

A stock assessment for eastern Bering Sea snow crab

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

2. Catches: trends and current levels

Retained catches increased from relatively low levels in the early 1980s (e.g. retained catch of 13.32 kt 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 kt, respectively). The stock was declared overfished in 1999 at which time retained catches dropped to levels similar to the early 1980s (e.g. retained catch during 2000 was 11.46 kt). Retained catches have slowly increased since 1999 as the stock rebuilt, although retained catch during 2016 was low (9.67 kt).

Discard mortality is the next largest source of mortality after retained catch and approximately tracks the retained catch. The highest estimated discard mortality occurred during 1992 at 17.06 kt which was 16% of the retained catch. The most recent estimated mortality was 1.31 kt which was 14% of the retained catch.

3. Stock Biomass:

Observed mature male biomass (MMB) at the time of the survey increased from an average of 160.81 kt in the early to mid-1980s to historical highs in the early and mid-nineties (observed MMB during 1990, 1991, and 1997 were 443.79, 466.61, and 326.75 kt, respectively). The stock was declared overfished in 1999 in response to the total mature biomass dropping below the minimum stock size threshold. MMB in that year decreased to 95.85 kt. Observed MMB slowly increased after 1999, and the stock was declared rebuilt in 2011 when estimated MMB at mating was above $B_{35\%}$. However, since 2011, the stock has declined again and the observed MMB at the time of survey dropped to an all time low in 2016 of 63.21 kt.

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 generally been above the average of the 'low' period, but are still beneath the average of the 'high' recruitment period. However, a large year class recruited to the survey gear in 2014 and has persisted to the present, which suggests large exploitable biomasses may be available in the near future.

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	75.8	91.6	18.4	18.4	21.4	61.5	55.4
2016/2017	69.7	94.4	9.7	9.7	11	23.7	21.3
2017/2018	69.7	99.6				28.4	25.6

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	167.1	201.9	40.57	40.57	47.18	135.6	122.1
2016/2017	153.7	208.1	21.38	21.38	24.25	52.25	46.96
2017/2018	153.7	219.6				62.61	56.44

6. Basis for the OFL

The OFL for 2017 from the chosen model (M17C D17a) was 28.41 kt fishing at $F_{OFL} = 0.89$ (68 % of the calculated $F_{35\%}$, 1.31). The calculated OFL was a 20% change from the 2016 OFL of 23.7 kt. The reported OFL is the median posterior value, but differs from the ML estimate by only 0.4 kt. The projected ratio of MMB at the time of mating to $B_{35\%}$ is 0.71.

7. Probability Density Function of the OFL

The probability 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 to be propagated forward into the OFL calculation. The chosen OFL was calculated as the median of its posterior distribution.

8. Basis for ABC

The ABC for the chosen model for 2016/2017 was 25.57 kt, calculated by subtracting a 10% buffer from the OFL as recommended by the SSC.

A. Summary of Major Changes

1. Management: None

2. Input data:

Data added to the assessment included: 2017 Bering Sea survey biomass and length frequency data, 2016 directed fishery retained and discard catch and length frequencies for retained and discard catch, and groundfish discard length frequency and discard from 2016.

3. Assessment methodology:

The recommended OFL was calculated using Bayesian methodologies in 2016, which was a departure from the previous projection framework (but still provided similar management advice). Both a 'jittering' approach within a maximum likelihood framework and a Bayesian treatment of the data were completed this year. Management quantities from the selected model are reported as the medians of posterior distributions resulting from application of a Markov Chain Monte Carlo.

4. Assessment results

The updated estimates of MMB (February 15, 2016) were 94.43 which placed the stock at 67% of $B_{35\%}$. Projected MMB on February 15, 2017 from the chosen model this assessment after fishing at the OFL was 99.57 kt, which will place the stock at 71% of $B_{35\%}$. Fits to all data sources were acceptable for the chosen model and estimated population processes were credible.

B. CPT May 2017 comments, SSC comments, and author response:

CPT and SSC comments

Five scenarios were recommended by the CPT, based on analyses presented during the May 2017 CPT meeting:

- Leave out length bins below the kink in growth and fit one straight line for growth.
- Estimate M for females, males, and immature crab. Change the prior on the multiplier to work in log space with a zero mean and an appropriate standard deviation.
- Start the model in 1982 and drop all data data before 1982.
- Split the survey selectivity periods in 1987 or 1988 - check the distribution of survey sampling to have a consistent area for each era.
- Estimate survey availability parameters for the BSFRF survey in logit space with a penalty.

The CPT also recommended resolving problems with any parameters hitting bounds.

The authors present 8 runs based on these 5 scenarios:

- “M16.D16” – Last year’s accepted model fit to last year’s data.
- “M16.D17” – Last year’s accepted model fit to this year’s data.
- “M16.D17a” – Last year’s accepted model fit to this year’s data, but dropping all survey data before 1982.
- “M17A.D17a” – Split survey selectivity periods in 1987, based on distribution of survey stations.
- “M17Aa.D17a” – Estimate survey availability parameters for BSFRF survey in logit space with a penalty
- “M17B.D17a” – Remove data in length bins below the kink in growth and fit a straight line for growth.
- “M17C.D17a” – Estimate M for females, males, and immature, change prior to be suitable in log space with zero mean and appropriate standard deviation. Retains all changes to this point.
- “M17BC.D17a” – Combines ‘M17B.D17A’ and ‘M17C.D17A’

The CPT also asked for:

- Bycatch from different sources presented in a figure in the assessment chapter.
- Documentation of the jittering approach.

Authors response

All changes were undertaken in a step-wise fashion and management quantities were calculated both via maximum likelihood methods and Bayesian methods. M17C D17a is the author preferred model based on fit to the data, number of assumptions placed on the data, and the stability of the model when jittered. Model scenarios include all CPT recommended models. ‘Jittering’ was performed for all models, but ultimately did not resolve all of the problems introduced by incomplete growth data (bimodal estimates of management quantities and poor convergence). Consequently, Bayesian posteriors were also used to calculated management quantities for all models.

Models in which smaller length bins were removed did not produce viable models. Removing the length bins was done to attempt to avoid the problem of estimating a breakpoint in the growth model. However, after removal of the length bins, estimates of survey selectivity and probability of maturing were no longer reasonable. It appears that the very low counts in the smallest length bins, coupled with a constant (and fairly well-informed via priors) natural mortality provided an anchor for selectivity, catchability, and maturity.

C. Introduction

Distribution

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

Life history characteristics

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

Natural Mortality

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

Tag recovery evidence from eastern Canada revealed observed maximum ages in exploited populations of 17-19 years (Nevissi, et al. 1995, Sainte-Marie 2002). A maximum time at large of 11 years for tag returns of terminally molted mature male snow crab in the North Atlantic has been recorded since tagging started about 1993 (Fonseca, et al. 2008). Fonseca, et al. (2008) estimated a maximum age of 7.8 years post terminal molt using data on dactal wear.

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 yr^{-1} in the base model. Mature male natural mortality was estimated in the base model with a prior constraint of mean of 0.23 yr^{-1} 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 yr^{-1} and a standard error of 0.154 in all models, save M17C D17A, which used a standard error of 0.054 for immature

crab to be consistent with the rationale above for maximum age estimates. Mature female natural mortality was also estimated in M17C D17A with the same prior.

Weight at length

Weight at length is calculated by a power function, the parameters for which were recalculated by the Kodiak lab in August 2016 and resulted in very small changes in weight at length for males, but rather large changes for females. New weight at length parameters were applied to all years of data, rather than just the most recent observations and were used starting in 2016 for calculation of the OFL. To provide context for the change, a juvenile female crab of carapace width 52.5 mm was previously estimated to weigh 65 g and now 48 g; a mature female crab of carapace 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 probability of maturing (which is different from the fraction mature at length) is estimated within the model for both sexes as a freely estimated (but smoothed) function of length.

Molting probability

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

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

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

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

Further complicating the process of quantifying reproductive capacity, clutch fullness and fraction of unmated females may not account for the fraction of females that may have unfertilized eggs, since these cannot be detected by the naked eye at the time of the survey. The fraction of barren females observed in the survey may not be an accurate measure of fertilization success because females may retain unfertilized eggs for months after extrusion. To examine this hypothesis, RACE personnel sampled mature females from the Bering Sea in winter and held them in tanks until their eggs hatched in March of the same year (Rugolo et al. 2005). All females then extruded a new clutch of eggs in the absence of males. All eggs were retained until the crabs were 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, though further analyses are underway. 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 4). 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

Data from the NMFS Kodiak holding study 2016 are new for this year's study and up to 70 new observations will be available soon. 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) using survey biomass estimates. The realized retained catch typically exceeded the GHL historically, resulting in exploitation rates for the retained catch on males >101mm ranging from about 10% to 80%. The estimated exploitation rate for total catch divided by mature male biomass ranged from 5% to 52% for the chosen model in this assessment (Figure 6).

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 is 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).

