A stock assessment for eastern Bering Sea snow crab

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Contents

Executive summary

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 13.32 t during 1981) to historical highs in the early and mid-nineties (retained catch during 1991, 1992, and 1998 were 143.02, 104.68, and 88.09 t, 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 t). Retained catches have slowly increased since 1999 as the stock rebuilt, although retained catch during 2015 was low (13.43 t).

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 1993 at 17.06 t which was 16% of the retained catch. The most recent estimated mortality was 3.52 t which was 11% of the retained catch.

3. Stock Biomass:

Observed mature male biomass (MMB) at the time of the survey has increased from an average of 160.81 t 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 t, 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 t. 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 2016 of 63.21 t during 2016.

4. Recruitment

Estimated recruitment shifts from a period of high recruitment to a period of low recruitment in the mid 1990s (late 1980s when lagged to fertilization). Recent estimated recruitments have been above the average of the 'low' period , but are still beneath the average of the 'high' recruitment period. Recent survey length frequency data reflect what may be the largest recruitment event seen since the early 1990s, but data informing the estimates of numbers in the smaller size classes are still uncertain.

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
2011/2012	77.3	165.2	40.3	40.5	42	73.5	66.2
2012/2013	77.1	170.1	30.1	30.1	32.4	67.8	61
2013/2014	71.5	126.5	24.5	24.5	27.7	78.1	69.3
2014/2015	73.2	129.3	30.8	30.8	34.3	69	62.1
2015/2016	73.2	123.5	13.4	13.4	16.4	61.5	55.4
2016/2017	77.5	109.4				32.4	29.2

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

Year	MSST	Biomass (MMB)	TAC	Retained catch	Total catch	OFL	ABC
2011/2012	170.4	364.2	88.85	89.29	92.59	162	145.9
2012/2013	170	375	66.36	66.36	71.43	149.5	134.5
2013/2014	157.6	278.9	54.01	54.01	61.07	172.2	152.8
2014/2015	161.4	285.1	67.9	67.9	75.62	152.1	136.9
2015/2016	161.4	272.3	29.54	29.54	36.16	135.6	122.1
2016/2017	170.9	241.2				71.43	64.37

6. Basis for the OFL

The OFL for 2016 from the chosen model was 32.43 t fishing at $F_{OFL} = 1.21$ (64 % of the calculated $F_{35\%}$, 1.88). The calculated OFL was a -47% change from the 2015 OFL of 61.5 t. The projected ratio of MMB at the time of mating to $B_{35\%}$ is 0.68.

7. Probability Density Function of the OFL

The probabillity density function of the OFL was characterized by using a Markov Chain Monte Carlo algorithm to sample from the a posterior distribution of the OFL. This allows all uncertainty in the data to which the model was fitted to be propagated forward into the OFL calculation.

8. Basis for ABC

The ABC calculated for the chosen model for 2016/2017 was specified as 29.19 t by subtracting a 10% buffer from the OFL as recommended by the SSC. The alternate 'P$_{star}$' approach of calculating the 49th quantile of the distribution of the OFL produced an ABC of 32.3 t.

A. Summary of Major Changes

1. Management: None

2. Input data:

Data added to the assessment included: 2016 Bering Sea survey biomass and length frequency data, 2015 directed fishery retained and discard catch and length frequencies for retained and discard catch, and groundfish discard length frequency and discard from 2015. Five additional data points for growth increment were included and weight at length parameters for both sexes were revised, with the largest impact being on female biomass.

3. Assessment methodology:

Six models are presented in this assessment with several incremental steps, each of which are illustrated. Model 0 represents the 2015 model with minor structural changes suggested by the CPT implemented and serves as a basis for comparison to the previous year's assessment. Model 1 addresses the way in which fishing mortality in the trawl fleet is estimated. Model 2 removes the priors on maturity. Model 3 changes the way maturity and female discards are estimated. Scenarios in which the weighting of survey size composition (Model 3a) and female growth data and natural mortality priors (Model 3b) are varied are also presented.

The OFL was calculated using Bayesian methodologies, which is different than the previous projection framework. Management quantities are identified as the medians of posterior distributions resulting from application of a Markov Chain Monte Carlo algorithm. This is preferable to the previous projection framework because it explicitly incorporates uncertainty in all parameters, rather than only numbers at length.

4. Assessment results

Based on last year's assessment results, MMB was 84% of $B_{35\%}$. The projected MMB (February 15, 2017) will be 68% of $B_{35\%}$. Estimated MMB on February 15, 2016 from this assessment was 109.41 t, which placed the stock at 71 % of $B_{35\%}$. Fits to all data sources were relatively good for the chosen model and estimated population processes were credible.

B. CPT May 2016 comments, SSC comments, and author response:

CPT and SSC comments

CPT comments are divided into two categories below. There were no significant comments from the SSC.

Changes to model structure and presentation of results

- Show fits to the pot CPUE data
- Provide a retrospective analysis
- Implement Francis weighting method and report weights
- Provide plots of the observed and model-predicted mean lengths
- Ensure catchability for all surveys is bounded at one
- Document the jittering approach

Model scenarios to explored

- Model 0:
    - Only small structural changes from above were implemented to provide a comparison to last year's model
- Model 1:
    - All changes in model 0
    - Estimate average F for the groundfish trawl, rather than specifying it
    - Remove penalties on F from 1992 to present
    - Estimate a separate vector of F_devs for 1978-90 and 1991-present
    - Estimate a constant of proportionality between fishing effort in the pot fishery and F for the females in the pot fishery
- Model 2:
    - All changes in model 1
    - Remove priors on probabillity of maturing for males and females
- Model 3:
    - Increase the weight on the smoothness penalty for the probability of maturity
    - Estimate the 50% selectivity parameter for female discard
- Model 3a:
    - All changes in model 3
    - Decrease the effective sample sizes for survey size composition data by applying Francis' weighting methodology
- Model 3b:
    - All changes in model 3
    - Increase weighting on female growth likelihood
    - Decrease the variance for the prior on natural mortality

Several other changes were made to the code, including: rearranging the code to improve readability and functionality (e.g. deleting legacy code and adding space in arrays to allow for calculation of reference points, alllowing the weight at length parameters to be input, rather than included in the .DAT file as a prespecified vector), migrating constants to control file, correcting the conversion for tonnes to million pounds, and adding a recruitment deviation for the end year.

All changes were undertaken in a stepwise fashion and the resulting changes in the estimated MMB and management quantities were recorded (Table 4). Only scenarios for which large changes in estimated parameters and MMB resulted from a given change in the model are presented in the figures and text.

Authors response

Nearly all requests by the CPT were fulfilled and described below. Model scenarios include all CPT recommended models, save one. Estimating a constant of proportionality between fishing effort in the pot fishery and fishing mortality in the trawl fishery was not performed because this is a stepbackwards from estimating a vector of deviations. 'Jittering' was not performed because the management advice produced from this assessment is Bayesian in nature–i.e. the estimated management quantities (e.g. MMB, $B_{35\%}$, OFL) are the medians of posterior distributions of these quantities. Consequently, 'jittering' would not influence the outcome of this assessment. Finally, although functions to calculate Francis weights were included in the assessment, the presented scenarios (except one included for illustrative purposes) use the previous weightings of 200 on the survey size composition data. The illustrative example also only specified weights at 20% of their previous values (i.e. 40) because the Francis weighting algorithm lowered the weights to a point at which a positive-definite Hessian was not produced. Given the need for an invertible Hessian to perform MCMC, using weights at only 20% of the previously used values was a necessary compromise and served to illustrate some of the problems with downweighting the survey size composition data (discussed below).

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 about 200 meters (Figure 1 & Figure 2). Smaller crabs tend to occupy more inshore northern regions (Figure 3) and mature crabs 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 Kastelle, 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.

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. Consequently, natural mortality for mature females was set to 0.23. Mature male natural mortality was estimated in the model with a prior constraint of mean of 0.23 with a standard error equal to 0.054 (estimated from using the 95% CI of +-1.7 years on maximum age estimates from dactal wear and tag return analysis in Fonseca, et al. (2008)). Natural mortality for immature males and females was estimated in the model with a mean of 0.23 and a standard error of 1.

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 (Figure 6). New weight at length parameters were applied to all years of data, rather than just the most recent observations. To provide context for the change, a juvenile female crab of carapace width 52.5 mm was previously estimated to weigh 65 g and now 48 g; a mature female crab of carapce width 57.5 mm was estimated to previously weigh 102 g and 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 probabillity 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 3 to 4 years old and would be expected to molt annually. The growth transition matrix was applied to animals that molt, resulting in new shell animals. Crab that do not molt become old shell animals. Further research on the relationship between shell condition and time from last molt is needed.

Mating ratio and reproductive success

Bering Sea snow crab are managed using mature male biomass as a proxy for reproductive potential. MMB is used as the currency for management because the fishery only keeps males. Male snow crab 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 crab 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 sacrificed 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 sacrificed. Indices of fertilized females based on the visual inspection method of assessing clutch fullness and percent unmated females may overestimate fertilized females and not an accurate index of reproductive success.

Growth

Little information exists on growth for Bering Sea snow crab. Tagging experiments were conducted on snow crab in 1980 with recoveries occurring in the Tanner crab (Chionoecetes bairdi) fishery in 1980 to 1982 (Mcbride 1982). However, data from this study are not used due to uncertainty about the effect of tagging on growth. Currently, 40 data points from 5 studies are used to estimate the post-molt length from pre-molt length for females and males (Table 5). The 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

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 postmolt 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 accepts animals 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) based on 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 6% to 46% for the models considered in this assessment (Figure 7).

The 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 was one half B_{MSY}. The harvest rate begins at 0.10 when total mature biomass exceeded 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).

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

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 BMSY

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 virgin 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 13.32 t during 1981) to historical highs in the early and mid-nineties (retained catch during 1991, 1992, and 1998 were 143.02, 104.68, and 88.09 t, 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 t). Retained catches have slowly increased since 1999 as the stock rebuilt, although retained catch during 2015 was low (13.43 t).

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 1993 at 17.06 t which was 16% of the retained catch. The most recent estimated mortality was 3.52 t which was 11% of the retained catch.

Discard from the directed pot fishery was estimated from observer data since 1992 and ranged from 11% to 64% (average 33%) of the retained catch of male crab biomass (Table 6). Female discard catch is very low compared to male discard catch and not a significant source of mortality. Discard of snow crab in groundfish fisheries from highest to lowest is the yellowfin sole trawl fishery, flathead sole trawl fishery, Pacific cod bottom trawl fishery, rock sole trawl fishery, and the Pacific cod hook-and-line and pot fisheries. Bycatch in the tanner crab fishery has historically been relatively low, but this year 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 undersize 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 frequencies of retained crab from the directed snow crab pot fishery from survey year 1978 to the 2015 were used in this analysis (Table 6). Size frequency data on the total catch (retained plus discarded) in the directed crab fishery were available from survey year 1992 to 2015. Total discarded catch was estimated from observer data from 1992 to 2015 (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 2015. The discard catch estimate was multiplied by the assumed mortality of discards from the pot fishery. The mortality of discarded crab was 30% for all model scenarios. This estimate differs from the current rebuilding harvest strategy used 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.

The following table contains the various data components used in the model and the time periods for which they are available:

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

Data component	Years
Retained male crab pot fishery size frequency by shell condition	1978 - 2015
Discarded Males and female crab pot fishery size frequencey	1992 - 2015
Trawl fishery bycatch size frequencies by sex	1991 - 2015
Survey size frequencies by sex and shell condition	1978 - 2016
Retained catch estimates	1978 - 2015
Discard catch estimates from crab pot fishery	1992 - 2015
Trawl bycatch estimates	1973 - 2015
Total survey biomass estimates and coefficients of variation	1978 - 2016
2009 study area biomass estimates, CVs, and size frequencey for BSFRF and NMFS tows	2009
2010 study area biomass estimates, CVs, and size frequencey 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). Since 1989, the survey has sampled stations farther north than previous years (it only reached to 61.2 N previous to 1989). In 1982 the survey net was changed resulting in a potential change in catchability. Consequently, survey selectivity was modeled in three 'eras' in the assessment (1978-1981, 1982-1988, 1989-present). 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 8 & Figure 9) 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 7). 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 were more prevalent on the south west portion of the shelf (Figure 4) while smaller males were more prevalent on the north west portion of the shelf (Figure 1). Females 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 also changed temporally. The centroids of abundance in the summer survey moved over time (Figure 10 & Figure 11). 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 back south again, but not to the extent seen in the early 1980s. This phenomenon was mirrored in centroids of abundance for large males (Figure 11).

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 had exceptions.

A difference between the summer survey distribution of large males and the fishery catch distribution existed. The origin of this difference is unknown. It is possible that crab moved between the fishery and the survey, but it is also possible that fishers did not target the centroids of abundance. 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 appeared to move south and west as they age, however, no tagging studies have been conducted to fully characterize the ontogenetic or annual migration patterns of this stock (Murphy et al. 2010).

Experimental study of survey selectivity

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 12). 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 13 & Figure 14) 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 '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 (model 0), 331 parameters were estimated. Parameters estimated witin the assessment included those associated with the population processes recruitment, growth, natural mortality (subject to a fairly informative prior), fishing mortality, selectivity (fishery and survey), catchabillity, and maturity (also sometimes subject to a prior; see Table 8 & Table 9). Molting probability, 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.

Samples were drawn from the posterior distributions of estimated parameters and derived quantities used in management (e.g. MMB and OFL) via MCMC. This involved conducting 2,000,000 cycles of the MCMC algorithm, implementing a 5% burn-in period, and saving every 500th draw. Chains were then thinned until diagnostic statistics (e.g. Geweke statistics) demonstrated a lack of evidence of non-convergence.

Model selection and evaluation

Models were evaluated based on their fit to the data (Table 10), the credibility of the estimated population processes, and the strength of the influence of the assumptions of the model on the outcomes of the assessment. A high-level overview of the changes in management quantities arising by step-wise changes in the assessment model are presented first, followed by a more in depth look at results for six selected models. Estimated parameters for the six selected models can be seen in Table 9 and their posterior distributions can be seen in Figure 15, Figure 16, Figure 17, and Figure 18.

Results

Relatively small changes in all management quantities appeared when making the small structural changes suggested by the CPT (e.g. estimate CPUE q, fix survey catchability to 1 for females; Table 4). Changing weight parameters influenced management quantities very little because parameters for males changed very little. However, downweighting the survey composition data (beginning with model 0) resulted in large changes to management quantities, which were manifested most strongly through changes in estimated natural mortality, survey catchability, and probability of maturing (when the priors were removed in model 3). The changes of the management quantities for steps within a 'scenario' (i.e. model 1a within model 1) were relatively small compared to these changes. Below, the results for six models are described (only one of which (model 3a) has the downweighted survey size composition data). The traces of the objective functions for each model were stationary, though several were slightly autocorrelated (Figure 19).

Fits to data

Survey mature biomass

Fits to the survey mature male biomass were similar for all models for the majority of years in the the time series (Figure 20). Model 0 deviated from the other models during the 2000s and model 3a deviated from the other models during the early 1990s. Each of these deviations improved the fit to the data. Estimates of survey MMB in the final year ranged from 67.5 to 105.7 t. Model 3a fit the final data point most closely.

Fits to the survey mature female biomass were also similar for all models for the majority of years in the time series (Figure 20). Model 0 deviated from the other models during the 1990s and model 3, 3a, and 3b

15

deviated from the other models during the early 1980s. Model 0's deviations improved the fit to the data, but deviations for the model 3 variants did not. Estimates of survey MFB in the final year ranged from 68.1 to 90.5 t. Model 3a again fits the final data point most closely.

Growth data

Three models provided adequate (but less than ideal) fits to the female growth data: model 0, 3a, and 3b (Figure 21). All models except for model 3a provide adequate fits to the male growth data. In sum, only models 0 and 3b fit both the male and female growth data acceptably.

Catch data

Retained catch data were fit by all models well, with no discernable differences among models (Figure 22). Female discard data were fit adequately given the specified uncertainty and very little difference in fits existed among models (Figure 22). Male discard data during the period for which data exist (early 1990s to the present) were well fit by every model with little discernable difference (Figure 22). Fits to the trawl data were adequate for all models given the uncertainty in the data (Figure 22). In general, models 1-3b fit the trawl data during the 2000s better than model 0, but this trend was reversed during the 2010s.

CPUE data

Fits to the fishery CPUE data were poor for all models, but vaguely reflected the trends in observed cpue (Figure 23).

Size composition data

Fits to the size composition data for the BSFRF data were similar for all models (Figure 24). The number of males was 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. Fits to female survey composition data were similar for all models in most years, but fits for models 0 and model 3a departed from the other models in some years (Figure 25). Similar patterns in fits among models can be seen for the male survey composition data (Figure 26); the fits of models 0 and 3a departed from the fits of the other models.

The distribution of residuals for male and female survey composition data for the chosen model varied by maturity state and sex. Immature females tended to be underestimated (Figure 27), whereas mature females tended to be overestimated (Figure 28). No clear skew towards overestimation or underestimation existed for immature males (Figure 29), and size composition data for mature males exhibited the best residual patterns of the fitted survey composition data (Figure 30).

Predicted average size by shell condition and maturity state in the survey were generally similar among models and fit the observed average size reasonably well, with the exception of the old shell mature females and new shell immature males (Figure 31). Model 3a performed more poorly than the other models for predicting new shell immature males; model 0 performed slightly better than the other models for the latter portion of the time series.

Retained catch size composition data were fit well by all models (Figure 32); trawl size composition data were generally well fit, with several notable exceptions. All models performed similarly in fitting the trawl size composition data (Figure 33).

Estimated population processes and derived quantities

Estimates of mature male biomass at the time of mating varied by 6-44% among models over the history of the fishery. Projected MMB for 2016 ranged from 97.0 to 170.9 t. Estimated mature female biomass at the time of mating varied by 6-35% over the length of the time series among models. Projected FMB for 2016 ranged from 125.7 to 189.9 t (Figure 34). In general, estimated fishing mortality in the recent past has been well below $F_{35\%}$, but estimated MMB has been less than $B_{35\%}$ since 2011 (Figure 35).

Estimated fishing mortality in the directed fishery was similar for all models except model 0 and model 3a (Figure 36). Estimated fishing mortality in model 0 was lower than the other models, while model 3a's was higher. This result was related to the relative differences in the estimates of male biomass (model 0 was highest; model 3a was lowest). The same catch taken from populations of different sizes results in different estimated fishing mortalities, provided directed selectivity remains similar. 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 36). Size at 50% selection in the trawl fishery increased for all models after model 0 because the parameter was fixed in the model 0, but estimated in all subsequent models (Figure 36). Size at 50% selection for discarded females increased for model 3, 3a a, and 3b because it was fixed in all models previous to these (Figure 36). Changes in selectivity for these fisheries was reflected in the estimated fishing mortalities. See Figure 15 and Figure 16 for posterior densities for all parameters related to mortality in the different fisheries.

Estimated survey selectivity was similar for all models during survey era 1 (Figure 37). Catchability for males was close to 1 and ranged from 0.7-1 for females with very narrow posteriors (Figure 16). Size at 50% selection in the survey gear ranged from ~36 mm to ~44 mm for both females and males (Figure 16 & Figure 17). Estimated survey selectivity for females during survey era 2 was similar for all models, with estimated catchability ranging from 0.32 to 0.35. Estimated catchability for males ranged from 0.48 to 0.61. Size at 50% selection in the survey gear ranged from ~41 mm to ~45 mm for both females and males (Figure 16 & Figure 17). Estimated catchability for males during survey era 3 ranged from 0.52 to 0.7; estimated female catchability ranged from 0.48 to 0.6. Size at 50% selection in the survey gear ranged from 33 mm to 34 mm for females and 34 mm to 40 mm for males (Figure 16 & Figure 17). BSFRF 'availability' curves varied from 2009 to 2010, with the availability of crab to the experimental survey increasing in 2010 (Figure 38).

The probability of maturing by size was fairly consistent among scenarios for both males and females. The probability of maturing by size for female crab was about 50% at about 48 mm and increased to 100% at 60mm (Figure 39). The probability of maturing for male crab was about 15% to 20% at 60 mm to 90mm and increased sharply to 50% at about 98mm, and 100% at 108 mm. Model 3a predicted higher probability of molting to maturity for both males and females, which increased $F_{35\%}$ substantially.

Patterns in recruitment were similar for all models–a period of high recruitment in which 3 large cohorts pass through the population occured during the 1980s and into the early 1990s. A period of low recruitment followed that period which persisted from the early 1990s to present. All models indicated a potentially large recruitment event occuring in the last few years (Figure 40). Recruitment entering the model was placed primarily in the first three size bins (Figure 40). Distinct stock recruitment relationships were not apparent between the estimates of MMB and recruitment for any model (Figure 40). Relationships were not apparent between mature female biomass and recruitment either. Estimated multipliers for natural mortality ranged from 1.3 to 2 for immature crab and 1.11 to 1.14 for mature crab (Table 9).

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 directed exploitation (bycatch exploitation was set to the estimated average value) to determine 'virgin' 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 virgin level (i.e. $F_{35\%}$ and $B_{35\%}$).

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).

$$F_{OFL} = \begin{cases} Bycatch & if \frac{MMB}{MMB_{35}} \leq 0.25 \\[3mm] \frac{F_{35}(\frac{MMB}{MMB_{35}} - \alpha)}{1 - \alpha} & if 0.25 < \frac{MMB}{MMB_{35}} < 1 \\[3mm] F_{35} & if MMB > MMB_{35} \end{cases} \qquad (2)$$

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).

Previously, reference points and the OFL were calculated by fitting the model to the data, then transferring the estimated parameters to a script with a projection model in which all parameters were assumed known. The projection script began in the final year of the assessment period and was initiated by pasting the numbers at length from the report file of the assessment into a data file read in by the projection script. Reference points were calculated by projecting the population into the future under no fishing mortalty (to find virgin biomass) and a fishing mortality was solved for that reduced the mature male biomass-per-recruit to 35% of virgin levels. The process was repeated to find the OFL, but, to allow for some uncertainty in the calculation, lognormal error was added to the initial numbers at length (i.e. those in the final year of assessment) and the F_{OFL} was calculated based on the harvest control rule outlined above. Many simulations with different lognormal errors were carried out to develop a distribution of the OFL which was then used to determine an ABC.

The previously used projection method does not propagate the uncertainty in all parameters forward, so a Bayesian methodology was adopted for this iteration of the assessment to more fully represent the uncertainty associated with model estimates of quantities used in management. In the Bayesian implementation of this assessment model, none of the equations changed (other than in the ways requested by the CPT), but distributions for the OFL, MMB, $B_{35\%}$, and $F_{35\%}$ were developed by sampling from the posterior distributions of these quantities via a Markov Chain Monte Carlo algorithm built into ADMB. Accomplishing this required building in functions to calculate reference points and extra storage space (see functions 'get_fut_mortality', 'find_OFL', 'find_F35' in the .TPL on github).

Calculated OFLs and interpretation

Medians of the posterior densities of the OFLs calculated for the suite of six presented models ranged from 9.36 to 32.43 (Table 12). Differences in OFLs are a result of differences in estimated MMB (see above), calculated $B_{35\%}$ (which ranged from 137.7 to 155t), Figure 42), $F_{35\%}$ (which ranged from 0.95 to 2.48, Figure 42), and F_{OFL} (which ranged from 0.67 to 1.23, Figure 42). Model 3a had the lowest calculated OFL, due in large part to the lowest estimated MMB among the six models.

G. Calculation of the ABC

The acceptable biological catch (ABC) was set in two different ways. First, the ABC was set below the OFL by a proportion based on a predeterminied probability that the ABC would exceed the OFL (P_{star}).

Currently, P_{star} is set to 0.49 and the ABC was calculated as the 49th quantile of the posterior distribution of the overfishing level (OFL). The second method, which was recommended by the SSC, set the ABC by subtracting a 10% buffer from the OFL.

Author recommendations

The process of selecting a preferred model began with excluding models that did not fit the data. Model 3a was eliminated first because, although it fit the survey biomass data the best, it did so without fitting the male growth data and produced poorer fits to survey composition data. Model 3a also tracked observed average size for new shell immature males poorly and estimated era 3 survey catchability much higher than the implied catchability from the observed ratios between the NMFS and BSFRF tows in 2009 and 2010. Downweighting the survey size composition data (as in model 3a) should be done, but it should be done in concert with other changes in the weighting of the model (and perhaps while directly fitting the estimates of selectivity from the selectivity experiments) to ensure fits to other data components and credible estimates of population processes.

Models 1, 2, and 3 fit female growth data poorly, but this didn't have a large influence on the calculated OFL. Aside from poor fits to the female growth data, there were no other serious problems in the fits to the data that would warrant the exclusion of a model. However, the consistent estimation of a higher size at 50% selection in the trawl selectivity by models in which that parameter was free suggests that model 0 should be eliminated. A similar reasoning could be applied to female discard mortality and model 1 and 2, which leaves model 3 and 3b as candidates for the author selected model. Model 3 fits the female growth data poorly and the multiplier for natural mortality hits its bound of 2, so, model 3b was chosen as the preferred model for the 2016 snow crab assessment.

Consequently, the recommended OFL for 2016 was 32.43 t fishing at $F_{OFL} = 1.21$ (64 % of the calculated $F_{35\%}$, 1.88). The projected ratio of MMB at the time of mating to $B_{35\%}$ is 0.68. The associated ABC was 29.19 (calculated via the 10% buffer suggested by the SSC).

