

A stock assessment for eastern Bering Sea snow crab

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1. Stock: Eastern Bering Sea snow crab, *Chionoecetes opilio*.

2. Catches: trends and current levels

Retained catches increased from relatively low levels in the early 1980s (e.g. retained catch of 11.85 kt during 1982) to historical highs in the early and mid-nineties (retained catch during 1991, 1992, and 1998 were 143.02, 104.68, and 88.09 kt, respectively). The stock was declared overfished in 1999 at which time retained catches dropped to levels similar to the early 1980s (e.g. retained catch during 2000 was 11.46 kt). Retained catches have slowly increased since 1999 as the stock rebuilt, although retained catch during 2017 was low (8.6 kt) as a result of low estimated mature biomass.

Discard mortality is the next largest source of mortality after retained catch and approximately tracks the retained catch. The highest estimated discard mortality occurred during 1992 at 17.06 kt which was 16% of the retained catch. The most recent estimated discard mortality was 1.93 kt which was 22% of the retained catch.

3. Stock Biomass:

Observed mature male biomass (MMB) at the time of the survey increased from an average of 234.14 kt in the early to mid-1980s to historical highs in the early and mid-nineties (observed MMB during 1990, 1991, and 1997 were 443.79, 466.61, and 326.75 kt, respectively). The stock was declared overfished in 1999 in response to the total mature biomass dropping below the minimum stock size threshold. MMB in that year decreased to 95.85 kt. Observed MMB slowly increased after 1999, and the stock was declared rebuilt in 2011 when estimated MMB at mating was above $B_{35\%}$. However, since 2011, the stock has declined again and the observed MMB at the time of survey dropped to an all time low in 2017 of 83.96 kt. This year's MMB (2018) marks the highest observed at the time of the survey since 1998.

4. Recruitment

Estimated recruitment shifted from a period of high recruitment to a period of low recruitment in the mid 1990s (late 1980s when lagged to fertilization). Recently, a large year class recruited to the survey gear, appears to have persisted to the present, and is beginning to be seen in the exploitable biomass.

5. Management

Table 1: Historical status and catch specifications for snow crab (1,000t).

Year	MSST	Biomass (MMB)	TAC	Retained catch	Total catch	OFL	ABC
2014/2015	73.2	129.3	30.8	30.8	69.0	69.0	62.1
2015/2016	75.8	91.6	18.4	18.4	61.5	61.5	55.4
2016/2017	75.8	96.1	9.7	9.7	23.7	23.7	21.3
2017/2018	79.7	99.6	8.6	8.6	28.4	28.4	22.7
2018/2019	62.7	122.5				42.1	33.7

Table 2: Historical status and catch specifications for snow crab (millions of lbs).

Year	MSST	Biomass (MMB)	TAC	Retained catch	Total catch	OFL	ABC
2014/2015	161.38	285.06	67.9	67.9	152.12	152.12	136.91
2015/2016	167.11	201.94	40.57	40.57	135.58	135.58	122.14
2016/2017	167.11	211.86	21.38	21.38	52.25	52.25	46.96
2017/2018	175.71	219.58	18.96	18.96	62.61	62.61	50.04
2018/2019	138.23	270.07				92.81	74.3

6. Basis for the OFL

The OFL for 2018 from the chosen model (Sep devs + loose prior) was 42.15 kt fishing at $F_{OFL} = 2.24$ (97 % of the calculated $F_{35\%}$, 2.29). The calculated OFL was a 48% change from the 2017 OFL of 28.4 kt. The projected ratio of MMB at the time of mating to $B_{35\%}$ is 0.98.

7. Probability Density Function of the OFL

The probability density function of the OFL was characterized for all models by using maximum likelihood estimates of the OFL and associated standard errors. PDFs of the OFL for selected models were characterized using a Markov Chain Monte Carlo algorithm to sample from its posterior distribution. Reported OFLs are maximum likelihood estimates because of pathologies in the MCMC output.

8. Basis for ABC

The ABC for the chosen model was 33.72 kt, calculated by subtracting a 20% buffer from the OFL as recommended by the SSC.

A. Summary of Major Changes

1. Management: None

2. Input data:

Data added to the assessment included: 2018 Bering Sea survey biomass and length frequency data, 2017 directed fishery retained and discard catch and length frequencies for retained and discard catch, and groundfish discard length frequency and discard from 2017. Growth data were updated with 70 observations of pre- and post-molt lengths (45 for females; 25 for males).

3. Assessment methodology:

The recommended OFL was calculated using Bayesian methodologies in 2016 and 2017, which was a departure from the previous projection framework (but provided similar management advice). Both a maximum likelihood approach (including ‘jittering’) and a Bayesian treatment of the data were completed for selected models this year. Management quantities from the author chosen model are reported as the maximum likelihood estimates because of convergence issues with MCMC.

4. Assessment results

The updated estimate of MMB (February 15, 2017) was 93.74 which placed the stock at 75% of $B_{35\%}$. Projected MMB on February 15, 2018 from this assessment’s chosen model was 122.47 kt after fishing at the OFL, which will place the stock at 98% of $B_{35\%}$. Fits to all data sources were acceptable for the chosen model and most estimated population processes were credible (see discussion below).

B. CPT May 2018 comments, SSC comments, and author response:

CPT and SSC comments

The CPT made three recommendations for scenarios to be presented in September based on analyses presented during the May 2018 CPT meeting:

- 2017 accepted model—Estimate M for females, males, and immature crab.
- Fix female M—The same model as above, but fix natural mortality for mature females at 0.23, to match the 2016 accepted model.
- Fit the model to total and retained size composition data, rather than the total and discarded size comps.

The CPT also recommended resolving problems with any parameters hitting bounds. The SSC agreed with these suggestions and proposed additional runs to explore the impact of priors on natural mortality. The SSC suggested exploring the potential that catchability for the BSFRF data was not 1 by locating information (e.g. underwater video of surveys) to inform this assumption. The SSC also noted potential issues with the mixing of several parameters when implementing an MCMC algorithm and suggested that the model ‘may now be getting too complicated’. The SSC supported an increase of the buffer for the ABC from 10% to 20%.

The author presents 7 runs based on these recommendations:

- “2017 Accepted” – Last year’s accepted model fit to last year’s data.
- “New Data” – Last year’s accepted model fit to this year’s data.
- “Fix fem M” – Last year’s accepted model fit to this year’s data, but turning off estimation of mature female natural mortality to more closely match the 2016 accepted model.
- “Loose prior M” – Estimate mature female natural mortality (and mature male and immature female and male), but use a less informative prior.
- “Looser prior M” – Estimate mature female natural mortality (and mature male and immature female and male), but use an even less informative prior.
- “Sep devs” – Estimate recruitment deviations for males and females instead of using a common recruitment between sexes. This is an addition of the author’s, given the runs in the residuals of the fits to the survey mature biomass and observed retrospective patterns. Female mature biomass is underestimated in recent years, whereas male biomass is overestimated. Potential rationale for fitting different recruitment deviations by sex include different growth rates between sexes (resulting in different ages of crab by sex in the first length bins) and different observed spatial distribution of immature females and males.
- “Sep devs + loose prior M” – Combine “Sep devs” and “Loose prior M”
- “Sep devs + looser prior M” – Combine “Sep devs” and “Looser prior M”
- “Sep devs + loose + growth” – Combine “Sep devs” and “Loose prior M”, but replace the the ‘kinked’ growth curves for males and females with linear growth.

Authors response

Most of the SSC and CPT’s suggestions are addressed in this assessment and changes within were undertaken in a step-wise fashion. Model scenarios include all CPT recommended models.

‘Jittering’ was performed for all models, but did not perform as well last year’s implementation in identifying a mode of likelihood to which many runs of the same model configuration converged. Jittering the models with all new data for 2018 produced less stable estimates of management quantities than in 2017, so two additional model runs were performed in which the newest catch and survey data and new growth data were added separately to explore their relative impact on the stability of the model. Bimodality was a problem in some models. Given what appears to be instability in convergence in the maximum likelihood estimation, Bayesian posteriors of management quantities were also calculated for selected models. However, the Bayesian methods also had difficulties converging. Retrospective analyses for selected models were also performed.

Tentatively, “Sep devs + loose prior” is the author preferred model based on fit to the data, the number of assumptions placed on the data, and the magnitude of retrospective patterns (see discussion below). However, the author looks forward to discussion and guidance from the CPT on this issue.

It should be noted that fitting the model to total and retained size composition is already done in previous assessments, but the data input as discards and retained composition data, then summed in the code. Also, the author has been in contact with the BSFRF and hopes to procure video to explore the assumption of $q = 1$ for the BSFRF gear in the future.

C. Introduction

Distribution

Snow crab (*Chionoecetes opilio*) are distributed on the continental shelf of the Bering Sea, Chukchi Sea, and in the western Atlantic Ocean as far south as Maine. In the Bering Sea, snow crab are distributed widely over the shelf and are common at depths less than ~200 meters (Figure 1 & Figure 2). Smaller crabs tend to occupy more inshore northern regions (Figure 3) and mature crabs occupy deeper areas to the south of the juveniles (Figure 4 & Figure 5; Zheng et al. 2001). The eastern Bering Sea population within U.S. waters is managed as a single stock; however, the distribution of the population may extend into Russian waters to an unknown degree.

Life history characteristics

Studies relevant to key population and fishery processes are discussed below to provide background for the model description in appendix A.

Natural Mortality

Natural mortality for snow crab in the Bering Sea is poorly known, due to relatively few targeted studies. In one of these studies, Nevissi, et al. (1995) used radiometric techniques to estimate shell age from last molt. The total sample size was 21 male crabs (a combination of Tanner and snow crab) from a collection of 105 male crabs from various hauls in the 1992 and 1993 NMFS Bering Sea survey. Representative samples for the 5 shell condition categories were collected that made up the 105 samples. The oldest looking crab within shell conditions 4 and 5 were selected from the total sample of SC4 and SC5 crabs to radiometrically age (Orensanz, Univ. of Washington, pers comm.). Shell condition 5 crab (SC5 = very, very old shell) had a maximum age of 6.85 years (s.d. 0.58, 95% CI approximately 5.69 to 8.01 years). The average age of 6 crabs with SC4 (very old shell) and SC5, was 4.95 years (range: 2.70 to 6.85 years). Given the small sample size, this maximum age may not represent the 1.5% percentile of the population that is approximately equivalent to Hoenig’s method (1983). Maximum life span defined for a virgin stock is reasonably expected to be longer than these observed maximum ages from exploited populations, particularly because fishing mortality was high before and during the time period during which this study was performed. Radiometric ages estimated by Nevissi, et al. (1995) may also be underestimated by several years, due to the continued exchange of material in crab shells even after shells have hardened (Craig Kestelle, pers. comm., Alaska Fisheries Science Center, Seattle, WA).

Tag recovery evidence from eastern Canada revealed observed maximum ages in exploited populations of 17-19 years (Nevissi, et al. 1995, Sainte-Marie 2002). A maximum time at large of 11 years for tag returns of terminally molted mature male snow crab in the North Atlantic has been recorded since tagging started about 1993 (Fonseca, et al. 2008). Fonseca, et al. (2008) estimated a maximum age of 7.8 years post terminal molt using data on dactal wear. Murphy et al. (2018) estimated time-varying natural mortality for eastern Bering Sea snow crab with a mean of 0.49 for females and 0.36 for males (based on the NMFS survey data and state space models).

The mean for the prior for natural mortality used in this assessment is based on the assumption (informed by the studies above) that longevity would be at least 20 years in a virgin population of snow crab. Under negative exponential depletion, the 99th percentile corresponding to age 20 of an unexploited population corresponds to a natural mortality rate of 0.23. Using Hoenig’s (1983) method a natural mortality equal to 0.23 corresponds to a maximum age of 18 years. Given this background, the mean of the prior on natural mortality for immature males and females, mature males, and mature females was set to 0.23 yr^{-1} .

In one model “Fix fem M”, mature female was not estimated. In all others, natural mortality was estimated with varying standard errors for the prior distribution around the mean. Natural mortality was estimated in

2017 with a standard error equal to 0.054. Models down-weighting the prior on natural mortality (e.g. “Loose prior M”, “Looser prior M”, and their derivatives), used standard errors of 0.154 and 2.154, respectively, to reduce the impact of the prior in model fitting (Figure 6). The standard error of 0.054 was estimated using the 95% CI of ± 1.7 years on maximum age estimates from dactal wear and tag return analysis in Fonseca, et al. (2008).

Weight at length

Weight at length is calculated by a power function, the parameters for which were recalculated by the Kodiak lab in August 2016 and resulted in very small changes in weight at length for males, but rather large changes for females. New weight at length parameters were applied to all years of data, rather than just the most recent observations and were used starting in 2016 for calculation of the OFL. To provide context for the change, a juvenile female crab of carapace width 52.5 mm was previously estimated to weigh 65 g and is now 48 g; a mature female crab of carapace width 57.5 mm was estimated to previously weigh 102 g and is now 67.7 g; and a male of carapace width 92.5 mm was previously estimated to weigh 450 g and now weighs 451 g.

Maturity

Maturity of females collected during the NMFS summer survey was determined by the shape of the abdomen, by the presence of brooded eggs, or egg remnants. Morphometric maturity for males was determined by chela height measurements, which were available starting from the 1989 survey (Otto 1998). Mature male biomass referenced throughout this document refers to a morphometrically mature male. A maturity curve for males was estimated using the average fraction mature based on chela height data and applied to all years of survey data to estimate mature survey numbers. The separation of mature and immature males by chela height may not be adequately refined given the current measurement to the nearest millimeter. Chela height measured to the nearest tenth of a millimeter (by Canadian researchers on North Atlantic snow crab) shows a clear break in chela height at small and large widths and shows fewer mature animals at small widths than the Bering Sea data measured to the nearest millimeter. Measurements taken in 2004-2005 on Bering Sea snow crab chela to the nearest tenth of a millimeter show a similar break in chela height to the Canadian data (Rugolo et al. 2005). The probability of maturing (which is different from the fraction mature at length) is estimated within the model for both sexes as a freely estimated (but smoothed) function of length.

Molting probability

Bering Sea male snow crab appear to have a terminal molt to maturity based on hormone level data and findings from molt stage analysis via setagenesis (Tamone et al. 2005). The models presented here assume a terminal molt for both males and females, which is supported by research on populations in the Bering Sea and the Atlantic Ocean (e.g., Dawe, et al. 1991).

Male snow crabs that do not molt (old shell) may be important in reproduction. Paul et al. (1995) found that old shell mature male Tanner crab out-competed new shell crab of the same size in breeding in a laboratory study. Recently molted males did not breed even with no competition and may not breed until after ~100 days from molting (Paul et al. 1995). Sainte-Marie et al. (2002) stated that only old shell males take part in mating for North Atlantic snow crab. If molting precludes males from breeding for a three month period, then males that are new shell at the time of the survey (June to July), would have molted during the preceding spring (March to April), and would not have participated in mating. The fishery targets new shell males, resulting in those animals that molted to maturity and to a size acceptable to the fishery of being removed from the population before the chance to mate. However, new shell males will be a mixture of crab less than 1 year from terminal molt and 1+ years from terminal molt due to the inaccuracy of shell condition as a measure of shell age. Crabs in their first few years of life may molt more than once per year, however, the smallest crabs included in the model are approximately 4 years old and would be expected to molt annually. Further research on the relationship between shell condition and time from last molt is needed.

Mating ratio and reproductive success

Bering Sea snow crabs are managed using mature male biomass (MMB) as a proxy for reproductive potential. MMB is used as the currency for management because the fishery only retains large male crabs. Male snow crabs are sperm conservers, using less than 4% of their sperm at each mating and females also will mate with more than one male. The amount of stored sperm and clutch fullness varies with sex ratio (Sainte-Marie 2002). If mating with only one male is inadequate to fertilize a full clutch, then females will need to mate with more than one male, necessitating a sex ratio closer to 1:1 in the mature population, than if one male is assumed to be able to adequately fertilize multiple females. Although mature male biomass is currently the currency of management, female biomass may also be an important indicator of reproductive potential of the stock.

Quantifying the reproductive potential of the female population from survey data can be less than straightforward. For example, full clutches of unfertilized eggs may be extruded and appear normal to visual examination, and may be retained for several weeks or months by snow crab. Resorption of eggs may occur if not all eggs are extruded resulting in less than a full clutch. Female snow crabs at the time of the survey may have a full clutch of eggs that are unfertilized, resulting in overestimation of reproductive potential. Barren females are a more obvious indication of low reproductive potential and increased in the early 1990s then decreased in the mid- 1990s then increased again in the late 1990s. The highest levels of barren females coincides with the peaks in catch and exploitation rates that occurred in 1992 and 1993 fishery seasons and the 1998 and 1999 fishery seasons. While the biomass of mature females was high in the early 1990s, it is possible the production may have been impacted by the spatial distribution of the catch and the resulting sex ratio in areas of highest reproductive potential. Biennial spawning is another confounding factor in determining the reproductive potential of snow crab. Laboratory analysis showed that female snow crab collected in waters colder than 1.5 degrees C from the Bering Sea spawn only every two years.

Further complicating the process of quantifying reproductive capacity, clutch fullness and fraction of unmated females may not account for the fraction of females that may have unfertilized eggs, since these cannot be detected by the naked eye at the time of the survey. The fraction of barren females observed in the survey may not be an accurate measure of fertilization success because females may retain unfertilized eggs for months after extrusion. To examine this hypothesis, RACE personnel sampled mature females from the Bering Sea in winter and held them in tanks until their eggs hatched in March of the same year (Rugolo et al. 2005). All females then extruded a new clutch of eggs in the absence of males. All eggs were retained until the crabs were euthanized near the end of August. Approximately 20% of the females had full clutches of unfertilized eggs. The unfertilized eggs could not be distinguished from fertilized eggs by visual inspection at the time they were euthanized. Indices of fertilized females based on the visual inspection method of assessing clutch fullness and percent unmated females may overestimate fertilized females and may not be an accurate index of reproductive success.

Growth

Historically, little information was available on growth for Bering Sea snow crab. However, this year's addition of 70 pre- and post-molt lengths brings the total to 110 data points derived from 6 studies used to estimate grow increments for females and males (Table 4). These studies include:

1. Transit study (Rugolo unpublished data, 2003); 14 crab
2. Cooperative seasonality study (Rugolo); 6 crab
3. Dutch harbor holding study; 9 crab
4. NMFS Kodiak holding study held less than 30 days; 6 crab
5. NMFS Kodiak holding study 2016; 5 crab
6. NMFS Kodiak holding study 2017; 70 crab.

Data from the NMFS Kodiak study 2017 are new for this year's assessment. In the "Transit study", pre- and post-molt measurements of 14 male crabs that molted soon after being captured were collected. The crabs were measured when shells were still soft because all died after molting, so measurements may be

underestimates of post-molt width (Rugolo, pers. com.). The holding studies include only data for crab held less than 30 days because growth of crabs held until the next spring's molting was much lower. Females molting to maturity were excluded from all data sets, since the molt increment is usually smaller. Crab missing more than two limbs were excluded due to other studies showing lower growth. Crab from Rugolo's seasonal study were excluded that were measured less than 3 days after molting due to difficulty in measuring soft crab accurately. In general, growth of snow crab in the Bering Sea appears to be greater than growth of some North Atlantic snow crab stocks (Sainte-Marie 1995).

Management history

ADFG harvest strategy

Before the year 2000, the Guideline Harvest Level (GHL) for retained crab only was a harvest rate 58% of the number of male crab over 101 mm CW estimated from the survey. The minimum legal size limit for snow crab is 78 mm, however, the snow crab market generally only accepts crab greater than 101 mm. In 2000, due to the decline in abundance and the declaration of the stock as overfished, the harvest rate for calculation of the GHL was reduced to 20% of male crab over 101 mm. After 2000, a rebuilding strategy was developed based on simulations by Zheng (2002) using survey biomass estimates. The realized retained catch typically exceeded the GHL historically, resulting in exploitation rates for the retained catch on males >101mm ranging from about 10% to 80%. The estimated exploitation rate for total catch divided by mature male biomass ranged from 5% to 49% for the chosen model in this assessment (Figure 7).

The ADFG harvest strategy since 2000 sets harvest rate based on estimated mature biomass. The harvest rate scales with the status of the population relative to B_{MSY} , which is calculated as the average total mature biomass at the time of the survey from 1983 to 1997 and MSST is one half B_{MSY} . The harvest rate begins at 0.10 when total mature biomass exceeds 50% MSST (230 million lbs) and increases linearly to 0.225 when biomass is equal to or greater than B_{MSY} (Zheng et al. 2002).

$$u = \begin{cases} \text{Bycatch} & \text{if } \frac{TMB}{TMB_{MSY}} \leq 0.25 \\ \frac{0.225(\frac{TMB}{TMB_{MSY}} - \alpha)}{1 - \alpha} & \text{if } 0.25 < \frac{TMB}{TMB_{MSY}} < 1 \\ 0.225 & \text{if } TMB > TMB_{MSY} \end{cases} \quad (1)$$

The maximum retained catch is set as the product of the exploitation rate, u , calculated from the above control rule and survey mature male biomass. If the retained catch in numbers is greater than 58% of the estimated number of new shell crabs greater than 101 mm plus 25% of the old shell crab greater than 101 mm, the catch is capped at 58%.

History of B_{MSY}

Prior to adoption of Amendment 24, B_{MSY} was defined as the average total mature biomass (males and females) estimated from the survey for the years 1983 to 1997 (921.6 million lbs; NPFMC 1998) and MSST was defined as 50% of B_{MSY} . Definitions of biological reference points based on the biomass over a range of years make a host of assumptions that may or may not be fulfilled. Currently, the biological reference point for biomass is calculated using a spawning biomass per recruit proxy, $B_{35\%}$ (Clark, 1993). $B_{35\%}$ is the biomass at which spawning biomass per recruit is 35% of unfished levels and has been shown to provide close to maximum sustainable yield for a range of steepnesses (Clark, 1993). Consequently, it is an often used target when a stock recruit relationship is unknown or unreliable.

Fishery history

Snow crab were harvested in the Bering Sea by the Japanese from the 1960s until 1980 when the Magnuson Act prohibited foreign fishing. After the closure to foreign fleets, retained catches increased from relatively low levels in the early 1980s (e.g. retained catch of 11.85 kt during 1982) to historical highs in the early and mid-nineties (retained catch during 1991, 1992, and 1998 were 143.02, 104.68, and 88.09 kt, respectively). The stock was declared overfished in 1999 at which time retained catches dropped to levels similar to the early 1980s (e.g. retained catch during 2000 was 11.46 kt). Retained catches have slowly increased since 1999 as the stock rebuilt, although retained catch during 2017 was low (8.6 kt).

Discard mortality is the next largest source of mortality after retained catch and approximately tracks the retained catch. The highest estimated discard mortality occurred during 1992 at 17.06 kt which was 16% of the retained catch. The most recent estimated mortality was 1.93 kt which was 22% of the retained catch.

Discard from the directed pot fishery has been estimated from observer data since 1992 and ranged from 11% to 64% (average 33%) of the retained catch of male crab biomass (Table 5). Female discard catch has been very low compared to male discard catch and has not been a significant source of mortality. Discard of snow crab in groundfish fisheries has been highest in the yellowfin sole trawl fishery, and decreases down through the flathead sole trawl fishery, Pacific cod bottom trawl fishery, rock sole trawl fishery, and the Pacific cod hook-and-line and pot fisheries, respectively (Figure 8). Bycatch in fisheries other than the groundfish trawl fishery has historically been relatively low, but in 2015 bycatch from sources other than the groundfish trawl fishery reached almost ~25% of the reported bycatch. Size frequency data and catch per pot have been collected by observers on snow crab fishery vessels since 1992. Observer coverage has been 10% on catcher vessels larger than 125 ft (since 2001), and 100% coverage on catcher processors (since 1992).

Several modifications to pot gear have been introduced to reduce bycatch mortality. In the 1978/79 season, escape panels were introduced to pots used in the snow crab fishery to prevent ghost fishing. Escape panels consisted of an opening with one-half the perimeter of the tunnel eye laced with untreated cotton twine. The size of the cotton laced panel was increased in 1991 to at least 18 inches in length. No escape mechanisms for undersized crab were required until the 1997 season when at least one-third of one vertical surface of pots had to contain not less than 5 inches stretched mesh webbing or have no less than four circular rings of no less than 3 3/4 inches inside diameter. In the 2001 season the escapement for undersized crab was increased to at least eight escape rings of no less than 4 inches placed within one mesh measurement from the bottom of the pot, with four escape rings on each side of the two sides of a four-sided pot, or one-half of one side of the pot must have a side panel composed of not less than 5 1/4 inch stretched mesh webbing.

D. Data

New time series of survey indices and size compositions were calculated from data downloaded from the AKFIN database. Bycatch data (biomass and size composition) were updated for the most recent year from the AKFIN database. Retained, total, and discarded catch (in numbers and biomass) and size composition data for each of these data sources were updated for the most recent year based on files provided by the State of Alaska.

Catch data

Catch data and size composition of retained crab from the directed snow crab pot fishery from survey year 1978 to the 2017 were used in this analysis (Table 5). Size composition data on the total catch (retained plus discarded) in the directed crab fishery were available from survey year 1992 to 2017. Total discarded catch was estimated from observer data from 1992 to 2017 (Table 1). The discarded male catch was estimated for survey year 1978 to 1991 in the model using the estimated fishery selectivities based on the observer data for the period of survey year 1992 to 2017. The discard catch estimate was multiplied by the assumed mortality of discards from the pot fishery. The assumed mortality of discarded crab was 30% for all model

scenarios. This estimate differs from the currently used strategy (since 2001) to the present by ADFG to set the TAC, which assumes a discard mortality of 25% (Zheng, et al. 2002). The discards prior to 1992 may be underestimated due to the lack of escape mechanisms for undersized crab in the pots before 1997. See Table 3 for a summary of catch data.

Table 3: Data included in the assessment. Dates indicate survey year.

Data component	Years
Retained male crab pot fishery size frequency by shell condition	1982 - 2017
Discarded Males and female crab pot fishery size frequency	1992 - 2017
Trawl fishery bycatch size frequencies by sex	1991 - 2017
Survey size frequencies by sex and shell condition	1982 - 2018
Retained catch estimates	1982 - 2017
Discard catch estimates from crab pot fishery	1992 - 2017
Trawl bycatch estimates	1993 - 2017
Total survey biomass estimates and coefficients of variation	1982 - 2018
2009 study area biomass estimates, CVs, and size frequency for BSFRF and NMFS tows	2009
2010 study area biomass estimates, CVs, and size frequency for BSFRF and NMFS tows	2010

Survey biomass and size composition data

Abundance was estimated from the annual eastern Bering Sea (EBS) bottom trawl survey conducted by NMFS (see Rugolo et al. 2003 for design and methods). In 1982 the survey net was changed resulting in a potential change in catchability and additional survey stations were added in 1989. Consequently, survey selectivity has been historically modeled in three ‘eras’ in the assessment (1978-1981, 1982-1988, 1989-present). Currently only data from 1982 onward are used in the assessment—a change adopted in the 2017 assessment (Figure 9). All survey data in this assessment used measured net widths instead of the fixed 50 ft net width based on Chilton et al.’s (2009) survey estimates. Carapace width and shell conditions were measured and reported for snow crab caught in the survey.

Mature biomass for males and females at the time of the survey were the primary indices of population size fit to in this assessment. Total survey numbers (Figure 10 & Figure 11) were input to the model via the .DAT file, after which MMB and FMB at the time of the survey were calculated based on the size composition data, which were delineated by shell condition, maturity state, and sex. Distinguishing between mature and immature crab for the size composition was accomplished by demarcating any female that had eggs reported in the survey as ‘mature’. Mature male size composition data were calculated by multiplying the total numbers at length for new shell male crab by a vector of observed proportion of mature males at length. The observed proportion of mature males at length was calculated by chelae height and therefore refers only to ‘morphometrically’ mature males. All old shell crab of both sexes were assumed to be mature. New shell crab were demarcated as any crab with shell condition index ≤ 2 . The biomass of new and old shell mature individuals was calculated by multiplying the vector of numbers at length by weight at length. These vectors were then summed by sex to provide the index to which the model was fit (Table 6). The size composition data were also fit within the assessment.

Spatial distribution of survey abundance and catch

Spatial gradients exist in the survey data by maturity and size for both sexes. For example, larger males have been more prevalent on the south west portion of the shelf (Figure 4) while smaller males have been more prevalent on the north west portion of the shelf (Figure 1). Females have exhibited a similar pattern

(compare Figure 2 to Figure 5). In addition to changing spatially over the size and shelf, distributions of crab by size and maturity have also changed temporally. The centroids of abundance in the summer survey have moved over time (Figure 12 & Figure 13). Centroids of mature female abundance early in the history of the survey were the farther south, but moved north during the 1990s. Since the late 1990s and early 2000s, the centroids moved south again, but not to the extent seen in the early 1980s. This phenomenon was mirrored in centroids of abundance for large males (Figure 13).

Centroids of the catch were generally south of 58.5 N, even when ice cover did not restrict the fishery moving farther north. This is possibly due to proximity to port and practical constraints of meeting delivery schedules. The majority of catch was taken west and north of the Pribilof Islands, but this rule has had exceptions.

The distribution of large males during the summer survey and the fishery catch are different. The origin of this difference is unknown. It is possible that crab move between the fishery and the survey, but it is also possible that fishers did not target all portions of the distribution of large male crab equally. The underlying explanation of this phenomenon could hold implications for relative exploitation rates spatially and it has been suggested that high exploitation rates in the southern portion of the snow crab range may have resulted in a northward shift in snow crab distribution (Orensanz, 2004). Snow crab larvae likely drift north and east after hatching in spring. Snow crab appear to move south and west as they age (Parada et al., 2010), however, little tagging data exists to fully characterize the ontogenetic or annual migration patterns of this stock (Murphy et al. 2010).

Experimental study of survey selectivity

The Bering Sea Fisheries Research Foundation (BSFRF) conducted a survey of 108 tows in 27 survey stations (hereafter referred to as the ‘study area’) in the Bering Sea in summer 2009 (Figure 14). The BSFRF performed a similar study during 2010 in which the study area covered a larger portion of the distribution of snow crab than the 2009 study area. The mature biomass and size composition data gleaned from each of these experiments (and their complimentary NMFS survey observations; Figure 15 & Figure 16) are incorporated into the model by fitting them as an extra survey that is linked to the NMFS survey through a shared selectivity (see appendix A for a description of the way in which the surveys are related in the assessment model). Abundances estimated by the industry surveys were generally higher than the NMFS estimates, which provides evidence that the catchability of the NMFS survey gear is less than 1. Larger females are an exceptions to this observation, but this difference may be due to different towing locations for the two nets within the study area, or to variable catchability of females due to aggregation behavior.

E. Analytic approach

History of modeling approaches for the stock

Historically, survey estimates of large males (>101 mm) were the basis for calculating the Guideline Harvest Level (GHL) for retained catch. A harvest strategy was developed using a simulation model that pre-dated the current stock assessment model (Zheng et al. 2002). This model has been used to set the GHL (renamed total allowable catch, ‘TAC’ since 2009) by Alaska Department of Fish and Game (ADFG) since the 2000/2001 fishery. Currently, NMFS uses an integrated size-structured assessment to calculate the overfishing level (OFL), which constrains the ADFG harvest strategy.

Model description

The integrated size-structured model used by NMFS (and presented here) was developed following Fournier and Archibald’s (1982) methods, with many similarities to Methot (1990). The model was implemented using automatic differentiation software developed as a set of libraries under C++ (ADModel Builder). ADModel

Builder can estimate a large number of parameters in a non-linear model using automatic differentiation software extended from Greiwank and Corliss (1991) and developed into C++ class libraries.

The snow crab population dynamics model tracked the number of crab of sex s , shell condition v , maturity state m , during year y at length l , $N_{s,v,m,y,l}$. A terminal molt was modeled in which crab move from an immature to a mature state, after which no further molting occurred. The mid-points of the size bins tracked in the model spanned from 27.5 to 132.5mm carapace width, with 5 mm size classes. For the base assessment (2017 model_new data), 323 parameters were estimated. Parameters estimated within the assessment included those associated with the population processes recruitment, growth, natural mortality (historically subject to a fairly informative prior), fishing mortality, selectivity (fishery and survey), catchability, and maturity (also sometimes subject to a prior; see Table 7 & Table 8). Weight at length, discard mortality, bycatch mortality, and parameters associated with the variance in growth and proportion of recruitment allocated to size bin were estimated outside of the model or specified. See appendix A for a complete description of the population dynamics.

