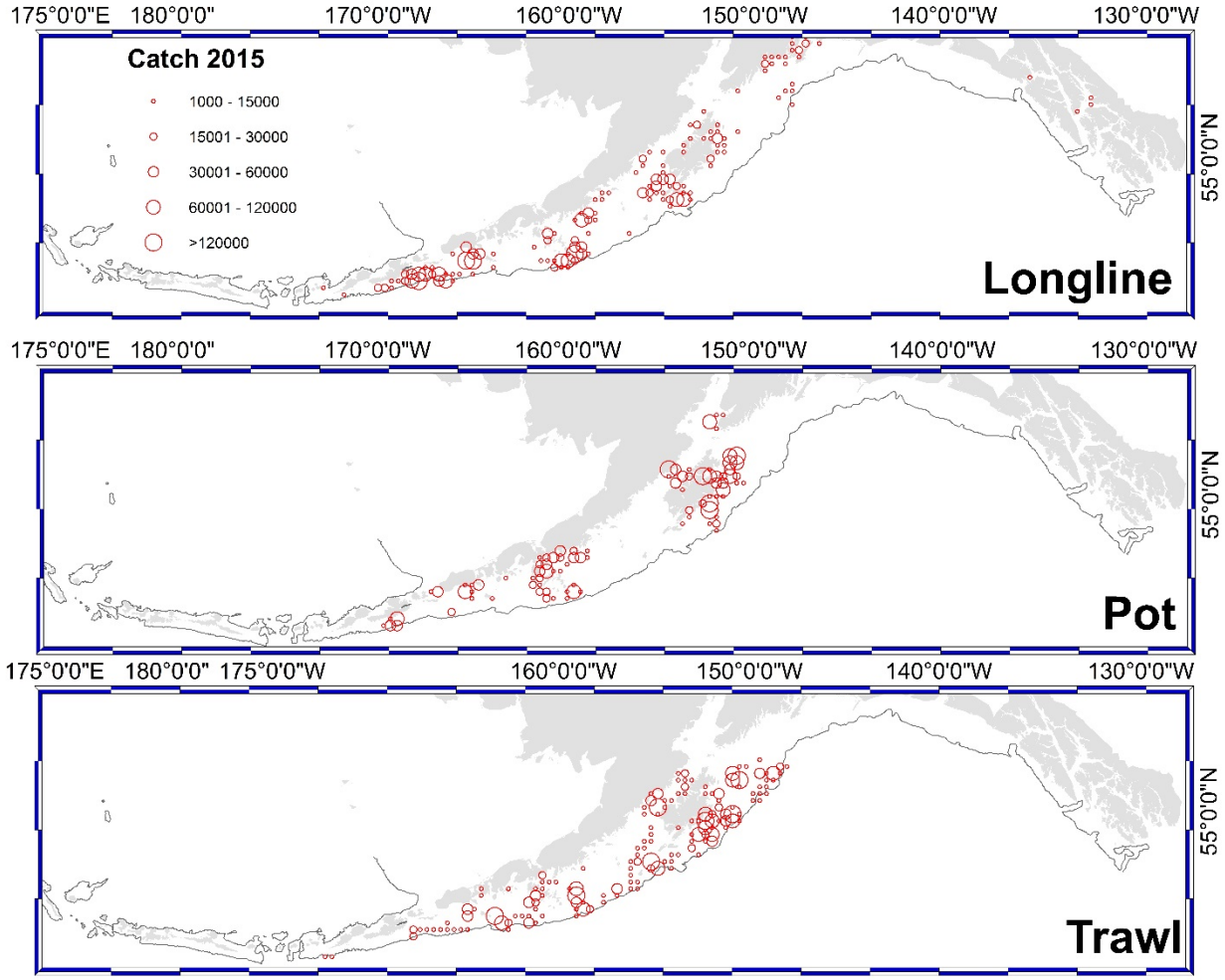


Figure 2.4 – Commercial catch of Pacific cod in the Gulf of Alaska by 20km^2 grid for 2015.

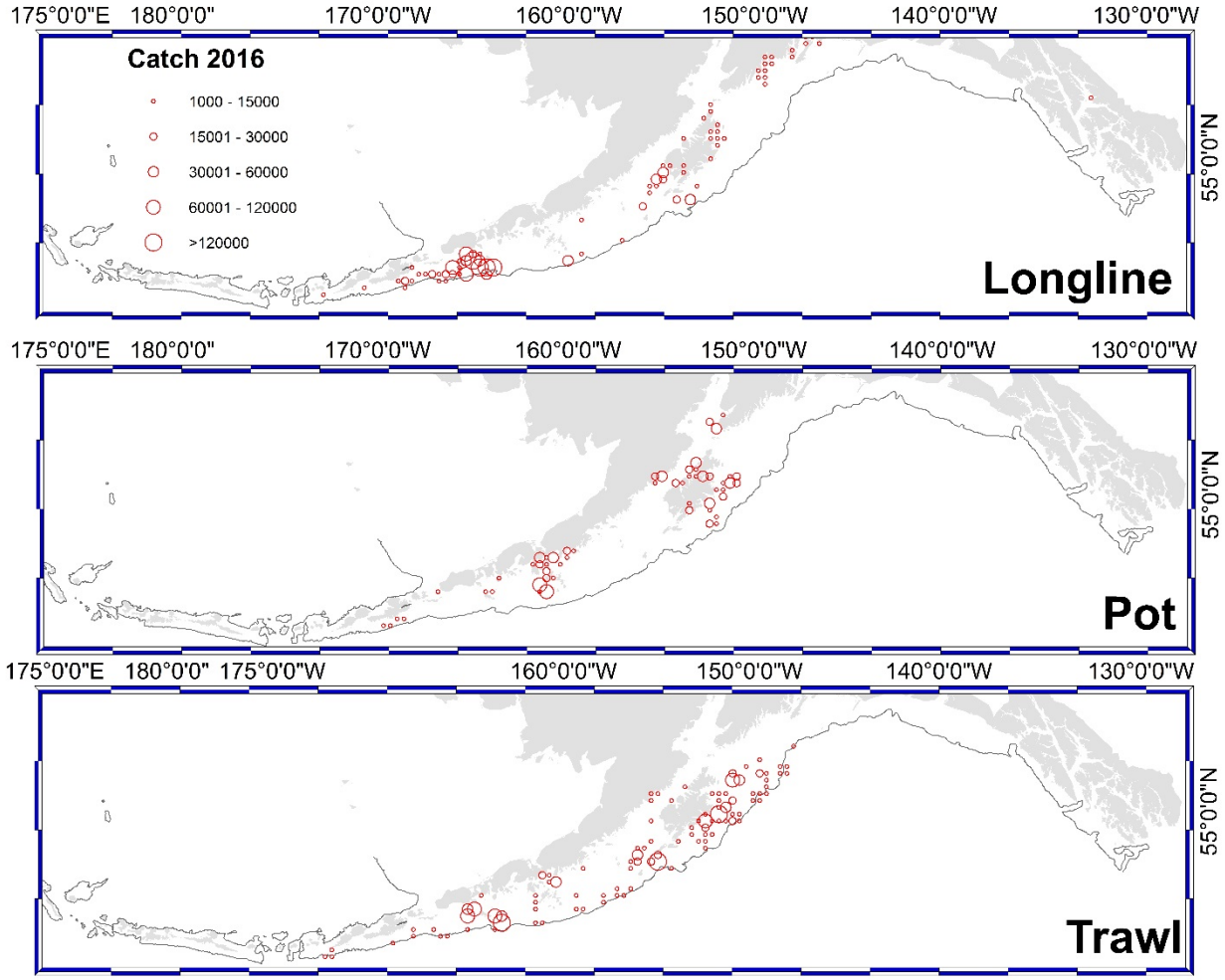


Figure 2.5 – Commercial catch of Pacific cod in the Gulf of Alaska by 20km^2 grid for 2016 as of October 17.

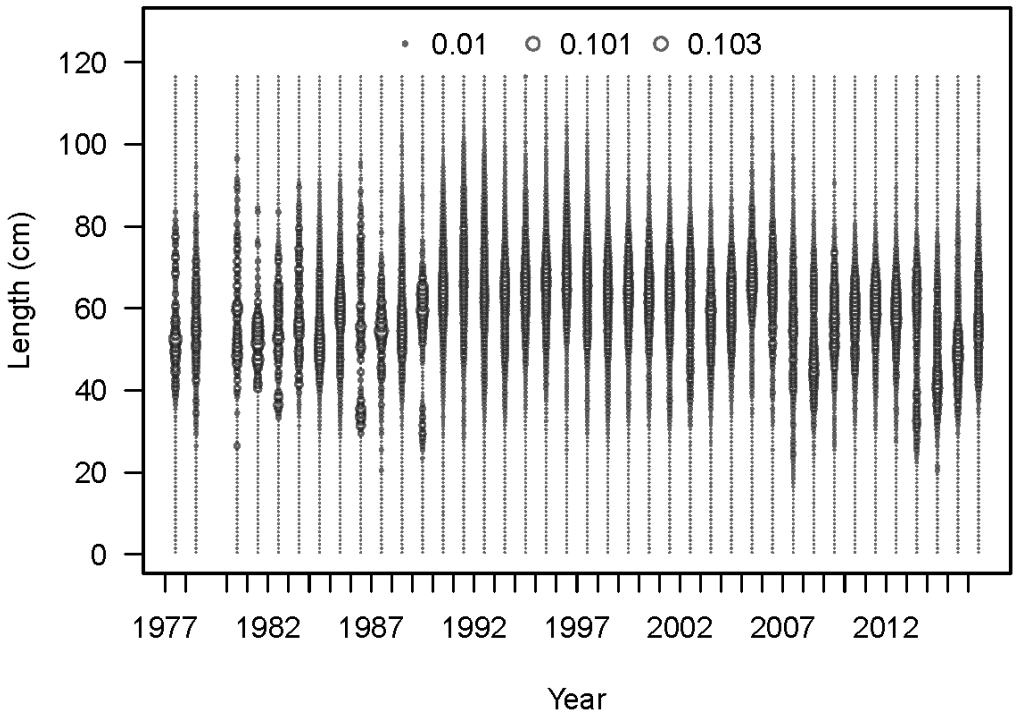


Figure 2.6 – Length composition from the Gulf of Alaska Pacific cod trawl fishery (max = 0.1).

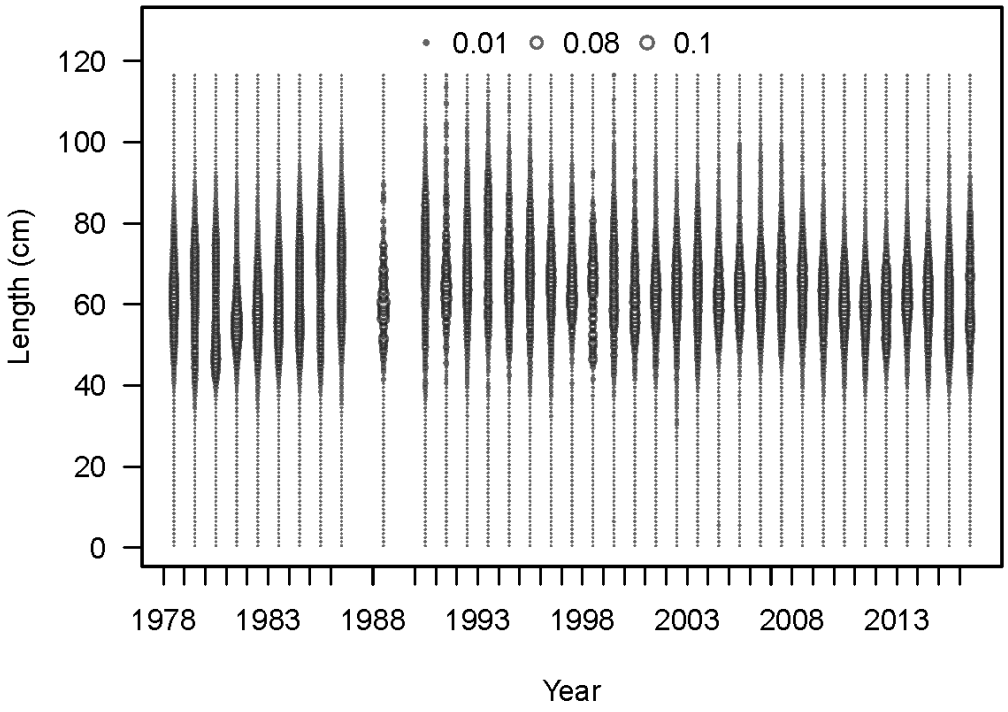


Figure 2.7 – Length composition from the Gulf of Alaska Pacific cod longline fishery (max = 0.08).

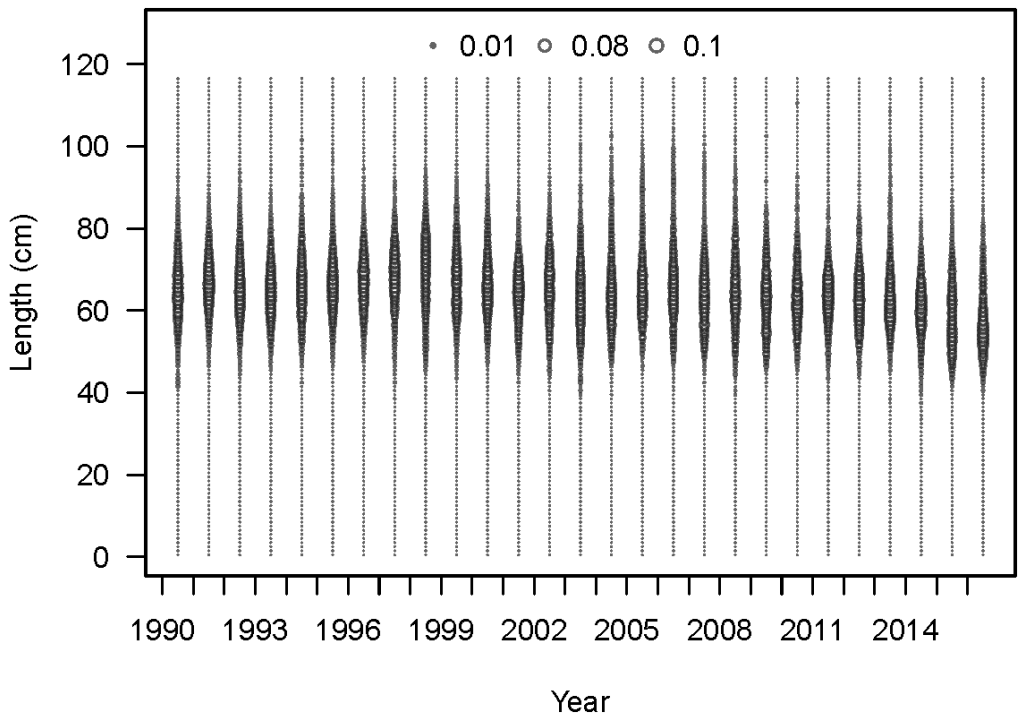


Figure 2.8 – Length composition from the Gulf of Alaska Pacific cod pot fishery (max = 0.07).

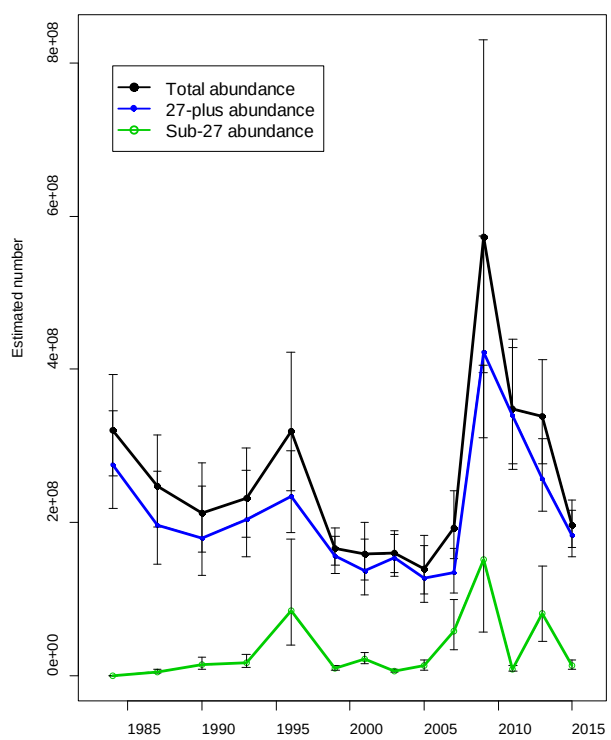


Fig. 2.9 – GOA NMFS bottom trawl survey abundance estimates (in numbers).

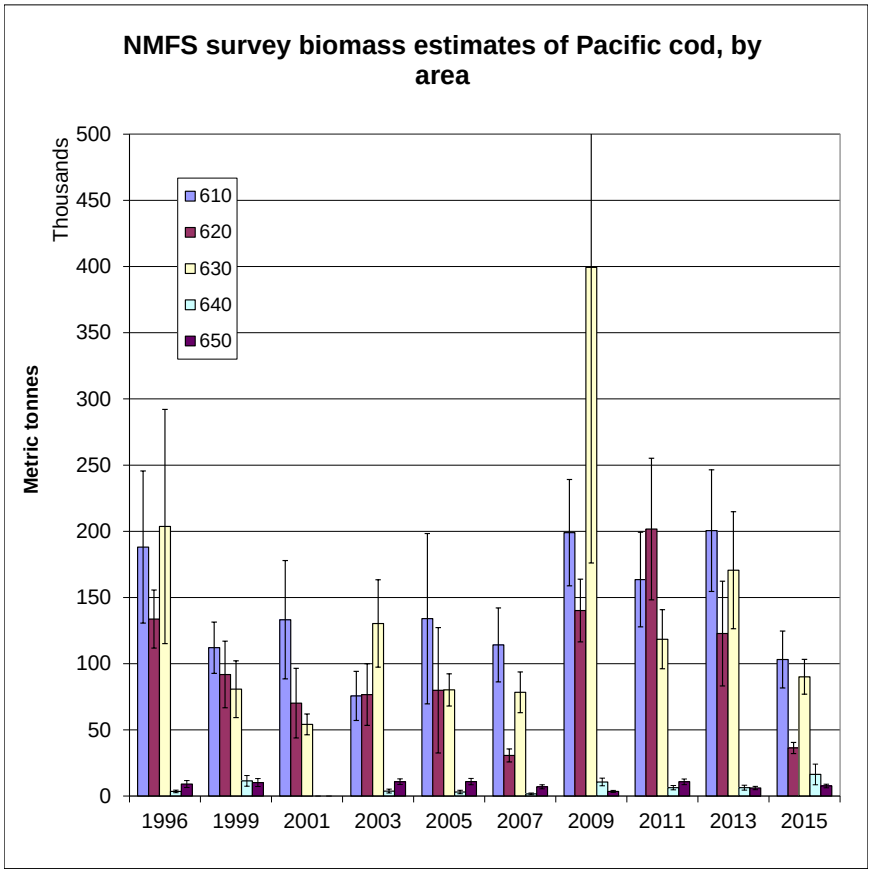


Figure 2.10 – GOA NMFS bottom trawl survey biomass estimates by area (in t)

Figure 2.11 – Maps of GOA NMFS bottom trawl survey biomass estimates.

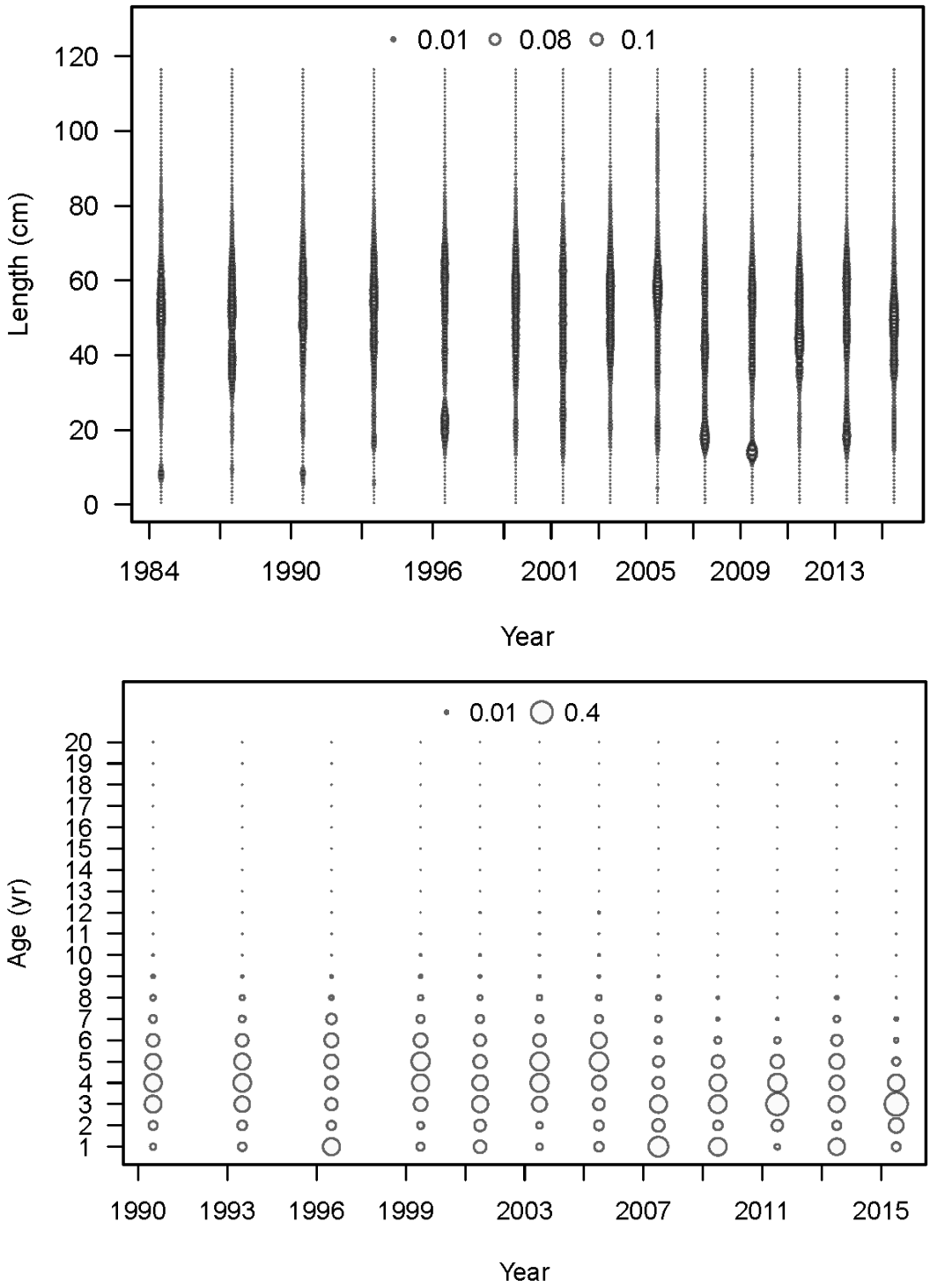


Figure 2.12 – Pacific cod length (top) and age (bottom) composition from the Gulf of Alaska bottom trawl survey

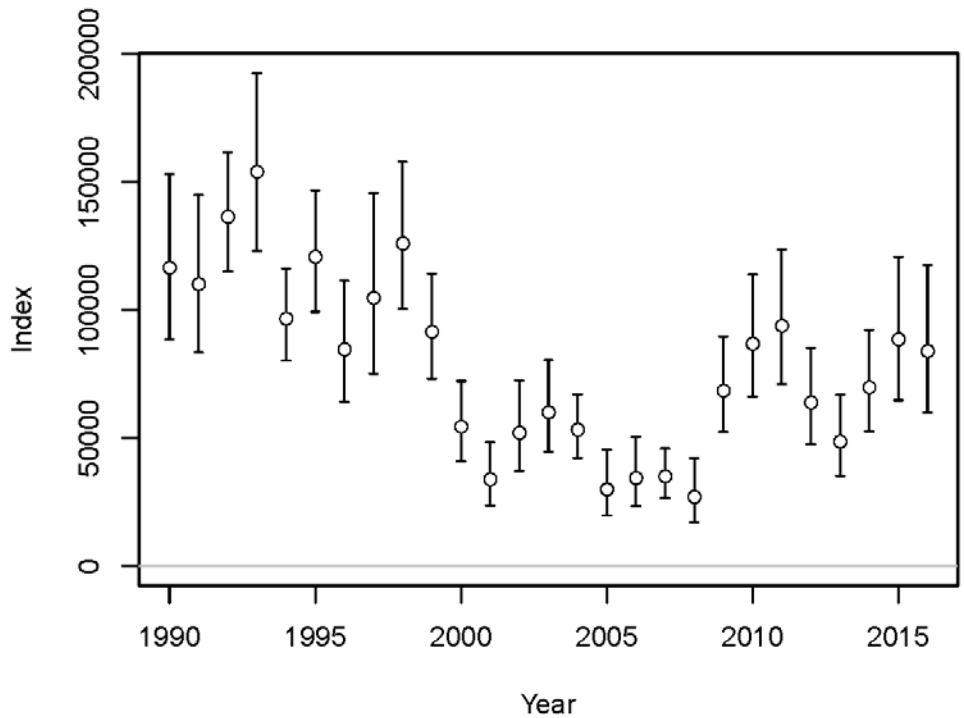


Figure 2.13 – Auke Bay Laboratory Gulf of Alaska longline Pacific Cod relative population number (RPN) index 1990 – 2015.

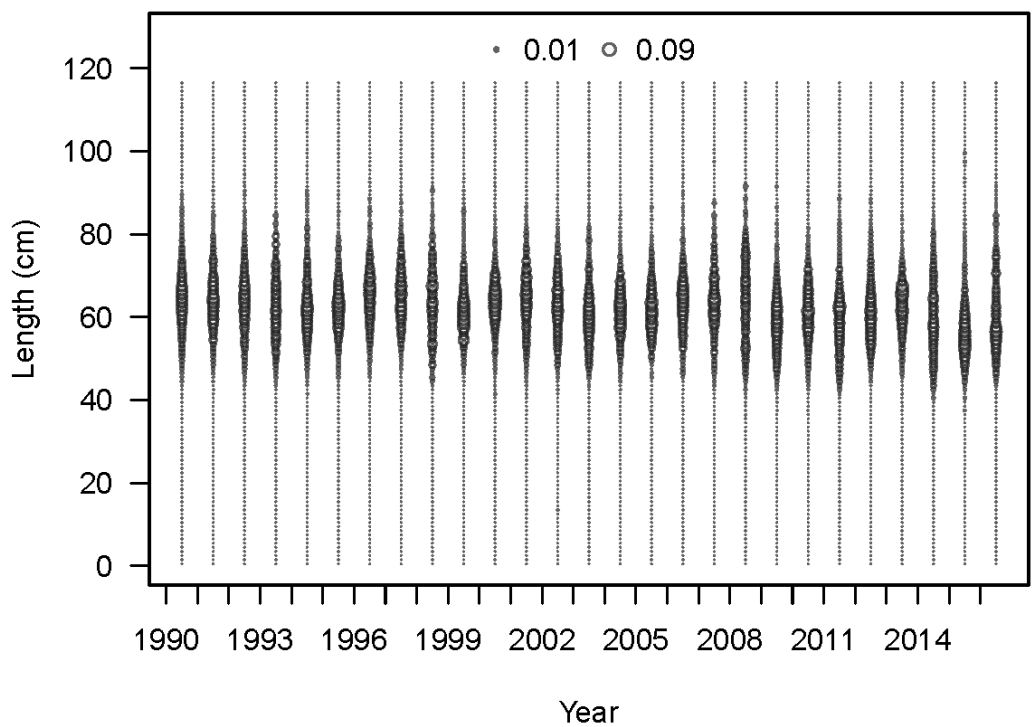


Figure 2.14 – Pacific cod length composition from the Auke Bay laboratory Gulf of Alaska longline survey (max = 0.09).

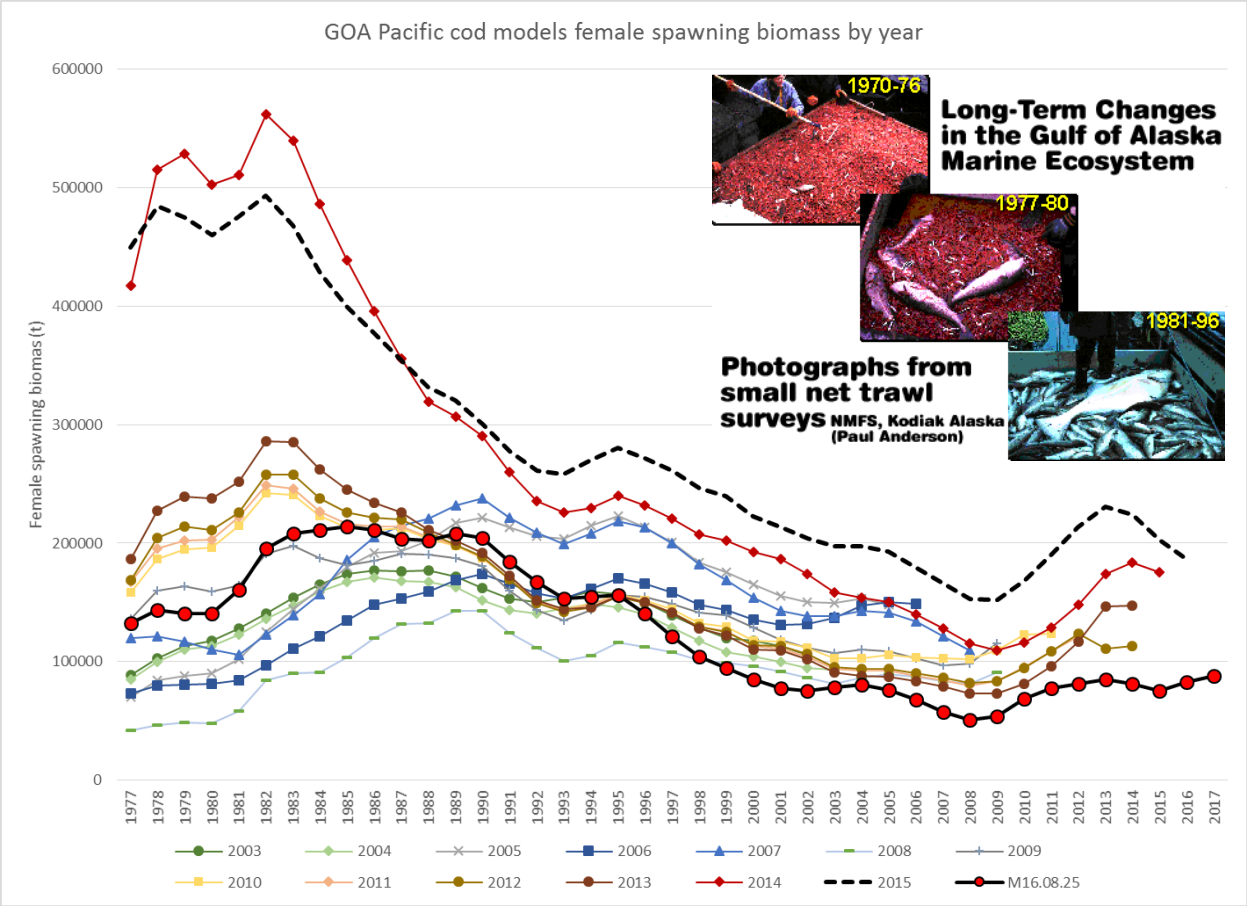


Figure 2.15 – 1977-2015 Gulf of Alaska Pacific cod female spawning biomass from the 2003 through 2015 stock assessments with the author's preferred Model 16.08.25 and (inset) images from the NMFS small net surveys off Kodiak Alaska showing change in species composition over time from: http://www.thexxnakedscientists.com/HTML/articles/article/brucewrightcolumn1.htm/

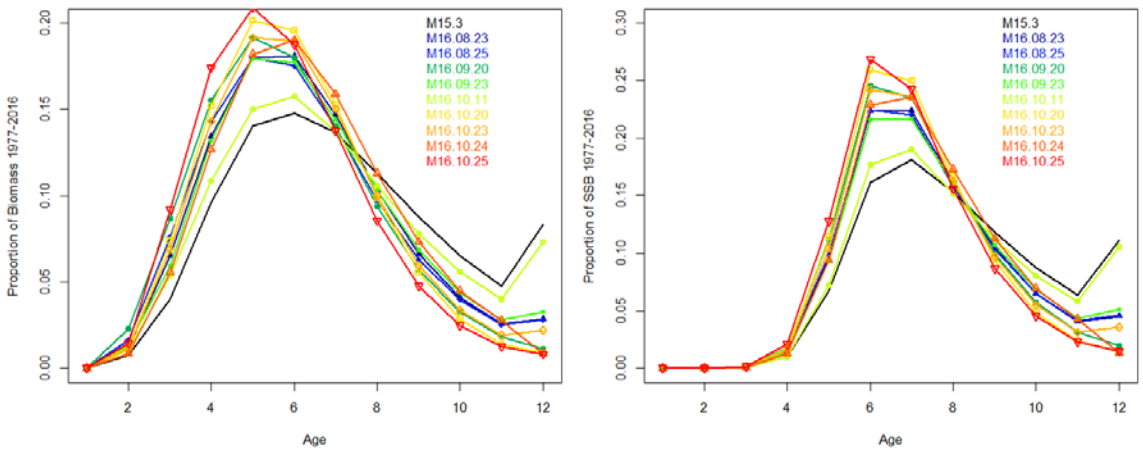


Figure 2.16 – Proportion of total biomass and female spawning biomass by age aggregated for 1977-2016 for selected models.

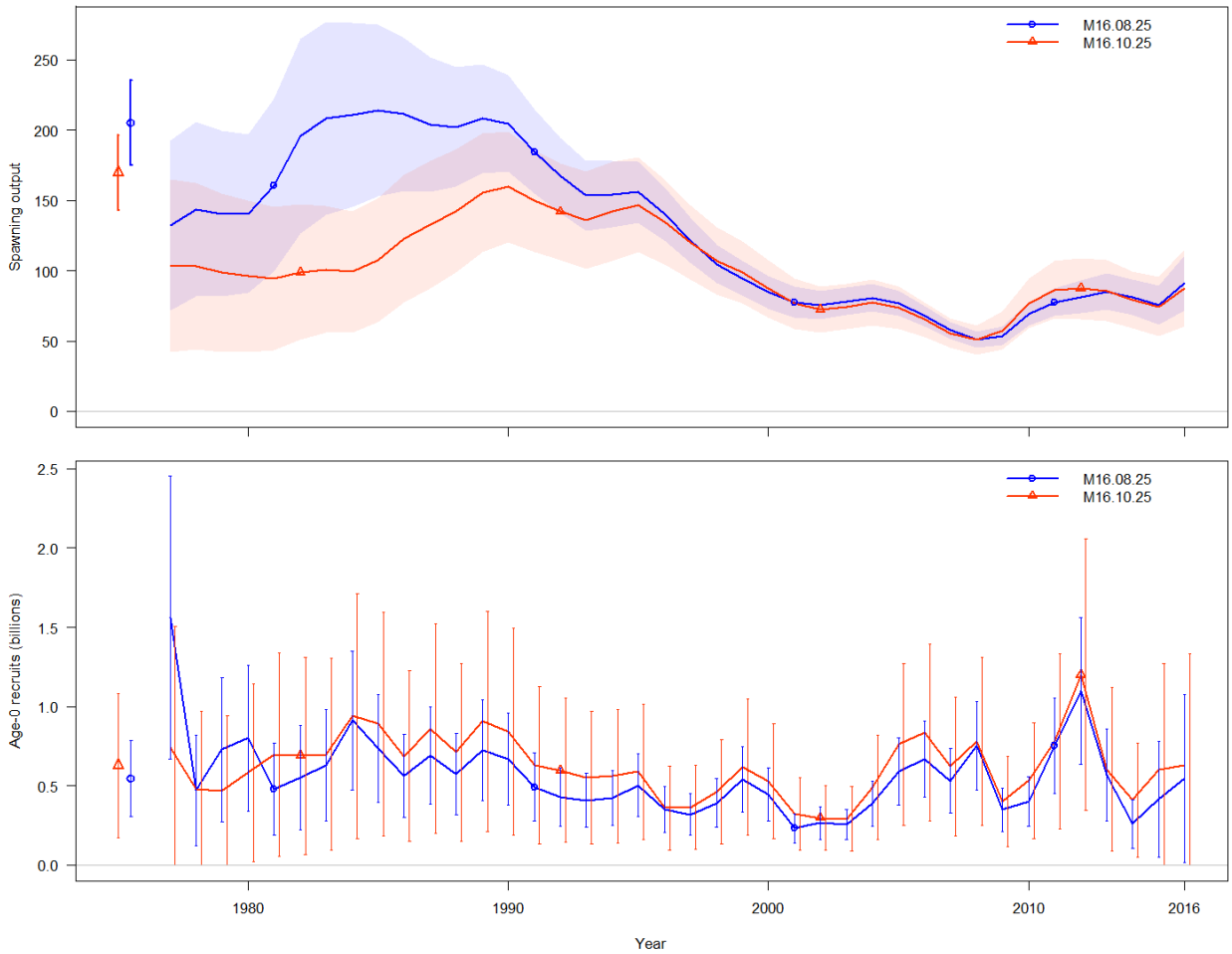


Figure 2.17 – Estimates of female spawning biomass (t; top) and age-0 recruits (billions; bottom) for Model 16.08.25 without tuning and Model 16.10.25 with Francis TA1.8 tuning.

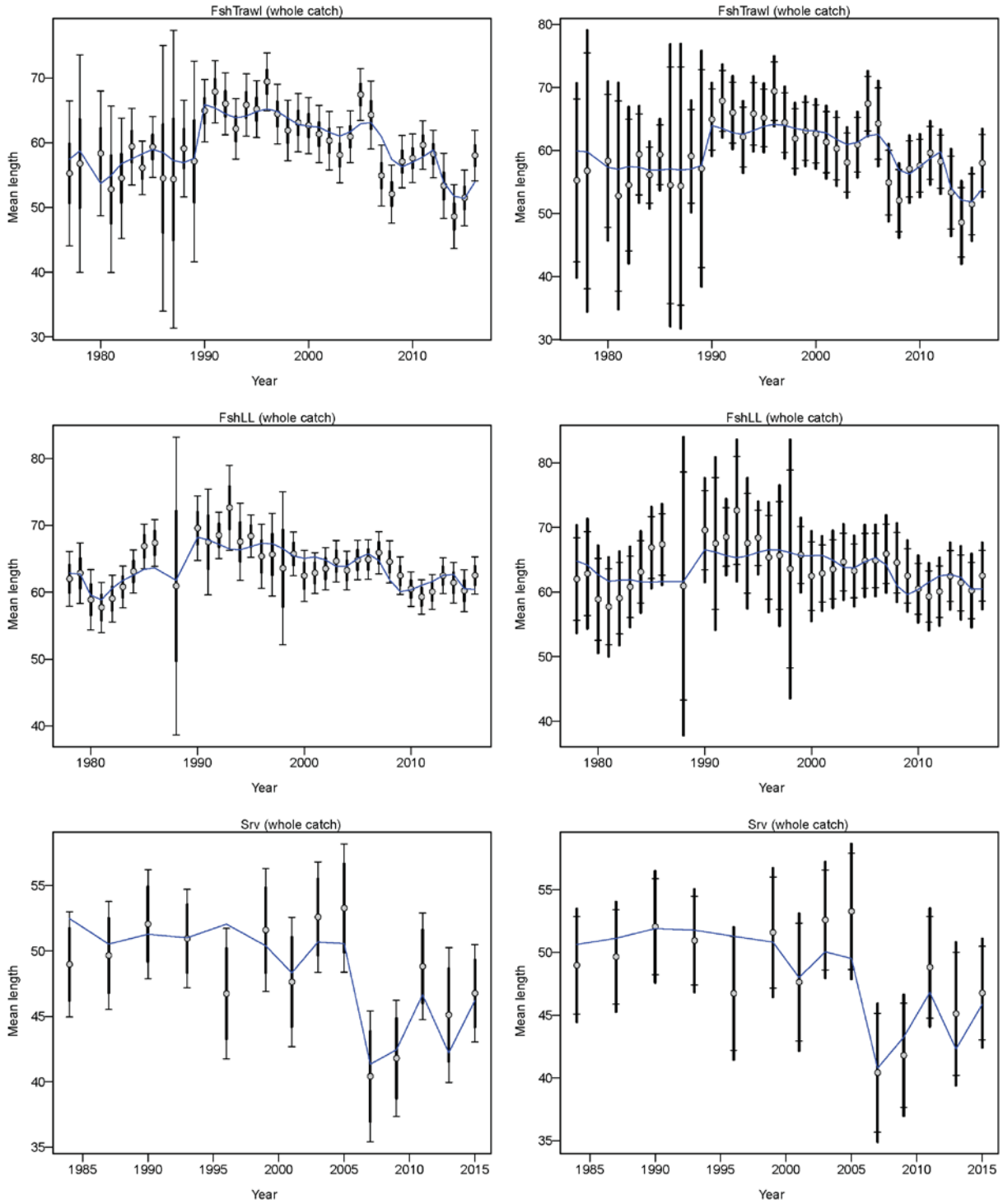


Figure 2.18 – Trawl fishery (top), Longline fishery (middle), and NMFS bottom trawl survey (bottom) mean length and model fits for (left) M16.08.25 and (right) M16.10.25.

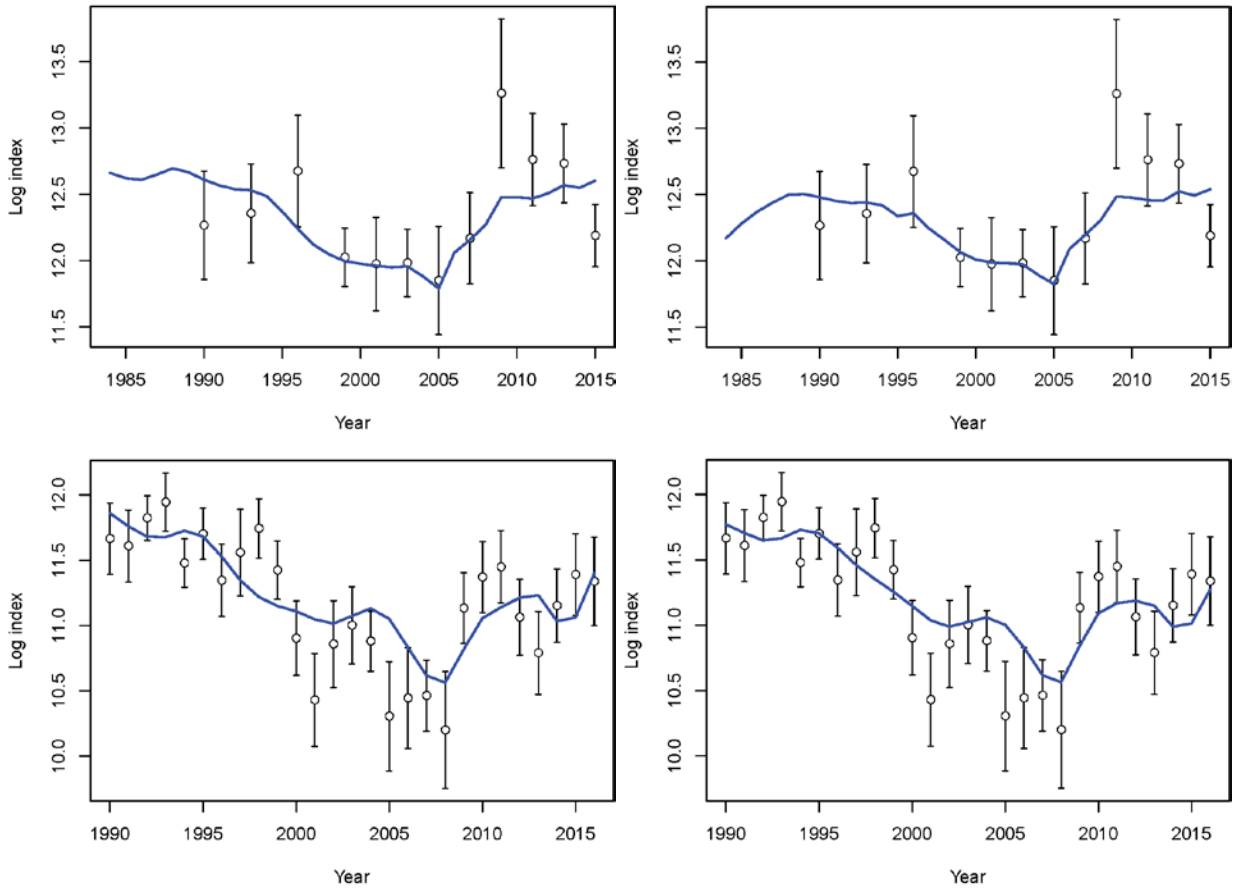


Figure 2.19 – NMFS bottom trawl survey index (top) and Auke Bay Laboratory longline survey index and model fits for (left) M16.08.25 and (right) M16.10.25.