H. Data gaps and research priorities

Data sources

With the shift to a Bayesian paradigm, as many raw data sources as possible should be included in the assessment. Estimating parameters outside of the model and inputing them as 'known' artificially decreases the uncertainty represented in the 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, standardizing and automating the creation of data files from the survey and catch databases would be very useful given the short time frame of the assessment cycle.

Modeling

The model in its current state appeared to be internally consistent, but there are several model features that could be tested for their impact on management quantities and estimation. For example, bycatch was assumed to come entirely from the groundfish trawl fisheries. However, almost a quarter of it came from the pot fisheries in 2016, so it may be useful to model more fisheries for bycatch. Testing other forms of the relationship between pre- and post-molt length may also be useful. Visually, the need for a piece-wise model was not immediately clear. Often times piece-wise fits are used when growth changes after maturity as more energy is directed towards reproduction. However, given a terminal molt for both sexes, this should not impact the growth relationship. When incorporating weight at length data into the assessment, it may be

useful to consider a split in parameters for mature and immature males as is done for females. Revisiting the use of BSFRF data to more directly determine selectivity in the most recent survey era may provide stability needed to allow for the downweighting of the survey composition data.

Linking the catchability coefficients for the different survey eras may provide for more intuitive interpretation of the relationships between the parameters. The relationship between catchability in different eras can greatly influence the perceived status and impacts of fishing on the population. The survey data were originally split because of an increase in the area surveyed (era 1 to era 2) and a change in gear type (era 2 to era 3). Presumably, this means that catchability in era 2 should always be higher than era 1 (fewer stations were sampled in era 1). When splitting the mature males in the first year, it is assumed that they are all new shell, but the females are split out between new and old shell condition. Finally, considering the impact of basing natural mortality off of longevity and then splitting it into immmature and mature M on the calculation of reference points may improve the interpretability of estimates of natural mortality.

Weighting

Different weighting of likelihood components can have drastic impacts on the management advice provided from an assessment (as seen here in model 3a). 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. 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, but is poorly known. Tagging studies targeted at estimating natural mortality could be very 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. In general, exploring the spatial dynamics of the population may allow for patterns and influences of the fishery and environment on the producitivity of the stock to be more easily identified. Preliminary analyses suggest that retrospective biases may be a problem for the snow crab assessment (Figure 41; also compare the trajectory of MMB in last year's assessment to this year). Retrospective biases can result from unaccounted for time-varying processes in the population dynamics of the model (Hurtado et al., 2015). Focused research on the potential for retrospective biases in the snow crab assessment should be pursued.

Style

Although the code was trimmed considerably, 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 .REP files.

I. Ecosystem Considerations

Recruitment for snow crab can be divided into two periods via regime shift algorithms (e.g. Rodionov, 2004). The shift in recruitment corresponds with a change in the Pacific Decadal Oscillation (Szuwalski and Punt,

2013), but also with a period of intense fishing mortality. 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.

J. Literature cited

(to come)

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.

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

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

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

The dynamics after the initial year were described by:

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

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:

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

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. $Z_{x,v,m,y,l}$ 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 seletivity 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 8; this formulation effectively specified a mean and standard deviation for a prior distribution for M).

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

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).

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

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

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

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

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 occured 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.

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

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

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

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

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 ($F_{dev,y}^{log}$).

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

Selectivity for the survey was estimated for 3 eras: 1978-1981, 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.

$$S_{surv,s,l,e} = \frac{q_{s,e}}{1 + e^{-log(19)\frac{L_l - s50,s,e}{s95,s,e - s50,s,e}})}$$ (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.

$$S_{ind,s,l,y} = \begin{cases} \frac{q_{ind,s,y}}{1 + e^{-log(19)\frac{L_l - s50,s,y}{s95,s,y - s50,s,y}})} & \text{if s = female} \\ q_{ind,s,y}S_y^{free} & \text{if s = male} \end{cases}$$ (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.

$$S_{nmfs,s,l,y} = S_{ind,s,l,y}S_{surv,s,l,y}$$ (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, $w_{s,l}$:

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

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

$$w_{s,l} = \alpha_{wt,s}L_l^{\beta_{wt,s}}$$ (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. Immmature crab were assumed to molt every year with an estimated probabillity 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 variabillity around that relationship was characterized by a discretized and renormalized gamma function, $Y_{s,l,l'}$.

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

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

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

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

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

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

$\hat{L}_{s,l}^{post,1}$ 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.

An average recruitment for the assessment period (1978-present) and yearly deviations around this average were estimated within the assessment. 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.

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

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

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:

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

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 overweighting the size composition data and washing out the signal from the indices of abundance. The method of implementation used here is discussed below.

Lognormal likelihoods were implemented in the form:

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

L_x was the contritbution 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 lognormal likelihood components were included in this assessment (see Table 11 for descriptions, weighting factors, and CVs).

Normal likelihoods were implemented in the form:

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

L_x was the contritbution 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 this 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. Code for this assessment can be found on github.com/szuwalski/SnowCrab.

Francis weighting

Downweighting size compositon data associated with indices of abundance is a suggested practice. Using the raw effective samples sizes can lead to overfitting the size composition data at the expense of poor fits to the index, which is one of the most important pieces of information to be fit in an assessment. Here, Francis' method (2011) of iterative reweighting of the size composition data was implemented by calculating a weighting factor by which to multiply the input sample sizes for the size composition of the survey data.

$$Francis = \frac{1}{var_y\left(\frac{\bar{L}_y - \hat{L}_y}{SE(\hat{L}_y)}\right)} \tag{34}$$

$$\bar{L}_y = \sum_l \bar{L}_L p_{y,L} \tag{35}$$

$$\hat{L}_y = \sum_l \bar{L}_L \hat{p}_{y,L} \tag{36}$$

$$SE(\hat{L}_y) = \sqrt{\frac{\sum_L \hat{p}_{y,L}(\bar{L}_y - \hat{L}_y)^2}{N_y}} \tag{37}$$

Where $\bar{L}_y$ was the observed mean length of the catch in year y, $\hat{L}_y$ was the predicted mean length of the catch in year y, and $SE(\hat{L}_y)$ was the predicted standard error of the mean length of the catch in year y. $\bar{L}_L$ was the mide-point of a size bin and $p_{y,L}$ was the proportion of catch in sizebin L inyear y. N_y is the number of observation in year y. The weights were iteratively calculated and applied to the effective sample sizes for survey size composition data by sex (i.e. combining shell condition and maturity state) until the output Francis weights converged on a value <1.05 and > 0.95.

Tables and figures

Table 4: Changes in management quantities for stepwise changes in assessment model. Reported quantites are the MLEs because running MCMC for every model was prohibitively time-consuming. The MLEs for scenarios in which MCMCs were performed are very close to the medians of the posterior distributions.

Model	MMB	B35	F35	FOFL	OFL
Base	140.3	163.8	1.49	1.07	44.15
Base 2 CPUEq	137.4	163.2	1.48	1.06	42.81
Base 3 SurvFq	139.1	163.4	1.48	1.06	43.47
Base 4 AddRetroFrancis	139.1	163.4	1.48	1.06	43.47
Base 5 ChangeWtPars	139.3	164.7	1.43	1.03	43.17
Model 0	116.7	146.6	0.96	0.7	34.25
Model 1a TrawlF_estAvg	95.54	140.2	1.12	0.74	26.4
Model 1b TrawlF_NoPen	96.3	141.2	1.27	0.83	26.73
Model 1c TrawlF_2vec	86.83	137.7	1.25	0.79	23.09
Model 2a MatPrior	55.3	134.1	2.05	0.95	7.81
Model 3a SmoothMat_Weight	58.47	136.1	2.4	1.17	9.24
Model 3b SmoothMat_Disc50	59.02	135.9	2.44	1.2	9.53
Model 1c TrawlF_2vec_200	101.8	150.9	2.02	1.25	28.35
Model 2a MatPrior_200	96.99	148.9	1.72	1.04	26.54
Model 3a SmoothMat_Weight_200	101.1	151.4	2.03	1.24	28.57
Model 3b SmoothMat_Disc50_200	99.73	150.5	2.02	1.23	28.14

Table 5: Observed growth increment data by sex

Female premolt length (mm)	Female postmolt length (mm)	Male premolt length (mm)	Male postmolt length (mm)
19.37	24.24	21.23	26.41
20.7	27.4	22.2	28.1
21.25	28.73	23.48	28.27
21.94	28.71	29.9	39.9
23.09	29.26	30.3	40.3
32.8	44.9	30.7	40.5
35.3	47.6	44.2	58.7
38.3	50.9	44.7	57.3
38.9	53	64.7	82.7
41	55.8	67.6	86
42.1	54.6	67.9	85.3
44.2	59.5	74.5	93.9
44.3	59.3	79.9	97.8
44.8	59.7	89.8	110
45.2	59.6	89.9	112.1
46.9	60.4	89.9	112.3
47	61.4	93.8	117.6
47.9	61.4	20	26.3
20.6	25.1	NA	NA
20.8	27.6	NA	NA
22	28.2	NA	NA
22.9	28.6	NA	NA

Table 6: Observed retained catches, discarded catch, and bycatch

Survey year	Retained catch (numbers)	Retained catch (lbs)	Discarded females (numbers)	Discarded males (numbers)	Trawl bycatch (numbers)
1978	4021	5227	26.94	1407	1318
1979	5002	7503	33.51	1751	1053
1980	4462	6693	29.9	1562	766
1981	2409	2936	16.9	615.1	319.6
1982	2385	2613	23	554.9	130
1983	2401	2681	16.1	313.1	167.5
1984	5290	6600	15.94	893.8	178
1985	7650	9798	16.05	1464	152.8
1986	8131	10190	35.36	1410	656.3
1987	10572	13535	51.13	1851	1.92
1988	11262	14946	54.35	1527	235.4
1989	12898	16182	70.66	1904	273.3
1990	26512	32865	75.28	13782	209
1991	22738	31530	86.21	4808	805.5
1992	16956	23079	177.2	15967	1132
1993	11478	14978	118.3	5190	1301
1994	6061	7525	85.41	4788	835.9
1995	5291	6571	23.15	5634	448.8
1996	9998	11954	102.2	7398	330.1
1997	19352	25219	7.98	5159	530.3
1998	15104	19420	9.65	4157	290.2
1999	2508	3329	0.59	474.3	157.3
2000	1943	2526	0.62	520.4	152.5
2001	2515	3263	0.62	1574	104.9
2002	2325	2832	6.28	1401	66.59
2003	1867	2394	0.92	487.8	214.5
2004	1799	2489	0.92	550.6	348.9
2005	2455	3697	3.47	1125	133.1
2006	2968	3636	1.1	1630	234.8
2007	5253	6303	15.73	2237	159.2
2008	4595	5855	12.12	1771	109.5
2009	3529	4801	10.74	1066	234.4
2010	3768	5426	8.95	488.4	71.71
2011	6056	8883	260.9	1339	66.16
2012	4746	6625	40.83	1907	89.64
2013	4193	5398	96.3	3309	41.05
2014	5503	6794	249.5	3343	51.59
2015	4061	2961	101.5	2577	51.77
2016	NA	NA	NA	NA	NA

Table 7: Observed mature male and female biomass at the time of the survey and coefficients of variation

Survey year	Female mature biomass	Female CV	Mature male biomass	Male CV
1978	101.7	0.2	193.5	0.12
1979	216.8	0.2	241.3	0.12
1980	281.3	0.32	187.5	0.17
1981	123.3	0.17	113.5	0.11
1982	144.4	0.15	176.8	0.14
1983	90.13	0.2	161.6	0.13
1984	42.32	0.19	177.7	0.12
1985	6.12	0.2	71.84	0.11
1986	15.74	0.18	89.81	0.11
1987	122.6	0.16	194.6	0.11
1988	169.9	0.17	259.4	0.15
1989	264.2	0.25	299.2	0.11
1990	182.9	0.19	443.8	0.14
1991	214.9	0.19	466.6	0.15
1992	131.4	0.18	235.5	0.09
1993	132.1	0.16	183.9	0.1
1994	126.2	0.15	171.3	0.08
1995	168.7	0.14	220.5	0.13
1996	107.3	0.14	288.4	0.12
1997	103.8	0.2	326.8	0.1
1998	72.73	0.25	206.4	0.09
1999	30.89	0.21	95.85	0.09
2000	96.46	0.52	96.39	0.14
2001	77.24	0.28	136.5	0.12
2002	30.22	0.28	93.17	0.23
2003	41.71	0.31	79.07	0.12
2004	50.16	0.26	79.57	0.14
2005	64.85	0.17	123.5	0.11
2006	51.93	0.18	139.3	0.26
2007	55.89	0.22	153.1	0.15
2008	57.15	0.19	142	0.1
2009	52.16	0.21	148.2	0.13
2010	98.01	0.18	162.8	0.12
2011	175.8	0.18	167.1	0.11
2012	149.4	0.2	122.2	0.12
2013	131.4	0.18	97.46	0.12
2014	119.7	0.19	163.5	0.16
2015	85.13	0.17	80.04	0.12
2016	55.39	0.21	63.21	0.11

Table 8: Parameter bounds and symbols

Parameter	Lower	Upper	Symbol
af	-100	0	α_f
am	-50	0	α_m
bf	1	10	$\beta_{f,1}$
bm	1	5	$\beta_{m,1}$
b1	1	1.5	$\beta_{f,2}$
bf1	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	$F_{dev,trawl,era1}^{log}$
fmort_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	55	$S_{50,f,09,ind}$
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	$\gamma_{natM,mat,m}$
cpueq	8.77e-05	0.00877	q_{cpue}

Table 9: Estimated parameter values by scenario

Parameter	Model 0	Model 1	Model 2	Model 3	Model 3a	Model 3b
af	-3.99	-3.27	-3.54	-3.59	-4.78	-5.09
am	-10.65	-11.94	-12.14	-5.56	-11.55	-5.72
bf	1.47	1.44	1.45	1.45	1.51	1.53
bm	1.76	1.82	1.83	1.53	1.78	1.54
b1	1.17	1.16	1.16	1.15	1.11	1.15
bf1	1.12	1.04	1.01	1	1.05	1.02
deltam	27.59	27.42	27.42	32.17	34.06	32.19
deltaf	34.37	32.6	32.77	32.44	33.94	34.37
st_gr	0.5	0.5	0.5	0.5	0.5	0.5
growth_beta	vector	vector	vector	vector	vector	vector
mateste	vector	vector	vector	vector	vector	vector
matestfe	vector	vector	vector	vector	vector	vector
mean_log_rec	NA	NA	NA	NA	NA	NA
rec_devf	vector	vector	vector	vector	vector	vector
alpha1_rec	11.5	11.5	11.5	11.5	11.5	11.5
beta_rec	4	4	4	4	4	4
mnatlen_styr	vector	vector	vector	vector	vector	vector
fnatlen_styr	vector	vector	vector	vector	vector	vector
log_avg_fmort	-0.61	-0.14	-0.24	-0.18	0.2	-0.23
fmort_dev	vector	vector	vector	vector	vector	vector
log_avg_fmortdf	-6.64	-6.74	-6.79	-5.55	-5.58	-6.44
fmortdf_dev	vector	vector	vector	vector	vector	vector
log_avg_fmortt	-5.4	-4.23	-4.43	-4.33	-3.96	-4.3
fmortt_dev_era1	NA	vector	vector	vector	vector	vector
fmort_dev_era2	NA	NA	NA	NA	NA	NA
log_avg_sel50_mn	4.65	4.68	4.67	4.67	4.67	4.67
log_avg_sel50_mo	4.5	4.5	4.5	4.5	4.5	4.5
fish_slope_mn	0.18	0.18	0.19	0.19	0.21	0.19
fish_fit_slope_mn	0.4	0.41	0.41	0.42	0.41	0.42
fish_fit_sel50_mn	96.36	95.77	95.83	95.82	95.34	95.85
fish_slope_mo2	1.95	1.95	1.95	1.95	1.95	1.95
fish_sel50_mo2	159.5	159.5	159.5	159.5	159.5	159.5
fish_slope_mn2	1	1	1	1	1	1
fish_sel50_mn2	130	130	130	130	130	130
fish_disc_slope_f	0.29	0.3	0.29	0.23	0.24	0.24
fish_disc_sel50_f	4.2	4.2	4.2	4.32	4.31	4.26
fish_disc_slope_tf	0.09	0.08	0.09	0.09	0.09	0.08
fish_disc_sel50_tf	94.88	114.23	109.42	111.81	113.55	113.46
srv1_q	1	1	1	1	1	1
srv1_q_f	0.8	1	1	1	0.77	1
srv1_sel95	51.86	62.88	63.1	63.3	54.68	60.01
srv1_sel50	36.2	44.07	44.16	44.34	38.84	42.7
srv2_q	0.64	0.5	0.51	0.5	0.64	0.48
srv2_q_f	0.35	0.35	0.35	0.35	0.37	0.32
srv2_sel95	64.29	67.57	68.26	67.73	72.76	61.12
srv2_sel50	41.13	44.27	44.66	44.63	46.16	41.21
srv3_q	0.62	0.61	0.63	0.61	0.7	0.59
srv3_sel95	48.15	60.5	61.93	60.56	52.16	56.96
srv3_sel50	34.35	39.67	40.18	39.95	37.35	38.3
srv3_q_f	0.6	0.48	0.49	0.47	0.55	0.48

Parameter	Model 0	Model 1	Model 2	Model 3	Model 3a	Model 3b
srv3_sel95_f	42.04	44.24	44.32	44.72	44.45	43.18
srv3_sel50_f	33	33.92	33.97	34.14	34.38	33.34
srvind_q	0.38	0.34	0.38	0.35	0.37	0.35
srvind_q_f	0.13	0.11	0.11	0.11	0.12	0.11
srvind_sel95_f	55	56.92	56.95	56.06	55.5	55
srvind_sel50_f	49.17	50.2	50.24	49.82	49.63	49.22
srv10in_q	NA	NA	NA	NA	NA	NA
srv10ind_q_f	1	1	1	1	1	1
selsmo10ind	vector	vector	vector	vector	vector	vector
selsmo09ind	vector	vector	vector	vector	vector	vector
Mmult_imat	1.3	1.96	2	2	2	1.78
Mmult	1.11	1.12	1.11	1.13	1.11	1.14
cpueq	0	0	0	0	0	0

Table 10: Contribution to the objective function by individual likelihood component by modeling scenario

Likelihood component	Model 0	Model 1	Model 2	Model 3	Model 3a	Model 3b
Recruitment deviations	39.88	39.19	38.89	39.82	47.33	40.14
Initial numbers old shell males small length bins	1.54	2.19	2.19	2.18	1.38	2.17
ret fishery length	354.3	380	374.3	380	345.5	378.6
total fish length (ret + disc)	823.9	822.1	818.2	822.1	810	822.1
female fish length	225.8	235.7	235.4	229.5	224.9	221.5
survey length	996.5	4497	4487	4483	1005	4636
trawl length	301.1	283.5	288.1	281.3	319.4	287.1
2009 BSFRF length	-86.84	-81.72	-80.2	-81.67	-84.95	-83.03
2009 NMFS study area length	-71.23	-67.94	-66.92	-68.78	-69.65	-67.99
M multiplier prior	4.29	5.15	5.01	5.99	4.86	19.79
maturity smooth	54.23	56.59	5.34	39.67	23.62	40.82
growth males	55.22	38.44	38.63	37.38	52.28	39.22
growth females	43.39	93.75	101.9	114.8	29.59	133.2
2009 BSFRF biomass	0.17	0.2	0.22	0.19	0.31	0.19
2009 NMFS study area biomass	0.09	0.08	0.1	0.09	0.19	0.07
cpue q	0.14	0.19	0.19	0.19	0.27	0.18
retained catch	2.83	4.47	4.26	4.54	2.45	4.33
discard catch	128.5	190.2	180.3	190.3	38.73	197.6
trawl catch	6.55	9.35	8.95	9.14	5.74	10.14
female discard catch	6.23	6.17	6.2	6.36	7.19	5.96
survey biomass	339.4	360.9	359	359.7	336.3	366.1
F penalty	77.7	38.19	36.01	37.37	43.47	37.09
2010 BSFRF Biomass	7.43	2.4	2.56	2.21	5.19	2.36
2010 NMFS Biomass	0.68	0.81	0.96	0.82	1.47	0.7
Extra weight survey lengths first year	102.1	510.9	511.9	512.2	100.3	510.5
2010 BSFRF length	-53.47	-57.66	-57.61	-58	-55.84	-55.31
2010 NMFS length	-57.85	-64.33	-64.39	-65.11	-60.25	-59.85
smooth selectivity	3.88	3.31	3.41	3.23	3.23	3.34
smooth female selectivity	0	0	0	0	0	0
init nos smooth constraint	38.76	40.43	42.06	41.46	35.5	40.53

Table 11: Likelihoods form, weighting, and priors for the base model

Likelihood component	Form	Weighting	Prior
Recruitment deviations	normal	sd = 0.71	0
Initial numbers old shell males small length bins	normal	sd = 707.11	NA
ret fishery length	multinomial	EffN = 200	NA
total fish length (ret + disc)	multinomial	EffN = 200	NA
female fish length	multinomial	EffN = 200	NA
survey length	multinomial	EffN = 40	NA
trawl length	multinomial	EffN = 200	NA
2009 BSFRF length	multinomial	EffN = 200	NA
2009 NMFS study area length	multinomial	EffN = 200	NA
M multiplier prior	normal	sd = 0.23	1
maturity smooth	normal	sd = 3.16	NA
growth males	normal	sd = 0.5	NA
growth females	normal	sd = 0.5	NA
2009 BSFRF biomass	lognormal	cv = 1.64,1.79 (f,m)	NA
2009 NMFS study area biomass	lognormal	cv = 0.46,0.32 (f,m)	NA
cpue q	normal	sd = 0.32	NA
retained catch	normal	sd = 0.22	NA
discard catch	normal	sd = 3	NA
trawl catch	normal	sd = 0.22	NA
female discard catch	normal	sd = 17	NA
survey biomass	lognormal	cv = 0.14-0.57; 0.084-0.227 (f,m)	NA
F penalty	normal	sd = 0.5	1.15
2010 BSFRF Biomass	lognormal	cv = 0.19,0.29 (f,m)	NA
2010 NMFS Biomass	lognormal	cv = 0.13,0.21 (f,m)	NA
Extra weight survey lengths first year	multinomial	EffN = 200	NA
2010 BSFRF length	multinomial	EffN = 200	NA
2010 NMFS length	multinomial	EffN = 200	NA
smooth selectivity	norm2(firstdiff(firstDiff))	wt = 2	NA
smooth female selectivity	norm2(firstdiff(firstDiff))	wt = 3	NA
init nos smooth constraint	norm2(firstdifference)	wt = 1	NA

Table 12: Projected status and catch specifications for snow crab (1,000t).