In the past a ‘jittering’ approach was explored in order to find the parameter vector that produced the smallest negative log likelihood (Turnock, 2016). Jittering was implemented here by running each model to produce a .PAR file, then creating 70 replicates of a .PIN file using that .PAR file. Each .PIN file consisted of the values in the .PAR file multiplied by a random normal error term with a mean of 1 and a standard deviation of 0.1. Only values for parameters that are estimated were ‘jittered’. Each of the .PIN files were used as starting values to run the model and the output was stored and compared among model scenarios. The model that returned the lowest negative log likelihood within a given model scenario was then used for comparison here.

Samples were also drawn from the posterior distributions of estimated parameters and derived quantities used in management (e.g. MMB and OFL) via MCMC for select models. This involved conducting 10,000,000 cycles of the MCMC algorithm, implementing a 5% burn-in period, and saving every 2000th draw. Chains were then thinned until diagnostic statistics (e.g. Geweke statistics and autocorrelation) demonstrated a lack of evidence of non-convergence (if possible).

Retrospective analyses were performed in which the terminal year of data was removed sequentially and a given model was refit to each subset of the data. Then estimated management quantities (like MMB) were compared between the most recent model and successive ‘peels’ of the data to identify retrospective patterns. A retrospective pattern is a consistent directional change in assessment estimates of management quantities (e.g. MMB) in a given year when additional years of data are added to an assessment.

Model selection and evaluation

Models were evaluated based on their fit to the data (Table 9), the credibility of the estimated population processes, stability of the model (Figure 17, Figure 18, Figure 19), and the strength of the influence of the assumptions of the model on the outcomes of the assessment. Maximum likelihood estimates of parameters can be seen in Table 8 and their posterior distributions can be seen for selected models in Figure 20, Figure 21, Figure 22, and Figure 23 (these posterior distributions are for illustrative purposes only in this assessment given poor convergence).

Results

Several of the models exhibited unstable behavior when jittered (Figure 18). The new survey and catch data appear to be a bigger driver of the instability than the additional growth data (Figure 17). Models appeared to ‘converge’ (i.e. small gradients) over a wide range of likelihood values and derived management quantities exhibited bimodality to some degree for several models. This bimodality can still be linked to the change point growth model (Figure 24).

In addition to jittering, MCMC was performed for selected models (“2017 model_new data” & “Loose prior M”). Both models appeared to converge acceptably on first glance (Figure 19). However, MCMC for “2017

model_new data” failed—ten millions draws (~65 hours) produced posteriors with very little variability (in spite of what appeared to be plausible var/covar matrices; see Figure 20).

All models for which retrospective analyses were performed displayed retrospective patterns (Figure 25). However, models in which separate recruitment deviations for males and females were estimated had smaller retrospective patterns.

Below, the fits to the data and estimated population processes for eight models are described. The data for all eight models were the same, however, the priors on natural mortality changed. Consequently, only the total likelihood of those models with the same prior on natural mortality can be directly compared. Individual likelihood components can be compared among models with the understanding that changing the weighting or data for one likelihood component influences others.

Fits to data

Survey biomass data

Fits to the survey mature male biomass were visually similar for all models for the majority of years in the time series (Figure 26); models in which separate recruitment deviations for males and females were estimated fit the data significantly better than those that did not. (Table 9). Estimates of survey MMB in the final year ranged from 85.84 to 141.6 kt. All models underestimated the final year of observed survey MMB (198.384 kt).

Fits to the survey mature female biomass (MFB) changed markedly when separate recruitment deviations were estimated for males and females (Figure 26). Models in which priors on natural mortality were less informative also improved the fit. All models overestimated the final year of observed survey MFB (165.895 kt).

Growth data

A range of shapes of growth curve were estimated to fit the female growth increment data (Figure 27). Models in which the prior on natural mortality for mature females was less informative, but separate recruitment deviations were not estimated, fit the female growth data the best (Table 9). These models estimate a linear relationship between growth increment and pre-molt length. The shapes of the growth curves for males were generally similar, save the linear growth curve imposed by “Sep devs + loose + linear growth”. Improved fits to the male growth data resulted from less informative priors on natural mortality, but, in contrast to females, so did estimating separate recruitment deviations (Table 9). The model in which a linear growth curve was fit (“Sep devs + loose + growth”) was very unstable—only 2 of 70 jittered models had gradients less than 0.005 (and most were $\gg 1$).

Catch data

Retained catch data were fit by all models well, with no visually discernible differences among models (Figure 28). Female discard data were fit adequately given the specified uncertainty (Figure 28 & Table 9). Male discard data during the period for which data exist (early 1990s to the present) were well fit by every model with little visually discernible difference (Figure 28). Models in which separate recruitment deviations were estimated returned significantly lower likelihoods for male discard data (Table 9). Fits to the trawl data were adequate for all models given the uncertainty in the data (Figure 28).

Size composition data

Retained catch size composition data were fit well by all models (Figure 29); total catch size composition data were similarly well fit (Figure 30). Trawl size composition data were generally well fit, with several exceptions

in certain years. All models performed similarly in fitting the trawl size composition data (Figure 31 & Table 9).

Models that estimated separate recruitment deviations for males and females fit the BSFRF size composition data better than those that did not (Figure 32 & Table 9). The number of males was generally underestimated by the industry survey in 2009 and overestimated by the NMFS survey, while the opposite pattern was seen for females. Fits to the 2010 survey size composition data were better than the 2009 fits. Models that estimated separate recruitment deviations for males and females fit the survey composition data better than those that did not (Figure 33, Figure 34, & Table 9). The distribution of residuals for male and female survey composition data for the chosen model varied by sex. Female and male size composition data from the survey sum to 1 in a given year. Size composition data for females tended to be overestimated (Figure 35), whereas males tended to be underestimated (Figure 36).

Estimated population processes and derived quantities

Population processes and derived quantities varied among models, sometimes widely. Projected MMB for 2018 ranged from 101.38 to 135.01 kt (Figure 37). In general, estimated fishing mortality in the recent past has been well below $F_{35\%}$, save the years 2012-2014, which were close to $F_{35\%}$ (Figure 38). Estimated MMB has been less than $B_{35\%}$ since 2010, and estimates from “Sep devs + loose prior” suggest that the population may have been overfished in 2015 (Figure 38). Still, the estimated MMB is currently above MSST and is projected to exceed $B_{35\%}$ in the coming year.

Estimates of selectivity and catchability varied among models (Figure 39). Estimated catchability in both eras was lower for males than for females. In era 1 (1982-1988), catchability ranged from 0.31 - 0.52 for males; for females, it ranged from 0.35 - 0.75. In era 2 (1989-present), catchability ranged from 0.48 - 0.78 for males; for females, it ranged from 0.74 - 1. Estimated size at 50% selection in the survey gear for era 1 ranged from ~38 mm to ~45 mm for both females and males. Size at 50% selection in the survey gear during era 2 ranged from 34 mm to 42 mm for females and 34 mm to 41 mm for males. BSFRF ‘availability’ curves varied widely from 2009 to 2010 and among models, with the availability of crab to the experimental survey generally increasing in 2010 (Figure 40).

The probability of maturing by size was dependent upon the strength of the prior on natural mortality. The probability of maturing at length for males when the prior was informative was less than scenarios in which the prior was less informative (Figure 41). In general, the shape of the curve representing the probability of maturing for both sexes was consistent, but the magnitude of the probabilities varied. For all models, the probability of maturing by size for female crab was ~50% at ~47.5 mm and increased to 100% at ~60mm (Figure 41). The probability of maturing for male crab was ~15% to 20% at ~60 mm and increased sharply to 50% at ~97.5mm, and 100% at 107.5 mm. The region from 60 mm to 90 mm male carapace width displayed the largest differences in estimates of the probability of maturing among models.

Estimated fishing mortality in the directed fishery was similar for all models, except for in the most recent years. In those year, models that estimated separate recruitment deviations for males and females estimated higher fishing mortalities (Figure 42). Total and retained fishery selectivity was very similar for all models because of the weight put on the retained catch and its associated size composition data (Figure 42). Estimated size at 50% selection in the trawl fishery varied more than selectivity in the directed fishery, ranging from 108 - 113 mm (Figure 42). Size at 50% selection for discarded females was similar for all models (Figure 42).

Patterns in recruitment were similar for all models that estimated recruitment similarly (i.e. models that estimated a single vector of recruitment deviations vs. models that estimated a vector each for males and females). A period of high recruitment was observed in which 3 large cohorts passed through the population during the 1980s and into the early 1990s. Following that, a period of low recruitment persisted from the early 1990s to 2013. All models indicated a large (relative to the past) recruitment to the survey gear occurred in the last few years (Figure 43). Recruitment entering the model was placed primarily in the first three size bins (Figure 43). Stock recruitment relationships were not apparent between the estimates of MMB and recruitment for any model (Figure 43). Relationships were not apparent between mature female biomass and recruitment either (not shown).

Estimated natural mortality ranged from 0.27 to 0.35 for immature crab, 0.26 to 0.61 for mature male crab, and 0.345 to 1.04 for mature females (Table 8). Some of these estimates are markedly higher than previous estimates of M from the assessment and literature.

F. Calculation of the OFL

Methodology for OFL

The OFL was calculated using proxies for biomass and fishing mortality reference points and a sloped control rule. Proxies for biomass and fishing mortality reference points were calculated using spawner-per-recruit methods (e.g. Clark, 1991). After fitting the assessment model to the data and estimating population parameters, the model was projected forward 100 years using the estimated parameters under no exploitation to determine ‘unfished’ mature male biomass-per-recruit. Projections were repeated in which the bisection method was used to identify a fishing mortality that reduced the mature male biomass-per-recruit to 35% of the unfished level (i.e. $F_{35\%}$ and $B_{35\%}$). Calculations of $F_{35\%}$ were made under the assumption that bycatch fishing mortality was equal to the estimated average value.

Calculated values of $F_{35\%}$ and $B_{35\%}$ were used in conjunction with a control rule to adjust the proportion of $F_{35\%}$ that is applied based on the status of the population relative to $B_{35\%}$ (Amendment 24, NMFS).

$$F_{OFL} = \begin{cases} \text{Bycatch} & \text{if } \frac{MMB}{MMB_{35}} \leq 0.25 \\ \frac{F_{35}(\frac{MMB}{MMB_{35}} - \alpha)}{1 - \alpha} & \text{if } 0.25 < \frac{MMB}{MMB_{35}} < 1 \\ F_{35} & \text{if } MMB > MMB_{35} \end{cases} \quad (2)$$

Where MMB is the projected mature male biomass in the current survey year after fishing at the F_{OFL} , $MMB_{35\%}$ is the mature male biomass at the time of mating resulting from fishing at $F_{35\%}$, $F_{35\%}$ is the fishing mortality that reduces the mature male biomass per recruit to 35% of unfished levels, and α determines the slope of the descending limb of the harvest control rule (set to 0.1 here).

Calculated OFLs and interpretation

Maximum likelihood estimates of OFLs calculated for the suite presented models ranged from 29.74 to 79.54kt (Figure 44 & Table 10). Differences in OFLs were a result of differences in estimated MMB (see above), calculated $B_{35\%}$ (which ranged from 108.89 to 142.77kt), Table 10), $F_{35\%}$ (which ranged from 1.19 to 9.42 yr^{-1} , Table 10), and F_{OFL} (which ranged from 0.88 to 9.42 yr^{-1} , Table 10).

G. Calculation of the ABC

The acceptable biological catch (ABC) was set by subtracting a 20% buffer from the OFL to account for scientific uncertainty, which was recommended by the SSC.

Author recommendations

Selecting an author preferred model was challenging. Models without separate recruitment deviations for males and females displayed large retrospective patterns in estimated MMB, a key determinant of the OFL. Models in which the prior for natural mortality was less informative fit the data best and not all of this improvement was derived from the decreased contribution of the prior to the likelihood. However, estimates of natural mortality from models with the least informative priors were unrealistic and the mid-range prior has little rationale for selection (though Murphy et al., (2018) suggest that natural mortality may be higher than currently assumed in the assessment). Still, given the confounding between natural mortality and recruitment (and other parameters) freeing recruitment up by estimating separate recruitment deviations by sex, but placing a strong prior on M are not very satisfying model assumptions. Estimates of female catchability equaling 1 in the survey are also likely unreasonable. Several models also still estimate a kink in the growth curve, in spite of what appears to be very linear data, however the linear growth model had convergence issues.

The model construction in which male and female recruitment deviations are separate and the prior on natural mortality is relatively uninformative (“Sep devs + loose M”) is the most attractive of the presented models because it imposes fewer assumptions on the data without allowing most key parameters to stray into unbelievable territory. Further, the model that imposes linear growth in this model is even more attractive because the growth data are best fit by a linear model, but that model had serious convergence problems. Only 2% of models converged after jittering and there was a 40kt difference in the OFLs from the 2 converged models.

H. Data gaps and research priorities

Data sources

As many raw data sources as possible should be included in the assessment. Estimating parameters outside of the model and inputting them as ‘known’ artificially decreases the uncertainty represented in the standard errors and posteriors of management quantities. Weight at length data, data used to develop priors for natural mortality and maturity, and the selectivities calculated from the BSFRF data should be considered for inclusion in the model to comprehensively represent the uncertainty in management quantities. In addition to pulling as much data into the model as possible, continuing to standardize and automate the creation of data files from the survey and catch databases would be very useful given the short time frame of the assessment cycle.

Additional growth data for males would be useful because there are regions of pre-molt length for which we have no data. This is particularly important if the ‘kinked’ growth model is retained—if not, these data become less important.

Modeling and weighting

In theory, we have data to inform all of the confounded processes. Catchability is informed by the BSFRF studies. Natural mortality is informed by the survey length composition data as a result of large portions of the population being unfished. Recruitment is also informed by the survey length composition data and growth is increasingly well characterized due to the efforts of the Kodiak lab. In spite of these data, just changing the prior on M can result in large changes in many different estimated population processes. This suggests that data weighting is a key hurdle to providing management advice using this assessment and needs to be carefully considered.

It is not clear in practice which parameters can be reliably estimated with the currently available data and assessment model. Different weightings of likelihood components can have drastic impacts on the management advice provided from an assessment. A close look at the way CVs, sample sizes, and other weighting factors

are calculated and their influence on assessment results could provide better understanding of how well the model is balanced. Simulations may be useful to understand both the estimability of the parameters in the current model with the current data and the impact of the weights assigned to different data sources. Standardization of the weighting schemes would also improve readability of the code (for example, some size composition data have both ‘weights’ and ‘sample sizes’).

Scientific uncertainty

Natural mortality exerts a large influence over estimated management quantities and population processes (as shown above), but is poorly known. Tagging studies targeted at estimating natural mortality could be useful and could also shed light on the migration patterns, which could help us understand the impact of the fishery (e.g. centroids of large male abundance in the survey and catch do not match—is this because the crab are moving or because the fishery operates in a specific place? The answer to this question could influence priors on catchability.)

Similarly, establishing measures of reproductive capacity that include females, the spatial overlap of mature individuals, the role water temperature plays in biennial spawning, and the effectiveness of mating by size for males may allow for relationships between recruitment and mature biomass to be found (e.g. Murphy et al. 2017). In general, exploring the spatial dynamics of the population may allow for patterns and influences of the fishery and environment on the productivity of the stock to be more easily identified.

Previous analyses suggest that retrospective patterns may be a problem for the snow crab assessment (Szuwalski and Turnock, 2016), which was supported by this analysis. Retrospective patterns can result from unaccounted for time-varying processes in the population dynamics of the model (Hurtado et al., 2015). The retrospective patterns in MMB for snow crab appears to be at least partially a result of an large estimate of survey MMB in 2014 and the assumption of shared recruitment deviations between male and females. The large survey MMB may have caused by a change in catchability for that year and focused research on time-variation in important population processes for snow crab should be pursued to confront retrospective biases.

Additionally, moving to a designation of the ABC based on the standard errors or posterior distributions (similar to the p-star methods) rather than a flat percentage buffer may represent the uncertainty in the data better, but would require including more data sources into the estimation procedure.

Style

Although the code has been trimmed considerably recently, legacy code and unused variables still exist within the assessment. Streamlining the code makes it more readable and reduces the probability of bugs. Most constants were migrated from the .TPL to the .CTL file, but parameter bounds have not yet been moved. Adjusting the manner in which output files are opened when evaluating MCMC output should also be implemented to avoid overwriting output files. A move to GMACs would obviate the need for these corrections, but the GMACs code still needs to be adapted to accommodate snow crab life history.

I. Ecosystem Considerations

Historically, recruitment for snow crab could be divided into two periods via regime shift algorithms (e.g. Rodionov, 2004). Szuwalski and Punt (2013) reported that the shift in recruitment corresponded with a change in the winter Pacific Decadal Oscillation (Szuwalski and Punt, 2013), but also with a period of intense fishing mortality. The recent observed large recruitments may suggest a new ‘regime’ has begun.

Checking the new estimates of recruitment against the winter PDO (from Szuwalski and Punt, 2013) showed that the relationship has broken down with the addition of new data (which is a common phenomenon; Myers 2001). However, the PDO is highly correlated with the Arctic Oscillation (AO) and the AO is significantly

correlated with estimated snow crab recruitment (Figure 45). Negative values of the AO are associated with high pressure in the polar region and greater movement of polar air into lower latitudes. This relationship may be another clue in the search for mechanistic explanations for changes in snow crab recruitment.

Regime-based management strategies have been evaluated for snow crab, but found that only small improvements in long-term yield are derived from changing the target reference points based on a change point algorithm and those changes come at a higher risk of overfishing (Szuwalski and Punt, 2012). Given the uncertainty around whether or not the environment or the fishery precipitated changes in recruitment, the precautionary principle guides managers to assume it is the fishery. Spatial analyses of recruitment, mature biomass, environmental drivers, and the impact of the fishery may provide insight to the population dynamics of snow crab, but modeling techniques capable of fully-spatial stock assessment are only recently feasible. The most recent large recruitment events will likely divide the recruitment time series into three periods and present an intriguing opportunity for further study of the relationship between environmental variables and recruitment success.

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Appendix A: Model structure

Population dynamics

Numbers of sex s of shell condition v and maturity state m at length l in the initial year of the assessment, $N_{s,v,m,y=1,l}$, were calculated from an estimated vector of numbers at length l by sex s and maturity state m for males, $\lambda_{s,m,l}$ and numbers at length l by sex s and shell condition v for females (i.e. 2 vectors for each sex were estimated). Estimated vectors of initial numbers at length by maturity for females were calculated by splitting the estimated vectors at length by the observed proportion mature in the first year of the survey.

$$N_{s,v,m,y=1,l} = \begin{cases} \Omega_{s,l}^{obs} \lambda_{s,1,l} & \text{if } v = \text{new}; m = \text{mat}, s = \text{fem} \\ 1 - \Omega_{s,l}^{obs} \lambda_{s,1,l} & \text{if } v = \text{new}; m = \text{imat}, s = \text{fem} \\ \lambda_{s,2,l} & \text{if } v = \text{old}; m = \text{mat}, s = \text{fem} \\ 0 & \text{if } v = \text{old}; m = \text{imat} \end{cases} \quad (3)$$

Initial numbers at length for males were all assumed to be new shell.

$$N_{s,v,m,y=1,l} = \begin{cases} \lambda_{s,1,l} & \text{if } v = \text{new}; m = \text{mat}, s = \text{male} \\ \lambda_{s,2,l} & \text{if } v = \text{new}; m = \text{imat}, s = \text{male} \\ 0 & \text{if } v = \text{old}; m = \text{mat}, s = \text{male} \\ 0 & \text{if } v = \text{old}; m = \text{imat}, s = \text{male} \end{cases} \quad (4)$$

The dynamics after the initial year were described by:

$$N_{s,v,m,y+1,l} = \begin{cases} \Omega_{s,l} \kappa_{s,l'} Q_{s,imat,y,l'} X_{s,l',l} & \text{if } v = \text{new}; m = \text{mat} \\ 1 - \Omega_{s,l} \kappa_{s,l'} Q_{s,imat,y,l'} X_{s,l',l} + Rec_y^\epsilon Pr_l & \text{if } v = \text{new}; m = \text{imat} \\ Q_{s,mat,y,l'} & \text{if } v = \text{old}; m = \text{mat} \\ (1 - \kappa_{s,l'}) Q_{s,imat,y,l'} & \text{if } v = \text{old}; m = \text{imat} \end{cases} \quad (5)$$

Where $\Omega_{s,l}$ was the probability of maturing at length l for sex s (a freely estimated vector for both males and females constrained by penalties on smoothness and a prior in some scenarios), $\kappa_{s,l'}$ was the probability of molting for an immature crab of sex s at length l' (set to 1 for all immature crab), and $X_{s,l,l'}$ was the size transition matrix describing the probability of transitioning from size l' to size l for sex s . $Q_{s,m,y,l'}$ was the number of crab of sex s , maturity state m , and length l' surviving natural and fishing mortality during year y :

$$Q_{s,m,y,l} = \sum_v N_{s,v,m,y,l} e^{Z_{s,v,m,y,l}} \quad (6)$$

Where $N_{s,v,m,y,l}$ represented the numbers, N , of sex s during year y of shell condition v and maturity state m at length l . $Z_{s,v,m,y,l}$ represented the total mortality experienced by the population and consisted of the sum of instantaneous rates of natural mortality by sex and maturity state, $M_{s,m}$, and fishing mortality, $F_{s,f,y,l}$ from each fishery. Each fishing mortality was subject to selectivity by length l , which varied between sexes s and fisheries f (and by year y if specified). $M_{s,m}$ was specified in the model and a multiplier $\gamma_{natM,m}$

was estimated subject to constraints (see Table 7; this formulation effectively specified a mean and standard deviation for a prior distribution for M).

$$Z_{s,v,m,y,l} = \gamma_{natM,m} M_{s,m} + \sum_f S_{s,f,y,l} F_{s,f,y,l} \quad (7)$$

Selectivities in the directed and bycatch fisheries were estimated logistic functions of size. Different selectivity parameters were estimated for females and males in the directed fisheries ($S_{fem,dir,l}$ and $S_{male,dir,l}$, respectively), a single selectivity for both sexes was estimated for bycatch in the groundfish trawl fishery ($S_{trawl,l}$), and a retention selectivity was estimated for the directed fishery for males ($R_{dir,l}$; all females were discarded).

$$S_{male,dir,l} = \frac{1}{1 + e^{-S_{slope,m,d}(L_l - S_{50,m,d})}} \quad (8)$$

$$S_{fem,dir,l} = \frac{1}{1 + e^{-S_{slope,f,d}(L_l - S_{50,f,d})}} \quad (9)$$

$$S_{trawl,l} = \frac{1}{1 + e^{-S_{slope,t}(L_l - S_{50,t})}} \quad (10)$$

$$R_{dir,l} = \frac{1}{1 + e^{-S_{slope,m,d}(L_l - S_{50,m,d})}} \quad (11)$$

Where $S_{slope,s,f}$ was the slope of the logistic curve for sex s in fishery f and $S_{50,s,f}$ was the length at 50% selection for sex s in fishery f . Catches for all fisheries were modeled as pulse fisheries in which all catch was removed instantaneously (i.e. no natural mortality occurred during the fishery). Catch in fishery f during year y was calculated as the fraction of the total fishing mortality, $F_{s,f,y,l}$, applied to a given sex s in a fishery f times the biomass removed by all fisheries for that sex.

$$C_{male,dir,y} = \sum_l \sum_v \sum_m w_{male,l} \frac{R_l F_{male,dir,y,l}}{F_{male,dir,y,l} + F_{trawl,y,l}} N_{male,v,m,y,l} e^{-\delta_y M_{s,m}} (1 - e^{-(F_{male,dir,y,l} + F_{trawl,y,l})}) \quad (12)$$

$$C_{male,tot,y} = \sum_l \sum_v \sum_m w_{male,l} \frac{F_{male,dir,y,l}}{F_{male,dir,y,l} + F_{trawl,y,l}} N_{male,v,m,y,l} e^{-\delta_y M_{s,m}} (1 - e^{-(F_{male,dir,y,l} + F_{trawl,y,l})}) \quad (13)$$

$$C_{fem,dir,y} = \sum_l \sum_v \sum_m w_{fem,l} \frac{F_{fem,dir,y,l}}{F_{fem,dir,y,l} + F_{trawl,y,l}} N_{fem,v,m,y,l} e^{-\delta_y M_{s,m}} (1 - e^{-(F_{fem,dir,y,l} + F_{trawl,y,l})}) \quad (14)$$

$$C_{m+f,trawl,y} = \sum_s \sum_l \sum_v \sum_m w_{s,l} N_{s,v,m,y,l} e^{-\delta_y M_{s,m}} (1 - e^{-F_{trawl,y,l}}) \quad (15)$$

Where δ_y was the mid point of the fishery (all fisheries were assumed to occur concurrently and the midpoint was based on the directed fishery, which accounts for the vast majority of the fishing mortality) and $w_{s,l}$ was the weight at length l for sex s . Trawl data and discard data were entered into the model with an assumed mortality of 80% and 30%, respectively. Fully-selected fishing mortality parameters for fishery f were estimated as a logged average over a given time period (F_{avg}^{log}) with yearly deviations around that mean ($F_{dev,y}^{log}$).

$$F_{f,y} = e^{(F_{avg,f}^{log} + F_{dev,f,y}^{log})} \quad (16)$$

Selectivity for the survey was estimated for 2 eras in the base model: 1982-1988 and 1989-present. Selectivity was assumed to be logistic and separate parameters representing the length at which selection probability

equal 50% and 95% ($s_{50,s,e}$ and $s_{95,s,e}$, respectively) were estimated for males and females in the third era (1989-present). Separate catchability coefficients ($q_{s,e}$) were estimated for males and females in all eras.

$$S_{surv,s,l,e} = \frac{q_{s,e}}{1 + e^{-\log(19) \frac{L_l - s_{50,s,e}}{s_{95,s,e} - s_{50,s,e}}}} \quad (17)$$

Survey selectivity was informed by experimental surveys during the years 2009 and 2010. A portion of the NMFS summer survey tows were accompanied by an industry vessel using nephrops trawls with an assumed selectivity of 1 for all size classes. To represent the proportion of the population covered by the experiment, a vector was freely estimated for males, S_y^{free} (subject to a scaling parameter), and a logistic curve was estimated for females.

$$S_{ind,s,l,y} = \begin{cases} \frac{q_{ind,s,y}}{1 + e^{-\log(19) \frac{L_l - s_{50,s,y}}{s_{95,s,y} - s_{50,s,y}}}} & \text{if } s = \text{female} \\ q_{ind,s,y} S_y^{free} & \text{if } s = \text{male} \end{cases} \quad (18)$$

Based on this logic, after identifying the fraction of the crab at length covered by the experimental surveys, the length frequencies of the NMFS data collected simultaneously with the experimental trawls can be calculated by multiplying the numbers at length ‘available’ to the experimental trawls by the overall survey selectivity, $S_{surv,s,l,y}$. The predicted numbers at length for the NMFS and industry data from the selectivity experiment were calculated by multiplying the respective selectivities by the survey numbers at length.

$$S_{nmfs,s,l,y} = S_{ind,s,l,y} S_{surv,s,l,y} \quad (19)$$

Mature male and female biomass (MMB and FMB, respectively) were fitted in the objective function and were the product of mature numbers at length during year y and the weight at length, $w_{s,l}$:

$$MMB_y = \sum_{l,v} w_{male,l} N_{male,v,mat,y,l} \quad (20)$$

$$FMB_y = \sum_{l,v} w_{fem,l} N_{fem,v,mat,y,l} \quad (21)$$

$$w_{s,l} = \alpha_{wt,s} L_l^{\beta_{wt,s}} \quad (22)$$

Mature biomass can be calculated for different time through out the year, in which case the numbers at length are decremented by the estimated natural mortality. Parameters $\alpha_{wt,s}$ and $\beta_{wt,s}$ were estimated outside of the assessment model and specified in the control file.

Molting and growth occur before the survey. Immature crab were assumed to molt every year with an estimated probability of molting to maturity based on length l (in all the scenarios presented here, the probability of molting was 1 for all immature animals). For crab that do molt, the growth increment within the size-transition matrix, $X_{s,l,l'}$, was based on a piece-wise linear relationship between predicted pre- and post-molt length, ($\hat{L}_{s,l}^{pred}$ and $\hat{L}_{s,l}^{post}$, respectively) and the variability around that relationship was characterized by a discretized and renormalized gamma function, $Y_{s,l,l'}$.

$$X_{s,l,l'} = \frac{Y_{s,l,l'}}{\sum_{l'} Y_{s,l,l'}} \quad (23)$$

$$Y_{s,l,l'} = (\Delta_{l,l'})^{\frac{L_{s,l} - (\bar{L}_l - 2.5)}{\beta_s}} \quad (24)$$

$$\hat{L}_{s,l}^{post,1} = \alpha_s + \beta_{s,1} L_l \quad (25)$$

$$\hat{L}_{s,l}^{post,2} = \alpha_s + \delta_s(\beta_{s,1} - \beta_{s,2}) + \beta_{s,2}L_l \quad (26)$$

$$\hat{L}_{s,l}^{post} = \hat{L}_{s,l}^{post,1}(1 - \Phi(\frac{L_l - \delta_{a,x}}{stgr})) + \hat{L}_{s,l}^{post,2}(\Phi(\frac{L_l - \delta_{a,x}}{stgr})) \quad (27)$$

$$\Delta_{l,l'} = \bar{L}_{l'} + 2.5 - L_l \quad (28)$$

$\hat{L}_{s,l}^{post,1}$ and $\hat{L}_{s,l}^{post,2}$ were predicted post-molt lengths from each piece of the piece-wise relationship, and $\Phi()$ was a cumulative normal distribution in which $\delta_{a,x}$ was an estimated change point. The model in which linear growth was estimated removed equations 26 and 27 from the model.

An average recruitment for the assessment period (1982-present) and yearly deviations around this average were estimated within the assessment for models in which only a single vector of recruitment deviations was estimated. The sex ratio of recruitment was assumed to be 50/50 male to female. Each year's estimated recruitment was allocated to length bins based on a discretized and renormalized gamma function with parameters specified in the control file.

$$Rec_y = e^{(Rec_{avg} + Rec_{dev,y})} \quad (29)$$

$$Pr_l = \frac{(\Delta_{1,l})^{\alpha_{rec}/\beta_{rec}} e^{-\Delta_{1,l}/\beta_{rec}}}{\sum_{l'} (\Delta_{1,l'})^{\alpha_{rec}/\beta_{rec}} e^{(-\Delta_{1,l'}/\beta_{rec})}} \quad (30)$$

For models in which separate vectors of recruitment deviations were estimated for males and females, a separate average recruitment was also estimated (in log space). Each vector of deviations was also subject to a smoothing penalty, but were not linked directly in any way (e.g. priors on the ratio of estimated male to female average recruitment).

Likelihood components

Three general types of likelihood components were used to fit to the available data (Table 11). Multinomial likelihoods were used for size composition data, log-normal likelihoods were used for indices of abundance data, and normal likelihoods were used for catch data, growth data, priors, and penalties. Multinomial likelihoods were implemented in the form:

$$L_x = \lambda_x \sum_y N_{x,y}^{eff} \sum_l p_{x,y,l}^{obs} \ln(\hat{p}_{x,y,l}/p_{x,y,l}^{obs}) \quad (31)$$

L_x was the likelihood associated with data component x , where λ_x represented an optional additional weighting factor for the likelihood, $N_{x,y}^{eff}$ was the effective sample sizes for the likelihood, $p_{x,y,l}^{obs}$ was the observed proportion in size bin l during year y for data component x , and $\hat{p}_{x,y,l}$ was the predicted proportion in size bin l during year y for data component x . 10 multinomial likelihood components were included in the assessment (see Table 11 for descriptions, weighting factors, and effective sample sizes).

Iterative methods for determining appropriate effective samples sizes for composition data are suggested to avoid over-weighting the size composition data and washing out the signal from the indices of abundance. Although the code has the capability to implement these methods, they were not used for this assessment.