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

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

History of 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 unfished levels and has been shown to provide close to maximum sustainable yield for a range of steepnesses (Clark, 1993). Consequently, it is an often used target when a stock recruit relationship is unknown or unreliable.

Fishery history

Snow crab were harvested in the Bering Sea by the Japanese from the 1960s until 1980 when the Magnuson Act prohibited foreign fishing. After the closure to foreign fleets, retained catches increased from relatively low levels in the early 1980s (e.g. retained catch of 11.85 kt during 1982) to historical highs in the early and mid-nineties (retained catch during 1991, 1992, and 1998 were 143.02, 104.68, and 88.09 kt, respectively). The stock was declared overfished in 1999 at which time retained catches dropped to levels similar to the early 1980s (e.g. retained catch during 2000 was 11.46 kt). Retained catches have slowly increased since 1999 as the stock rebuilt, although retained catch during 2016 was low (9.67 kt).

Discard mortality is the next largest source of mortality after retained catch and approximately tracks the retained catch. The highest estimated discard mortality occurred during 1992 at 17.06 kt which was 16% of the retained catch. The most recent estimated mortality was 1.31 kt which was 14% of the retained catch.

Discard from the directed pot fishery has been estimated from observer data since 1992 and ranged from 11% to 64% (average 33%) of the retained catch of male crab biomass (Table 5). Female discard catch has been very low compared to male discard catch and has not been a significant source of mortality. Discard of snow crab in groundfish fisheries has been highest in the yellowfin sole trawl fishery, and decreases down through the flathead sole trawl fishery, Pacific cod bottom trawl fishery, rock sole trawl fishery, and the Pacific cod hook-and-line and pot fisheries, respectively (Figure 7). Bycatch in fisheries other than the groundfish trawl fishery has historically been relatively low, but in 2015 bycatch from sources other than the groundfish trawl fishery reached almost ~25% of the reported bycatch. Size frequency data and catch per pot have been collected by observers on snow crab fishery vessels since 1992. Observer coverage has been 10% on catcher vessels larger than 125 ft (since 2001), and 100% coverage on catcher processors (since 1992).

Several modifications to pot gear have been introduced to reduce bycatch mortality. In the 1978/79 season, escape panels were introduced to pots used in the snow crab fishery to prevent ghost fishing. Escape panels consisted of an opening with one-half the perimeter of the tunnel eye laced with untreated cotton twine. The size of the cotton laced panel was increased in 1991 to at least 18 inches in length. No escape mechanisms for undersized crab were required until the 1997 season when at least one-third of one vertical surface of pots had to contain not less than 5 inches stretched mesh webbing or have no less than four circular rings of no less than 3 3/4 inches inside diameter. In the 2001 season the escapement for 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 composition of retained crab from the directed snow crab pot fishery from survey year 1978 to the 2016 were used in this analysis (Table 5). Size composition data on the total catch (retained plus discarded) in the directed crab fishery were available from survey year 1992 to 2016. Total discarded catch was estimated from observer data from 1992 to 2016 (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 2016. 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 currently used strategy (since 2001) to the present by ADFG to set the TAC, which assumes a discard mortality of 25% (Zheng, et al. 2002). The discards prior to 1992 may be underestimated due to the lack of escape mechanisms for undersized crab in the pots before 1997. See Table 3 for a summary of catch data.

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

Data component	Years
Retained male crab pot fishery size frequency by shell condition	1978 - 2016
Discarded Males and female crab pot fishery size frequency	1992 - 2016
Trawl fishery bycatch size frequencies by sex	1991 - 2016
Survey size frequencies by sex and shell condition	1978 - 2017
Retained catch estimates	1978 - 2016
Discard catch estimates from crab pot fishery	1992 - 2016
Trawl bycatch estimates	1973 - 2016
Total survey biomass estimates and coefficients of variation	1978 - 2017
2009 study area biomass estimates, CVs, and size frequency for BSFRF and NMFS tows	2009
2010 study area biomass estimates, CVs, and size frequency for BSFRF and NMFS tows	2010

Survey biomass and size composition data

Abundance was estimated from the annual eastern Bering Sea (EBS) bottom trawl survey conducted by NMFS (see Rugolo et al. 2003 for design and methods). Since 1988, the survey has sampled more stations than pre-1988 (compare Figure 8 to Figure 9)). In 1982 the survey net was changed resulting in a potential change in catchability. Consequently, survey selectivity has been historically modeled in three ‘eras’ in the assessment (1978-1981, 1982-1988, 1989-present, Figure 10). 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 11 & Figure 12) were input to the model via the .DAT file, after which MMB and FMB at the time of the survey were calculated based on the size composition data, which were delineated by shell condition, maturity state, and sex. Distinguishing between mature and immature crab for the size composition was accomplished by demarcating any female that had eggs reported in the survey as ‘mature’. Mature male size composition data were calculated by multiplying the total numbers at length for new shell male crab by a vector of observed proportion of mature males at length. The observed proportion of mature males at length was calculated by chelae height and therefore refers only to ‘morphometrically’ mature males. All old shell crab of both sexes were assumed to be mature. New shell crab were demarcated as any crab with shell condition index ≤ 2 . The biomass of new and old shell mature individuals was calculated by multiplying the vector of numbers at length by weight at length. These vectors were then summed by sex to provide the index to which the model was fit (Table 6). The size composition data were also fit within the assessment.

Spatial distribution of survey abundance and catch

Spatial gradients exist in the survey data by maturity and size for both sexes. For example, larger males have been more prevalent on the south west portion of the shelf (Figure 4) while smaller males have been more prevalent on the north west portion of the shelf (Figure 1). Females have exhibited a similar pattern (compare Figure 2 to Figure 5). In addition to changing spatially over the size and shelf, distributions of crab

by size and maturity also changed temporally. The centroids of abundance in the summer survey moved over time (Figure 13 & Figure 14). Centroids of mature female abundance early in the history of the survey were the farther south, but moved north during the 1990s. Since the late 1990s and early 2000s, the centroids moved south again, but not to the extent seen in the early 1980s. This phenomenon was mirrored in centroids of abundance for large males (Figure 14).

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

The distribution of large males during the summer survey and the fishery catch are different. The origin of this difference is unknown. It is possible that crab move between the fishery and the survey, but it is also possible that fishers did not target 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 appear to move south and west as they age (Parada et al., 2010), 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

The Bering Sea Fisheries Research Foundation (BSFRF) conducted a survey of 108 tows in 27 survey stations (hereafter referred to as the “study area”) in the Bering Sea in summer 2009 (Figure 15). 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 16 & Figure 17) are incorporated into the model by fitting them as an extra survey that is linked to the NMFS survey through a shared selectivity (see appendix A for a description of the way in which the surveys are related in the assessment model). Abundances estimated by the industry surveys were generally higher than the NMFS estimates, which provides evidence that the catchability of the NMFS survey gear is less than 1. Larger females are an exceptions to this observation, but this difference may be due to different towing locations for the two nets within the study area, or to variable catchability of females due to aggregation behavior.

E. Analytic approach

History of modeling approaches for the stock

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

Model description

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

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

The snow crab population dynamics model tracked the number of crab of sex s , shell condition v , maturity state m , during year y at length l , $N_{s,v,m,y,l}$. A terminal molt was modeled in which crab move from an immature to a mature state, after which no further molting occurred. The mid-points of the size bins tracked in the model spanned from 27.5 to 132.5mm carapace width, with 5 mm size classes. For the base assessment (M16 D17), 338 parameters were estimated. Parameters estimated within 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), catchability, and maturity (also sometimes subject to a prior; see Table 7 & Table 8). 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.

In its current formulation, a gap in observations of premolt sizes from ~25 to ~35 mm carapace width impedes estimation of the change point in the growth function. This data gap results in unstable behavior of the model. In the past a ‘jittering’ approach was explored in order to find the parameter vector that produced the smallest negative log likelihood (Turnock, 2016). A jittering approach was implemented here by running each model to produce a .PAR file, then creating 100 replicates of a .PIN file using that .PAR file. Each .PIN file consisted of the values in the .PAR file multiplied by a random normal error term with a mean of 1 and a standard deviations of 0.1. Each of the .PIN files were used as starting values to run the model and the output was stored and compared among model scenarios.

Samples were also 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 and autocorrelation) demonstrated a lack of evidence of non-convergence (if possible).

Model selection and evaluation

Models were evaluated based on their fit to the data (Table 9), the credibility of the estimated population processes, stability of the model (Figure 18, Figure 19, Figure 20), and the strength of the influence of the assumptions of the model on the outcomes of the assessment. Maximum likelihood estimates of parameters can be seen in Table 8 and their posterior distributions can be seen in Figure 21, Figure 22, Figure 23, and Figure 24.