Model	OFL	B35	MMB	Status	F35	FOFL	ABC
Model 0	31.18	144.6	110	0.74	0.95	0.67	28.06
Model 1	27.75	149.2	100.1	0.65	1.95	1.19	24.97
Model 2	26.28	149.2	96.81	0.64	1.7	1.01	23.65
Model 3	27.54	150.4	98.9	0.65	2.03	1.23	24.79
Model 3a	9.36	137.7	59.81	0.54	2.48	1.19	8.42
Model 3b	32.43	155	109.4	0.68	1.88	1.21	29.19
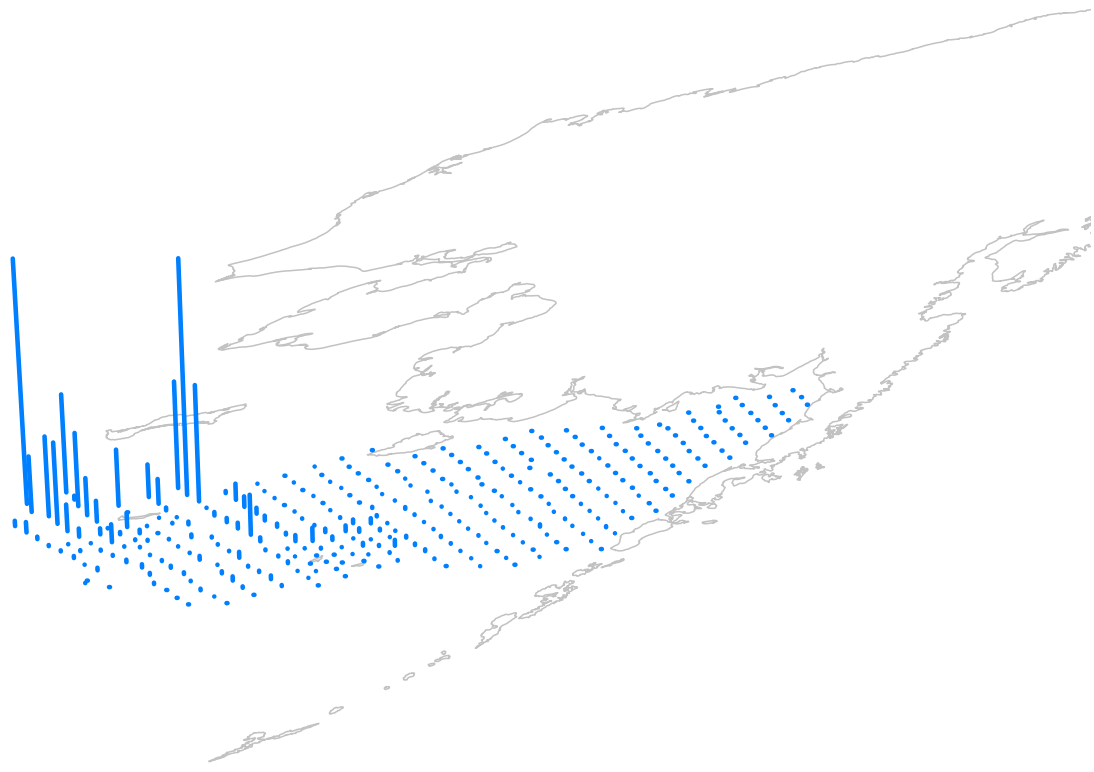
Figure 1: Observed relative density of all males at the time of the 2016 NMFS summer survey
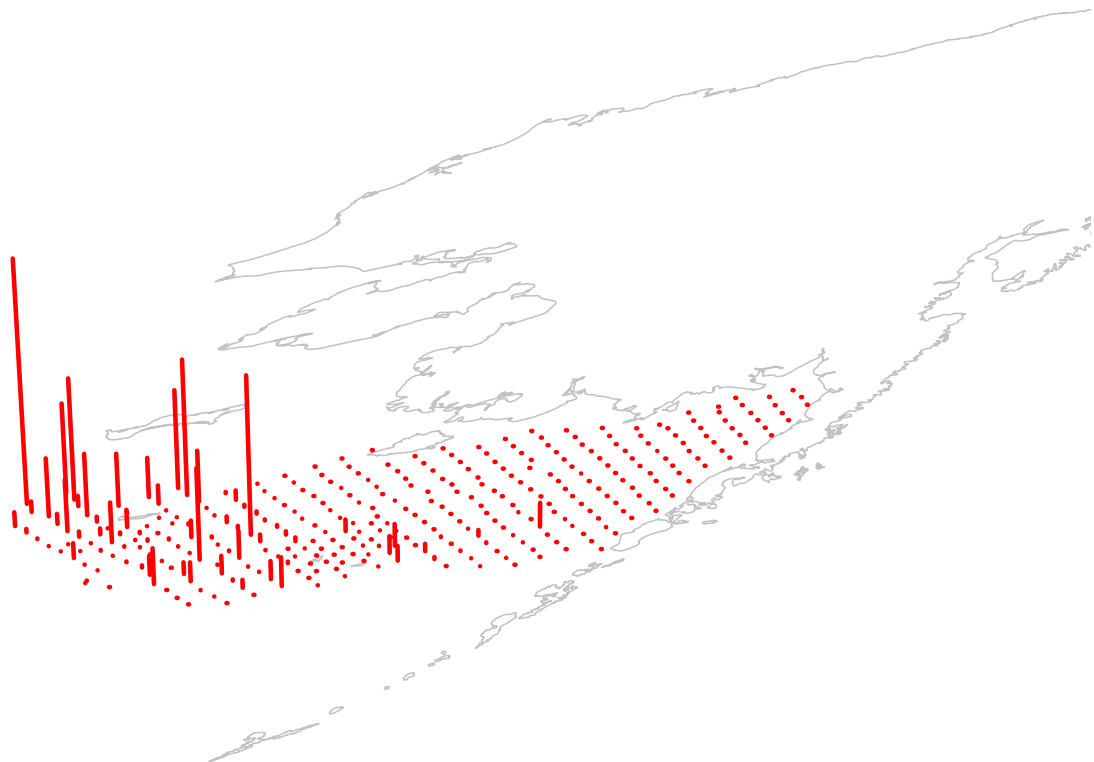
Figure 2: Observed relative density of all females at the time of the 2016 NMFS summer survey
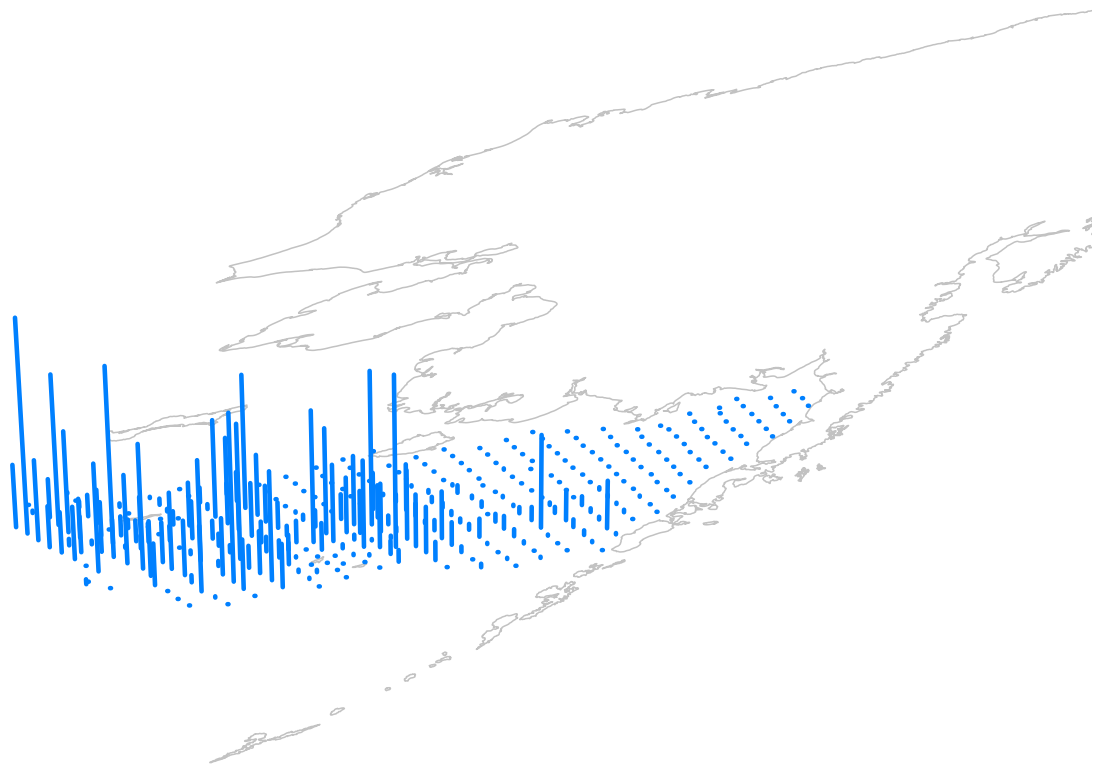
Figure 3: Observed relative density of males >77mm carapace width at the time of the 2016 NMFS summer survey
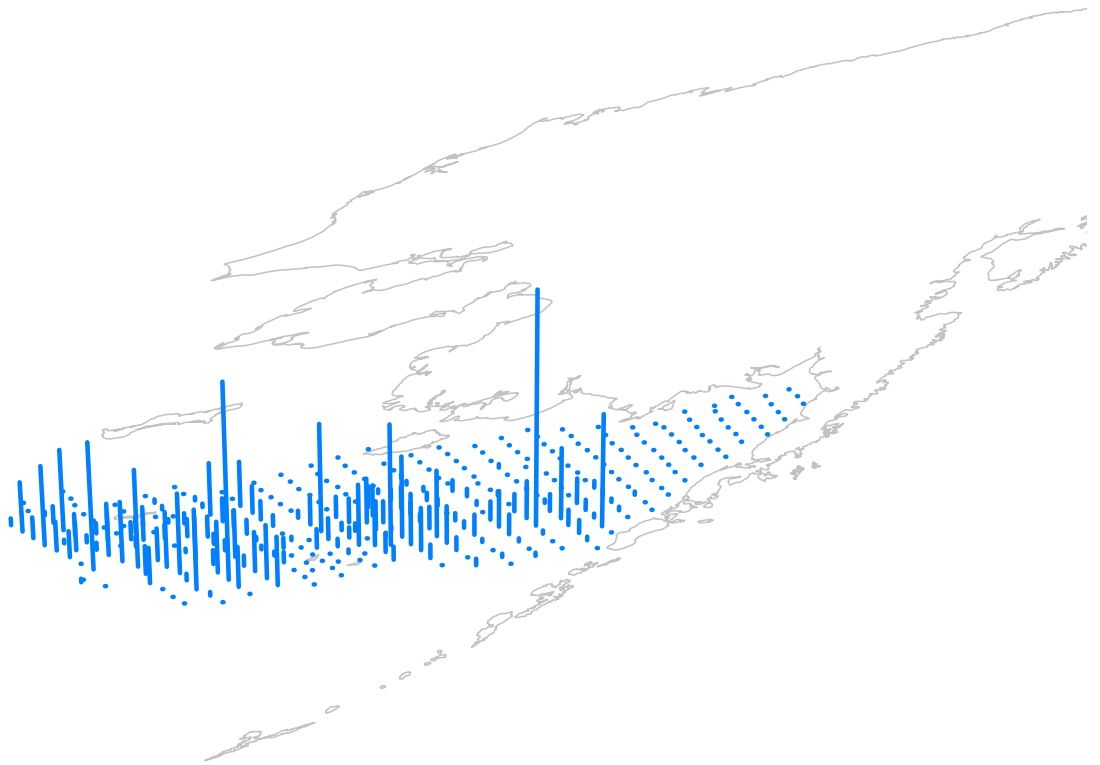
Figure 4: Observed relative density of males >101mm carapace width at the time of the 2016 NMFS summer survey
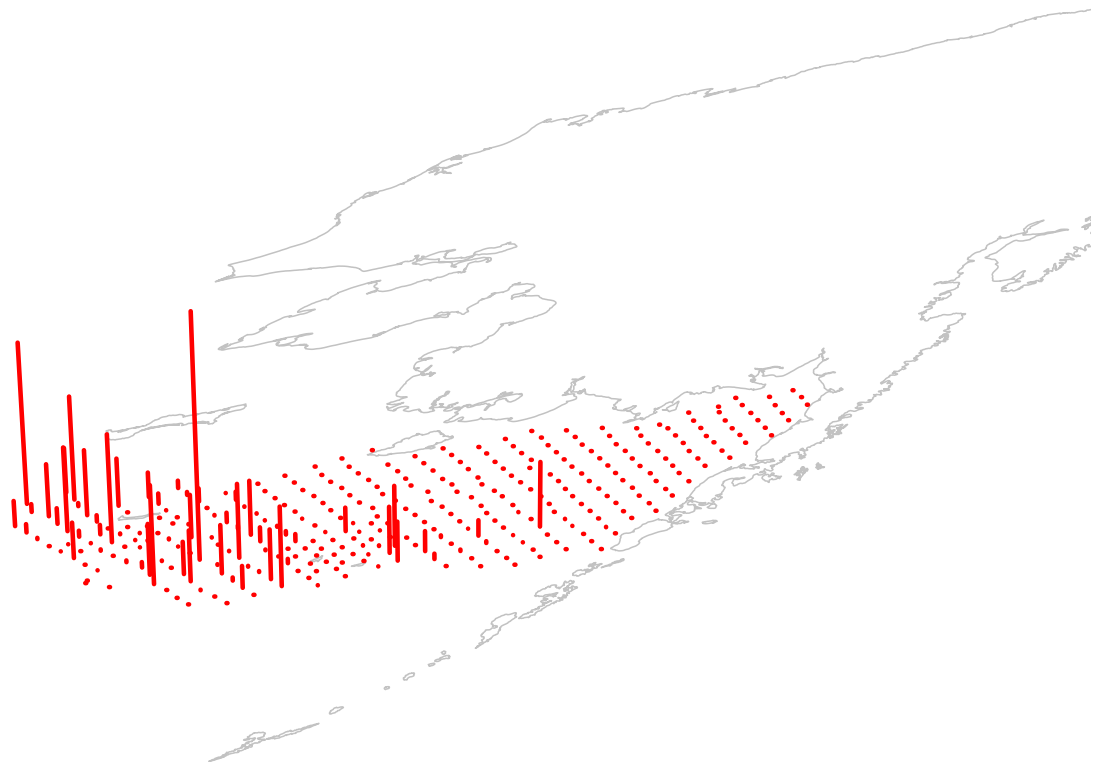
Figure 5: Observed relative density of all females at the time of the 2016 NMFS summer survey
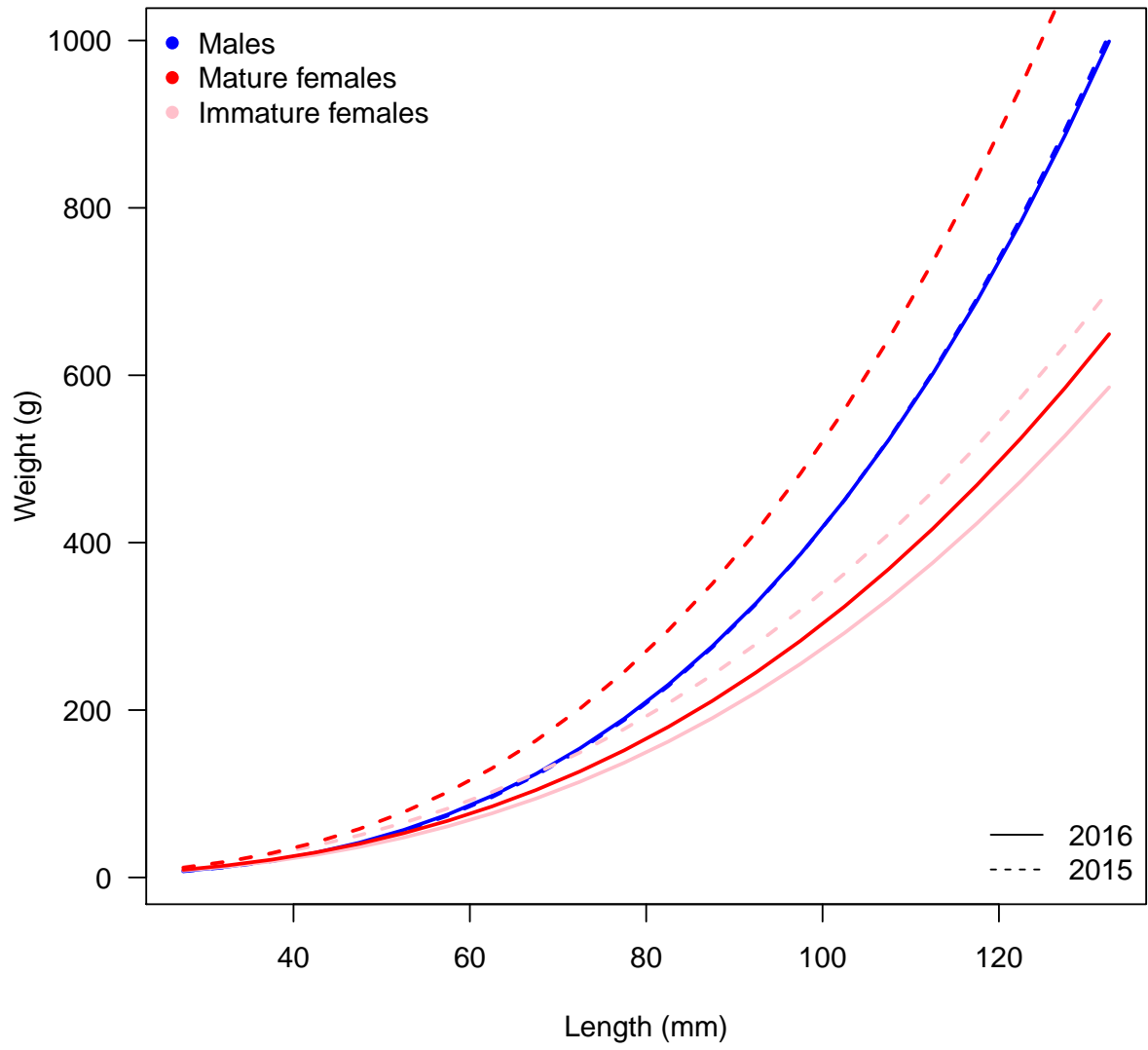
Figure 6: Changes in weight at length from 2015 to 2016 assessment
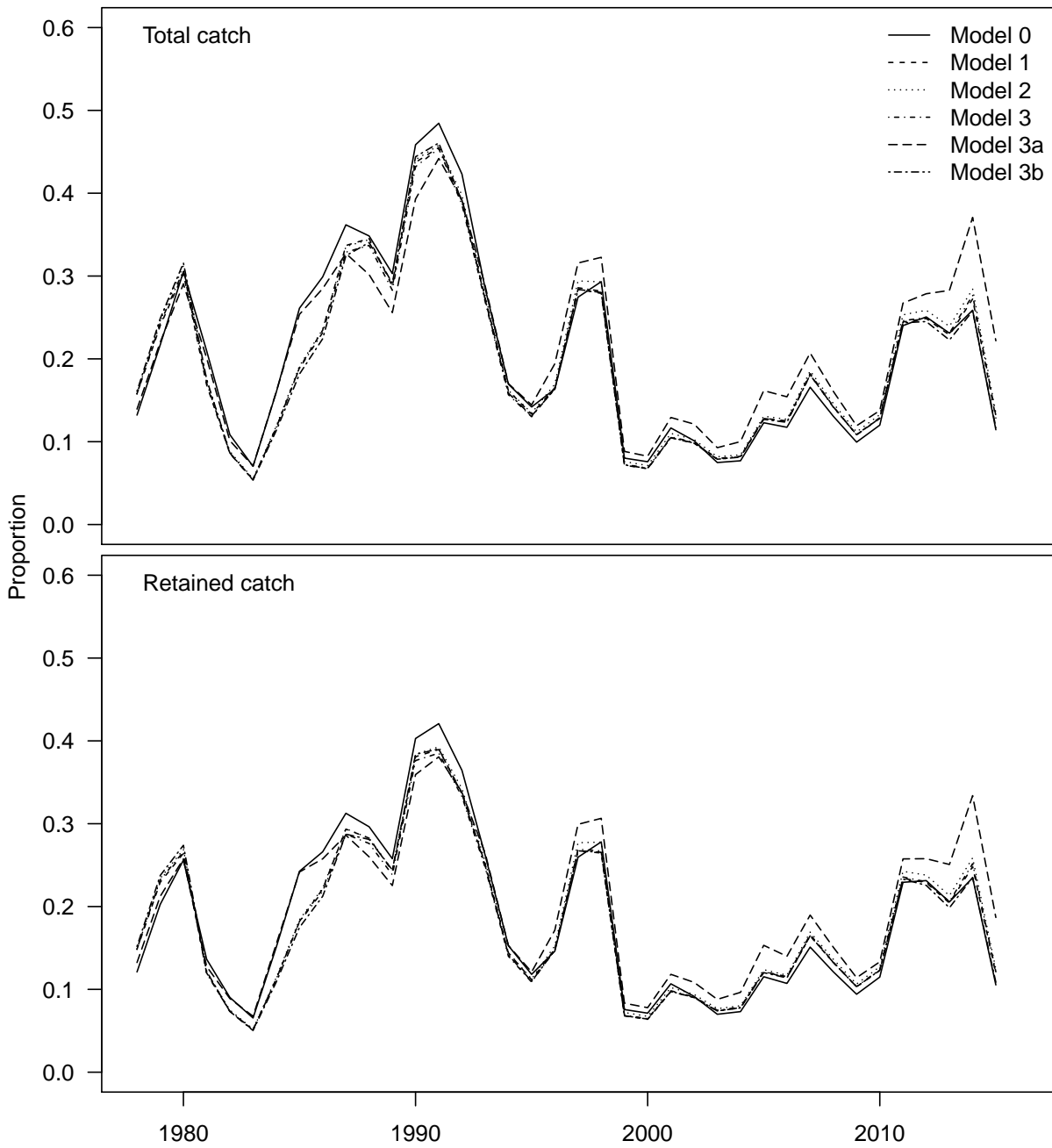
Figure 7: Model predicted ratio of catch to mature male biomass

Total females
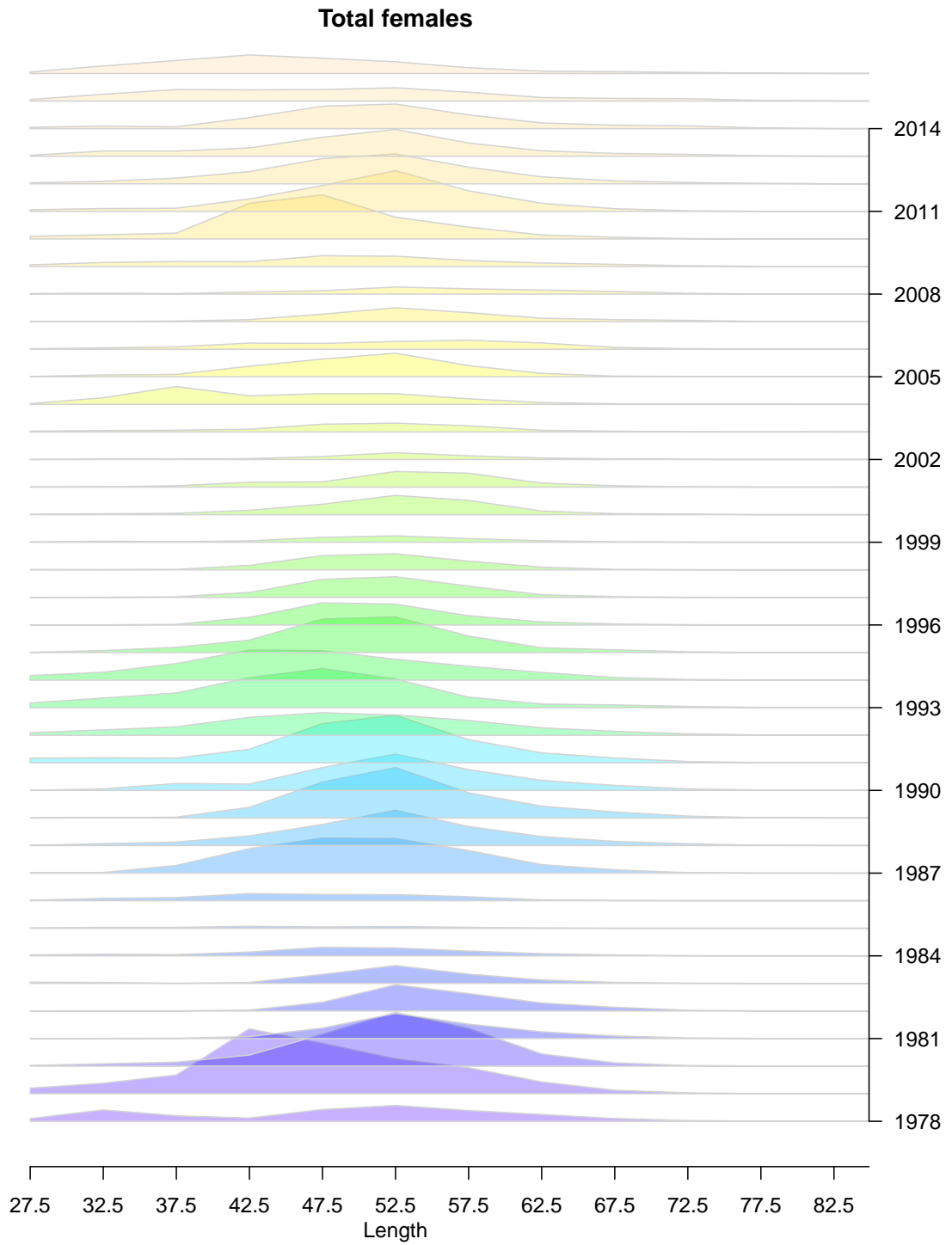
Figure 8: Observed relative numbers at length at the time of the survey