Log normal likelihoods were implemented in the form:

$$L_x = \lambda_x \sum_y \frac{(\ln(\hat{I}_{x,y}) - \ln(I_{x,y}))^2}{2(\ln(CV_{x,y}^2 + 1))} \quad (32)$$

L_x was the contribution to the objective function of data component x , λ_x was any additional weighting applied to the component, $\hat{I}_{x,y}$ was the predicted value of quantity I from data component x during year y , $I_{x,y}$ was the observed value of quantity I from data component x during year y and $CV_{x,y}$ was the coefficient of variation for data component x during year y . 5 log normal likelihood components were included in this assessment (see Table 11 for descriptions, weighting factors, and CVs).

Normal likelihoods were implemented in the form:

$$L_x = \lambda_x \sum_y (\hat{I}_{x,y} - I_{x,y})^2 \quad (33)$$

L_x was the contribution to the objective function of data component x , λ_x was represents the weight applied to the data component (and can be translated to a standard deviation), $\hat{I}_{x,y}$ was the predicted value of quantity I from data component x during year y , $I_{x,y}$ was the observed value of quantity I from data component x during year y . 12 normal likelihood components were included in the base assessment (see Table 11 for descriptions, weighting factors, and translated standard deviations).

Smoothing penalties were also placed on some estimated vectors of parameters in the form of normal likelihoods on the second differences of the vector.

Table 4: Observed growth increment data by sex

Female premolt length (mm)	Female postmolt length (mm)	Male premolt length (mm)	Male postmolt length (mm)
20.7	27	57.63	68.6
25.2	32	20.6	28.9
28.7	37.1	25.6	31.4
28.2	36.22	25.9	31.1
25.9	32.7	20	26.3
26.9	34.4	25.2	32.8
26.4	31.8	21	27.8
29	36.7	20.3	26.4
23	31.2	21.9	28.4
21.6	27.7	20.7	27.7
24.2	30.9	20.1	28
20.8	27.3	19.8	26.5
20.3	26.2	26	32.2
22.2	29.7	62.3	81.8
21.4	28	56.5	70
19.3	25.2	57	70
26.9	34.5	58.7	72.5
25.7	32.5	60.8	78.4
19.8	26.9	59.3	75.1
27.4	35.1	64	84.7
20.4	26.4	60.3	75.1
25.5	34.6	20.7	29.2
34.9	44.8	24	32.3
18.6	25.2	16.1	23
28.2	35.8	19.2	26.6
22.8	29.6	21.23	26.41
26.5	33.9	22.2	28.1
25.5	32.9	23.48	28.27
24.2	31.4	29.9	39.9
24.4	30.7	30.3	40.3
22.3	29.4	30.7	40.5
20.8	27.3	44.2	58.7
22.8	30.2	44.7	57.3
26.2	32.6	64.7	82.7
29.4	36.7	67.6	86
20.2	24.9	67.9	85.3
27.5	34.8	74.5	93.9
20.4	26.7	79.9	97.8
25.4	31.7	89.8	110
28.1	34.5	89.9	112.1
28.7	36	89.9	112.3
29.5	38.4	93.8	117.6
30.9	38.4	20	26.3
26	33.1		
29.1	38.4		
19.37	24.24		
20.7	27.4		
21.25	28.73		
21.94	28.71		

Female premolt length (mm)	Female postmolt length (mm)	Male premolt length (mm)	Male postmolt length (mm)
23.09	29.26		
32.8	44.9		
35.3	47.6		
38.3	50.9		
38.9	53		
41	55.8		
42.1	54.6		
44.2	59.5		
44.3	59.3		
44.8	59.7		
45.2	59.6		
46.9	60.4		
47	61.4		
47.9	61.4		
20.6	25.1		
20.8	27.6		
22	28.2		
22.9	28.6		

Table 5: Observed retained catches, discarded catch, and bycatch

Survey year	Retained catch (kt)	Discarded females (kt)	Discarded males (kt)	Trawl bycatch (kt)
1982	11.85	0.02	1.22	0.38
1983	12.16	0.01	1.2	0.49
1984	29.94	0.01	2.67	0.52
1985	44.45	0.01	3.88	0.45
1986	46.22	0.02	4.1	1.91
1987	61.4	0.03	5.34	0.01
1988	67.79	0.04	5.62	0.69
1989	73.4	0.05	6.46	0.8
1990	149.1	0.05	14.71	0.61
1991	143	0.06	11.6	1.88
1992	104.7	0.12	17.06	1.78
1993	67.94	0.08	5.32	1.76
1994	34.13	0.06	4.03	3.54
1995	29.81	0.02	5.75	1.34
1996	54.22	0.07	7.44	0.92
1997	114.4	0.01	5.73	1.47
1998	88.09	0.01	4.67	1.01
1999	15.1	0	0.52	0.61
2000	11.46	0	0.62	0.53
2001	14.8	0	1.89	0.39
2002	12.84	0	1.47	0.23
2003	10.86	0	0.57	0.76
2004	11.29	0	0.51	0.95
2005	16.77	0	1.36	0.36
2006	16.49	0	1.78	0.83
2007	28.59	0.01	2.53	0.43
2008	26.56	0.01	2.06	0.27
2009	21.78	0.01	1.23	0.63
2010	24.61	0.01	0.62	0.17
2011	40.29	0.18	1.69	0.16
2012	30.05	0.03	2.32	0.22
2013	24.49	0.07	3.27	0.12
2014	30.82	0.17	3.52	0.16
2015	18.42	0.07	2.96	0.16
2016	9.67	0.02	1.31	0.08
2017	8.6	0.02	1.93	0.02

Table 6: Observed mature male and female biomass (1000 t) at the time of the survey and coefficients of variation.

Survey year	Female mature biomass	Female CV	Mature male biomass	Male CV	Males >101mm (kt)	Males >101mm (million)
1982	144.4	0.15	176.8	0.14	33.34	60.91
1983	90.13	0.2	161.6	0.13	38.09	70.09
1984	42.32	0.19	177.7	0.12	88.73	151.8
1985	6.12	0.2	71.84	0.11	43.39	72.84
1986	15.74	0.18	89.81	0.11	46.7	77.91
1987	122.6	0.16	194.6	0.11	74.44	128.6
1988	169.9	0.17	259.4	0.15	104.7	173.1
1989	264.2	0.25	299.2	0.11	92.31	158.9
1990	182.9	0.19	443.8	0.14	224.7	386.4
1991	214.9	0.19	466.6	0.15	292.2	452.9
1992	131.4	0.18	235.5	0.09	143.9	227.3
1993	132.1	0.16	183.9	0.1	78.11	126.7
1994	126.2	0.15	171.3	0.08	44.78	72.57
1995	168.7	0.14	220.5	0.13	37.75	65.18
1996	107.3	0.14	288.4	0.12	87.57	155.2
1997	103.8	0.2	326.8	0.1	168.7	280.6
1998	72.73	0.25	206.4	0.09	126.7	209.7
1999	30.89	0.21	95.85	0.09	52.53	85.2
2000	96.46	0.52	96.39	0.14	41.88	69.83
2001	77.24	0.28	136.5	0.12	41.51	70.69
2002	30.22	0.28	93.17	0.23	36.56	64.16
2003	41.71	0.31	79.07	0.12	32.57	55.61
2004	50.16	0.26	79.57	0.14	35.99	57.42
2005	64.85	0.17	123.5	0.11	40.67	63.26
2006	51.93	0.18	139.3	0.26	71.13	120.9
2007	55.89	0.22	153.1	0.15	73.62	127.5
2008	57.15	0.19	142	0.1	66.56	113.6
2009	52.16	0.21	148.2	0.13	78.92	129.9
2010	98.01	0.18	162.8	0.12	88.35	138.3
2011	175.8	0.18	167.1	0.11	94.67	147.6
2012	149.4	0.2	122.2	0.12	53.17	85.35
2013	131.4	0.18	97.46	0.12	42.93	71.79
2014	119.7	0.19	163.5	0.16	81.39	138.8
2015	85.13	0.17	80.04	0.12	35.77	56.11
2016	55.39	0.21	63.21	0.11	21.96	36.51
2017	106.8	0.21	83.96	0.11	20.52	35.02
2018	165.9	0.21	198.4	0.17	26.75	48.08

Table 7: Parameter bounds and symbols

Parameter	Lower	Upper	Symbol
af	-100	5	α_f
am	-50	5	α_m
bf	1	10	$\beta_{f,1}$
bm	1	5	$\beta_{m,1}$
b1	1	1.5	$\beta_{f,2}$
bfl	1	2	$\beta_{m,2}$
deltam	10	50	δ_m
deltaf	5	50	δ_f
st_gr	0.5	0.5	stgr
growth_beta	0.749	0.751	β_g
mateste	-6	-1e-10	$\Omega_{m,l}$
matestfe	-6	-1e-10	$\Omega_{f,l}$
mean_log_rec	“-inf”	Inf	Rec_{avg}
rec_devf	-15	15	$Rec_{f,dev,y}$
alpha1_rec	11.49	11.51	α_{rec}
beta_rec	3.99	4.01	β_{rec}
mnatlen_styr	-3	15	$\lambda_{male,v,l}$
fnatlen_styr	-10	15	$\lambda_{fem,v,l}$
log_avg_fmort	“-inf”	Inf	$F_{avg,dir}^{log}$
fmort_dev	-5	5	$F_{dev,dir,y}^{log}$
log_avg_fmortdf	-8	-1e-04	$F_{avg,disc}^{log}$
fmortdf_dev	-15	15	$F_{dev,disc,y}^{log}$
log_avg_fmortt	-8	-1e-04	$F_{avg,trawl}^{log}$
fmortt_dev_era1	-15	15	$F_{dev,trawl,era1}^{log}$
fmortt_dev_era2	-15	15	$F_{dev,trawl,era2}^{log}$
log_avg_sel50_mn	4	5	$S_{50,new,dir}$
log_avg_sel50_mo	4	5	$S_{50,old,dir}$
fish_slope_mn	0.1	0.5	$S_{slope,m,d}$
fish_fit_slope_mn	0.05	0.5	$S_{slope,m,d}$
fish_fit_sel50_mn	85	120	$S_{50,old,dir}$
fish_slope_mo2	1.9	2	$S_{slope,m,d}$
fish_sel50_mo2	159	160	$S_{50,old,dir}$
fish_slope_mn2	0.01	2	$S_{slope,m,d}$
fish_sel50_mn2	100	160	$S_{50,old,dir}$
fish_disc_slope_f	0.1	0.7	$S_{slope,m,d}$
fish_disc_sel50_f	1	5	$S_{50,old,dir}$
fish_disc_slope_tf	0.01	0.3	$S_{slope,trawl}$
fish_disc_sel50_tf	30	120	$S_{50,trawl}$
srv1_q	0.2	1	$q_{m,era1,surv}$
srv1_q_f	0.2	1	$q_{f,era1,surv}$
srv1_sel95	30	150	$S_{95,era1,surv}$
srv1_sel50	0	150	$S_{50,era1,surv}$
srv2_q	0.2	1	$q_{m,era2,surv}$
srv2_q_f	0.2	1	$q_{f,era2,surv}$
srv2_sel95	50	160	$S_{95,era2,surv}$
srv2_sel50	0	80	$S_{50,era2,surv}$
srv3_q	0.2	1	$q_{m,era3,surv}$
srv3_sel95	40	200	$S_{95,m,era2,surv}$
srv3_sel50	25	90	$S_{50,m,era2,surv}$

Parameter	Lower	Upper	Symbol
srv3_q_f	0.2	1	$q_{f,era3,surv}$
srv3_sel95_f	40	150	$S_{95,f,era2,surv}$
srv3_sel50_f	0	90	$S_{50,f,era2,surv}$
srvind_q	0.1	1	$q_{m,09,ind}$
srvind_q_f	0.01	1	$q_{f,09,ind}$
srvind_sel95_f	55	120	$S_{95,f,09,ind}$
srvind_sel50_f	-50	110	$S_{50,f,09,ind}$
srv10in_q	0.1	1	$q_{m,10,ind}$
srv10ind_q_f	0.01	1	$q_{f,10,ind}$
selsmo10ind	-4	-0.001	SelVecMaleInd09
selsmo09ind	-4	-0.001	SelVecMaleInd10
Mmult_imat	0.2	2	$\gamma_{natM,imm}$
Mmult	0.2	2	$\gamma_{natM,mat,m}$
Mmultf	0.2	2	$\gamma_{natM,mat,f}$
cpueq	0.0000877	0.00877	q_{cpue}

Table 8: Estimated parameter values by scenario (these are maximum likelihood estimates)

Parameter	2017 model_old data	2017 model_new data	Fix fem M	Loose prior M	Looser prior M	Sep devs	Sep devs + loose prior	Sep devs + looser prior	Sep devs + loose + growth
af	-5.26	2.61	2.63	2.61	2.61	-1.46	-0.91	-1.01	-0.46
am	-5.34	-0.95	-1.02	-1.02	-1.01	-0.78	-0.72	1.04	3.4
bf	1.53	1.18	1.18	1.18	1.18	1.35	1.33	1.33	1.31
bm	1.52	1.37	1.37	1.37	1.37	1.36	1.36	1.28	1.2
b1	1.15	1.16	1.16	1.16	1.17	1.17	1.17	1.17	
bfl	1.04	1.34	1.34	1.35	1.35	1.04	1	1	
deltam	32.13	32.55	32.56	32.62	32.63	32.53	32.57	41.75	
deltaf	34.13	26.22	26.23	26.22	26.22	41.1	44.38	44.37	
mateste	vector	vector	vector	vector	vector	vector	vector	vector	vector
matestfe	vector	vector	vector	vector	vector	vector	vector	vector	vector
rec_devf	vector	vector	vector	vector	vector	vector	vector	vector	vector
mnatlen_styr	vector	vector	vector	vector	vector	vector	vector	vector	vector
fnatlen_styr	vector	vector	vector	vector	vector	vector	vector	vector	vector
log_avg_fmort	-0.29	-0.29	-0.26	-0.36	-0.44	-0.17	-0.22	-0.24	-0.18
fmort_dev	vector	vector	vector	vector	vector	vector	vector	vector	vector
log_avg_fmortdf	-5.66	-5.93	-6.16	-5.99	-6.11	-5.62	-5.53	-5.42	-5.91
fmortdf_dev	vector	vector	vector	vector	vector	vector	vector	vector	vector
log_avg_fmortt	-4.61	-4.64	-4.73	-4.77	-4.75	-4.62	-4.69	-4.7	-4.62
fmortt_dev_era1	vector	vector	vector	vector	vector	vector	vector	vector	vector
fmortt_dev_era2	vector	vector	vector	vector	vector	vector	vector	vector	vector
log_avg_sel50_mn	4.67	4.66	4.66	4.66	4.66	4.66	4.66	4.67	4.67
fish_slope_mn	0.19	0.19	0.19	0.19	0.2	0.19	0.2	0.2	0.19
fish_fit_slope_mn	0.43	0.44	0.44	0.44	0.44	0.43	0.43	0.43	0.44
fish_fit_sel50_mn	96.07	96.09	96.08	96.15	96.25	96.14	96.2	96.23	96.11
fish_disc_slope_f	0.25	0.26	0.25	0.27	0.28	0.26	0.27	0.28	0.27
fish_disc_sel50_f	4.25	4.23	4.25	4.22	4.22	4.25	4.25	4.25	4.22
fish_disc_slope_tf	0.07	0.08	0.09	0.08	0.08	0.08	0.08	0.09	0.08
fish_disc_sel50_tf	112.95	111.88	108.82	110.43	111.85	110.18	109.96	110.2	111.13
srv2_q	0.43	0.44	0.44	0.36	0.31	0.52	0.43	0.36	0.43
srv2_q_f	0.51	0.52	0.52	0.41	0.35	0.75	0.65	0.55	0.67
srv2_sel95	54.52	55.78	55.43	59.73	64.24	58.85	62.83	66.06	65.52
srv2_sel50	38.26	39.05	38.96	41.39	43.3	39.99	42.9	45.2	44.14
srv3_q	0.71	0.73	0.77	0.64	0.48	0.78	0.68	0.55	0.67
srv3_sel95	48.02	49.08	50.26	55.9	60.37	49.04	56.18	61.35	59.44
srv3_sel50	34.38	34.84	35.46	38.16	40	34.94	38.42	41.14	39.73
srv3_q_f	1	1	0.74	1	0.83	1	1	0.82	1
srv3_sel95_f	45.58	46.79	43.82	50.52	52.47	47.2	51.58	54.94	51.26
srv3_sel50_f	35.22	36.05	33.72	38.98	40.51	36.1	39.48	42.3	39.23
srvind_q	1	1	1	1	1	1	1	1	1
srvind_q_f	0.17	0.17	0.13	0.16	0.14	0.16	0.17	0.17	0.15
srvind_sel95_f	55	55	55	52.74	53.39	54.56	56.22	57.13	49.54
srvind_sel50_f	49.39	49.46	49.28	48.85	49.15	49.79	50.86	51.51	49.5
srv10ind_q_f	1	1	1	1	1	1	0.94	0.75	0.97
selsmo10ind	vector	vector	vector	vector	vector	vector	vector	vector	vector
selsmo09ind	vector	vector	vector	vector	vector	vector	vector	vector	vector

Parameter	2017 model_old data	2017 model_new data	Fix fem M	Loose prior M	Looser prior M	Sep devs	Sep devs + loose prior	Sep devs + looser prior	Sep devs + loose + growth
Mmult_imat	1.22	1.21	1.28	1.56	1.33	1.18	1.49	1.38	1.48
Mmult	1.16	1.17	1.14	1.54	2.7	1.14	1.51	2.48	1.55
Mmultf	1.55	1.51		2.19	3.08	1.57	2.48	4.48	2.38
cpueq	0	0	0	0	0	0	0	0	0

Table 9: Contribution to the objective function by individual likelihood component by modeling scenario. Values in columns after Model 0 are the likelihood contribution of Model 0 minus the likelihood contribution of the model in the column. Positive values represent improvements in fit. Note that some of the model scenarios involve changing the weightings of data sources which invalidate the comparison of likelihoods for a data source among models.

Likelihood component	2017 model_old data	2017 model_new data	Fix fem M	Loose prior M	Looser prior M	Sep devs	Sep devs + loose prior	Sep devs + looser prior	Sep devs + loose + growth
Recruitment	38.81	40.06	42.5	34.61	27.79	70.18	62.23	53.01	63.23
deviations									
Initial	4.73	4.66	4.71	4.51	4.09	4.62	4.47	4.1	4.61
numbers									
old shell									
males									
small									
length									
bins									
ret fishery	305.31	322.53	321.01	323.98	326.97	320.96	320.32	325.14	329.39
length									
total fish	866.83	924.56	921.06	925.59	929.29	920.93	919.63	922.26	925.17
length (ret									
+ disc)									
female fish	233.89	238.86	238.41	237.26	235.43	241.32	239.74	237.81	237.09
length									
survey	4266.95	4482.15	4598.46	4379.56	4352.86	4293.05	4210.37	4190.75	4228.96
length									
trawl	265.69	279.01	315.53	271.09	271.59	300.15	289.07	292.49	289.09
length									
2009	-93.56	-93.63	-89.83	-93.89	-94.44	-92.24	-93.54	-93.24	-81.4
BSFRF									
length									
2009	-74.83	-73.93	-70.65	-75.45	-75.95	-75.15	-75.89	-76.05	-40.61
NMFS									
study area									
length									
M	81.53	73.63	20.21	60.92	1.42	77.61	72.88	2.04	68.84
multiplier									
prior									
maturity	36.73	45.47	47.67	40.09	34.42	43.65	38.44	31.12	42.19
smooth									
growth	36.46	142.25	142.28	141	139.27	140.07	138.18	128.83	136.57
males									
growth	117.57	335.98	342.93	332.09	331.39	394.96	359.65	355.02	384.94
females									
2009	0.38	0.39	0.52	0.22	0.03	0.47	0.26	0.07	0.22
BSFRF									
biomass									

Likelihood component	2017 model_old data	2017 model_new data	Fix fem M	Loose prior M	Looser prior M	Sep devs	Sep devs + loose prior	Sep devs + looser prior	Sep devs + loose + growth
2009 NMFS study area biomass	0.12	0.14	0.19	0.06	0	0.22	0.1	0.02	0.11
cpue q	0.18	0.2	0.21	0.2	0.18	0.21	0.22	0.22	0.23
retained	3.88	4.59	4.48	4.54	4.43	3.65	3.66	3.94	3.98
catch									
discard	157.39	170.33	157.17	182.94	198.96	116.77	121.99	134.52	133.47
catch									
trawl	7.08	7.86	8.4	7.65	6.51	6.95	6.55	6.01	6.5
catch									
female	5.36	6.03	5.94	6.16	6.35	4.17	4.13	4.22	4.09
discard									
catch									
survey	281.73	287.32	306.48	274.77	269.54	207.32	183.12	160.24	186.12
biomass									
F penalty	24.64	25.58	25.49	25.89	25.74	23.51	23.35	23.77	24.86
2010	20.78	22.33	11.38	17.59	9.18	9.58	6.63	3.72	6.15
BSFRF									
Biomass									
2010	1.45	1.14	1.81	0.76	0.09	3.44	2.83	1.19	2.9
NMFS									
Biomass									
Extra	553.32	551.54	558.89	547.77	544.01	547.47	541.06	531.03	773.64
weight									
survey									
lengths									
first year									
2010	-49.58	-48.28	-47.31	-49.79	-49.27	-51.66	-50.52	-45.11	-49.44
BSFRF									
length									
2010	-58.37	-59.94	-55.2	-65.77	-68.77	-64.14	-69.05	-71.81	-67.74
NMFS									
length									
smooth	2.99	3.95	3.61	3.97	3.94	2.44	2.38	2.42	2.31
selectivity									
smooth	0	0	0	0	0	0	0	0	0
female									
selectivity									
init nos	45.81	45.4	46.55	45.2	45.12	43.32	43.24	42.2	37.19
smooth									
constraint									
Total	7083.27	7740.18	7862.9	7583.52	7480.17	7493.83	7305.5	7169.93	7652.66

Table 10: Changes in management quantities for each scenario considered. Reported management quantities are median posterior values.

Model	MMB	B35	F35	FOFL	OFL
2017 model_old data	96.97	140.5	1.28	0.88	29.92
2017 model_new data	107.2	137.8	1.32	1.2	40.37
Fix fem M	103.5	141.9	1.19	1.12	39.19
Loose prior M	116.2	121.3	2.3	2.28	54.67
Looser prior M	144.4	108.9	9.42	9.42	79.54
Sep devs	85.84	142.8	1.22	1.04	29.74
Sep devs + loose prior	93.74	125.4	2.29	2.24	42.15
Sep devs + looser prior	109.3	109.5	8.13	8.13	59.21
Sep devs + loose + growth	94.89	124.4	2.57	2.52	43.28

Table 11: Likelihoods form and weighting for each likelihood component for models in the analysis (continued below)

Likelihood component	Form	2017 model_old data
Recruitment	normal	0.71
deviations		
Initial numbers old	normal	707.1
shell males small		
length bins		
ret fishery length	multinomial	200
total fish length	multinomial	200
(ret + disc)		
female fish length	multinomial	200
survey length	multinomial	200
trawl length	multinomial	200
2009 BSFRF length	multinomial	200
2009 NMFS study	multinomial	200
area length		
M multiplier prior	normal	0.23
maturity smooth	normal	3.16
growth males	normal	0.71
growth females	normal	0.32
2009 BSFRF	lognormal	NA
biomass		
2009 NMFS study	lognormal	NA
area biomass		
cpue q	normal	0.32
retained catch	normal	0.22
discard catch	normal	3
trawl catch	normal	0.22
female discard	normal	17
catch		
survey biomass	lognormal	NA
F penalty	normal	0.5
2010 BSFRF	lognormal	NA
Biomass		
2010 NMFS	lognormal	NA
Biomass		
Extra weight	multinomial	200
survey lengths first		
year		
2010 BSFRF length	multinomial	200
2010 NMFS length	multinomial	200
smooth selectivity	norm2(firstdiff(firstDiff))	2
smooth female	norm2(firstdiff(firstDiff))	3
selectivity		
init nos smooth	norm2(firstdifference)	1
constraint		

2017 model_new data	Fix fem M	Loose prior M	Looser prior M	Sep devs	Sep devs + loose prior	Sep devs + looser prior	Sep devs + loose + growth
0.71	0.71	0.71	0.71	0.71	0.71	0.71	200
707.1	707.1	707.1	707.1	707.1	707.1	707.1	NA
200	200	200	200	200	200	200	NA
200	200	200	200	200	200	200	NA
200	200	200	200	200	200	200	NA
NA	NA	NA	NA	NA	NA	NA	NA
200	200	200	200	200	200	200	NA
200	200	200	200	200	200	200	NA
200	200	200	200	200	200	200	NA
0.23	0.23	0.39	1.47	0.23	0.39	1.47	NA
3.16	3.16	3.16	3.16	3.16	3.16	3.16	NA
0.71	0.71	0.71	0.71	0.71	0.71	0.71	NA
0.32	0.32	0.32	0.32	0.32	0.32	0.32	NA
NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA
0.32	0.32	0.32	0.32	0.32	0.32	0.32	NA
0.22	0.22	0.22	0.22	0.22	0.22	0.22	NA
3	3	3	3	3	3	3	NA
0.22	0.22	0.22	0.22	0.22	0.22	0.22	NA
17	17	17	17	17	17	17	NA
NA	NA	NA	NA	NA	NA	NA	NA
0.5	0.5	0.5	0.5	0.5	0.5	0.5	NA
NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA
200	200	200	200	200	200	200	NA
200	200	200	200	200	200	200	NA
200	200	200	200	200	200	200	200
2	2	2	2	2	2	2	2
3	3	3	3	3	3	3	3
1	1	1	1	1	1	1	1

Table 13: Predicted mature male (MMB), mature female (FMB), and males >101mm biomass (1000 t) and numbers (in millions) at the time of the survey from the chosen model. Columns 2-5 are subject to survey selectivity; columns 6-9 are the population values (i.e. the numbers at length are not modified by multiplying them by a selectivity curve—they are estimates of the underlying population). These are maximum likelihood estimates that will differ slightly from the median posterior values.

Survey year	FMB	MMB	Male >101 biomass	Male >101 (millions)	FMB	MMB	Male >101 biomass	Male >101 (millions)
1982	86.34	133.7	35.5	67.55	158.8	313.9	59.18	112.6
1983	59.2	136.9	60.52	108.1	106.8	321.5	100.9	180.2
1984	37.3	138.9	80.36	137.8	67.38	326.9	133.9	229.7
1985	29.7	128.3	78.89	133.2	54.28	302.9	131.5	222
1986	37.87	111.6	42.41	71.51	70.21	265	98.98	166.9
1987	99.2	112.1	35.34	61.53	186.6	268.9	82.48	143.6
1988	242.9	205.2	38.02	66.49	255.9	306.2	88.75	155.2
1989	239.6	248.2	47.11	82.63	251.2	370.2	110	192.9
1990	188.9	310.1	74.1	128.8	197.3	461.1	172.9	300.7
1991	155	289.1	68.29	118.2	162.4	429.3	159.4	275.8
1992	140	239.2	55.69	97.14	146.8	355.2	130	226.7
1993	147.2	203.9	76.66	129.7	154.8	304.3	113	191.2
1994	164.6	179.3	45.69	76.26	173.2	268.4	67.35	112.4
1995	176.4	205.5	44.69	79.19	185.5	306.7	65.88	116.7
1996	151	286.4	111.8	196.5	158	425	164.9	289.6
1997	112	329.8	176.2	295.9	117	488.2	259.8	436.1
1998	81.88	238.9	122.9	203.5	85.55	353.8	181.2	300
1999	66.35	144.2	60.25	100.9	69.49	214	88.82	148.7
2000	64.45	111.5	43.27	72.08	67.71	165.9	63.78	106.3
2001	58.26	93.91	31.53	53.34	61.04	139.7	46.48	78.63
2002	48.44	90.88	31.51	54.73	50.7	135	46.45	80.68
2003	39.84	98.06	43.43	73.98	41.71	145.6	64.02	109.1
2004	44.27	99.26	47.58	79.05	46.64	147.6	70.14	116.5
2005	74.42	97.34	40.75	67.58	78.78	145.1	60.07	99.62
2006	89.95	106.9	38.12	65.14	94.61	159.4	56.2	96.03
2007	87.12	135.4	54.2	93.26	91.38	201.3	79.9	137.5
2008	72.63	157.6	72.66	123.7	76	233.8	107.1	182.4
2009	57.67	165.2	85.67	143.6	60.33	244.7	126.3	211.7
2010	101.8	155.1	85.88	142.3	107.9	229.8	126.6	209.8
2011	127.6	128.9	68.98	113.5	134.3	191.2	101.7	167.3
2012	117.5	92.54	38.02	64.07	123	137.5	56.05	94.46
2013	99.28	79.07	28.7	50.16	104	117.5	42.32	73.95
2014	87.36	75.37	30.44	52.17	91.59	112	44.87	76.9
2015	77	61.64	21.21	36.2	80.7	91.84	31.27	53.36
2016	83.09	61.08	17.71	30.4	87.45	91.42	26.1	44.81
2017	134	84.79	23.87	41.08	141.8	127.6	35.18	60.56
2018	193.9	135.8	38.36	65.8	204.7	203.9	56.54	97

Table 14: Maximum likelihood estimates of predicted mature male biomass at mating, mature female biomass at mating (in 1000 t), recruitment (millions) from the chosen model, and estimated fully-selected total fishing mortality. These are maximum likelihood estimates that will differ slightly from the median posterior values.