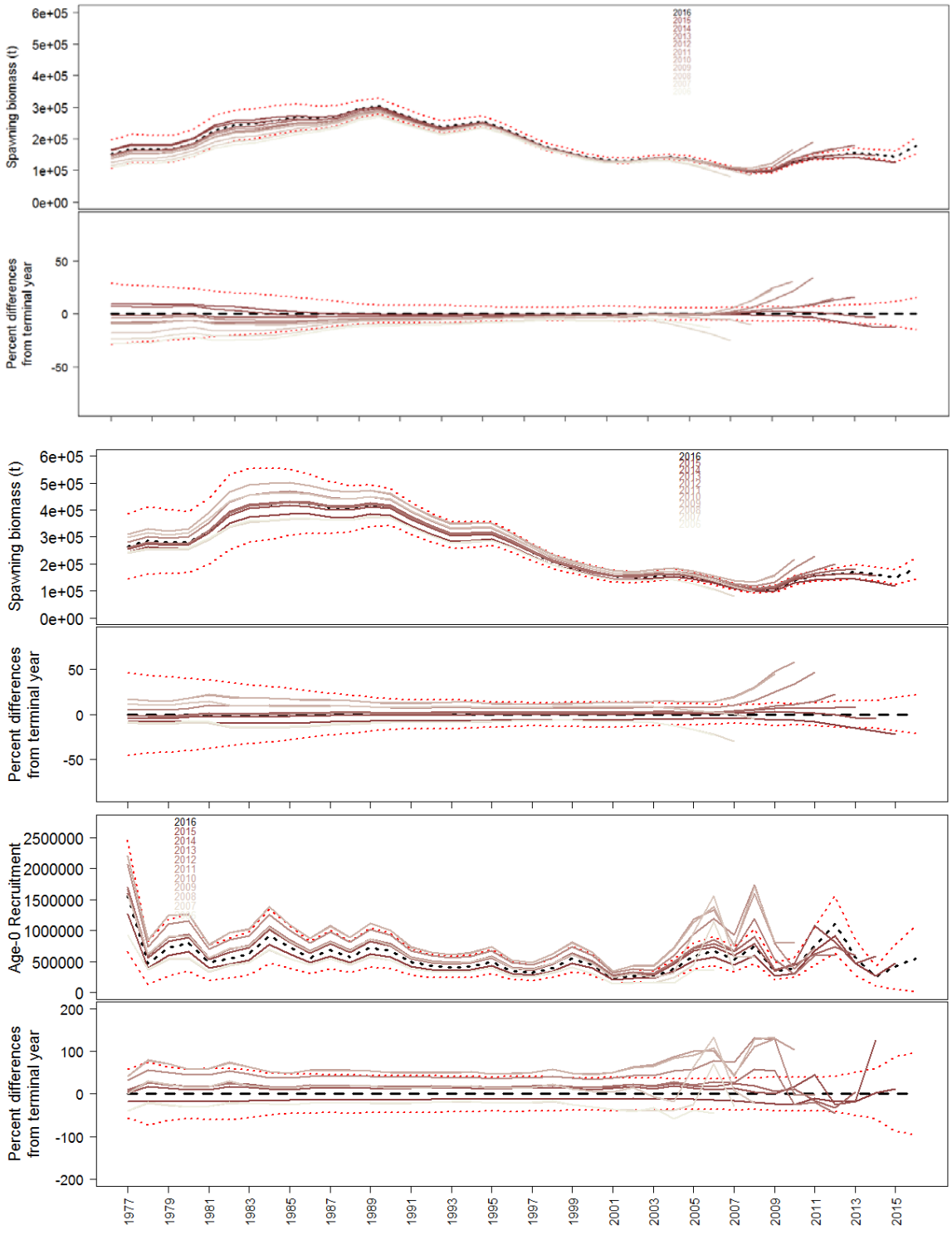


Figure 2.20 – Model 16.08.25 retrospective analyses for biomass (top pair) and age-0 recruitment (bottom pair).

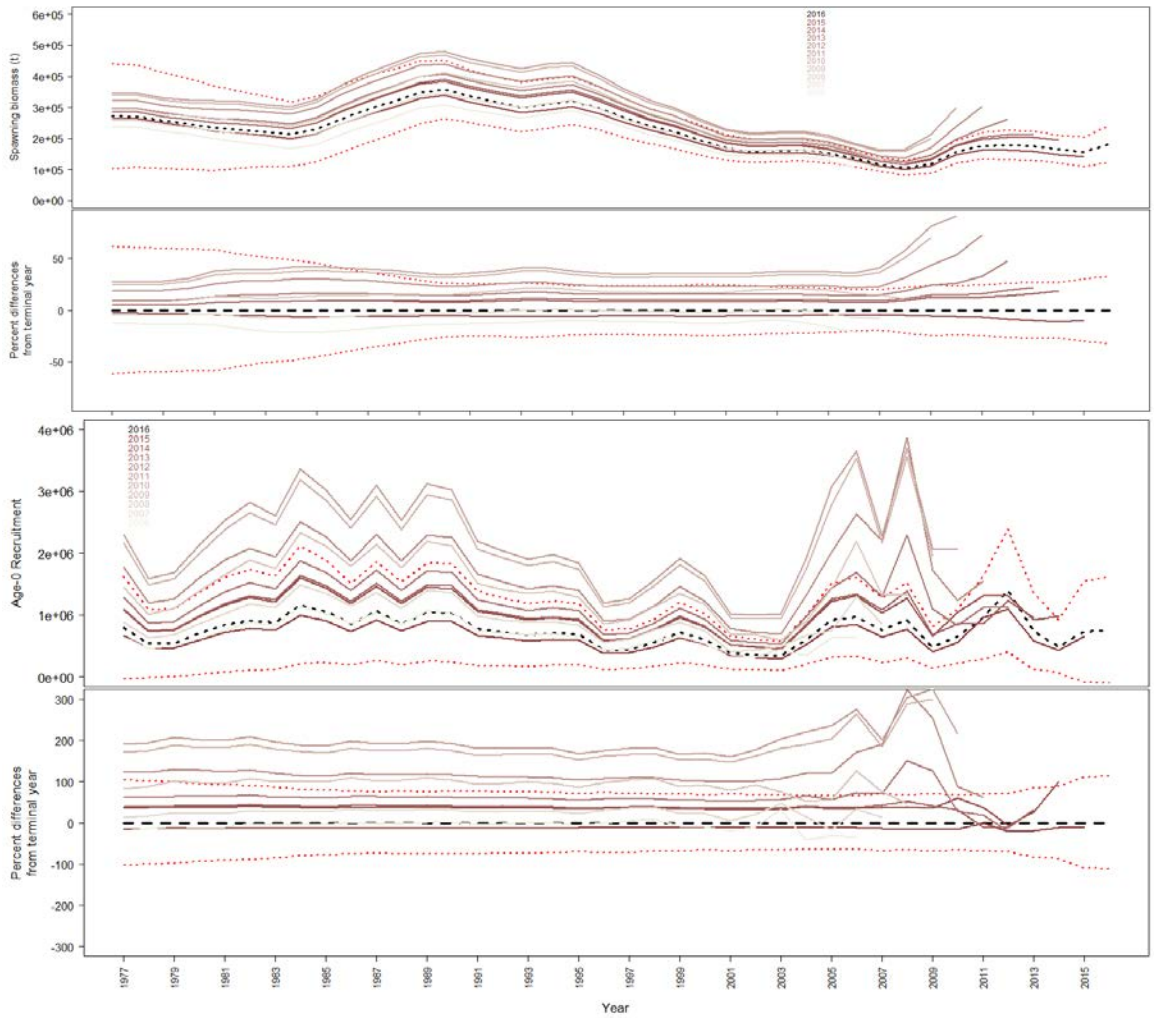


Figure 2.21 – Model 16.10.25 retrospective analyses for biomass (top pair) and age-0 recruitment (bottom pair).

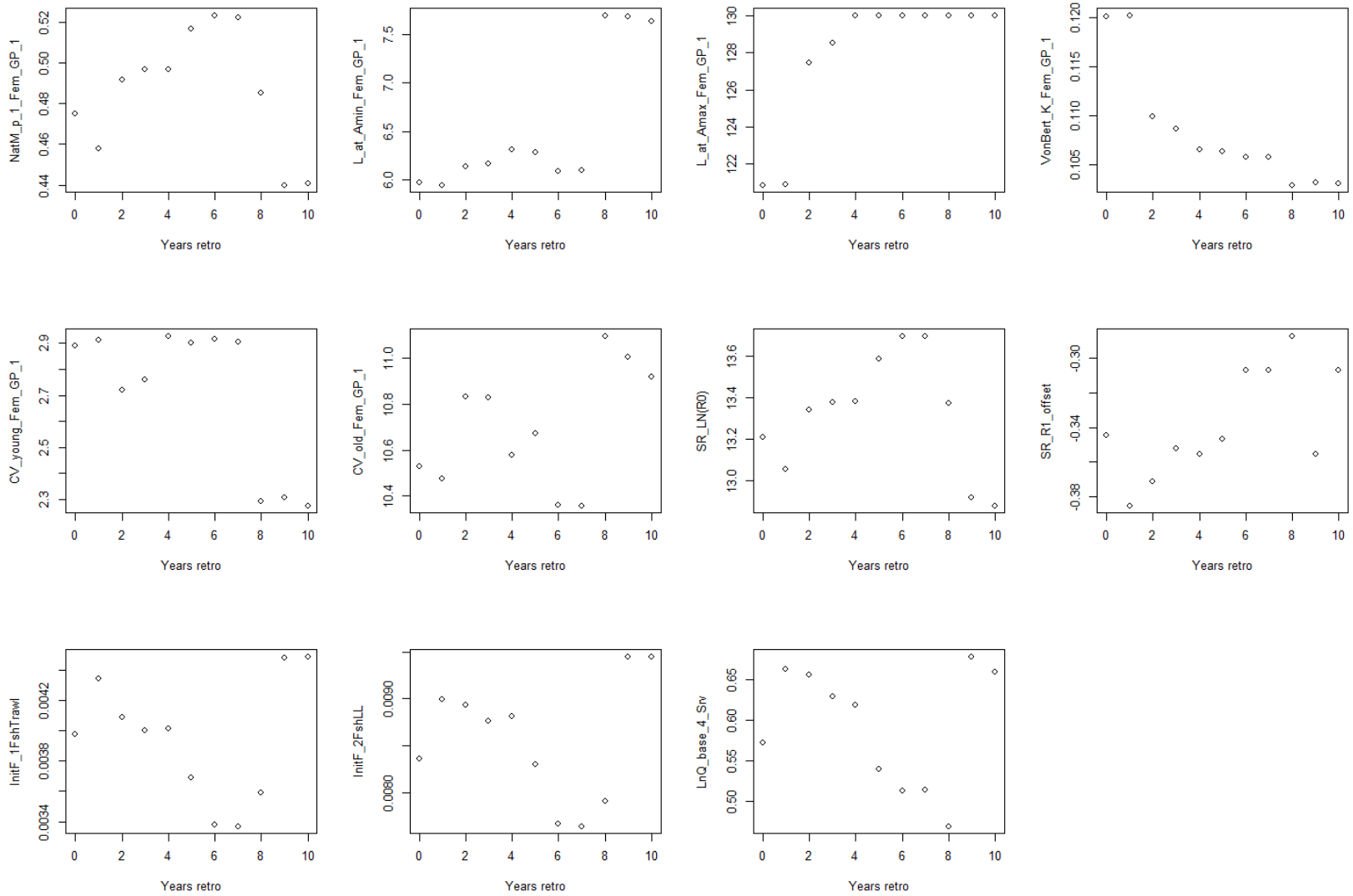


Figure 2.22 – Parameter estimates from the -10 year retrospective analysis for Model 16.08.25.

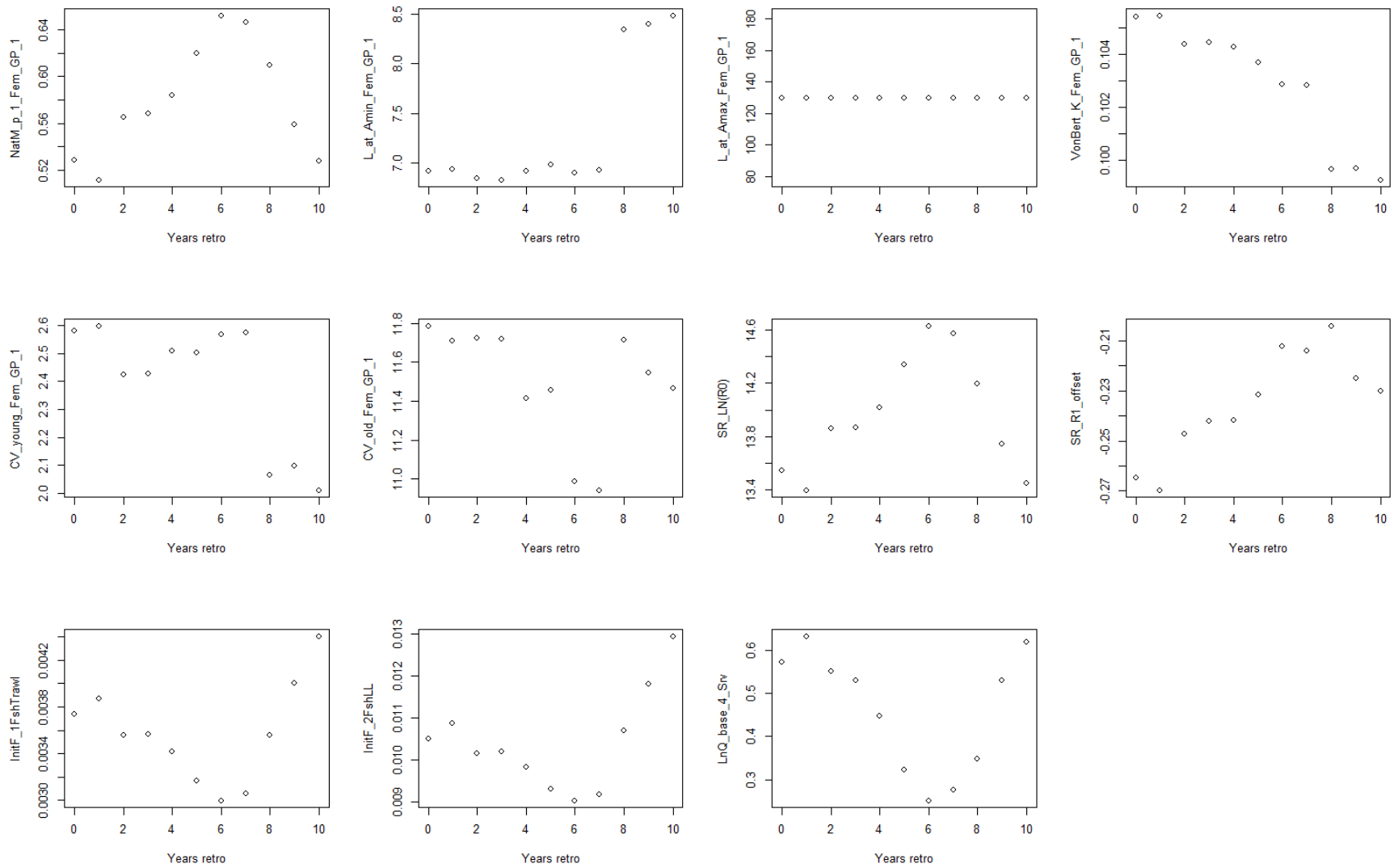


Figure 2.23 – Parameter estimates from the -10 year retrospective analysis for Model 16.10.25.

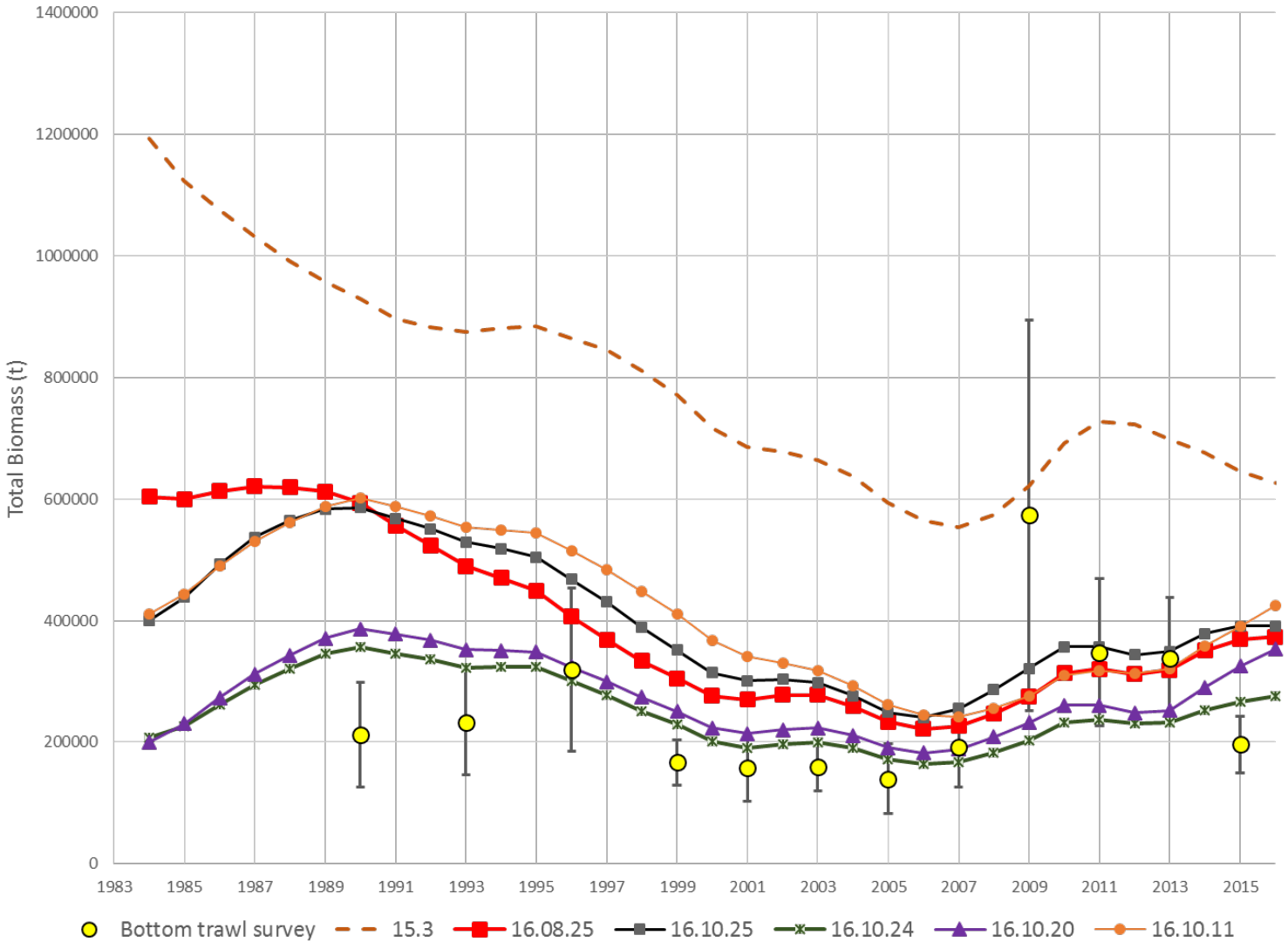


Figure 2.24 – Total biomass estimates from reviewed models and NMFS bottom trawl survey biomass estimates with 95% confidence bounds.

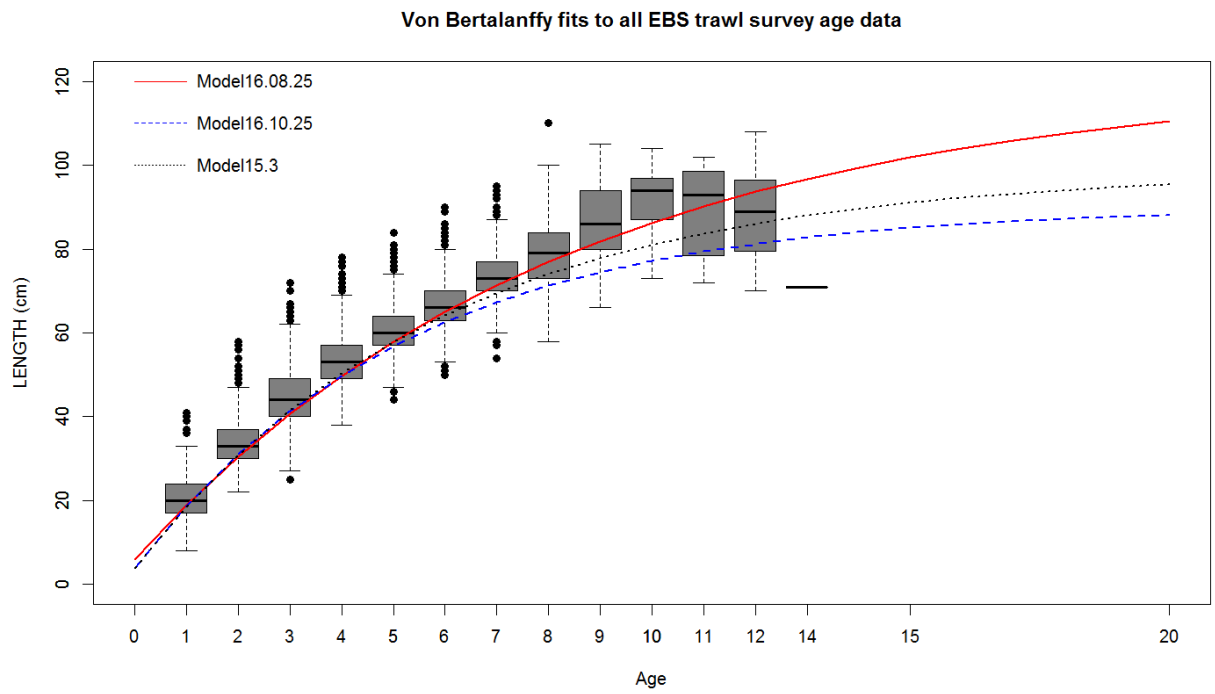


Figure 2.25 – Boxplot of NMFS bottom trawl survey age at length data for 1990 through 2015 with growth curves for Model 16.08.25, Model 16.10.25, and Model 15.3.

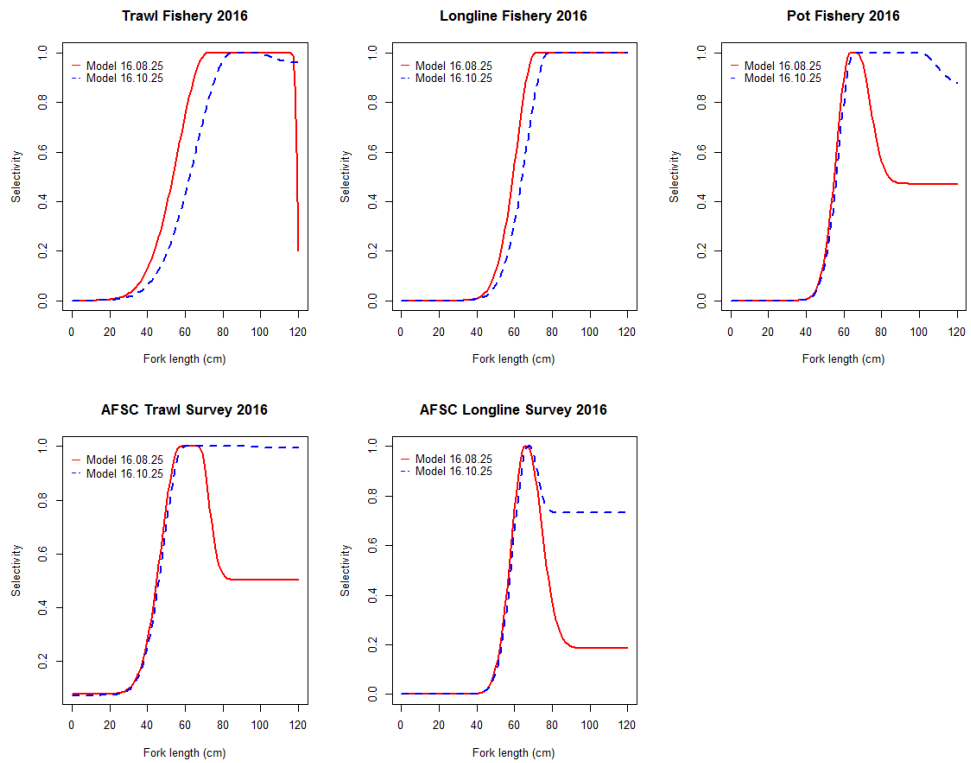


Figure 2.26 – 2016 selectivity curves for Model 16.08.25 (red line) and Model 16.10.25 (blue dashed line) for all length composition components.

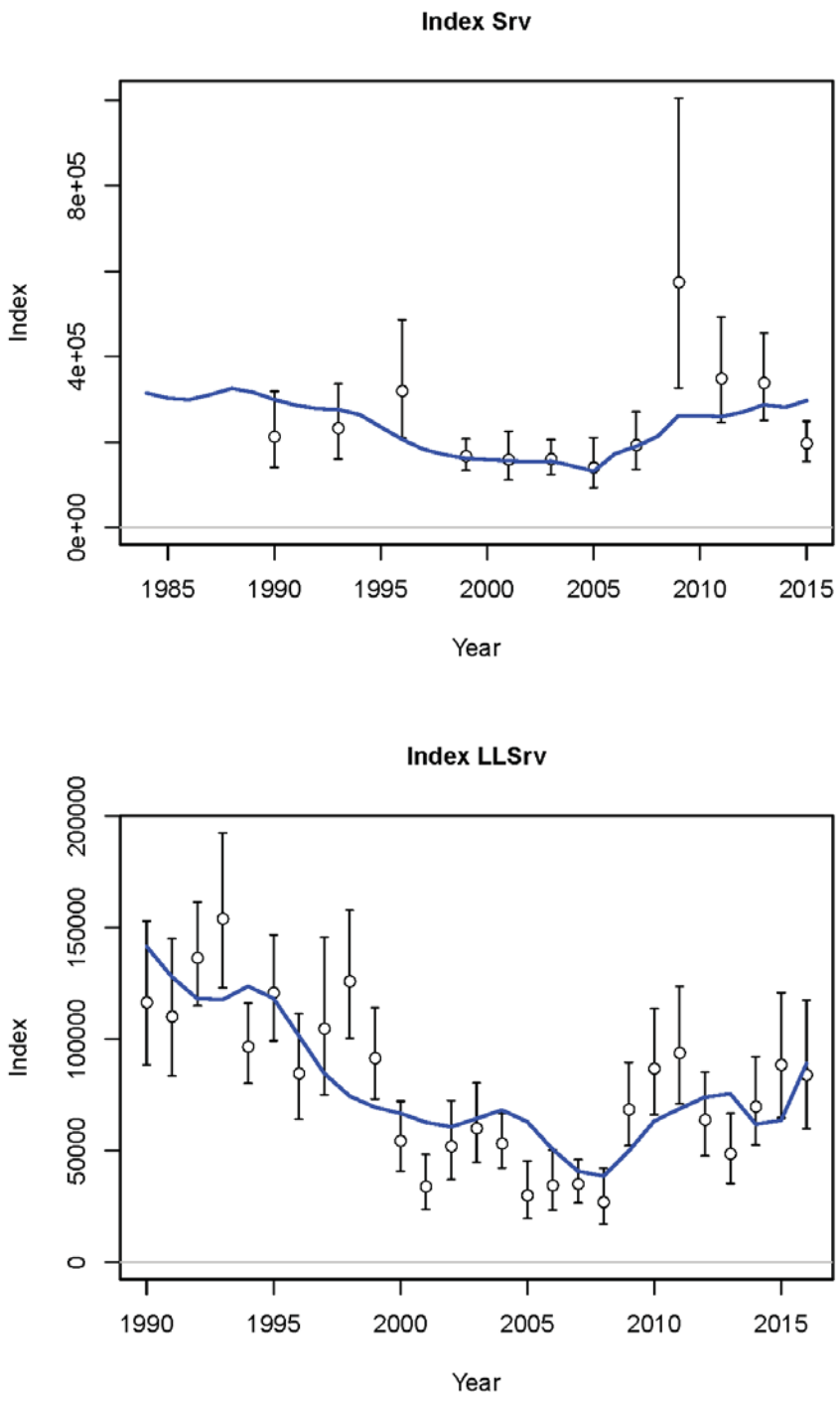


Figure 2.27 – Model fits to NMFS bottom trawl survey (Srv; tons) and Auke Bay longline survey (LLSrv; RPN) index surveys for Model 16.08.25.

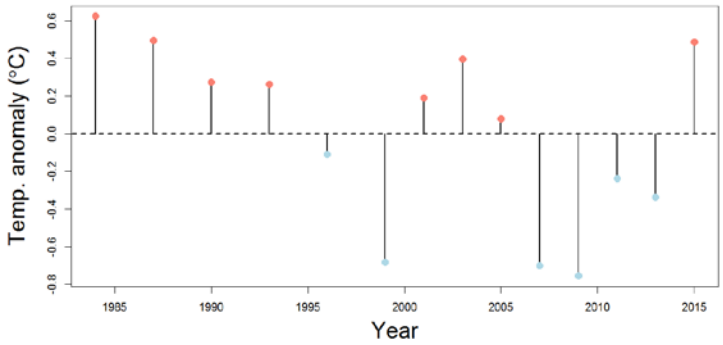


Figure 2.28 – Bottom temperature anomaly from the NMFS bottom trawl survey average 1984-2015.

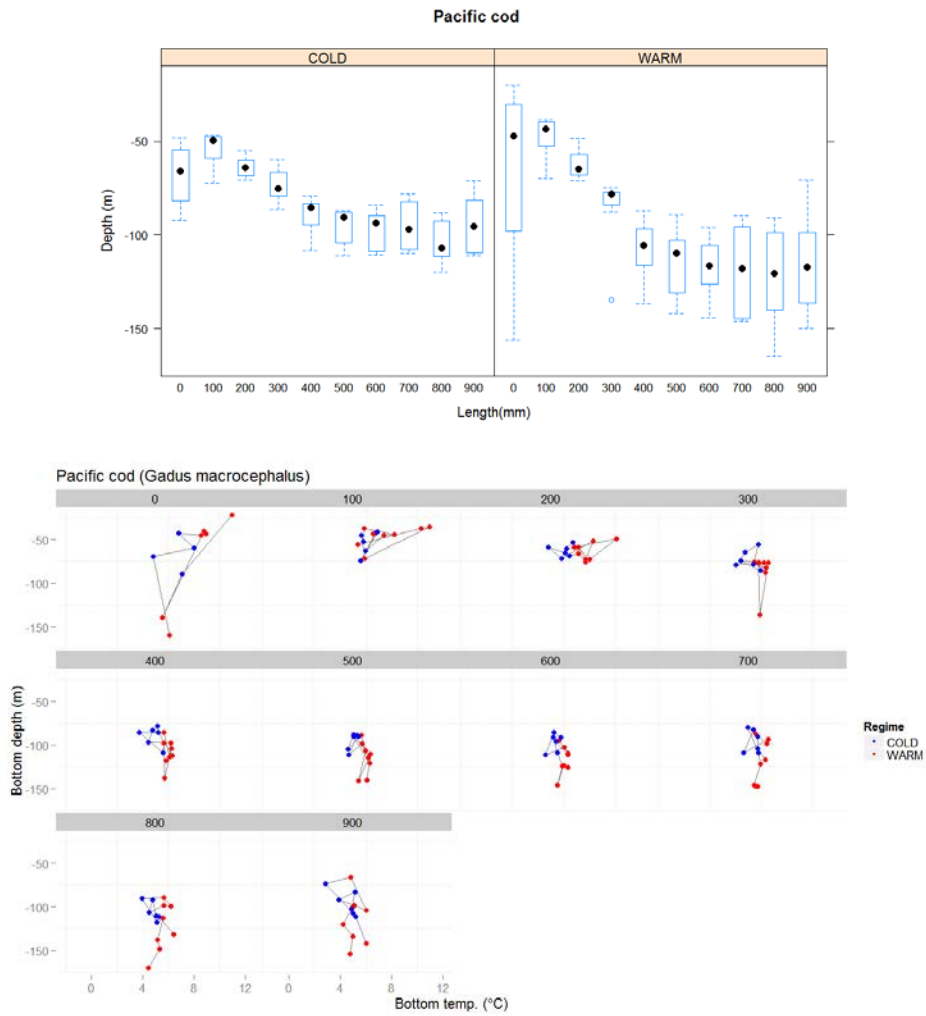


Figure 2.29 – Distribution of pacific cod in the NMFS bottom trawl survey by length (mm) for depth (top) and depth and temperature (bottom) showing larger cod at deeper depths in warmer years.

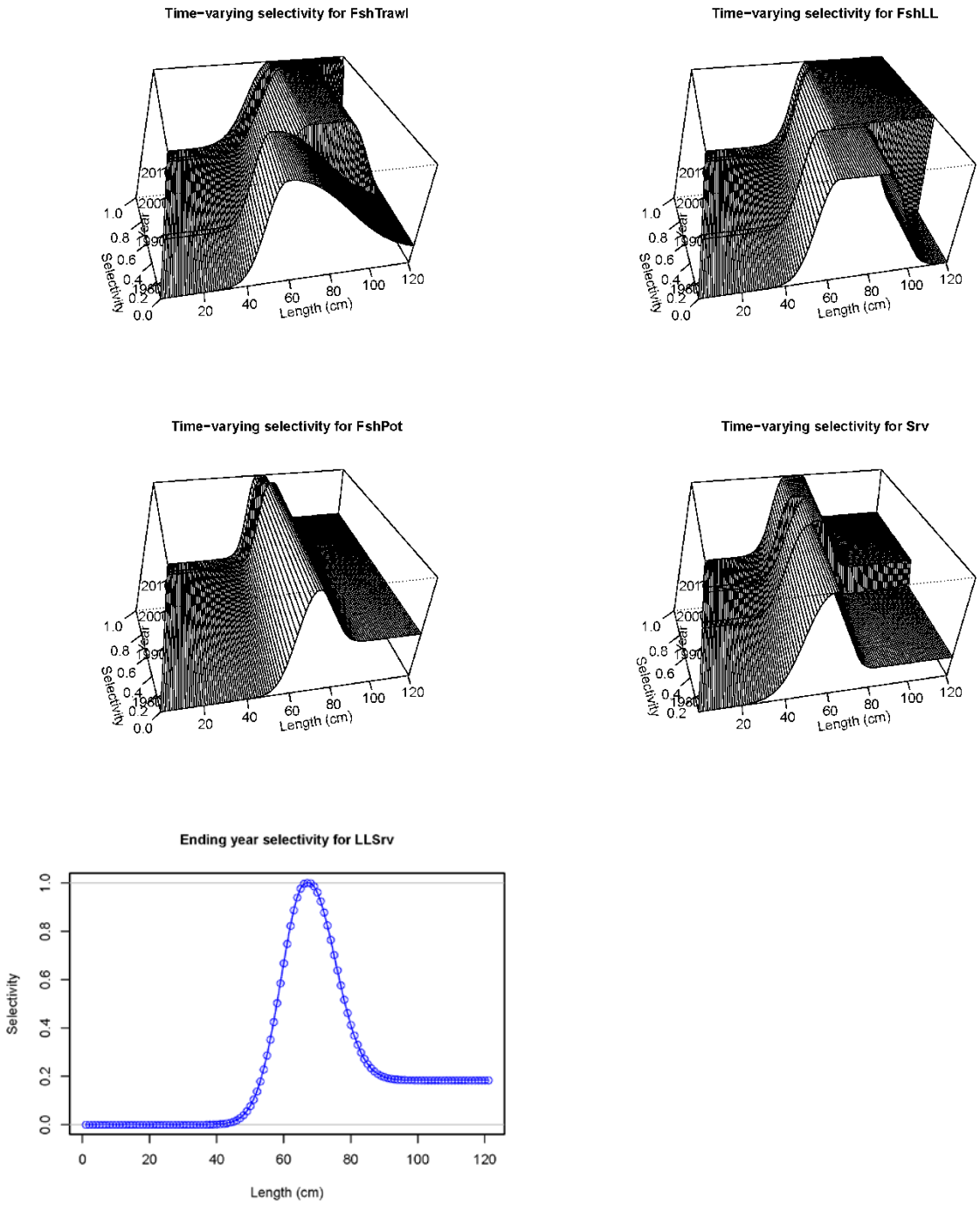


Figure 2.30 – Selectivity curves for Model 16.08.25 Trawl fishery (FshTrawl), longline fishery (FshLL), pot fishery (FshPot), NMFS bottom trawl survey (Srv), and Auke Bay longline survey (LLSrv) length composition data.

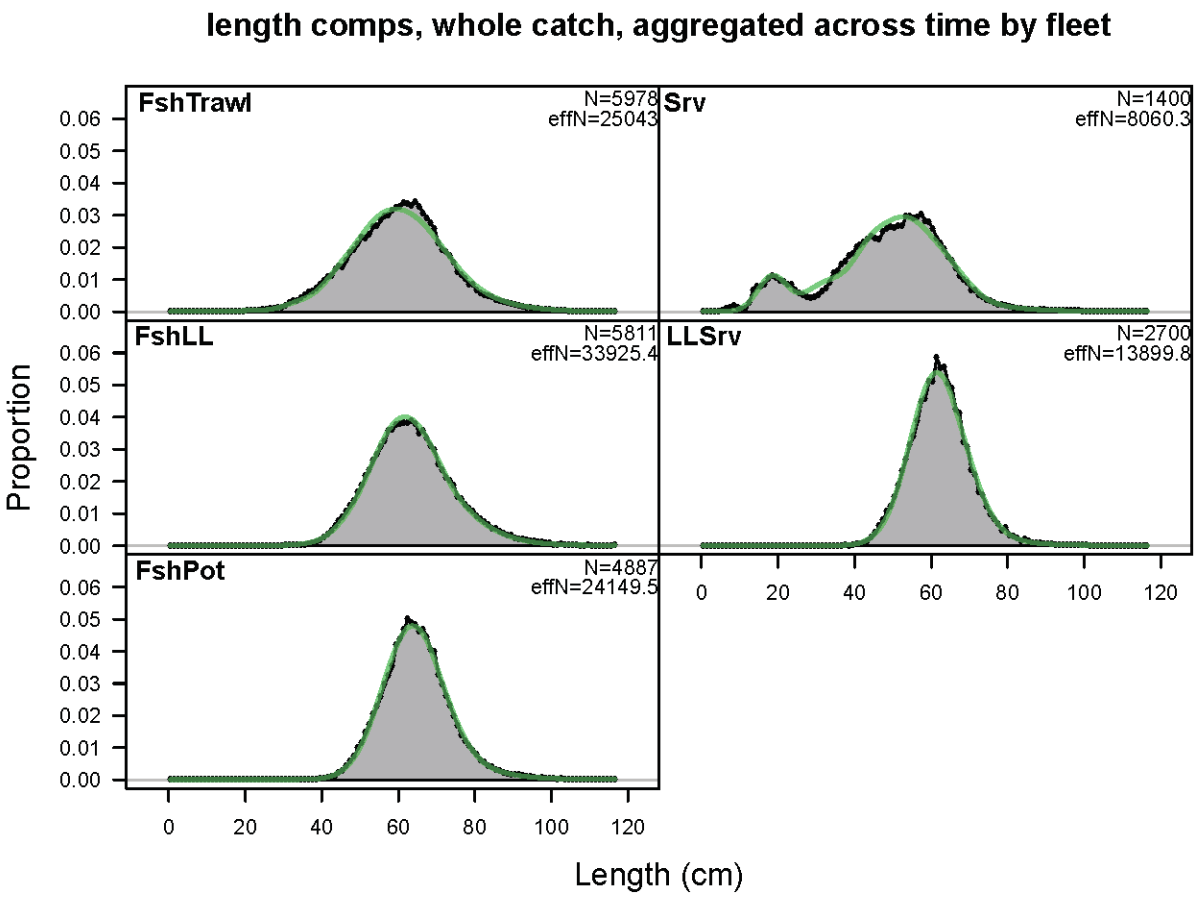


Figure 2.31 – Overall Model 16.08.25 fits to Trawl fishery (FshTrawl), longline fishery (FshLL), pot fishery (FshPot), NMFS bottom trawl survey (Srv), and Auke Bay longline survey (LLSrv) length composition data.

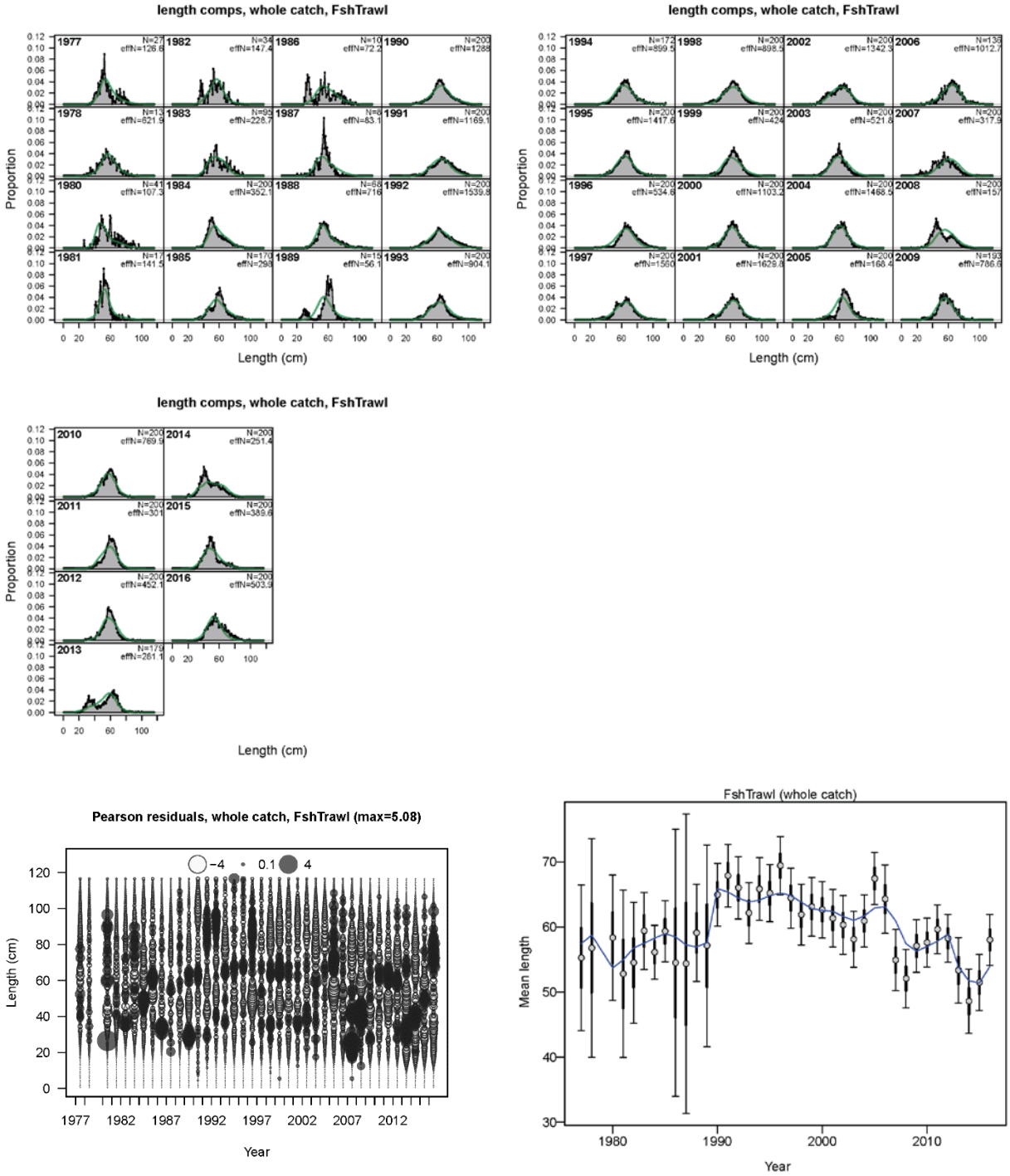


Figure 2.32 – Trawl fishery length composition and Model 16.08.25 fit (top), Pearson residuals (left bottom), and mean length (cm; right bottom).

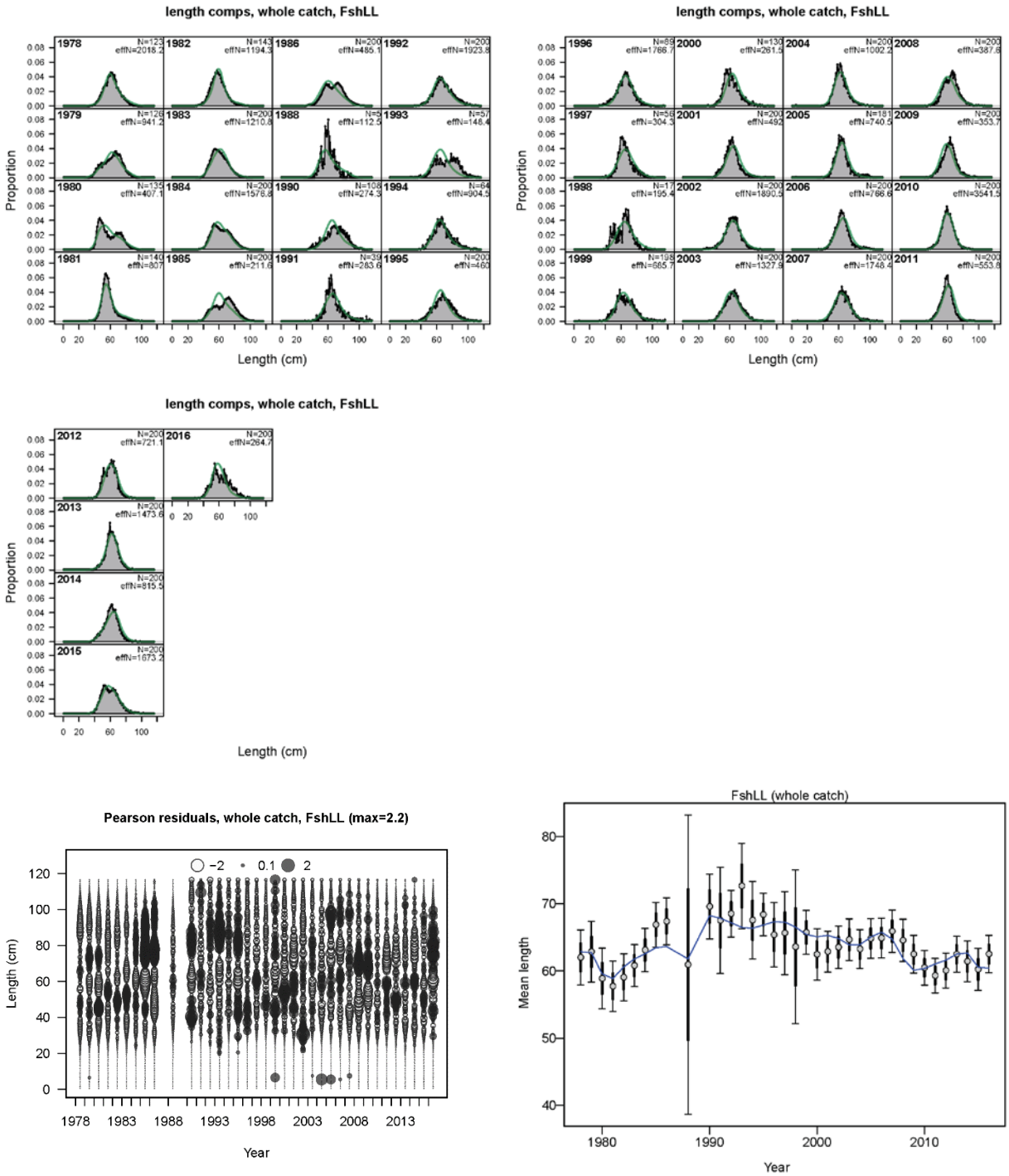


Figure 2.33 – Longline fishery length composition and Model 16.08.25 fit (top), Pearson residuals(left bottom), and mean length (cm; right bottom).