Total males
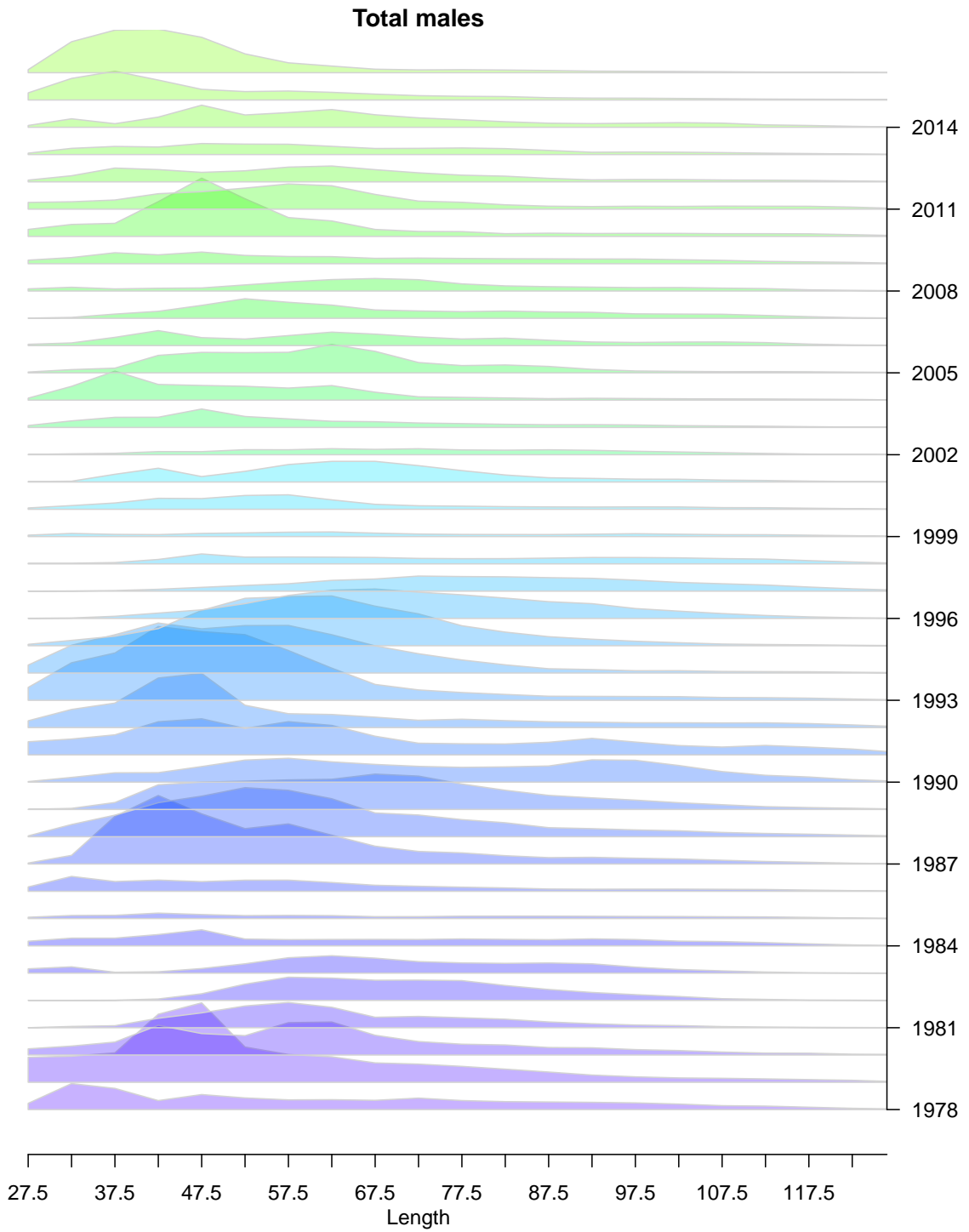
Figure 9: Observed relative numbers at length at the time of the survey
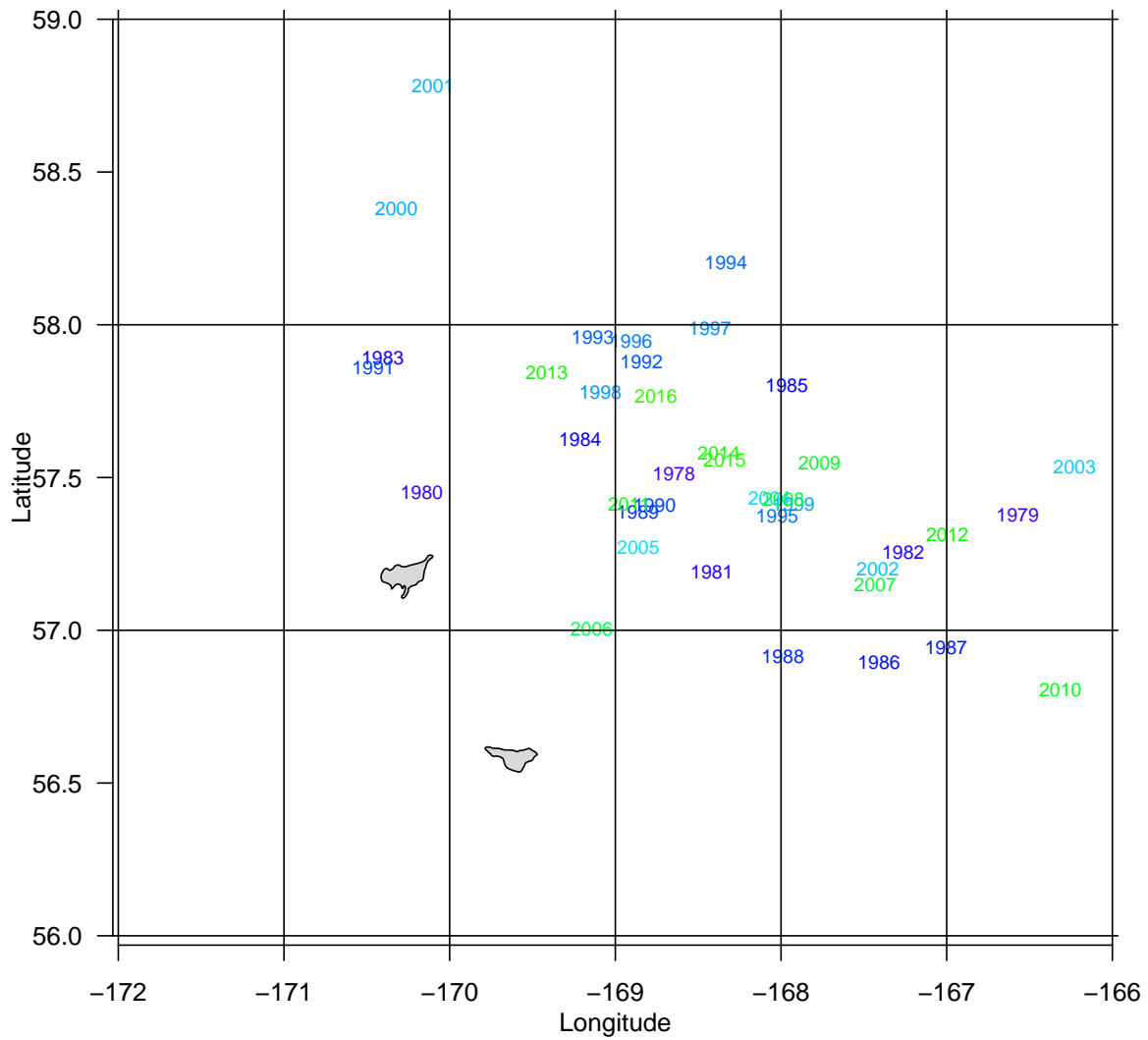
Figure 10: Centroid of mature females observed in the survey over time. Dark blue indicates years early in the time series; green are the most recent years in the time series.
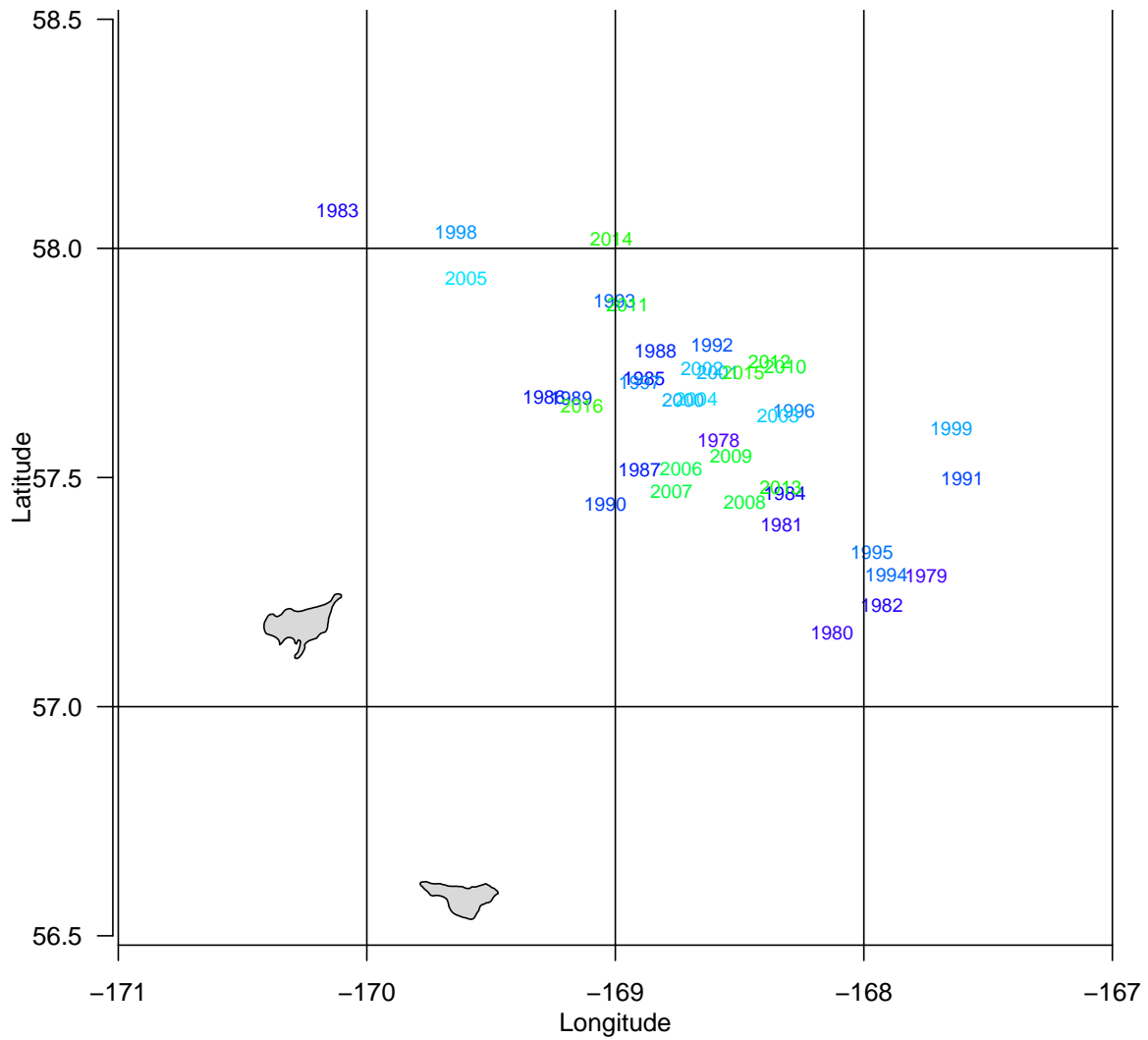
Figure 11: Centroid of large males observed in the survey over time. Dark blue indicates years early in the time series; green are the most recent years in the time series.
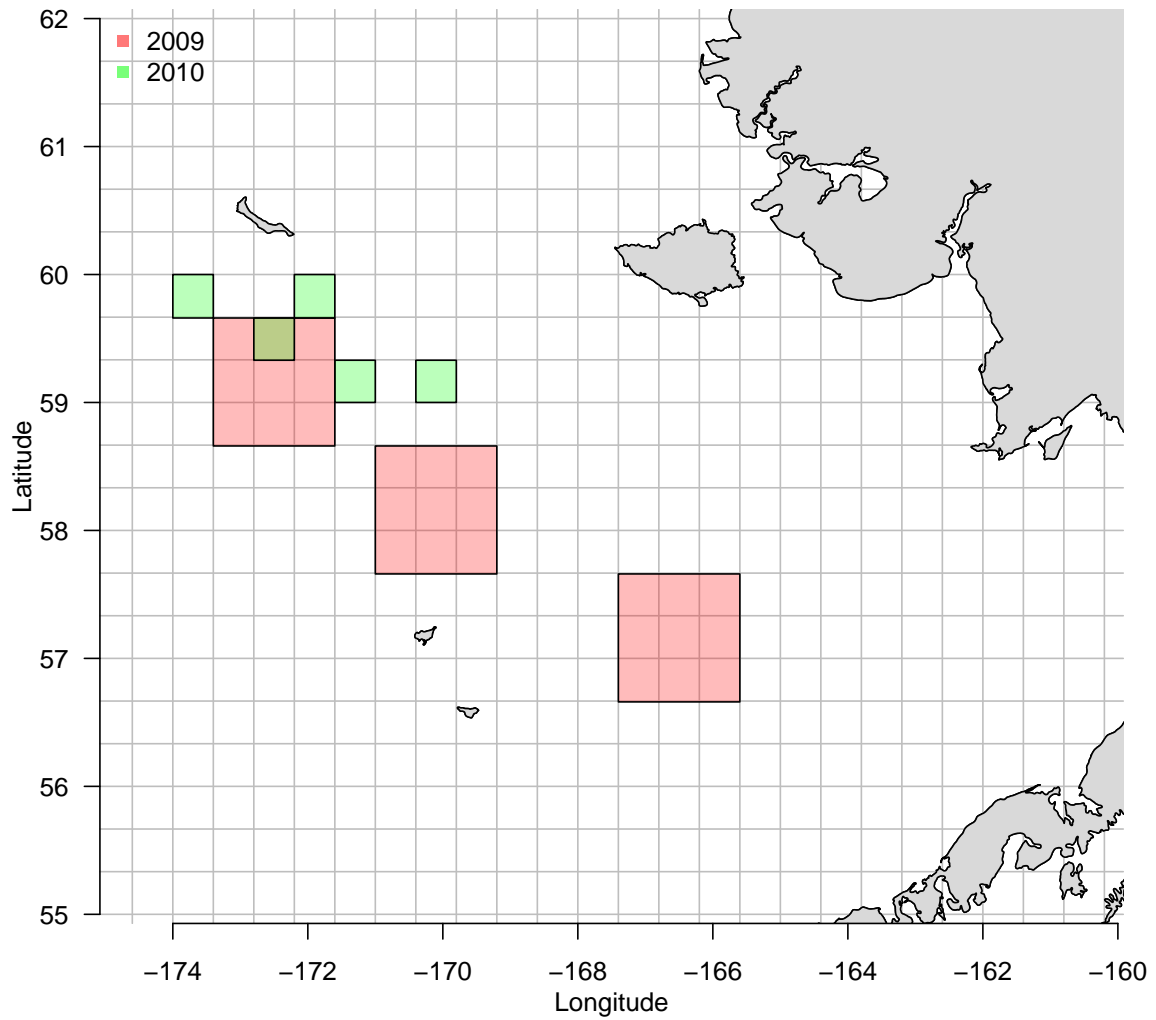
Figure 12: Location of survey selectivity experiments (2009 & 2010)
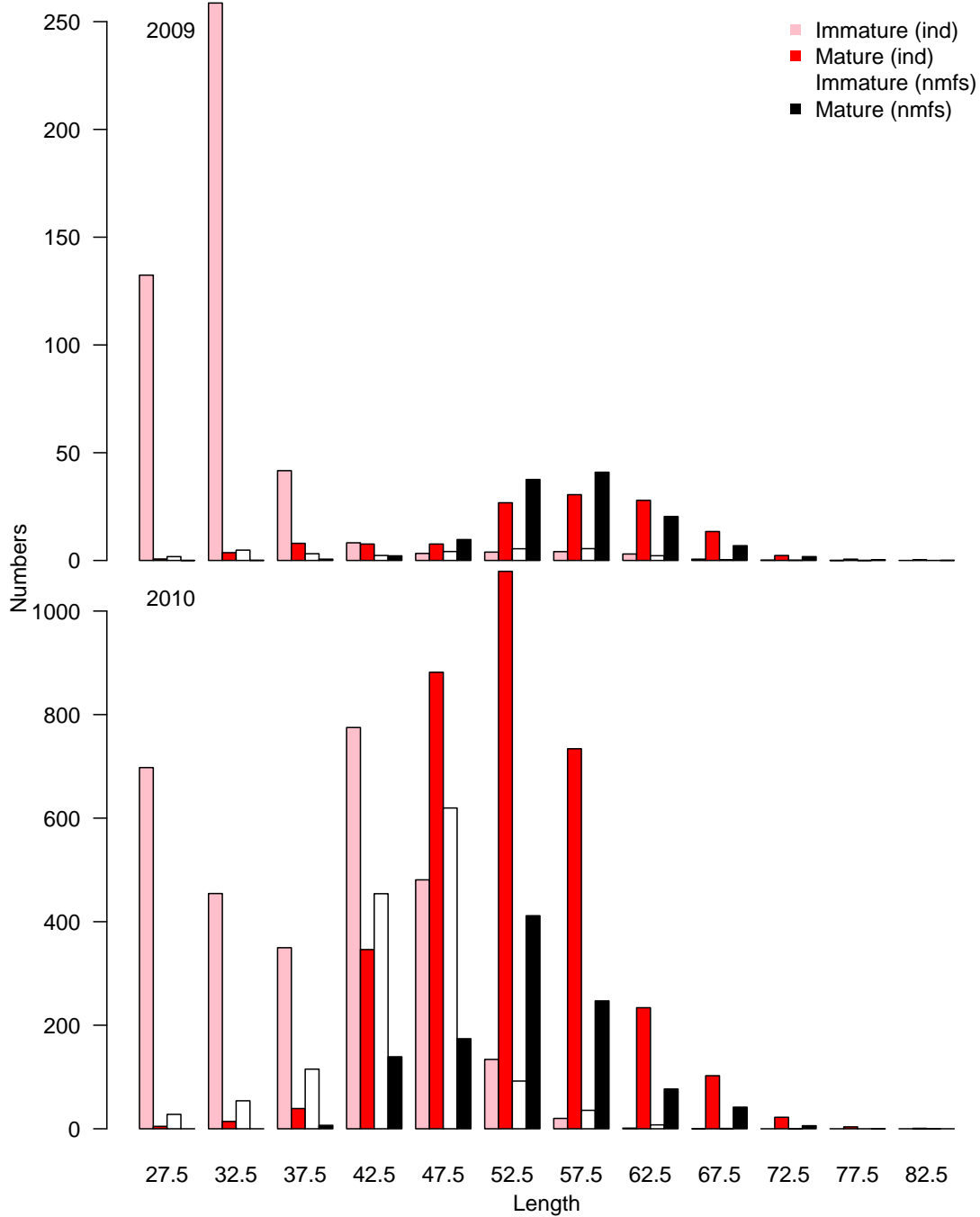
Figure 13: Raw female numbers from BSFRF survey selectivity experiments (2009 & 2010)
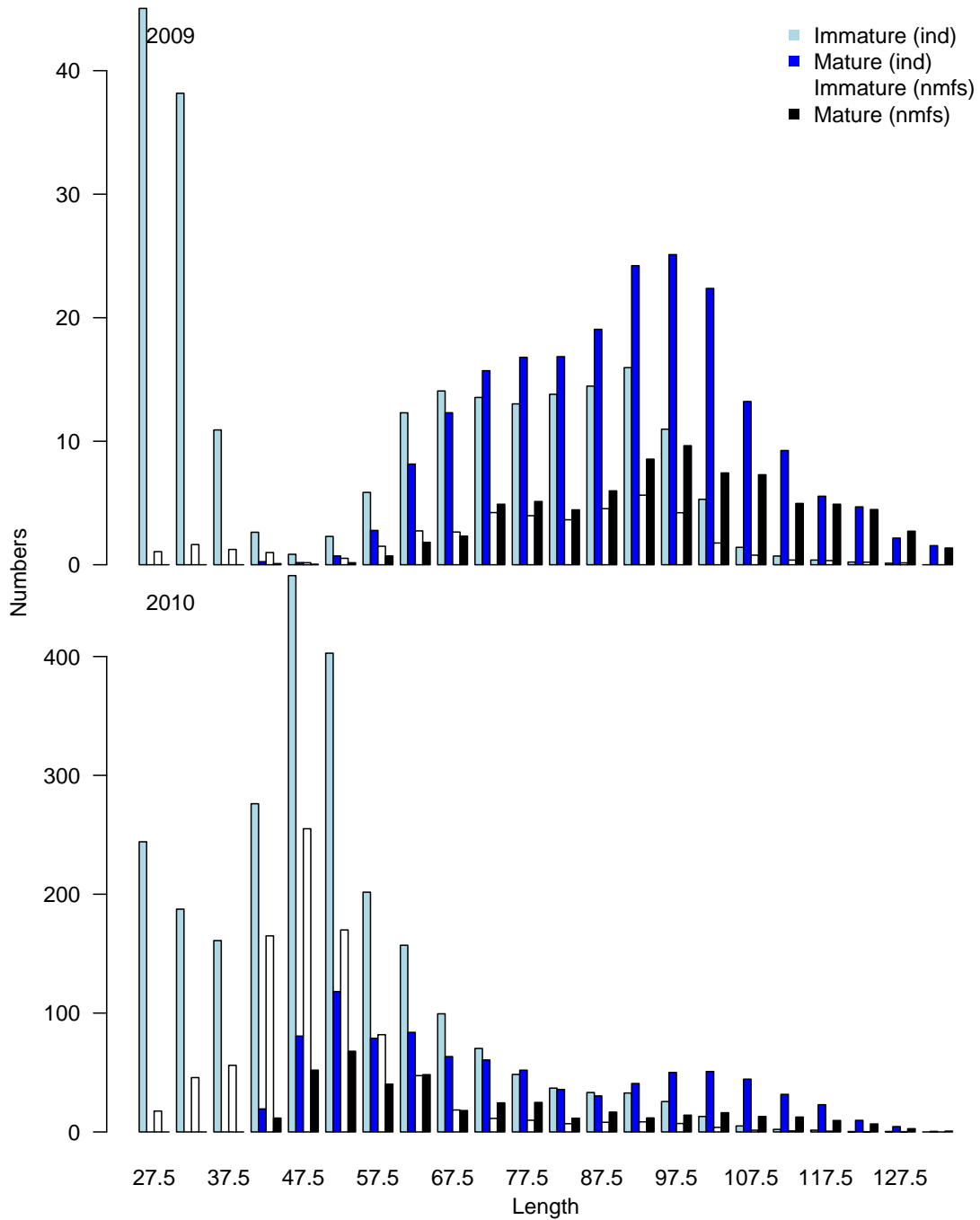
Figure 14: Raw male numbers from BSFRF survey selectivity experiments (2009 & 2010)
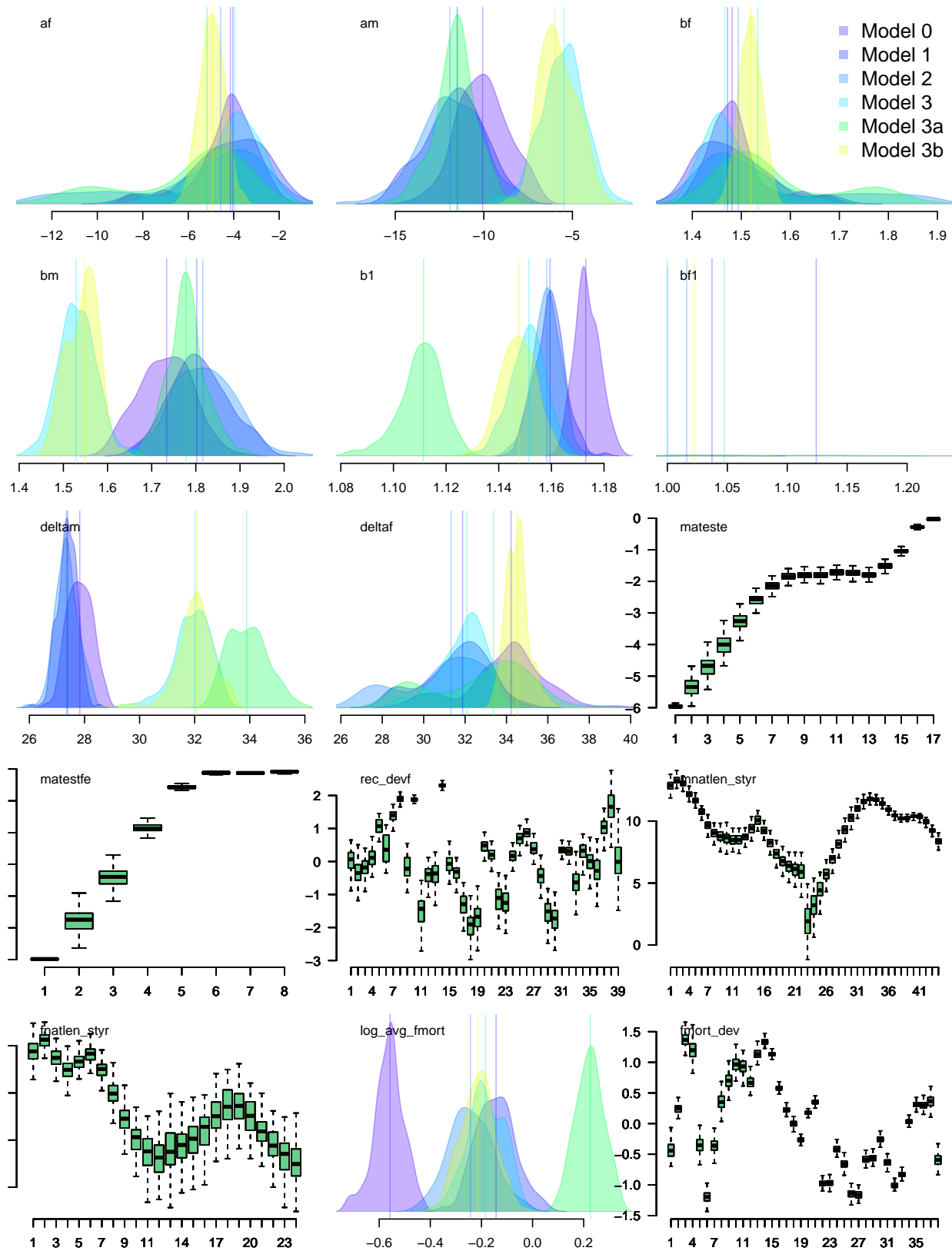
Figure 15: Posterior densities for estimated parameters by scenario
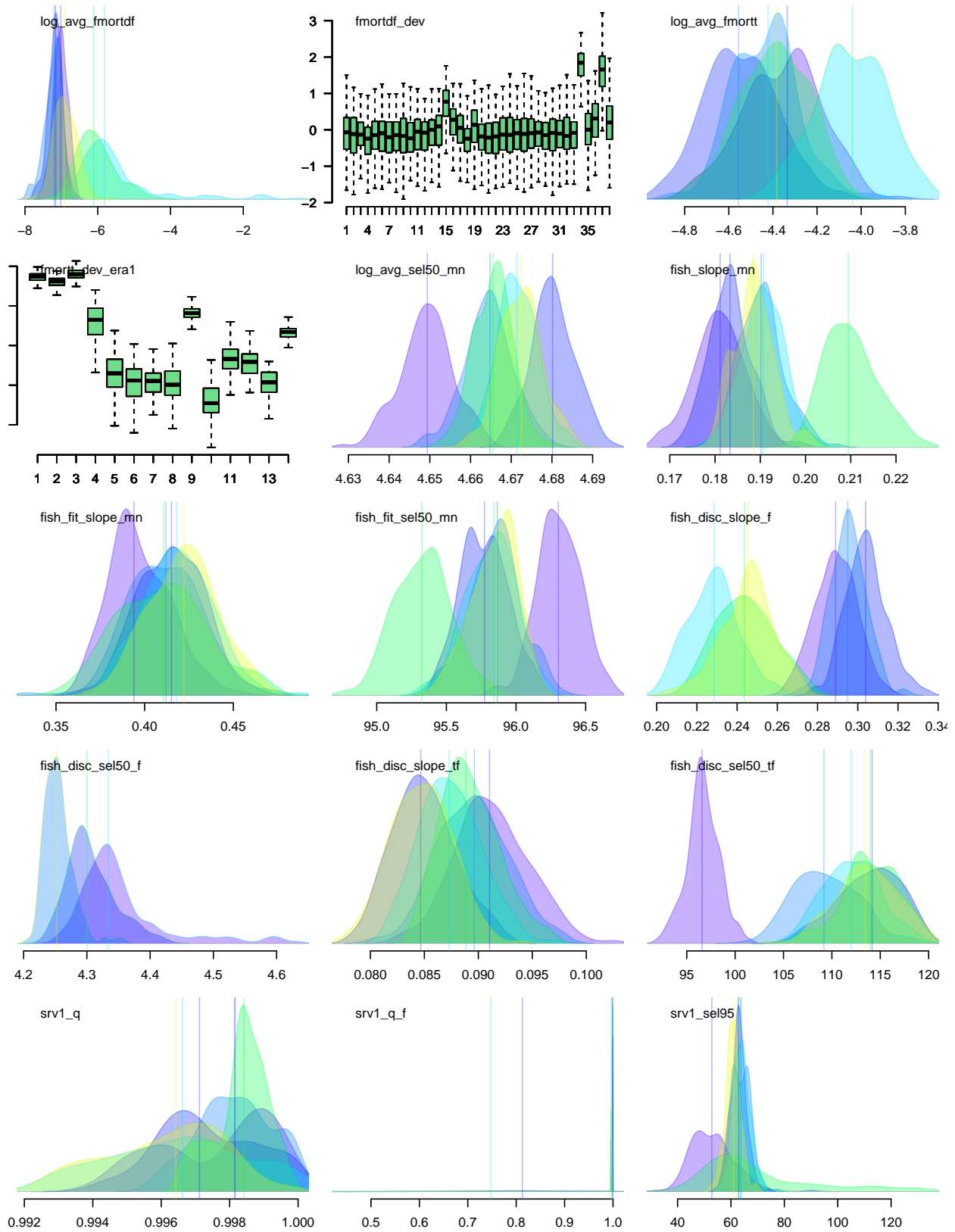
Figure 16: Posterior densities for estimated parameters by scenario