Survey year	Mature male biomass	Mature female biomass	Recruits	Fishing mortality
1982	239	111.1	274	0.36
1983	245.5	74.68	664.7	0.21
1984	231.7	47.14	1605	0.41
1985	197.7	37.97	6618	0.67
1986	164.3	49.1	3216	1.04
1987	153.7	130.6	2241	2.22
1988	178.4	179.1	700	2.34
1989	225.4	175.8	1754	1.77
1990	224.6	138.1	1571	3.23
1991	202.7	113.6	2429	3.75
1992	181.8	102.7	2594	2.7
1993	175.5	108.3	2434	1.57
1994	178.5	121	653.7	1.19
1995	216.6	129.7	531.3	0.95
1996	288.5	110.5	504	0.65
1997	277.9	81.86	673.2	0.97
1998	194.2	59.84	955.9	1.12
1999	156.2	48.61	430.4	0.3
2000	121.2	47.37	381	0.32
2001	96.7	42.7	338.8	0.63
2002	95.53	35.47	920.8	0.52
2003	105.8	29.18	2100	0.3
2004	106.7	32.62	1067	0.28
2005	99.44	55.12	889.6	0.53
2006	111.3	66.19	454.3	0.56
2007	133.5	63.93	431.1	0.72
2008	161.6	53.17	3543	0.46
2009	174.6	42.2	1412	0.3
2010	159.9	75.51	893.4	0.34
2011	112.6	93.86	896.8	0.83
2012	79.57	86.07	946.9	1.29
2013	69.68	72.72	720.3	1.44
2014	58.87	63.97	1550	1.99
2015	54.79	56.44	3719	1.52
2016	63.57	61.18	3813	0.76
2017	93.74	99.18	1459	0.46

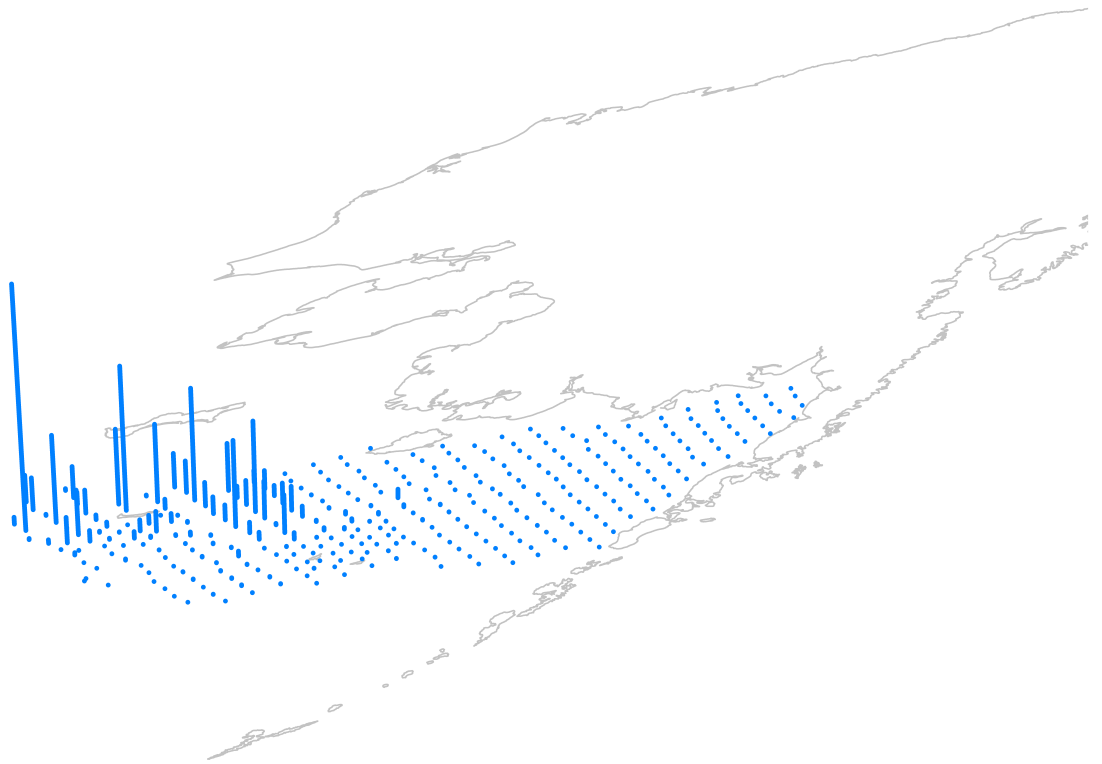


Figure 1: Observed relative density of all males at the time of the 2018 NMFS summer survey

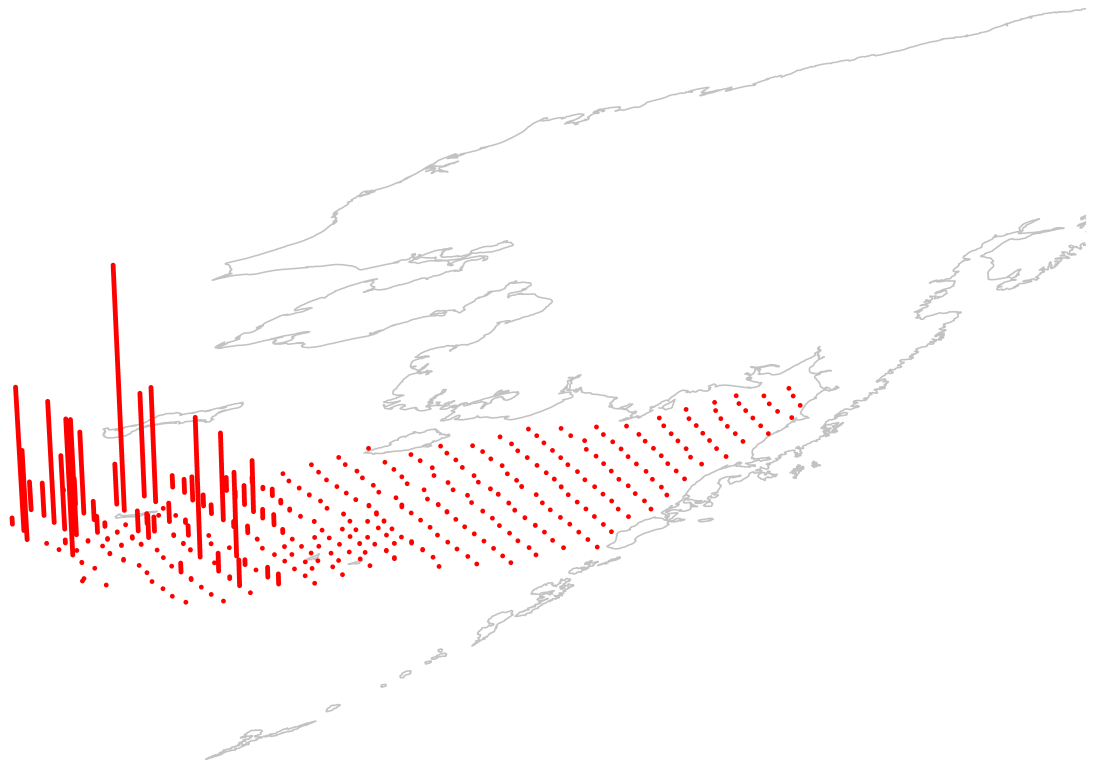


Figure 2: Observed relative density of all females at the time of the 2018 NMFS summer survey

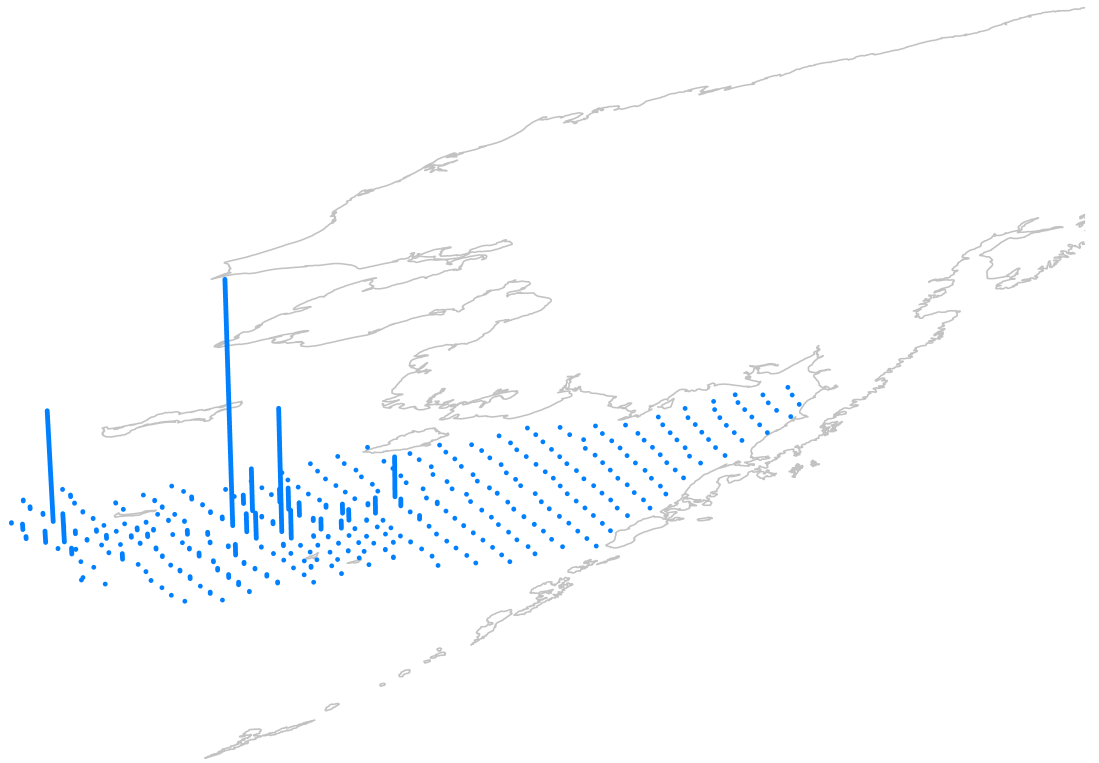


Figure 3: Observed relative density of males $>77\text{mm}$ carapace width at the time of the 2018 NMFS summer survey

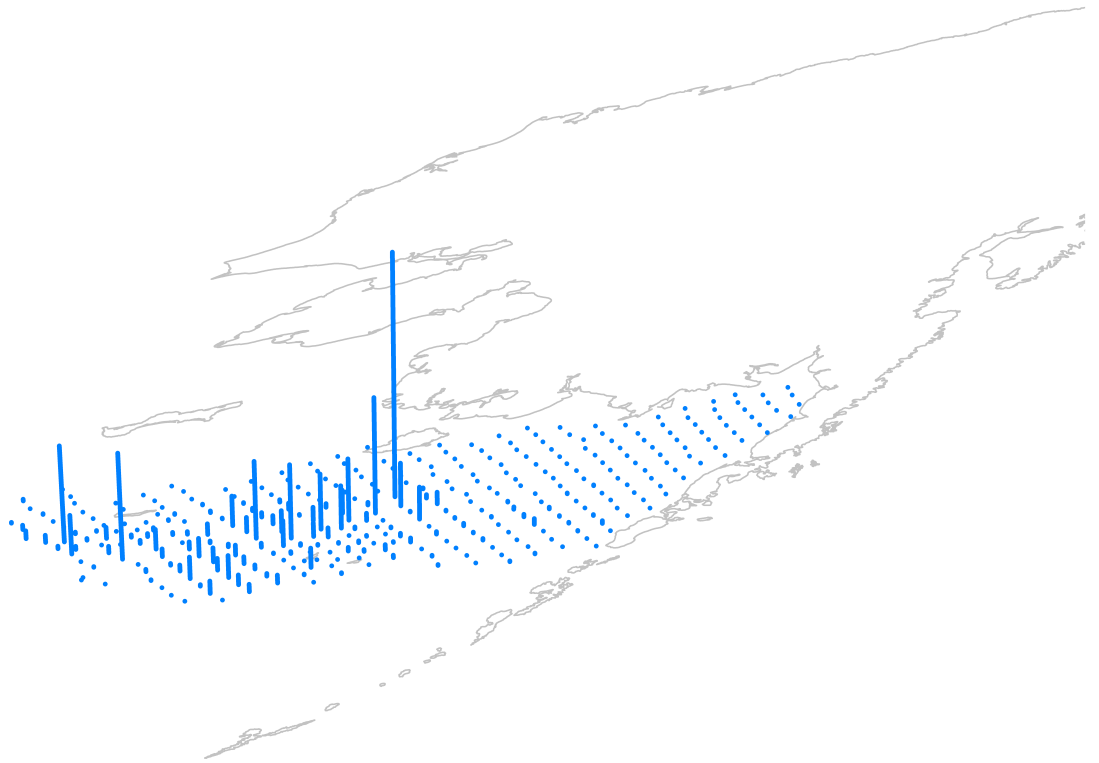


Figure 4: Observed relative density of males $>101\text{mm}$ carapace width at the time of the 2018 NMFS summer survey

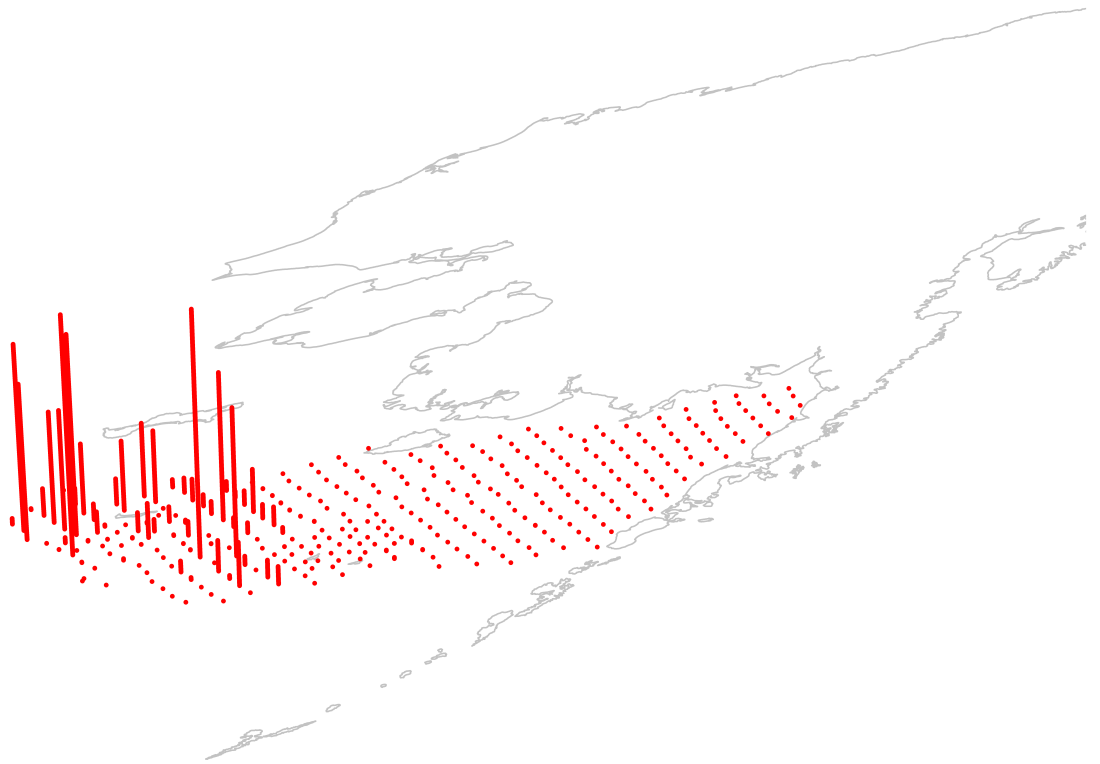


Figure 5: Observed relative density of mature females at the time of the 2018 NMFS summer survey

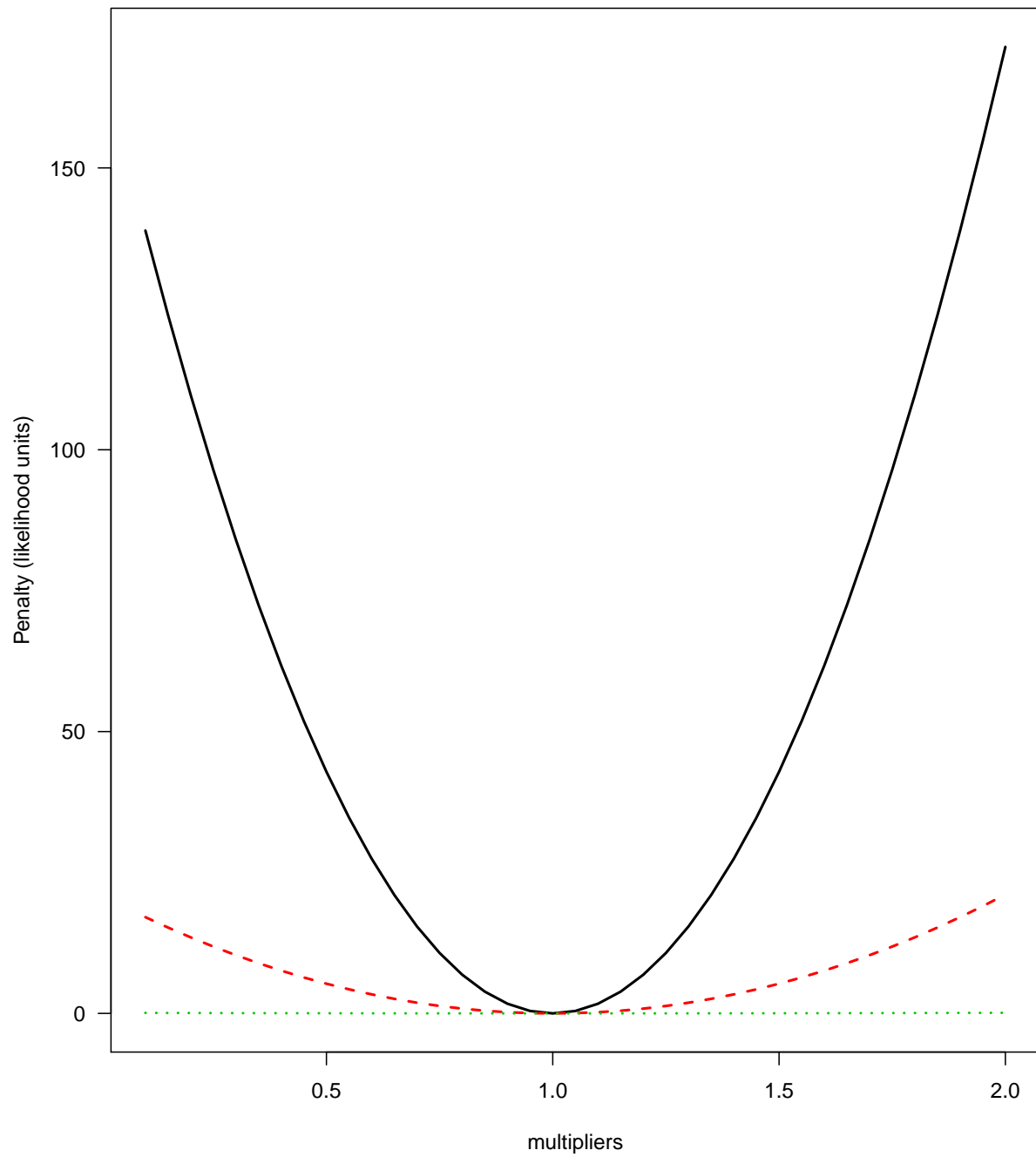


Figure 6: Prior on multiplier for mature natural mortality. Black is 0.054. Red is 0.154. Green is 2.154

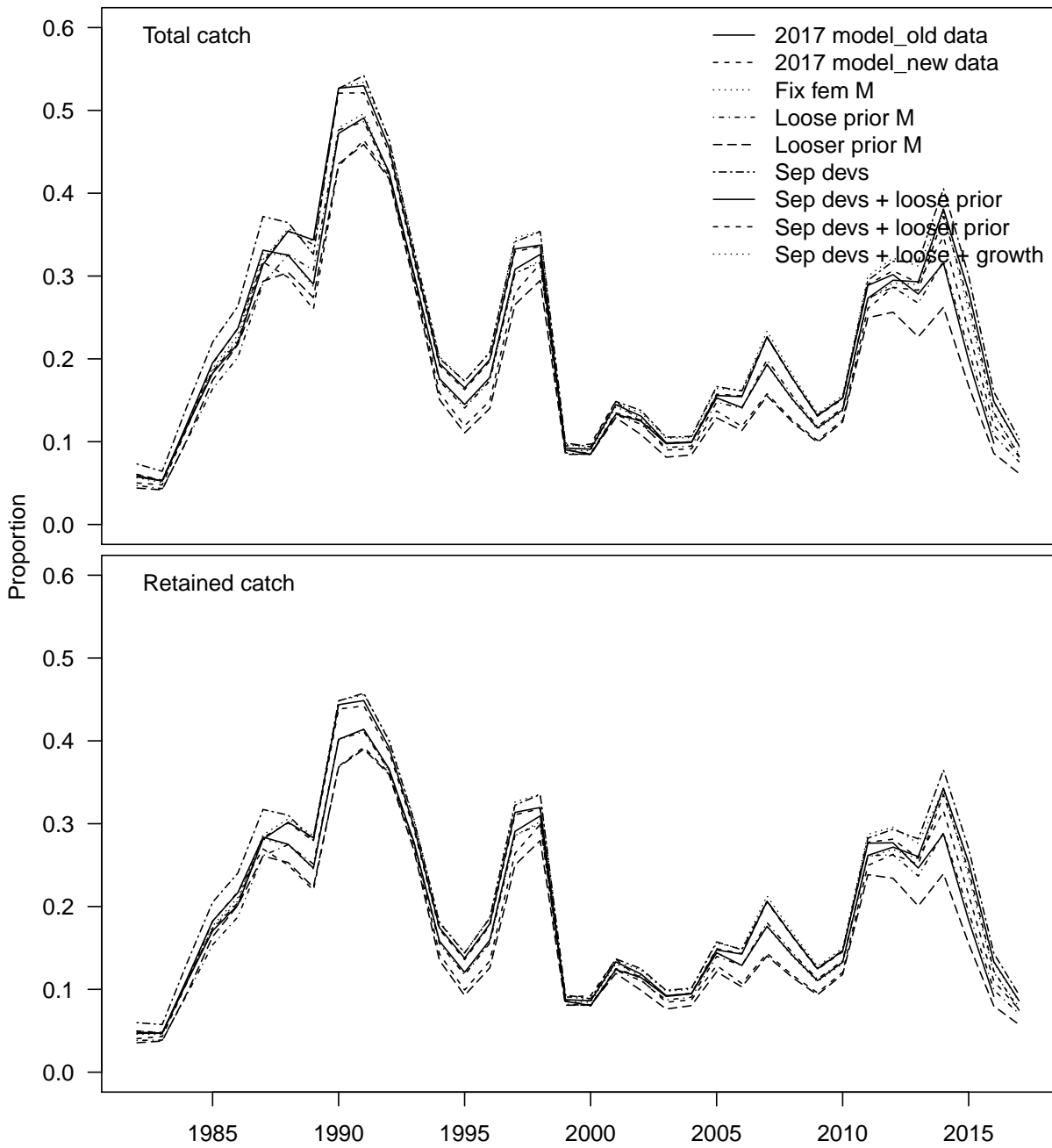


Figure 7: Model predicted ratio of catch to mature male biomass

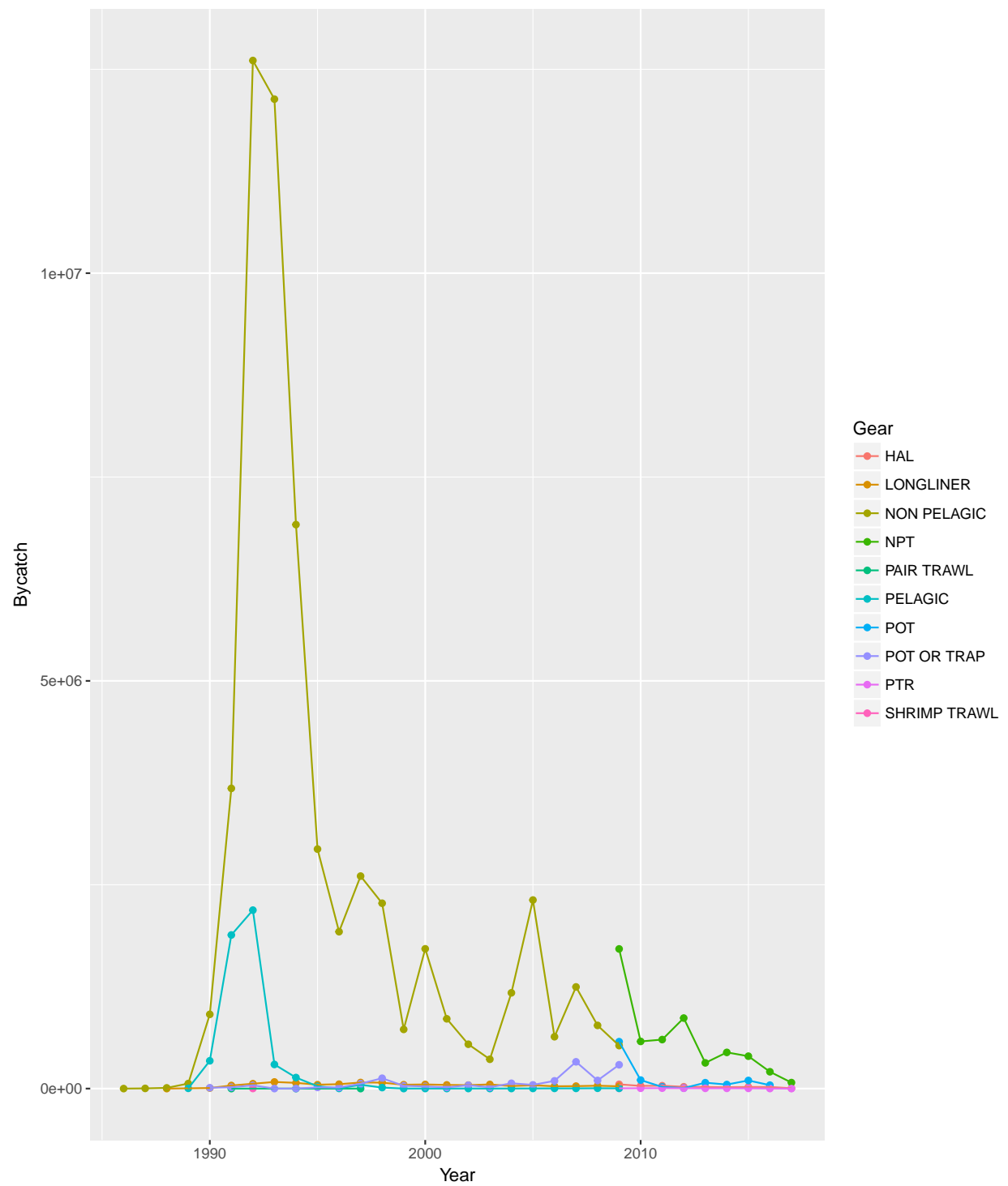


Figure 8: Bycatches in other fishing fleets.

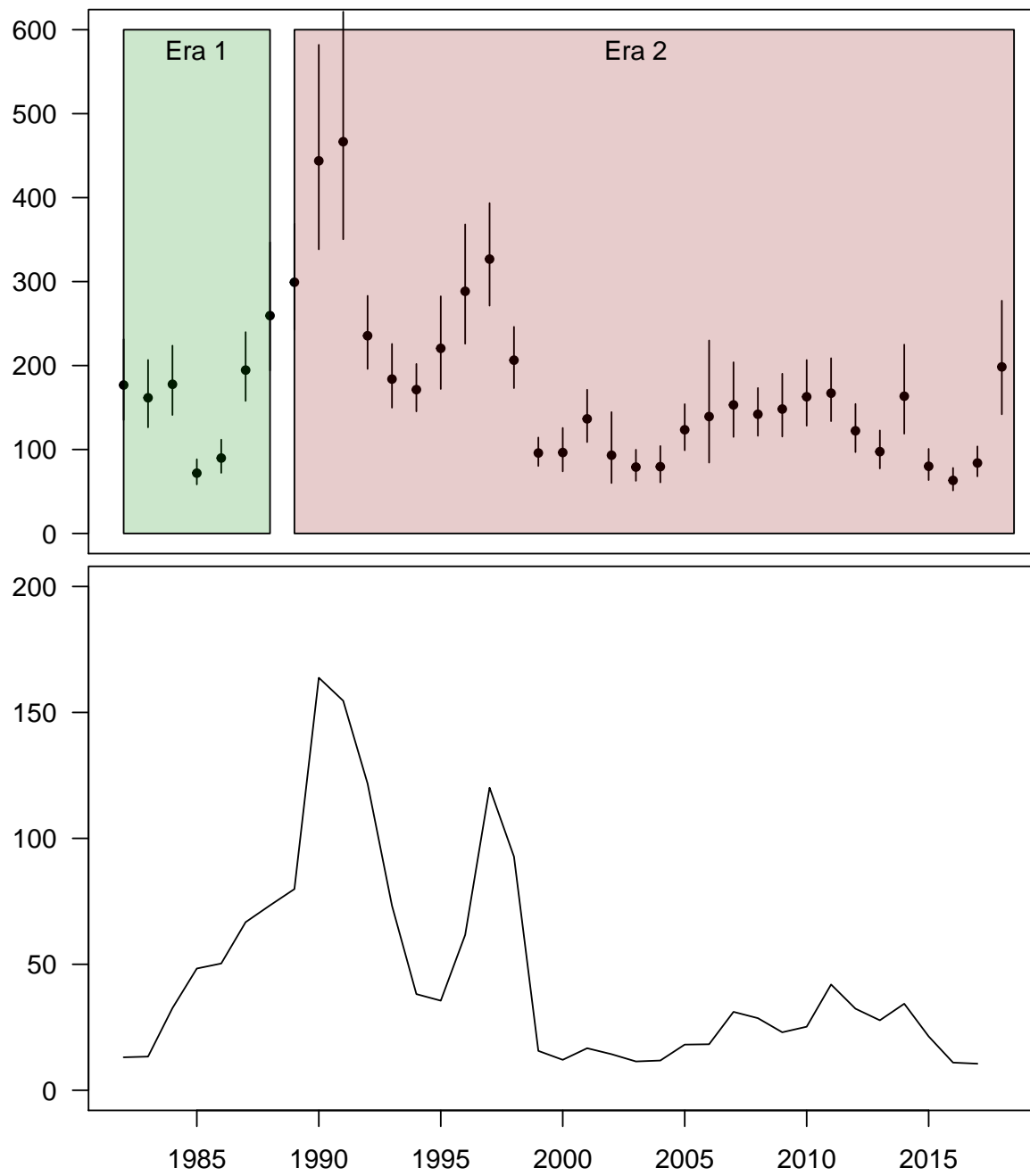


Figure 9: Divisions of survey data for estimation of q (MMB shown for reference; top) and total catches (bottom)