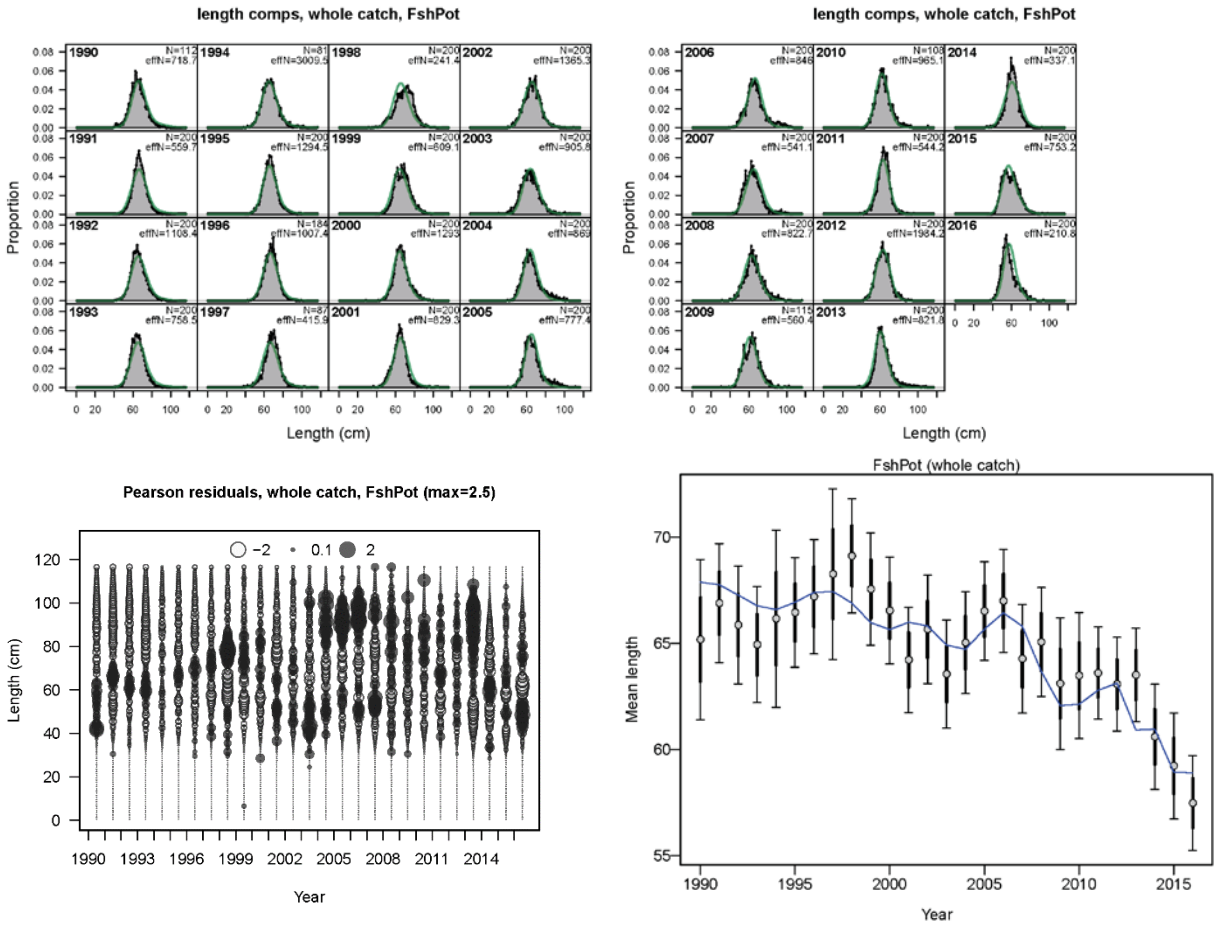


Figure 2.34 – Pot fishery length composition and Model 16.08.25 fit (top), Pearson residuals (left bottom), and mean length (cm; right bottom).

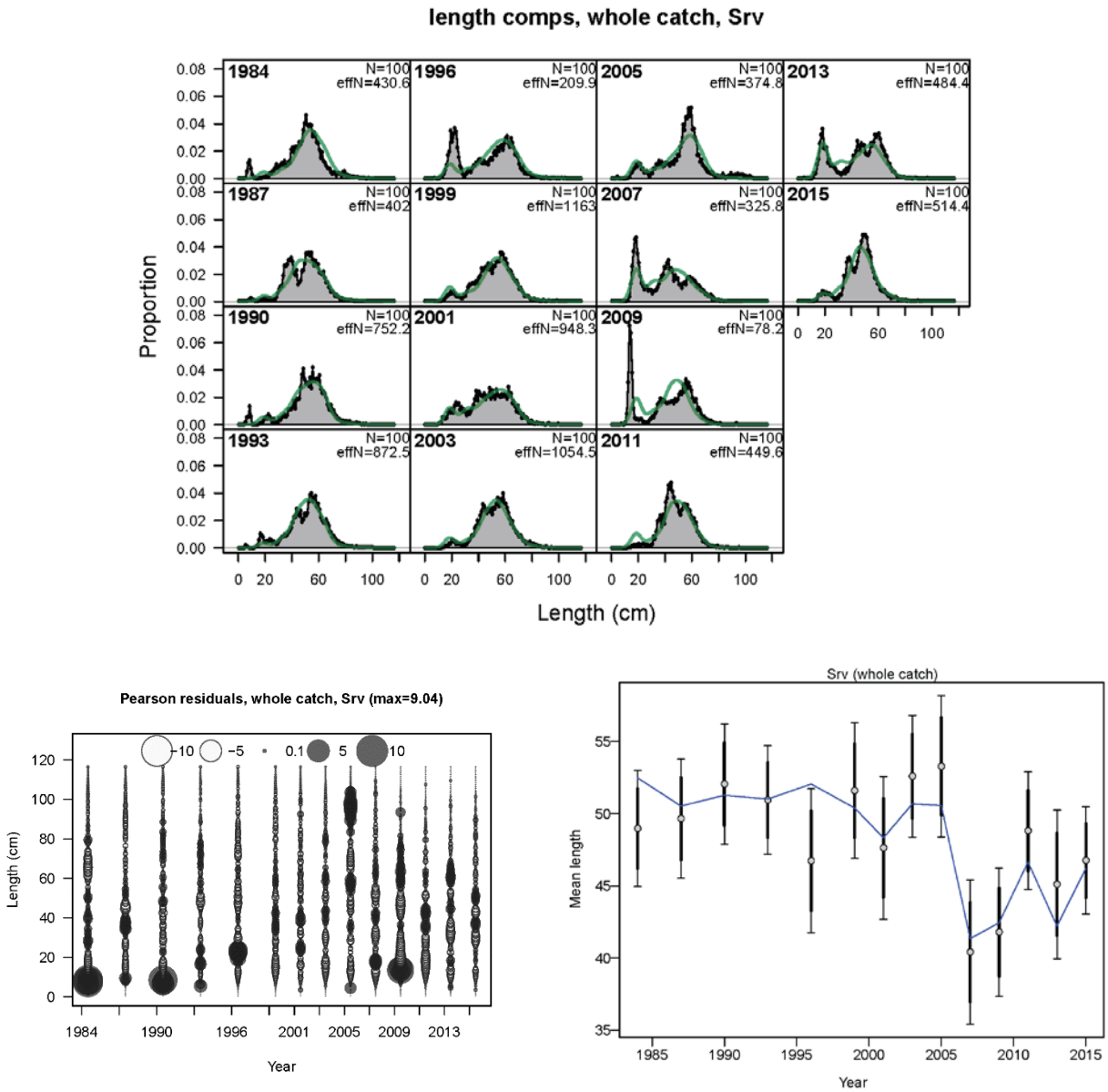


Figure 2.35 – NMFS bottom trawl survey length composition and Model 16.08.25 fit (top), Pearson residuals (left bottom), and mean length (cm; right bottom).

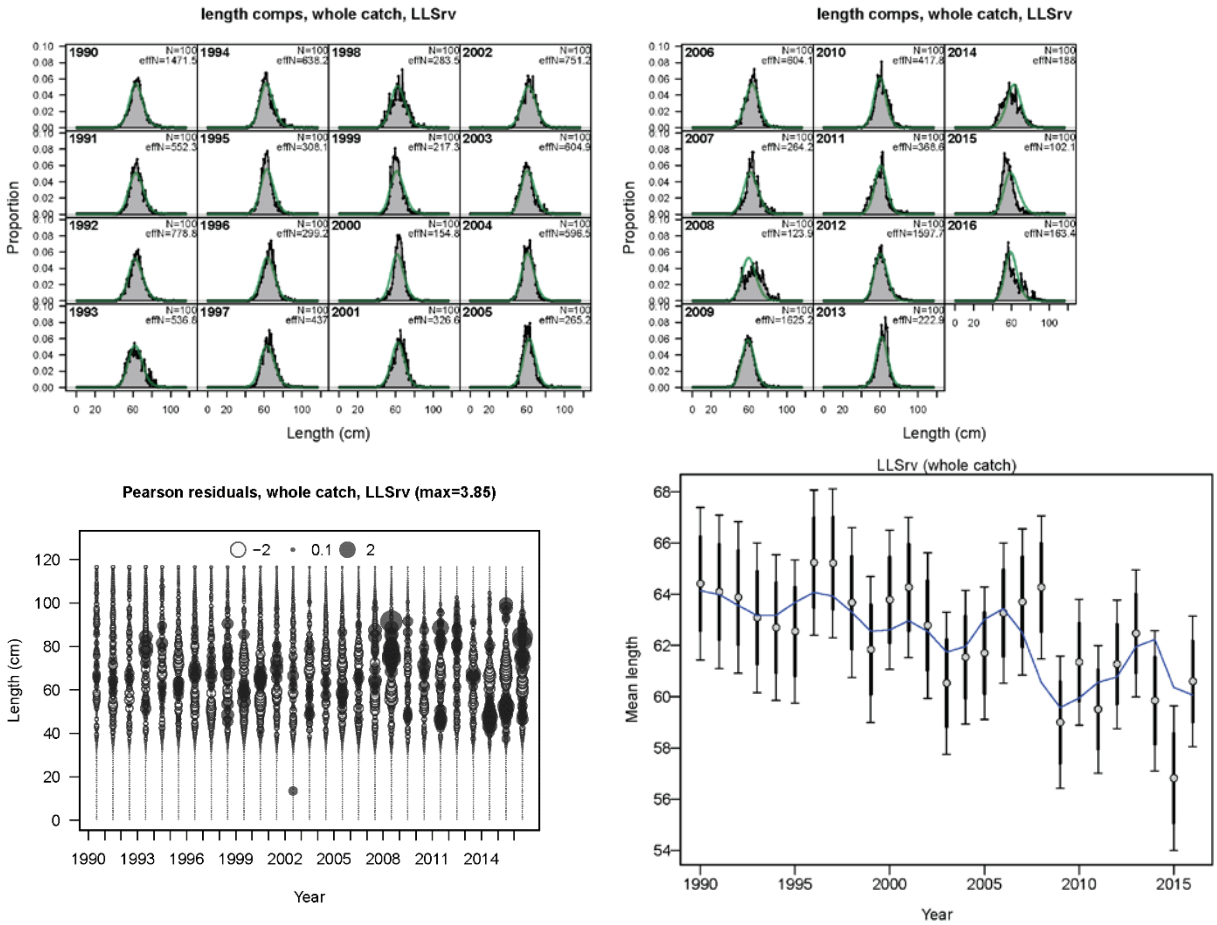


Figure 2.36 – Auke Bay longline survey length composition and Model 16.08.25 fit (top), Pearson residuals (left bottom), and mean length (cm; right bottom).

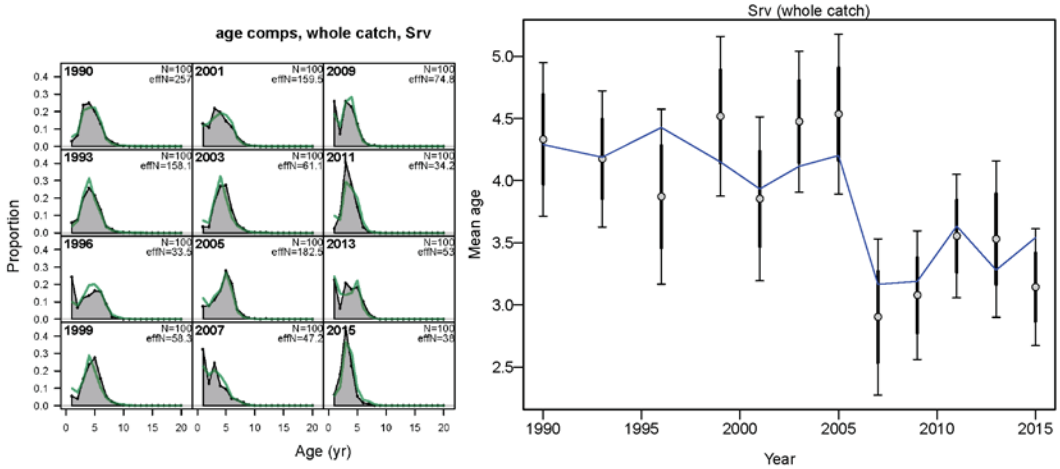


Figure 2.37 – NMFS bottom trawl survey (Srv) age composition and Model 16.08.25 fit (left) and mean age (right).

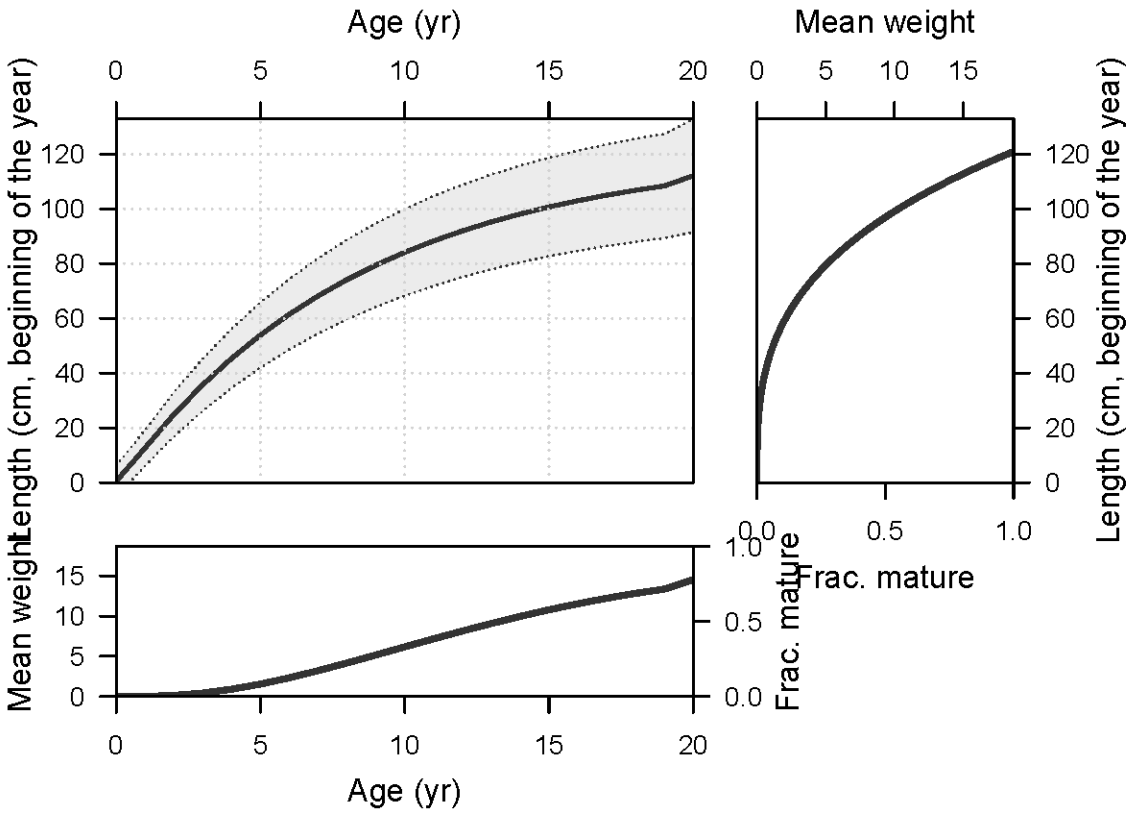


Figure 2.38 – Model 16.08.25 length at age, weight at age, weight at length, and fraction mature at length, weight, and age.

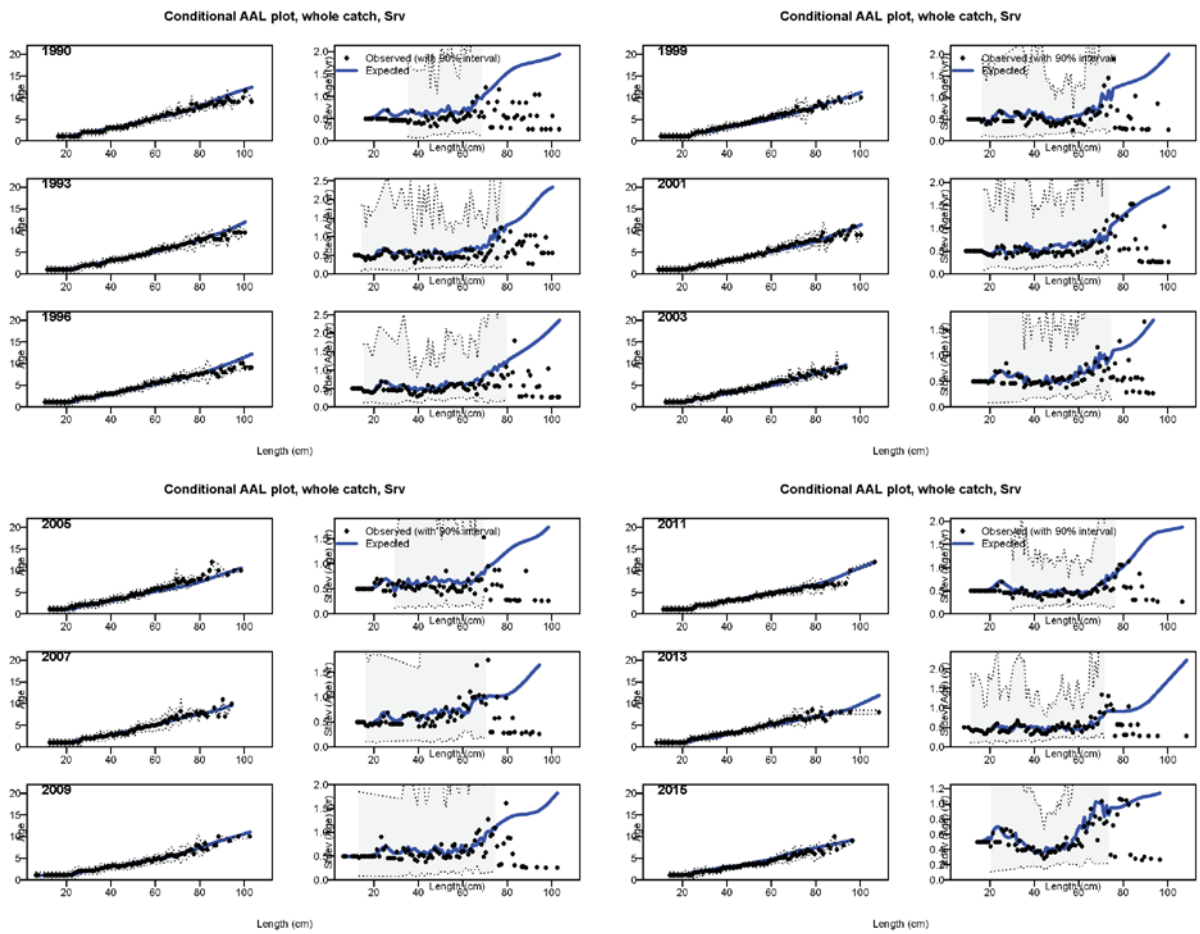


Figure 2.39 – NMFS bottom trawl survey (Srv) conditional length-at-age data and Model 16.08.25 fit.

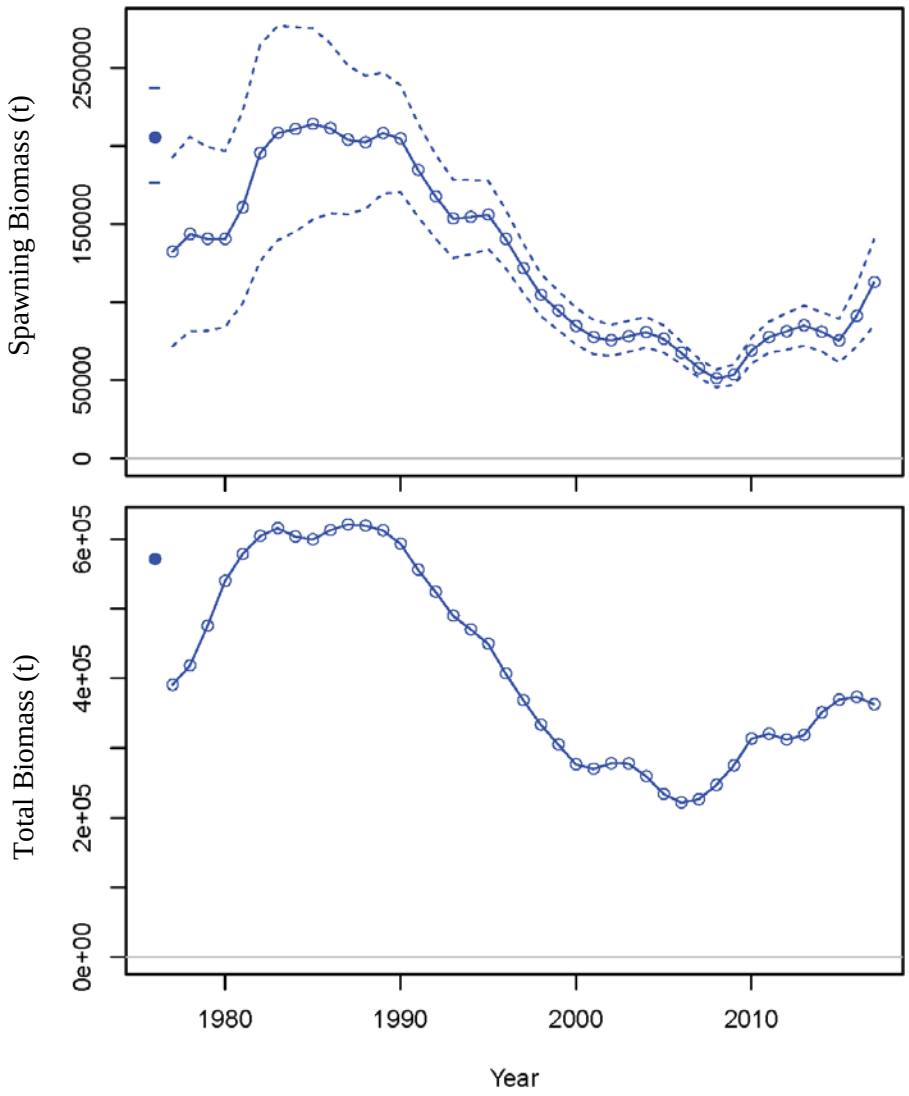


Figure 2.40 – Model 16.08.25 predicted spawning output (femal spawning biomass; t) with 95% asymtotic error intervals (top) and total biomass (t).

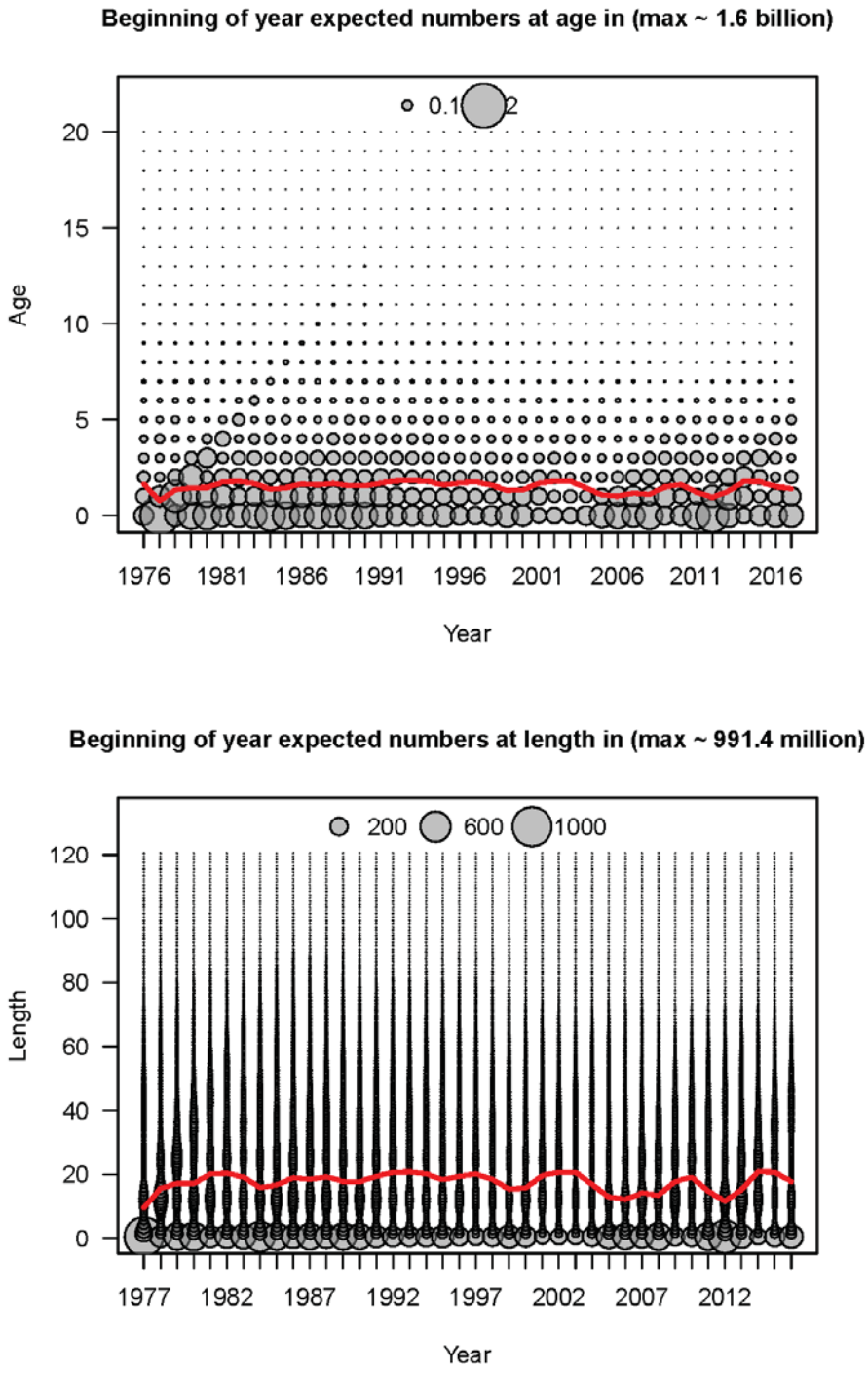


Figure 2.41 – Model 16.08.25 predictions of number at age (top) with mean age (red line) and numbers at length (cm; bottom) with mean length (red line).

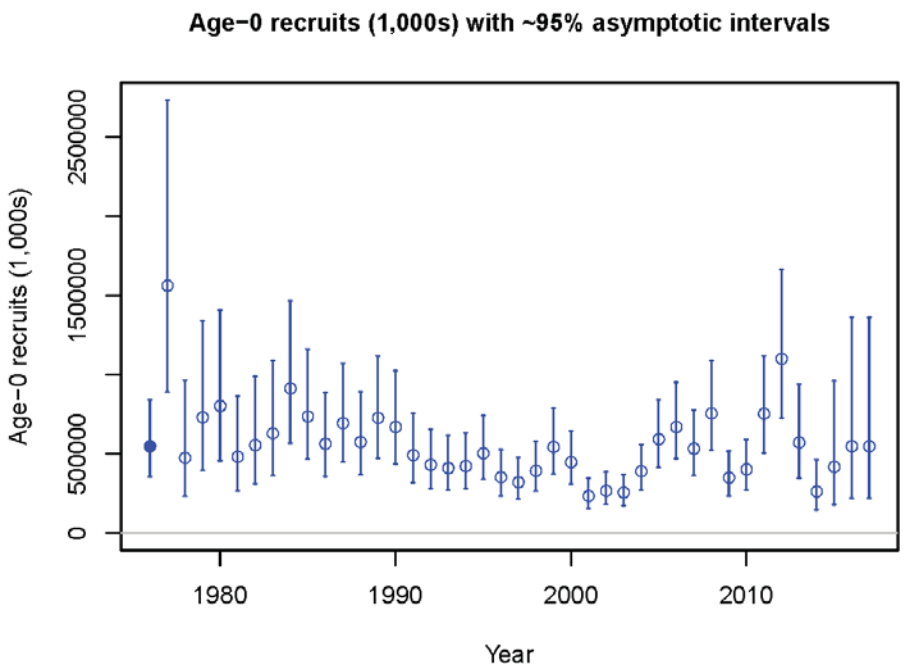


Figure 2.42 – Model 16.08.25 age-0 recruitment (1000's) with 95% asymtotic error intervals.

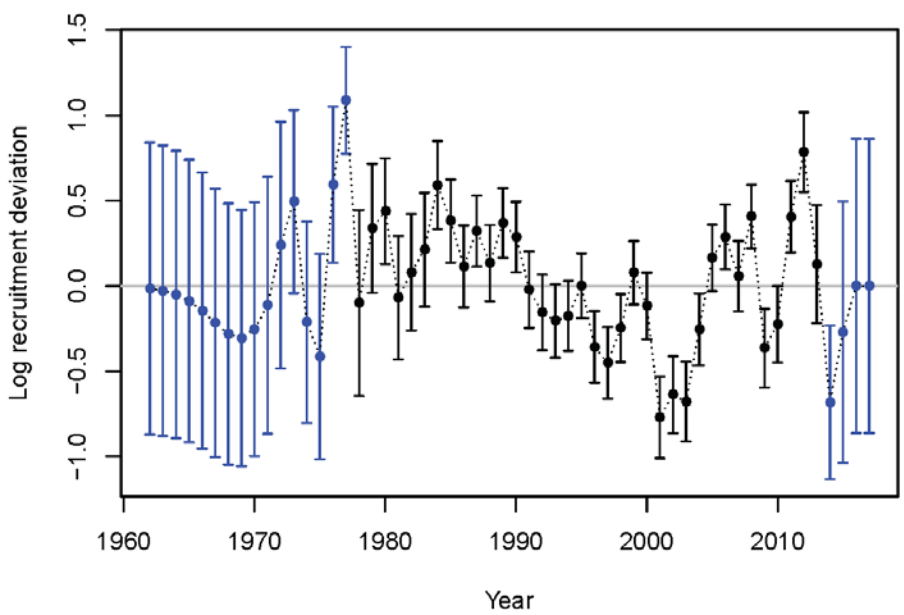


Figure 2.43 – Model 16.08.25 log recruitment deviations with 95% asymtotic error intervals.

.

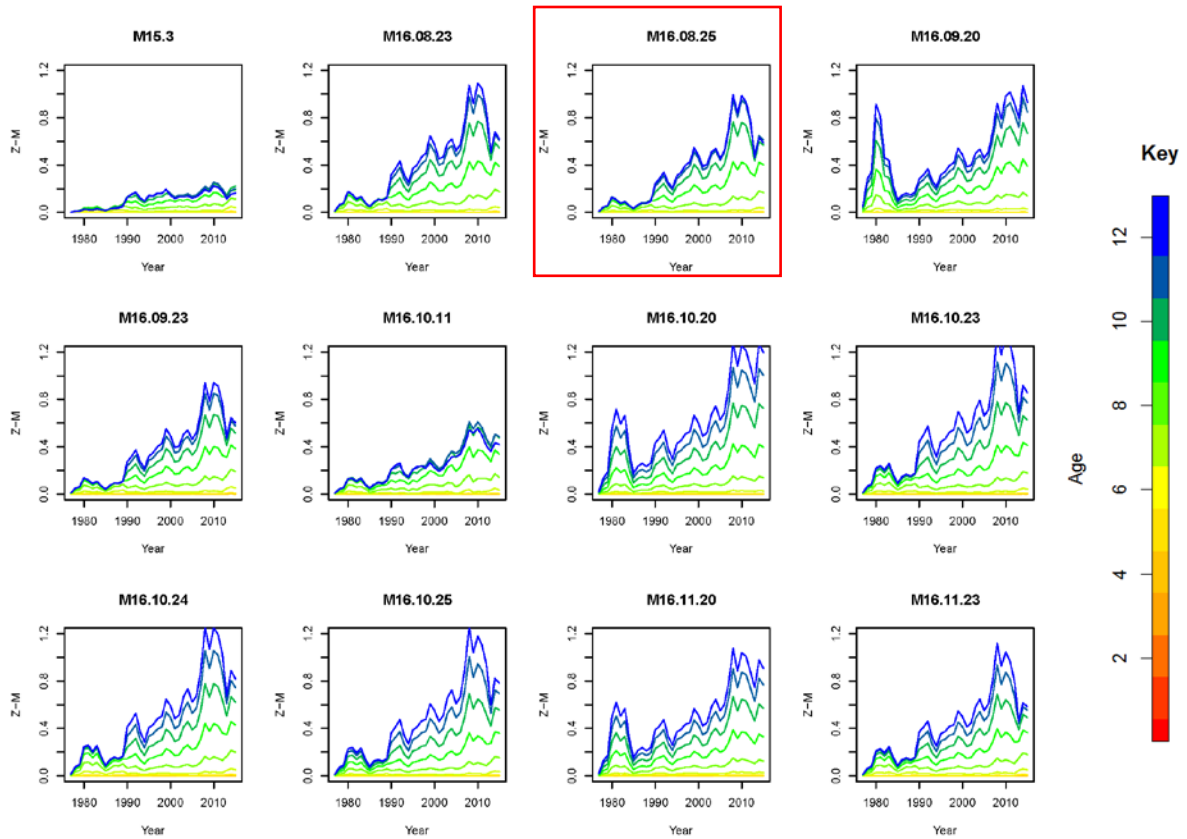


Figure 2.44 – Total fishing mortality (Z-M) by age for all models evaluated. Model16.08.25 is highlighted.

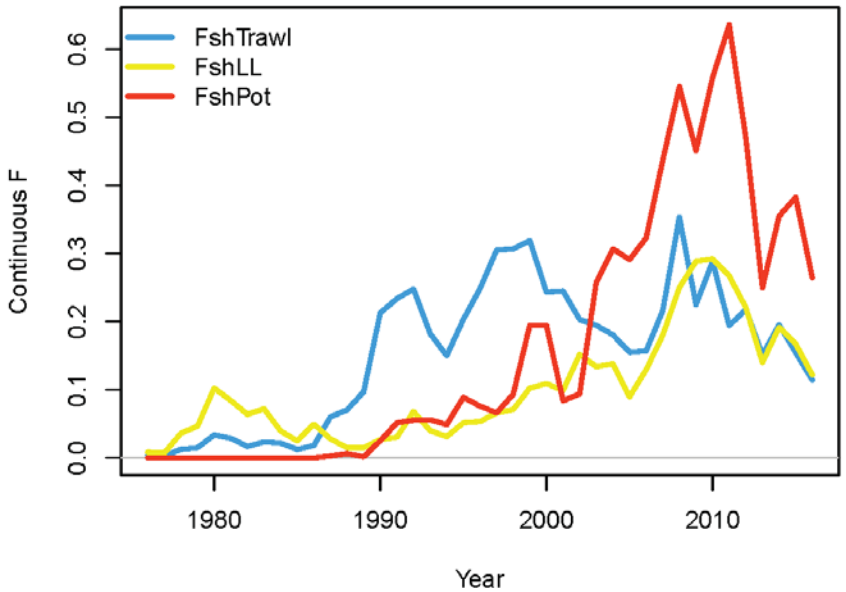


Figure 2.45 – Model 16.08.25 continuos fishing mortality by trawl (FshTrawl), longline (FshLL) and pot (FshPot) fisheries

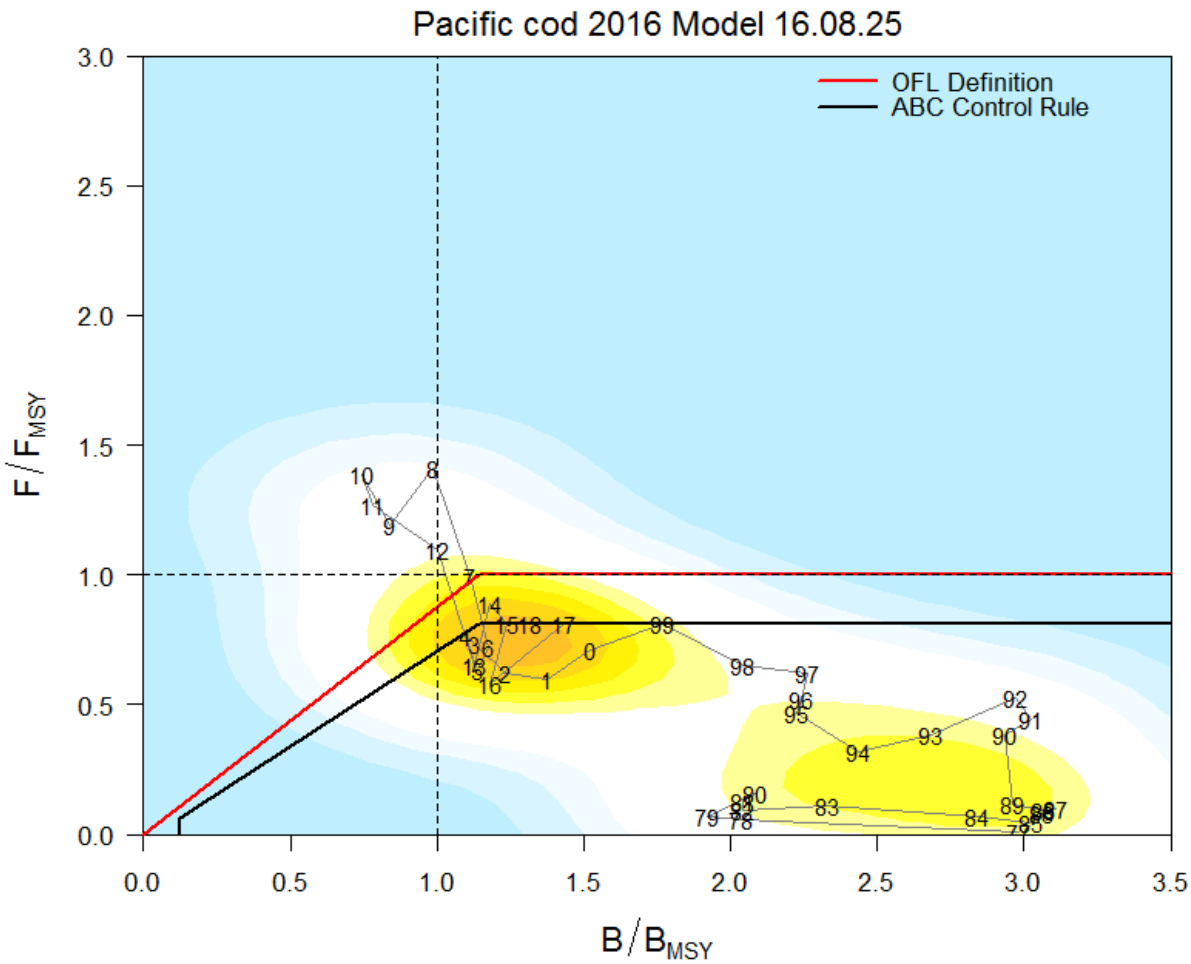
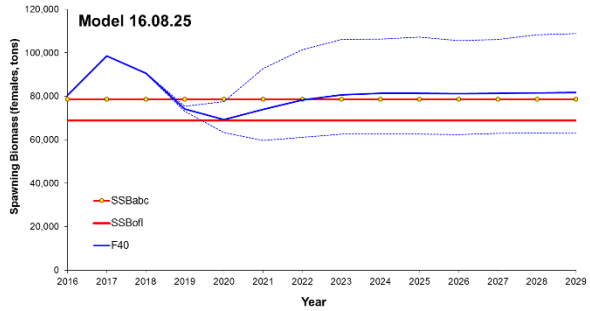
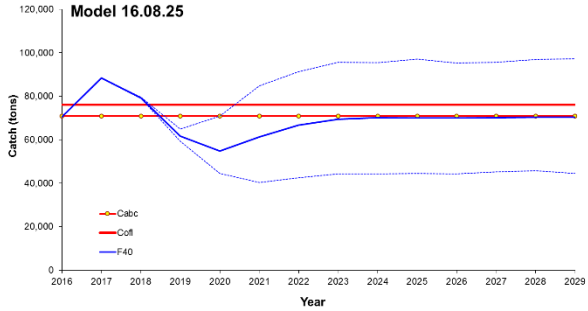


Figure 2.46 – For Model 16.08.25 ratio of historical F/F_{msy} versus female spawning biomass relative to B_{msy} for GOA pacific cod, 1977-2018. Note that the proxies for F_{msy} and B_{msy} are $F_{35\%}$ and $B_{35\%}$, respectively. The Fs presented are the sum of the full Fs across fleets.





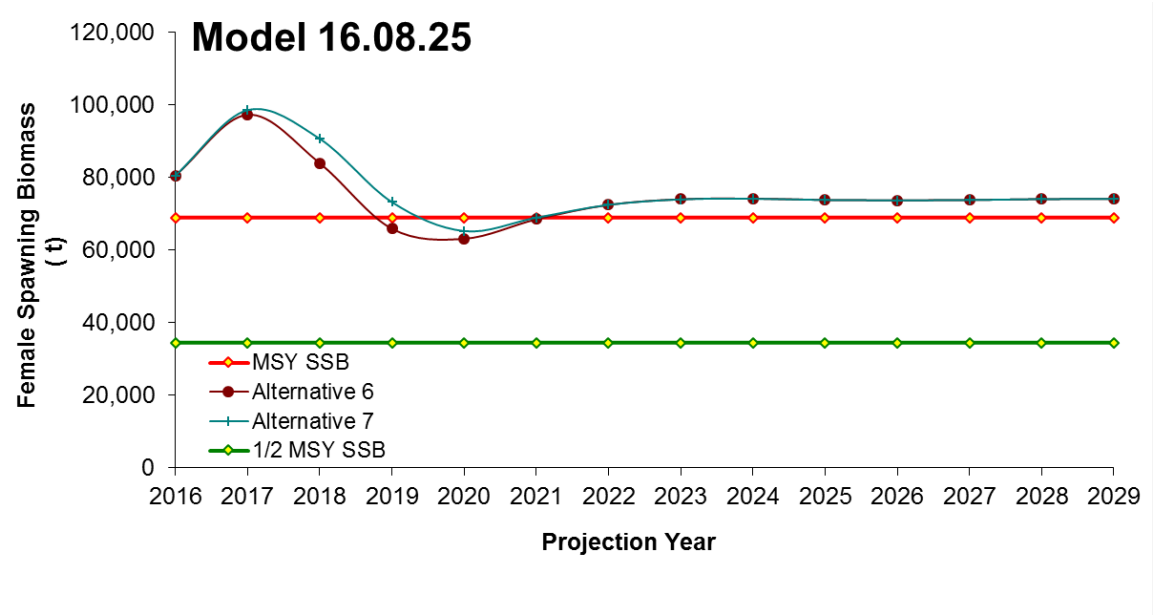


Figure 2.47 – Model 16.08.25 projections of female spawning biomass (top left), catch (top right), and female spawning biomass from scenarios 6 and 7 for status determination.

Appendix 2.1: Exploration of Gulf of Alaska Pacific cod (*Gadus macrocephalus*) stock dynamics for September Plan Team

Steven Barbeaux

Introduction

This report presents alternative assessment models for the Gulf of Alaska (GOA) Pacific cod stock. The objective of this report was to provide the Plan Team and SSC with an overview of model and methods being developed for the Gulf of Alaska Pacific cod stock. This approach involves a number of simplifications compared to the relatively complex models presented in recent years for GOA Pacific cod. A goal was to disentangle interactions among modeled components, particularly the seasonal fishery selectivities, to ease interpretation. Growth and selectivity treatments were also simplified so that alternative hypotheses could be explored. Another benefit of model simplification was detailing data compilation issues and gaining familiarity with available data. New datasets (the AFSC sablefish longline survey index for Pacific cod along with length composition data from this survey) are also introduced. In the course of this study, over 150 models were developed and examined. This document represents a subset of models deemed to be most informative for discussion and stock management going forward.

There has been wide-array of models presented over the past 16 years (see Amar and Palsson 2015 for a summary). While model fits to data have been reasonable, historical retrospectives over different assessments suggest that the recent models had quite different pre-1980 biomass estimates compared to others (Fig. A.2.1.1). The female spawning biomass for 1977-1987 from the 2014 and 2015 models was also more than double previous model results (Fig. A.2.1.1). The large 1977 year class (Fig. A.2.1.2) was estimated to be 2.7 times larger than the next largest year class (2012), despite limited data suggesting such a large deviation. This large year class estimate in the selected 2015 stock assessment model configuration (hereafter referred to as the 2015 Model) apparently occurred by limiting the range of aging bias parameters. Data suggesting a high 1977 year class was limited to a pulse of fish observed in the longline fishery length composition data in 1980 (consistent with the length of 3 year old Pacific cod). Data from the trawl fishery were sparse but failed to indicate a similar influx.

Models presented here are intended as examples to stimulate discussion and help provide guidance rather than candidate final model configurations for management recommendations.

General Approach

Stock Synthesis version 3.24U was applied. To the extent practical, among the models examined, 20 were selected to sets of hypotheses and/or model fits (Fig. A.2.1.3). Overall results are summarized in Table A.2.1.1 and Fig. A.2.1.4. The main differences between all models below and the 2015 model are:

1) Seasons were aggregated (annual data),
2) All selectivities were modeled using the double normal option in SS,
3) Fishery selectivities were constant over time,
4) Ages were restricted to 12 ages with a 12+ group instead of extending 20 years
5) Age determination bias was dropped from model estimation,
6) Lengths were binned from 0.5 cm to 116.5 cm at 1 cm increments, instead of to 109.5cm,
7) Multinomial sample size for fishery composition data was set at the number of hauls or 200 (instead of 400 from the 2015 Model), whichever was smallest,
8) Age composition and size at age data were included,
9) Conditional age at length data were excluded,
10) Age of L_0 in the von Bertalanffy model set to 0.5,
11) The initial recruitment offset (R1 option in SS) was dropped.