54
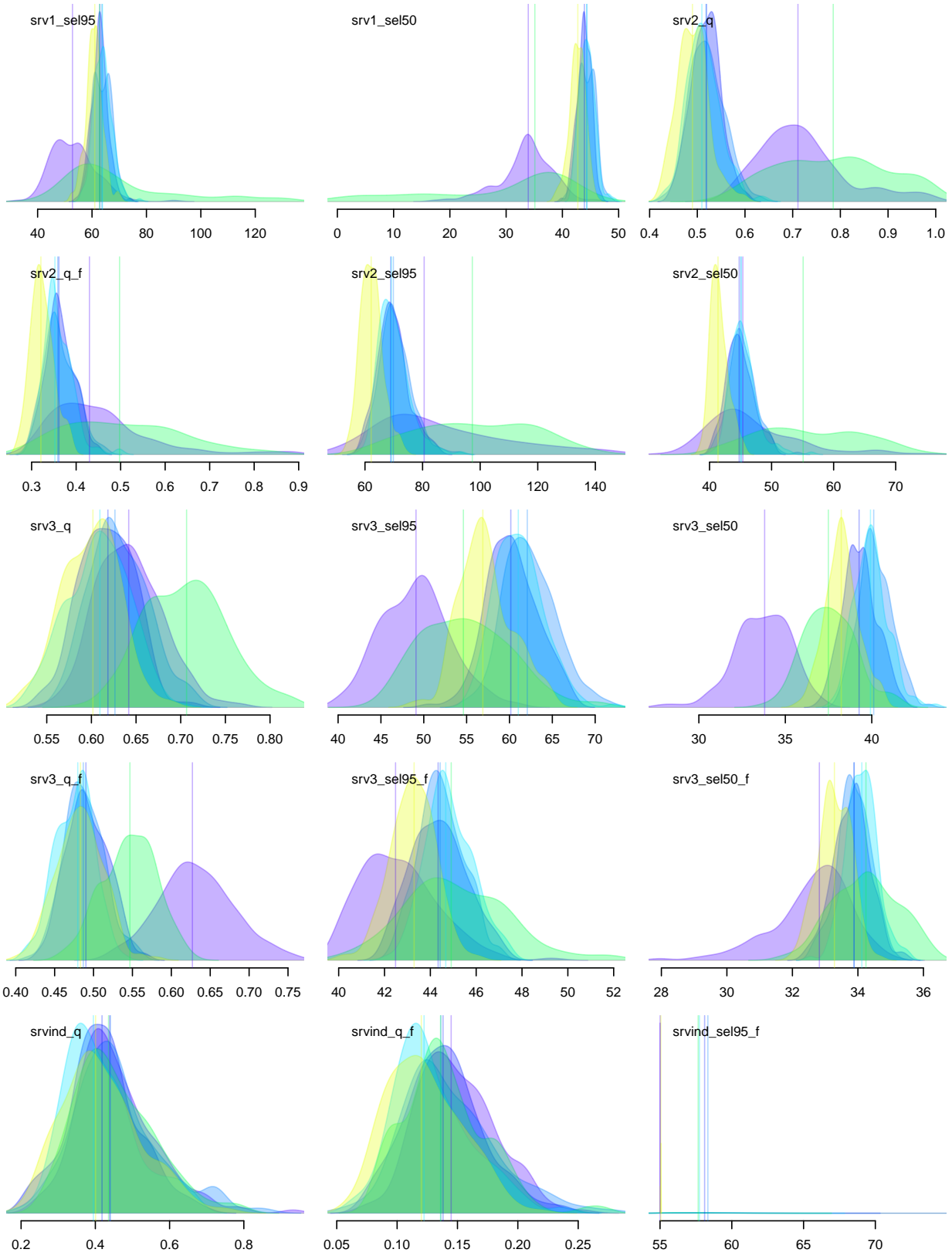
Figure 17: Posterior densities for estimated parameters by scenario
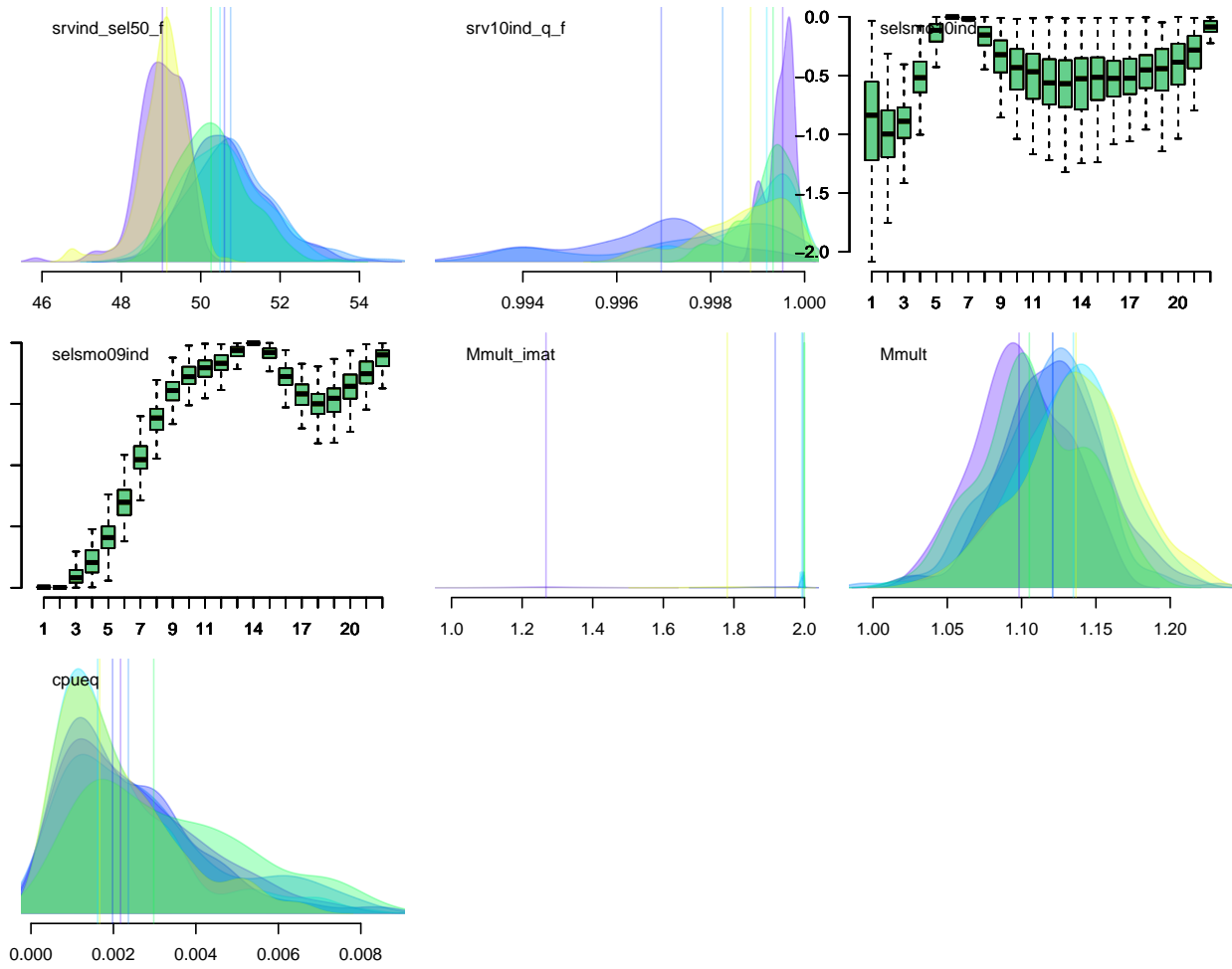
Figure 18: Posterior densities for estimated parameters by scenario
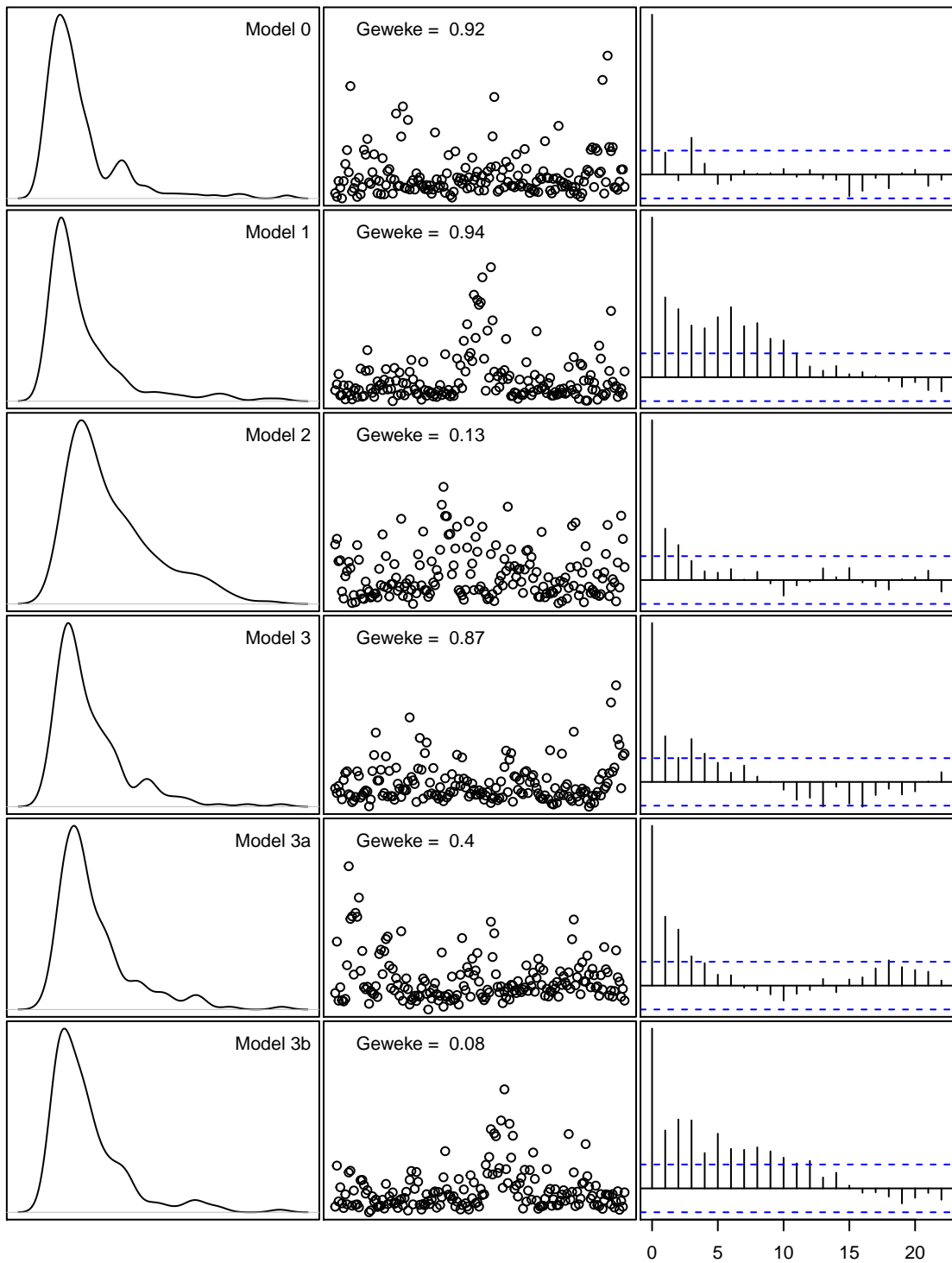
Figure 19: MCMC diagnostics. Density of the objective function value (left), traces of the objective function value (middle) with Geweke diagnostic statistic (i.e. the p value of a two sample t test where the first sample is the first 10% of the trace and the second sample is the last 50% of the trace)Traces of the objective function value from MCMC by model, autocorrelation of the trace of the objective function (right)