Results

Several of the models exhibited unstable behavior when undergoing ‘jittering’ (Figure 18). Models appeared to ‘converge’ (i.e. small gradients) over a wide range of likelihood values and derived management quantities exhibited bimodality. This bimodality can be linked to the interaction of the change point in the growth model with a fixed natural mortality for females, because when natural mortality for mature females is estimated (M17C.D17a), the bimodality disappears (Figure 18). In addition to jittering, MCMC was performed for all models. Models in which the two smallest length bins were removed and the growth curve was estimated without a change point did not have stationary traces of the objective function (i.e. they did not converge (Figure 19) and most parameters were poorly behaved (Figure 20)). Below, the results for seven models are described. Only the total likelihoods for M16.D17, M17A.D17a, and M17Aa.D17a are directly comparable because they have the same data and weighting schemes. Individual likelihood components can be compared among models with the understanding that changing the weighting or data for one likelihood component influences others.

Fits to data

Survey biomass data

Fits to the survey mature male biomass were visually similar for all models for the majority of years in the time series (Figure 25), yet model M17C.D17a fit the survey biomass better than other models according to the likelihoods (Table 9). Estimates of survey MMB in the final year ranged from 101.5 to 109.8 kt. All models overestimated the final year of survey MMB (83.9572 kt).

Fits to the survey mature female biomass were also similar for all models, particularly in recent years (Figure 25). Models in which natural mortality for mature females was estimated (M17C.D17a & M17BC.D17a) fit the mature female biomass better than others in the earlier years. Estimates of survey MFB in the final year ranged from 131.9 to 143.7 kt. All models overestimated the final year of survey MFB (106.847 kt).

Growth data

All models provided adequate fits to the female and male growth data, but model M17C.D17a returned the lowest likelihood for the male data and the second lowest for female (Figure 26).

Catch data

Retained catch data were fit by all models well, with no little discernible differences among models (Figure 27). Female discard data were fit adequately given the specified uncertainty (Figure 27 & (Table 9)). Male discard data during the period for which data exist (early 1990s to the present) were well fit by every model with little discernible difference (Figure 27). M17C.D17a returned a significantly lower likelihood for male discard data (Table 9). Fits to the trawl data were adequate for all models given the uncertainty in the data (Figure 27). Fits to the fishery CPUE data were poor for all models, but vaguely reflected the trends in observed cpue (Figure 28).

Size composition data

Retained catch size composition data were fit well by all models (Figure 29); trawl size composition data were generally well fit, with several exceptions. All models performed similarly in fitting the trawl size composition data (Figure 30 & Table 9).

Fits to the size composition data for the BSFRF data were qualitatively similar for all models (Figure 31 & (Table 9)). 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, although fits for the models in which lower length bins were excluded depart from the other models in some years (Figure 32). Similar patterns in fits among models can be seen for the male survey composition data (Figure 33). The distribution of residuals for male and female survey composition data for the chosen model varied by sex. Female and male size composition data from the survey sum to 1 in a given year and females tended to be overestimated (Figure 34), whereas males tended to be underestimated (Figure 35).

Estimated population processes and derived quantities

The fits to the data were similar for all models, but the credibility of the estimated population processes varied. 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 2017 ranged from 95.88 to 123.74 kt. 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 2017 ranged from 125.7 to 189.9 kt (Figure 36). In general, estimated fishing mortality in the recent

past has been well below $F_{35\%}$, save the years 2012-2014, which were close to $F_{35\%}$. Estimated MMB has been less than $B_{35\%}$ since 2010, but never below MSST (Figure 37).

Estimates of selectivity and catchability varied widely among models (Figure 38). For models that estimated selectivity parameters in era 1 (only 2 models), catchability for males and females was essentially 1 with very narrow posteriors (Figure 22). Size at 50% selection in the survey gear during era 1 ranged from ~40 mm to ~46 mm for both females and males (Figure 22 & Figure 23). All models estimated selectivity parameters for era 2, and removing the ‘anchor’ of the survey data in era 1 resulted in lower estimated of catchability for males (e.g. 0.49 to 0.33-0.44) and higher estimated catchability for females (e.g. from 0.32 to 0.38-0.52; Figure 23). Size at 50% selection in the survey gear ranged from ~39 mm to ~41 mm for both females and males (Figure 22 & Figure 23). Estimated catchability for males during survey era 3 ranged from 0.52 to 0.7; estimated female catchability increased from 0.61 to 0.64-0.72. Size at 50% selection in the survey gear ranged from 31 mm to 35 mm for females and 35 mm to 37 mm for males (Figure 22 & Figure 23). BSFRF ‘availability’ curves varied widely from 2009 to 2010 and among models, with the availability of crab to the experimental survey generally increasing in 2010 (Figure 39).

The probability of maturing by size was fairly consistent among scenarios for both males and females, except the scenarios in which the first two length bins were removed. Aside from these two models, the probability of maturing by size for female crab was ~50% at ~47.5 mm and increased to 100% at ~60mm (Figure 40); the probability of maturing for male crab was ~15% to 20% at ~60 mm to 90mm and increased sharply to 50% at ~97.5mm, and 100% at 107.5 mm. The probability of maturity was unreasonably high for smaller length bins when the two smallest length bins were removed.

Estimated fishing mortality in the directed fishery was similar for all models (Figure 41). 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 41). Estimated size at 50% selection in the trawl fishery varied more than selectivity in the directed fishery, ranging from 109 - 120 mm (Figure 41). Size at 50% selection for discarded females was similar for all models (Figure 41). See Figure 21 and Figure 22 for posterior densities for all parameters related to mortality in the different fisheries.

Patterns in recruitment were similar for all models. A period of high recruitment was observed in which 3 large cohorts passed through the population during the 1980s and into the early 1990s. Following that, a period of low recruitment persisted from the early 1990s to 2013. All models indicated a large recruitment to the survey gear occurred in the last few years (Figure 42). Recruitment entering the model was placed primarily in the first three size bins (Figure 42). Stock recruitment relationships were not apparent between the estimates of MMB and recruitment for any model (Figure 42). Relationships were not apparent between mature female biomass and recruitment either. Estimated multipliers for natural mortality ranged from 1.23 to 1.89 for immature crab, 1.06 to 1.123 for mature male crab, and 1 to 1.97 for mature females (Table 8).

F. Calculation of the OFL

Methodology for OFL

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

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

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

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

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 mortality (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 included 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 presented models ranged from 23.91 to 35.3kt (Figure 43 & Table 10). Differences in OFLs were a result of differences in estimated MMB (see above), calculated $B_{35\%}$ (which ranged from 134.18 to 157.14kt), Figure 43), $F_{35\%}$ (which ranged from 1.31 to 1.96 yr⁻¹, Figure 43), and F_{OFL} (which ranged from 0.89 to 1.33 yr⁻¹, Figure 43).

G. Calculation of the ABC

The acceptable biological catch (ABC) was set by subtracting a 10% buffer from the OFL to account for scientific uncertainty, which was recommended by the SSC.

Author recommendations

Models in which the lower two length bins were removed were eliminated from consideration because they did not provide credible estimates of survey selectivity and the probability of maturing. It appears low numbers of small crab in small length bins combined with a constant natural mortality informs catchability and survey selectivity. Once survey selectivity is estimated conditional upon the paucity of observations of small crab, the probability of maturing can be estimated to fit the observed mature male biomass. Consequently, efforts should be made to fill the holes in the data in this range, rather than excluding smaller length bins.

The small changes introduced to the model should all be adopted. Excluding the first survey era is advisable because it provided an artificial anchor to survey catchability, the influence of which stretched across eras. Little is known about catchability in the first era and an estimated catchability of 1 in that era is counter-intuitive given the smaller size of the surveyed area. Changing the timing of the second survey era needed to be implemented because the current number of sampled stations began in 1988, not 1989. Finally, changing the BSFRF selectivities to logit space needed to be implemented because some of these parameters were consistently hitting their bounds.

Each of the CPT-recommended small changes resulted in small changes to the model output, but, even with these changes, the bimodality and instability in management quantities persisted. Estimating natural mortality for mature females removed this instability and returned an intuitive relationship between the natural mortalities of mature males and females. The bimodality in the MLEs and derived management quantities appeared originally because the change point in growth flips from one state to another and natural mortality for mature females was fixed. When mature female natural mortality is estimated, the confounded processes of growth and natural mortality can ‘accommodate’ one another and avoid the sharp bimodality. The largest departure from earlier models brought by estimating natural mortality for mature female was a large increase in survey catchability, but this is somewhat consistent with the BSFRF studies which generally showed higher catchability for females than males (perhaps due to aggregation behavior).

For these reasons, the authors’ selected model is M17C D17a. It incorporates all the small changes suggested by the CPT, estimates natural mortality for all sex/maturity state combinations, and returns credible estimates for all population processes.

H. Data gaps and research priorities

Data sources

If a Bayesian paradigm is used to provide management advice, as many raw data sources as possible should be included in the assessment. Estimating parameters outside of the model and inputting them as ‘known’ artificially decreases the uncertainty represented in the 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.

Although estimating natural mortality for mature females eliminated the bimodality in management quantities, jittering still revealed considerable instability in the model. Additional growth data in the size bins for which pre-molt observations are absent would likely improve the stability of the model. Dr. Foy from the Kodiak lab has provided these data, but not in time for inclusion in this assessment.