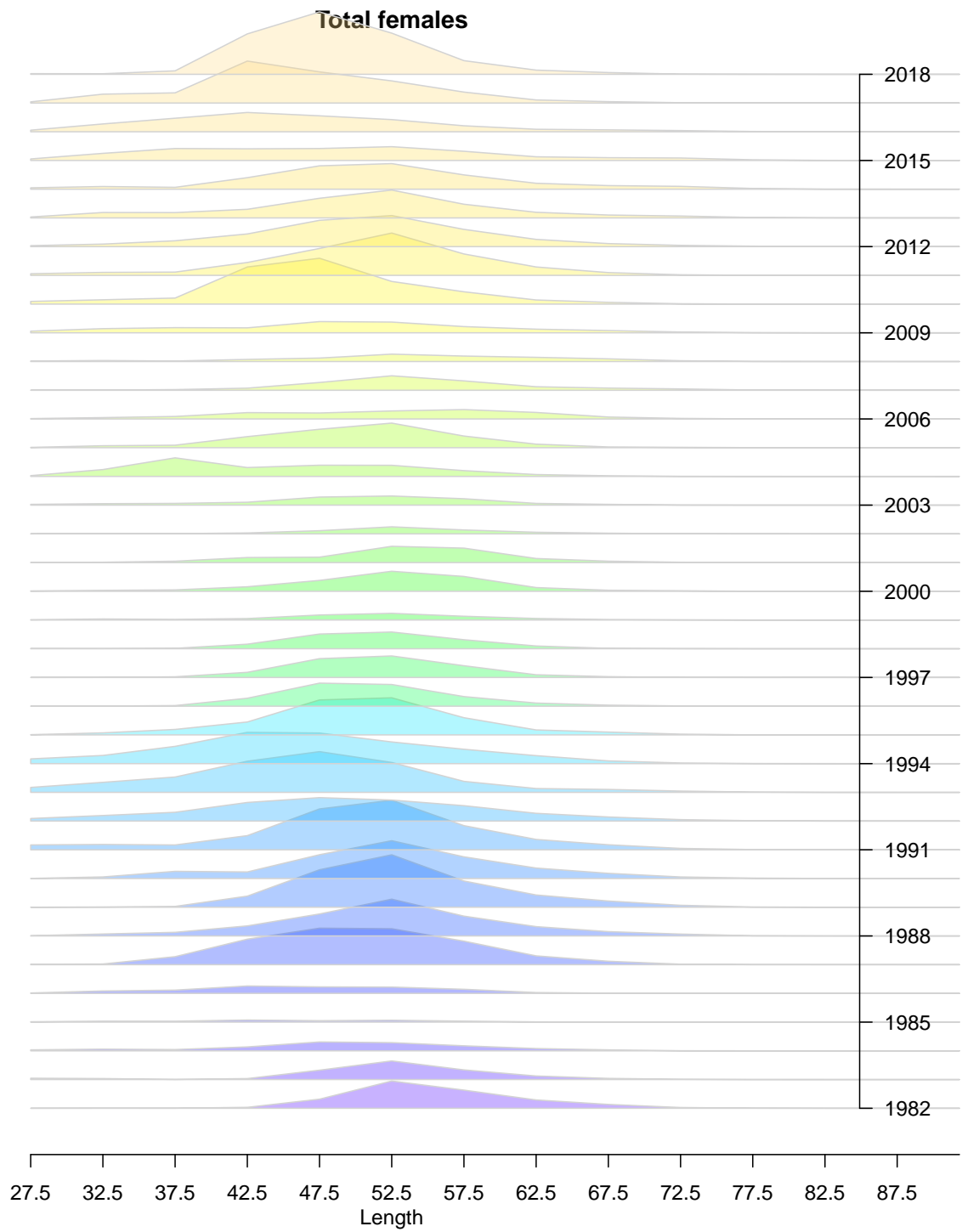


Figure 10: Observed relative numbers at length at the time of the survey

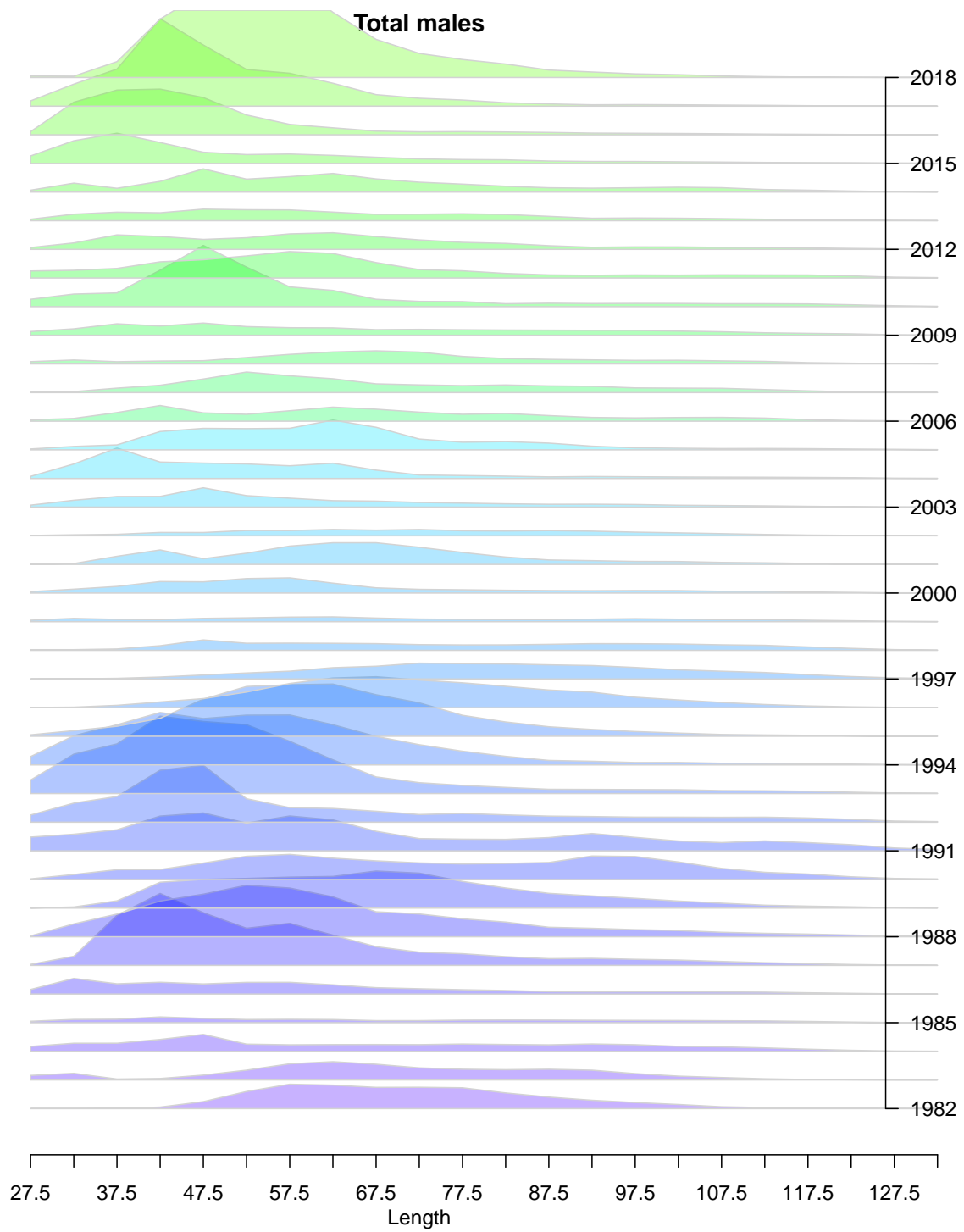


Figure 11: Observed relative numbers at length at the time of the survey

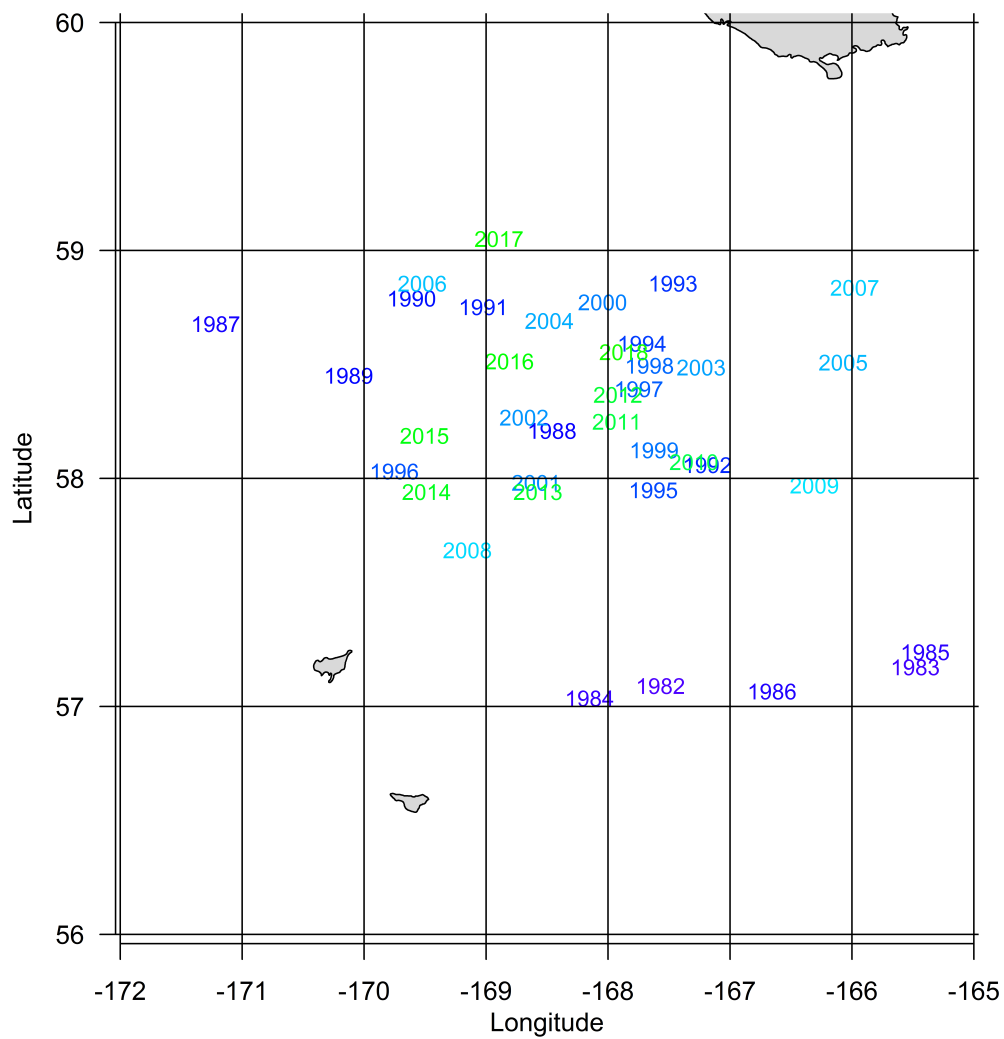


Figure 12: Centroid of mature females observed in the survey over time. Dark blue indicates years early in the time series; green are the most recent years in the time series.

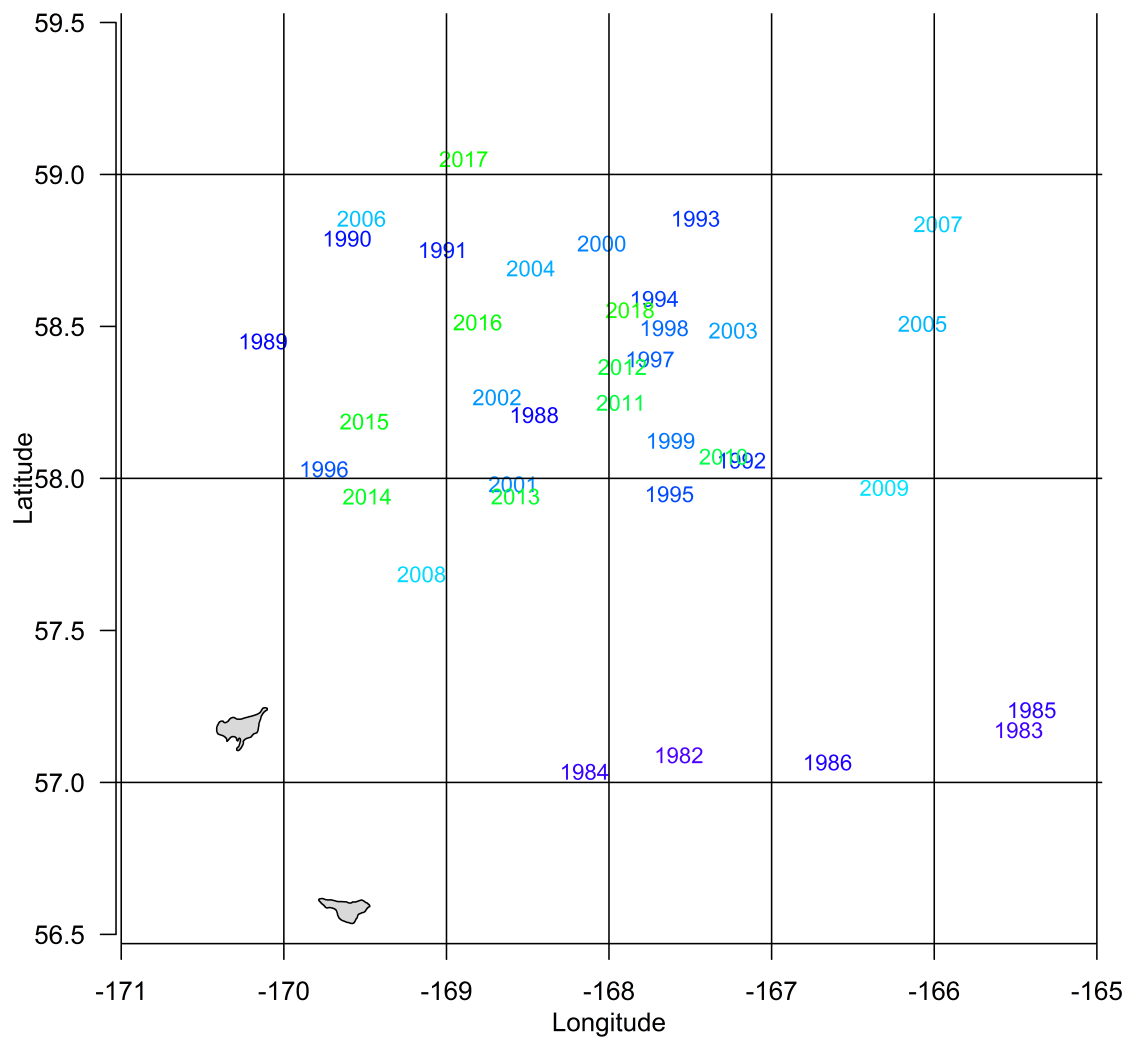


Figure 13: Centroid of large males observed in the survey over time. Dark blue indicates years early in the time series; green are the most recent years in the time series.

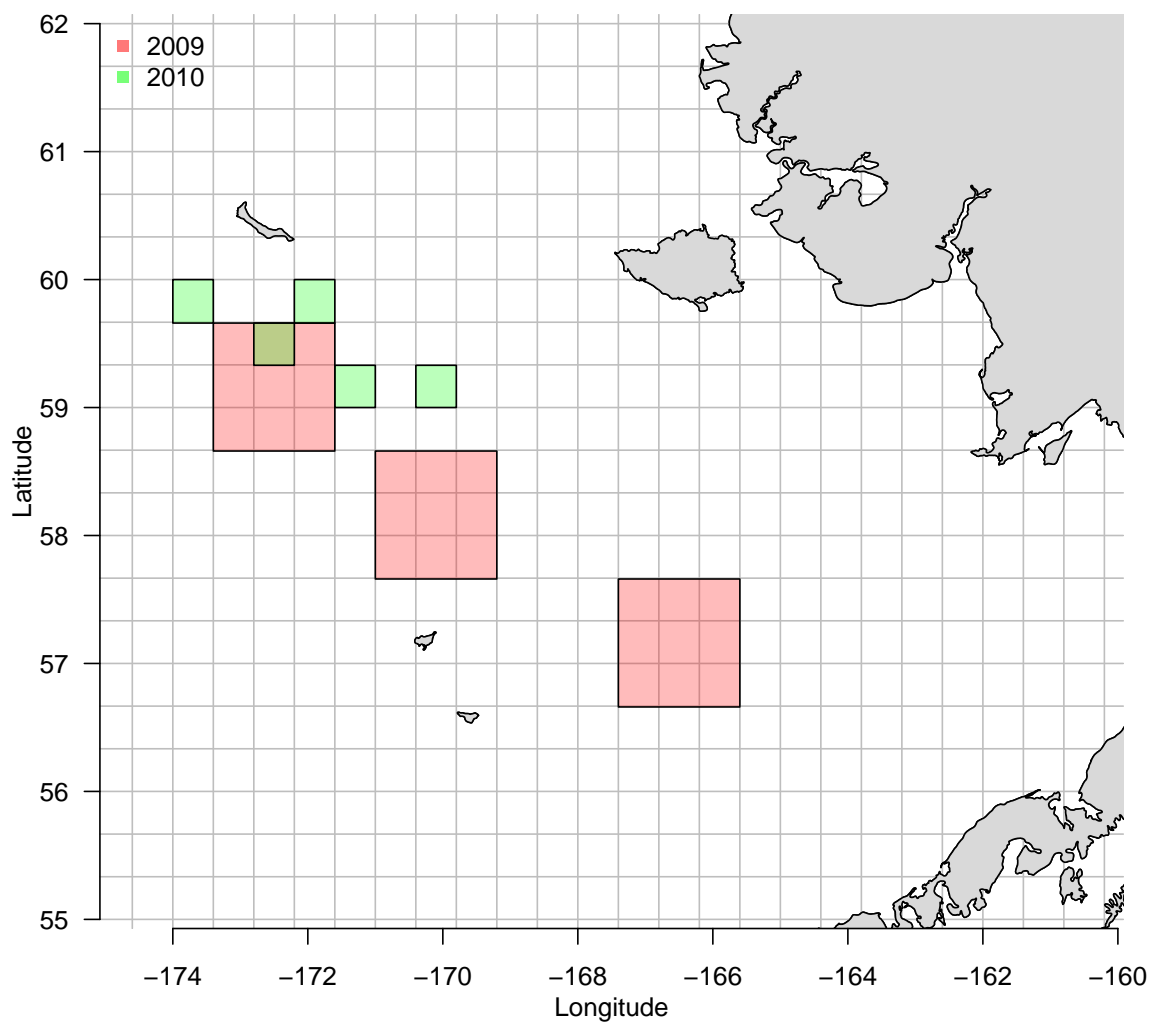


Figure 14: Location of survey selectivity experiments (2009 & 2010; this was reproduced from the 2015 SAFE; revise this figure with BSFRF data)

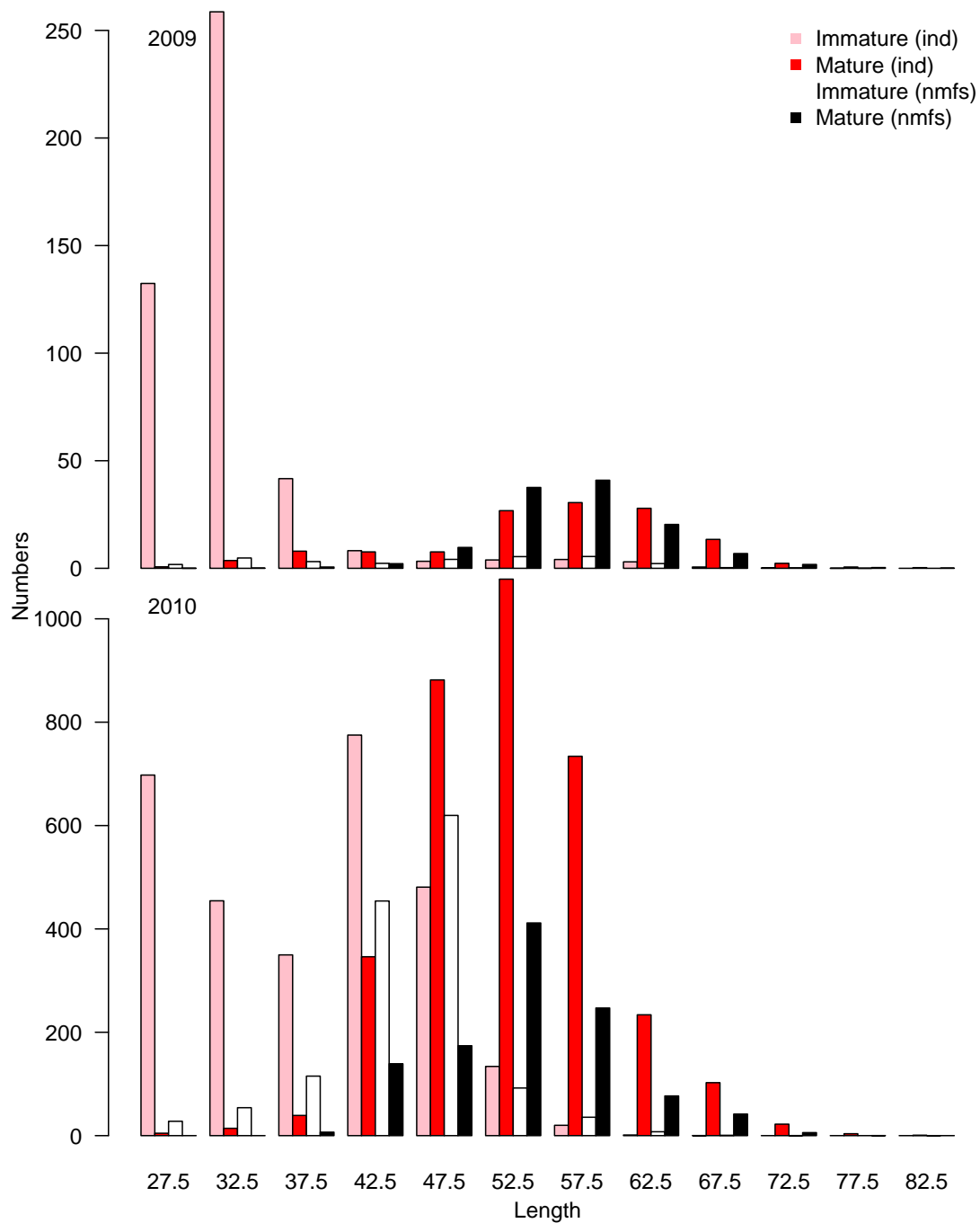


Figure 15: Raw female numbers from BSFRF survey selectivity experiments (2009 & 2010). Note a change in scale on the y-axis from 2009 to 2010

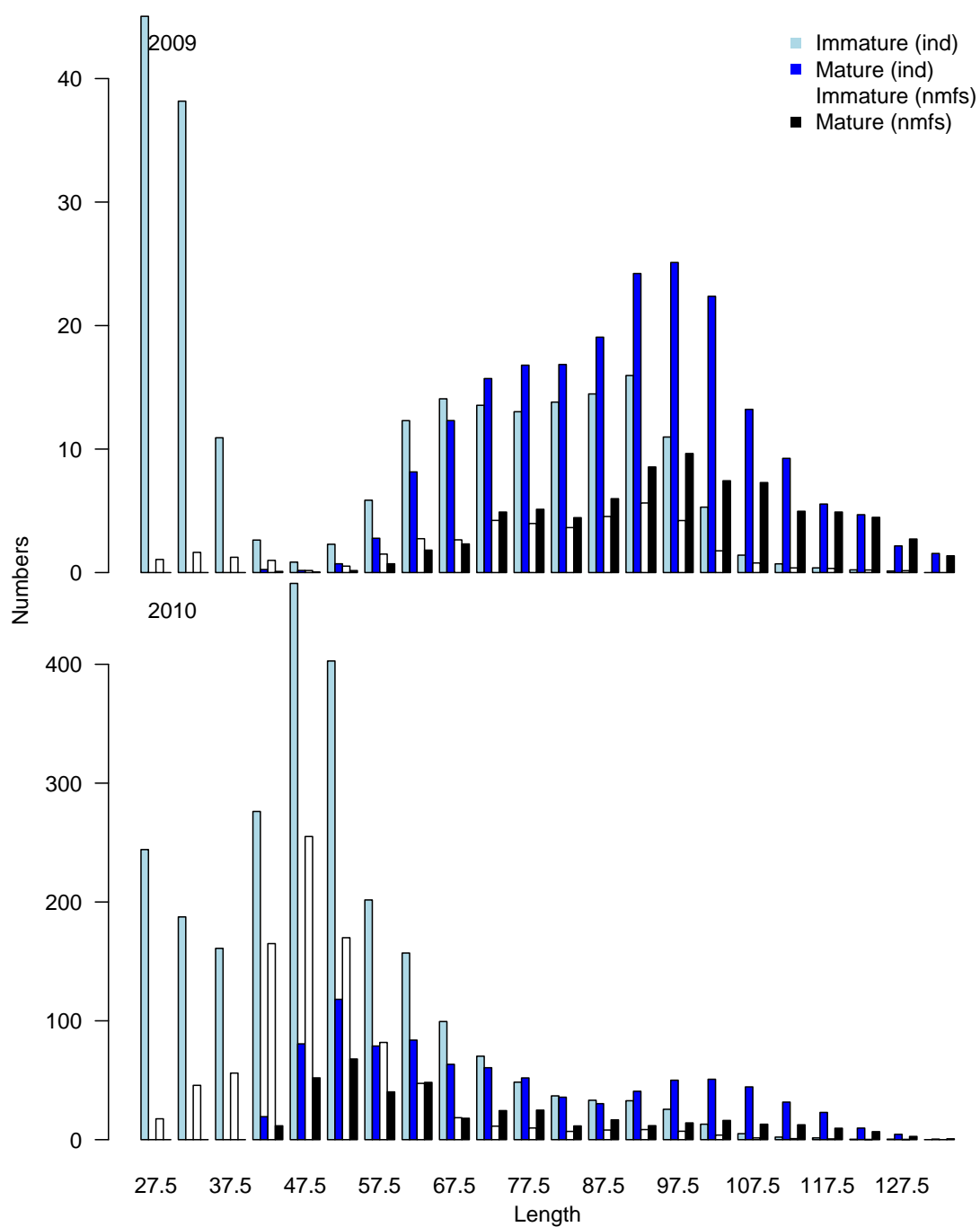


Figure 16: Raw male numbers from BSFRF survey selectivity experiments (2009 & 2010). Note a change in scale from 2009 to 2010 on the y-axis.

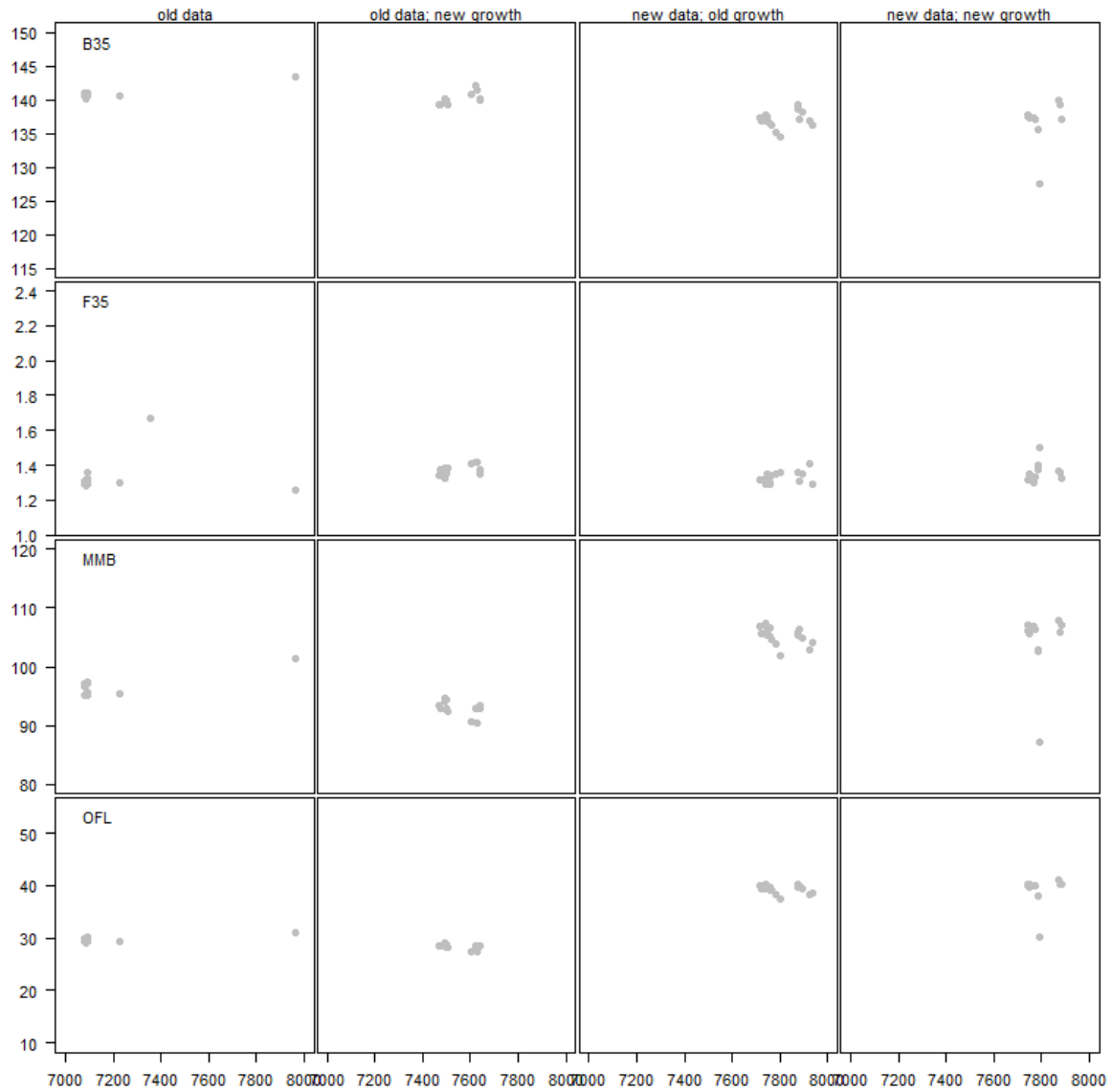


Figure 17: Management quantities after jittering the base model with different configurations of new data sources. X-axis is the negative log likelihood

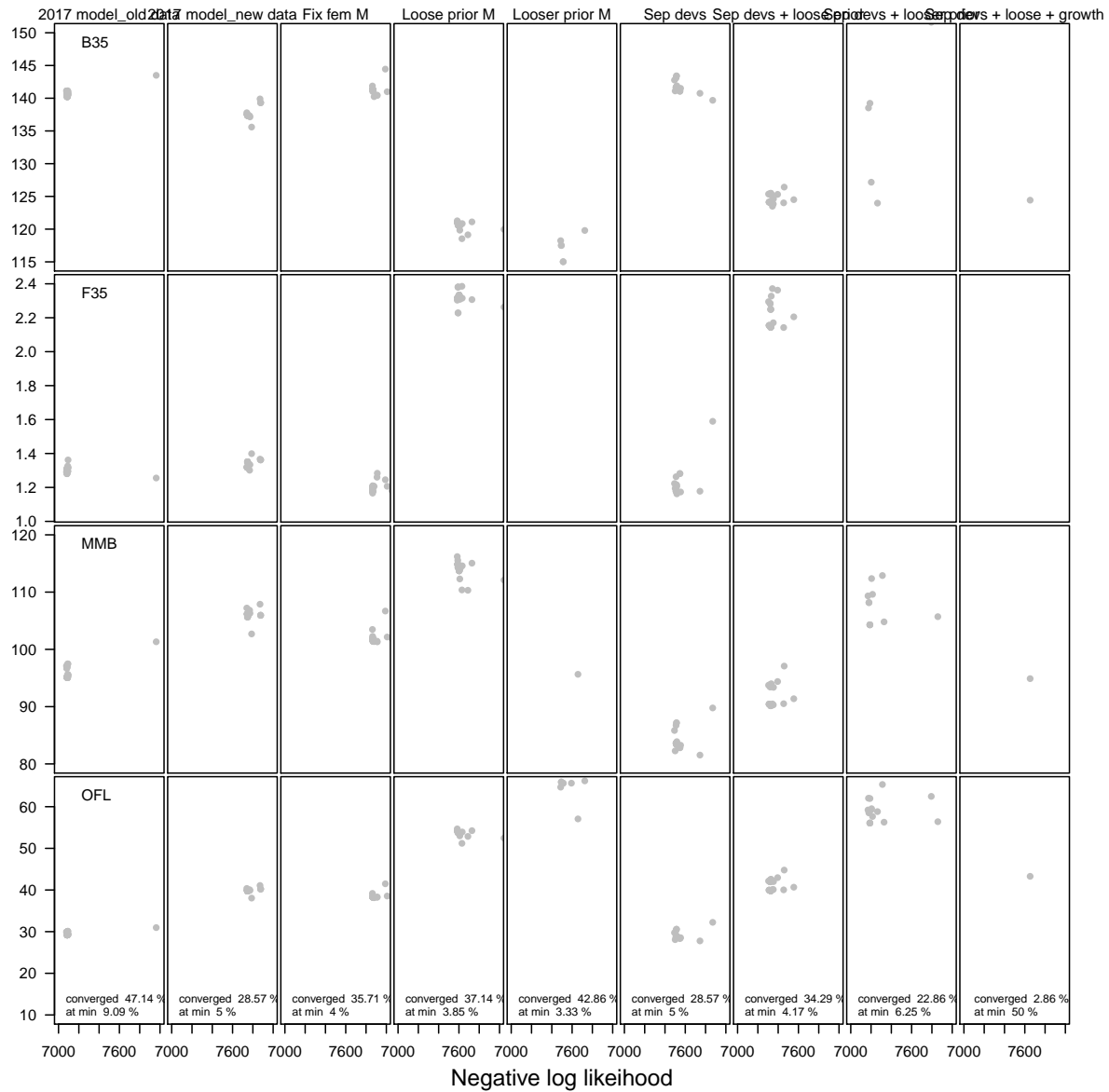


Figure 18: Management quantities after jittering selected models. Converged % indicates the % of jittered models that had a maximum gradient component < 0.005 . at min % indicates the number of runs that converged to the minimum observed negative log likelihood

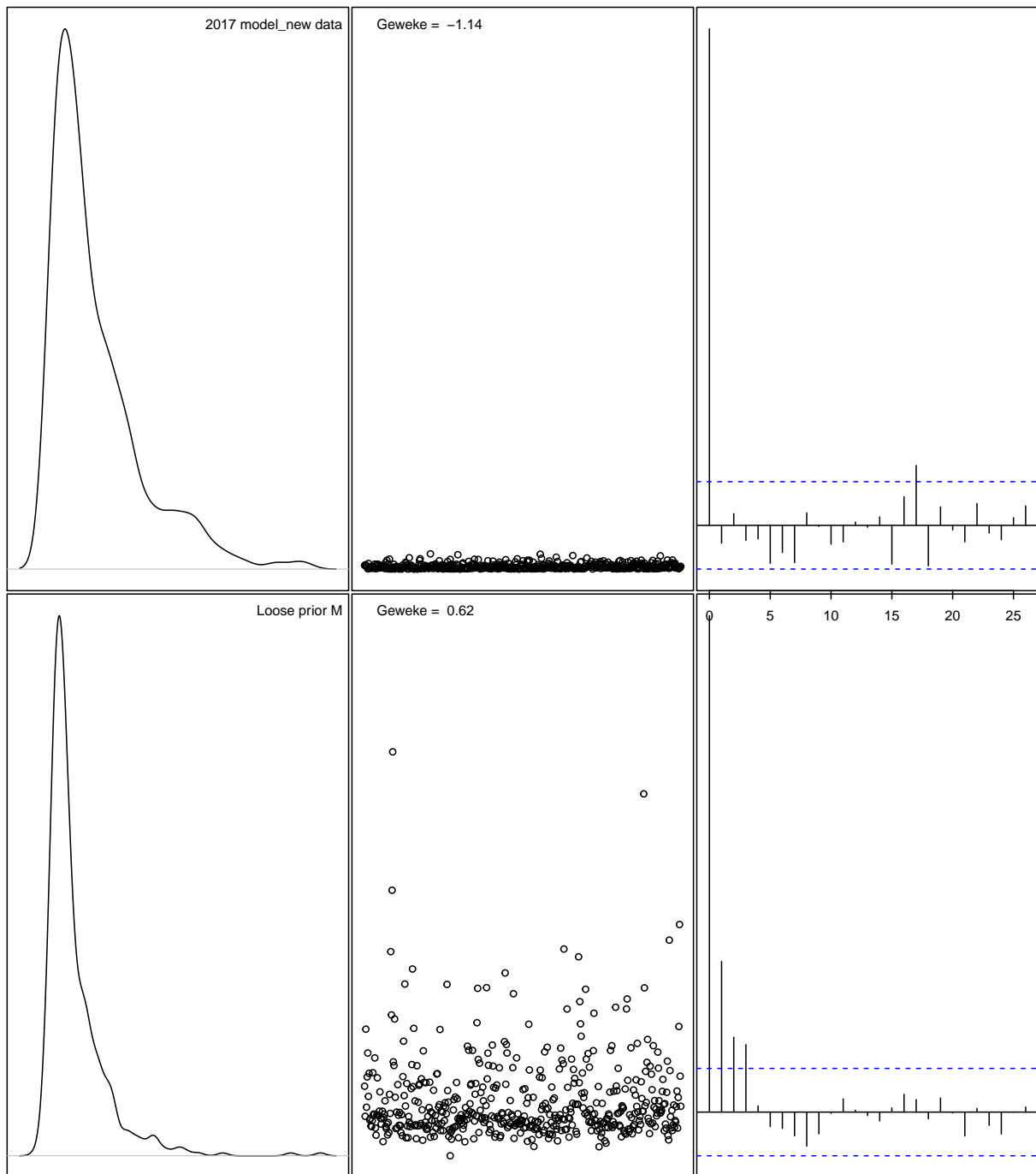


Figure 19: Basic MCMC diagnostics. Left column is the density of the value of the objective function. Middle column is the trace of the objective function. Number in the upper left of each panel is the z-score of the Geweke diagnostic. Right is the autocorrelation in the objective function value.