Alternative models considered:

1) AFSC GOA sablefish longline survey (longline survey) index of Pacific cod abundance
2) Length composition from the longline survey
3) Model tuning using the Francis method
4) M estimation
5) Dome-shaped selectivity
6) Estimating Q
7) Time-varying fishery selectivity (different than “blocks”)
8) Separate catchability and selectivity for pre-1993 bottom trawl survey data
9) Removing pre-1990 bottom trawl survey data
10) Excluding 27cm from survey data, and

The Base Model - Model 16.6

Model 16.6 is considered to be the most basic model presented in this here with subsequent model building from this initial framework (Fig. A.2.1.3). The age-based model included ages 1 to 11 and an age 12+ group for all older fish. Note that the previous assessments had ages up to 20, but the oldest cod ever aged in the Gulf of Alaska was 14, and limited to a single individual. Of the 8,362 Pacific cod aged since 1987 from the bottom trawl survey there have only been nine cod aged 12 years old or older. For this model there was assumed to be no aging error or bias in the age data.

Natural mortality (M) was assumed M = 0.38 based on equation 7 of Jensen (1996) and ages at 50% maturity reported by Stark (2007). From Stark (2007) A_{50} = 8.539/1.963 = 4.35 and therefore M=1.65/A_{50} = 0.38 following Jensen (1996). Maturity was calculated as a function of age following Stark (2007) with A_{50} at 4.3499 and slope of -1.9632. Fishing mortality was estimated through a hybrid method in which the Pope’s approximation provides initial values for an iterative adjustment of the continuous F values which then closely approximates the observed catch. These parameterizations were the same in the 2015 Model.

For this analysis weight was fit in a two parameter lognormal linear model with no priors and starting values based on a linear regression of length at age data from the 1990-2013 bottom trawl survey data. Unlike the 2015 Model there were no seasonal differences in weight at length included in the model,

however final model results (Fig. A.2.1.5) closely matched the average weight at length model used in the 2015 Model. Growth was modeled using the original three parameter von Bertalanffy growth curve as in the 2015 Model. All parameters were fit within the model with no priors and starting values based on fits to all available length at age data from the bottom trawl survey (Fig. A.2.1.5 and Fig. A.2.1.6). Age at L_0 was set at 0.5 cm. Using different ages at L_0, between 0.5 and 1.5, were also explored but showed little influence on model results. Models using a four parameter Richards formulation were explored, but made little difference within the model and were not presented here.

Recruitment was modeled as a standard Beverton-Holt recruitment curve with steepness assumed to be 1.0 assuming no relationship between stock size and recruitment, Sigma-R was assumed to be 0.44, (based on a series of sensitivity runs with an earlier model, not shown), and a uniform prior on $Ln(R_0)$ with no R_1 offset. Recruitment deviations were fit in two phases with main recruitment deviations 1977-2015 fit in phase 1 and early recruitment deviations 1965-1976 fit in phase 2. Model 16.6 results are provided in Table 1.

The AFSC summer bottom trawl survey number of fish was the single index of abundance used in this model. The survey was conducted tri-annually from 1984-1999 and biannually 1999-2015 (Fig. A.2.1.7). Catchability (Q) was assumed to be 1.0 in this model. Model 16.6 had a poor fit to the bottom trawl survey index, particularly for years with large increases in abundance as in 1984, 1996, 2009, 2011, and 2013 (Fig. A.2.1.7). The estimates for these years were well below the observed values.

Size composition data were collected for all survey years, the survey length composition data were binned from 0.5 cm to 116.5 cm at 1 cm increments. Initial models had a maximum size at 109.5 cm, but test runs showed this impacted results under differing assumptions on M, Q, and selectivity. We iteratively increased the size by 1 cm until the maximum size category no longer impacted model results. Length selectivity was fit as a single double normal curve (Fig. 8). This functional form is constructed from two underlying and rescaled normal distributions, with a horizontal line segment joining the two peaks. This form uses the following six parameters:

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

All but parameter 1 (beginning of peak region) are transformed: The widths are log-transformed and the other parameters are logit-transformed. For this model the survey selectivity was restricted to be asymptotic with the two parameters controlling the downward limb of the curve (parameters 4 descending width and 6 final selectivity) fixed to force the curve asymptotic. The remaining four parameters were fit with bounded uniform priors. The multinomial sample sizes for the survey length composition data were set at 100 for all years. This was a strong assumption on the consistency of the surveys over the years to properly measure species composition of the surveyed population, even when sample sizes changed among years. Although survey timing was variable, particularly in the 1980s, we assumed a survey date of 0.583 (July 1), the same as the fisheries. SS3 did not allow for annually varying timing for the survey.

The choice of asymptotic selectivity for the bottom trawl survey has substantial impacts on the results of the stock assessment model. It assumes (with a fixed catchability of Q = 1.0 and fixed mortality at M=0.38) that all fish above a certain size are fully available to the survey and with fixed catchability and natural mortality will produce conservative estimates of recruitment and abundance. Different assumptions are explored in models presented below.

Aged based and length based selectivities using non-parametric selectivity patterns were initially investigated for the bottom trawl survey composition data in models not presented here. In order to conduct "Jitter" and retrospective analyses the waypoints needed substantial bounding to function or created many local likelihood minima that made model fitting problematic. Results from the double-normal were more easily interpretable and functioned better during "jitter" exercises in finding a consistent "true" minima. The logistic model was also explored for asymptotic selectivities, however the restricted double normal provided better fits in all cases and allowed for easy conversion to dome-shaped when needed.

Age composition data for 1990-2013 were available and although they were included in the model likelihood (Fig. A.2.1.5), they were not fit independently from the length composition data with selectivity being modeled as a function of length. Weight and length at age data were available for 1990-2013 and inform the growth model (Fig A.2.1.10).

Fishery dependent data were aggregated into three gear types: trawl, longline, and pot (Fig. A.2.1.11). Unlike the 2015 Model, seasons were not implemented in this model. Catch estimates were available for 1977-2015 for all three fisheries and match those used in the 2015 Model in aggregate. Equilibrium catch for the trawl and longline fisheries were set at 1,000 t and 2,000 t based on historic fish records (Major 1985). The pot fishery had 0 catch until 1987 and therefore equilibrium set at 0. In comparison the 2015 Model had equilibrium catch set at 5,600 t for the January-April trawl fishery and 0 for all others. This makes little difference in model results since catch was relatively low. Standard errors in all catch estimates were assumed to be 0.05 and fishery timing was set at 0.583 (the end of June) for all fisheries.

Fishery catch length composition data were treated the same as the data used in the 2015 Model except once calculated, seasonally separated data were then collapsed into a single value per year and gear with proportions weighted by gear and seasonal catch biomass estimates (Fig. A.2.1.12, Fig. A.2.1.13, and Fig. A.2.1.14). This method assumes that observer coverage is proportional to seasonal catch. The sample size was set at the number of hauls up to a maximum of 200 for each gear type and year, no tuning of the model was performed.

Fishery length composition selectivity was fit for each gear as single double normal curves and for all but the pot fishery, restricted to be asymptotic with the two parameters controlling the downward limb of the curve (parameters 4 descending width and 6 final selectivity) fixed to force the curve asymptotic. For the pot fishery parameters 4 and 6 were fit within the model allowing for a dome-shaped selectivity. For all fisheries parameter 5, which controls the selectivity at the first length bin, was fixed at -999. This setting ignores the initial selectivity algorithm and simply decays the small fish selectivity according to parameter 3 (Fig A.2.1.8).

Length composition predictions fit the overall shape of the distribution across all years, however annual variability in the distributions and lack of flexibility in the chosen selectivity curves show some trends in the residuals. In general mean predicted lengths were reproduced (Fig. A.2.1.15), however the predicted length distributions were broader and missed the highest peaks of the distributions (Fig A.2.1.16) as shown in the Pearson's residual plots (Fig. A.2.1.16). In addition the model does not fit the bottom trawl survey data well in years where a large number of small fish were observed such as 2009. The large number of small fish causes survey availability to fit above zero ($S_{0.5cm}*Q = 0.118$) for the smallest fish (Fig. A.2.1.8).

Addition of Sablefish longline data - Model16.6.0

Model 16.6.0 had the same configuration as Model 16.6 except Gulf of Alaska AFSC Sablefish longline survey data were added (Fig. A.2.1.18). These data included the Relative Population numbers (RPN) of Pacific cod as an index of abundance and Pacific cod length composition data for 1990 through 2015 (Fig A.2.1.18). These data were provided by Dr. Dana Hanselman of the Auke Bay Laboratory and a

description of the methods for the AFSC sablefish longline survey and how the datasets were developed can be found in Hanselman et al. (2015) and Echave et al. (2013).

This index mirrors the trend observed in the bottom trawl survey for 1990 through 2015 with a decline in abundance from 1990 through 2008 and a sharp increase in 2009. Unlike the bottom trawl survey, the longline survey encounters few small fish (Fig. A.2.1.19 and Fig. A.2.1.20). The data reveal consistent and steep unimodal distributions with a decreasing trend in mean size since the mid-1990s, matching the trend observed in all three fisheries, but not in the bottom trawl survey (Fig. A.2.1.21 and Fig. A.2.1.16). Catchability (Q) for this index was set as a floating estimate with no bias adjustment. The multinomial sample sizes for the length composition data were set at 100 for all years.

Selectivity for the longline survey length composition data was modeled using a single double normal selectivity curve with parameters 4 and 6 (see above) fixed such that selectivity was constrained to be asymptotic (Fig. A.2.1.22). It was the opinion of the survey managers that the survey was well distributed throughout the Gulf of Alaska sampling across depths from 50 m to 1000 m and was therefore thought to be a thorough survey of adult Pacific cod in the region. Parameter 5 was set to -999 which ignores the initial selectivity algorithm and simply decays the small fish selectivity to near 0 as per parameter 3.

Model 16.6.0 predictions of the longline survey index follows the 1990-2008 decline in abundance and although it does increase in 2009, the model fails to match the sharp increase in the data for 2009-2011 (Fig. A.2.1.18). Fits to the length composition data consistently underestimate the high peak of the mode and overestimates the abundance of fish larger than 75 cm (Fig. A.2.1.23 and Fig. A.2.1.24). For the other data components model fits were similar to that of Model 16.6 (Fig. A.2.1.21 and Table A.2.1.1). There was some degradation of the fit to the bottom trawl survey index, but the fit to the bottom trawl survey length and age data was improved (Table A.2.1.2). Further the addition of the longline survey data improved the fit to the trawl length composition data, but degraded the fit to the pot and longline length composition data.

Ten-year retrospective analyses (Hanselman et al. 2013) show a marked improvement in the Mohn's rho and RMSE when the longline survey data were added with little impact on the Wood's Hole rho (Table A.2.1.3 and Fig. A.2.1.25), suggesting an improvement in stability in the most recent estimates with little effect on predictions of earlier data. The effects of the large and uncertain recent year classes were still apparent with large deviations from the most terminal estimate in the first 6 years of the retrospective.

Length and age composition sample size explorations - Model 16.6.1.2

We implemented the Francis method (reference) for tuning the model and explore the model sensitivity to the length composition sample size as implemented in the R4SS package (Hicks et al. 2016). Model 16.6.1.2 was a Francis method tuned Model 16.6.0. The model was tuned over three iterations, until the Francis weights diagnostics neared 1.0 for the length and age composition data.

The Francis method resulted in adjustment factors between 0.07 and 0.74 (Table A.2.1.4) and impacted the model with lower weighting of the length and age composition data. Fits to both survey indices were improved (Fig. A.2.1.26 and Fig. A.2.1.27) with a decrease in the RMSE of bottom trawl survey by 14% and longline survey by 8% (Table A.2.1.4). Fits to the trawl and longline fishery length composition were degraded (Fig. A.2.1.28) with 30% and 27% decreases in harmonic mean effective Ns. The bottom trawl survey length and age composition had a 21% and 25% decrease in the harmonic mean effective Ns. Fit to the pot fishery length composition data did not change as much as the other fisheries, with an 8% decrease in the effective sample size. The harmonic mean effective N for the longline survey length composition increased by 16% indicating an overall improvement to the longline survey data.

The largest impact to the model was the reduction in the magnitude of the 1973 and 1977 year classes (Fig A.2.1.25). This was a direct result of down-weighting the longline fishery composition data where fish of sizes consistent with these year classes were most strongly observed. The bottom trawl survey

index did not see an increase in abundance consistent with such large year classes and therefore the re-weighting of the model components settled on lower recruitments for these years. The 2011 and 2012 year classes were similarly diminished as they had most strongly been observed in the trawl and longline fishery and bottom trawl survey length composition data, but less strong in the pot fishery and longline survey length composition data. The change in the model estimates of early cod abundance was counter to the prevailing view that there was a large increase in cod starting in the 1980's. This is likely the result of reduced weight of the early fishery length composition data weighting causing the model to over fit the early trawl survey index data, which shows a stable to declining trend for this time period. It should be noted that the bottom trawl survey index data prior to 1990 are considered problematic because methods differed from the methods employed since 1990. This issue will be addressed below.

Exploring catchability, natural mortality, and dome-shaped selectivity

Five models were developed that have different assumptions on catchability, natural mortality, and selectivity. In the models presented above we assumed asymptotic selectivity for all survey selectivities, M = 0.38, and bottom trawl survey Q = 1.00. This is a compromise which provides conservative model results in comparison with if these were allowed to be fit freely in the model without strong constraints. For the models presented in this section we build on Model 16.6.1.2 using the same tuned settings so that model likelihoods and fits could be readily compared.

Model	**Model parameterization**
16.6.2.1 Q	Fit bottom trawl survey Catchability (Q) with an uniform prior
16.6.2.2 M	Fit natural mortality with a normal prior mean = 0.38,stedev =0.1
16.6.2.3 S	Allow dome-shaped selectivity
16.6.2.4 QM	Fit bottom trawl survey catchability with a uniform prior and natural mortality with a lognormal prior M=0.38, CV=0.1
16.6.2.5 QMS	Fit catchability, natural mortality as above, and allow dome-shaped selectivity

In Model 16.6.2.1Q the bottom trawl survey catchability (Q) was fit in the model with an uninformative prior. Catchability above 1.0 assumes an abundance (conditioned on selectivity) lower than survey estimates resulting in lower recruitment and higher estimated fishing mortality. Allowing Q to be fit in the model improved fits to all of the bottom trawl survey data components and the longline survey size composition, but degraded the fit to all other components (Table A.2.1.5). The overall likelihood improved by -79.28 with the inclusion of this single parameter, however log catchability was estimated at 1.047 (Q=2.85; Fig. A.2.1.30) reducing the biomass on average 24% from Model 16.6.1 and 9% lower on average than the raw survey estimate (without considering selectivity). The better fits to the bottom trawl survey index and length composition data were achieved by reducing overall biomass and increasing estimated fishing mortality (Fig. A.2.1.30). The effect of allowing Q to increase was not only a reduction in overall abundance across all ages, but also a reduced proportion of fish at older ages (Fig. A.2.1.31).

In Model 16.6.2.2M natural mortality (M) was fit in the model with an informative normal prior having a mean of 0.38 and standard deviation of 0.1. This model fits M at 0.81 (Fig. A.2.1.30), well above most reasonable estimates of M in the literature for this species (Table 6; A'mar and Palsson 2015). All data components, except the pot fishery length composition data were fit better than in Model 16.6.1.2 for an overall improvement on the objective function of -108.59. The majority of this improvement was in a

better fit to the length and age composition data from the two surveys. Both the longline and survey index fits were also improved (Table A.2.1.5). This assumes higher R_0 and B_0 (Fig. A.2.1.32) allowing higher recruitment and higher overall abundance in the model estimates. This model assumes a much higher proportion of young fish in the population (Fig. A.2.1.31) in aggregate across years, the sum of the apical F was slightly lower that Model 16.6.1.

In Model 16.6.2.3S we allow all selectivities, except for the longline fishery to be dome-shaped fitting parameters 4 and 6 in the double normal selectivity curves with uninformative priors (Fig. A.2.1.33). The longline fishery remained asymptotic to provide stability to the model. Reviewing the distribution of the longline fishery (Fig. A.2.1.34 and Fig. A.2.1.35) shows it has the widest spatial extent and is deeper on average than either trawl or pot where larger cod should be encountered. The raw length frequency data (Fig. A.2.1.20) shows a larger proportion of fish > 80 cm in the longline fishery. The addition of the 6 selectivity parameters improved the fit to the model by -127.1. Allowing for dome-shaped selectivity showed a greater improvement to both surveys than either fitting M or Q. Improvement was also attained in the fits to the composition data for all but the pot and longline fishery length composition data. The dome-shaped selectivity in the longline survey removed the pattern of higher positive residuals in the larger fish (Fig. A.2.1.33). Allowing for dome-shaped selectivity in the surveys and fisheries allows a higher biomass at the fixed natural mortality by assuming a larger portion of the population are not observed. This model places greater than 5% of the pacific cod population biomass in the 12+ age group and assumes there is a cryptic elder component of the stock resulting in a much higher historic biomass estimates and much lower fishing mortality estimates than Model 16.6.1. The sum of the Apical Fs in this model closely follow those produced in the 2015 Model (Fig A.2.1.31). Estimates of both R_0 and B_0 were also similar (Fig. A.2.1.35). Although initial abundance estimates are much lower (Fig. A.2.1.32), the proportion of biomass by age in aggregate across all years considered also closely matches the 2015 Model (Fig. A.2.1.31). This model produces the highest historical biomass estimates of all models evaluated.

Model 16.6.2.3QM fits both catchability and natural mortality within the model. Catchability was parameterized with a uniform prior and natural mortality as a normal prior with a mean of 0.38 and standard deviation of 0.1. The model fit M at 0.69 (Fig. A.2.1.35), substantially higher than independent estimates of M for pacific cod. Log catchability was estimated at 0.634 (Q=1.89). The improvement in fit from Model 16.6.2.2 M with the addition of 1 parameter (Q) was less than 0.4 overall (Table A.2.1.1 and Table A.2.1.5), yet the model results were substantially different. The model fit the bottom trawl survey index better (-5.26 to -3.35) than Model 16.6.2.2M, as expected, however it fit worse to the longline survey index data (-4.71 to -2.76). In addition improvements to the longline survey, trawl, and pot fishery length composition and bottom trawl age composition fits were counteracted by worse fits to the trawl survey and longline length composition data. Although the positive residuals on older fish in the longline survey persisted in this model, they were less pronounced than in models in which M was not fit (Fig. 33). As one would expect, the model predictions were intermediate of Models 16.6.2.1Q and 16.6.2.3M (Fig. A.2.1.31 and Fig. A.2.1.32) as the model was balancing the effects of Q and M to achieve the best fit (Fig. 30)

Model 16.6.2.3QMS fits both catchability and natural mortality within the model and allows selectivity for the trawl and pot fisheries and bottom trawl and longline surveys to be dome-shaped. As in the previous model, catchability was parameterized with a uniform prior and natural mortality as a normal prior with a mean of 0.38 and standard deviation of 0.1. In this model, the same as Model 16.6.2.3S, the six parameters controlling the downward arm of the double normal for the trawl fishery and bottom trawl and longline surveys were fit allowing the shapes to become dome-shaped (Fig. A.2.1.33). This model produced the best fit of all the models evaluated. The addition of the 6 parameters improved the model by -41 likelihood points above Model 16.6.2.4QM (Table A.2.1.1). The model fit M at 0.5 (Fig A.2.1.30). A natural mortality of 0.5 was higher than that produced by the Jenson (1996) method (M=0.38), but the same as estimated by Thompson and Zenger (1995), and lower than 5 of the 12 estimates retrieved from

the literature (Table A.2.1.6). Log of catchability was estimated at 0.49 (Q=1.64; Fig. A.2.1.30). Selectivity at larger sizes (>70 cm) was higher in this model than in Model 16.6.2.3S showing the influence of both M and Q on model fitting. All data components, except Longline survey length composition and bottom trawl survey index, were fit better than any other 16.6.2 models. The fit to the longline survey length composition was surpassed by Model 16.6.2.3S and the fit to the bottom trawl survey was only surpassed by the two other models that fit catchability (Models16.6.2.1Q and 16.6.2.4QM). Although Q was greater than 1.0 due to selectivity estimates the total biomass was on average 182% higher than raw bottom trawl survey estimates across all surveyed years (Fig. 36) and 151% higher than estimates from Model 16.6.1 with Q=1.0. Unlike Models 16.6.2.3S and the 2015 Model which had a significant proportion (~6%) of population biomass in the 12+ age group, the higher M in Model 16.6.2.5QMS had on average less than 2% of the population biomass in the 12+ age group. Virgin female spawning biomass (B_0) was estimated at near 200 kt, below the 300 kt estimate from the 2015 Model, but above the 184 kt from Model 16.6.1. R_0 was estimated at the third highest value after the two other models (16.6.2.2M and 16.6.2.4QM) that estimated higher natural mortality.

Model 16.6.3

Model 16.6.3 follows the same configuration as Model 16.6.1.2 using the same Francis method adjustment factors, but differs in having annually varying selectivity parameters for the trawl and longline fisheries and time blocks for the bottom trawl survey (Fig. A.2.1.37). The Francis method adjustment factors were retained from Model 16.6.1 so that model likelihoods could be readily compared. For trawl and longline fisheries parameters 1, 2, and 3 were allowed to vary annually using multiplicative deviations between 1977 and 2015 and 1978 and 2015 with a standard deviation of 0.2. Parameters 1, 2, and 3 of the bottom trawl survey length composition selectivity were allowed to differ between time blocks 1977-1993 and 1994-2015. Survey selectivity was allowed to change after 1993 when the survey changed from 30 minute to 15 minute tow durations. Although models with annually varying pot fishery selectivity parameters were evaluated they showed no appreciable improvement in fit and therefore not presented here.

The addition of time varying selectivity added 234 “parameters” to the model, but only decreased the objective function by -58.57 points. However, 231 of these parameters were penalized random deviations on the main selectivity parameters for the fishery selectivities and should not be considered true parameters for comparisons of log likelihoods and AIC analyses of model fit. As would be expected the longline and trawl fishery length composition fits improved as well as the fit to the bottom trawl survey age composition and longline survey length composition. Fits to both survey indices and all other length composition data were slightly degraded (Table A.2.1.7).

The predicted results from Model 16.6.3 were similar between Model 16.6.1 and Model 16.6.3 (Fig. A.2.1.37), particularly for the more recent portion of the time series. The main difference in predictions were in higher initial (1977-1985) spawning biomass levels (Fig. A.2.1.38) and fishing mortality in the Mid-1990s (Fig. A.2.1.39 and Fig. A.2.1.40). Neither R_0 nor virgin spawning biomass for Model 16.3.1 and Model 16.6.2 were substantially different at R_0 = 0.22 log (billions) and 0.23 log (billions) and B_0 = 184.63 kt and 197.8 Kt. Similar results would likely be achieved by fixing selectivity in both the longline and trawl fisheries after 1990 when the domestic fisheries started while greatly reducing the number of parameters in the model, similarly there was little difference in the bottom trawl survey selectivity for the two time blocks and these could be discarded with little to no impact on model results.

The retrospective analysis of female spawning biomass resulted in a slight increase in the Mohn’s rho from 0.07 for Model 16.6.1 to 0.08 in Model 16.6.3, Woods Hole rho from 0.001 to -0.003, and similarly negligible improvement in retrospective RMSE from 0.041 to 0.040. The divergence from the final results back to 2008 were still apparent and due to the exceptionally large recruitments observed in this time period.

Alternatives for the pre-1993 bottom trawl survey data - Model 16.6.4.1 and Model 16.6.4.2
Differences in survey methods support treating earlier surveys differently than later surveys. The 1984 and 1987 bottom trawl surveys were conducted by Japanese researchers using different trawl gear than used in later surveys. Prior to 1996 survey haul duration was 30 minutes, while the 1996 and later surveys had a 15 minute duration. The 2015 Gulf of Alaska walleye pollock stock assessment (Dorn et al. 2015) excludes the pre-1990 trawl survey data from the stock assessment model. Model 16.6.4.1 mirrors this approach with the 1984 and 1987 trawl survey data not included in the model and the block selectivity for the bottom trawl survey was also removed.

In the 2015 Model trawl survey catchability was set at 1.0 for the 1996-2015 surveys and a linear adjustment was fit with a uniform prior for earlier surveys. In addition separate catchability curves for the length composition data were fit in time blocks: 1977-1989, 1990-1995, 1996-2006, and 2007-2015. Model 16.6.4.2 mirrors this approach with adding a single parameter linear adjustment to catchability for pre-1996 surveys with a uniform prior and two blocks for survey selectivity: 1977-1995 and 1996-2006. For this model catchability for 1977-1993 was fit at 1.75, higher than 1.25 fit in the 2015 Model.

For the likelihoods of the non-bottom trawl components, the two models end up being less than 1 point different from each other and six likelihood points different from Model 16.6.3. Fits to the survey data between model 16.6.4.2 and 16.6.3 differed by -8 likelihood points. Across all data components Model 16.6.4.2 differed from Model 16.6.3 by -12 points for 1 additional parameters. Taking out or fitting the early trawl survey data reduced the fit to the longline survey index between -1 and -1.5 points. The fits in effect did not change between the two alternative configurations, and showed a minor improvement to Model 16.6.3.

Model 16.6.4.1 with the bottom trawl survey data removed demonstrated a difference in early recruitment from Model 16.6.3 and 16.6.4.2. Model 16.6.3 and Model 16.6.4.2 had well above average 1980 year class and stronger 1981-1983 year classes than Model 16.6.4.1 (Fig. A.2.1.41). In addition predictions for R_0 and B_0 were higher in Model 16.6.3 while in Model 16.6.4.1 and Model 16.6.4.2 there was little difference between these values (Fig. A.2.1.41). Higher recruitment in Models 16.6.4.2 resulted in higher abundance and biomass in the mid-1980s in the models retaining the early survey data. In effect there were only minor differences in the results from these two alternative models.

Model 16.6.11S Model 16.6.15QM, Model 16.6.20, and Model 16.6.22QMS
These set of models were conducted to evaluate how the removal of the 1984 and 1987 survey data have on the fitting parameters in Models 16.6.1, 16.6.2.3S, 16.6.2.4QM, and 16.6.2.5QMS. Model 16.6.20 was parameterized the same as Model 16.6.1 and Model 16.6.22 was parameterized the same as Model 16.6.2.5QMS without the 1984 and 1987 bottom trawl survey data. Model 16.6.11S was parameterized the same as model 16.6.2.3S and Model 16.6.15 was parameterized the same as Model 16.6.2.4QM, except with annually varying selectivity as parameterized in Model 16.6.3 and without the 1984 and 1987 bottom trawl survey data.

Differences in parameter fits are shown in Figure A.2.1.42. For the models where M and Q were not fit the impact of removing these data were consistent. For all but one modeling pair the differences between parameters were minor. In each pair the results were similar in that recruitment in the early 1980s was reduced when the 1984 and 1987 trawl data were removed (Fig. A.2.1.43) resulting in lower abundance in the mid-1980s. There was also a consistent decrease in B_0 between the models with and without the 1984 and 1987 trawl survey data. The largest changes were observed in the parameters between Model 16.6.2.4QM and Model 16.6.15QM (Q and M fit and asymptotic selectivity) with shifts in both natural mortality and catchability. This in turn resulted in a substantial increase in R0, a decrease in initial Fishing mortalities for the longline and trawl fisheries, and decline in the B0. In addition overall recruitment and abundance was reduced throughout the time series in response to these changes. Where selectivity was allowed to become dome-shaped but Q and M were fit (Models 16.6.2.5QMS and Model

16.6.22QMS) no similar changes in Q and M were encountered and the only change of substance between these modeled pair was the CV of young fish parameter. Retrospectives for all models with Q or M fit were abysmal (Table A.2.1.3).

Removing age 1 (<27cm) fish from bottom trawl survey – Series 16.7
The bottom trawl survey data on occasion encountered extremely high numbers of age 1 fish, the magnitude of which is not always observed in following years. In previous stock assessments the approach to dealing with these problem fish was to remove them from the data. This series of models looks at the effects of removing these fish from some of the models explored above.

In every case the removal of the small fish caused the fit to the trawl survey selectivity curve to go to 0 for the young fish where it had previously been above 0 even for the smallest fish (Fig. A.2.1.44). The fit all the other length composition data remained nearly the same and the fit to the > 27cm survey length composition data remained rather poor. Although a numerical comparison of fit was not done between the two sets of models for the bottom trawl survey abundance index, a visual inspection of the fits (Fig. A.2.1.45) appears to show a more reasonable fit was achieved to this index when the age 1 fish were removed. In every example for the growth parameters L0.5 was increased, Linf was decreased, K increased, CV of young fish decreased, and CV of old fish increased (Table A.2.1.1 and Fig. A.2.1.46). In every case R0 decreased and B0 increased (Fig. A.2.1.47) while initial Fs decreased with the removal of the Age 1 fish from the bottom trawl survey data. In all cased recruitment and abundance increased with slight decreases in F in response (Fig. A.2.1.47 and Fig. A.2.1.48).

The retrospective analyses for these models shows an increase in all of the metrics, a visual inspection of the predictions show a more consistent positive bias in the models without the small fish for the end years (Fig. A.2.1.49). Model 16.7 was particularly poor with a Mohn's rho at 0.49.

Summary and conclusions

The decreasing trend in mean size of Pacific cod in the catch since the 1990s is a concern for this stock as it has been observed in every fishery. While possible, a simple trend in selectivity across all of the fleets seems unlikely. A look at length at age over time (Fig. A.2.1.50) shows that growth has apparently been stable. Consequently, it seems that the trend may reflect a reduction in the number of older fish in the stock. The models examined to date suggest fishing mortality has increased and abundance declined over this period. The longline survey size composition data suggest increased recruitment in the near term. However, these signs have yet to appear in the fisheries data and the apparently strong 2012 year class remains highly uncertain.

Our results show that sampling effort matters. Fits to the historical data are affected by changing the sample size of the length composition data. The Francis method likely undervalues the fishery length composition data and relies too heavily on the bottom trawl survey abundance index when we know that there are issues with the reliability of this dataset in the early years.

Second, a choice needs to be made on how to treat selectivity, dome-shaped assumes a portion of the older fish are cryptic and never observed, however using asymptotic selectivity without fitting Q and M likely results in an underestimate of abundance as the model reduces recruitment to fit the lack of older /larger fish in the data. Fitting either Q or M by itself results in estimates that appear outside the bounds of what is reasonable, this also greatly inflates the abundance of cod, in addition retrospective patterns become very poor/biased as the influx of new recruits in recent years reduces the estimates of each. Although not presented models fitting Q and M where the young fish are removed results in more stable retrospectives, although still rather poor. Inflated Q assumes lower abundance, inflated M shifts the population to younger fish and inflates the abundance. The worst retrospective bias was observed where M and Q were fit and selectivities were allowed dome-shaped curves. Again the model was sensitive to the influx of new recruits in recent times.

Future work will evaluate more fully models with aging error and conditional age at length data. Preliminary indications suggest that these model additions have much effect on model outcomes. Some models not presented here were fit with aging bias free in the model and tended result in quite a substantial negative bias in the older fish at -2 to -4 years. Such results were not substantiated by the age and growth lab, so this was left out of all models presented. The 2015 model had had this parameter (older age bias) constrained to positive values.

Expanding on Models 16.6.11, 16.6.20, 16.6.22, and Model 16.7.3 and examining conditional age at length data seems to hold the most promise for this year's SAFE report. Model 16.3.20, with time varying selectivity restricted to the older fishery data, may also be worth considering.

References

A'mar, T., and W. Palsson. 2015. Assessment of the Pacific cod stock in the Gulf of Alaska. In Plan Team for Groundfish Fisheries of the Gulf of Alaska (compiler), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 173- 296. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501

Bakkala, R. G., and V. G. Wespestad. 1985. Pacific cod. In R. G. Bakkala and L. L. Low (editors), Condition of groundfish resources of the eastern Bering Sea and Aleutian Islands region in 1984, p. 37-49. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-83.

Echave, K., C. Rodgveller, and S.K. Shotwell. 2013. Calculation of the geographic area sizes used to create population indices for the Alaska Fisheries Science Center longline survey. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-253, 93 p.

Fournier, D. 1983. An analysis of the Hecate Strait Pacific cod fishery using an age-structured model incorporating density-dependent effects. Can. J. Fish. Aquat. Sci. 40:1233-1243.

Hanelsman, D. H., B.Clark, and M. Sigler. 2013. Report of the groundfish plan team retrospective investigations group, Part II: the compilation. Report to the North Pacific Fisheries Management Council Plan Team September 2013. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501. Available: http://www.afsc.noaa.gov/REFM/stocks/Plan_Team/2013/Sept/Retrospectives_2013_final3.pdf

Hanselman, D. H., C. Lunsford, and C. Rodgveller. 2015. Assessment of the sablefish stock in Alaska. In Stock assessment and fishery evaluation report for the groundfish resources of the GOA and BS/AI. North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306 Anchorage, AK 99501.

Hicks, A. Garrison, T.M., Punt, A.E., and others. 2016. r4ss: R Code for Stock Synthesis. R package version 1.24.4. https://github.com/r4ss

Jung, S., I. Choi, H. Jin, D.-w. Lee, H.-k. Cha, Y. Kim, and J.-y. Lee. 2009. Size-dependent mortality formulation for isochronal fish species based on their fecundity: an example of Pacific cod (Gadus macrocephalus) in the eastern coastal areas of Korea. Fisheries Research 97:77-85.

Ketchen, K.S. 1964. Preliminary results of studies on a growth and mortality of Pacific cod (Gadus macrocephalus) in Hecate Strait, British Columbia. J. Fish. Res. Bd. Canada 21:1051-1067.

Low, L. L. 1974. A study of four major groundfish fisheries of the Bering Sea. Ph.D. Thesis, Univ. Washington, Seattle, WA. 240 p.

Major, R. 1985. Condition of groundfish resources of the Gulf of Alaska region as assessed in 1984. NOAA Technical Memorandum NMFS F/NWC-80. U.S. Dept. Comm. National Oceanic and Atmospheric Administration National Marine Fisheries Service P. 211

Shimada, A. M., and D. K. Kimura. 1994. Seasonal movements of Pacific cod (Gadus macrocephalus) in the eastern Bering Sea and adjacent waters based on tag-recapture data. U.S. Natl. Mar. Fish. Serv., Fish. Bull. 92:800-816

Thompson, G. G., and A. M. Shimada. 1990. Pacific cod. In L. L. Low and R. E. Narita (editors), Condition of groundfish resources of the eastern Bering Sea-Aleutian Islands region as assessed in 1988, p. 44-66. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-178.

Thompson, G. G, and H. H. Zenger. 1993. Pacific cod. In Plan Team for Groundfish Fisheries of the Gulf of Alaska (editor), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska as projected for 1994, chapter 2. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Thompson, G. G., and H. H. Zenger. 1995. Pacific cod. In Plan Team for the Groundfish Fisheries of the Gulf of Alaska (editor), Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska as projected for 1996, chapter 2. North Pacific Fishery Management Council, 605 W. 4th Avenue Suite 306, Anchorage, AK 99501.

Ueda, Y., Y. Kanno, and T. Matsuishi, T. 2004. Weight- based virtual population analysis of Pacific cod Gadus macrocephalus off the Pacific coast of southern Hokkaido, Japan. *Fisheries science*, *70*(5), pp.829-838.

Wespestad, V., R. Bakkala, and J. June. 1982. Current abundance of Pacific cod (Gadus macrocephalus) in the eastern Bering Sea and expected abundance in 1982-1986. NOAA Tech. Memo. NMFS F/NWC-25, 26 p.

Tables

Table A.2.1.1. Model likelihoods and results. Colors indicate same data and weighting. Note that the 2015 Model, Model 16.6, and Model 16.6.0 have different adjustments to the size composition data and therefore composition likelihoods should not be compared with other models.

Label	2015 Model	16.6	16.6.0	16.6.1	16.6.2.1 Q	16.6.2.2 M	16.6.2.3 S	16.6.2.4 QM	16.6.2.5 QMS
Parameters	244	79	82	82	83	83	88	84	90
TOTAL_like	2352.55	1604.16	1848.62	672.57	593.29	563.98	545.47	563.59	528.35
Survey_like	25.76	22.72	44.48	20.58	-2.12	-5.37	-5.24	-6.11	-7.01
Length_comp_like	1990.68	1176.06	1390.51	374.44	340.81	321.61	303.82	321.76	290.27
Age_comp_like	347.06	89.67	82.48	26.74	18.67	19.27	21.29	18.86	18.42
Parm_priors_like	0	0	0	0	0	9.11	0	4.89	0.82
Size_at_age_like	0	282.50	289.42	258.65	238.93	238.47	242.96	237.02	238.01
R0_billions	0.31	0.22	0.20	0.22	0.18	5.06	0.35	1.75	0.61
SR_BH_steep	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Natural Mortality	0.38	0.38	0.38	0.38	0.38	0.81	0.38	0.69	0.51
L at Amin	44.59	5.34	5.87	5.53	5.45	5.83	4.39	5.78	4.98
L at Amax	89.84	105.32	106.13	107.91	115.03	119.64	111.48	120.23	117.08
VonBert K	0.23	0.15	0.15	0.15	0.14	0.13	0.15	0.13	0.14
SPB_Virgin_thousand_mt	304.87	174.03	160.53	184.63	156.70	219.00	323.47	154.99	200.53
Bratio_2015	0.87	0.35	0.42	0.35	0.25	0.71	0.41	0.54	0.40
SPRratio_2014	0.99	1.16	1.13	1.14	1.25	0.46	0.93	0.74	0.95
Trawl survey Q 1994-2015	1.00	1.00	1.00	1.00	2.85	1.00	1.00	1.89	1.60
Trawl survey Q 1977-1993	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Label	16.6.3	16.6.4.1	16.6.4.2	16.6.11 S	16.6.15 QM	16.6.20	16.6.22 QMS
Parameters	316	317	317	320	315	82	90
TOTAL_like	614.00	581.32	603.21	511.89	509.18	643.21	512.86
Survey_like	22.40	21.63	24.37	-8.91	-6.33	21.71	-4.90
Length_comp_like	322.30	295.82	313.51	261.21	259.96	348.60	276.25
Age_comp_like	27.35	27.31	26.87	21.14	18.96	26.62	17.64
Parm_priors_like	0	0	0	0	9.22	0	0.77
Size_at_age_like	255.28	248.03	249.87	240.98	236.25	250.29	235.98
R0_billions	0.23	0.22	0.22	0.34	3.17	0.20	0.59
SR_BH_steep	1	1.00	1	1.00	1.00	1.00	1.00
Natural Mortality	0.38	0.38	0.38	0.38	0.75	0.38	0.50
L at Amin	5.70	5.74	5.78	4.56	5.87	5.63	5.06
L at Amax	109.64	111.90	111.84	112.57	119.86	110.61	117.15
VonBert K	0.15	0.14	0.14	0.15	0.13	0.15	0.14
SPB_Virgin_thousand_mt	197.80	193.14	191.37	313.20	193.37	175.48	200.54
Bratio_2015	0.34	0.34	0.34	0.43	0.64	0.36	0.39
SPRratio_2014	1.15	1.16	1.16	0.94	0.58	1.15	0.97
Trawl survey Q 1994-2015	1.00	1.00	1.00	1.00	1.24	1.00	1.73
Trawl survey Q 1977-1993	1.00	1.00	1.75	1.00	1.00	1.00	1.00

Table A.2.1.1. Cont. Model likelihoods and results. Note that the 16.7 series of models have the <27 cm fish removed from bottom trawl survey index, and length and age composition data. Colors indicate same data and weighting.

Label	16.7	16.7.0	16.7.1	16.7.2	16.7.3
Parameters	79	82	82	316	82
TOTAL_like	1540.51	1784.01	638.93	577.08	627.93
Survey_like	54.30	65.09	16.73	15.40	22.64
Length_comp_like	1118.79	1333.48	358.45	304.60	346.14
Age_comp_like	60.70	55.21	20.03	20.43	19.84
Parm_priors_like	0.00	0.00	0.00	0.00	0.00
Size_at_age_like	279.96	297.66	255.86	252.99	247.97
R0_billions	0.24	0.23	0.25	0.26	0.23
SR_BH_steep	1.00	1.00	1.00	1.00	1.00
Natural Mortality	0.38	0.38	0.38	0.38	0.38
L at Amin	5.55	6.57	6.47	6.82	6.65
L at Amax	104.06	103.60	105.75	107.41	108.44
VonBert K	0.15	0.15	0.15	0.15	0.15
SPB_Virgin_thousand_mt	189.14	174.63	199.61	214.29	190.13
Bratio_2015	0.41	0.47	0.44	0.42	0.45
SPRratio_2014	1.09	1.07	1.05	1.06	1.06
Trawl survey Q 1994-2015	1.00	1.00	1.00	1.00	1.00
Trawl survey Q 1977-1993	1.00	1.00	1.00	1.00	1.00

Table A.2.1.2. Likelihoods by fleet for models 16.6 and 16.6.0 showing changes with the addition of the GOA AFSC sablefish longline survey.

Likelihoods	ALL	FshTrawl	FshLL	FshPot	Srv	LLSrv
Model 16.6						
Surv_like	22.72				22.72	
Length_like	1176.06	477.57	320.21	194.10	184.18	
Age_like	89.67				89.67	
sizeatage_like	282.50				282.50	
Model 16.6.0						
Surv_like	44.48				32.70	11.78
Length_like	1390.51	465.16	339.93	198.24	182.93	204.26
Age_like	82.48				82.48	
sizeatage_like	289.42				289.42	

Table A.2.1.3: Female spawning stock biomass retrospective analysis results for models evaluated. Reds are further from 0, blues are closer.

Model	Rho	WH Rho	RMSE
16.6	0.281	0.000	0.086
16.6.0	0.098	0.001	0.054
16.6.1	0.072	0.001	0.041
16.6.3	0.077	-0.003	0.040
16.6.4.1	0.070	-0.012	0.044
16.6.4.2	0.065	-0.017	0.048
16.6.11	0.258	0.110	0.123
16.6.15	0.322	0.153	0.169
16.6.20	0.065	-0.013	0.049
16.6.22	0.554	0.317	0.334
16.7	0.489	0.015	0.110
16.7.0	0.212	0.014	0.065
16.7.1	0.115	-0.007	0.051
16.7.3	0.120	-0.024	0.065

Table A.2.1.4. Model effective sample size and adjustments comparing un-tuned (Model 16.6.0) and Francis method tuned (Model 16.6.1) models.

FleetName	mean_effN	mean(inputN*Adj)	HarMean(effN)	Var_Adj	HarEffN/ MeanInputN	Index RMSE
Model 16.6.0						
FshTrawl	530.95	152.05	207.39	1.00	1.36	
FshLL	660.34	155.86	357.12	1.00	2.29	
FshPot	886.94	180.27	635.02	1.00	3.52	
Srv	415.15	100.00	274.82	1.00	2.75	0.56
LLSrv	374.28	100.00	311.66	1.00	3.12	0.34
Srv_Age	85.91	100.00	43.03	1.00	0.43	
Model16.6.1.2_Francis						
FshTrawl	452.91	14.69	144.82	0.10	9.86	
FshLL	560.76	11.33	260.50	0.07	22.99	
FshPot	885.98	39.87	582.27	0.22	14.60	
Srv	304.51	44.96	218.29	0.45	4.86	0.48
LLSrv	453.06	73.91	362.46	0.74	4.90	0.31
Srv_Age	39.50	24.36	32.15	0.24	1.32	

Table A.2.1.5. Fleet negative log likelihoods, red are highest for the category, blue are lowest.

Model	Label	ALL	FshTrawl	FshLL	FshPot	Srv	LLSrv
16.6.1	Age_like	26.74				26.74	
16.6.2.1 Q	Age_like	18.67				18.67	
16.6.2.2 M	Age_like	19.27				19.27	
16.6.2.3 S	Age_like	21.29				21.29	
16.6.2.4 QM	Age_like	18.86				18.86	
16.6.2.5 QMS	Age_like	18.42				18.42	
16.6.1	Length_like	374.44	59.05	38.70	48.37	102.23	126.09
16.6.2.1 Q	Length_like	340.81	59.39	46.65	50.11	83.21	101.47
16.6.2.2 M	Length_like	321.61	57.00	35.33	53.33	80.29	95.67
16.6.2.3 S	Length_like	303.82	56.33	42.25	49.65	81.62	73.96
16.6.2.4 QM	Length_like	321.76	56.45	38.22	52.97	81.58	92.53
16.6.2.5 QMS	Length_like	290.27	54.48	32.87	49.36	78.76	74.81
16.6.1	sizeatage_like	258.65				258.65	
16.6.2.1 Q	sizeatage_like	238.93				238.93	
16.6.2.2 M	sizeatage_like	238.47				238.47	
16.6.2.3 S	sizeatage_like	242.96				242.96	
16.6.2.4 QM	sizeatage_like	237.02				237.02	
16.6.2.5 QMS	sizeatage_like	238.01				238.01	
16.6.1	Surv_like	20.58				18.54	2.03
16.6.2.1 Q	Surv_like	-2.12				-5.26	3.14
16.6.2.2 M	Surv_like	-5.37				-0.67	-4.71
16.6.2.3 S	Surv_like	-5.24				-0.28	-4.97
16.6.2.4 QM	Surv_like	-6.11				-3.35	-2.76
16.6.2.5 QMS	Surv_like	-7.01				-2.87	-4.14

Table A.2.1.6. Estimates of Pacific cod natural mortality.

Area	Author	Year	Value
Eastern Bering Sea	Low	1974	0.3 - 0.45
Eastern Bering Sea	Wespestad et al.	1982	0.7
Eastern Bering Sea	Bakkala and Wespestad	1985	0.45
Eastern Bering Sea	Thompson and Shimada	1990	0.29
Eastern Bering Sea	Thompson and Methot	1993	0.37
Eastern Bering Sea	Shimada and Kimura	1994	0.96
Eastern Bering Sea	Shi et al.	2007	0.4 - 0.5
Gulf of Alaska	Thompson and Zenger	1993	0.27
Gulf of Alaska	Thompson and Zenger	1995	0.5
British Columbia	Ketchen	1964	0.56-0.63
British Columbia	Fournier	1983	0.65
Korea	Jung et al.	2009	0.82
Japan	Ueda et al.	2004	0.2

Table A.2.1.7. Fleet and data specific likelihoods for Model 16.6.1, Model 16.6.3, Model 16.6.4.1 and Model 16.6.4.2.