Modeling and weighting

Different weighting of likelihood components can have drastic impacts on the management advice provided from an assessment. A close look at the way CVs, sample sizes, and other weighting factors are calculated and their influence on assessment results could provide better understanding of how well the model is balanced. Standardization of the weighting schemes would also improve readability of the code (for example, some size composition data have both ‘weights’ and ‘sample sizes’).

Establishing a system for deciding to use Bayesian methods versus maximum likelihood methods would be useful given the amount of time required to perform both jittering and MCMC. If Bayesian methods are to be the mainstay of this assessment, priors for all parameters and the space in which parameters are estimated should be carefully considered. Additionally, moving to a designation of the ABC based on the posterior (similar to the p-star methods) rather than a flat percentage buffer would represent the uncertainty in the data better.

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 (e.g. Murphy et al. 2017). In general, exploring the spatial dynamics of the population may allow for patterns and influences of the fishery and environment on the productivity of the stock to be more easily identified. Previous analyses suggest that retrospective biases may be a problem for the snow crab assessment (Szuwalski and Turnock, 2016). Retrospective biases can result from unaccounted for time-varying processes in the population dynamics of the model (Hurtado et al., 2015) and the retrospective bias in MMB for snow crab appears to result from an anomalously large estimate of survey MMB in 2014. This was likely caused by a change in catchability for that year and focused research on potential time-variation in important population processes for snow crab should be pursued to confront retrospective biases.

Style

Although the code has been trimmed considerably over the last two years, legacy code and unused variables still exist within the assessment. Streamlining the code makes it more readable and reduces the probability of bugs. Most constants were migrated from the .TPL to the .CTL file, but parameter bounds have not yet been moved. Adjusting the manner in which output files are opened when evaluating MCMC output should also be implemented to avoid overwriting output files. A move to GMACs in 2018 will obviate the need for these corrections, however.

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. The most recent large recruitment events will likely divide the recruitment time series into three periods and present an intriguing opportunity for further study of the relationship between environmental variables and recruitment success.

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Appendix A: Model structure

Population dynamics

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

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

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

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

The dynamics after the initial year were described by:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Selectivity for the survey was estimated for 3 eras in the base model: 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.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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.

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

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

Likelihood components

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

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

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

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

Log normal likelihoods were implemented in the form:

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

L_x was the contribution to the objective function of data component x , λ_x was any additional weighting applied to the component, $\hat{I}_{x,y}$ was the predicted value of quantity I from data component x during year y ,

$I_{x,y}$ was the observed value of quantity I from data component x during year y and $CV_{x,y}$ was the coefficient of variation for data component x during year y . 5 log normal likelihood components were included in this assessment (see Table 11 for descriptions, weighting factors, and CVs).

Normal likelihoods were implemented in the form:

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

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

Smoothing penalties were also placed on some estimated vectors of parameters in the form of normal likelihoods on the second differences of the vector. Code for this assessment can be found on github.com/szuwalski/SnowCrab2017.

Table 4: 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		
20.8	27.6		
22	28.2		
22.9	28.6		

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

Survey year	Retained catch (kt)	Discarded females (kt)	Discarded males (kt)	Trawl bycatch (kt)
1978	23.71	0.02	2.05	3.84
1979	34.03	0.02	2.56	3.07
1980	30.36	0.02	2.28	2.23
1981	13.32	0.01	1.2	0.93
1982	11.85	0.02	1.18	0.38
1983	12.16	0.01	1.15	0.49
1984	29.94	0.01	2.57	0.52
1985	44.45	0.01	3.74	0.45
1986	46.22	0.02	3.96	1.91
1987	61.4	0.03	5.14	0.01
1988	67.79	0.04	5.42	0.69
1989	73.4	0.05	6.23	0.8
1990	149.1	0.05	14.17	0.61
1991	143	0.06	11.18	1.88
1992	104.7	0.12	17.06	1.78
1993	67.94	0.08	5.32	1.76
1994	34.13	0.06	4.03	3.54
1995	29.81	0.02	5.75	1.34
1996	54.22	0.07	7.44	0.92
1997	114.4	0.01	5.73	1.47
1998	88.09	0.01	4.67	1.01
1999	15.1	0	0.52	0.61
2000	11.46	0	0.62	0.53
2001	14.8	0	1.89	0.39
2002	12.84	0	1.47	0.23
2003	10.86	0	0.57	0.76
2004	11.29	0	0.51	0.95
2005	16.77	0	1.36	0.36
2006	16.49	0	1.78	0.83
2007	28.59	0.01	2.53	0.43
2008	26.56	0.01	2.06	0.27
2009	21.78	0.01	1.23	0.63
2010	24.61	0.01	0.62	0.17
2011	40.29	0.18	1.69	0.16
2012	30.05	0.03	2.32	0.22
2013	24.49	0.07	3.27	0.12
2014	30.82	0.17	3.52	0.16
2015	18.42	0.07	2.96	0.16
2016	9.67	0.02	1.31	0.08

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

Survey year	Female mature biomass	Female CV	Mature male biomass	Male CV	Males >101mm (kt)	Males >101mm (millions)
1978	101.7	0.2	193.5	0.12	98.95	163.4
1979	216.8	0.2	241.3	0.12	105	169.1
1980	281.3	0.32	187.5	0.17	69.98	116.4
1981	123.3	0.17	113.5	0.11	23.01	40.38
1982	144.4	0.15	176.8	0.14	33.34	60.91
1983	90.13	0.2	161.6	0.13	38.09	70.09
1984	42.32	0.19	177.7	0.12	88.73	151.8
1985	6.12	0.2	71.84	0.11	43.39	72.84
1986	15.74	0.18	89.81	0.11	46.7	77.91
1987	122.6	0.16	194.6	0.11	74.44	128.6
1988	169.9	0.17	259.4	0.15	104.7	173.1
1989	264.2	0.25	299.2	0.11	92.31	158.9
1990	182.9	0.19	443.8	0.14	224.7	386.4
1991	214.9	0.19	466.6	0.15	292.2	452.9
1992	131.4	0.18	235.5	0.09	143.9	227.3
1993	132.1	0.16	183.9	0.1	78.11	126.7
1994	126.2	0.15	171.3	0.08	44.78	72.57
1995	168.7	0.14	220.5	0.13	37.75	65.18
1996	107.3	0.14	288.4	0.12	87.57	155.2
1997	103.8	0.2	326.8	0.1	168.7	280.6
1998	72.73	0.25	206.4	0.09	126.7	209.7
1999	30.89	0.21	95.85	0.09	52.53	85.2
2000	96.46	0.52	96.39	0.14	41.88	69.83
2001	77.24	0.28	136.5	0.12	41.51	70.69
2002	30.22	0.28	93.17	0.23	36.56	64.16
2003	41.71	0.31	79.07	0.12	32.57	55.61
2004	50.16	0.26	79.57	0.14	35.99	57.42
2005	64.85	0.17	123.5	0.11	40.67	63.26
2006	51.93	0.18	139.3	0.26	71.13	120.9
2007	55.89	0.22	153.1	0.15	73.62	127.5
2008	57.15	0.19	142	0.1	66.56	113.6
2009	52.16	0.21	148.2	0.13	78.92	129.9
2010	98.01	0.18	162.8	0.12	88.35	138.3
2011	175.8	0.18	167.1	0.11	94.67	147.6
2012	149.4	0.2	122.2	0.12	53.17	85.35
2013	131.4	0.18	97.46	0.12	42.93	71.79
2014	119.7	0.19	163.5	0.16	81.39	138.8
2015	85.13	0.17	80.04	0.12	35.77	56.11
2016	55.39	0.21	63.21	0.11	21.96	36.51
2017	106.8	0.21	83.96	0.11	20.52	35.02

Table 7: 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	$F_{dev,trawl,era1}^{log}$
fmortt_dev_era2	-15	15	$F_{dev,trawl,era2}^{log}$
log_avg_sel50_mn	4	5	$S_{50,new,dir}$
log_avg_sel50_mo	4	5	$S_{50,old,dir}$
fish_slope_mn	0.1	0.5	$S_{slope,m,d}$
fish_fit_slope_mn	0.05	0.5	$S_{slope,m,d}$
fish_fit_sel50_mn	85	120	$S_{50,old,dir}$
fish_slope_mo2	1.9	2	$S_{slope,m,d}$
fish_sel50_mo2	159	160	$S_{50,old,dir}$
fish_slope_mn2	0.01	2	$S_{slope,m,d}$
fish_sel50_mn2	100	160	$S_{50,old,dir}$
fish_disc_slope_f	0.1	0.7	$S_{slope,m,d}$
fish_disc_sel50_f	1	5	$S_{50,old,dir}$
fish_disc_slope_tf	0.01	0.3	$S_{slope,trawl}$
fish_disc_sel50_tf	30	120	$S_{50,trawl}$
srv1_q	0.2	1	$q_{m,era1,surv}$
srv1_q_f	0.2	1	$q_{f,era1,surv}$
srv1_sel95	30	150	$S_{95,era1,surv}$
srv1_sel50	0	150	$S_{50,era1,surv}$
srv2_q	0.2	1	$q_{m,era2,surv}$
srv2_q_f	0.2	1	$q_{f,era2,surv}$
srv2_sel95	50	160	$S_{95,era2,surv}$
srv2_sel50	0	80	$S_{50,era2,surv}$
srv3_q	0.2	1	$q_{m,era3,surv}$
srv3_sel95	40	200	$S_{95,m,era2,surv}$
srv3_sel50	25	90	$S_{50,m,era2,surv}$