57
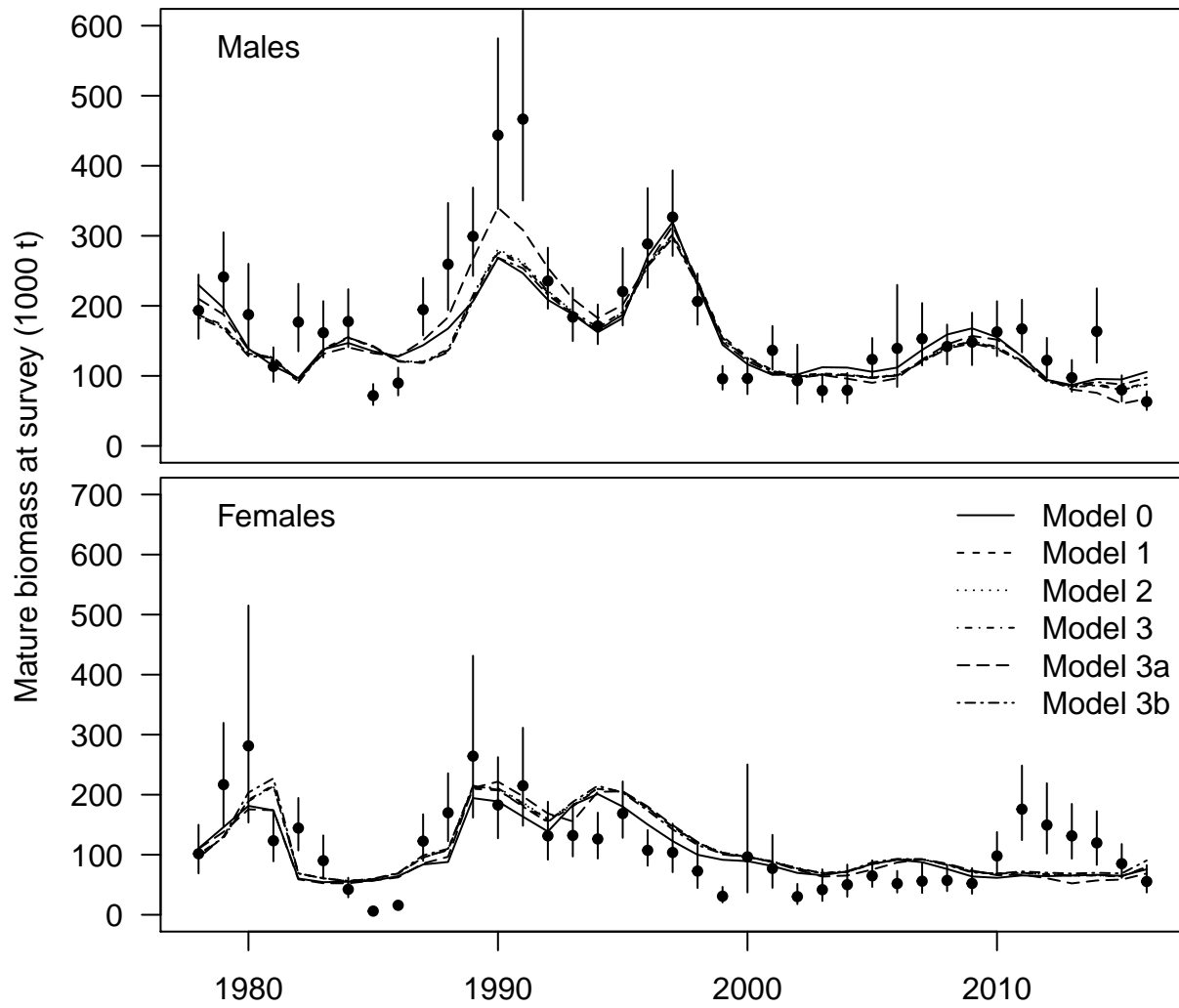
Figure 20: Model fits to the observed mature biomass at survey
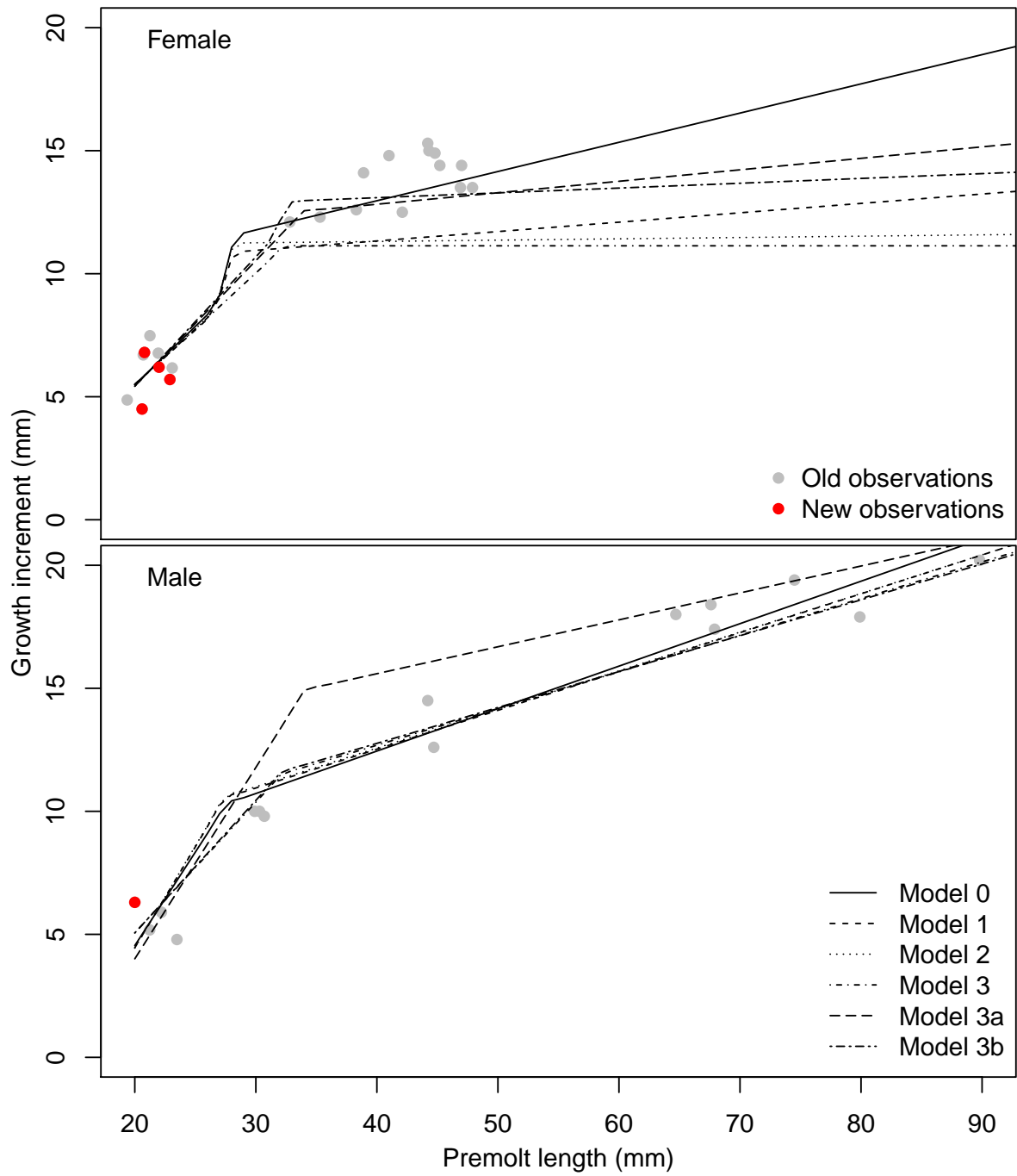
Figure 21: Model fits to the growth data
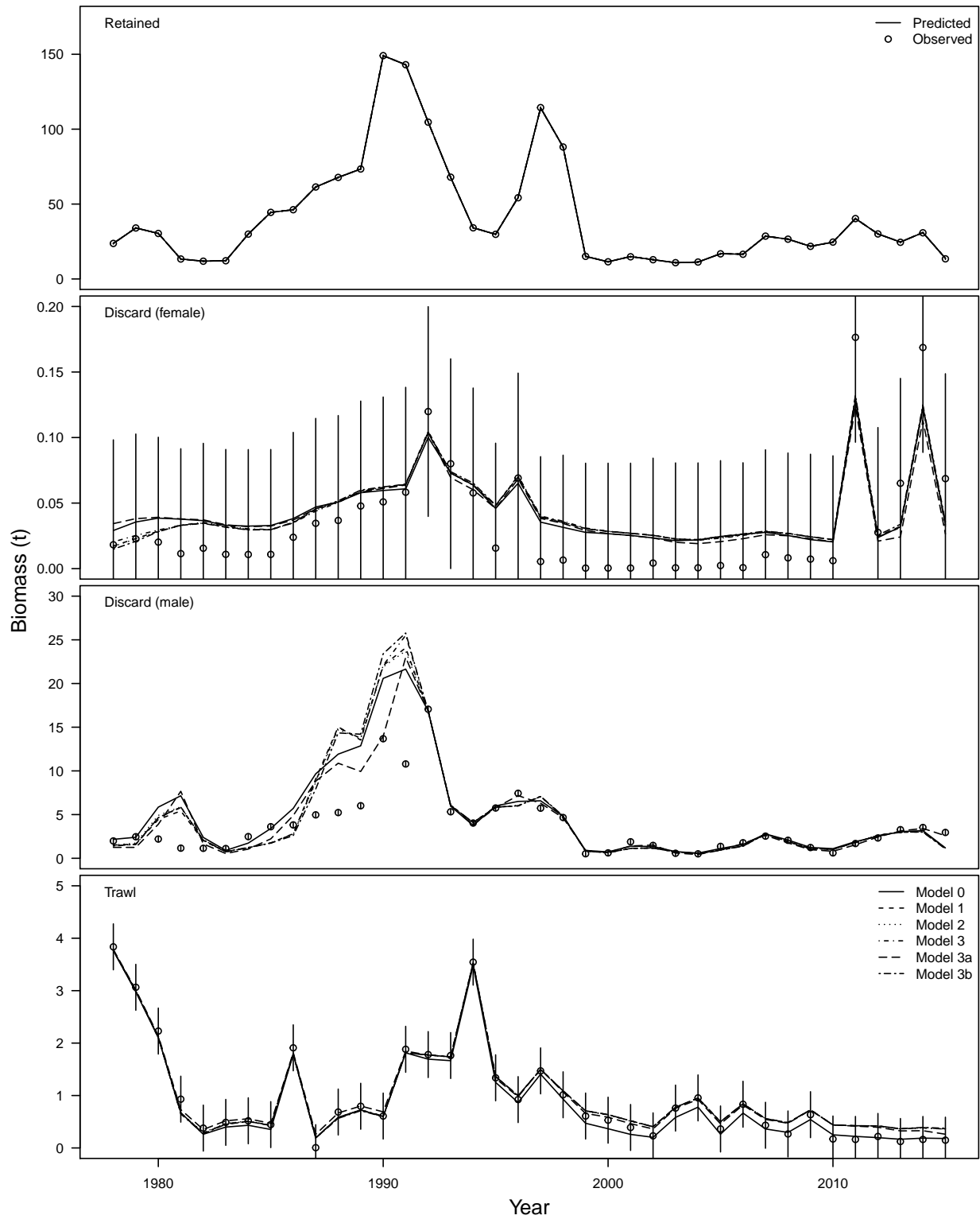
Figure 22: Model fits to catch data
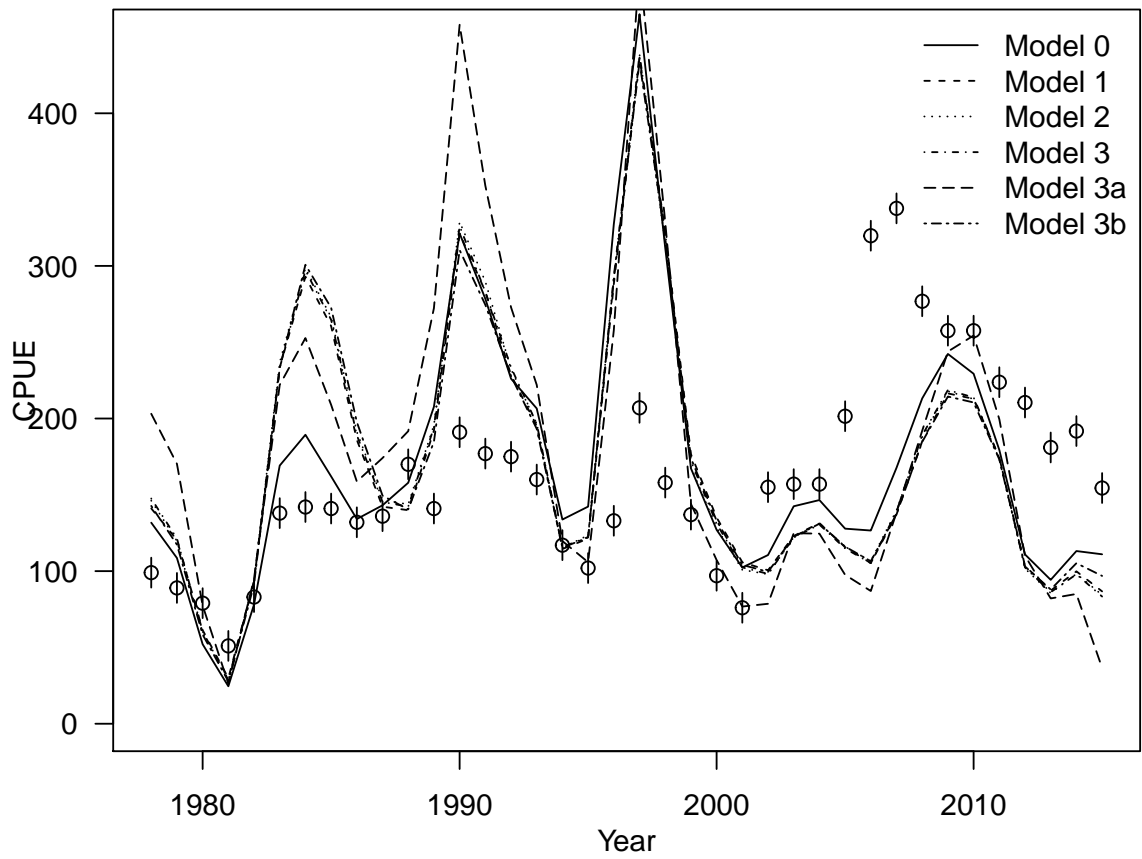
Figure 23: Model fits to pot CPUE data
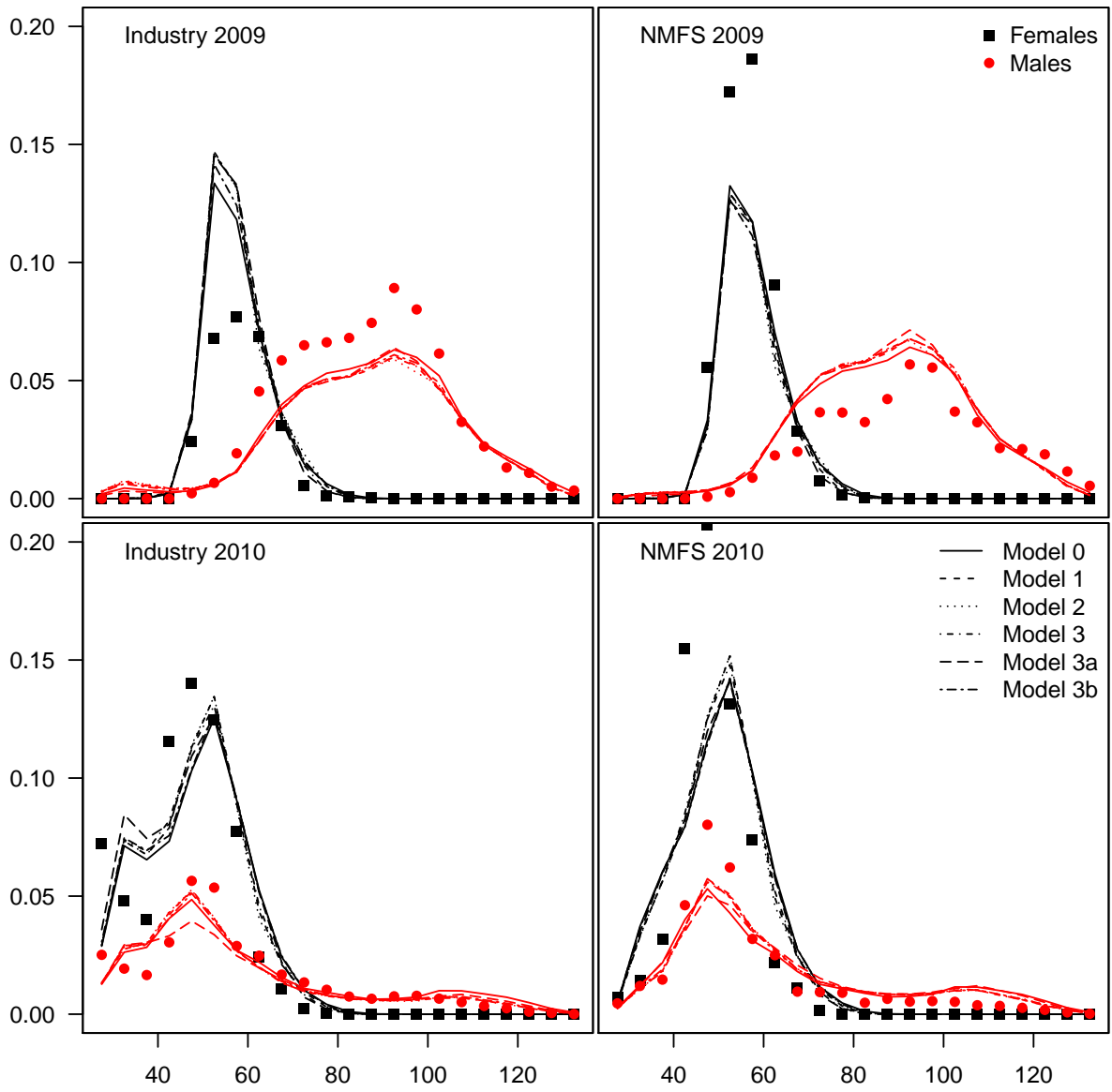
Figure 24: Model fits to size composition data from summer survey experiments (2009 & 2010)
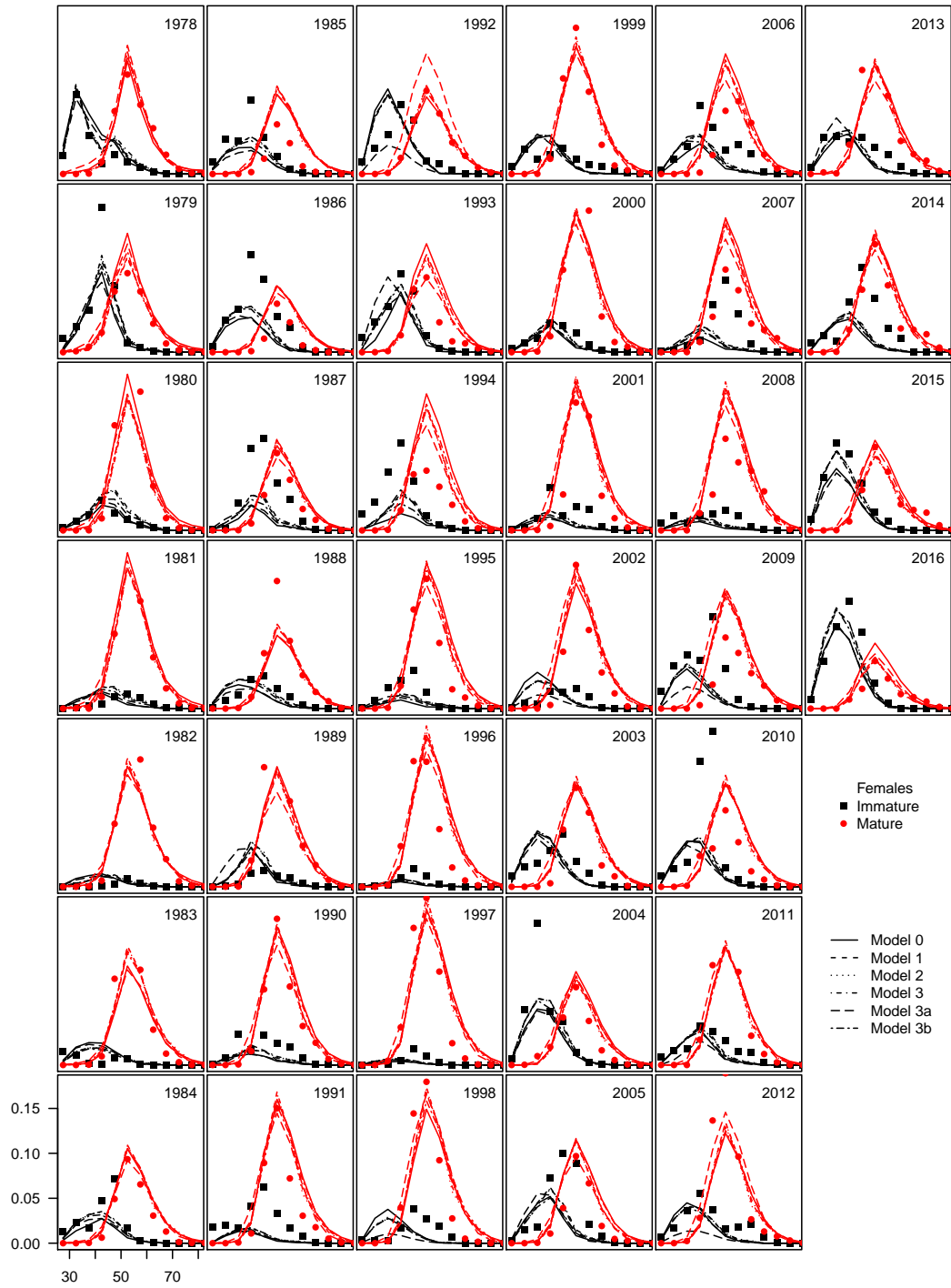
Figure 25: Model fits to female survey size composition data
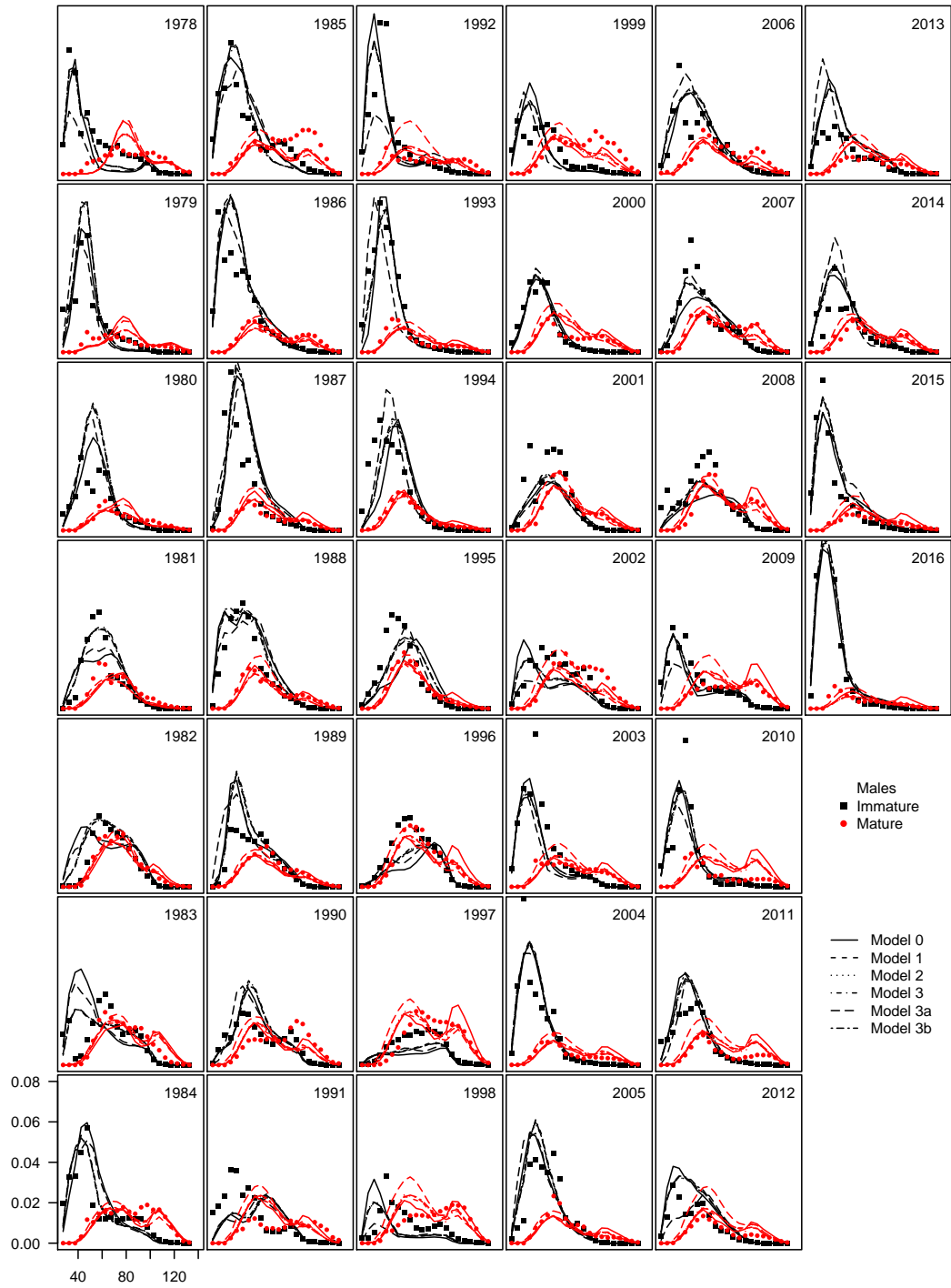
Figure 26: Model fits to male survey size composition data
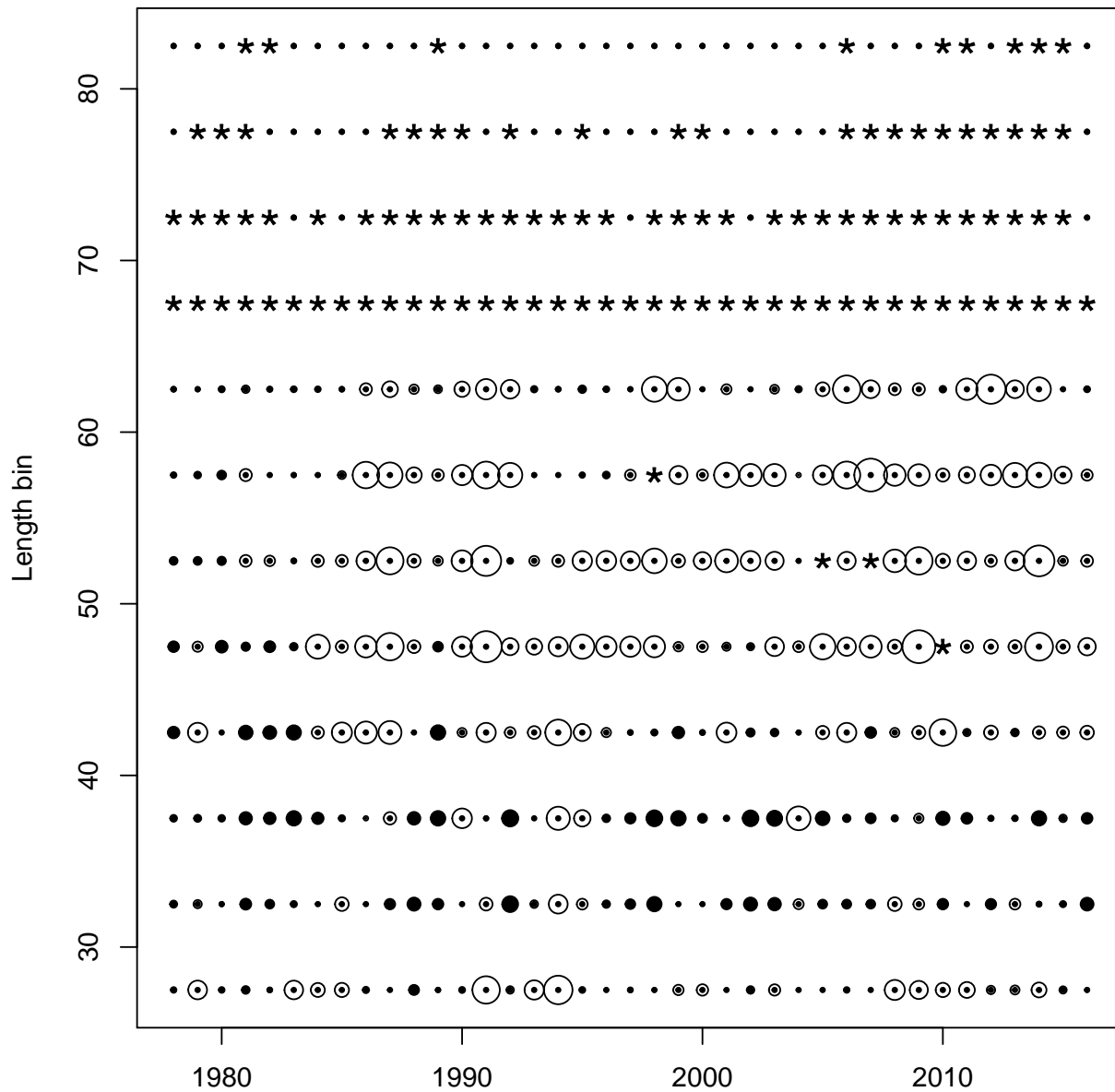
Figure 27: Residuals for immature female survey length proportion data. Open circles are positive residuals, filled are negative, and the size of the circle is proportional to the magnitude of the residual.
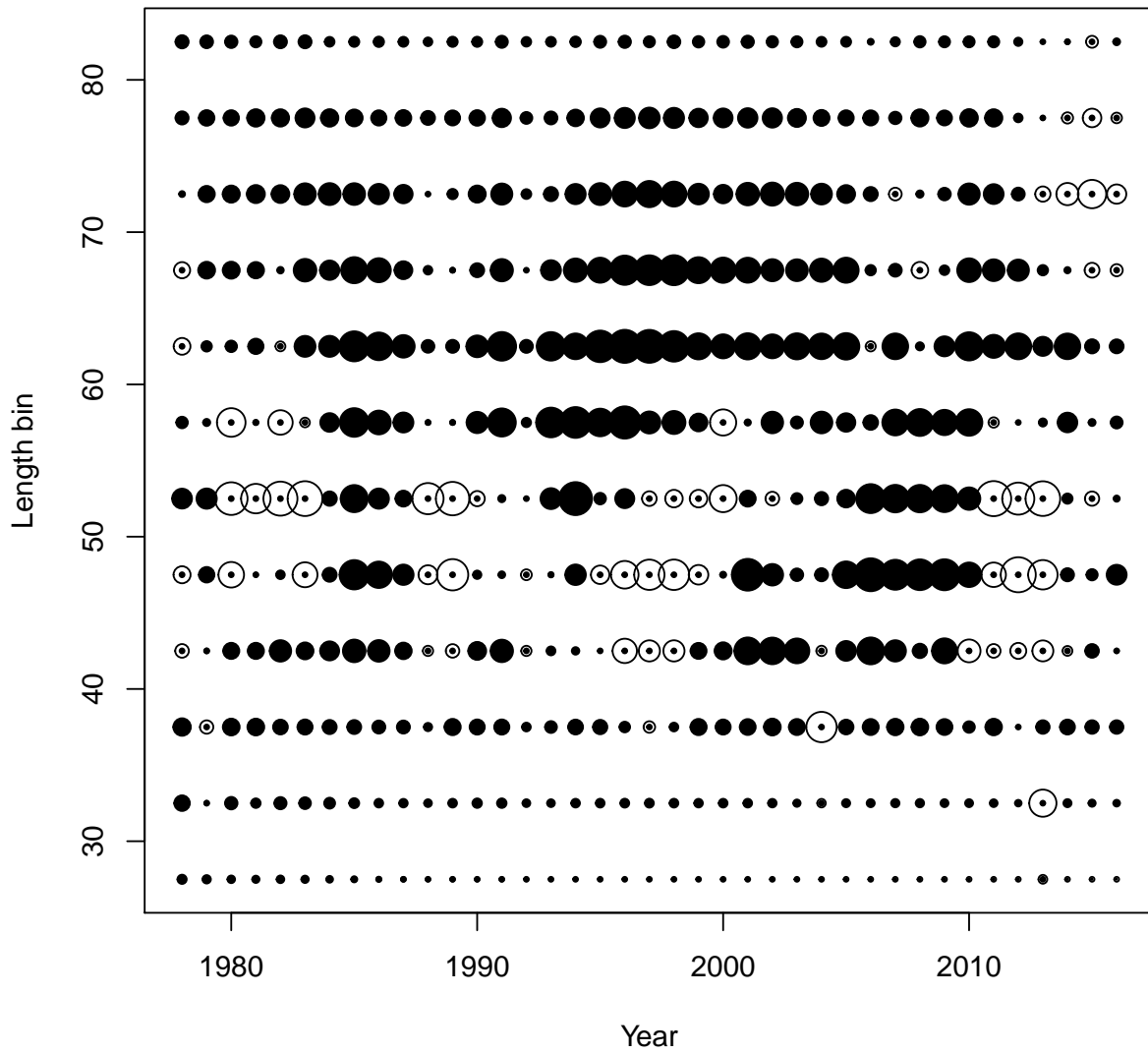