Label	ALL	FshTrawl	FshLL	FshPot	Srv	LLSrv
Model 16.6.1						
Surv_like	20.58				18.54	2.03
Length_like	374.44	59.05	38.70	48.37	102.23	126.09
Age_like	26.74				26.74	
sizeatage_like	258.65				258.65	
Model 16.6.3						
Surv_like	22.40				20.02	2.38
Length_like	322.30	33.13	18.82	48.53	105.81	116.01
Age_like	27.35				27.35	
sizeatage_like	255.28				255.28	
Model 16.6.4.1						
Surv_like	21.63				18.56	3.08
Length_like	295.82	34.27	19.62	47.31	86.00	108.62
Age_like	27.31				27.31	
sizeatage_like	248.03				248.03	
Model 16.6.4.2						
Surv_like	24.37				20.51	3.86
Length_like	313.51	33.43	19.78	47.89	104.10	108.31
Age_like	26.87				26.87	
sizeatage_like	249.87				249.87	
	24.37				20.51	3.86

Figures

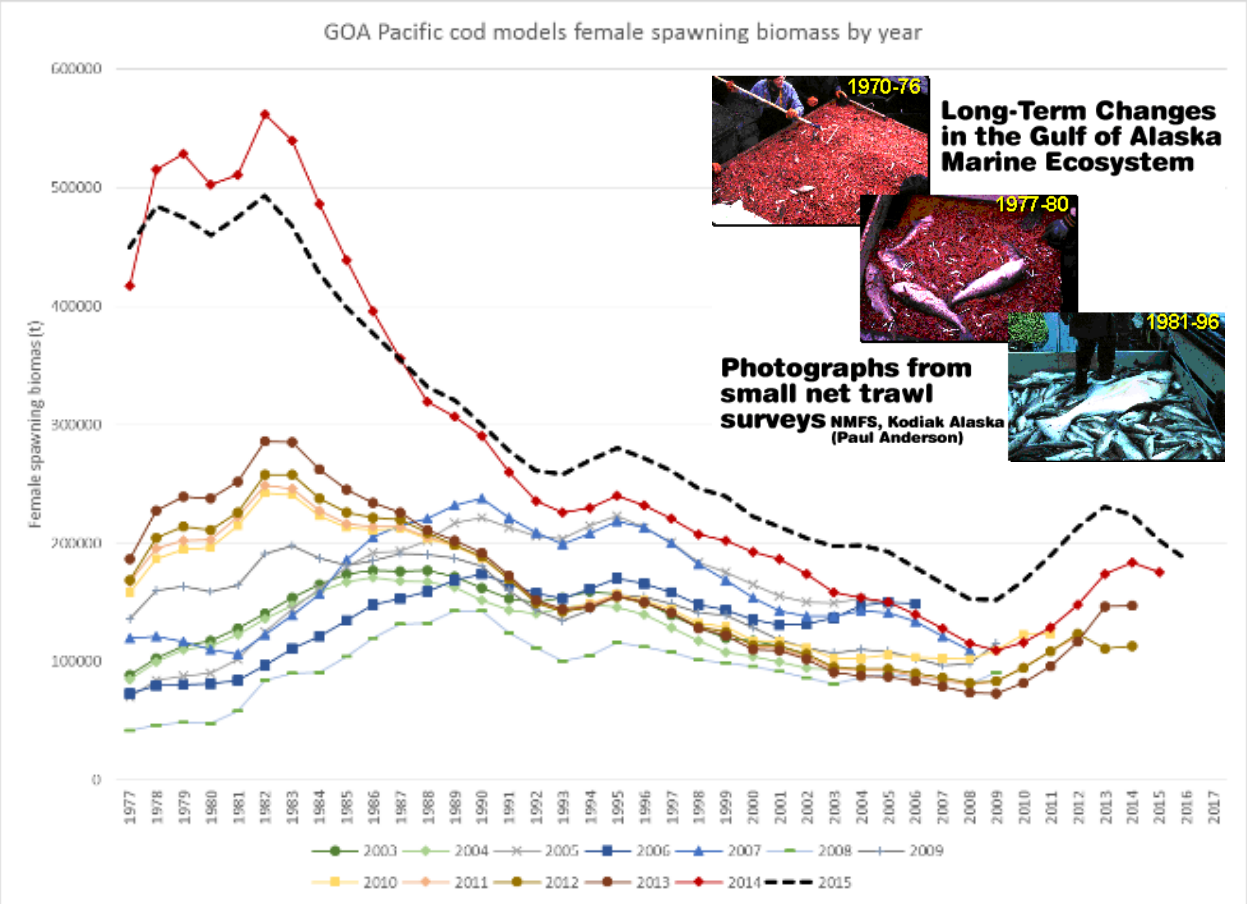


Figure A.2.1.1. 1977-2015 Gulf of Alaska Pacific cod female spawning biomass from the 2003 through 2015 stock assessments and (inset) images from the NMFS small net surveys off Kodiak Alaska showing change in species composition over time from: http://www.thenakedscientists.com/HTML/articles/article/brucewrightcolumn1.htm/

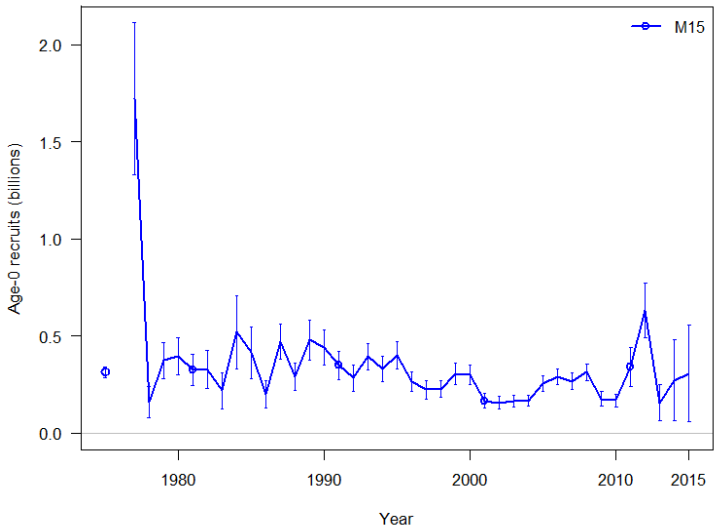


Figure A.2.1.2. 1977-2015 Gulf of Alaska Pacific cod numbers at age-0 from the 2015 Model.

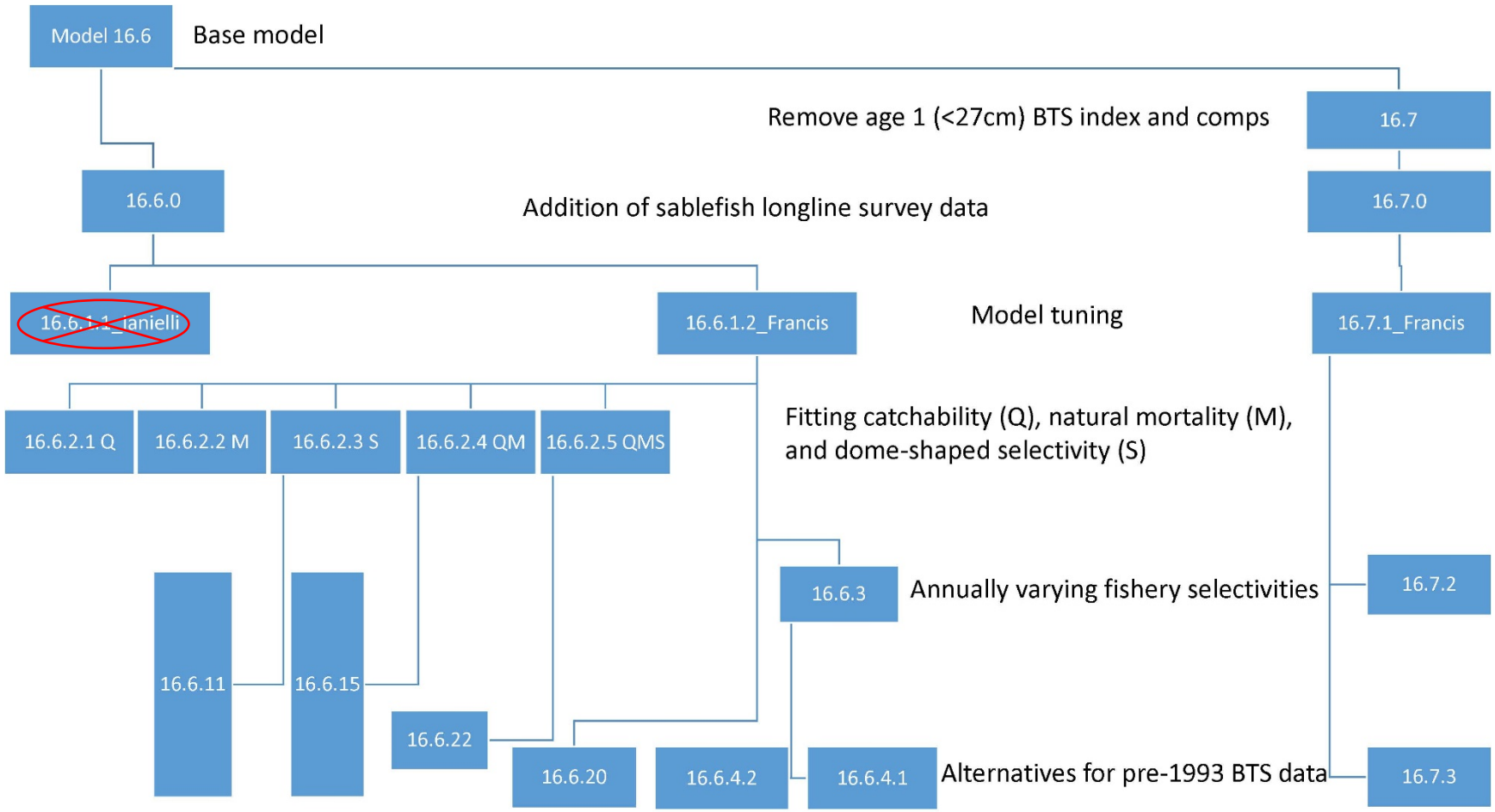


Figure A.2.1.3. Hierarchy for models evaluated in this document. Models with red x were not presented.

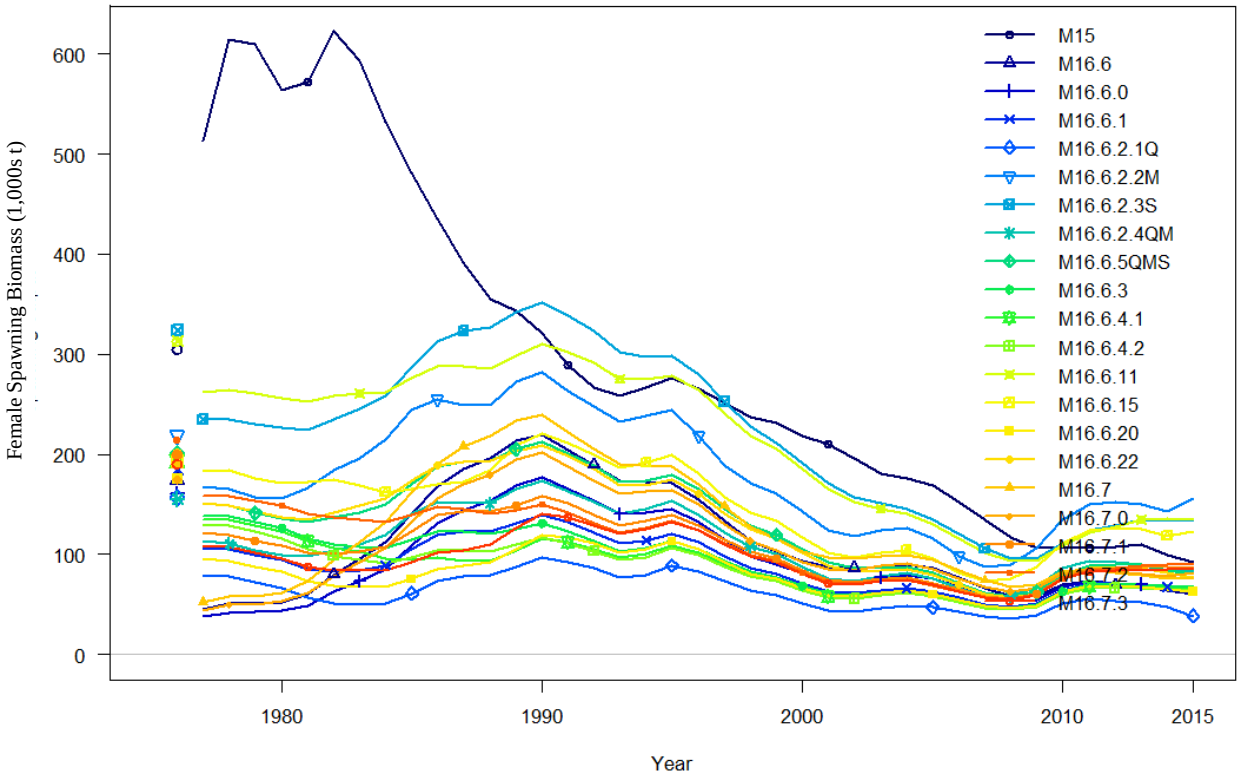


Figure A.2.1.4. Female spawning stock biomass in 1000's tons for the 2015 Model (M15) and models presented in this document. The points on the far left are estimates of female virgin spawning biomass.

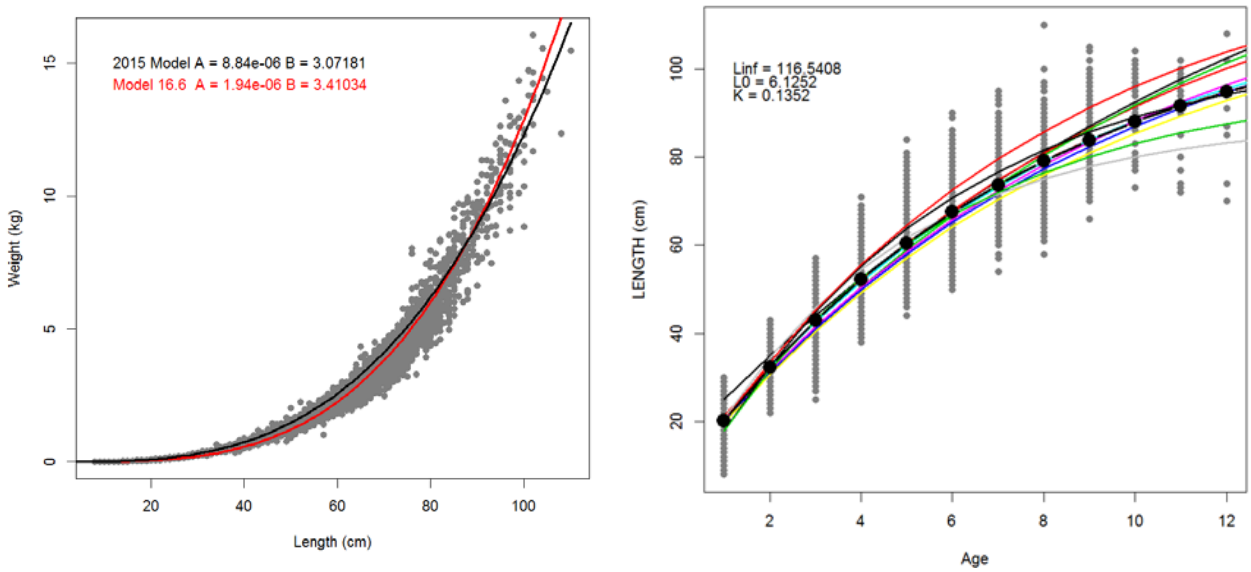


Figure A.2.1.5. Weight at length for Model 16.6 and 2015 Model (Left), and Von Bertalanffy fits to Pacific cod length at age data (right) from the 1990-2013 bottom trawl survey. In the right-hand figure black dots are the fit for all data combined, colored lines are fits to individual years.

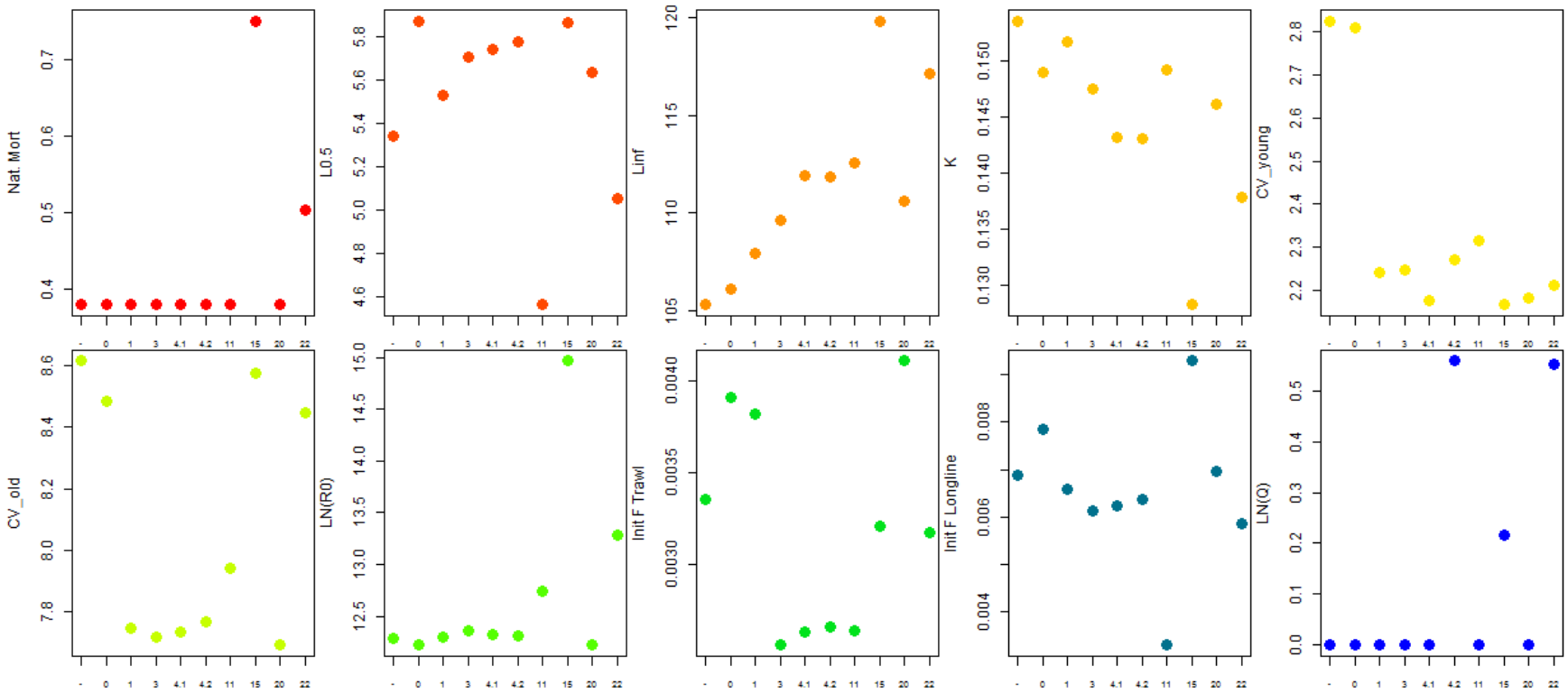


Figure A.2.1.6. Non-selectivity parameters for Models 16.6.xx.

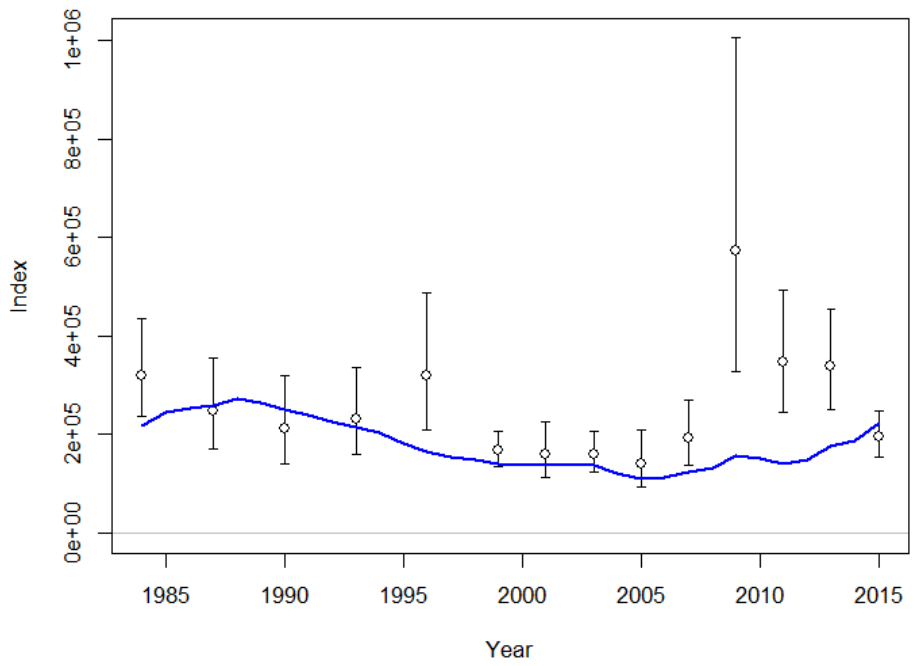


Figure A.2.1.7. Bottom trawl survey Pacific cod index of abundance for 1984-2015 in numbers of fish. The blue line is the Model 16.6 fit to the index.

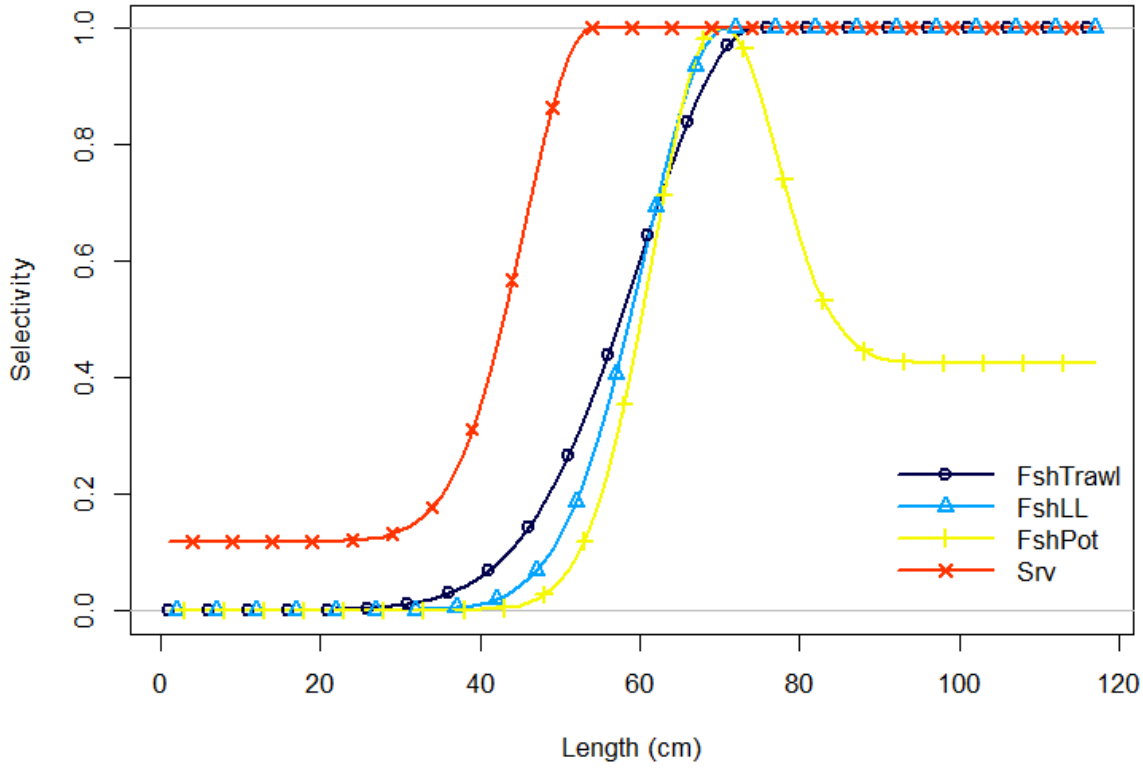


Figure A.2.1.8. Model 16.6 length based selectivity for all fisheries and the bottom trawl survey.

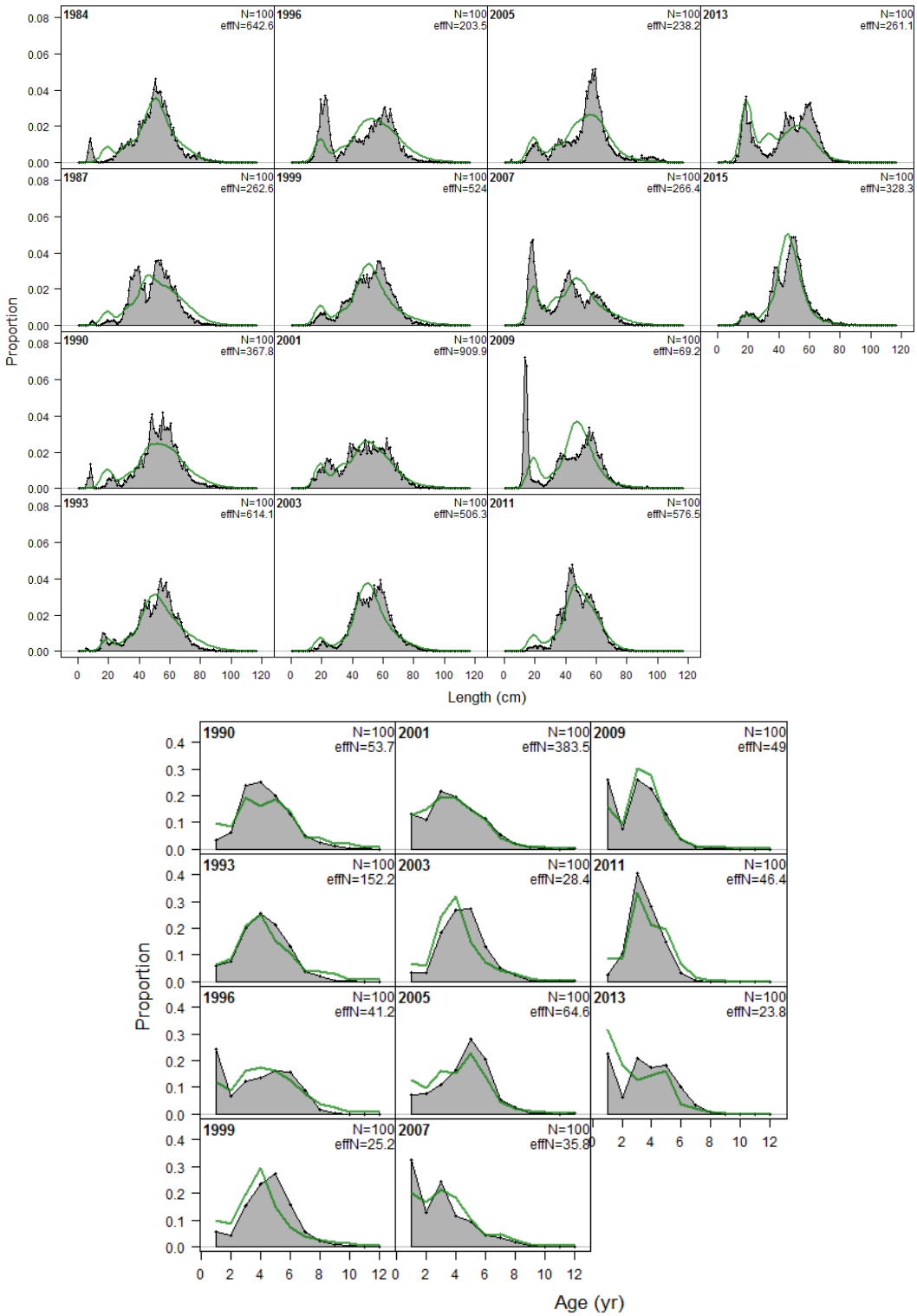


Figure A.2.1.9. Bottom trawl length composition (top) and age composition (bottom) data with Model16.6 estimates in green.

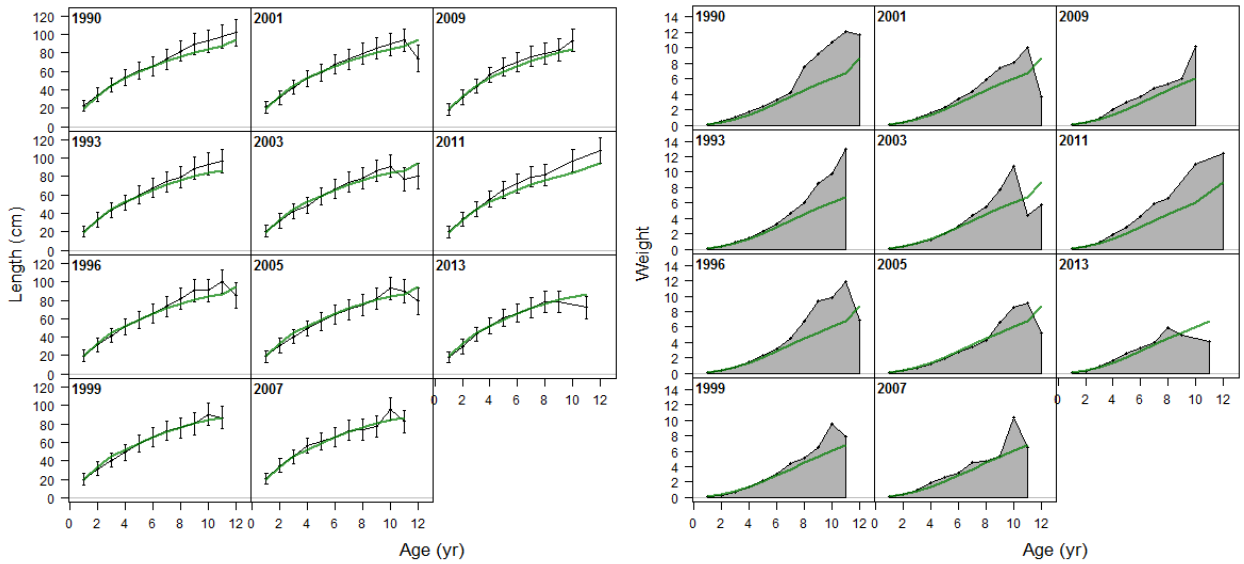


Figure A.2.1.10. Bottom trawl survey (left) length at age and (right) weight at age with Model 16.6 estimates in green.

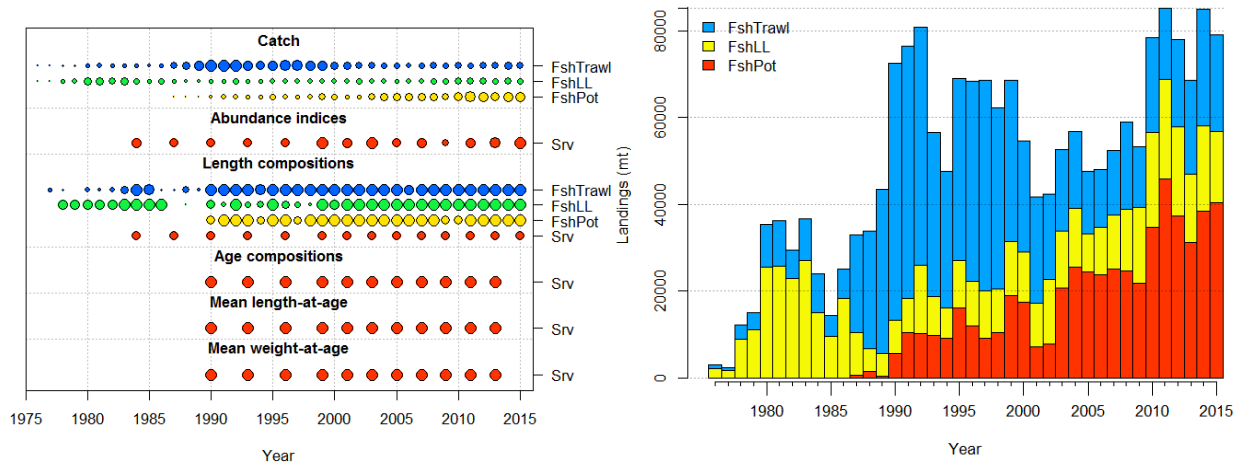


Figure A.2.1.11. (Left) Data types used in Model 16.6, circle area is relative to data precision for each data type and (right) fishery catch data for 1977-2015 for the three fisheries.

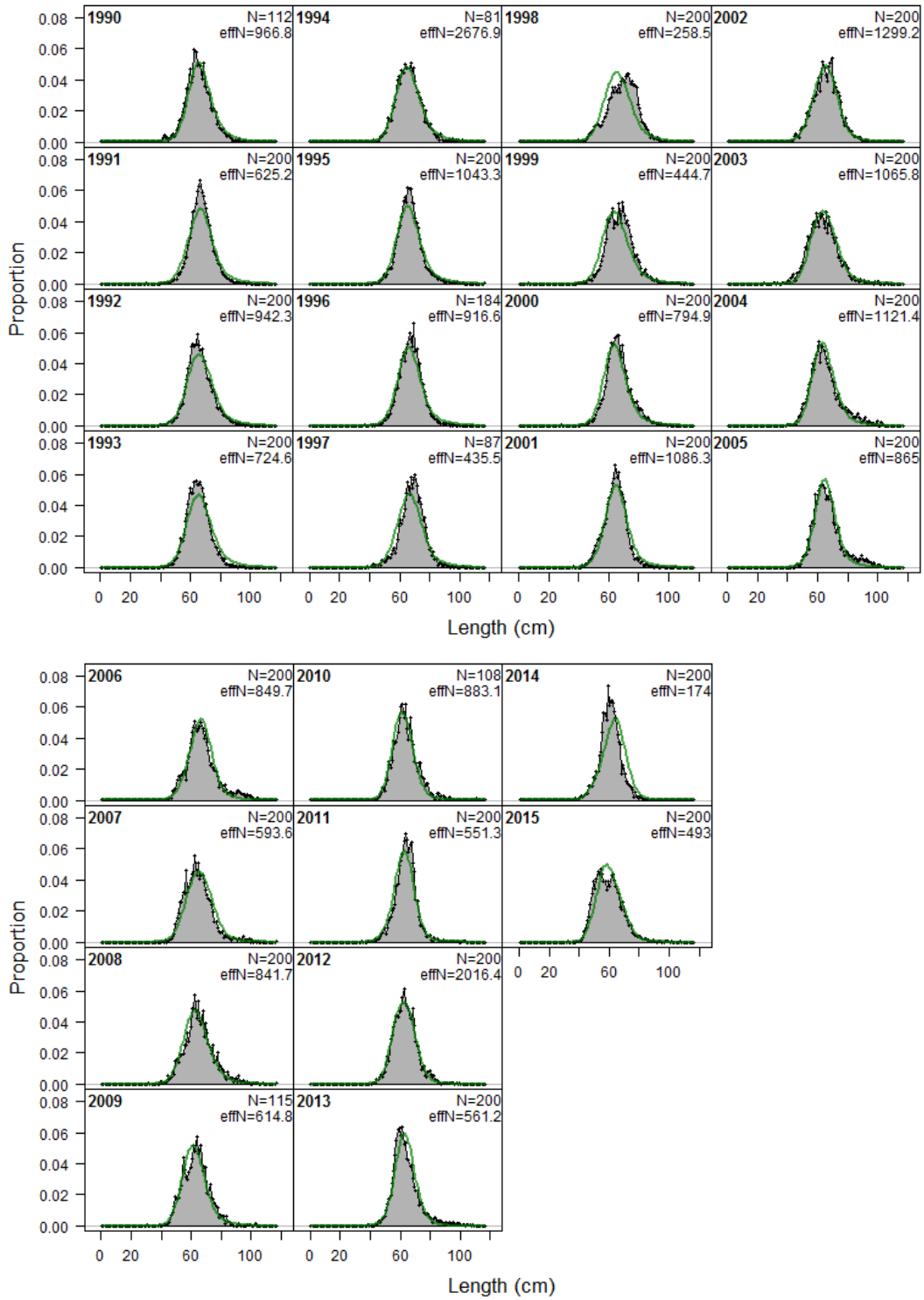


Figure A.2.1.12. Pot fishery length composition and Model 16.6 estimates (green line)..

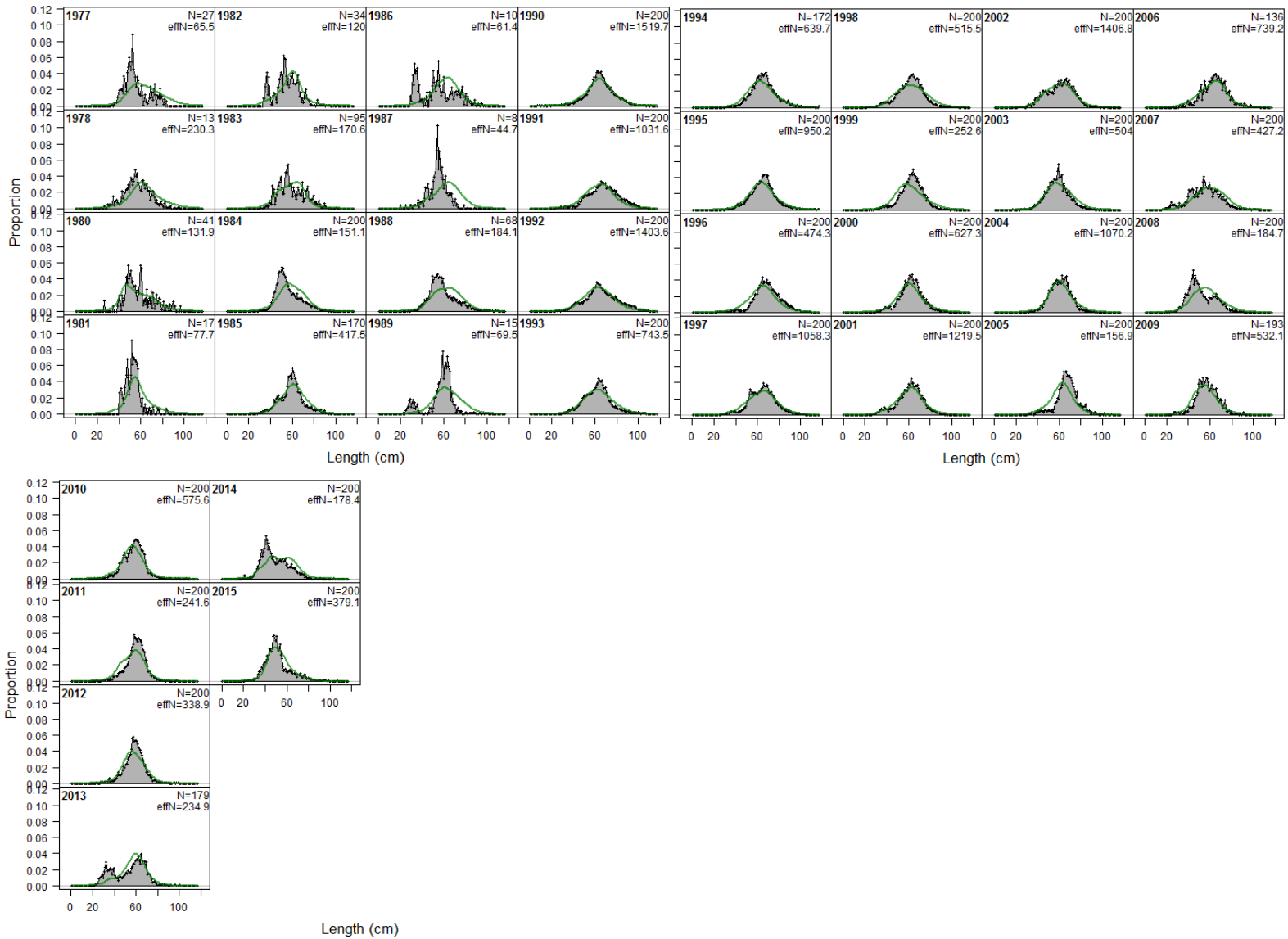


Figure A.2.1.13. Trawl fishery length composition data and Model 16.6 estimates (green line).

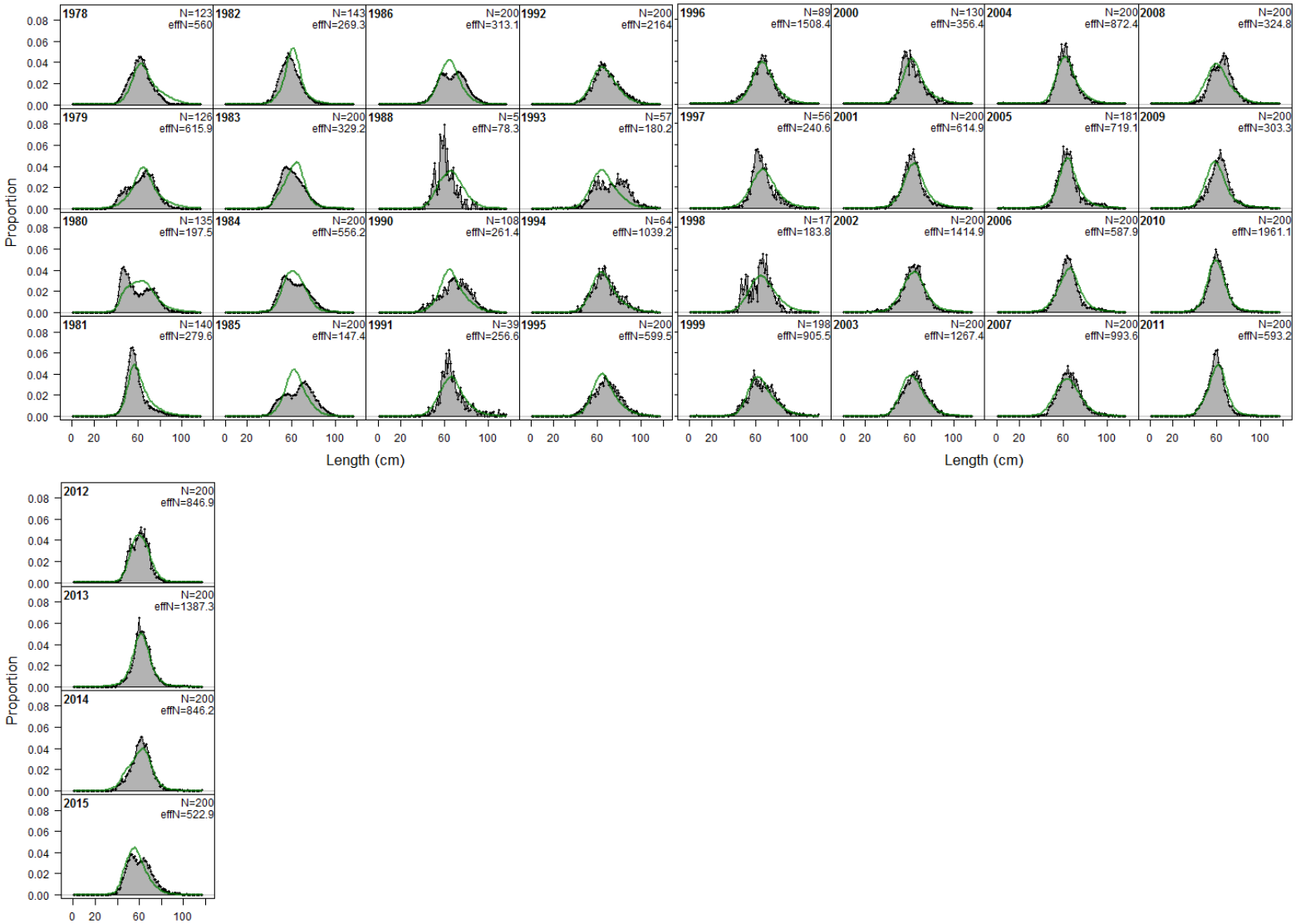


Figure A.2.1.14. Longline fishery length composition data and Model 16.6 estimates (green line).

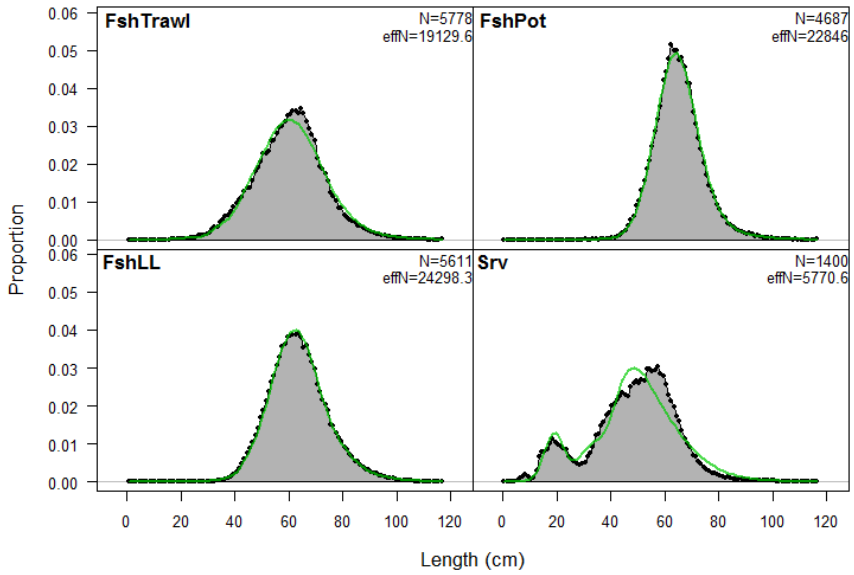


Figure A.2.1.15. Model 16.6 fit to length composition data for the four data components, green line being the model estimate.