Parameter	Lower	Upper	Symbol
srv3_q_f	0.2	1	$q_{f,era3,surv}$
srv3_sel95_f	40	150	$S_{95,f,era2,surv}$
srv3_sel50_f	0	90	$S_{50,f,era2,surv}$
srvind_q	0.1	1	$q_{m,09,ind}$
srvind_q_f	0.01	1	$q_{f,09,ind}$
srvind_sel95_f	55	120	$S_{95,f,09,ind}$
srvind_sel50_f	-50	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	$\gamma_{natM,mat,m}$
Mmultf	0.2	2	$\gamma_{natM,mat,f}$
cpueq	0.0000877	0.00877	q_{cpue}

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

Parameter	M16 D16	M16 D17	M16 D17a	M17A D17a	M17Aa D17a	M17B D17a	M17C D17a	M17BC D17a
af	-5.08	-4.95	-4.94	-2.49	-4.97	9.22	-5.23	7.58
am	-5.74	-5.57	-5.66	-5.49	-5.48	5.55	-5.35	5.2
bf	1.53	1.52	1.52	1.41	1.52	1.08	1.53	1.12
bm	1.54	1.53	1.53	1.53	1.53	1.17	1.52	1.18
b1	1.15	1.15	1.15	1.15	1.15	NA	1.15	NA
bfl	1.02	1.02	1.04	1	1.04	NA	1.04	NA
deltam	32.2	32.15	32.21	32.16	32.16	NA	32.11	NA
deltaf	34.37	34.41	34.34	39.01	34.33	NA	34.15	NA
st_gr	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
growth_beta	vector	vector	vector	vector	vector	vector	vector	vector
mateste	vector	vector	vector	vector	vector	vector	vector	vector
matestfe	vector	vector	vector	vector	vector	vector	vector	vector
rec_devf	vector	vector	vector	vector	vector	vector	vector	vector
alpha1_rec	11.5	11.5	11.5	11.5	11.5	11.5	10.55	11.5
beta_rec	4	4	4	4	4	4	3.62	4
mnatlen_styr	vector	vector	vector	vector	vector	vector	vector	vector
fnatlen_styr	vector	vector	vector	vector	vector	vector	vector	vector
log_avg_fmort	-0.15	-0.19	-0.27	-0.32	-0.3	-0.39	-0.24	-0.29
fmort_dev	vector	vector	vector	vector	vector	vector	vector	vector
log_avg_fmortdf	-6.42	-6.38	-6.32	-6.32	-6.35	-6.89	-5.65	-6.21
fmortdf_dev	vector	vector	vector	vector	vector	vector	vector	vector
log_avg_fmortt	-4.21	-4.29	-4.71	-4.8	-4.79	-4.59	-4.55	-4.37
fmortt_dev_era1	vector	vector	vector	vector	vector	vector	vector	vector
fmortt_dev_era2	vector	vector	vector	vector	vector	vector	vector	vector
log_avg_sel50_mn	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67
log_avg_sel50_mo	4.5	4.5	4.5	4.5	4.5	4.5	3.85	4.5
fish_slope_mn	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
fish_fit_slope_mn	0.42	0.42	0.42	0.42	0.42	0.43	0.43	0.44
fish_fit_sel50_mn	95.78	95.87	96.09	96.08	96.06	96.2	96.01	96.15
fish_slope_mo2	1.95	1.95	1.95	1.95	1.95	1.95	1.8	1.95
fish_sel50_mo2	159.5	159.5	159.5	159.5	159.5	159.5	181.89	159.5
fish_slope_mn2	1	1	1	1	1	1	0.89	1
fish_sel50_mn2	130	130	130	130	130	130	132.85	130
fish_disc_slope_f	0.24	0.25	0.24	0.24	0.24	0.21	0.25	0.23
fish_disc_sel50_f	4.26	4.26	4.26	4.26	4.26	4.25	4.25	4.22
fish_disc_slope_tf	0.08	0.09	0.09	0.09	0.09	0.08	0.08	0.07
fish_disc_sel50_tf	114.18	112.97	109.79	109.37	109.59	115.18	113.59	120
srv1_q	1	1	0.6	0.6	0.6	0.6	0.61	0.6
srv1_q_f	1	1	0.6	0.6	0.6	0.6	0.6	0.6
srv1_sel95	59.89	60.05	60	60	60	60.14	70.15	60.14
srv1_sel50	42.66	42.76	40	40	40	40.13	35.09	40.13
srv2_q	0.49	0.49	0.43	0.34	0.34	0.34	0.44	0.43
srv2_q_f	0.32	0.32	0.46	0.38	0.37	0.24	0.53	0.39
srv2_sel95	61.3	61.55	57.17	56.88	56.72	63.38	54.99	50
srv2_sel50	41.32	41.45	41.25	39.93	39.73	8.37	39.12	0
srv3_q	0.62	0.61	0.67	0.67	0.68	0.57	0.72	0.64
srv3_sel95	57.24	56.05	56.52	57.39	57.48	40	48.34	40
srv3_sel50	38.42	37.84	38.03	38.86	38.93	25	35.21	25

Parameter	M16 D16	M16 D17	M16 D17a	M17A D17a	M17Aa D17a	M17B D17a	M17C D17a	M17BC D17a
srv3_q_f	0.49	0.49	0.54	0.55	0.54	0.66	1	1
srv3_sel95_f	43.09	42.76	43.09	44.24	43.67	150	45.76	40
srv3_sel50_f	33.27	33.08	33.28	34.18	33.84	0	35.68	31.14
srvind_q	0.36	0.36	0.39	0.39	0.31	1	1	1
srvind_q_f	0.11	0.11	0.11	0.11	0.11	0.08	0.17	0.15
srvind_sel95_f	55	55	55	55	55	55.17	55	55.14
srvind_sel50_f	49.21	49.22	49.23	49.17	49.26	54.88	49.34	54.86
srv10ind_q_f	1	1	1	1	1	1	1	1
selsmo10ind	vector	vector	vector	vector	vector	vector	vector	vector
selsmo09ind	vector	vector	vector	vector	vector	vector	vector	vector
Mmult_imat	1.8	1.8	1.82	1.87	1.89	1.87	1.23	1.24
Mmult	1.13	1.13	1.08	1.07	1.06	1.09	1.16	1.23
Mmultf	1	1	1	1	1	1	1.55	1.97
cpueq	0	0	0	0	0	0	0	0

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

Likelihood component	M16 D16	M16 D17	M16 D17a	M17A D17a	M17Aa D17a	M17B D17a	M17C D17a	M17BC D17a
Recruitment deviations	40.33	40.53	39.6	39.09	39.23	32.32	39.2	29.87
Initial numbers old shell males small length bins	2.18	2.17	4.81	5.09	5.12	7.49	4.68	7.08
ret fishery length	382.62	396.03	304.71	306.59	307.77	325.78	304.04	326.43
total fish length (ret + disc)	821.72	868	867.11	866.16	867.03	881.56	864.32	881.41
female fish length	221.96	236.42	235.99	236.75	236.2	224.83	234.66	226.01
survey length	4639.21	4745.85	4331.35	4345.3	4329.27	4942.45	4266.18	4792.15
trawl length	290.39	304.29	308.63	310.19	310.89	344.22	268.44	267.58
2009 BSFRF length	-82.94	-83.06	-82.95	-82.53	-82.81	-92.62	-93.59	-97.15
2009 NMFS study area length	-67.8	-68.02	-67.69	-67.66	-67.11	-69.25	-74.8	-73.83
M multiplier	19.81	19.68	16.84	18.29	18.74	19.85	83.42	64.06
prior maturity	40.77	40.58	37.64	41.83	37.05	43.21	37.12	39.86
smooth growth	38.4	37	34.28	35.17	35.86	56.66	33.54	54.39
males growth	133.39	135.2	127.46	116.24	127.25	247.76	117.05	229.32
females 2009 BSFRF biomass	0.21	0.2	0.27	0.28	0.25	0.18	0.38	0.21
2009 NMFS study area biomass	0.09	0.08	0.13	0.15	0.17	0.02	0.13	0.06
cpue q	0.2	0.2	0.18	0.21	0.22	0.19	0.18	0.18
retained catch	4.06	4.04	3.86	3.86	3.97	4.23	3.68	4.23
discard catch	152.45	162.45	154.75	154.02	156.36	148.71	135.01	150.44