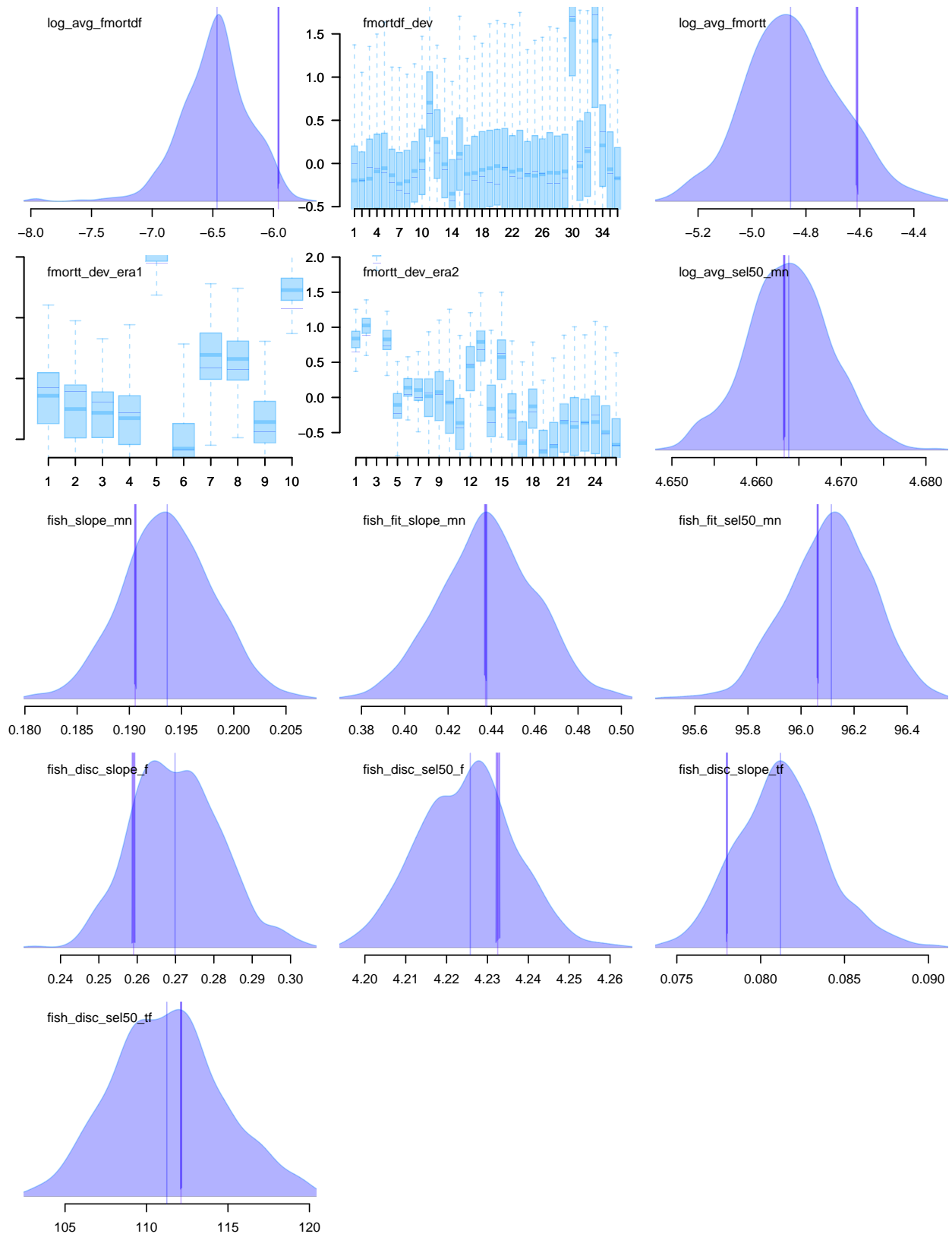


Figure 21: Posterior densities for estimated parameters by scenario

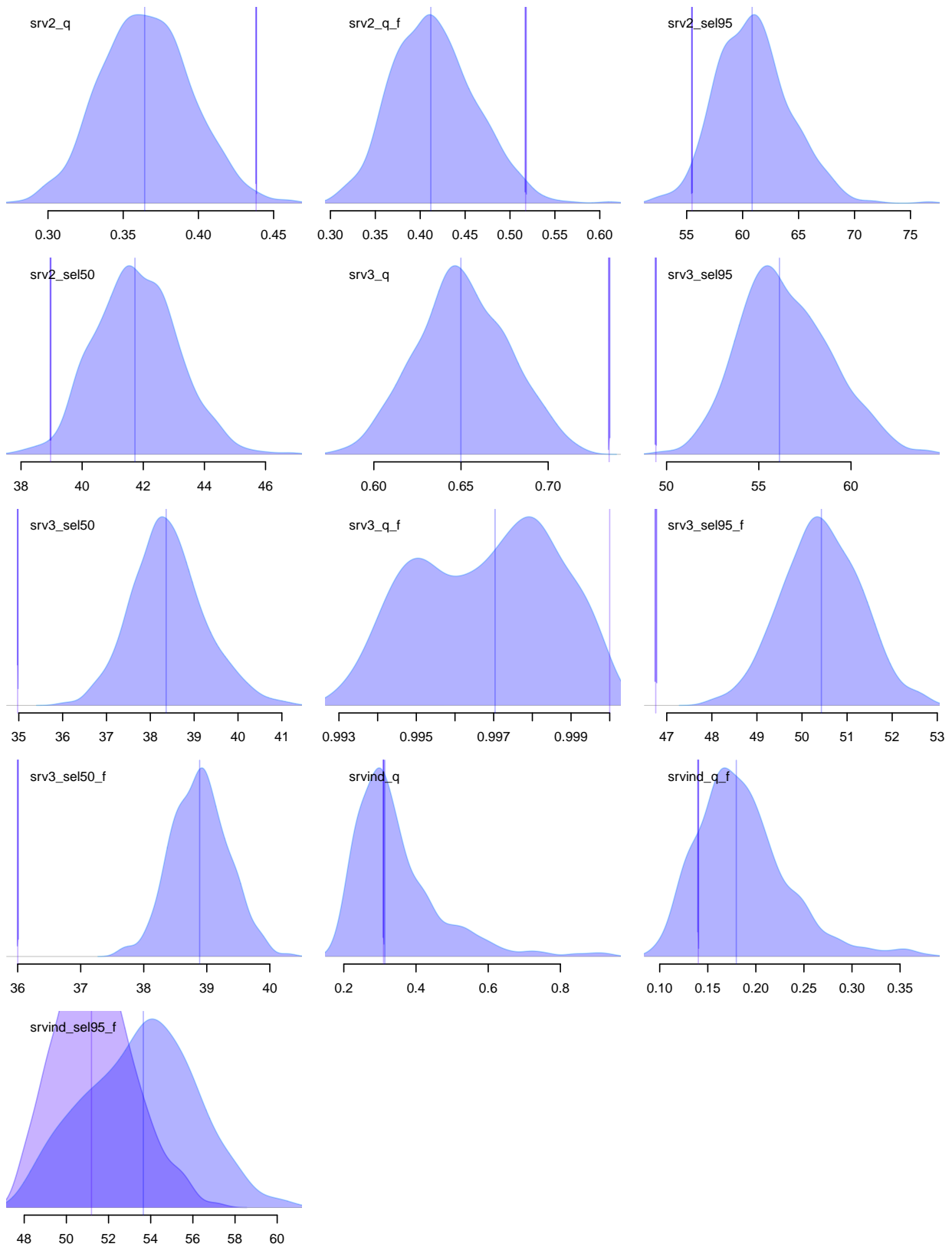


Figure 22: Posterior densities for estimated parameters by scenario

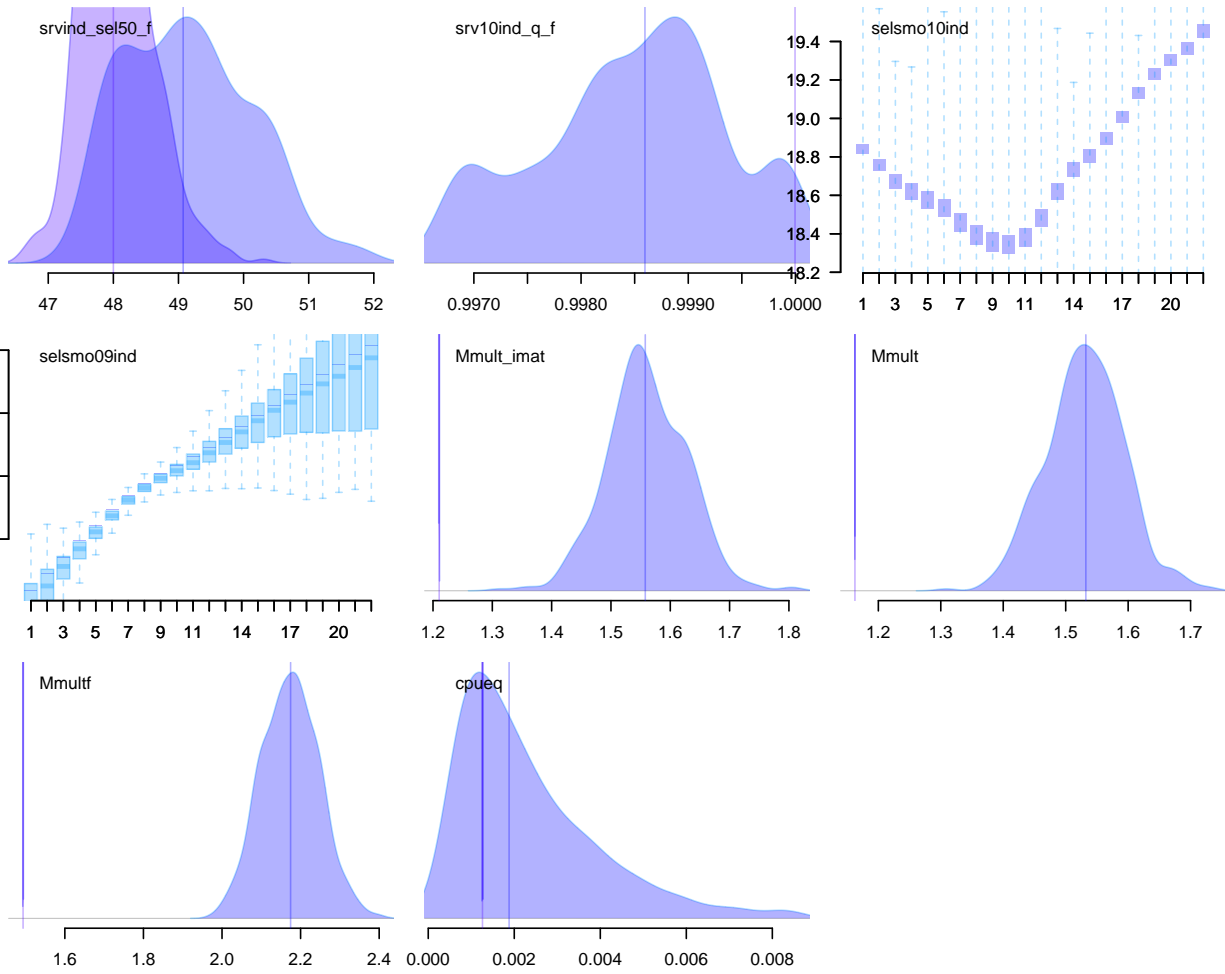


Figure 23: Posterior densities for estimated parameters by scenario

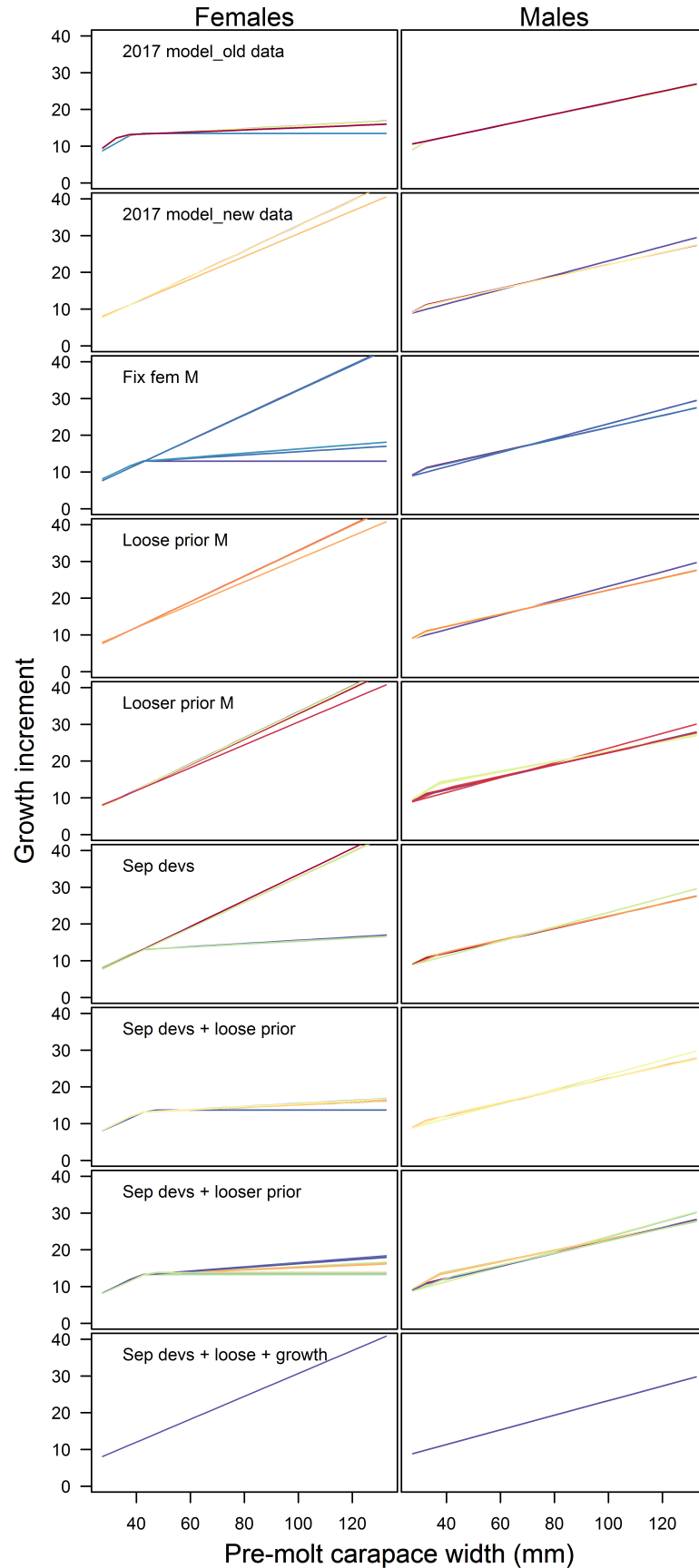


Figure 24: Estimated growth curves from jittered runs for all models. Colors represent the relative magnitude of the estimated OFL resulting from a given growth⁶⁷ curve. Actual magnitude is not important—this figure is meant to show that the bimodality in the OFL is related to the growth curve (in particular, the female growth curve).

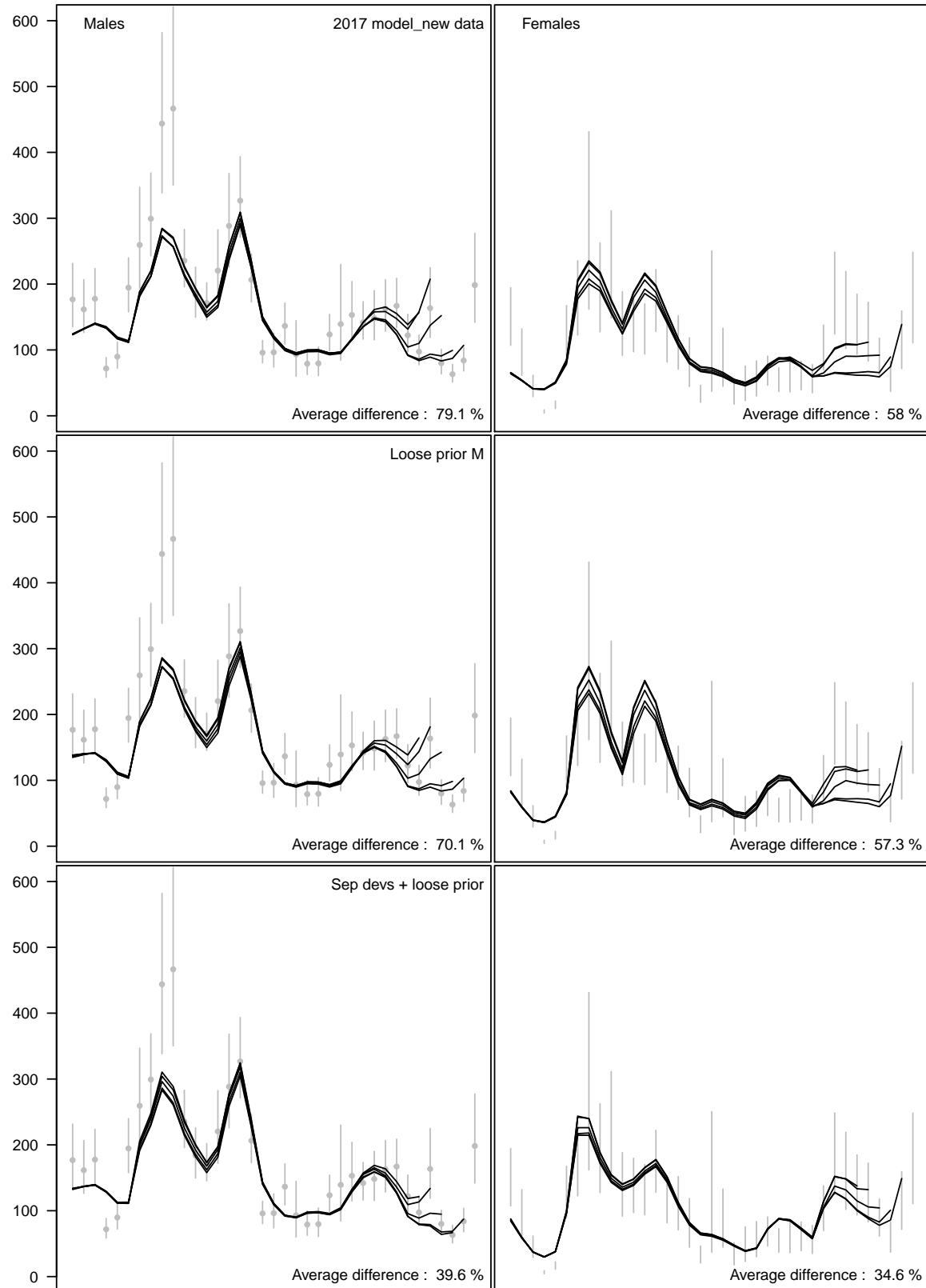


Figure 25: Retrospective analysis for selected models. Each line represents the model predictions for survey mature biomass when successively more years of data⁶⁸ are removed from the analysis. Average difference is calculated as the mean relative error over the retrospective period (i.e. $(\text{Peeled MMB} - 2017 \text{ MMB}) / 2017 \text{ MMB}$)