Figure 28: Residuals for mature female survey length proportion data. Open circles are positive residuals, filled are negative, and the size of the circle is proportional to the magnitude of the residual.
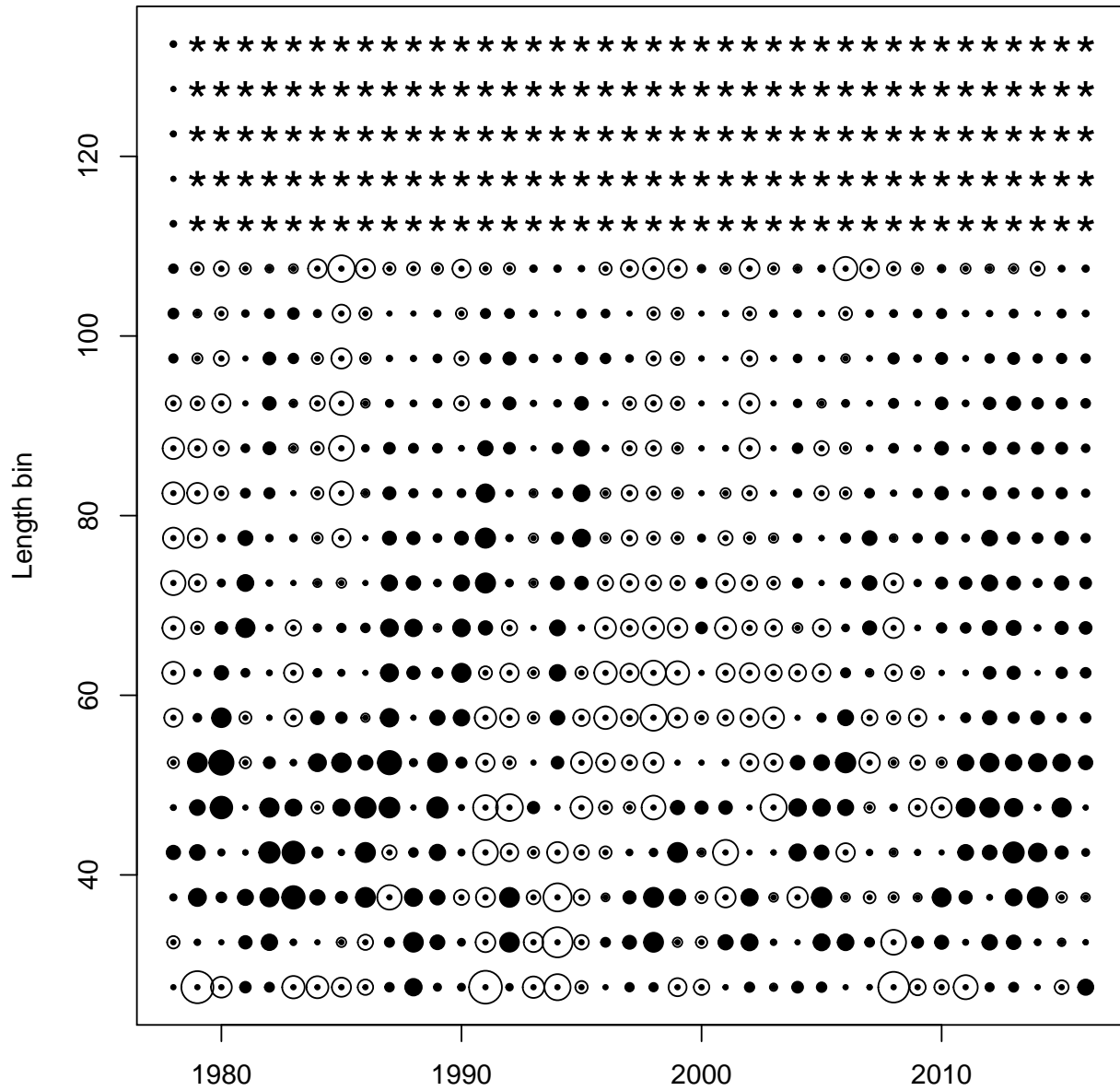
Figure 29: Residuals for fits to immature male survey proportion at length data. Open circles are positive residuals, filled are negative, and the size of the circle is proportional to the magnitude of the residual.
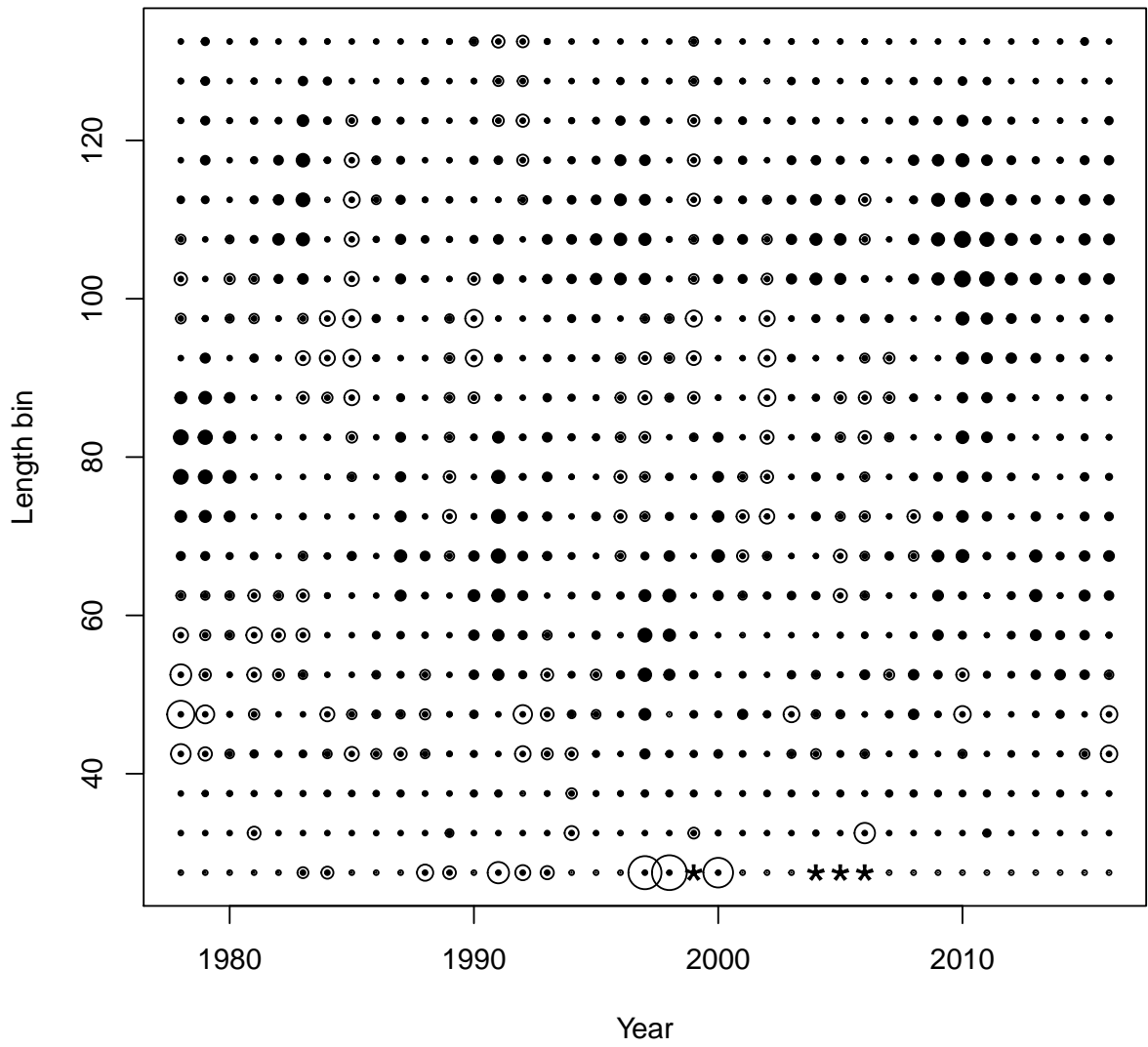
Figure 30: Residuals for fits to mature male survey proportion at length data. Open circles are positive residuals, filled are negative, and the size of the circle is proportional to the magnitude of the residual.
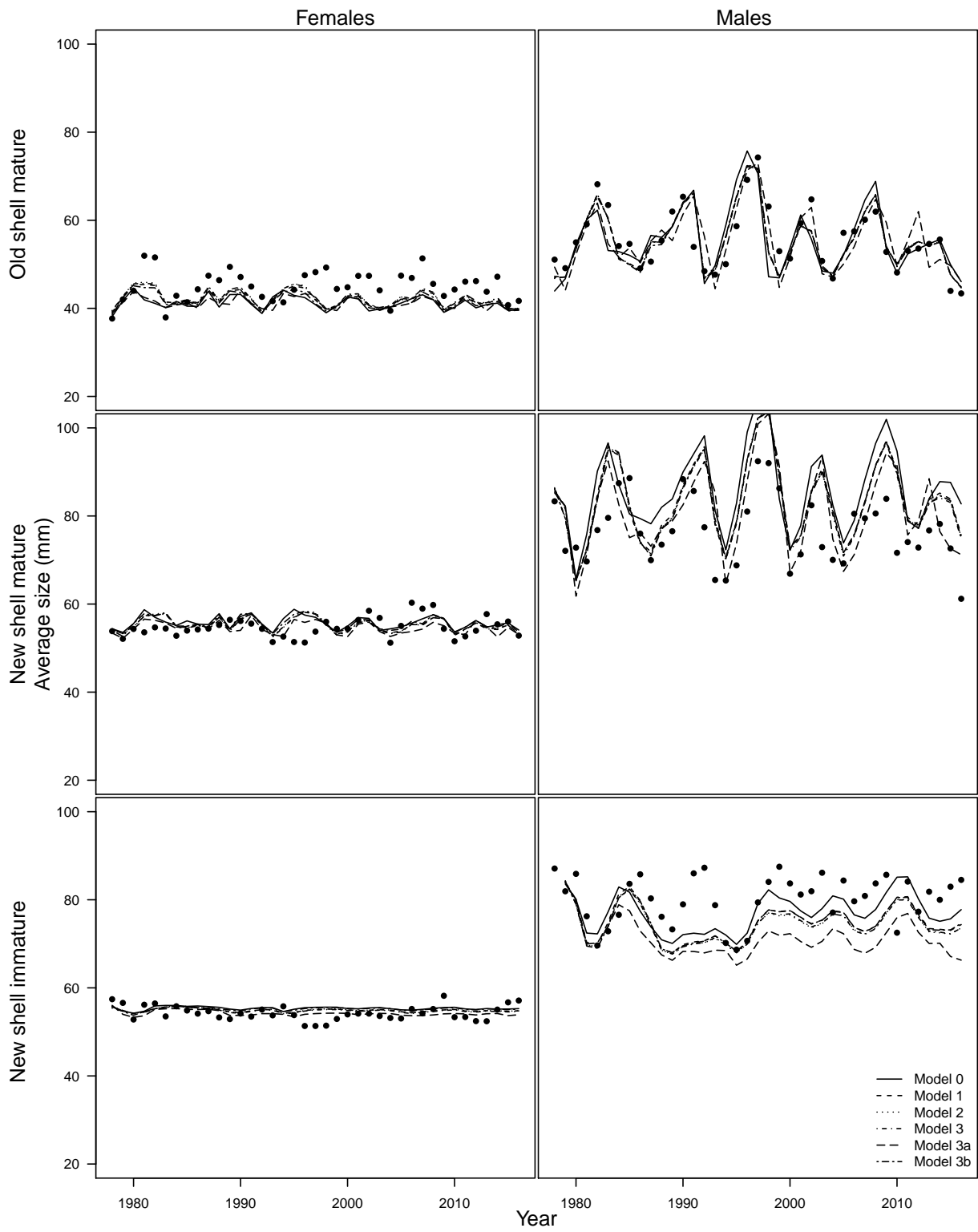
Figure 31: Observed and predicted average size in the survey composition data.
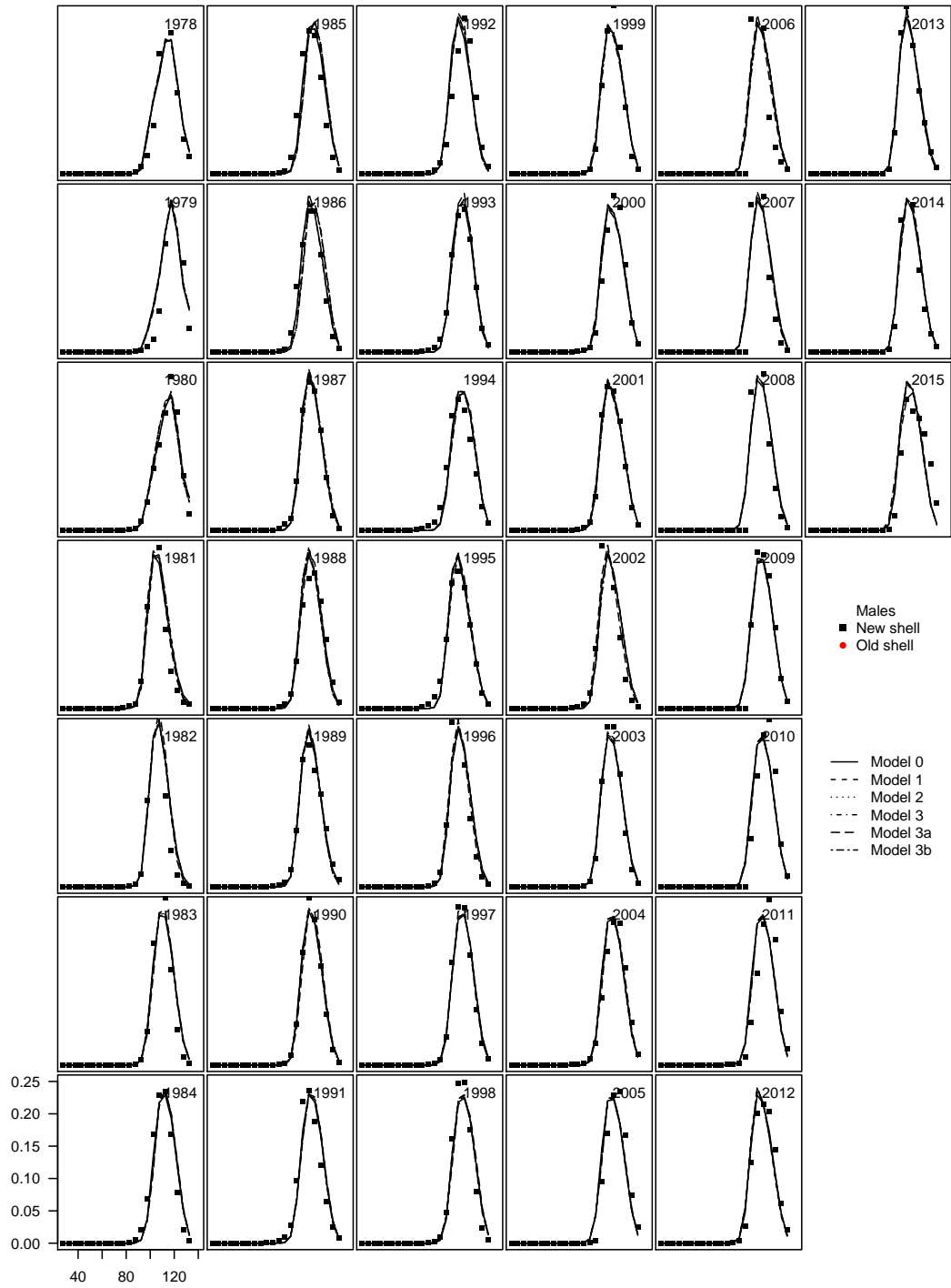
Figure 32: Model fits to retained catch size composition data