Likelihood component	M16 D16	M16 D17	M16 D17a	M17A D17a	M17Aa D17a	M17B D17a	M17C D17a	M17BC D17a
trawl catch	8.63	10.12	6.51	7.89	8.17	7.43	7.02	6.94
female	6.12	5.71	5.27	5.3	5.28	5.41	5.41	5.35
discard catch								
survey biomass	365.81	368.13	328.51	312.13	313.01	327.38	281.56	283.37
F penalty	37.39	38.04	24.63	25.08	25.51	24.55	25.11	26.04
2010 BSFRF Biomass	2.88	2.72	4.04	4.08	2.73	2.04	22.16	26.93
2010 NMFS Biomass	0.87	0.82	1.24	1.33	1.91	0.84	1.09	0.77
Extra weight survey lengths first year								
2010 BSFRF length	-54.58	-54.79	-54.36	-54.02	-51.86	-58.77	-47.77	-62.69
2010 NMFS length	-59.21	-59.53	-59.08	-58.71	-55.77	-43.58	-60.22	-57.87
smooth selectivity	3.3	3.3	3.35	3.34	1.25	2.71	2.35	2.68
smooth female selectivity	0	0	0	0	0	0	0	0
init nos smooth constraint	40.44	40.57	47.68	48.26	48.33	47.57	45.61	46.19
Total	7499.12	7707.09	7190.65	7187.95	7189.08	7995.99	7060.84	7729

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

Model	MMB	B35	F35	FOFL	OFL
M16 D16	90.98	151.5	1.96	1.12	23.91
M16 D17	104.9	151	1.9	1.33	34.04
M16 D17a	95.26	150	1.43	0.97	27.46
M17A D17a	93.86	148.5	1.41	0.96	26.99
M17Aa D17a	88.16	147.6	1.38	0.9	24.66
M17B D17a	111.3	157.1	1.54	1.17	35.3
M17C D17a	94.43	139.3	1.31	0.89	28.41
M17BC D17a	102.9	134.2	1.6	1.21	34.81

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

Likelihood component	Form	M16 D16	M16 D17
Recruitment deviations	normal	0.71	0.71
Initial numbers old shell males small length bins	normal	707.1	707.1
ret fishery length	multinomial	200	200
total fish length (ret + disc)	multinomial	200	200
female fish length	multinomial	200	200
survey length	multinomial	200	200
trawl length	multinomial	200	200
2009 BSFRF length	multinomial	200	200
2009 NMFS study area length	multinomial	200	200
M multiplier prior	normal	0.23	0.23
maturity smooth	normal	3.16	3.16
growth males	normal	0.71	0.71
growth females	normal	0.32	0.32
2009 BSFRF biomass	lognormal	NA	NA
2009 NMFS study area biomass	lognormal	NA	NA
cpue q	normal	0.32	0.32
retained catch	normal	0.22	0.22
discard catch	normal	3	3
trawl catch	normal	0.22	0.22
female discard catch	normal	17	17
survey biomass	lognormal	NA	NA
F penalty	normal	0.5	0.5
2010 BSFRF Biomass	lognormal	NA	NA
2010 NMFS Biomass	lognormal	NA	NA
Extra weight survey lengths	multinomial	200	200
first year			
2010 BSFRF length	multinomial	200	200
2010 NMFS length	multinomial	200	200
smooth selectivity	norm2(firstdiff(firstDiff))	2	2
smooth female selectivity	norm2(firstdiff(firstDiff))	3	3
init nos smooth constraint	norm2(firstdifference)	1	1

M16 D17a	M17A D17a	M17Aa D17a	M17B D17a	M17C D17a	M17BC D17a
0.71	0.71	0.71	0.71	0.71	0.71
707.1	707.1	707.1	707.1	707.1	707.1
200	200	200	200	200	200
200	200	200	200	200	200
200	200	200	200	200	200
200	200	200	200	200	200
200	200	200	200	200	200
200	200	200	200	200	200
200	200	200	200	200	200
0.23	0.23	0.23	0.23	0.23	0.23
3.16	3.16	3.16	3.16	3.16	3.16
0.71	0.71	0.71	0.41	0.71	0.41
0.32	0.32	0.32	0.27	0.32	0.27
NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA
0.32	0.32	0.32	0.32	0.32	0.32
0.22	0.22	0.22	0.22	0.22	0.22
3	3	3	3	3	3
0.22	0.22	0.22	0.22	0.22	0.22
17	17	17	17	17	17
NA	NA	NA	NA	NA	NA
0.5	0.5	0.5	0.5	0.5	0.5
NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA
200	200	200	200	200	200
200	200	200	200	200	200
200	200	200	200	200	200
2	2	2	2	2	2
3	3	3	3	3	3
1	1	1	1	1	1

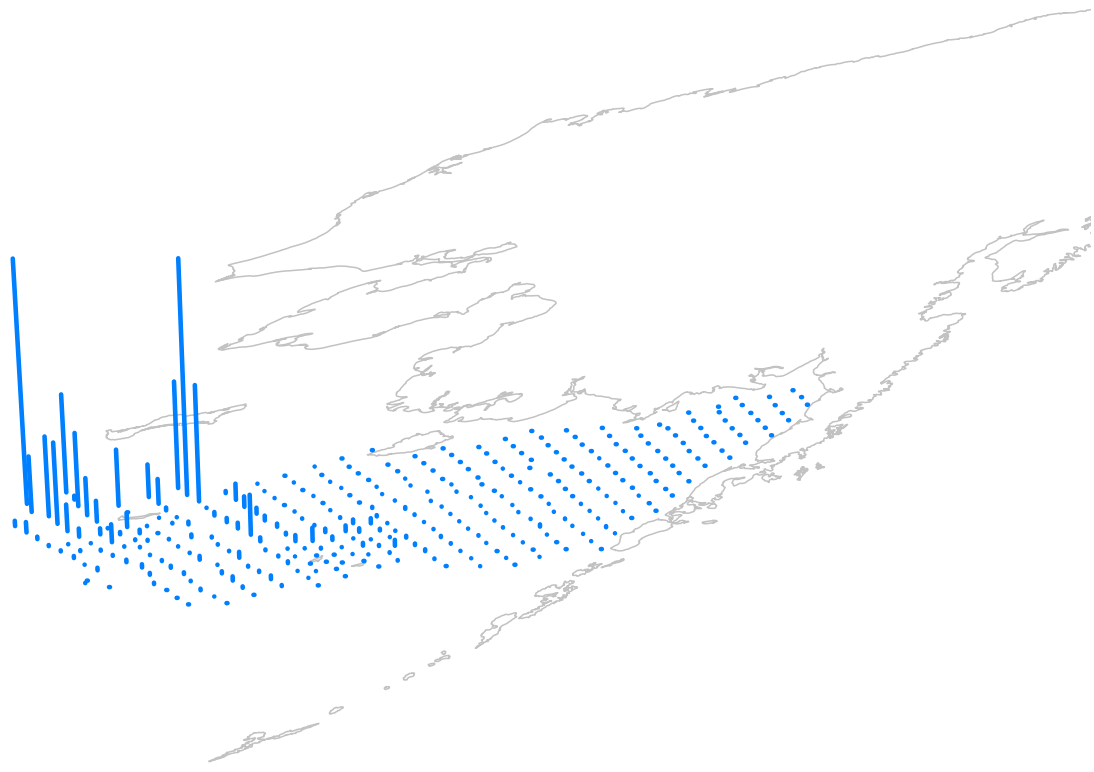


Figure 1: Observed relative density of all males at the time of the 2017 NMFS summer survey