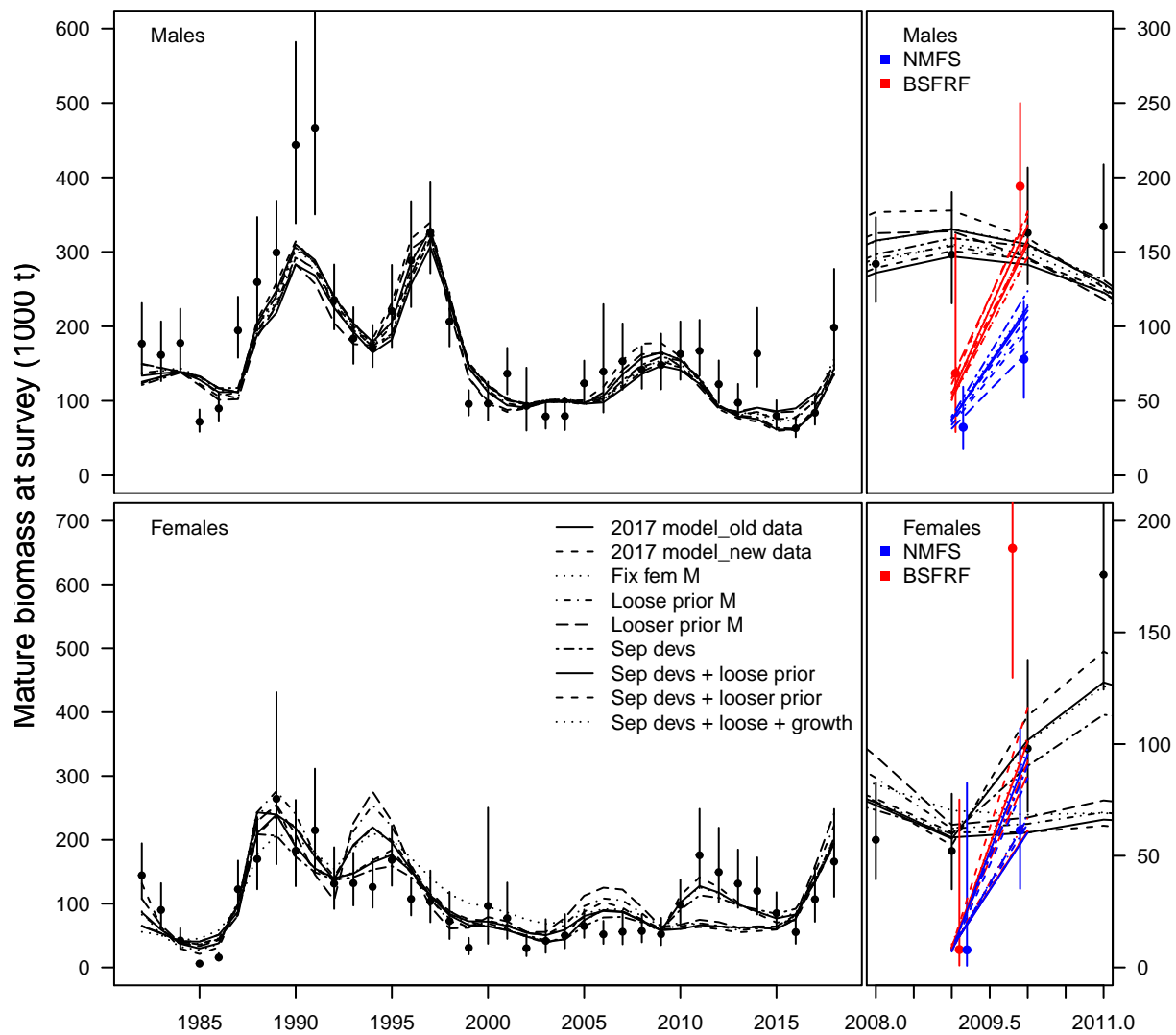


Figure 26: Model fits to the observed mature biomass at survey

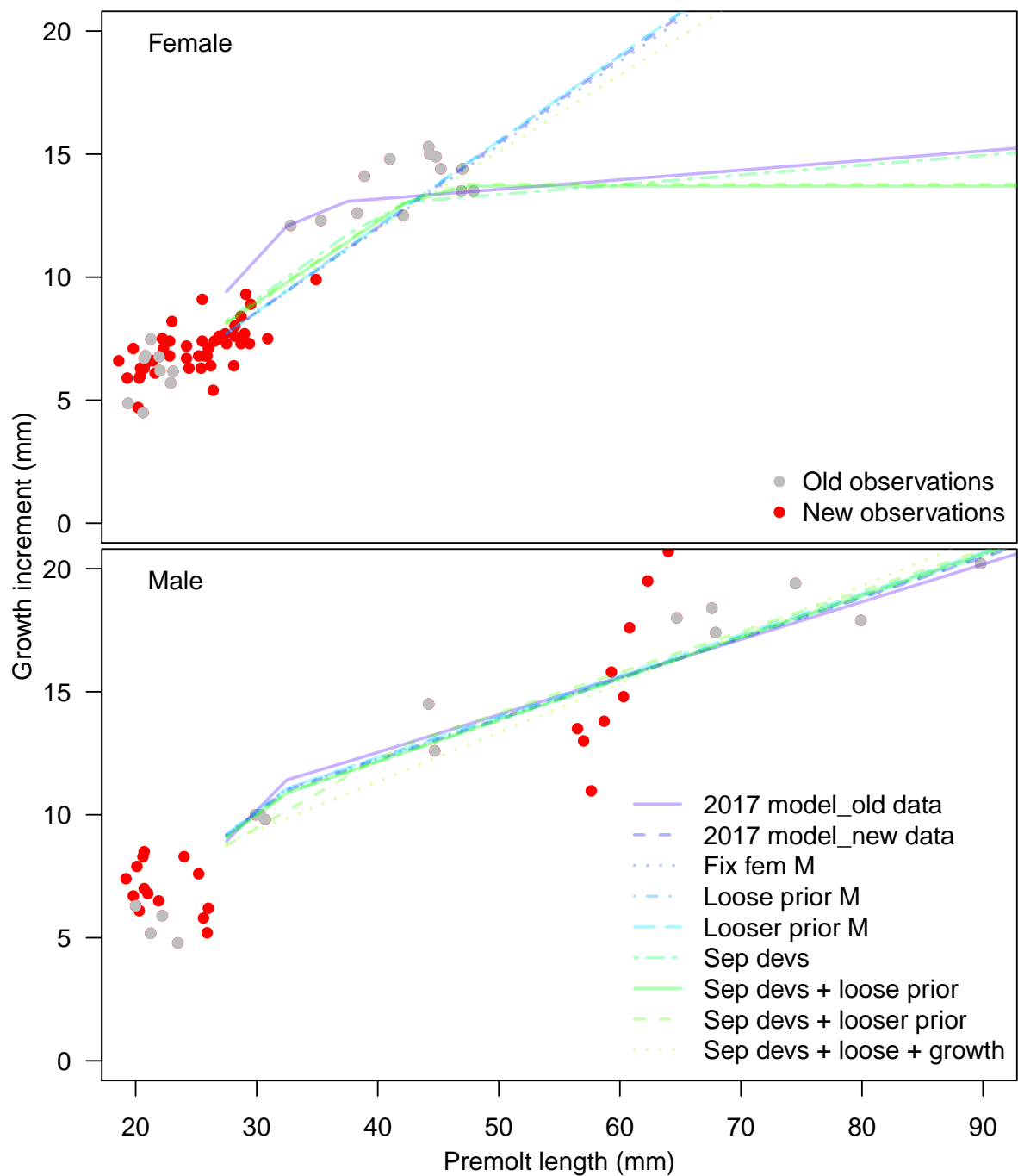


Figure 27: Model fits to the growth data

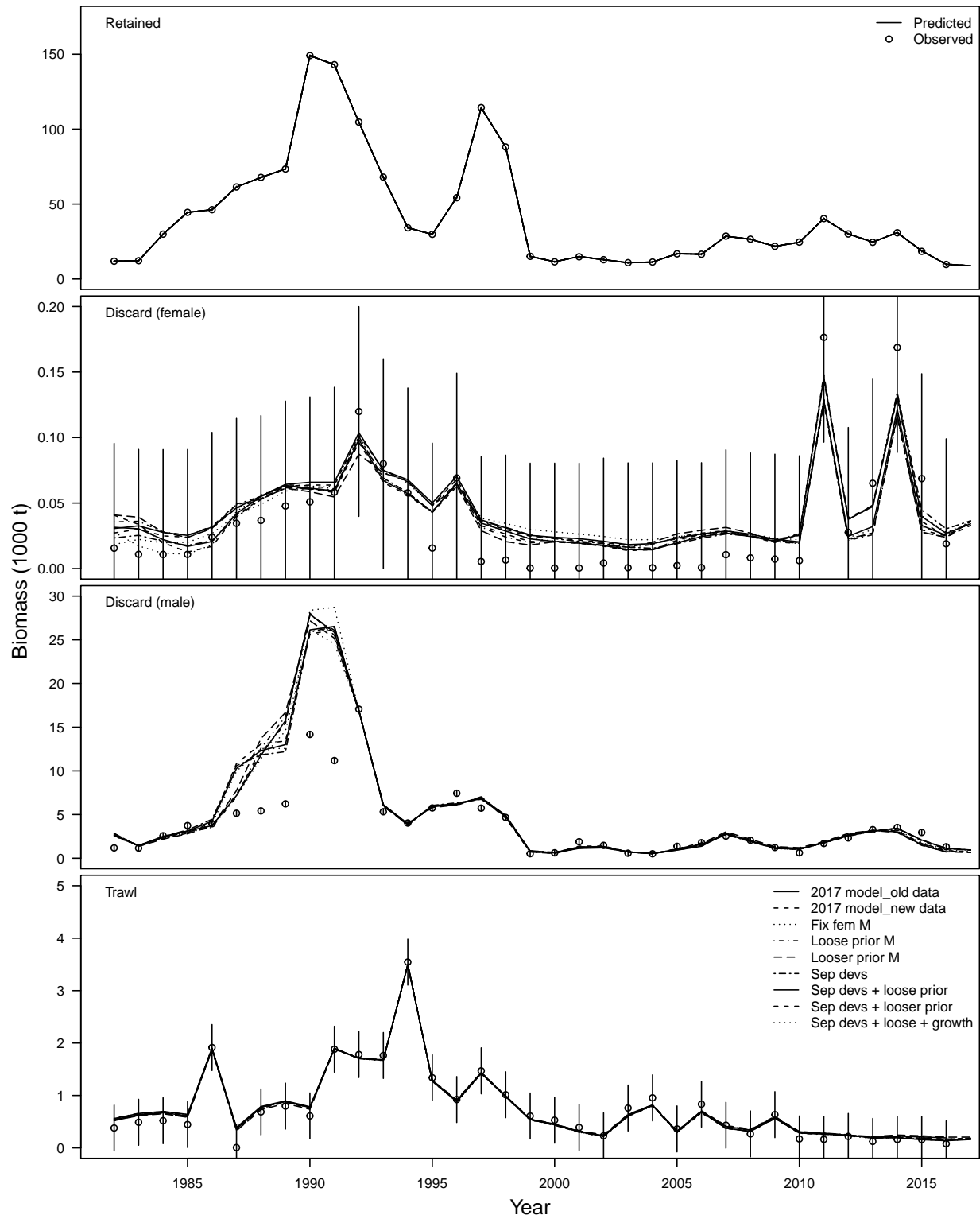


Figure 28: Model fits to catch data

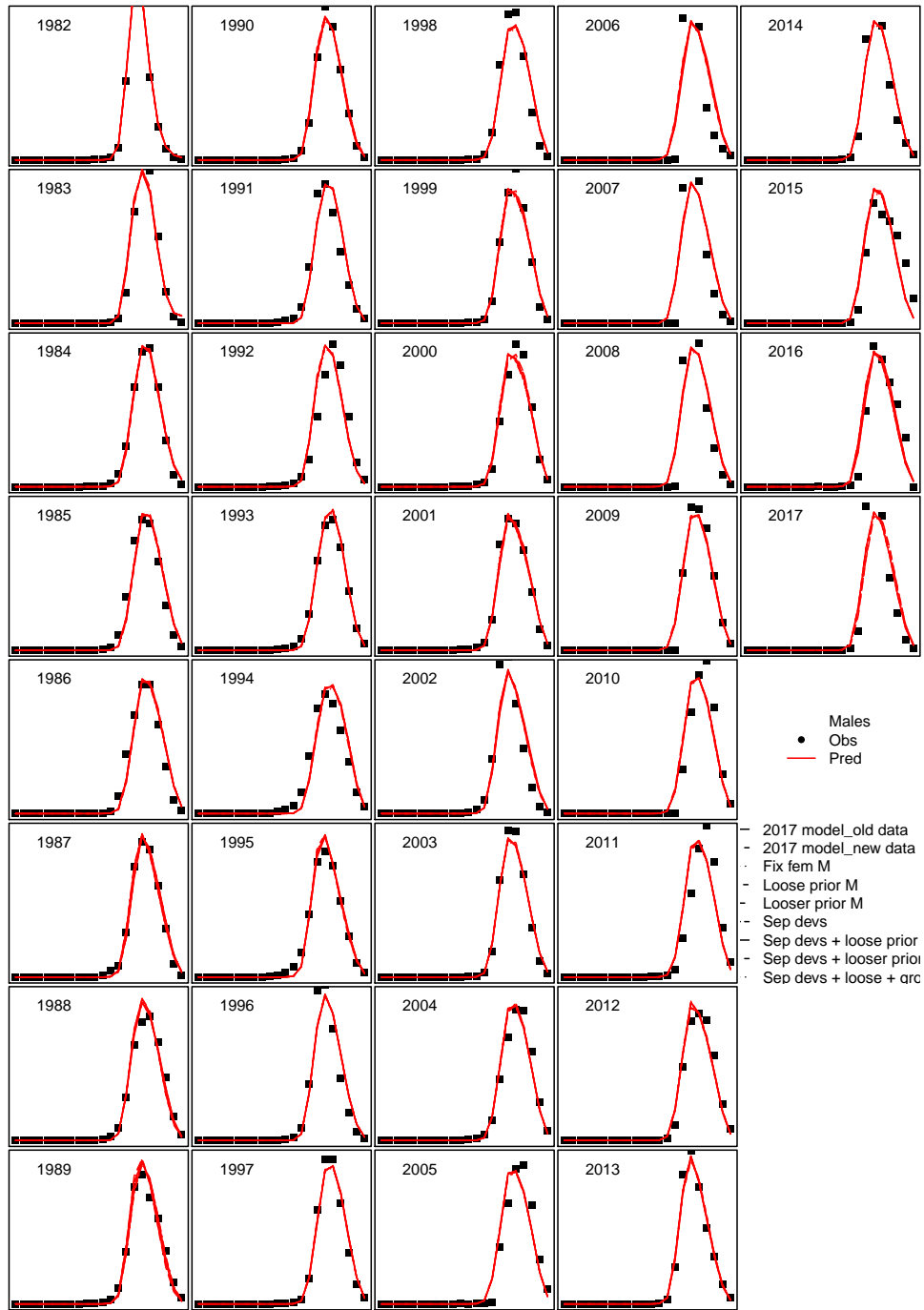


Figure 29: Model fits to retained catch size composition data

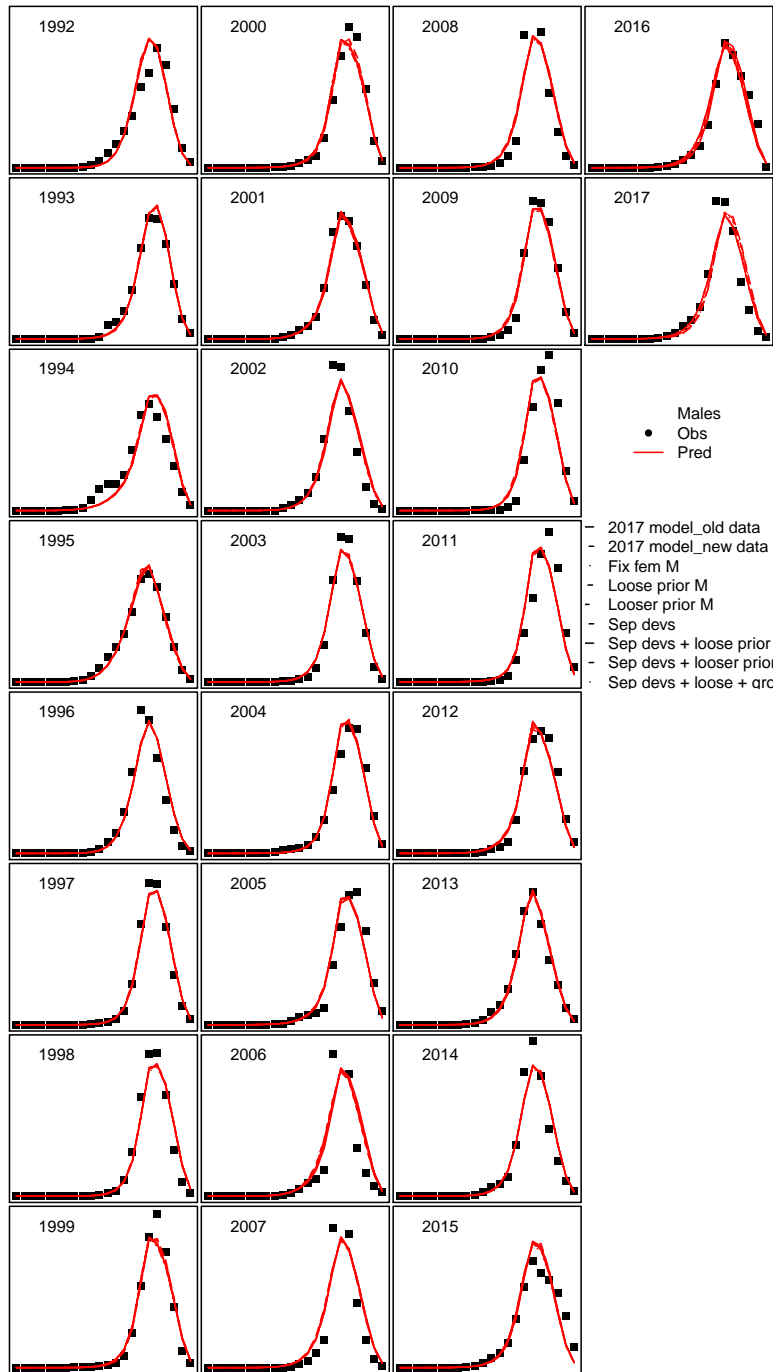


Figure 30: Model fits to total catch size composition data

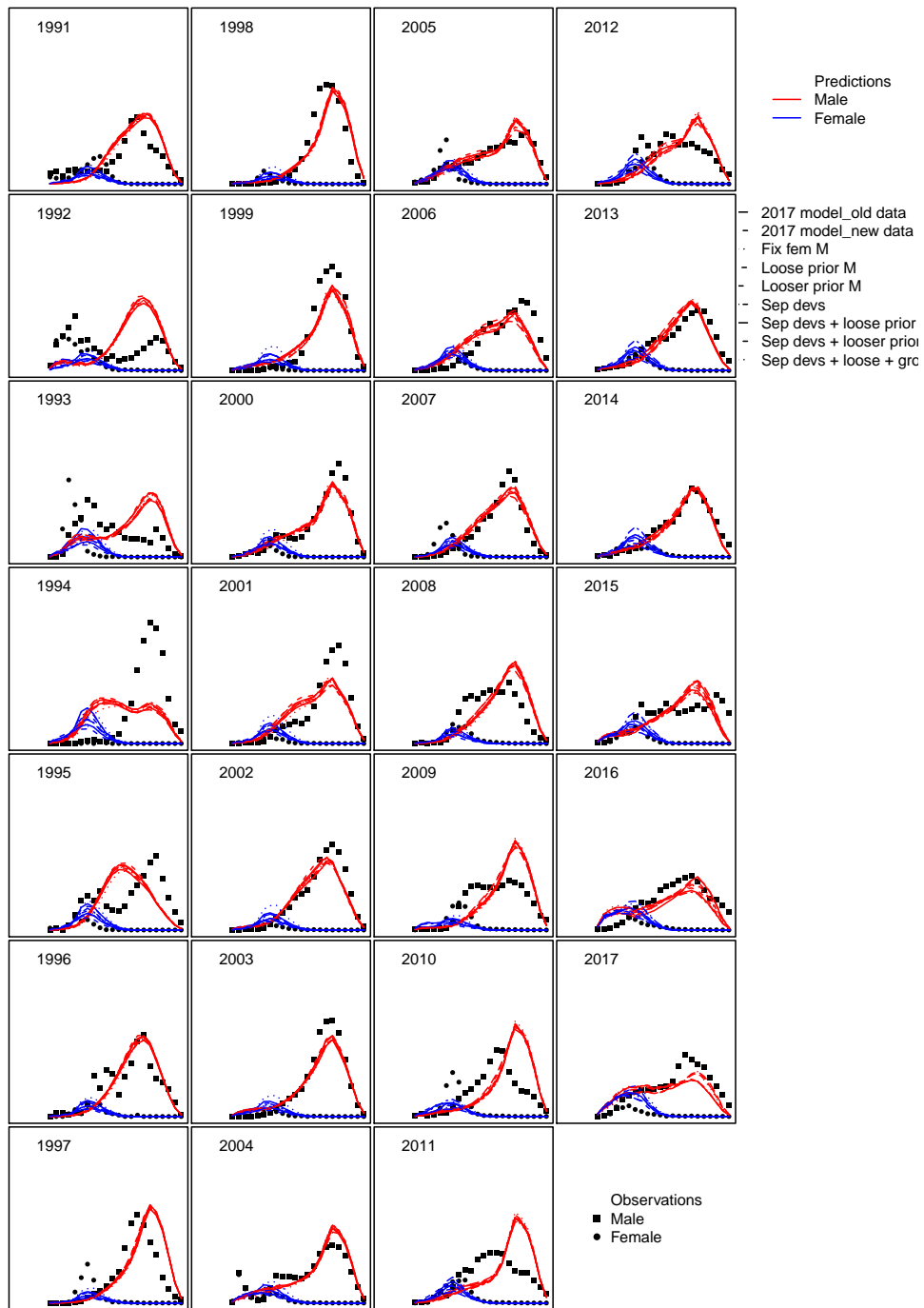


Figure 31: Model fits to trawl catch size composition data

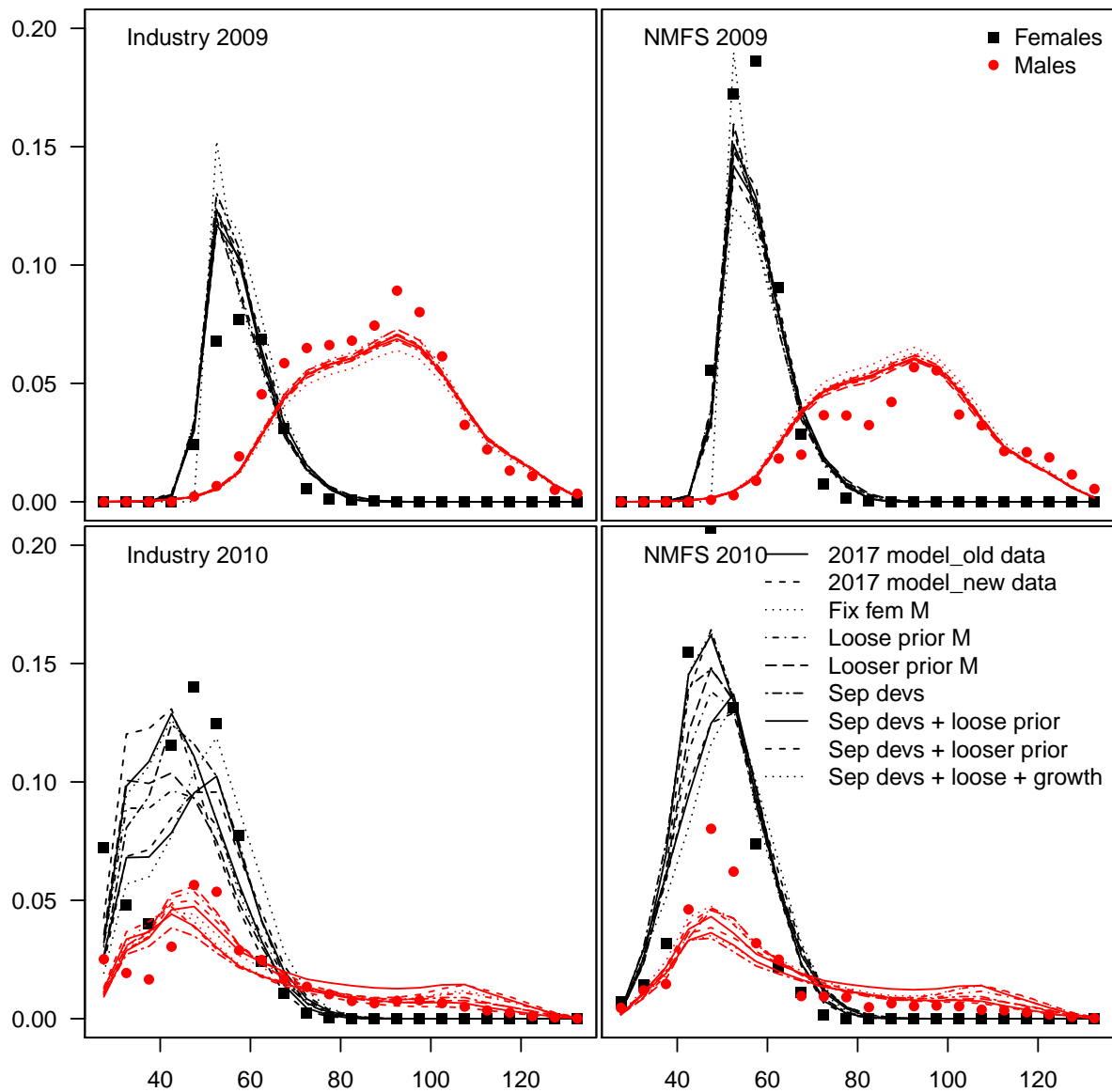


Figure 32: Model fits to size composition data from summer survey experiments (2009 & 2010)

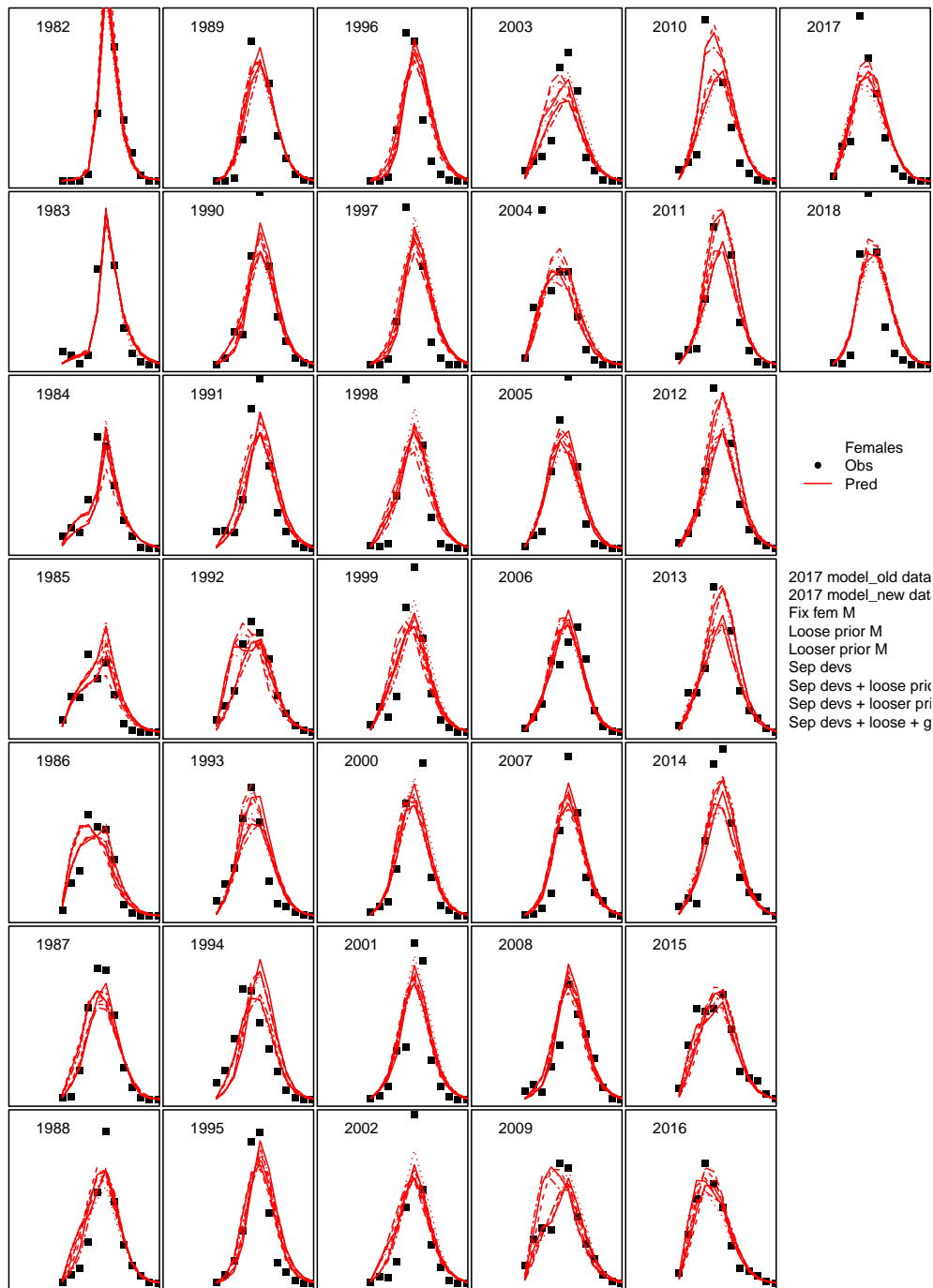


Figure 33: Model fits to female survey size composition data. Note that male and female survey selectivity proportions at length in a given year sum to 1. Consequently, the integral of predicted length compositions may appear to be different than the integral of the observed length composition data.

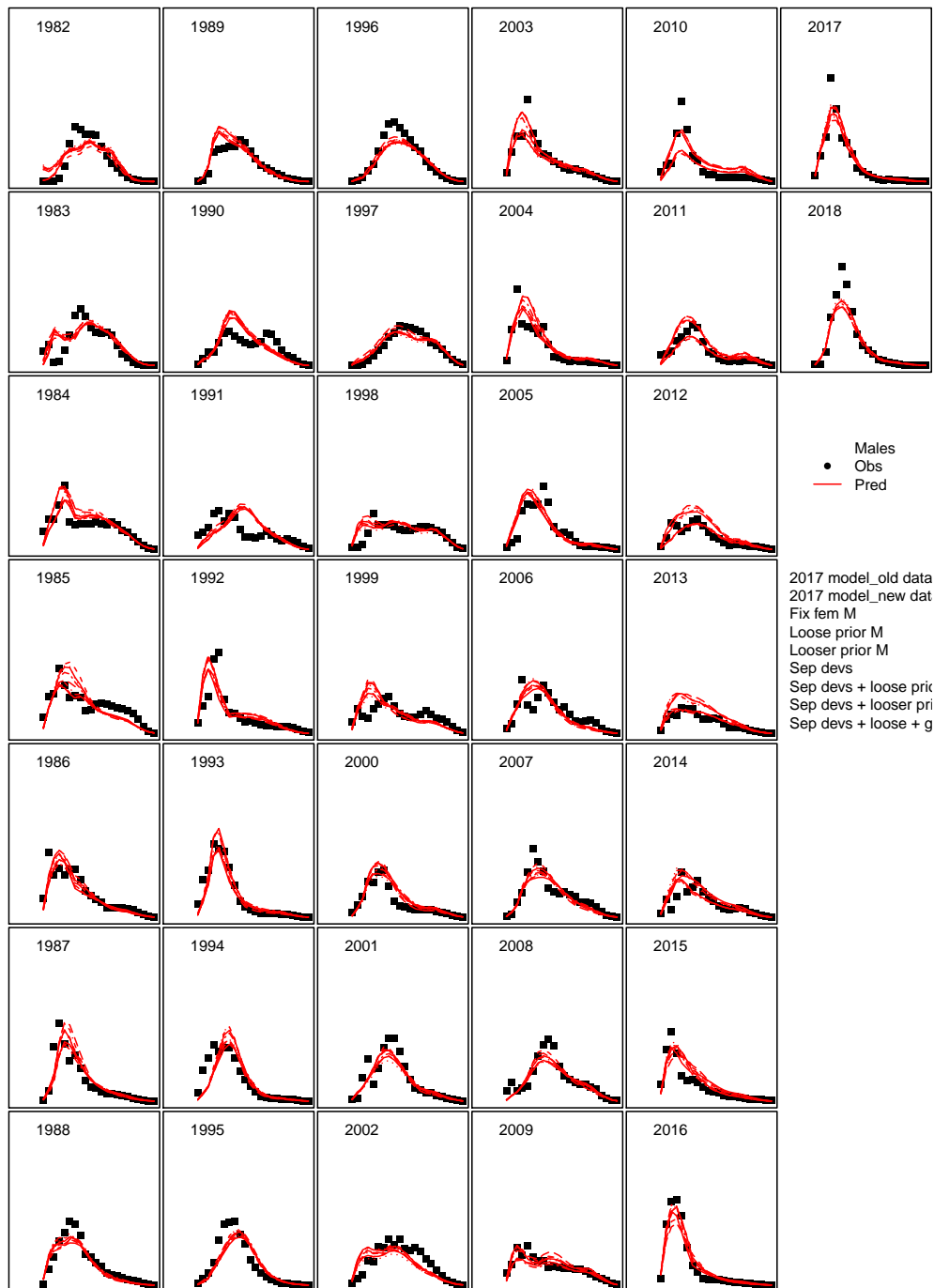


Figure 34: Model fits to male survey size composition data. Note that male and female survey selectivity proportions at length in a given year sum to 1. Consequently, the integral of predicted length compositions may appear to be different than the integral of the observed length composition data.

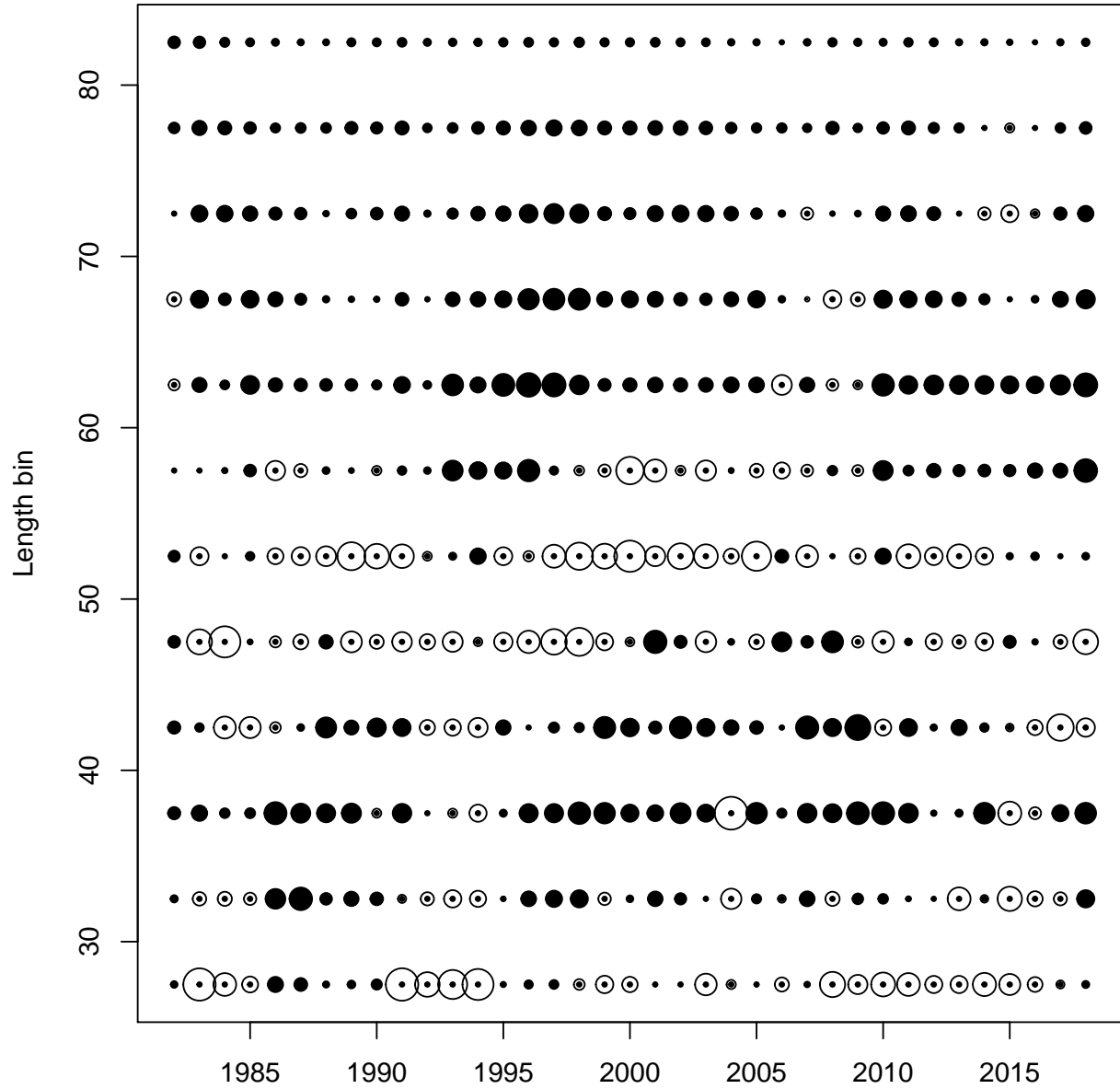


Figure 35: Residuals for female survey length proportion data for the author's preferred model (3b). Open circles are positive residuals, filled are negative, and the size of the circle is proportional to the magnitude of the residual. Stars are residuals > 5 .

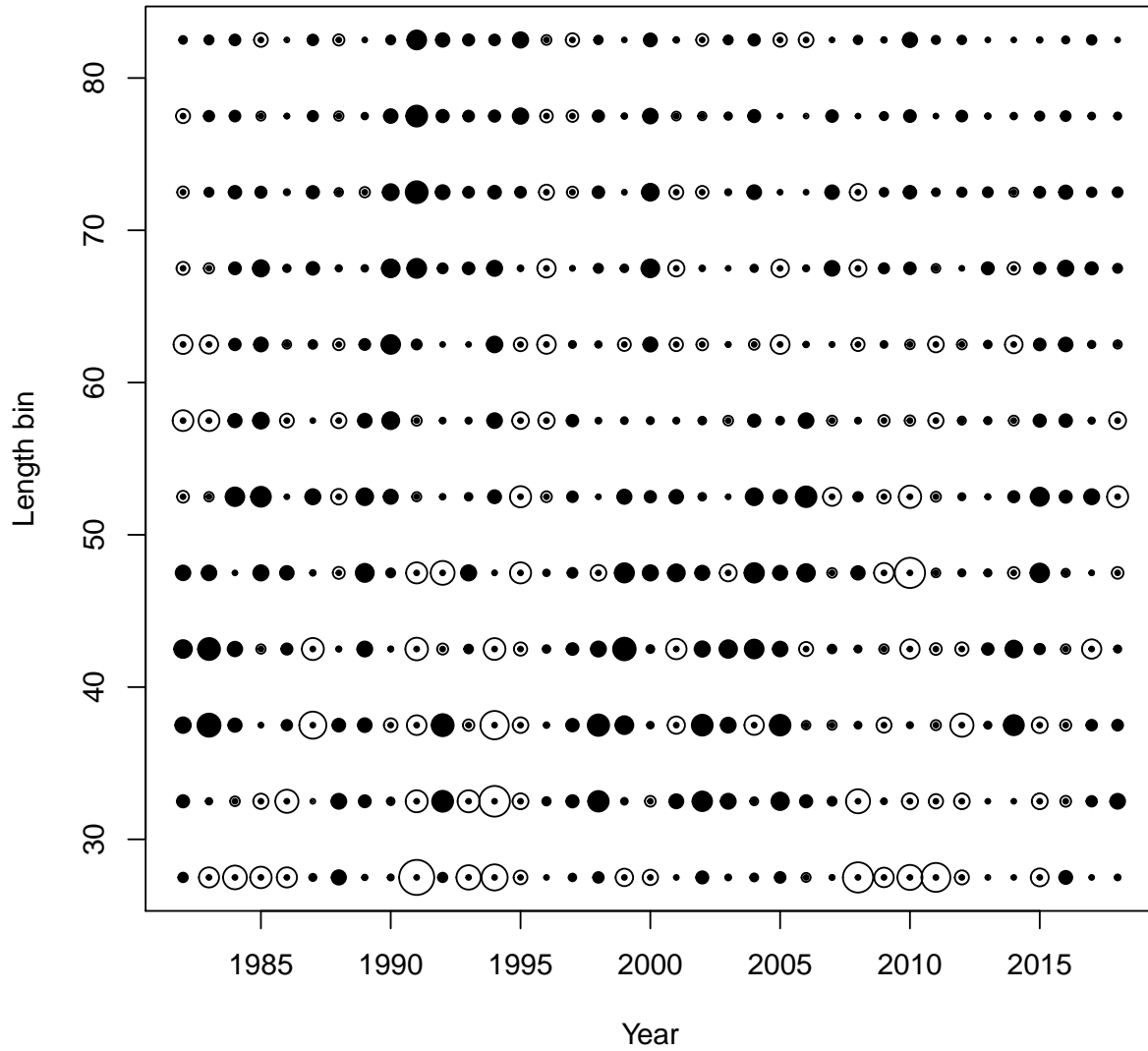


Figure 36: Residuals for male survey length proportion data for the author's preferred model (3b). Open circles are positive residuals, filled are negative, and the size of the circle is proportional to the magnitude of the residual. Stars are residuals > 5 .