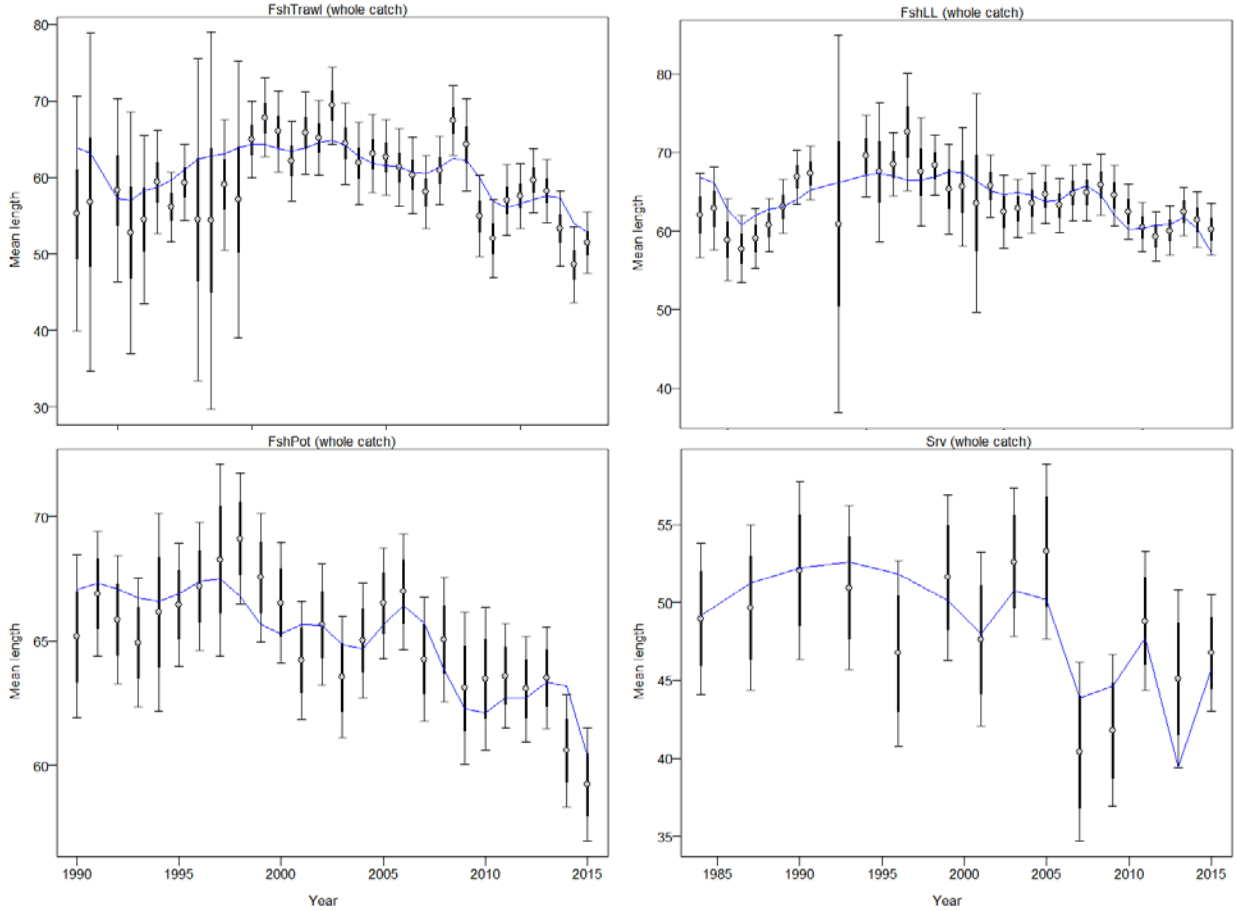


Figure A.2.1.16. Model 16.6 fit to mean length by year from the length composition data for the four components. Blue lines being model estimates.

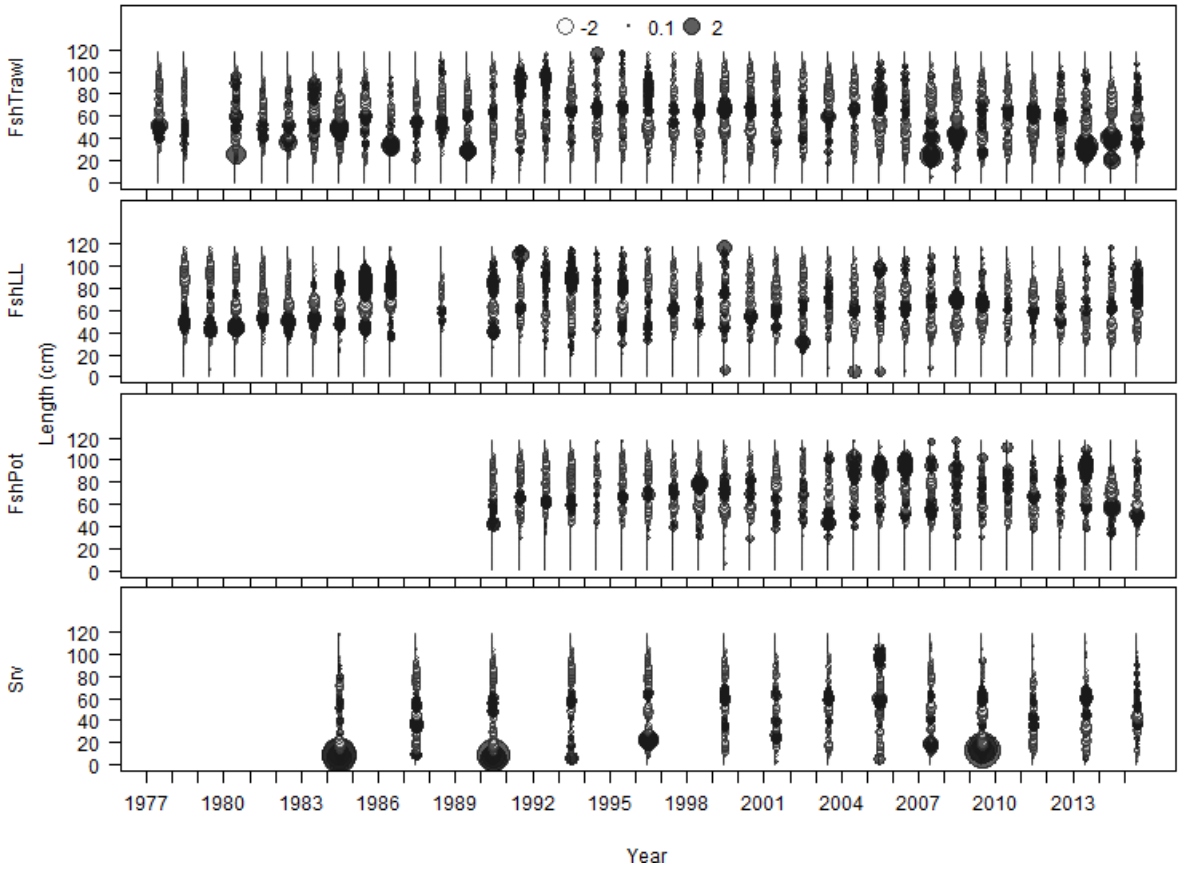


Figure A.2.1.17. Model 16.6 Pearson residuals for fit to length composition data for the four components.

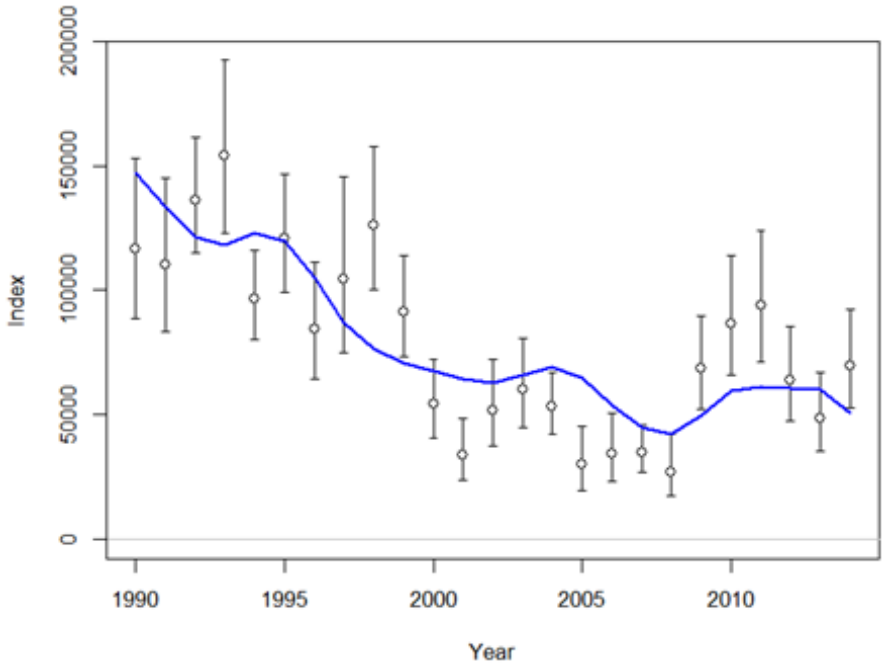


Figure A.2.1.18. Sablefish longline RPN index in numbers of fish with Model 16.6.0 estimate (blue line) .

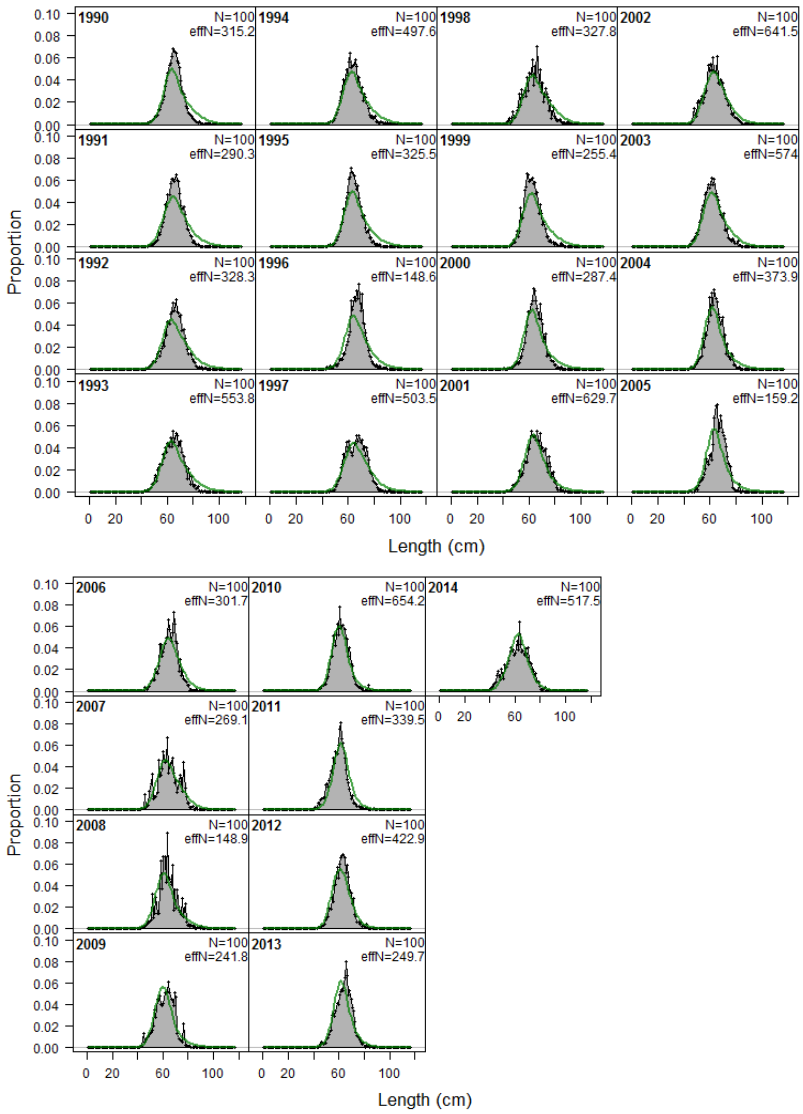


Figure A.2.1.19. Pacific cod length composition data from the Sablefish longline survey and Model 16.6.0 estimates (green lines).

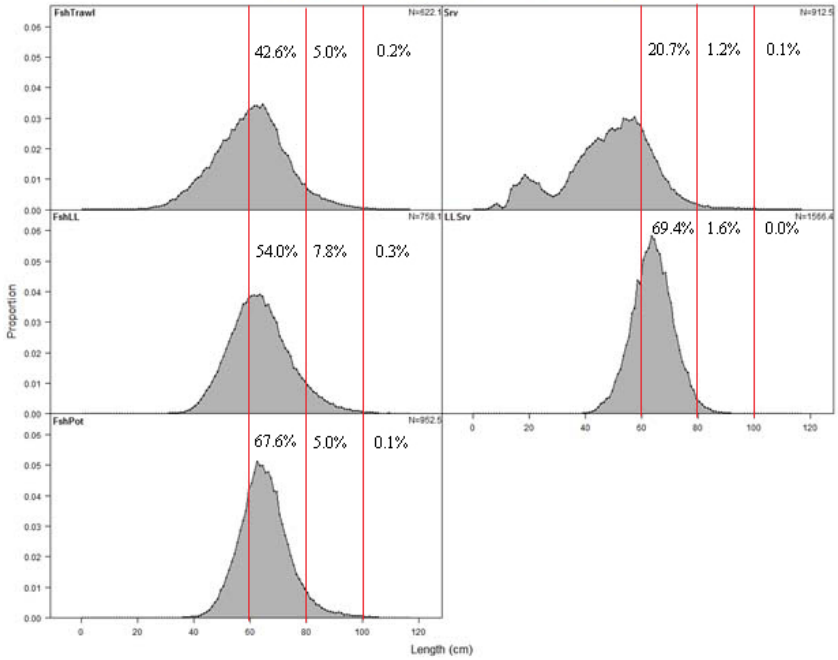


Figure A.2.1.20. Pacific cod length composition data aggregated for all years. Number within the red boxes are the percentage of the overall length data for each type within the length bounds.

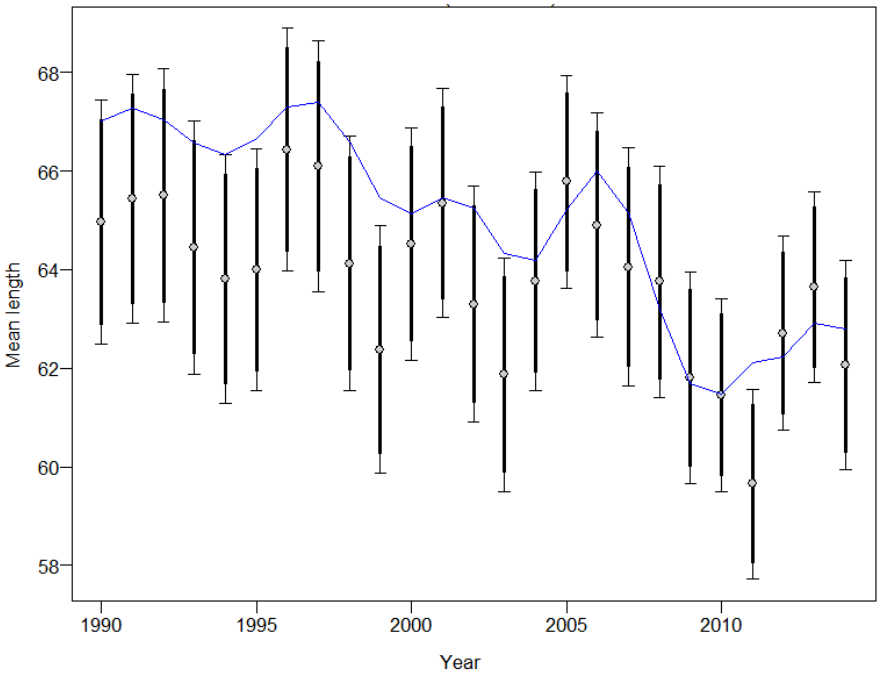


Figure A.2.1.21. Pacific cod mean length from the sablefish longline survey and Model 16.6.0 estimates (blue line).

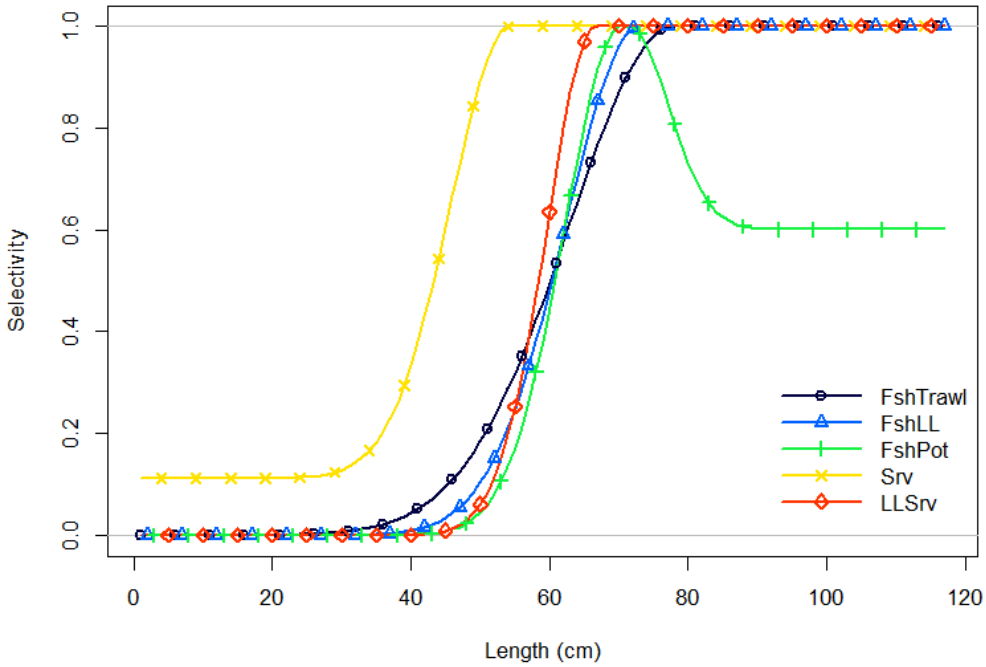


Figure A.2.1.22. Length-based selectivity for Model 16.6.0 for all length composition components.

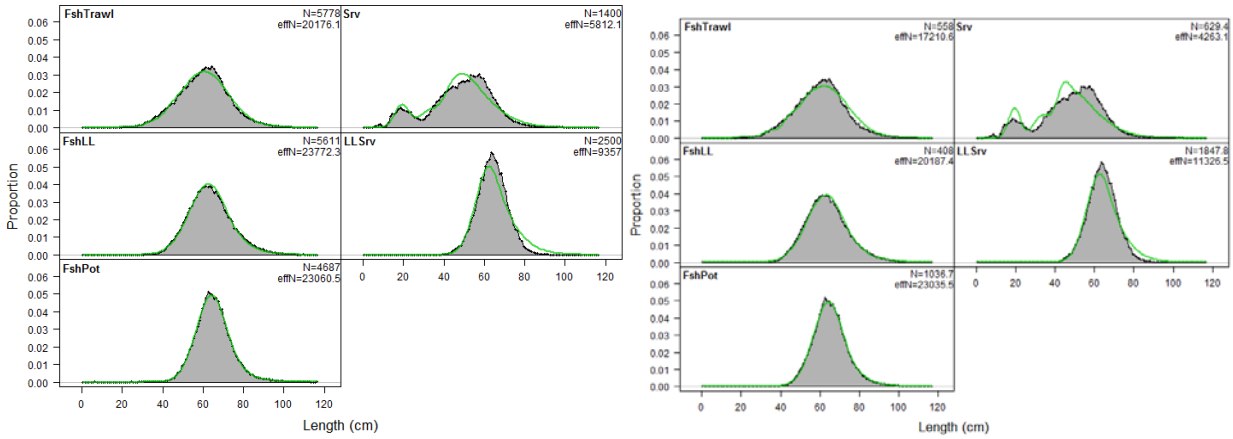


Figure A.2.1.23. Overall estimate (green line) to all length composition data combined for each gear in Model 16.6.0 (left) and Model 16.6.1 (right).

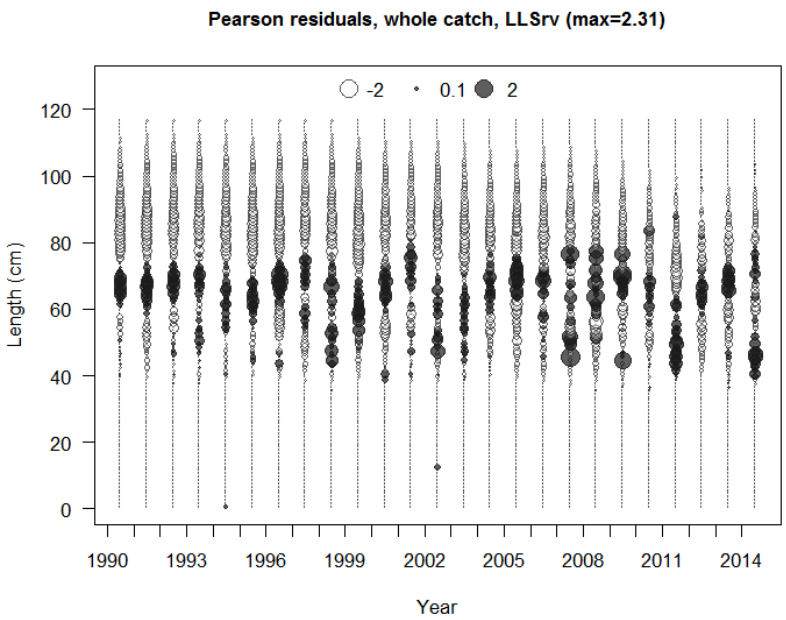


Figure A.2.1.24. Model 16.6.0 Pearson residuals for fit to longline survey length composition.

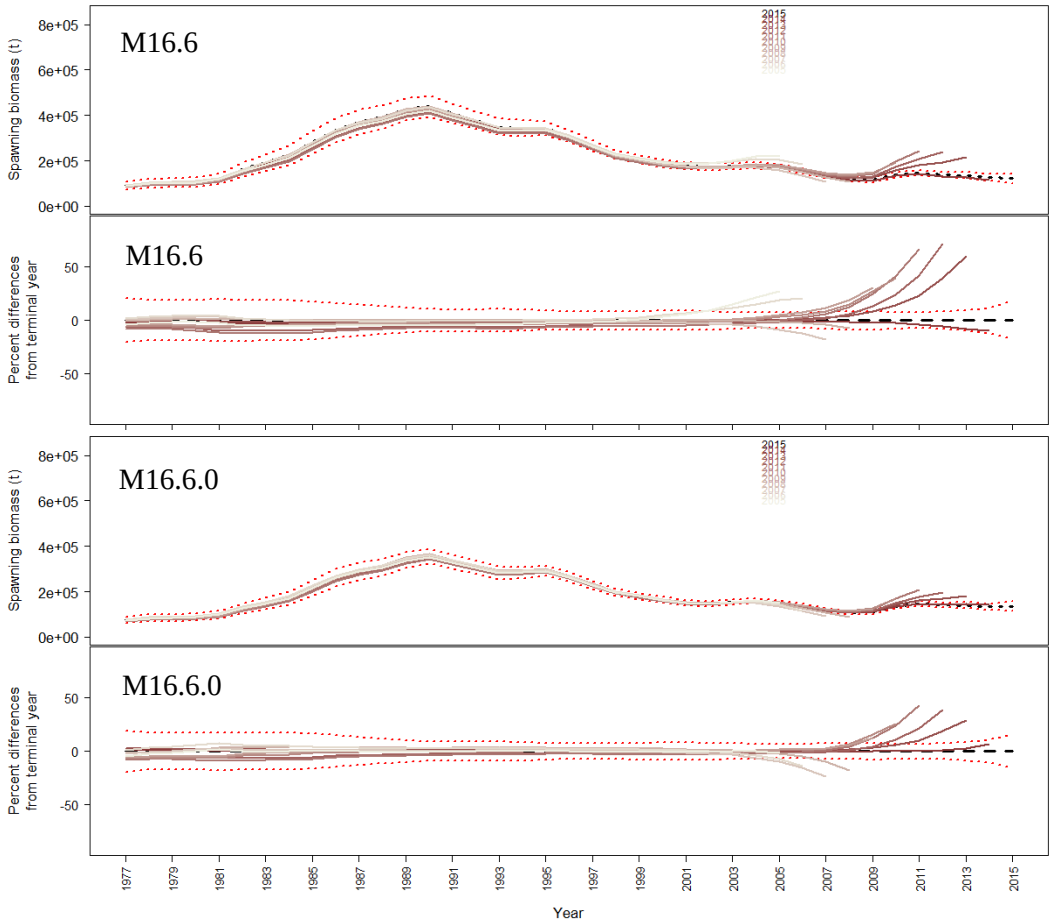


Figure A.2.1.25. Model 16.6 (top) and Model 16.6.0 (bottom) retrospective of spawning biomass in tons and percentage differences from the full model estimates for each year.

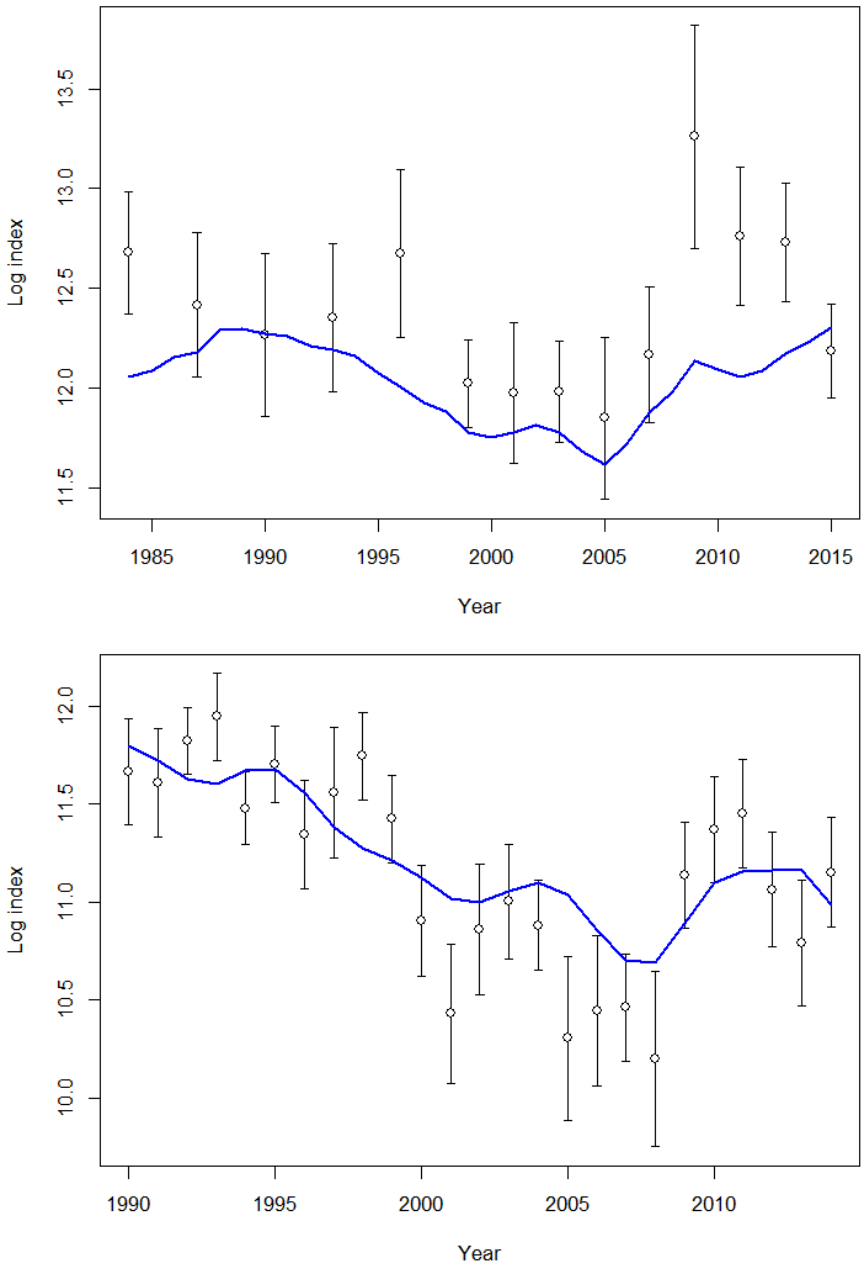


Figure A.2.1.26. Model 16.6.1 fit to the bottom trawl survey (top) and sablefish longline survey (bottom).

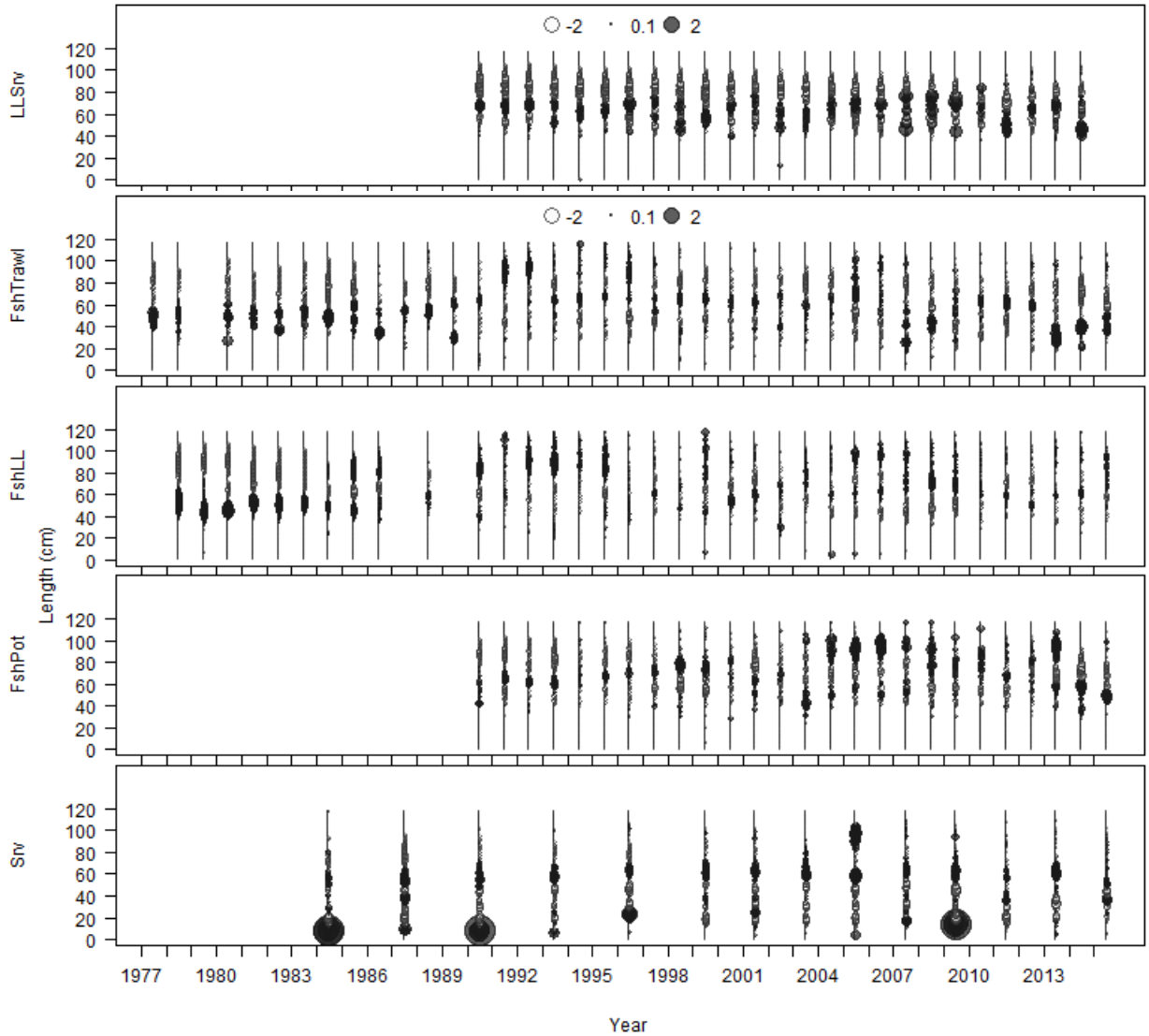


Figure A.2.1.27. Pearson residuals for Model 16.6.1 length composition data fits.

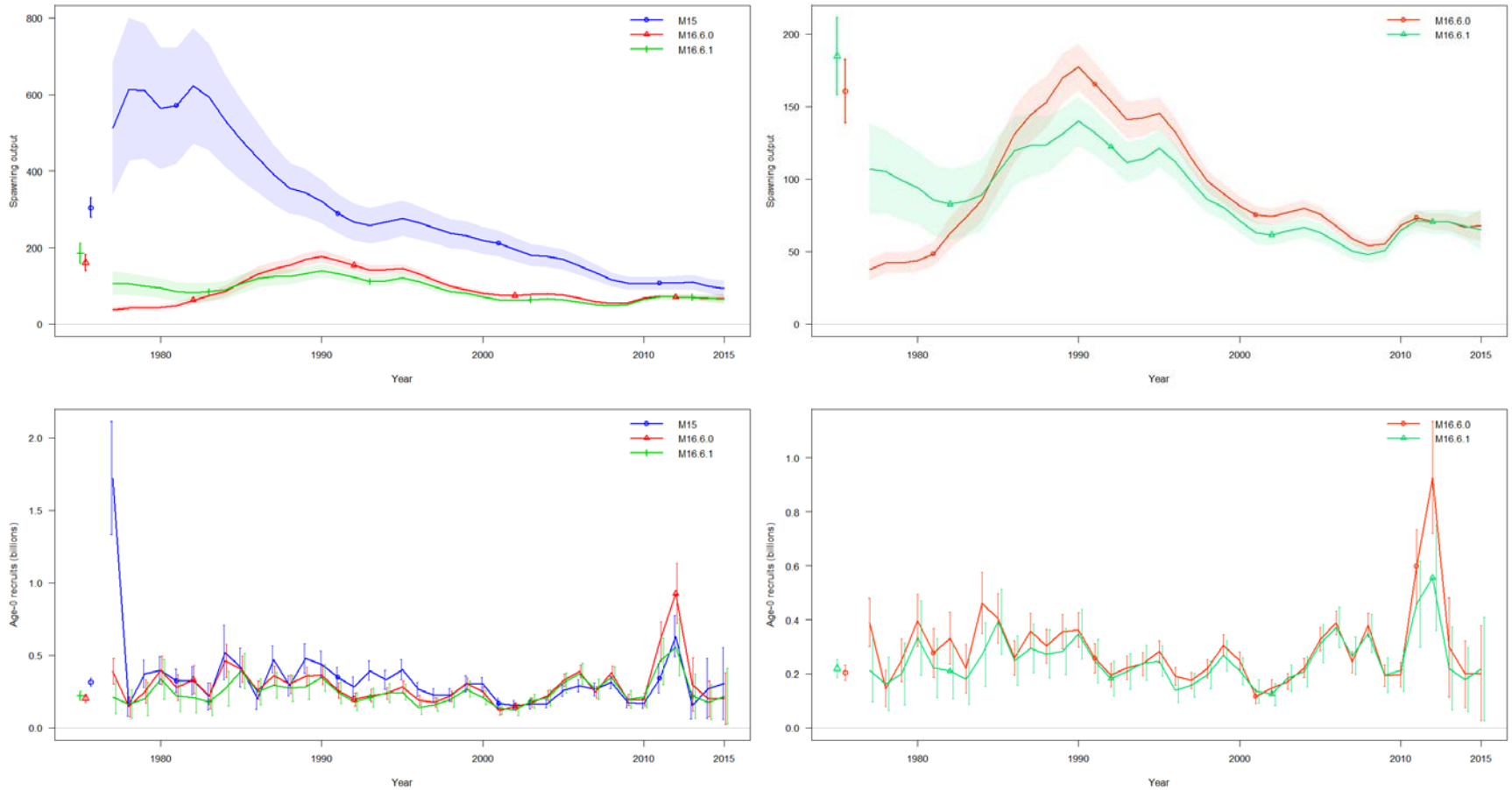


Figure A.2.1.28. Female spawning biomass (top) and age-0 Recruits (bottom) from 2015 Model (blue), Model 16.6.0 (red) and 16.6.1 (green).

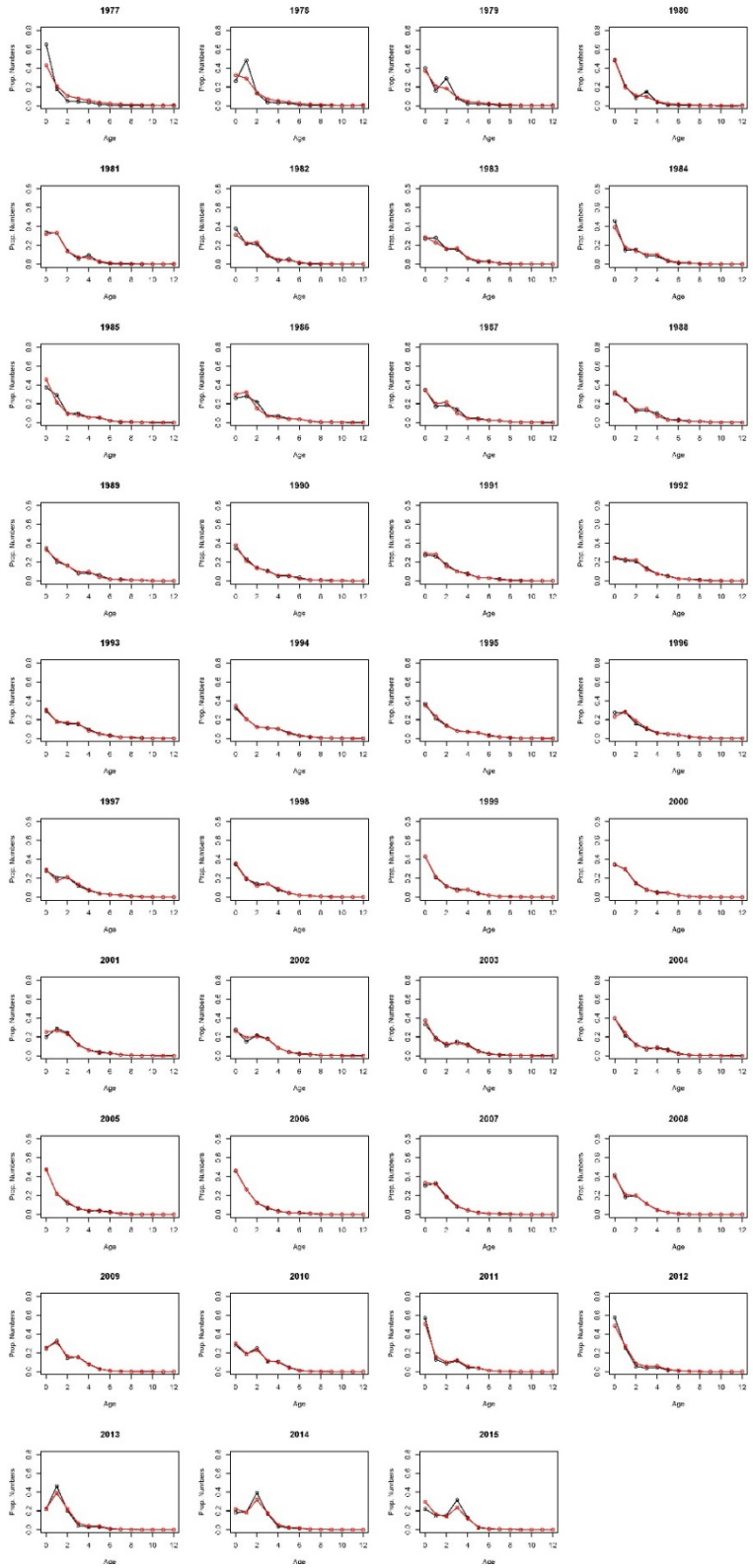


Figure A.2.1.29. Predicted population proportion of fish by age (numbers) for Model 16.6.0 (black) and Model 16.6.1 with Francis tuned composition sample sizes (red).

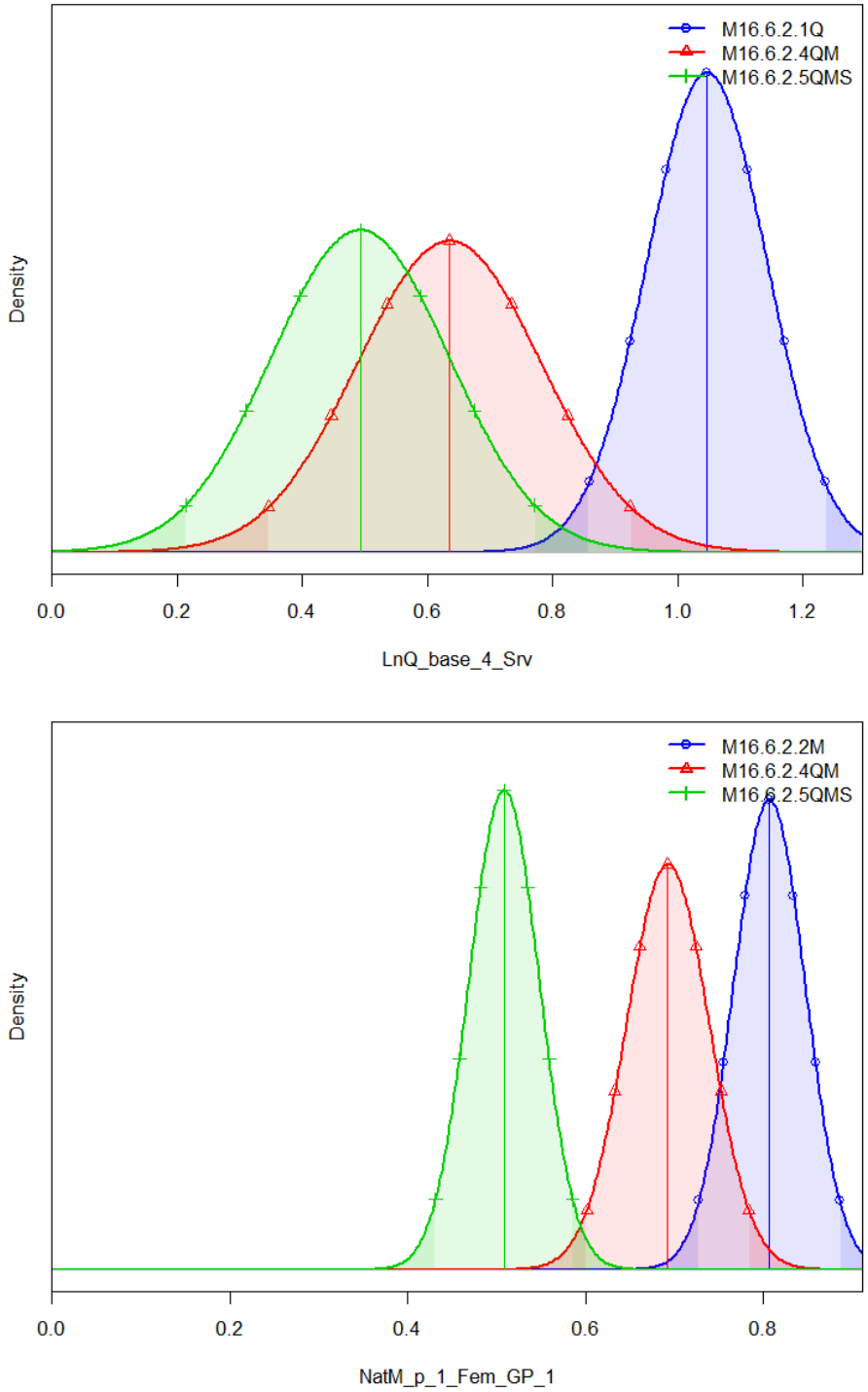


Figure A.2.1.30. Estimates for survey catchability (Log(Q)) from models M16.2.1Q, M16.2.4QM, M16.2.5QMS (top) and estimates for natural mortality from models M16.2.2M, M16.2.4QM, M16.2.5QMS (bottom). Q was set at 1.0 in Model 16.6.1 and the Jensen (1996) estimate for GOA Pacific cod natural mortality used in Model 16.6.1 was 0.38.

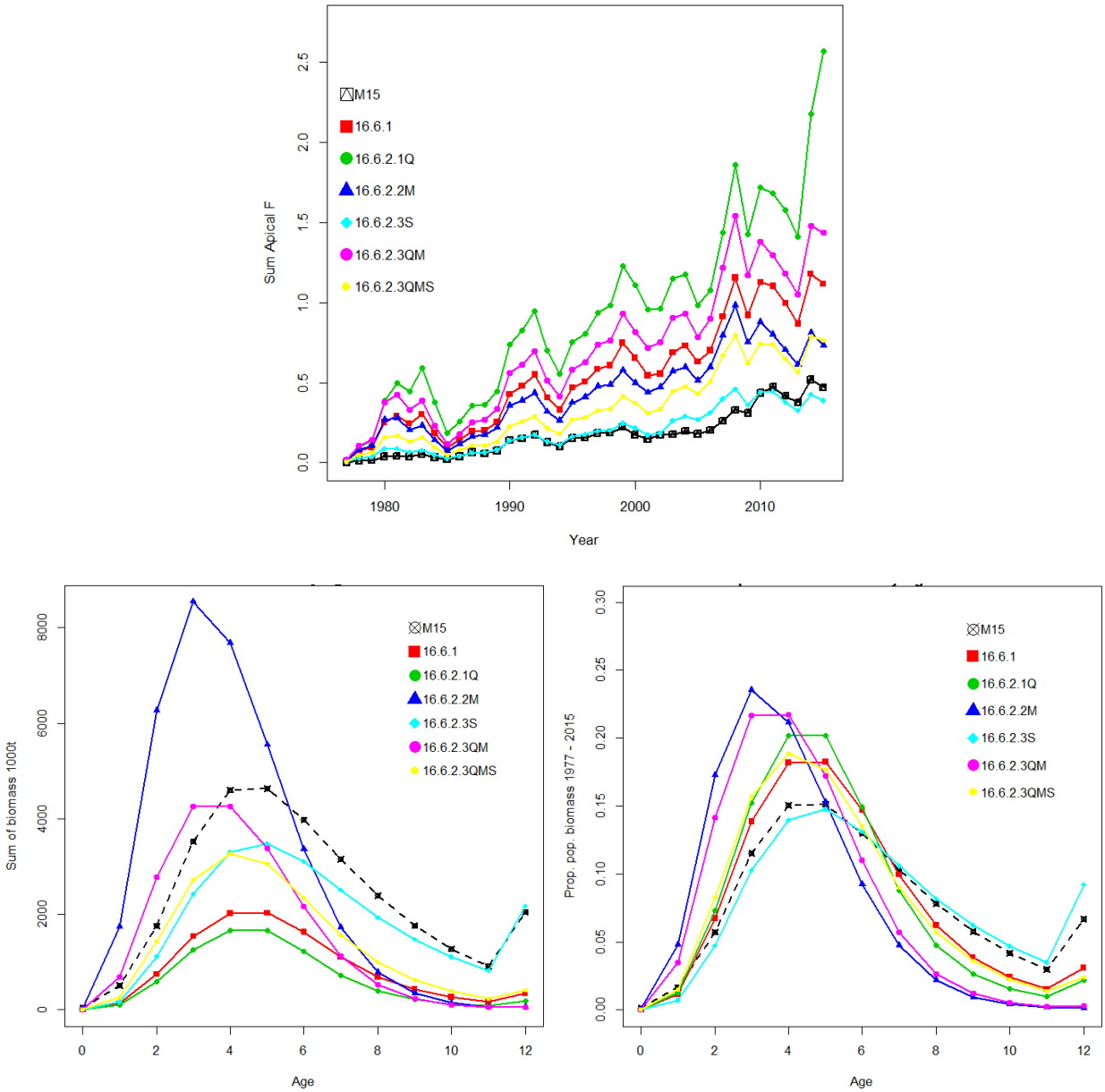


Figure A.2.1.31. Sum of the apical F for 1977-2015 (top), population biomass (left) and proportion of population biomass (right) at each age summed for all years 1977-2015 for the 2015 Model (M15) and models 16.6.1, 16.6.2.1Q, 16.6.2.2M, 16.6.2.3S, 16.6.2.4QM, and 16.6.2.5_QMS demonstrating model effects on fitting catchability, natural mortality, dome-shaped selectivity, and mixtures of each.