70
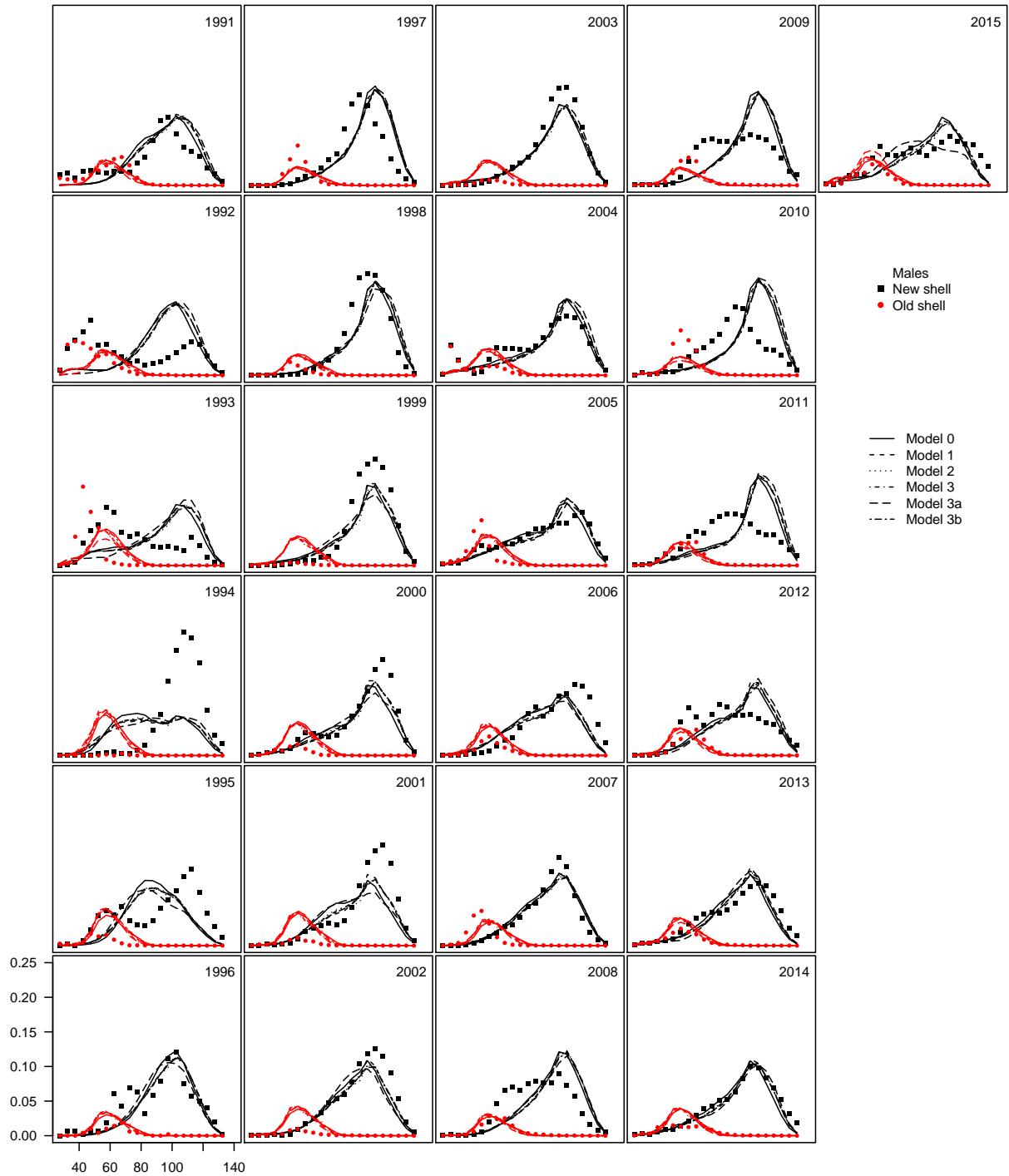
Figure 33: Model fits to trawl catch size composition data
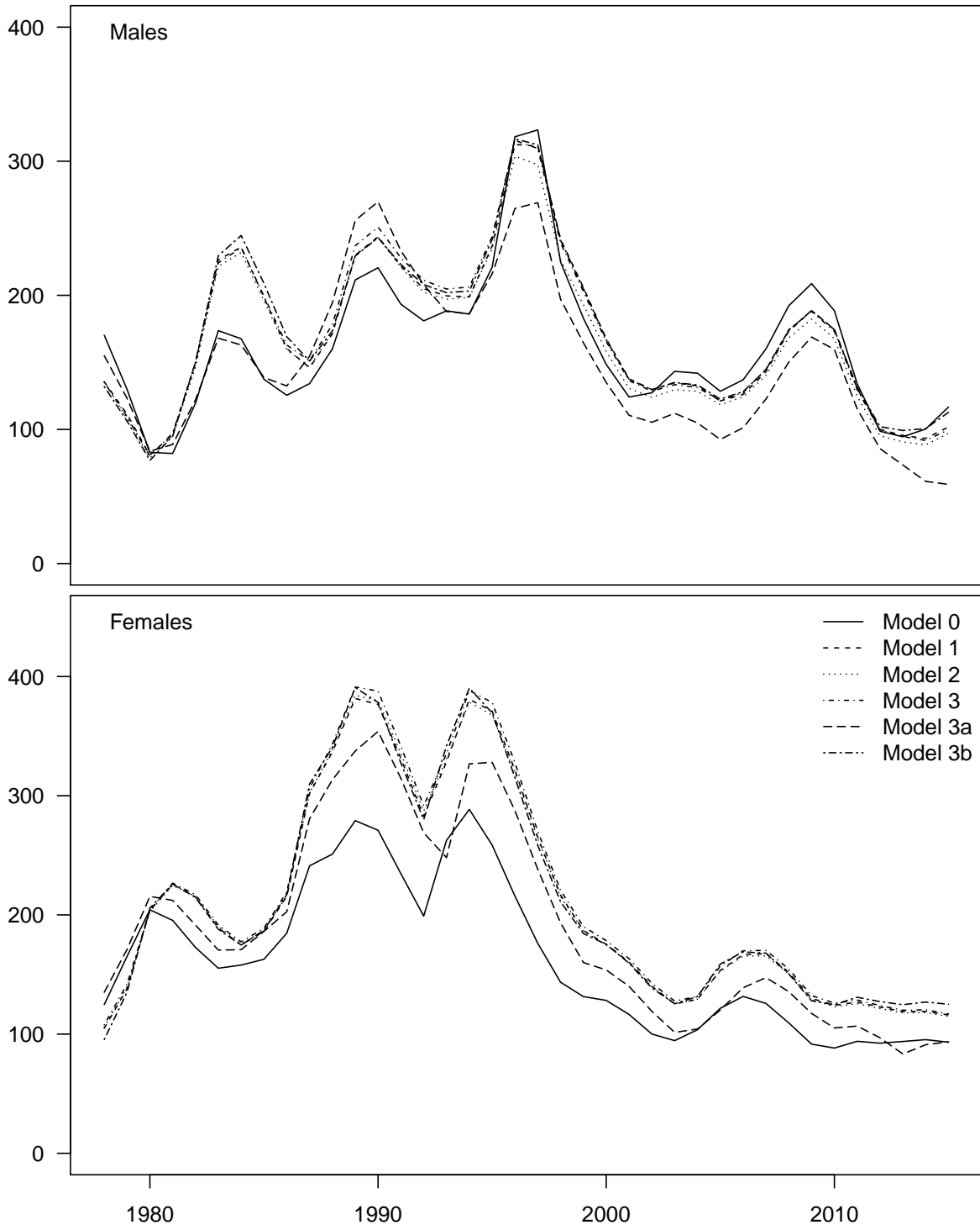
Figure 34: Model predicted mature male biomass at mating time
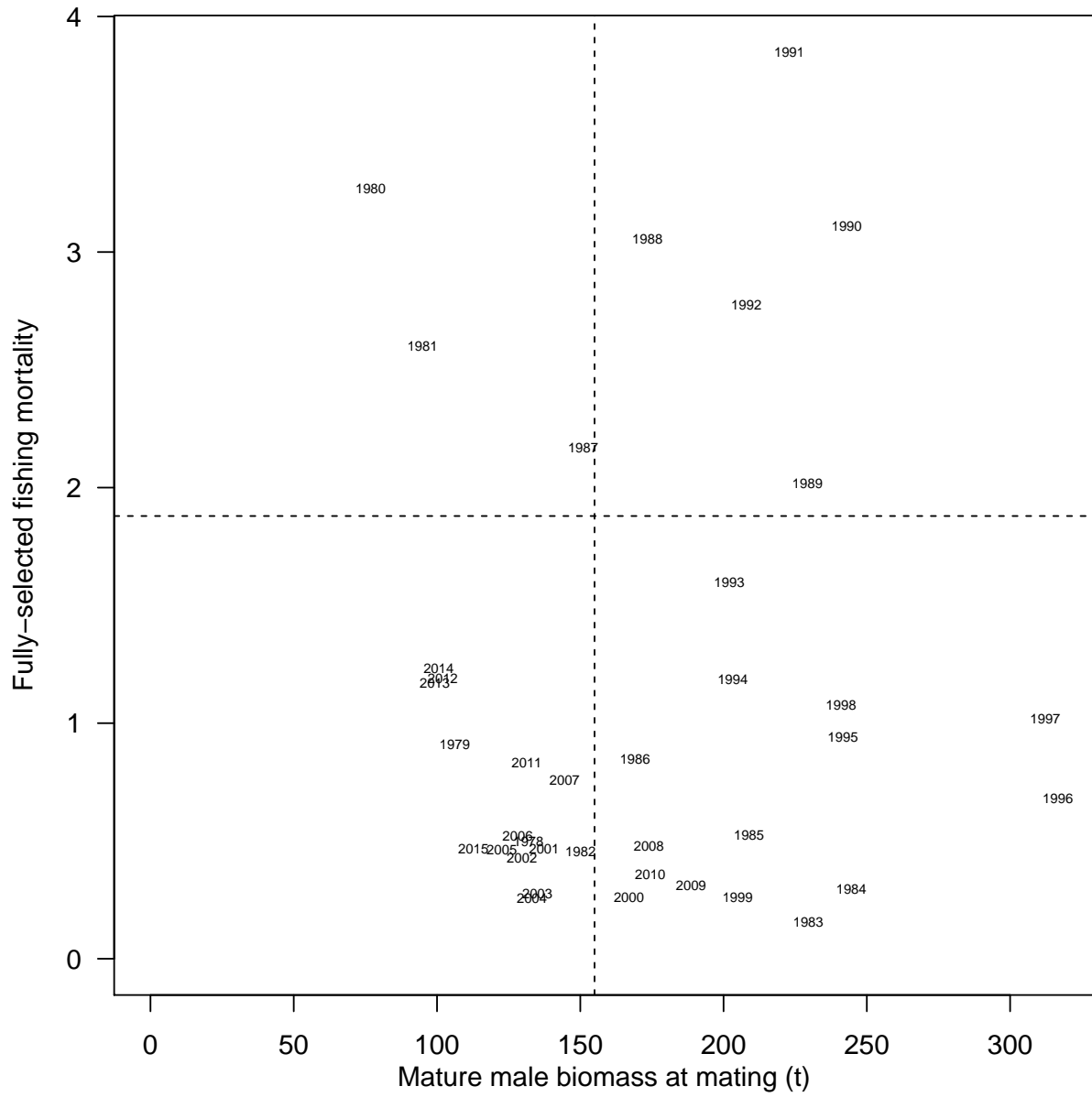
Figure 35: Kobe plot for the chosen model. Vertical line represents the median posterior value for B35; horizontal lines presents F35
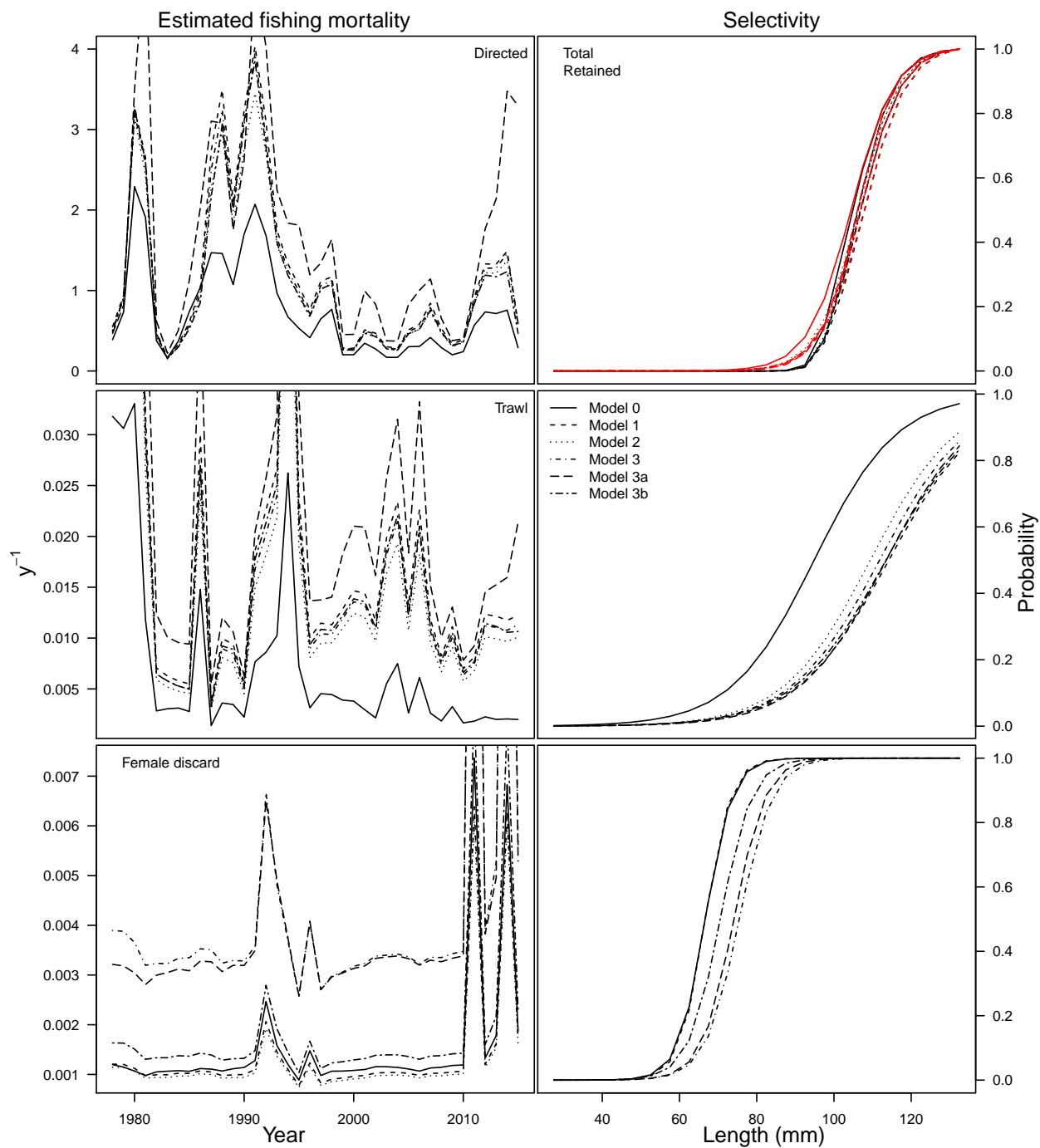
Figure 36: Model predicted fishing mortalities and selectivities for all sources of mortality
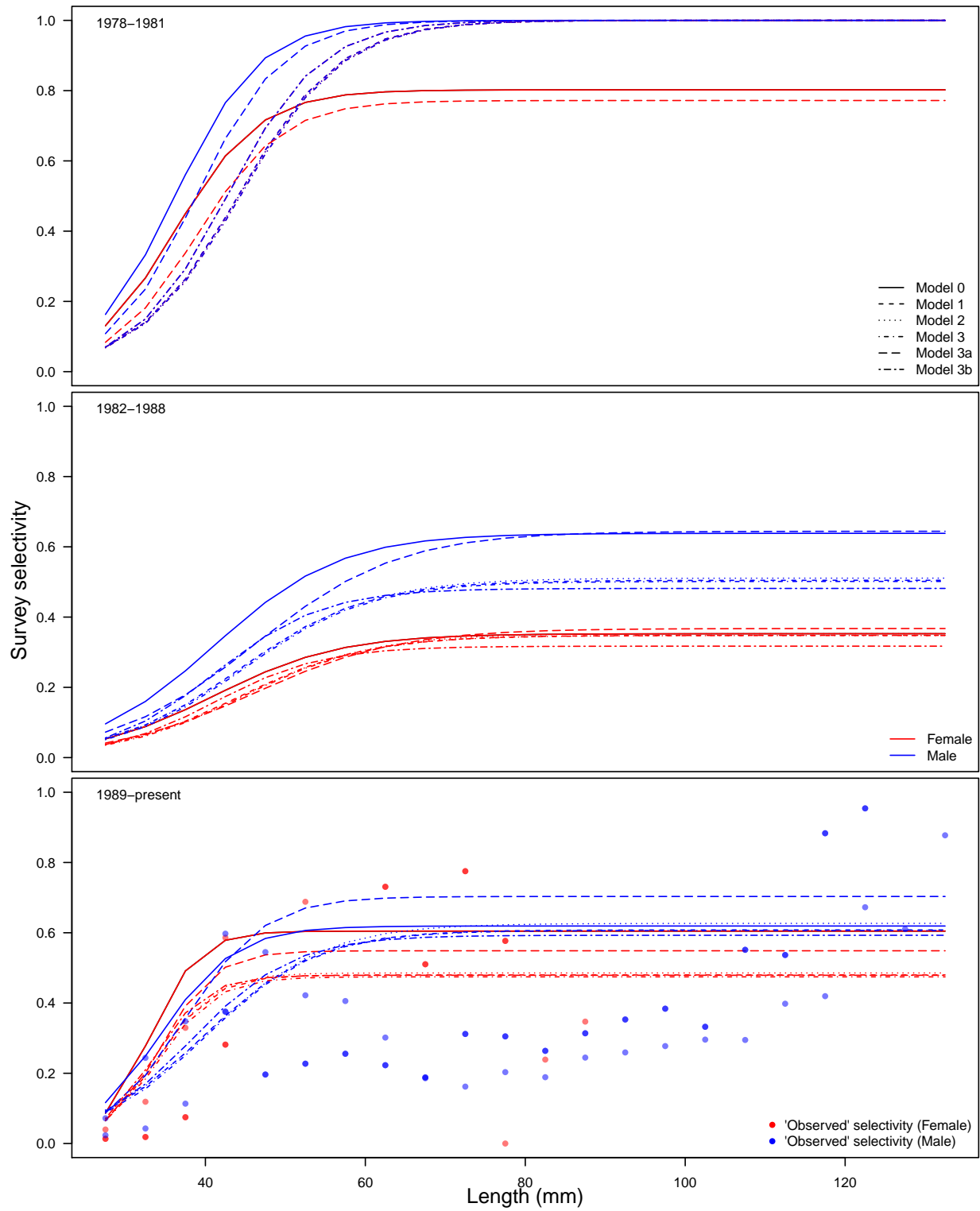
Figure 37: Estimated survey selectivity
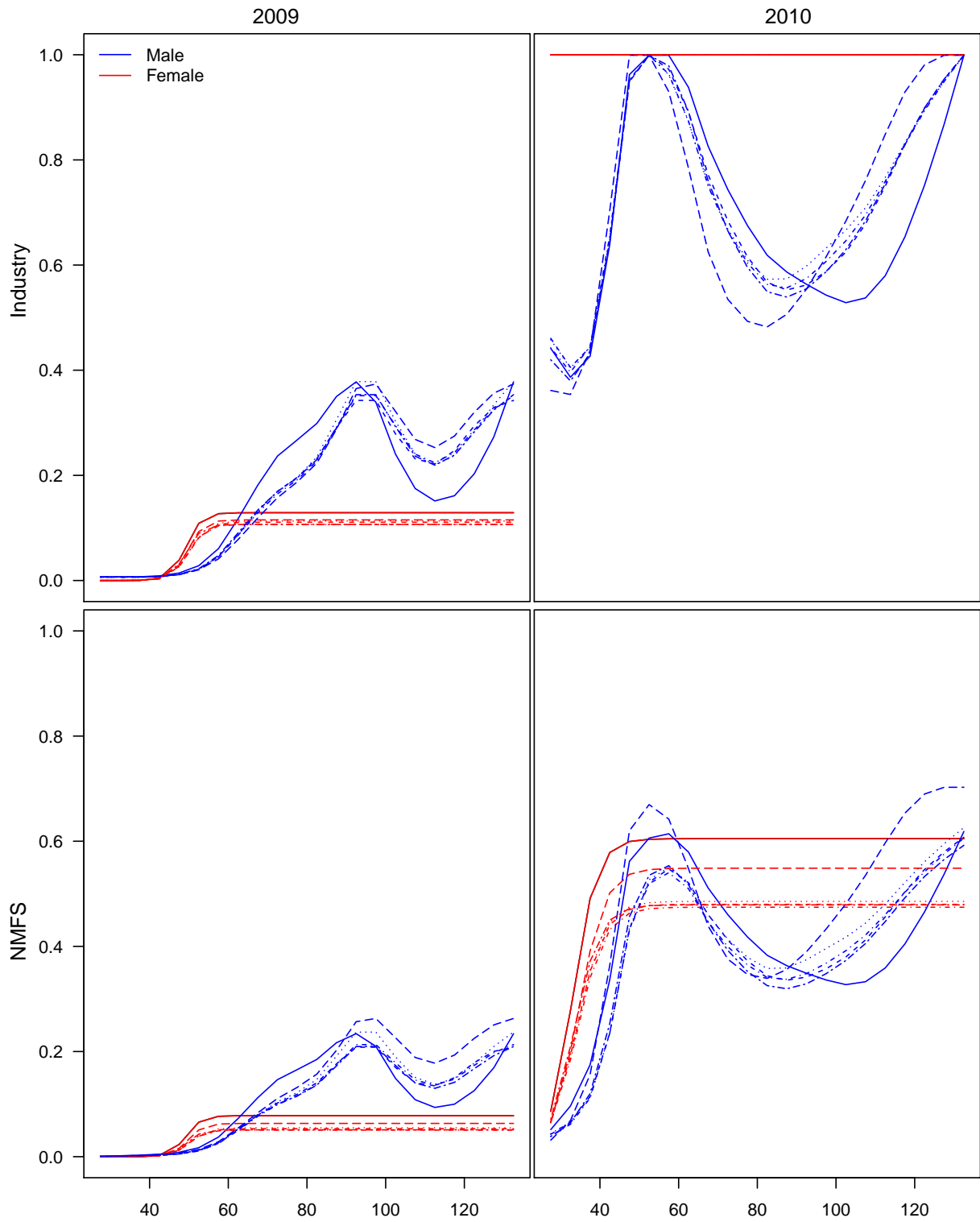
Figure 38: Estimated experimental survey selectivity
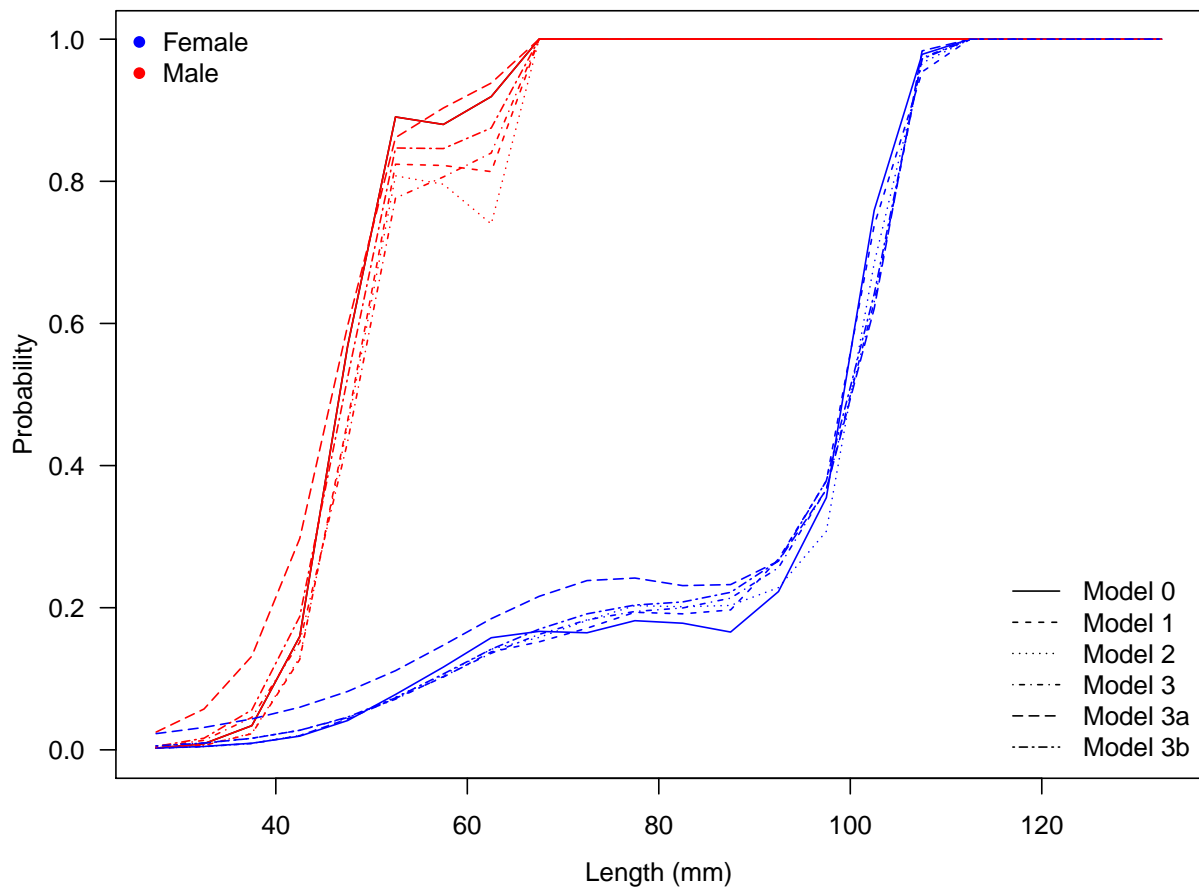
Figure 39: Estimated probability of maturing
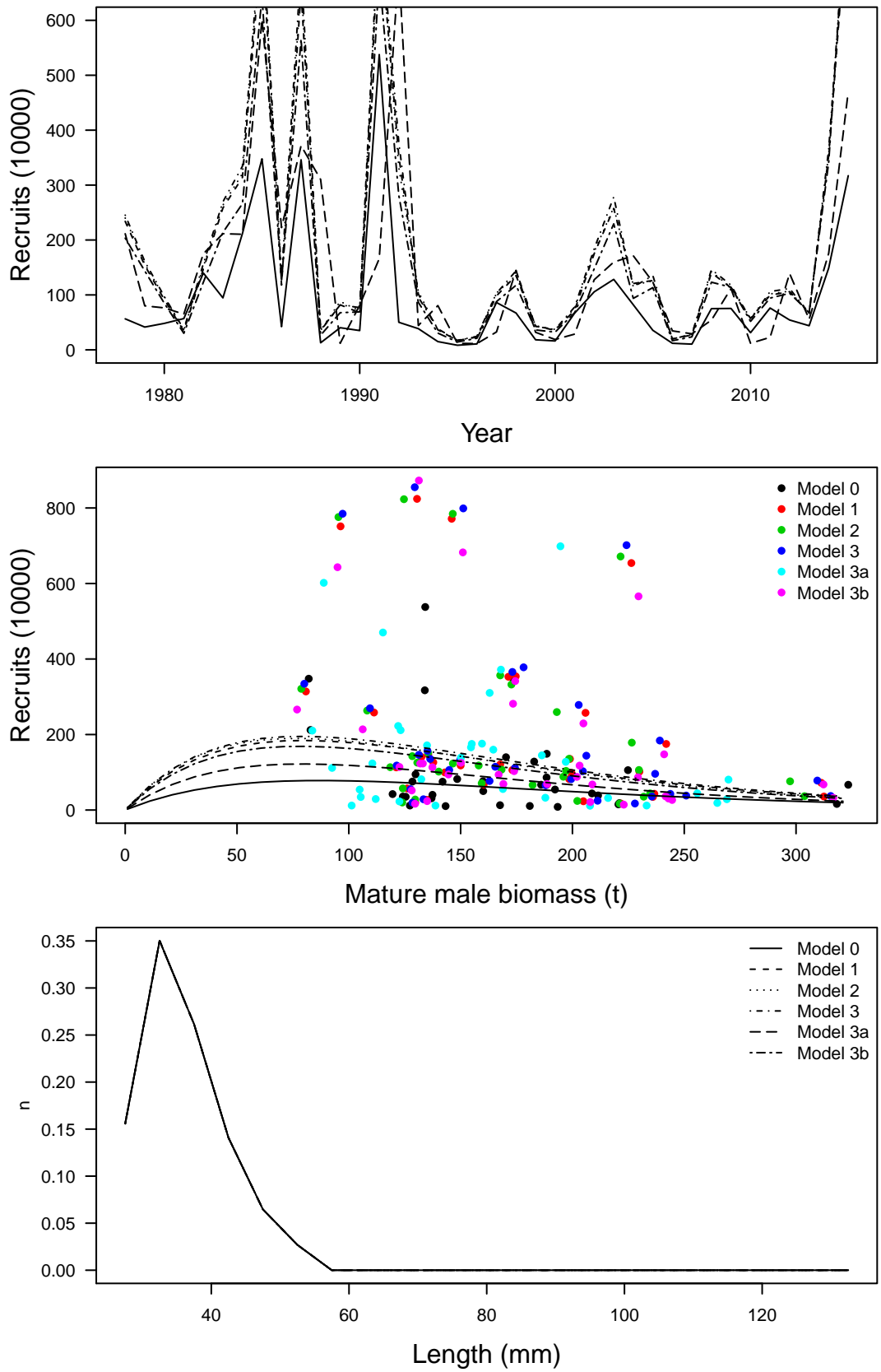
Figure 40: Estimated recruitment, fits to stock recruit curve (MMB lagged 5 years), and proportions recruiting to length bin
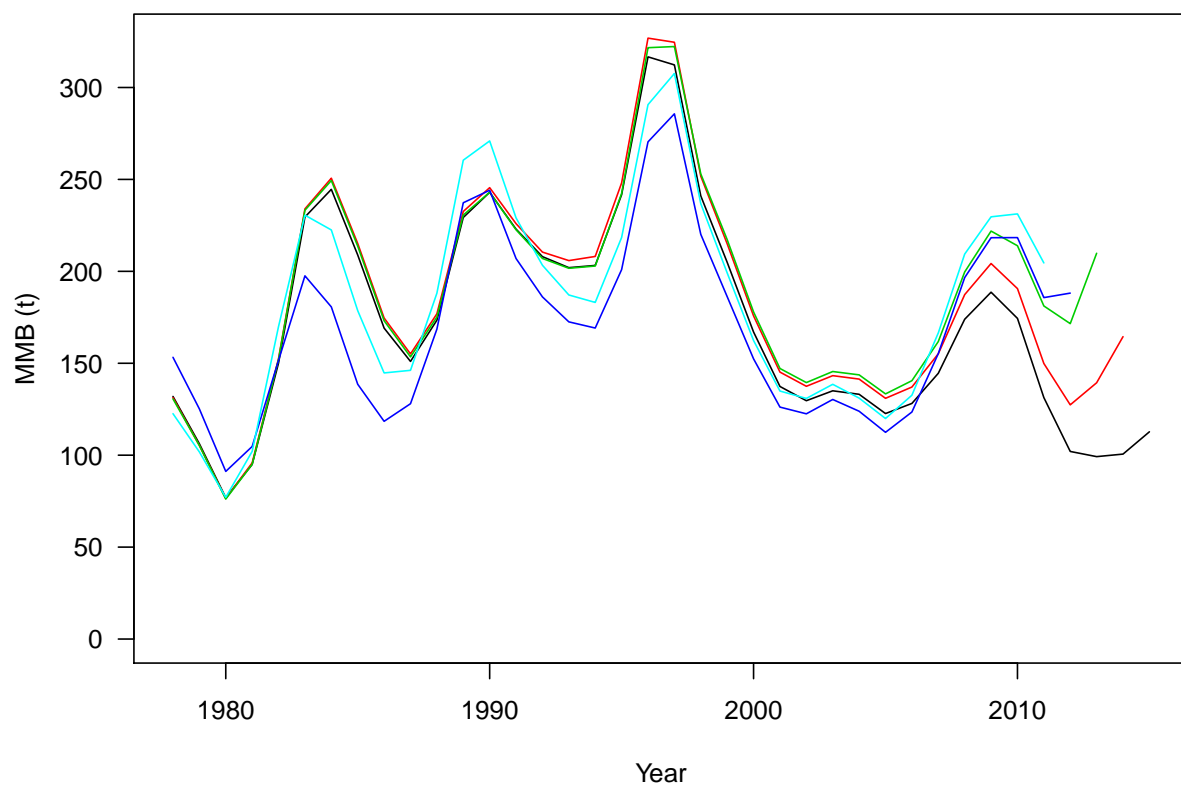
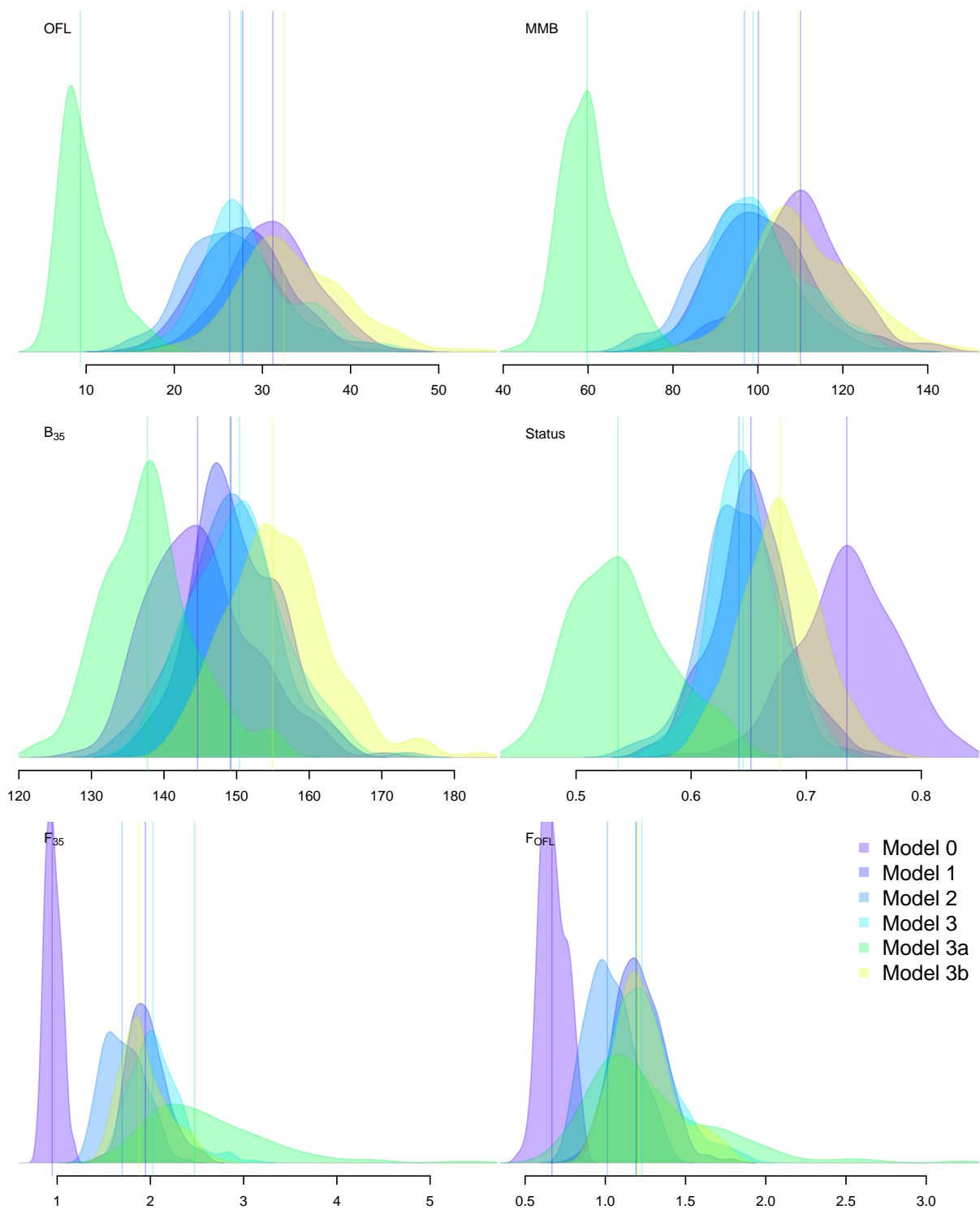Figure 41: Retrospective pattern in MMB for chosen model

Figure 42: Posterior densities for management quantities by scenario