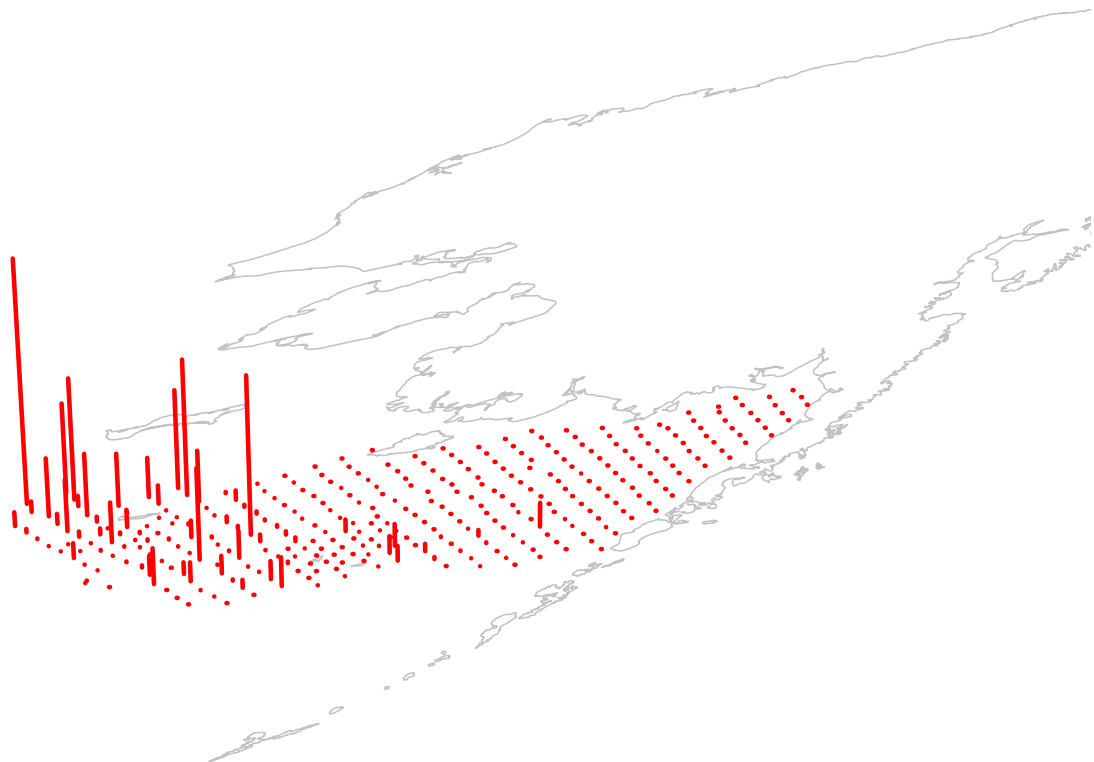


Figure 2: Observed relative density of all females at the time of the 2017 NMFS summer survey

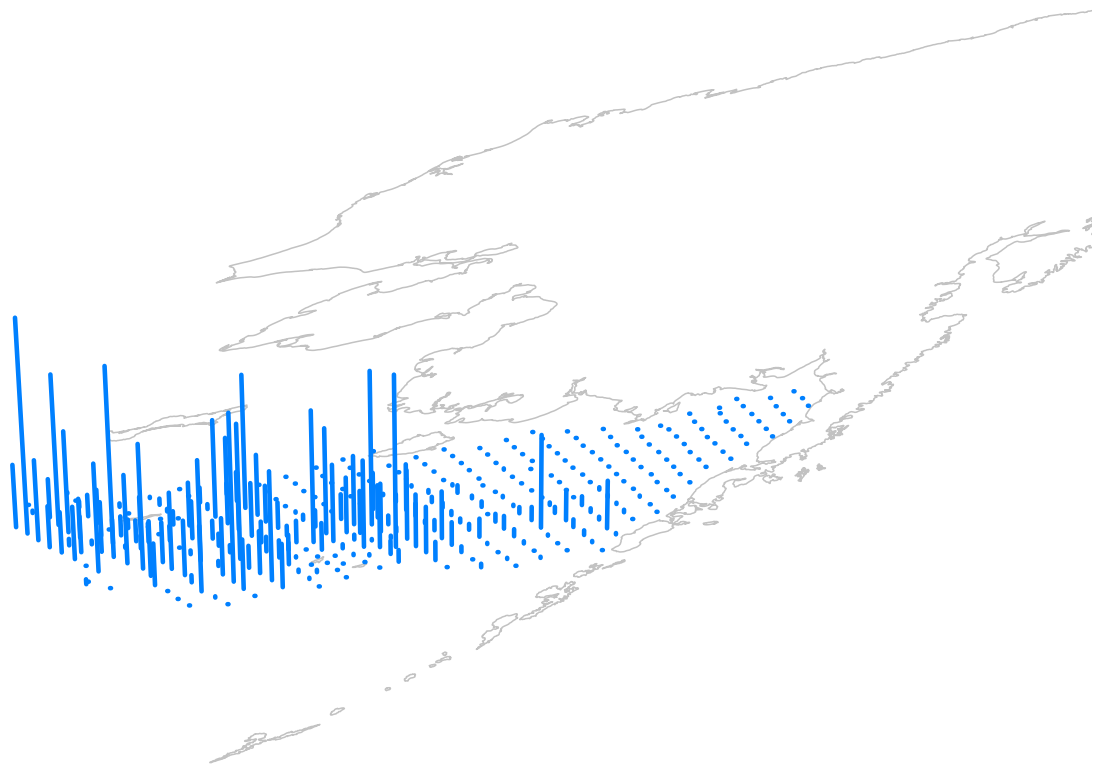


Figure 3: Observed relative density of males >77 mm carapace width at the time of the 2017 NMFS summer survey

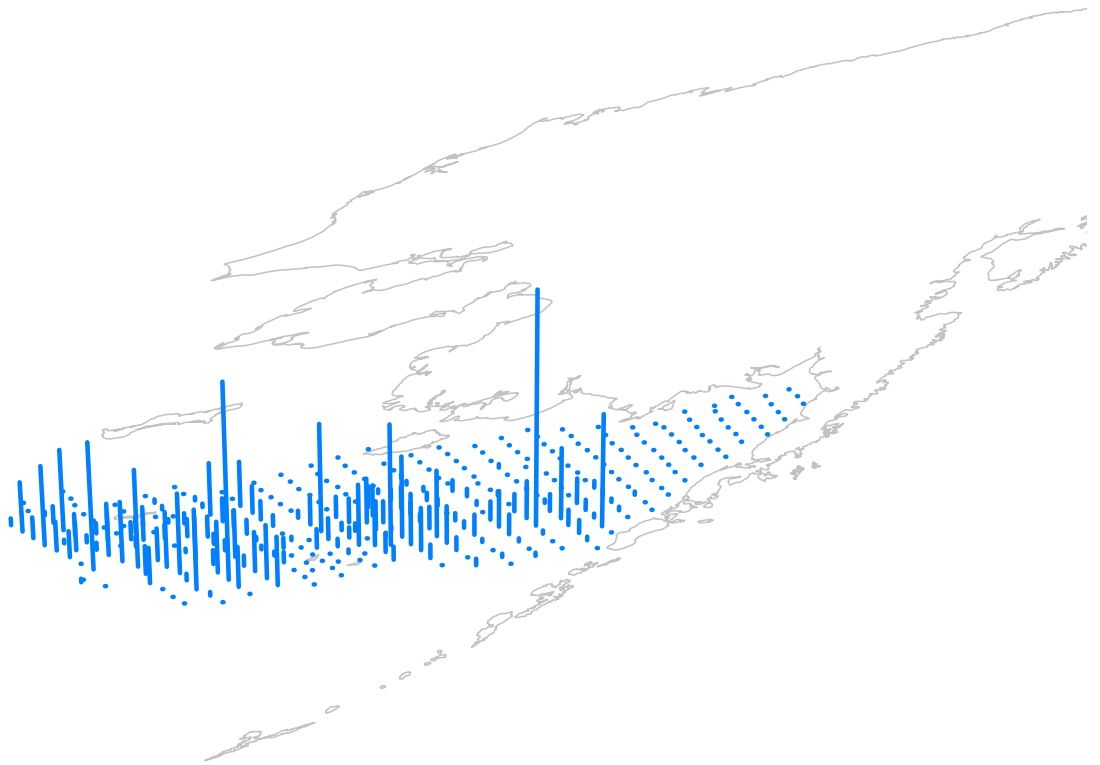


Figure 4: Observed relative density of males >101mm carapace width at the time of the 2017 NMFS summer survey

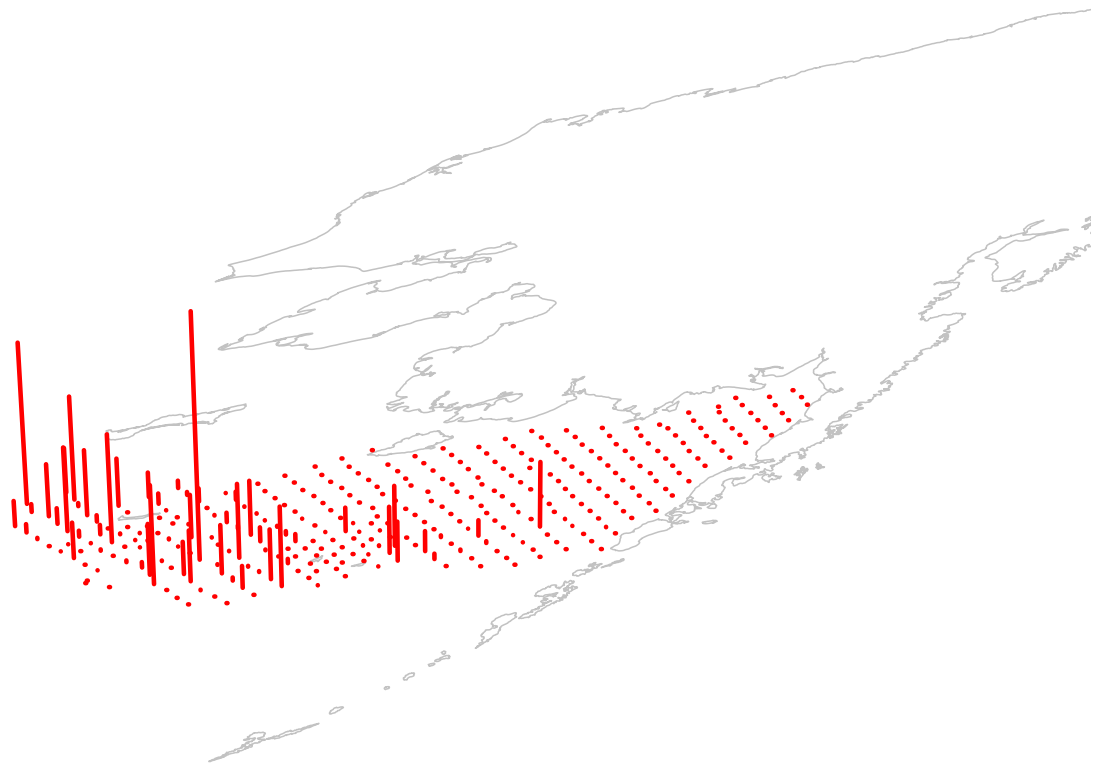


Figure 5: Observed relative density of mature females at the time of the 2017 NMFS summer survey