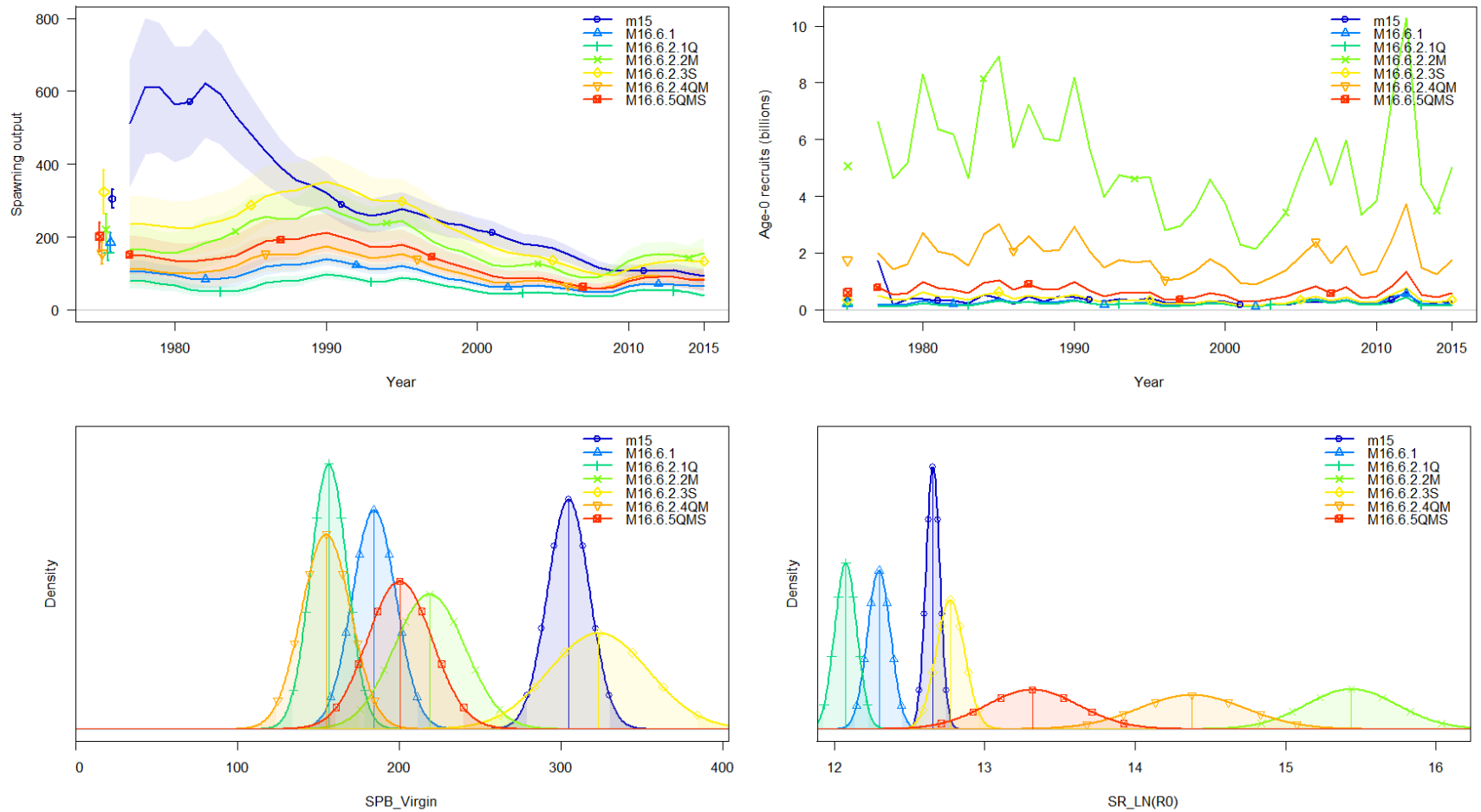


Figure A.2.1.32. Female spawning biomass (1000 t) (top left), age-0 recruits (billions) (top right), model estimates of female virgin spawning biomass (1000 t; bottom left), and log(R_0) (bottom right) for the 2015 Model and models 16.6.1, 16.6.2.1Q, 16.6.2.2M, 16.6. 2.3S, 16.6.2.4QM, and 16.6.2.5_QMS demonstrating model effects on fitting catchability, natural mortality, dome-shaped selectivity, and mixtures of each.

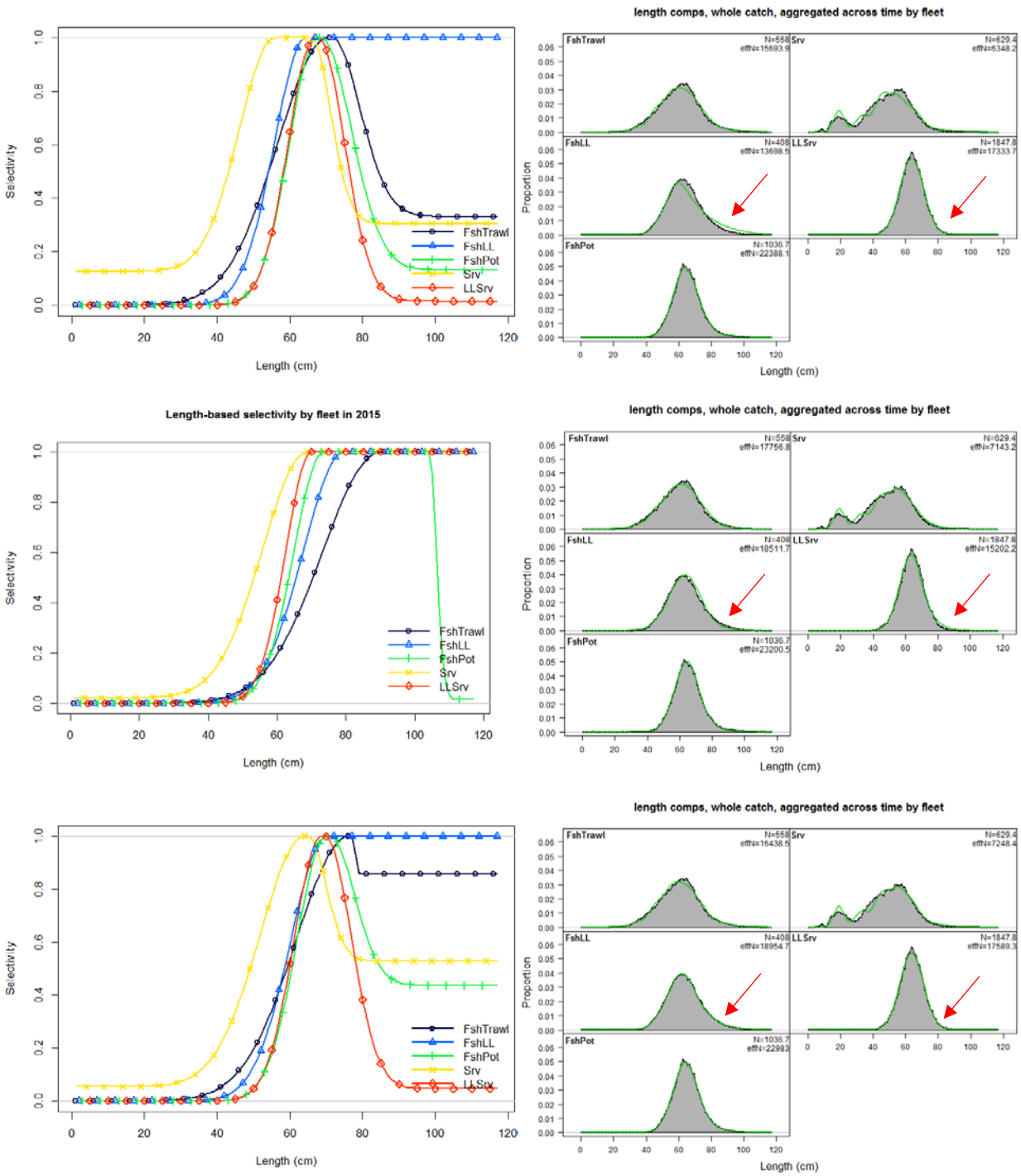


Figure A.2.1.33. Selectivity (left) for Model 16.6.2.3S (top), Model 16.6.2.4QM (middle), and Model 16.6.2.5QMS (bottom) with overall estimates of length composition data (right). Red arrow highlights estimates of fish >75cm most impacted by dome-shaped selectivity.

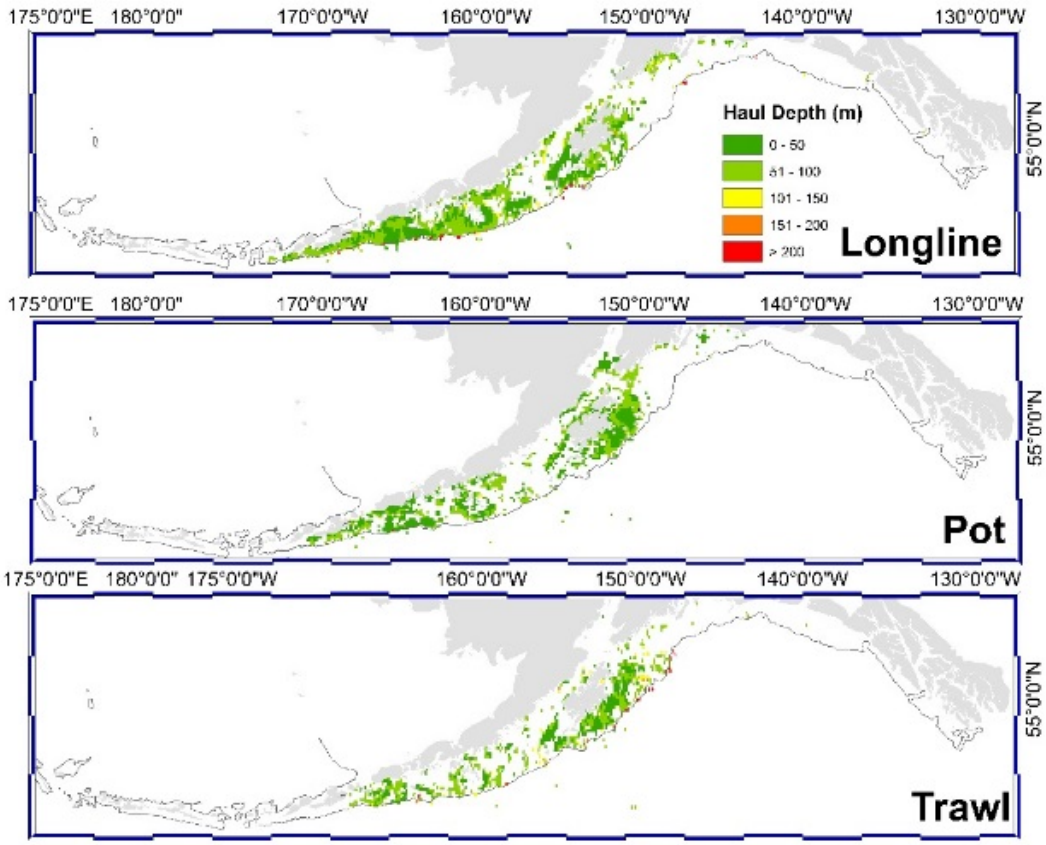


Figure A.2.1.34. Distribution of all observed Pacific cod fishing activity by gear type for 1998-2016, color denotes depth.

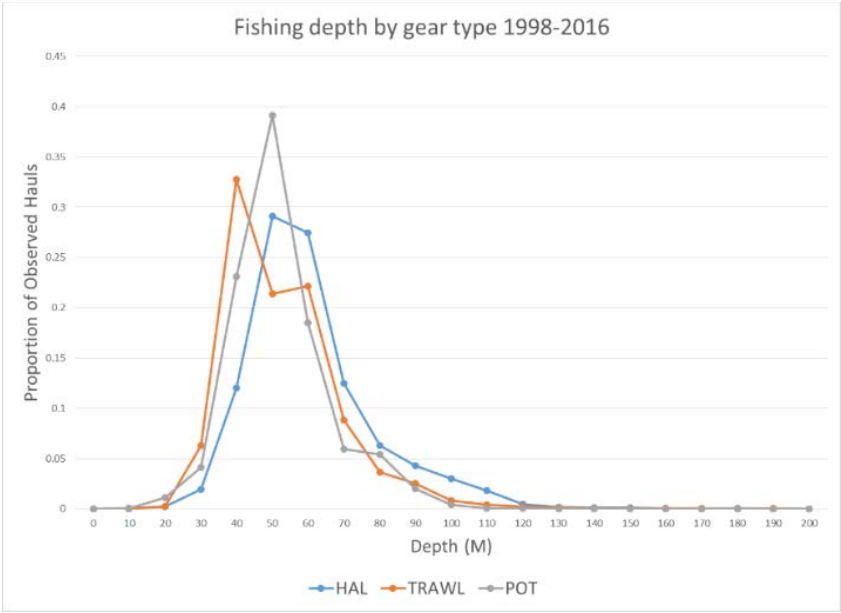


Figure A.2.1.35. Proportion of observed hauls by depth in the GOA for all observed Pacific cod fishing activity by gear type for 1998-2016.

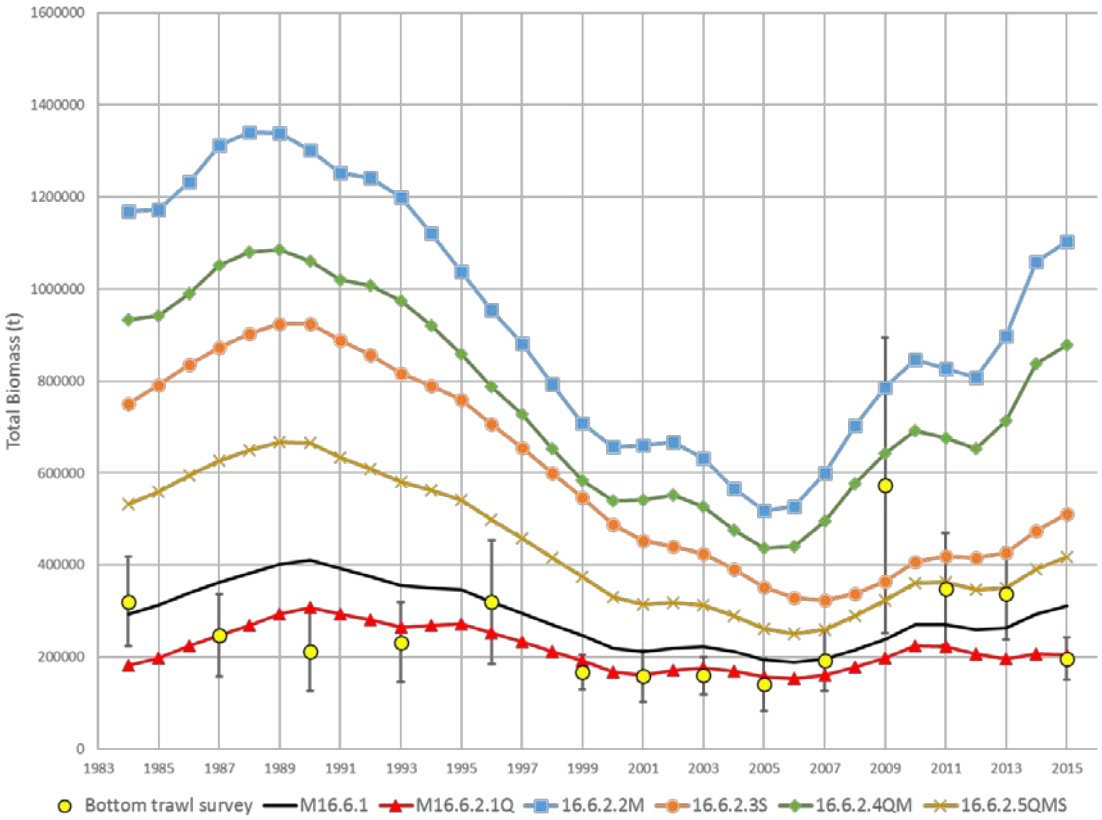


Figure A.2.1.36.Total biomass estimates Bottom trawl survey, Model 16.6.1 and 16.6.2 series models.

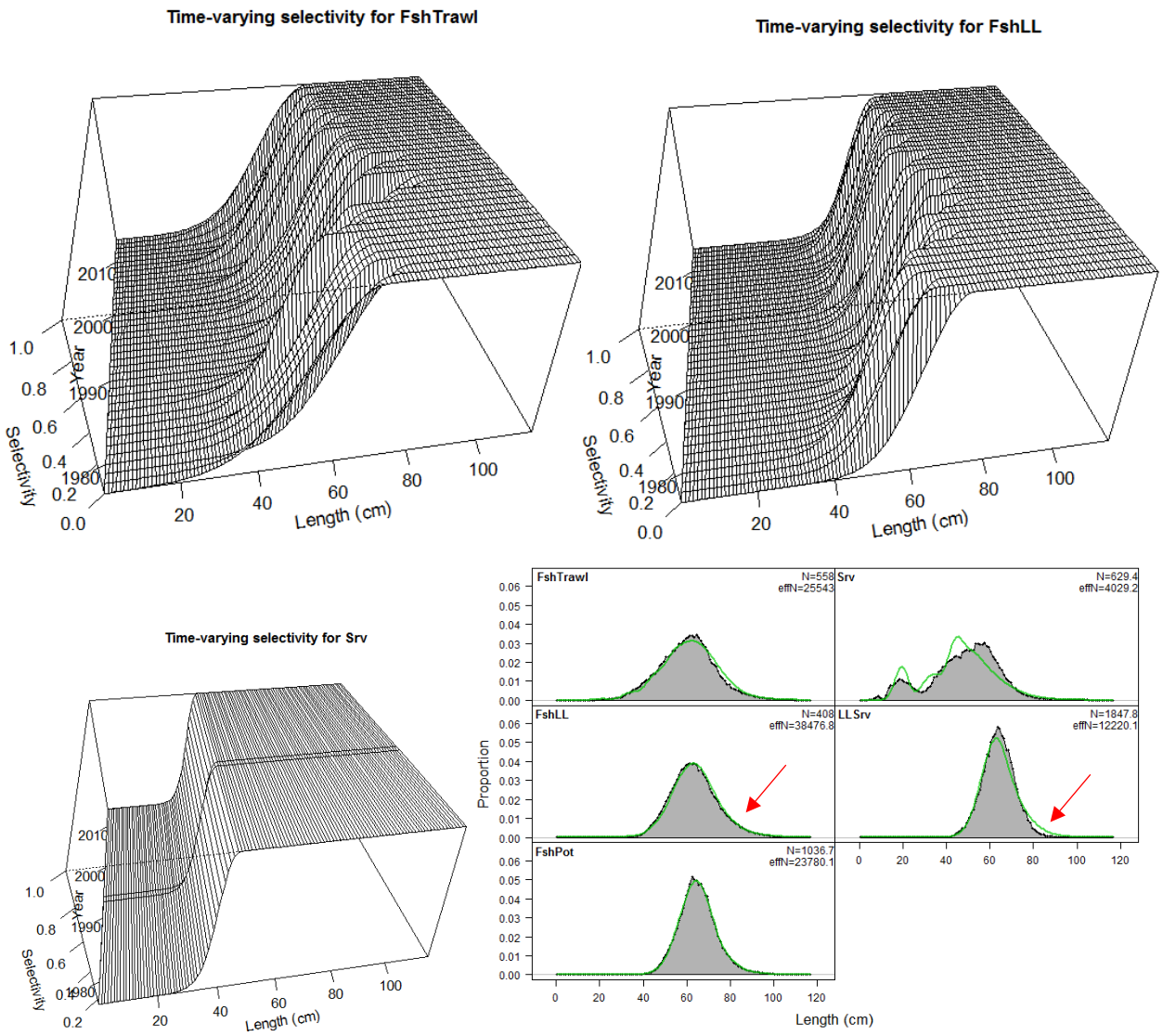


Figure A.2.1.37.Time varying selectivity curves fit in Model 16.6.3 and aggregated estimates of length composition data. Note that the y-axis for the bottom trawl survey (Srv) graph does not start at 0.

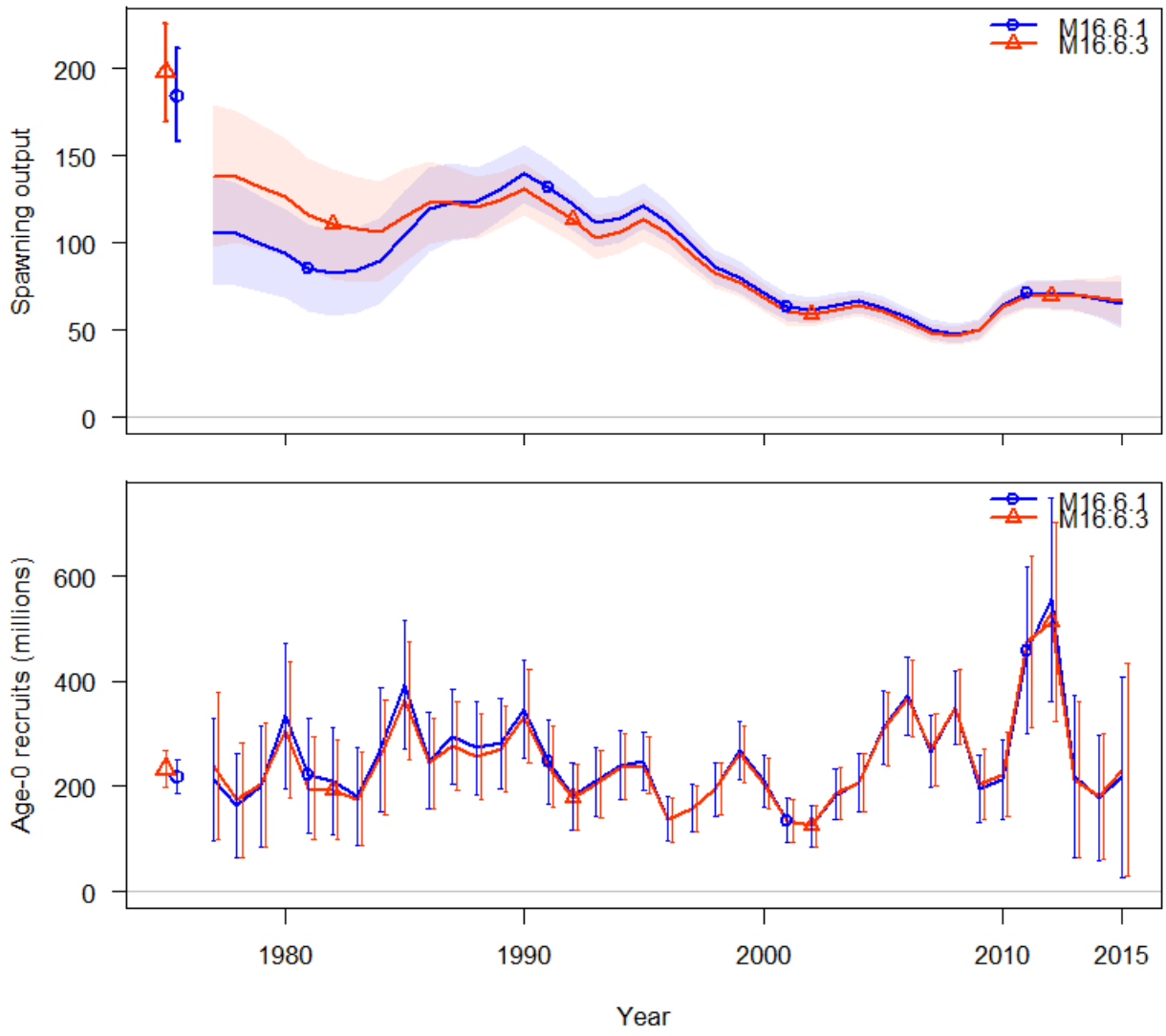


Figure A.2.1.38. Female spawning biomass (1000 t; top) and age-0 recruits (bottom) for in Model 16.6.1 and Model 16.6.3.

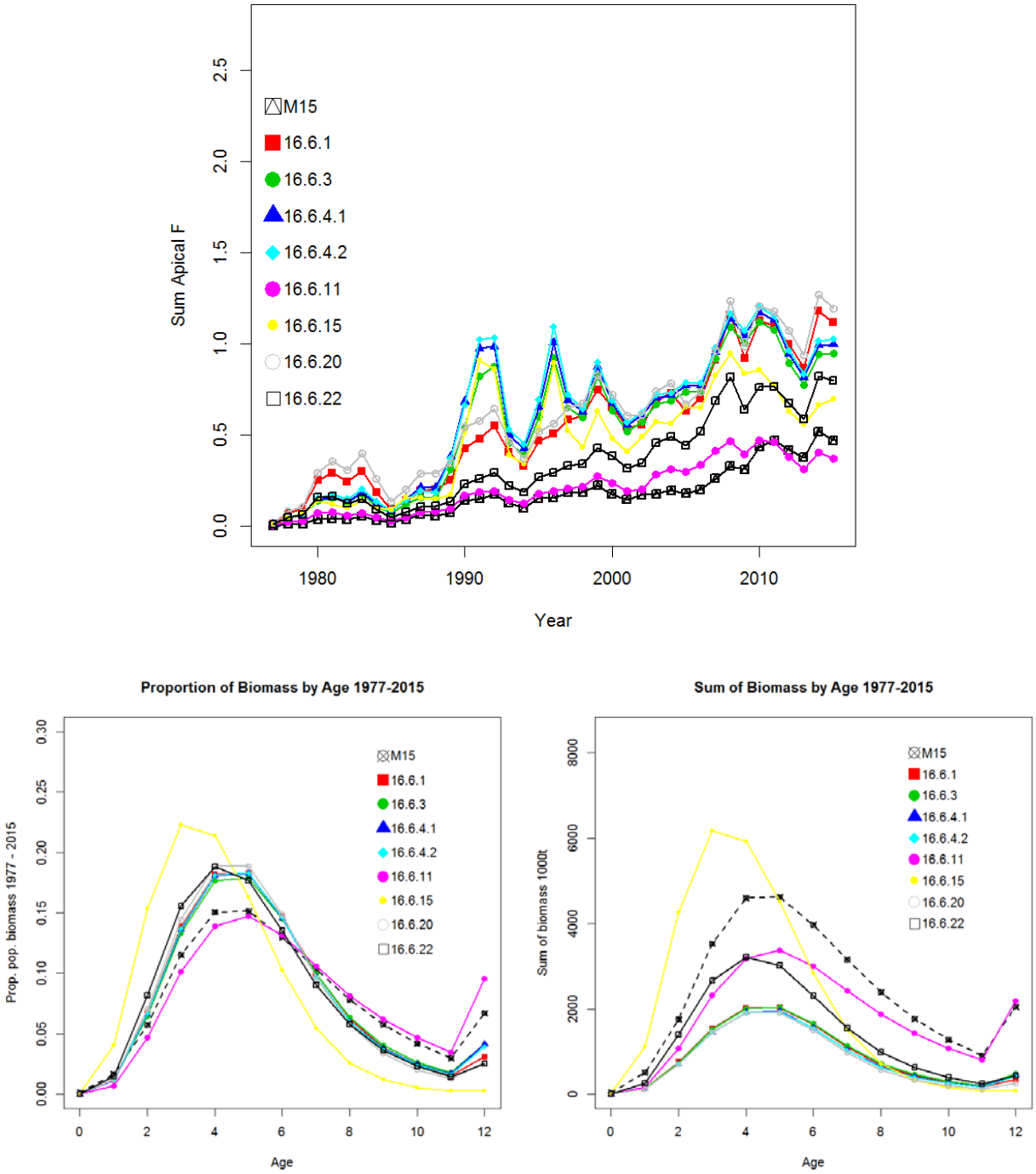


Figure A.2.1.39. Sum of the apical F for 1977-2015 (top), population biomass (left) and proportion of population biomass (right) at each age summed for all years 1977-2015 for the 2015 Model (M15) and models 16.6.1, 16.6.2.3, 16.6.4.1, 16.6.4.2, 16.6.11, 16.6.15, 16.6.20, and 16.6.22

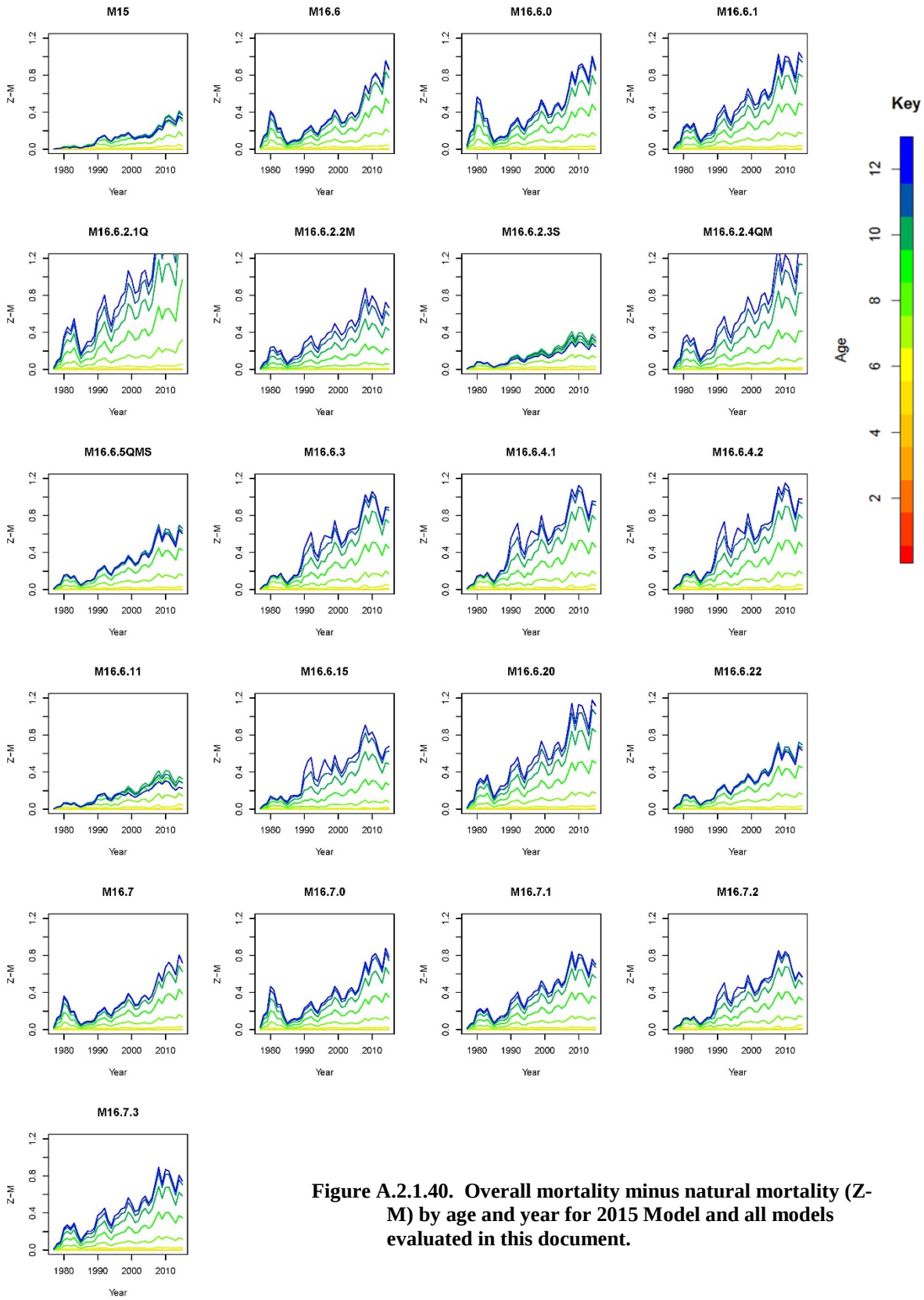


Figure A.2.1.40. Overall mortality minus natural mortality (Z-M) by age and year for 2015 Model and all models evaluated in this document.

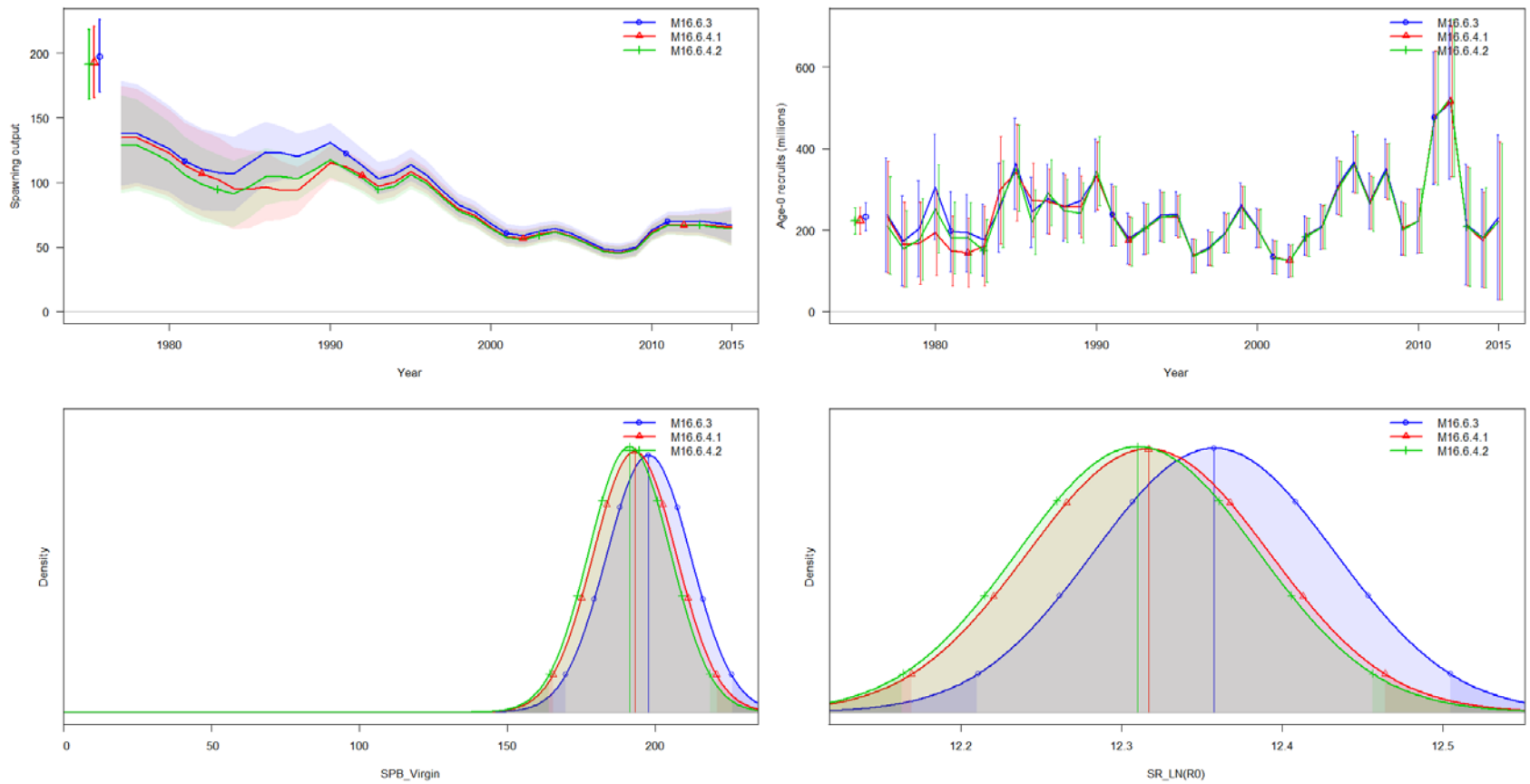


Figure A.2.1.41. Female spawning biomass (1000 t) (top left), age-0 recruits (billions) (top right), model estimates of female virgin spawning biomass (1000 t; bottom left), and log(R_0) (bottom right) for models 16.6.3, 16.6.4.1, and 16.6. 4.2.

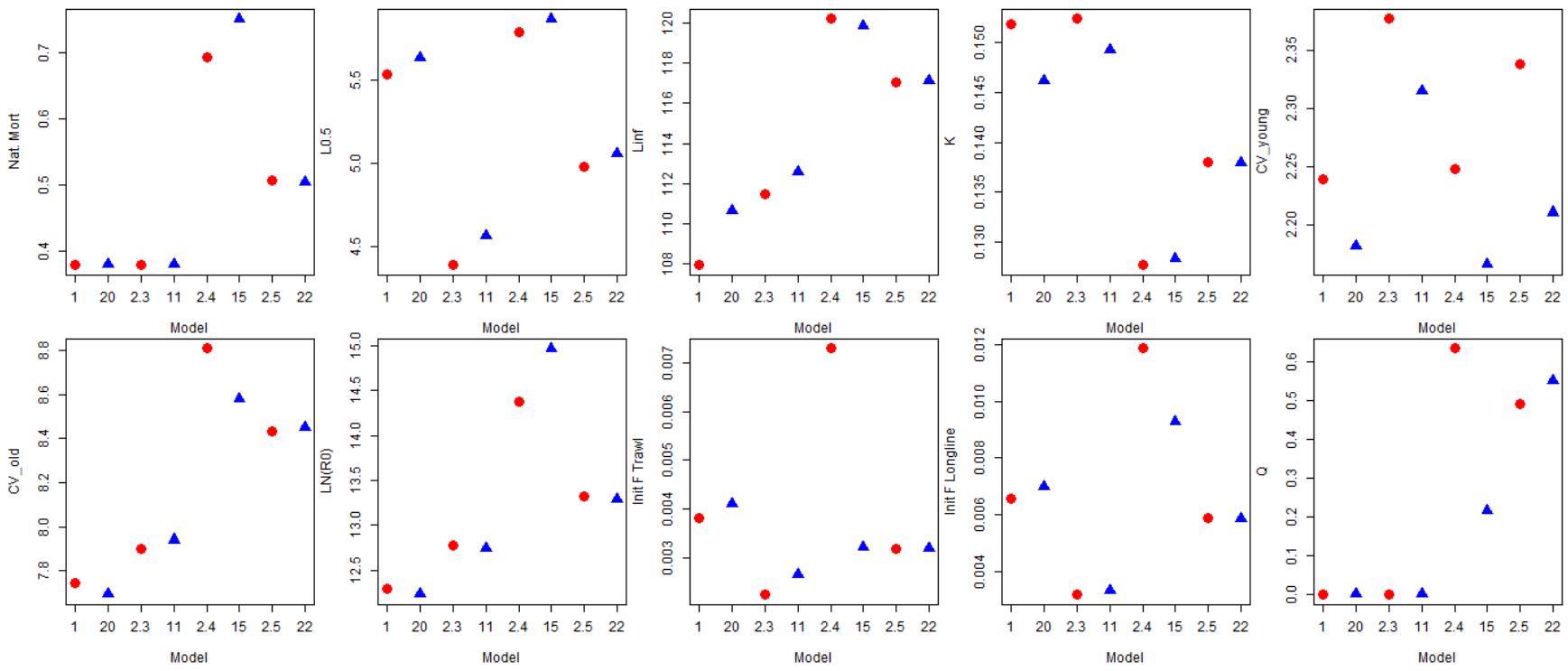


Figure A.2.1.42. Parameters for paired Models 16.6.xx. Red circles are from the initial models and blue triangles are from models without the 1984 and 1987 bottom trawl survey data. Note that Q in this figure should read LN(Q) .

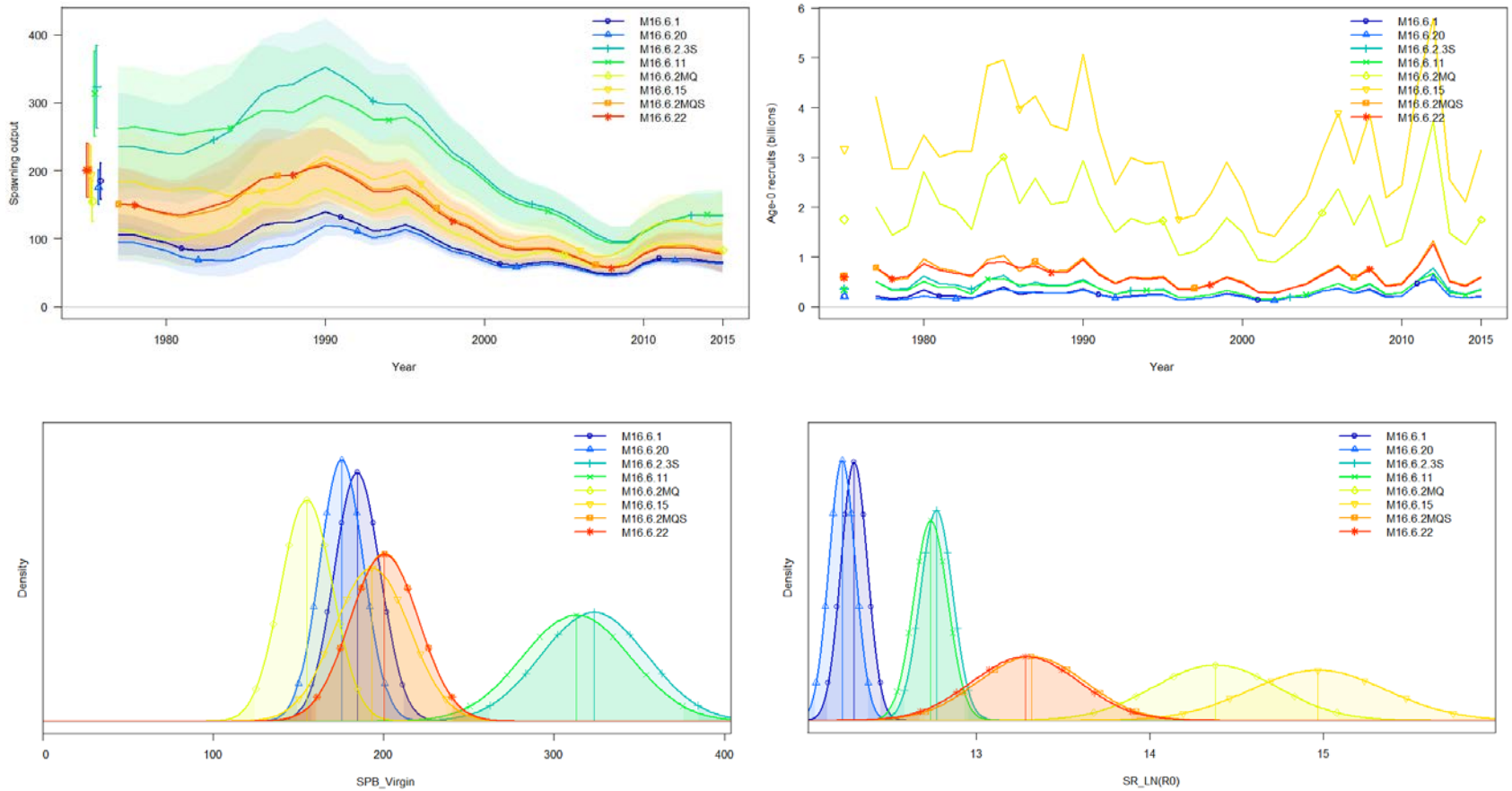


Figure A.2.1.43. Female spawning biomass (1000 t) (top left), age-0 recruits (billions) (top right), model estimates of the female virgin spawning biomass (1000 t; bottom left), and log(R_0) (bottom right) for paired Models 16.6.1 and 16.6.20,16.6.2.3S and 16.6.11, 16.6.2.4MQ, and 16.6.15, and 16.6.2.5MQS and 16.6.22.