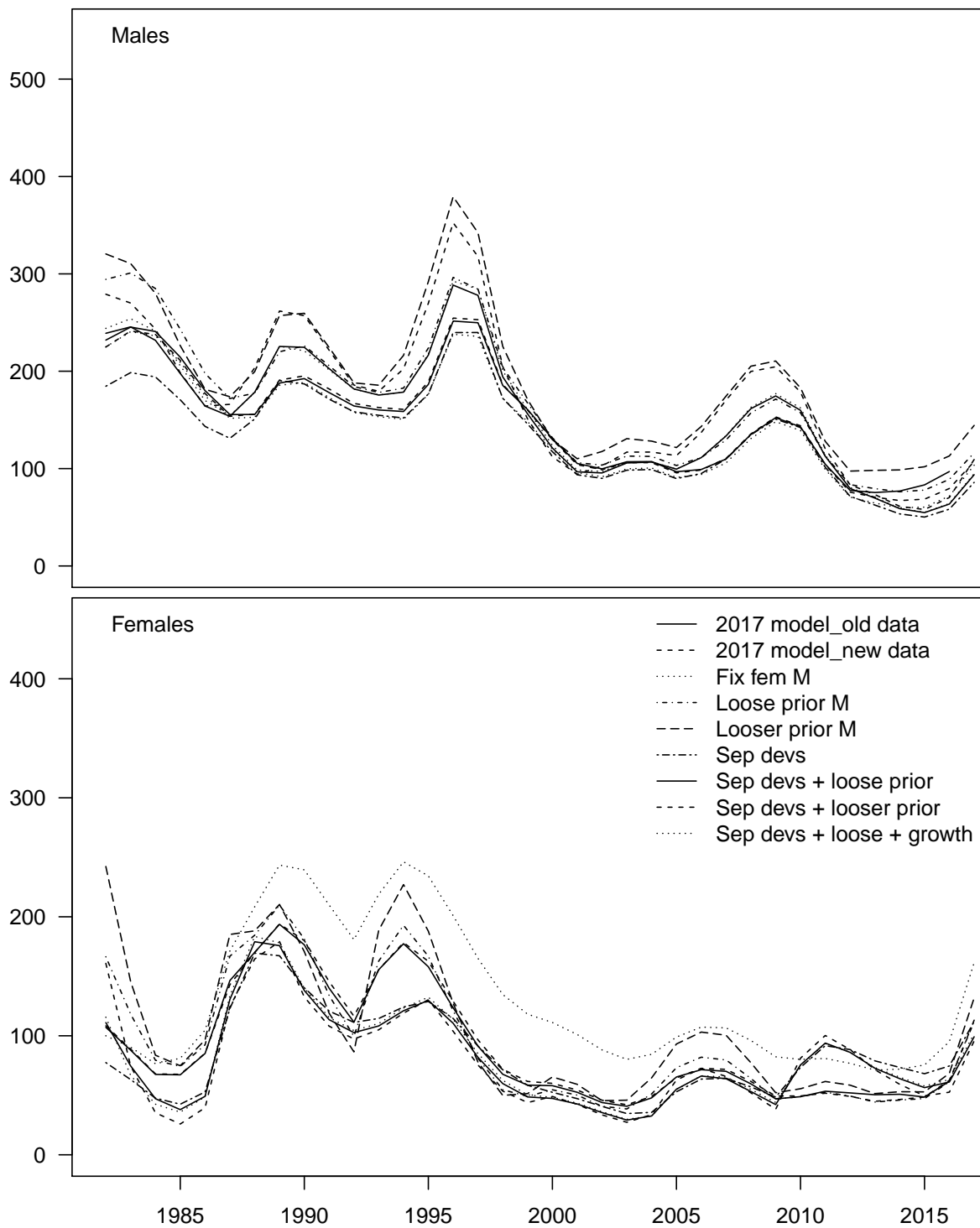


Figure 37: Model predicted mature male biomass at mating time

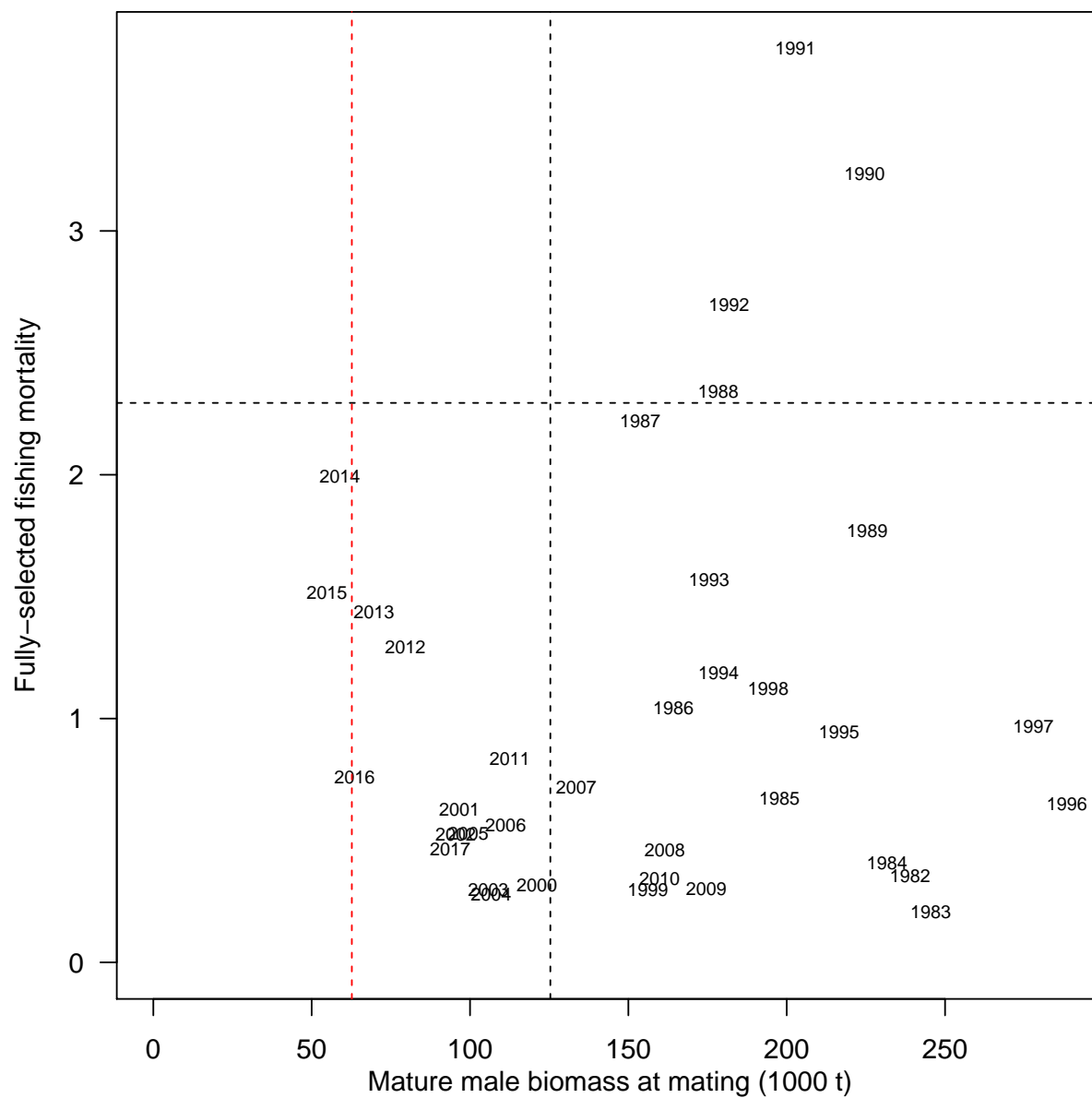


Figure 38: Kobe plot for the chosen model. Vertical dashed black line represents the median posterior value for B35; Vertical dashed red line represents the overfished level, horizontal dashed black line represents F35

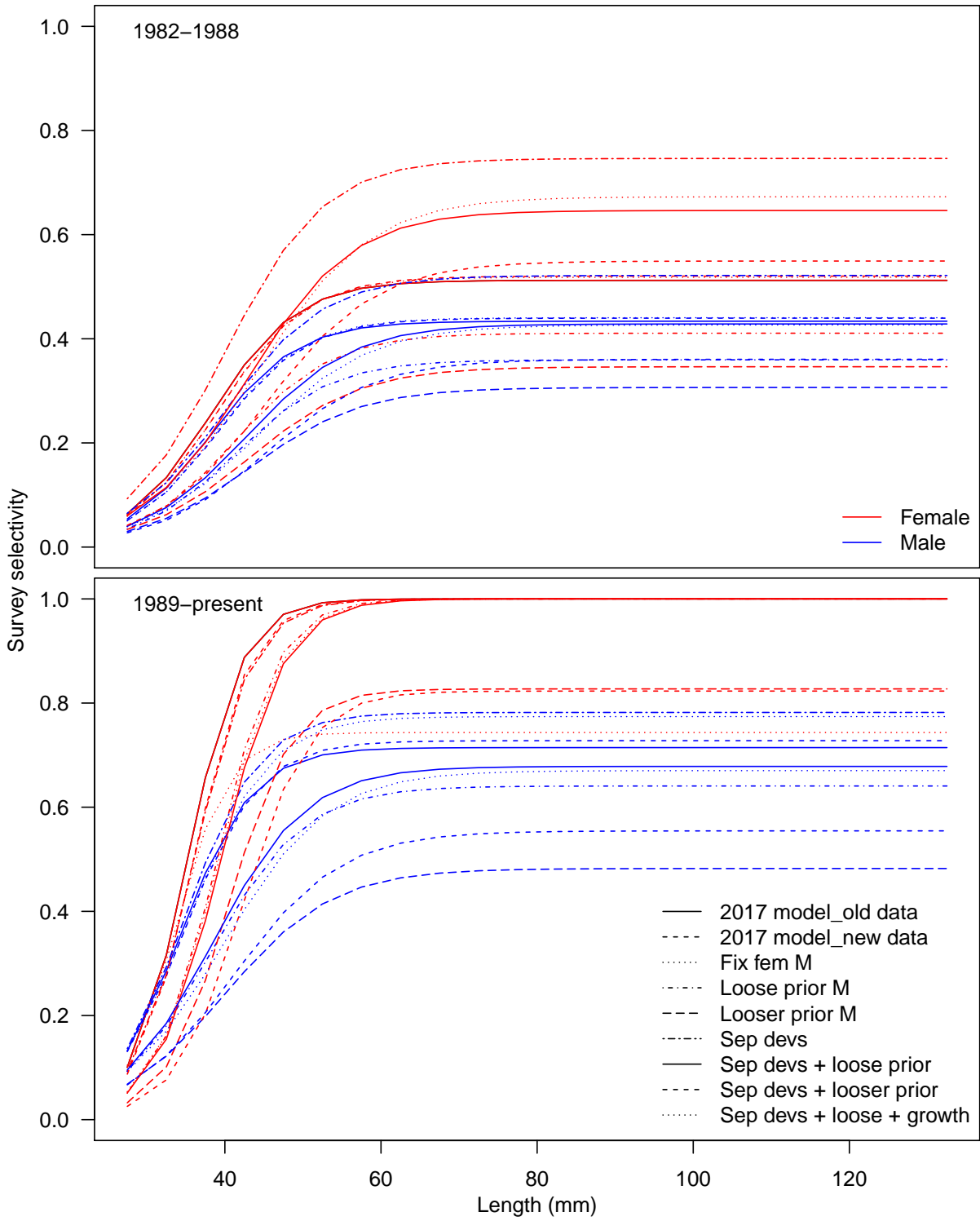


Figure 39: Estimated survey selectivity

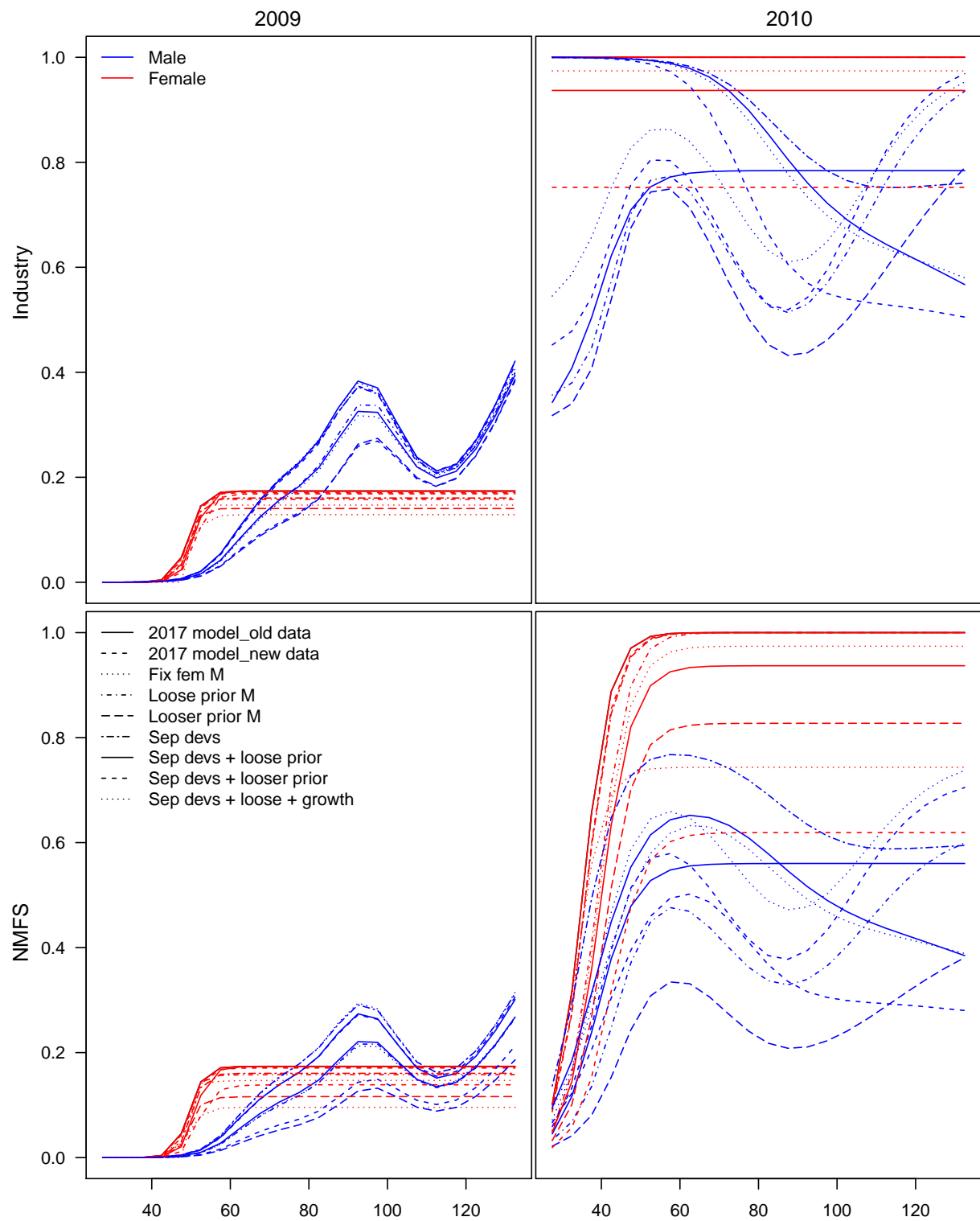


Figure 40: Estimated experimental survey selectivity (availability * survey selectivity)

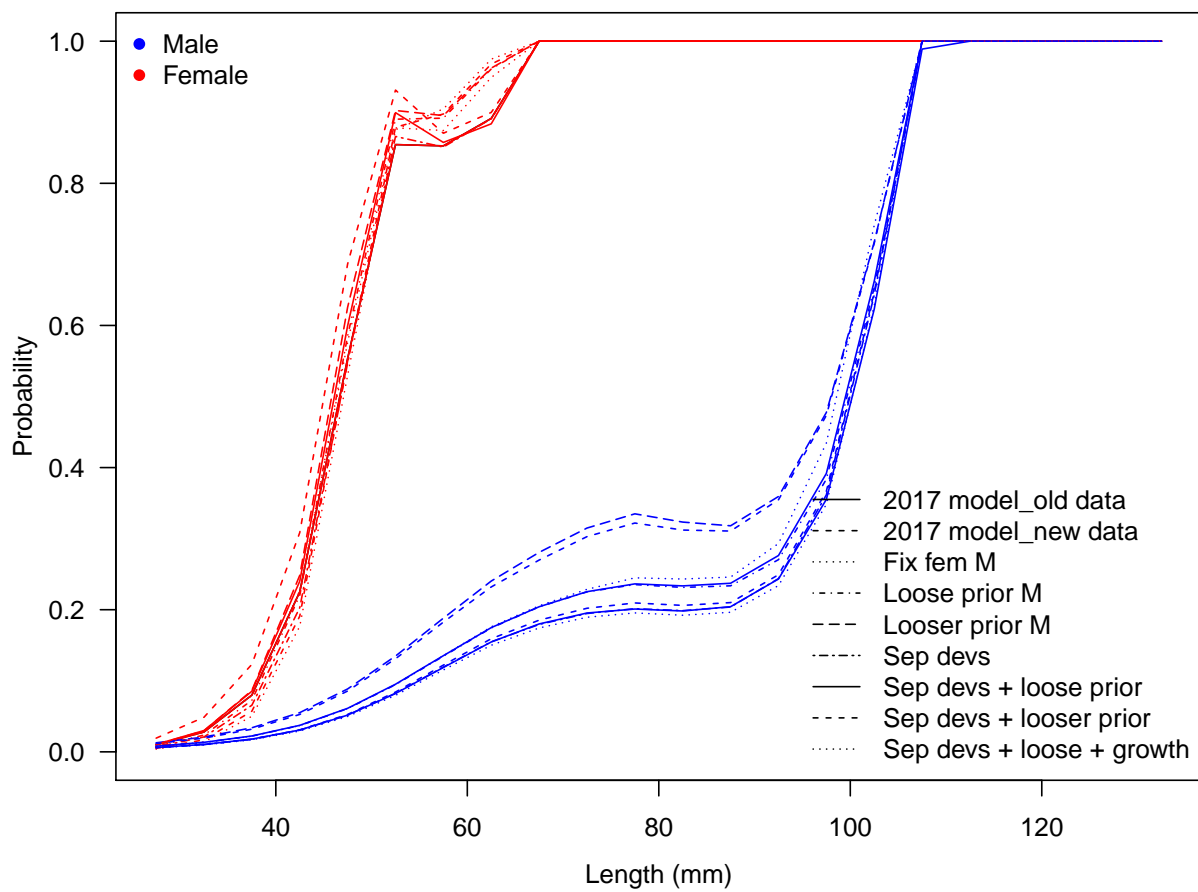


Figure 41: Estimated probability of maturing

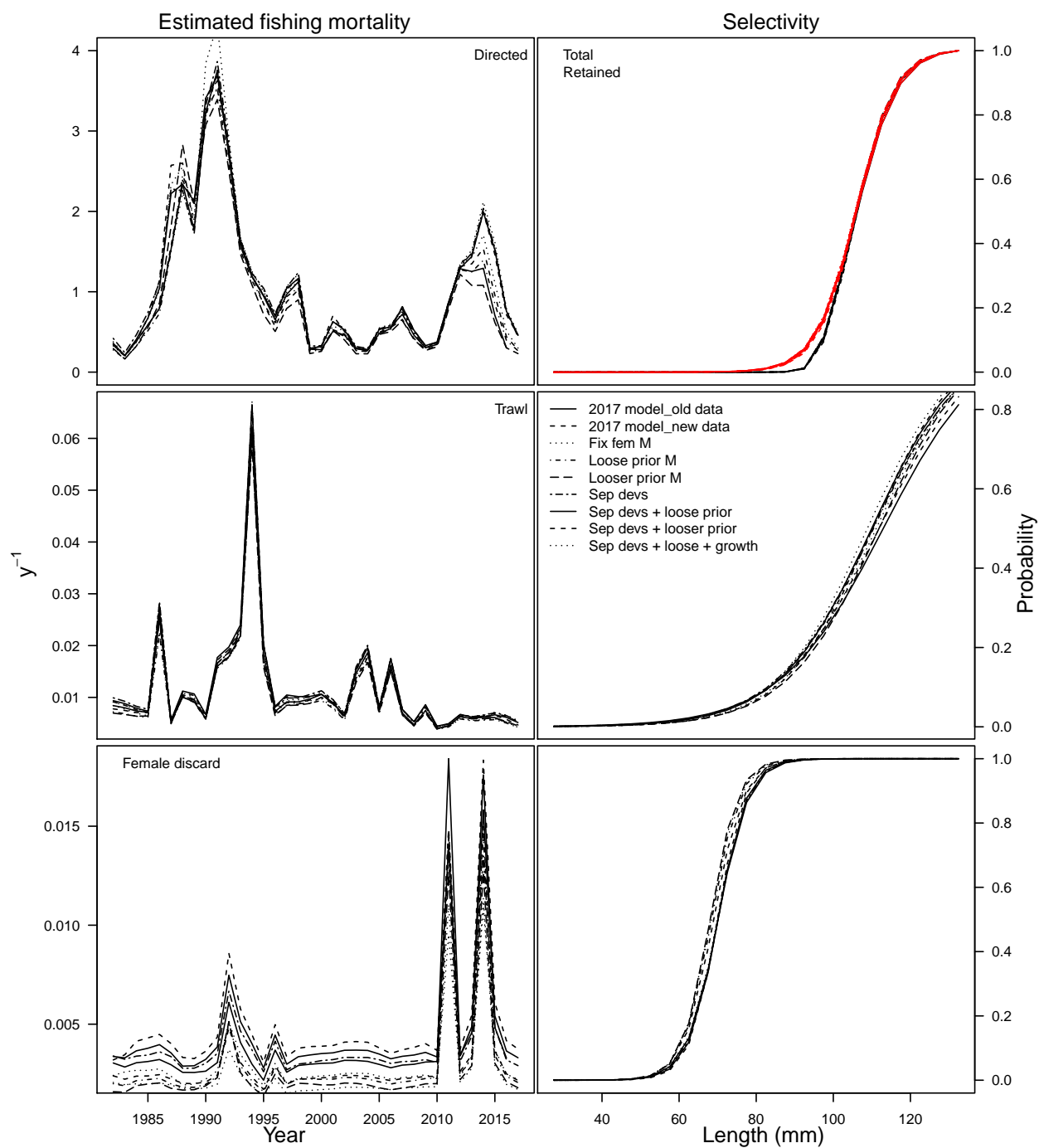


Figure 42: Model predicted fishing mortalities and selectivities for all sources of mortality

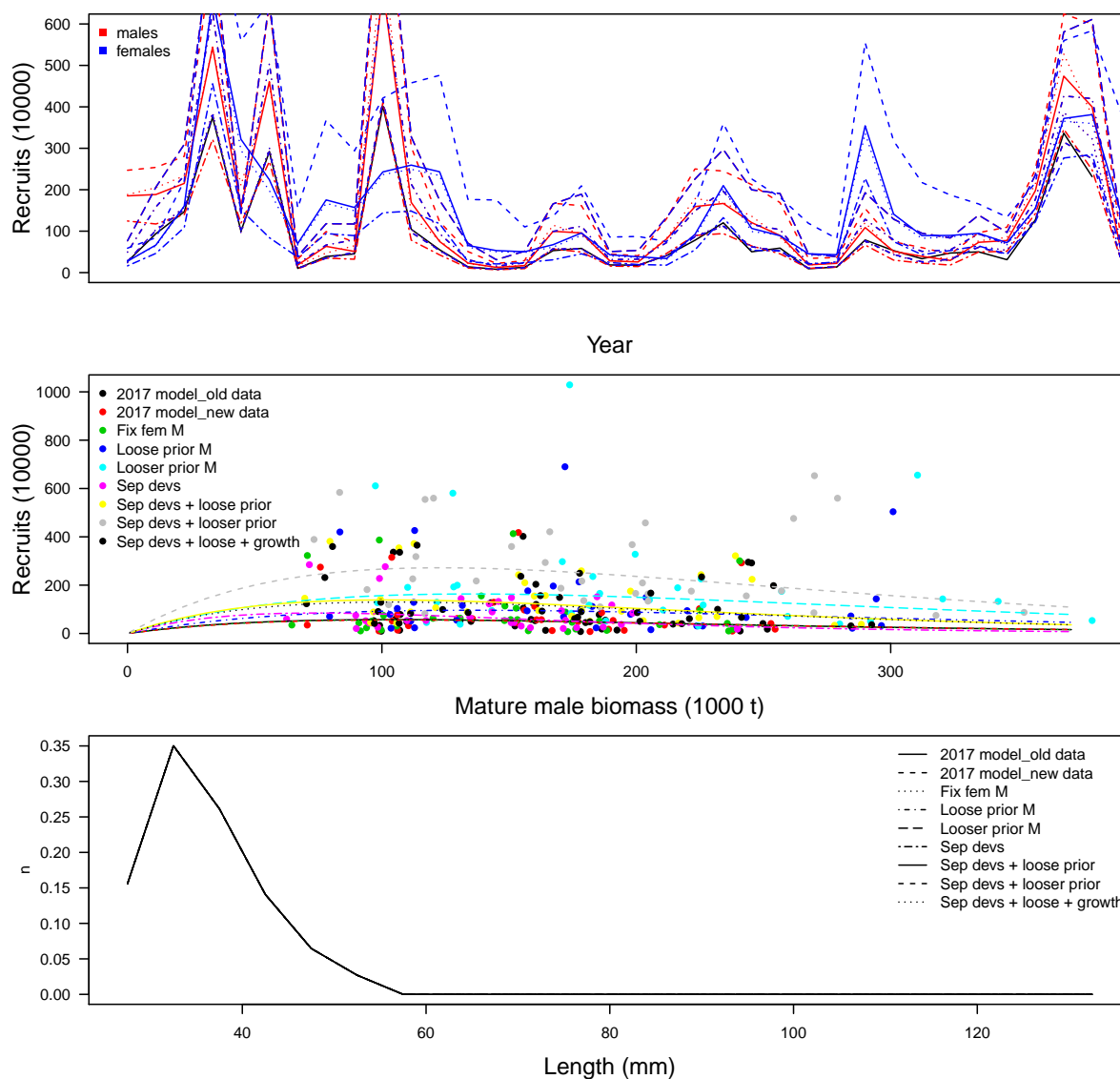


Figure 43: Estimated recruitment, fits to stock recruit curve (MMB lagged 5 years), and proportions recruiting to length bin

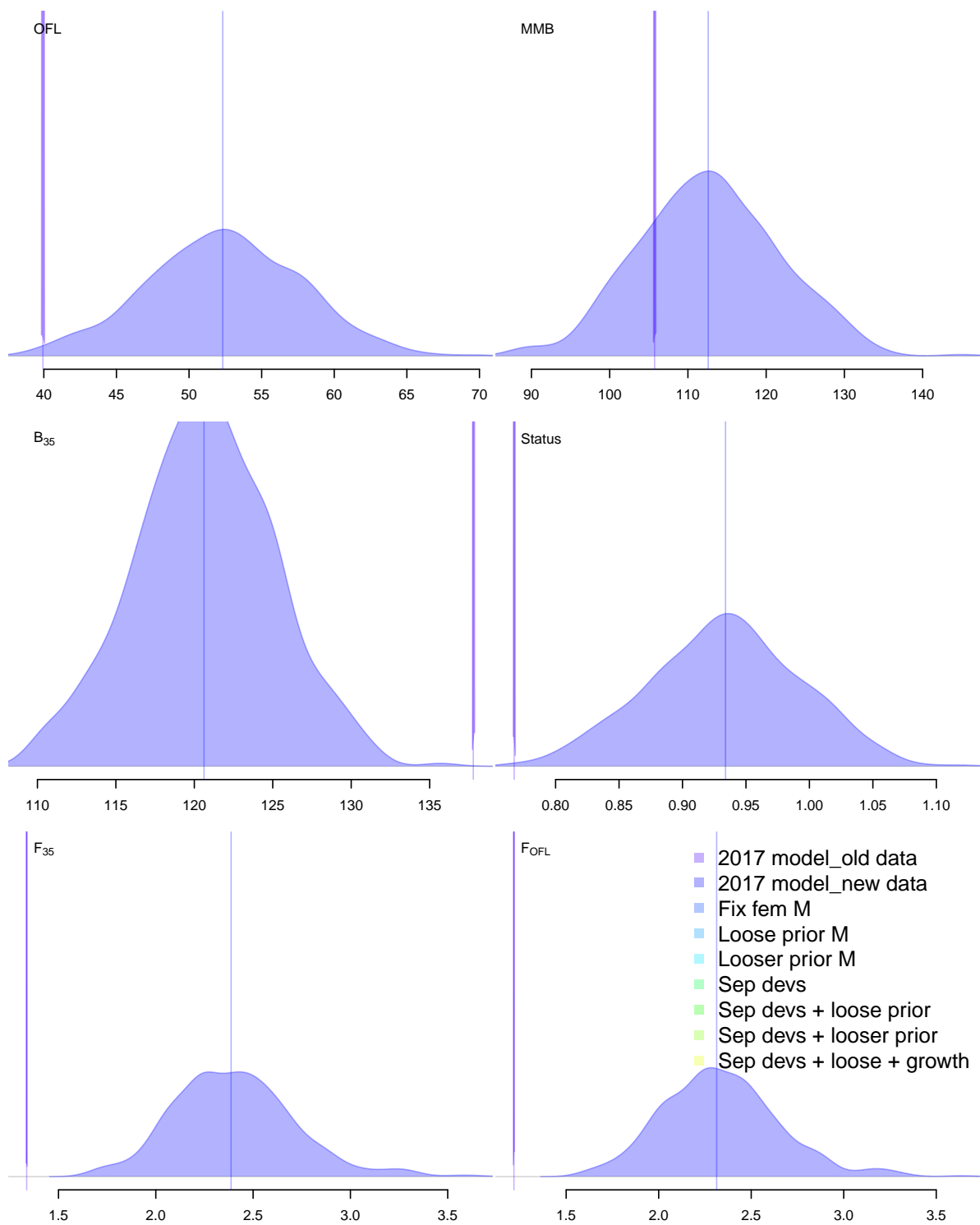


Figure 44: Posterior densities for management quantities by scenario

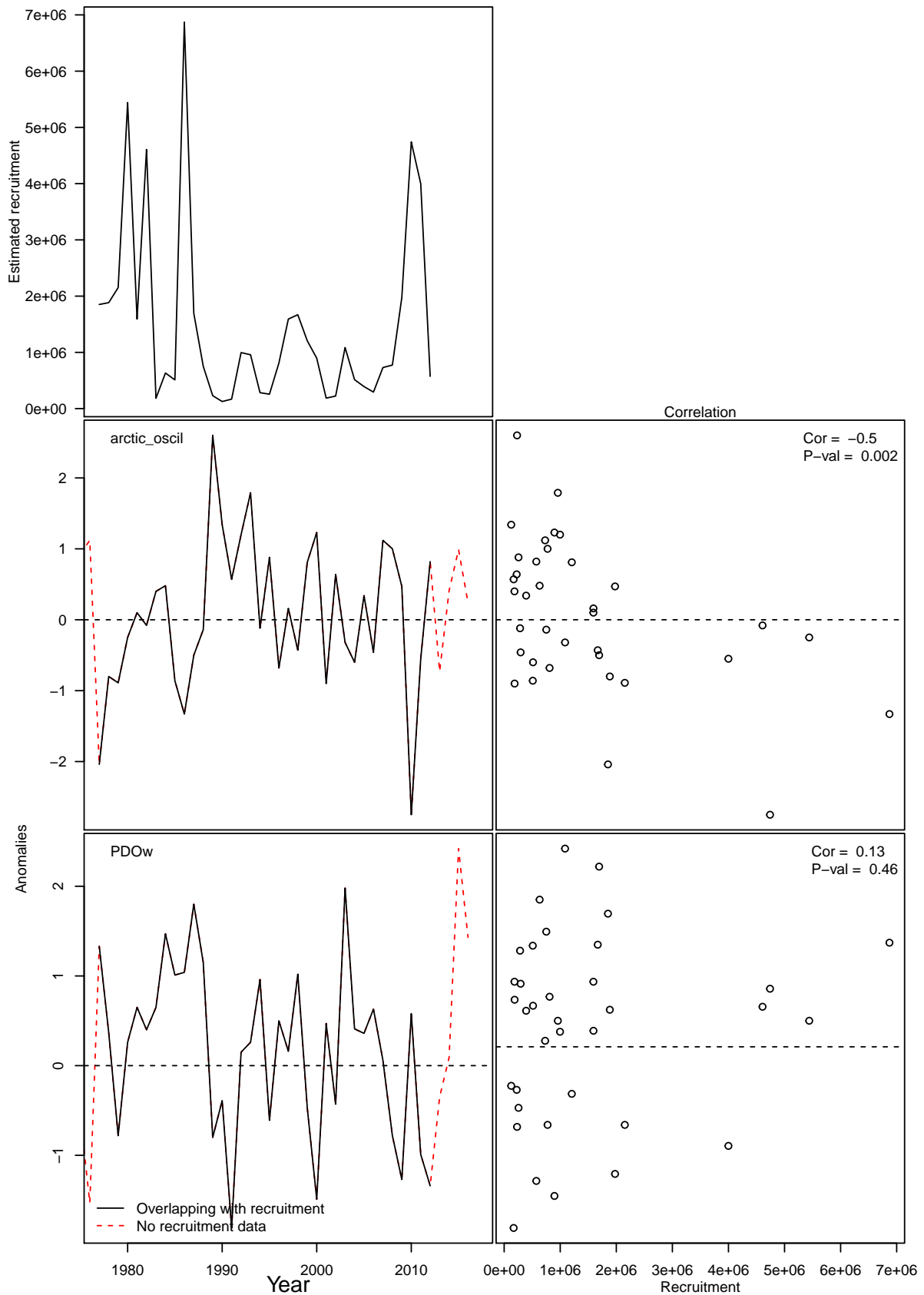


Figure 45: Comparison of estimated recruitment from the chosen model with the Pacific Decadal Oscillation and the Arctic Oscillation