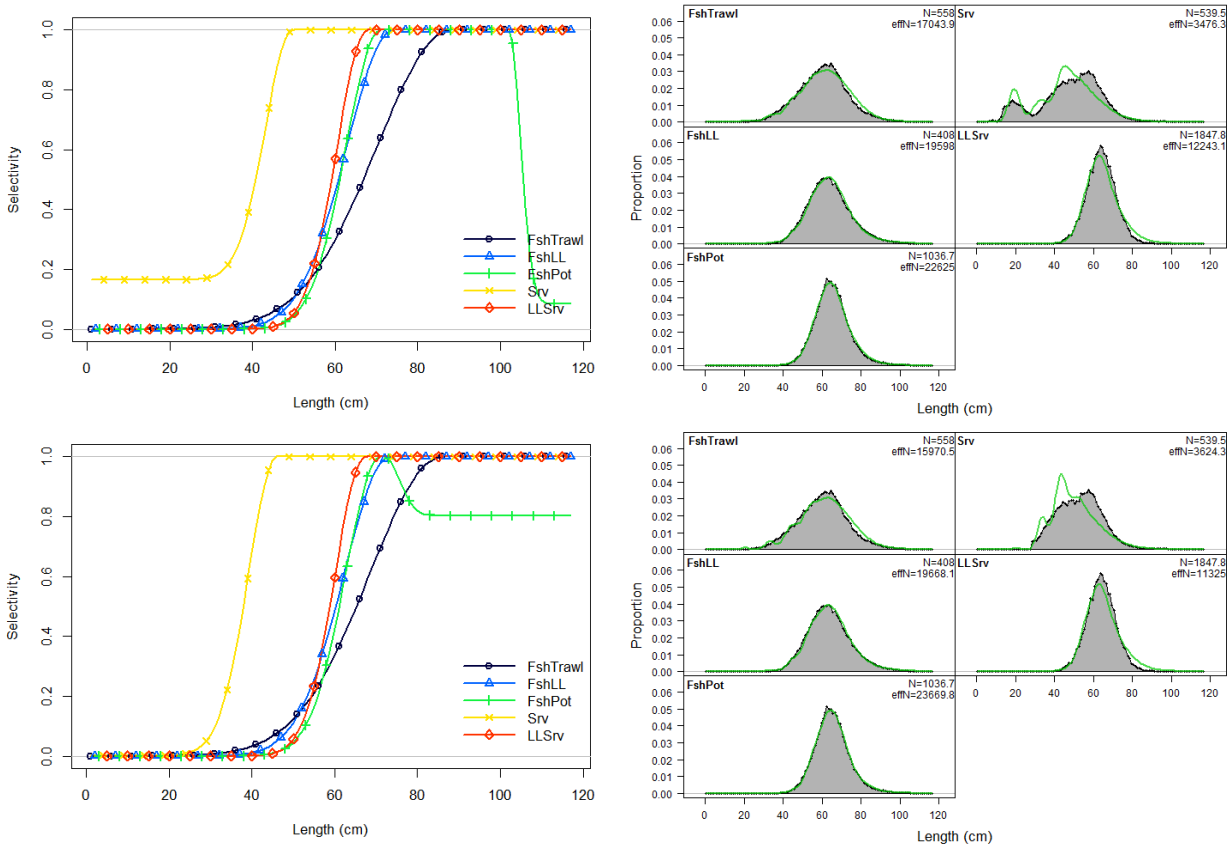


Figure A.2.1.44. Length-based selectivity (left) for Model 16.6.20 (top), Model 16.73 (bottom) with overall estimates of length composition data (right).

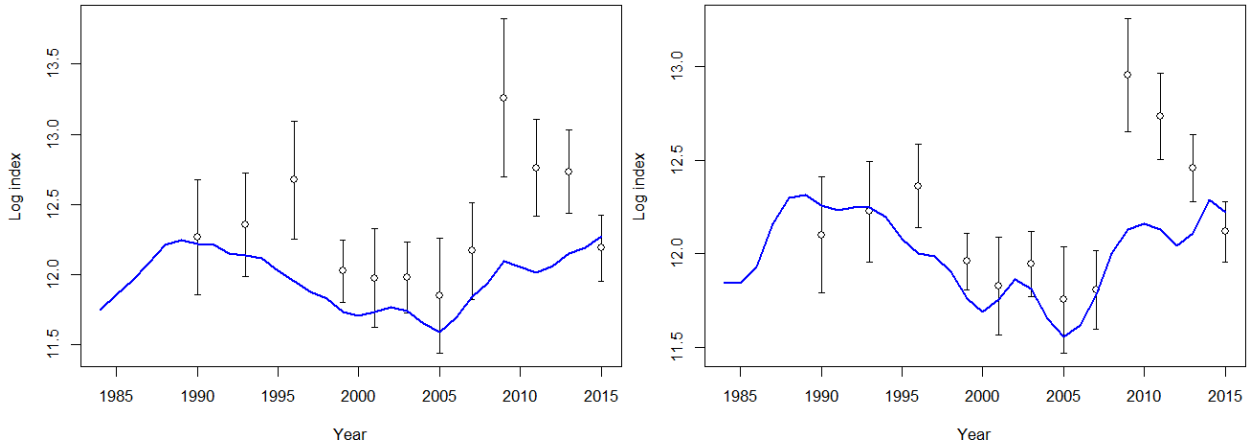


Figure A.2.1.45. Model 16.6.20 (left) and Model 16.7.3 observed versus predicted (blue line) bottom trawl survey abundance index.

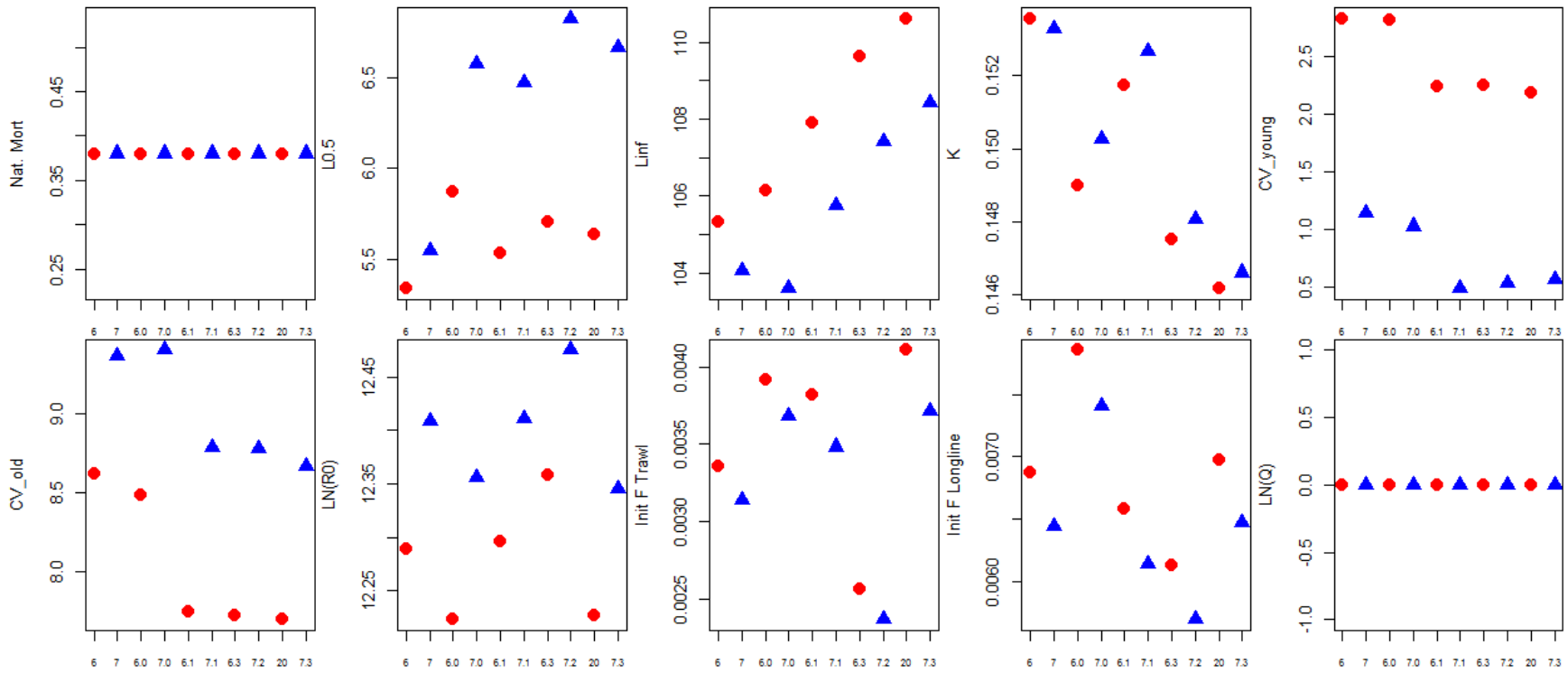


Figure A.2.1.46. Parameters for paired Models 16.xx. Red circles are from the initial models and blue triangles are from models without the Age 1 (<27cm) data for the bottom trawl survey index, length composition and age composition data.

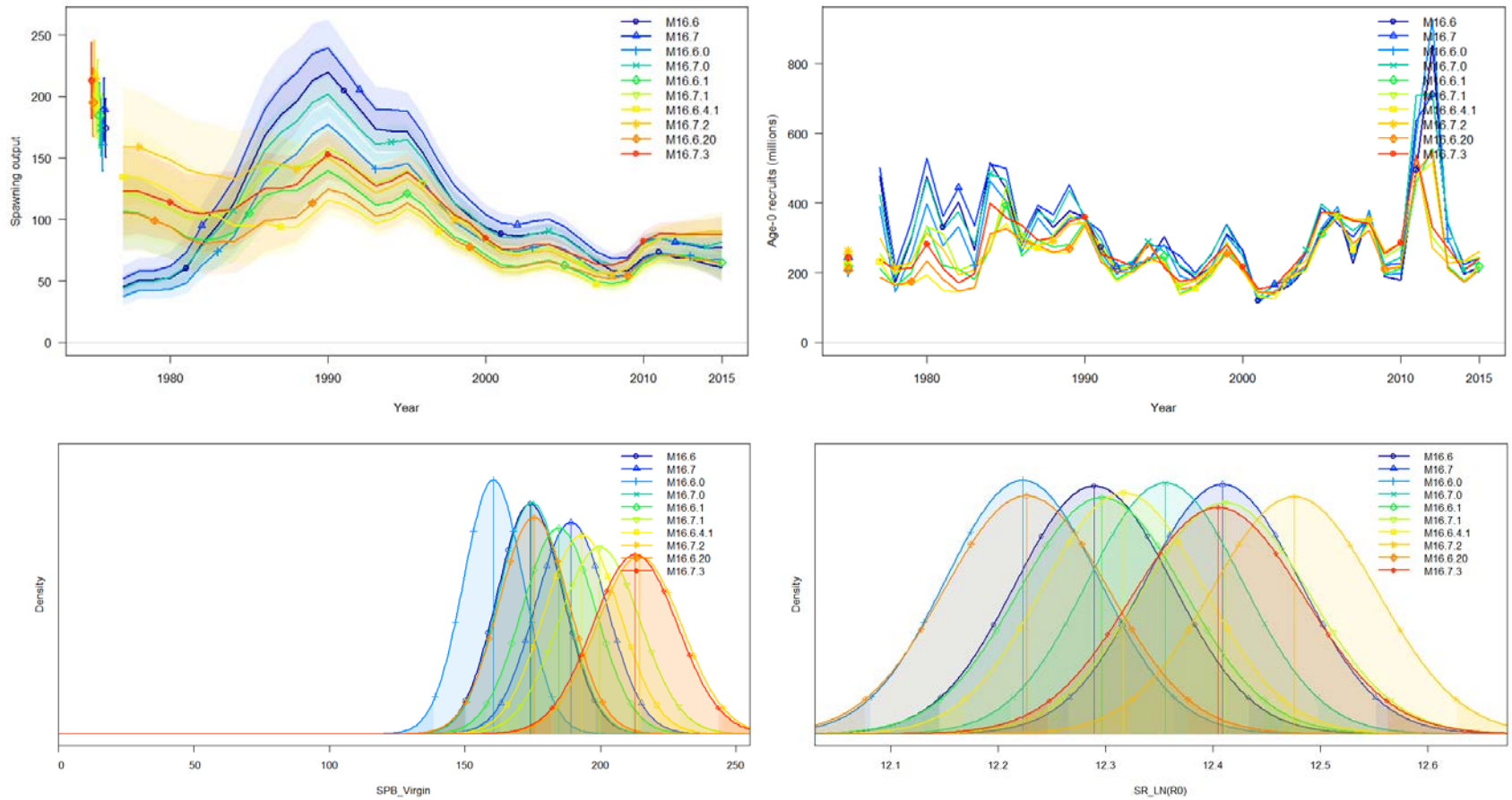


Figure A.2.1.47. Female spawning biomass (1000 t) (top left), age-0 recruits (billions) (top right), model estimates of the female virgin spawning biomass (1000 t; bottom left), and log(R_0) (bottom right) for models 16.6,16.7, 16.6.0,16.7.0,16.6.1, 16.7.1, 16.6.4.1, 16.7.2, 16.6.20, and 16.7.3.

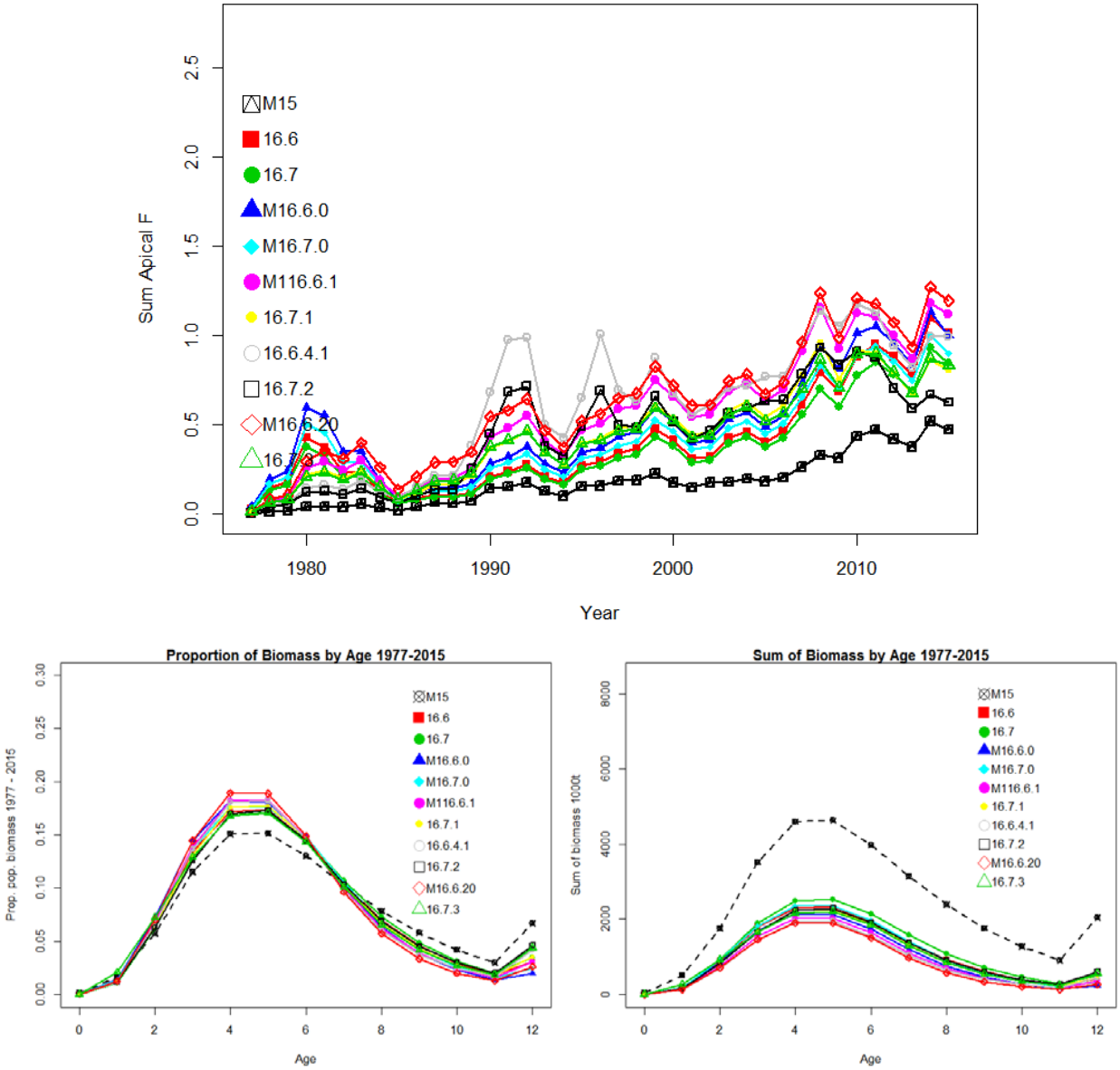
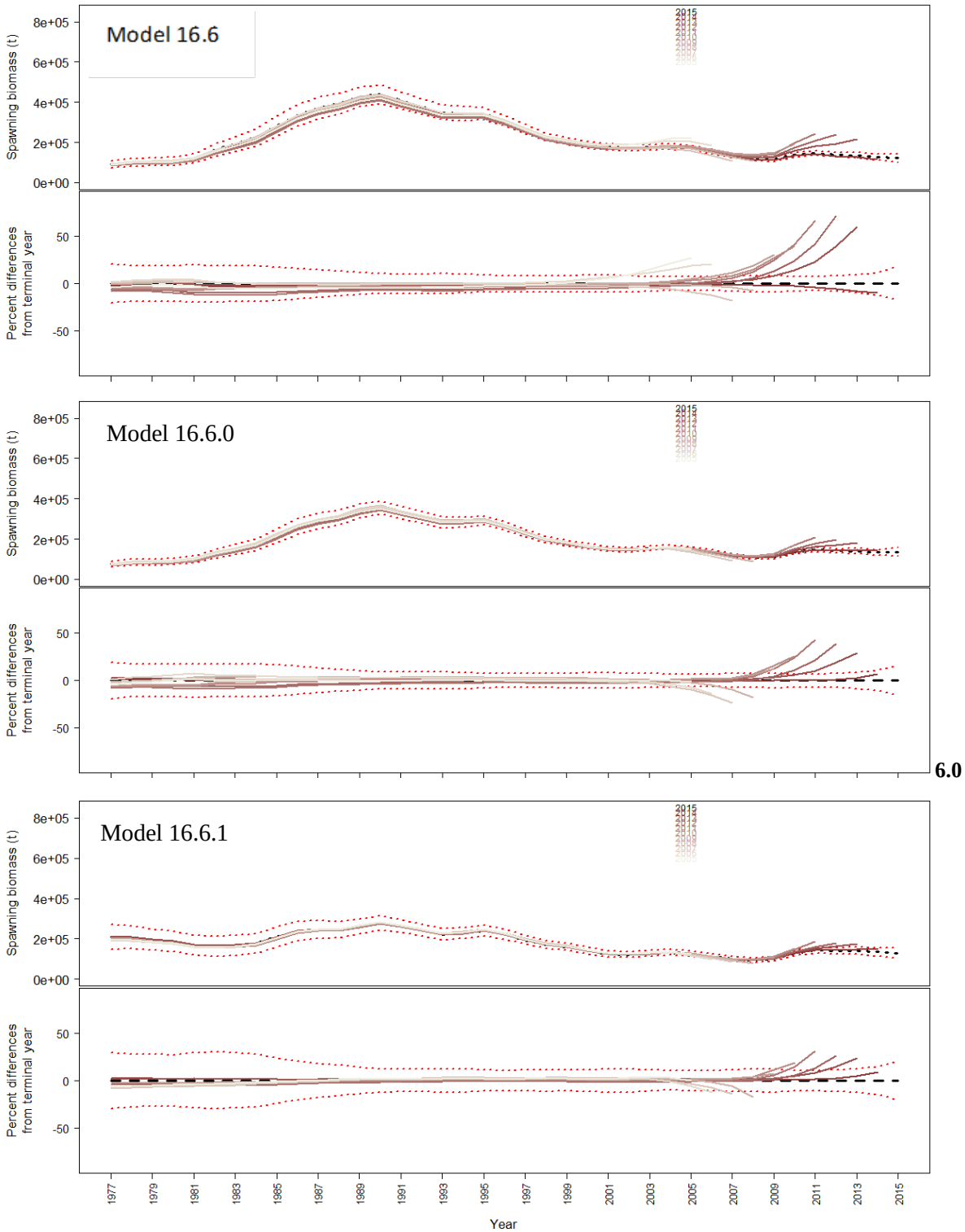


Figure A.2.1.48. Sum of the apical F for 1977-2015 (top), population biomass (left) and proportion of population biomass (right) at each age summed for all years 1977-2015 for the 2015 Model (M15) and models 16.6, 16.7, 16.6.0, 16.7.0, 16.6.1, 16.7.1, 16.6.4.2, 16.7.2, 16.6.20,and 16.7.3.



6.0

Figure A.2.1.49. Retrospective analysis of female spawning biomass (top of each pair) and percentage of difference in female spawning biomass (bottom of each pair).

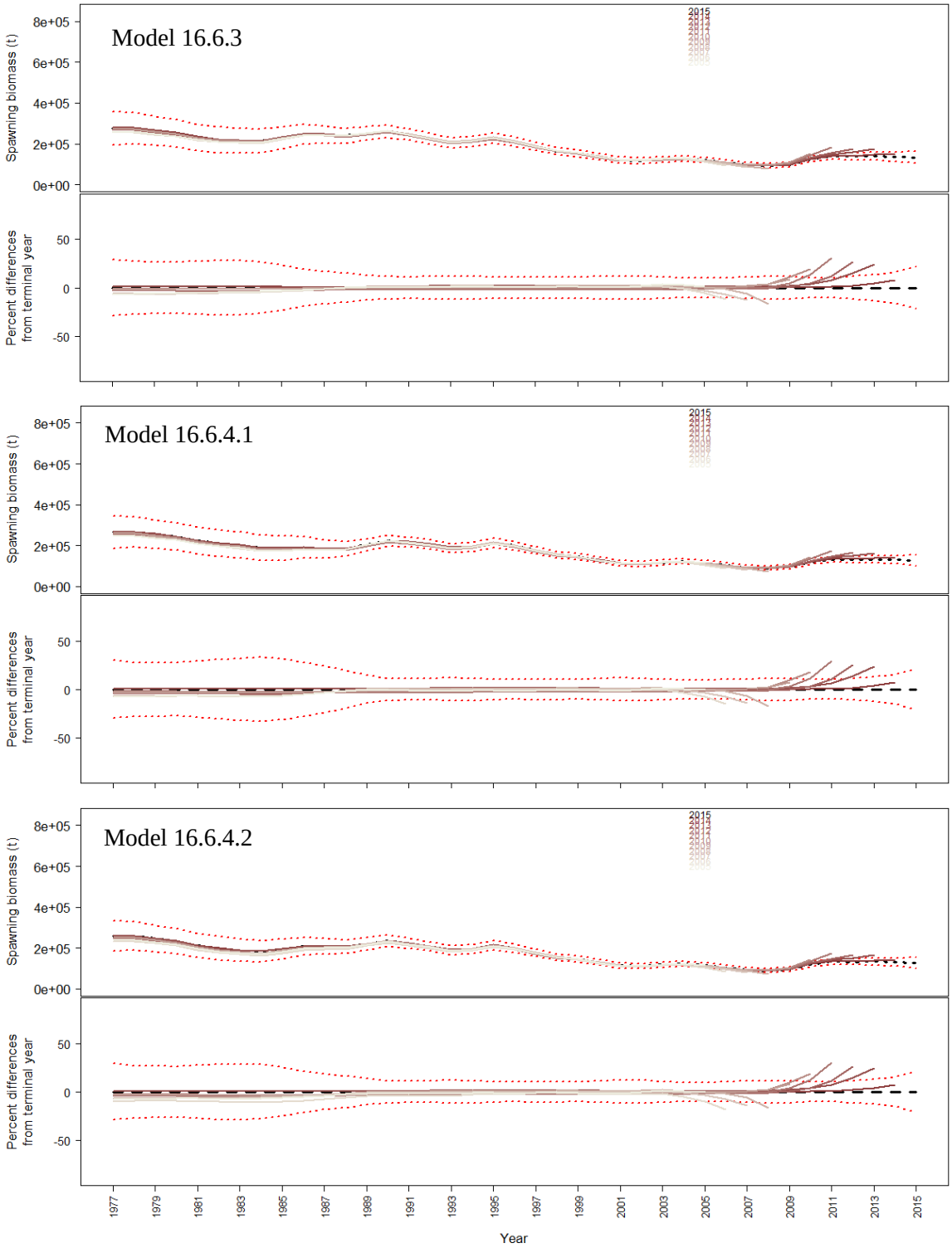


Figure A.2.1.49 cont. Retrospective analysis of female spawning biomass (top of each pair) and percentage of difference in female spawning biomass (bottom of each pair).

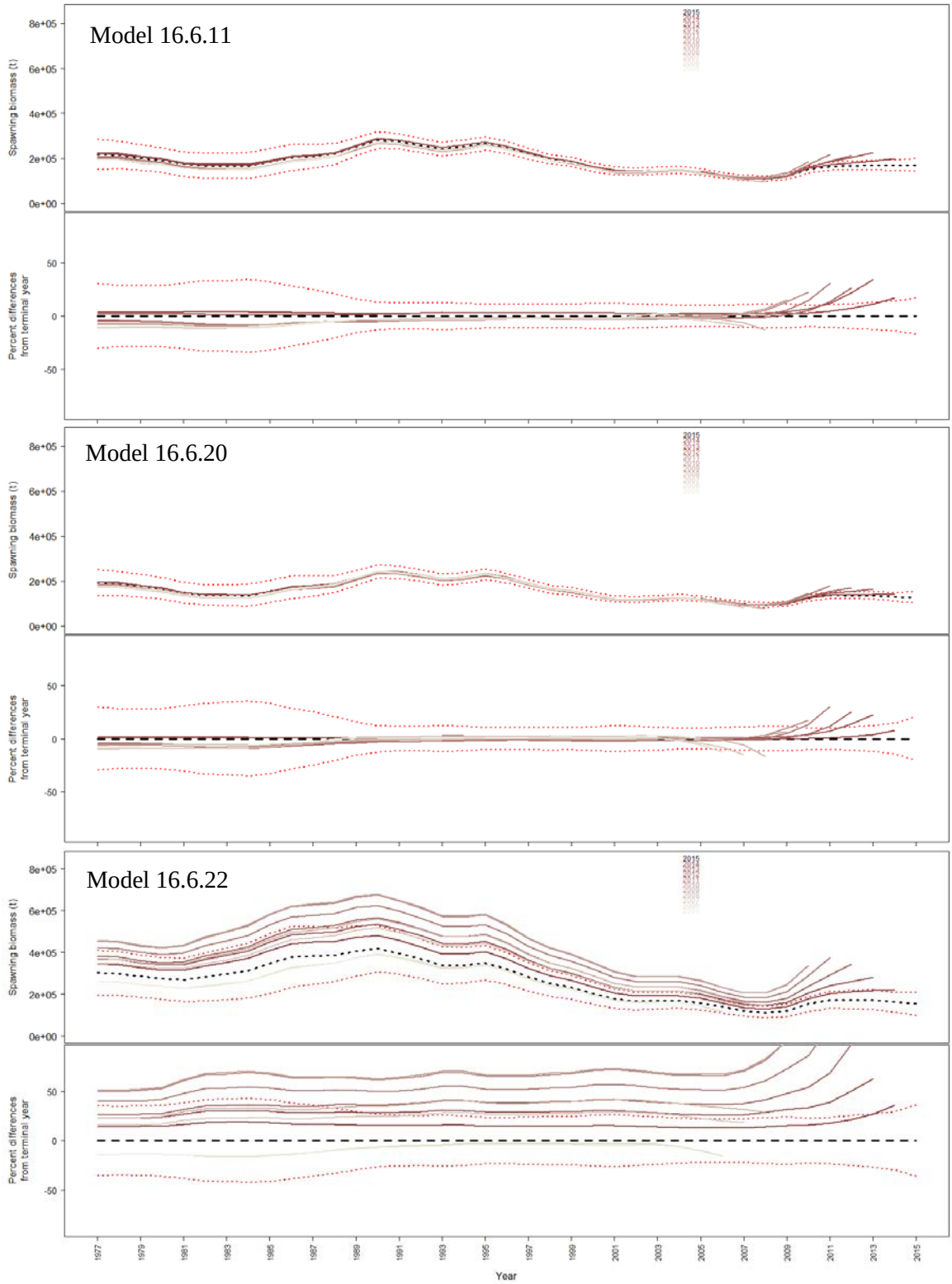


Figure A.2.1.49 cont. Retrospective analysis of female spawning biomass (top of each pair) and percentage of difference in female spawning biomass (bottom of each pair).

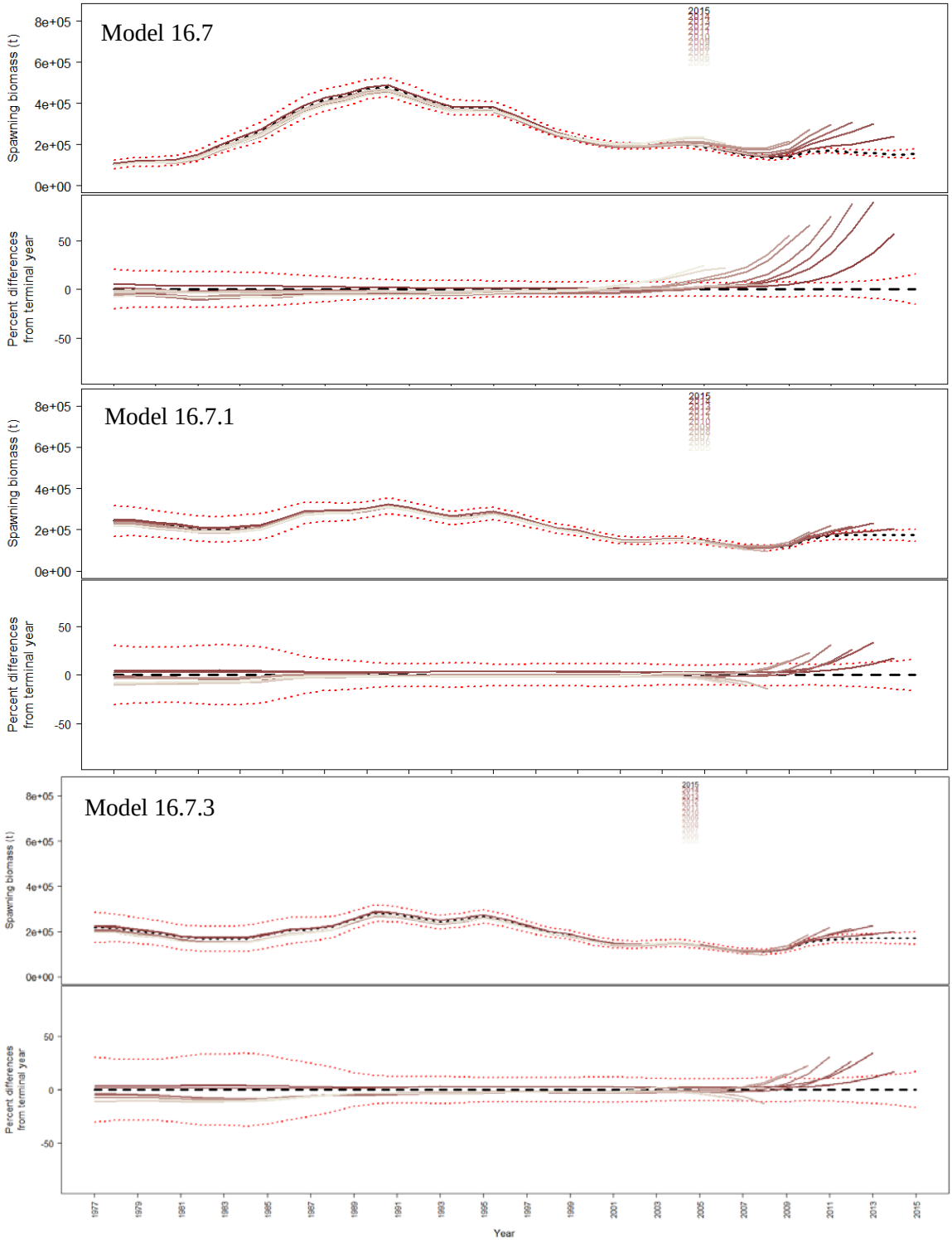


Figure A.2.1.49 cont. Retrospective analysis of female spawning biomass (top of each pair) and percentage of difference in female spawning biomass (bottom of each pair).

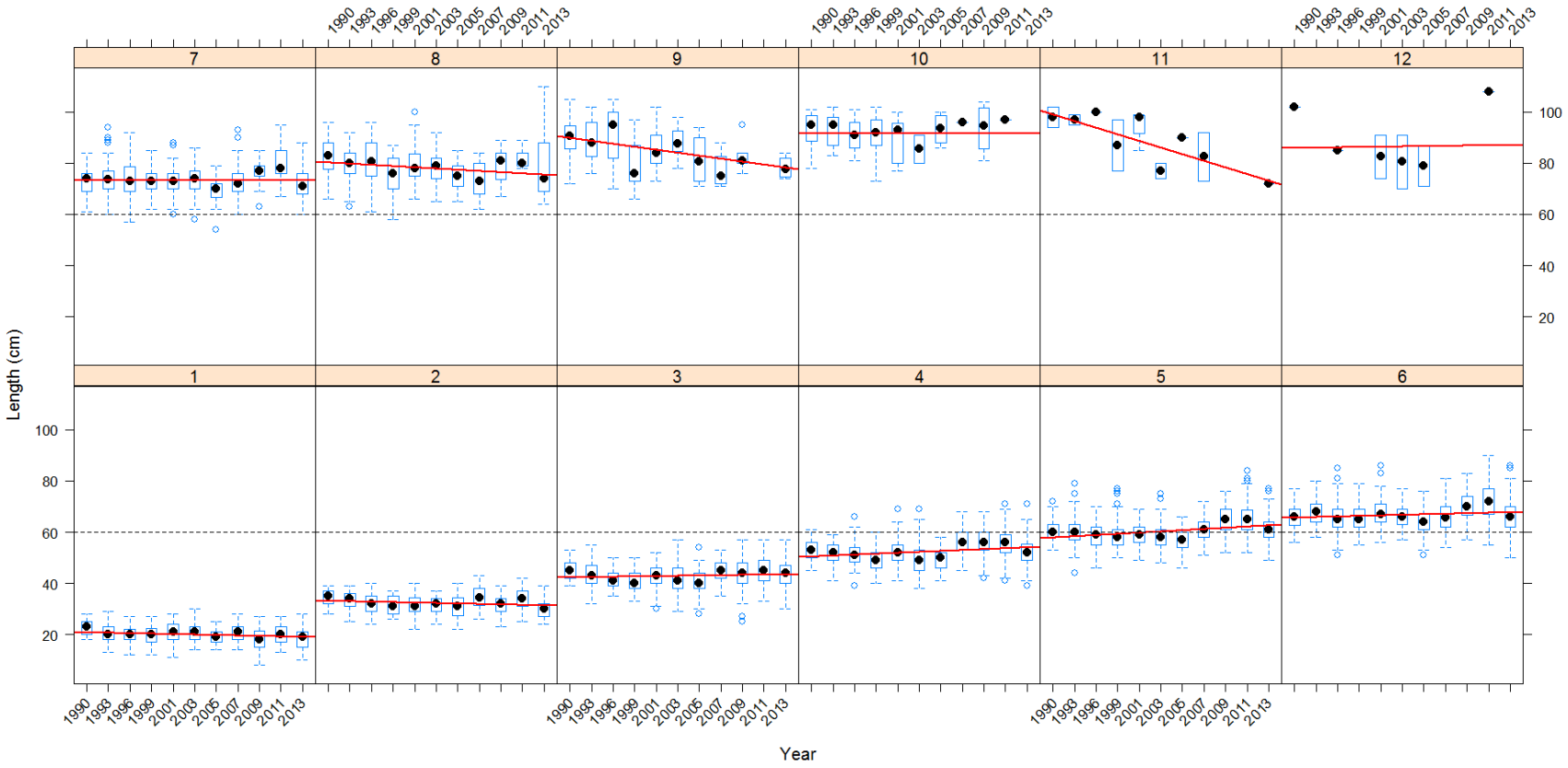


Figure A.2.1.50. Pacific cod length (cm) at age from the 1990 – 2013 bottom trawl survey data. Red line is a linear model fit to each age across time, black checkered line is a flat line at 60 cm for reference.

Appendix 2.3: Pacific cod (GOA) Economic Performance Report for 2015

Author: Ben Fissel

Pacific cod is a critical species in the catch portfolio of the Gulf of Alaska (GOA) fisheries. Pacific cod typically accounts for just under 30% of the GOA's FMP groundfish harvest and over 20% of the total Pacific cod harvest in Alaska. Retained catch of Pacific cod decreased 4% to 54 thousand t in 2015 (as a result of a mid-year closure of the fishery), and though down from its recent high of 60 thousand t in 2011, it is 30% higher than the 2006-2010 average (Table A2.3.1). The products made from GOA Pacific cod had a first-wholesale value was $103 million in 2015, which was down from $118 million in 2014 and above the 2006-2010 average of $190 million (Table A2.3.2). The higher revenue in recent years is largely the result of increased catch and production levels as the average first-wholesale price of Pacific cod products have declined in recent years.

The fishery for cod is an iconic fishery with a long history, particularly in the North Atlantic. Global catch was consistently over 2 million t through the 1980s, but began to taper off in the 1990s as cod stocks began to collapse in the northwest Atlantic Ocean. Over roughly the same period, the U.S. catch of Pacific cod (caught in Alaska) grew to approximately 250 thousand tons where it remained throughout the early to mid-2000s. European catch of Atlantic cod in the Barents Sea (conducted mostly by Russia, Norway, and Iceland) slowed and global catch hit a low in 2007 at 1.13 million t. U.S. Pacific cod's share of global catch was at a high at just over 20% in the early 2000s. Since 2007 global catch has grown to 1.85 million t in 2014 as catch in the Barents Sea has rebounded and U.S. catch has remained strong at over 300 thousand t since 2011. European Atlantic cod and U.S. Pacific cod remain the two major sources supplying the cod market over the past decade accounting for roughly 75% and 20%, respectively. Atlantic cod and Pacific cod are substitutes in the global market. Because of cod's long history, global demand is present in a number of geographical regions, but Europe and the U.S. are the primary consumer markets for many of the Pacific cod products. The market for cod is also indirectly affected by activity in the pollock fisheries which experienced a similar period of decline in 2008-2010 before rebounding. Cod and pollock are commonly used to produce breaded fish portions. Alaska caught Pacific cod in the GOA became certified by the Marine Stewardship Council (MSC) in 2010, a NGO based third-party sustainability certification, which some buyers seek. Changes in global catch and production account for much of the broader time trends in the cod markets. In particular, the average first-wholesale prices peak approximately $1.90 per pound in 2008 and subsequently declined precipitously to approximately $1.50 per pound in 2009-2010 as markets priced in consecutive years of approximately 100 thousand t increases in the Barents Sea cod catch in 2009-2011; coupled with reduced demand from the recession.

The Pacific cod total allowable catch (TAC) is allocated to multiple sectors. In the GOA, sectors are defined by gear type (hook and line, pot, trawl and jig) and processing capacity (catcher vessel (CV) and catcher processor (CP)). Within the sectoral allocations the fisheries effectively operate as open access with limited entry. Almost all of the GOA Pacific cod fisheries is caught by CVs which make deliveries to shore-based processors and accounts for 90% of the total GOA Pacific cod catch. Approximately 40% is caught by the trawl, 40% is caught by pot gear, and 20% caught by hook and line, though the number of hook and line vessels is far greater. The retained catch in the GOA decreased 4.4% increase to 54.3 thousand t in large part due to a mid-year closure of the fishery because the Chinook bycatch limit was reached. The value of CV deliveries (shoreside ex-vessel value) totaled $45.7 million in 2015, which was down from $47.3 million in 2014. Ex-vessel prices were basically unchanged decreasing 1% to an average of $0.295 per pound in 2015. Changes in ex-vessel prices are generally a response to in the price changes in wholesale markets. In 2013 catch was low relative to the TAC because of a $0.09 per pound drop in ex-vessel prices to $0.266 per pound with a commensurate drop in cod head-and-gut wholesale

prices; poor fishing conditions, particularly in the central Gulf, were an additional contributing factor. Catch from the fixed gear vessels (which includes hook-and-line and pot gear) typically receive a slightly higher price from processors because they incur less damage when caught, has recently been about $0.04 per pound.

The first-wholesale value of Pacific cod products was down 13% to $103.1 million in 2015, though revenues in recent years remain high as result of increased catch levels when compared with the average from 2006-2010. The decrease in revenue is the combined effect of price decreases and a shift in the production share from fillets to lower priced H&G. The average price of Pacific cod products in 2015 decreased 15% to $1.462 driven by decreases in H&G and fillet prices. The strength of the U.S. dollar in 2015 could have been a contributing factor in the price decrease. Production in the GOA is relatively balanced between fillets which are typically about 50% of the value, and head and gut (H&G) which are typically 35% of the value. This product mix can vary year to year depending on prices and market conditions. In 2013 H&G prices dropped $0.18 per pound as the Barents Sea catch increased roughly 240 thousand t and GOA H&G cod production dropped from 15.4 to 6.6 thousand t and production shifted to fillets where 2013 prices increased $0.30 per pound. Fillet prices in the GOA have remained fairly stable despite the relatively high global whitefish supply volume in recent years, though 2015 prices are on the low end of what been observed over the past 5 years.

U.S. exports of cod have risen almost proportionally with increasing U.S. cod production (Table A2.3.3). More than 90% of the exports are H&G, most of which goes to China for secondary processing and re-export. China’s rise as re-processor is fairly recent. Between 2001 and 2011 exports to China have increased nearly 10 fold. Japan and Europe (mostly Germany and the Netherlands) are also important export destinations. Approximately 30% of Alaska’s cod production is estimated to remain in the U.S. Because the GOA Pacific cod is a relatively small component of the broader cod market, changes in catch have little impact on wholesale prices. In 2016 Norway and Russia maintained their Barents Sea TAC at 2015 levels despite recommendations by ICES to reduce the TAC by roughly 10%. Reports indicate that marginal reduction in the Barents Sea catch is planned to take effect in 2017, but it is sufficiently small that it may not impact prices much.

Tables

Table A2.3.1. Gulf of Alaska Pacific cod catch and ex-vessel data. Total, Federal, and retained catch (thousand metric tons), number of vessel, hook and line and pot gear share of catch, inshore sector share of catch, inshore sector ex-vessel value (million US$) and price (US$ per pound); 2006-2010 average and 2011-2015.

	Avg 06-10	2011	2012	2013	2014	2015
Total catch K mt	58.1	85.2	78	68.6	84.8	79
Federal catch K mt	44.0	62	56	51	62	56
Retained catch K mt	41.3	59.9	55	46.4	56.8	54.3
Vessels #	442.6	536	538	369	369	403
Hook & line share of catch	30%	27%	27%	25%	26%	23%
Pot gear share of catch	32%	47%	38%	33%	32%	38%
Shoreside share of catch	85%	85%	91%	92%	87%	88%
Shoreside ex-vessel value M $	40.84	54.1	55.2	34.8	47.3	45.7
Shoreside ex-vessel price lb $	$0.392	$0.334	$0.353	$0.266	$0.298	$0.295

Source: NMFS Alaska Region Blend and Catch-accounting System estimates; NMFS Alaska Region At-sea Production Reports; and ADF&G Commercial Operators Annual Reports (COAR). Data compiled and provided by the Alaska Fisheries Information Network (AKFIN).

Table A2.3.2. Gulf of Alaska Pacific cod first-wholesale market data. First-wholesale production (thousand metric tons), value (million US$), price (US$ per pound), fillet and head and gut volume (thousand metric tons), value share, and price (US$ per pound), inshore share of value; 2006-2010 average and 2011-2015.

		Avg 06-10	2011	2012	2013	2014	2015
All Products	**volume K mt**	24.60	35.28	34.09	23.80	31.07	32.00
All Products	**value M $**	$90.96	$131.05	$113.60	$94.25	$118.13	$103.11
All Products	**price lb $**	$1.677	$1.685	$1.511	$1.796	$1.724	$1.462
Fillets	**volume K mt**	6.44	9.23	9.08	9.70	9.85	6.39
Fillets	**value share**	48.6%	47.3%	50.1%	71.3%	57.1%	39.0%
Fillets	**price lb $**	$3.114	$3.045	$2.844	$3.142	$3.103	$2.852
Head & Gut	**volume K mt**	10.55	17.29	15.37	6.63	13.95	19.05
Head & Gut	**value share**	35.9%	39.8%	35.4%	15.6%	32.6%	48.1%
Head & Gut	**price lb $**	$1.405	$1.370	$1.186	$1.005	$1.251	$1.181
Shoreside value share		87.2%	88.2%	91.7%	95.3%	92.2%	91.1%

Source: NMFS Alaska Region Blend and Catch-accounting System estimates; NMFS Alaska Region At-sea Production Reports; and ADF&G Commercial Operators Annual Reports (COAR). Data compiled and provided by the Alaska Fisheries Information Network (AKFIN).

Table A2.3.3. Cod U.S. trade and global market data. Global production (thousand metric tons), U.S. share of global production, and Europe's share of global production; U.S. export volume (thousand metric tons), value (million US$), and price (US$ per pound); U.S. cod consumption (estimated), and share of domestic production remaining in the U.S. (estimated); and the share of U.S. export volume and value for head and gut (H&G), fillets, China, Japan, and Germany and Netherlands; 2006-2010 average and 2011-2016.

		Avg 06-10	2011	2012	2013	2014	2015	2016 (thru June)
Global cod catch K mt		1,209	1,505	1,600	1,828	1,850	-	-
U.S. P. cod share of global catch		19.0%	20.0%	20.4%	16.9%	17.6%	-	-
Europe share of global catch		71.8%	73.1%	73.2%	76.7%	76.0%	-	-
Pacific cod share of U.S. catch		96.7%	97.4%	98.6%	99.3%	99.3%	-	-
U.S. cod consumption K mt (est.		80	88	98	105	115	108	-
Share of U.S. cod not exported		24%	24%	30%	31%	31%	26%	-
Export volume K mt		86.6	110.8	111.1	101.8	107.3	113.2	71.7
Export value M US$		$266.1	$371.3	$363.6	$308.0	$314.2	$334.9	$204.3
Export price lb US$		$1.393	$1.520	$1.485	$1.373	$1.328	$1.342	$1.293
Frozen (H&G)	volume Share	71%	74%	80%	91%	92%	91%	94%
	value share	69%	75%	80%	89%	91%	90%	93%
Fillets	volume Share	13%	9%	9%	4%	2%	3%	3%
	value share	16%	12%	11%	5%	4%	4%	4%
China	volume Share	23%	39%	46%	51%	54%	53%	64%
	value share	21%	37%	43%	48%	51%	51%	61%
Japan	volume Share	18%	20%	16%	13%	16%	13%	9%
	value share	18%	20%	16%	13%	16%	14%	9%
Netherlands & Germany	volume Share	11%	10%	8%	8%	9%	8%	5%
	value share	13%	11%	9%	9%	10%	8%	5%

Notes: Pacific cod in this table is for all U.S. Unless noted, `cod' in this table refers to Atlantic and Pacific cod. Russia, Norway, and Iceland account for the majority of Europe's cod catch which is largely focused in the Barents sea.

Source: FAO Fisheries & Aquaculture Dept. Statistics http://www.fao.org/fishery/statistics/en. NOAA Fisheries, Fisheries Statistics Division, Foreign Trade Division of the U.S. Census Bureau, http://www.st.nmfs.noaa.gov/commercial-fisheries/foreign-trade/index. U.S. Department of Agriculture http://www.ers.usda.gov/data-products/agricultural-exchange-rate-data-set.aspx.