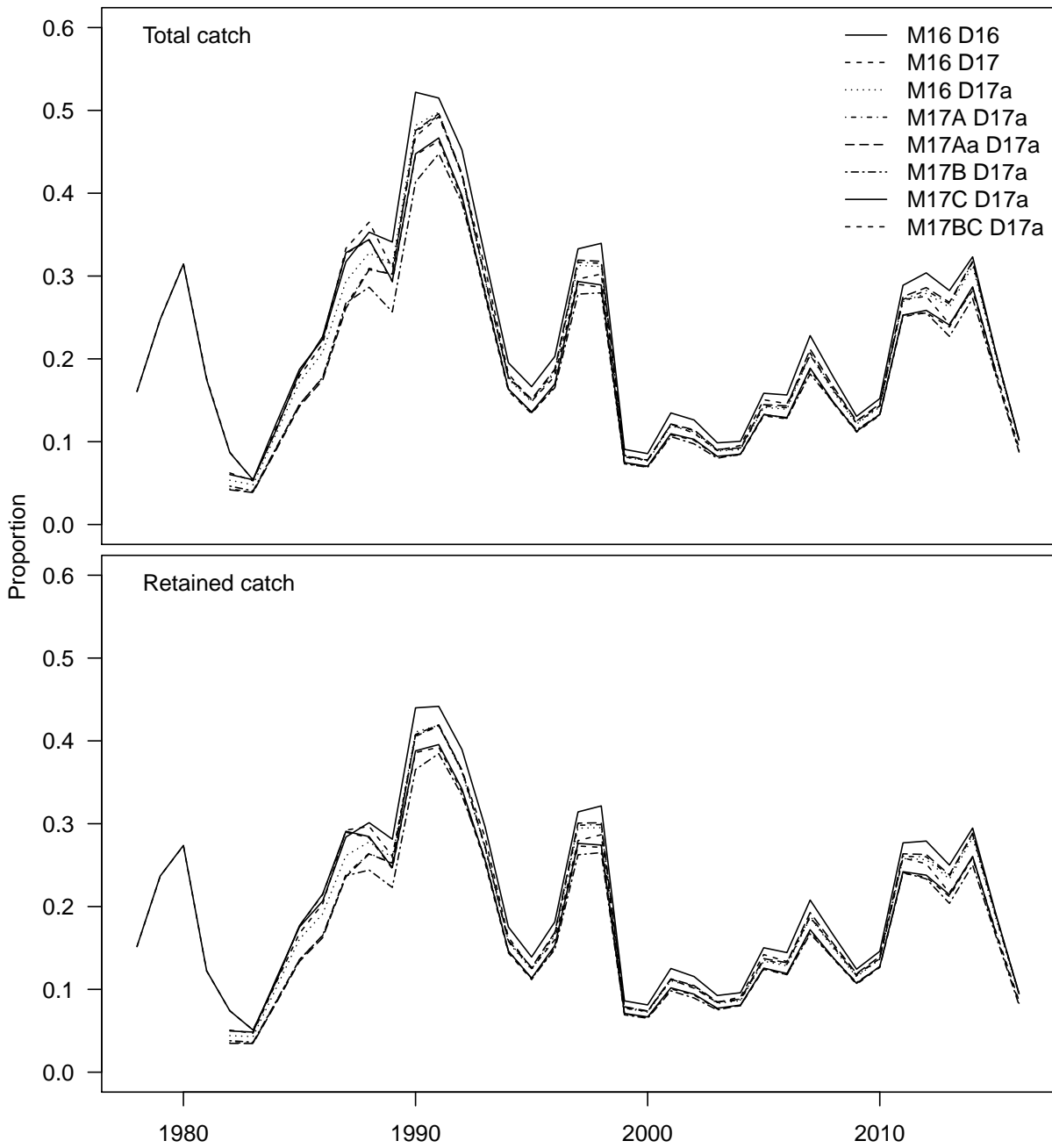


Figure 6: Model predicted ratio of catch to mature male biomass

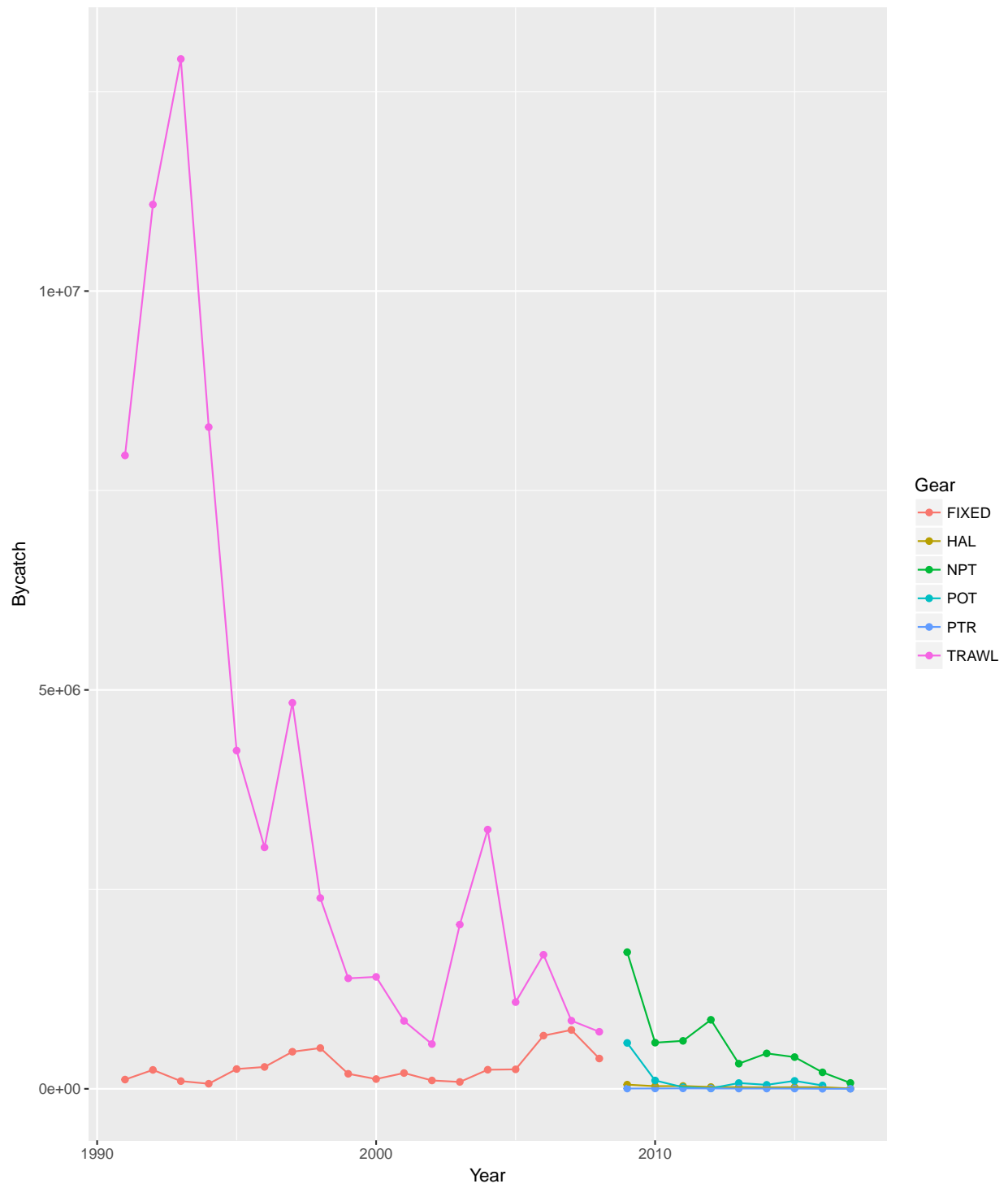


Figure 7: Bycatches in other fishing fleets.

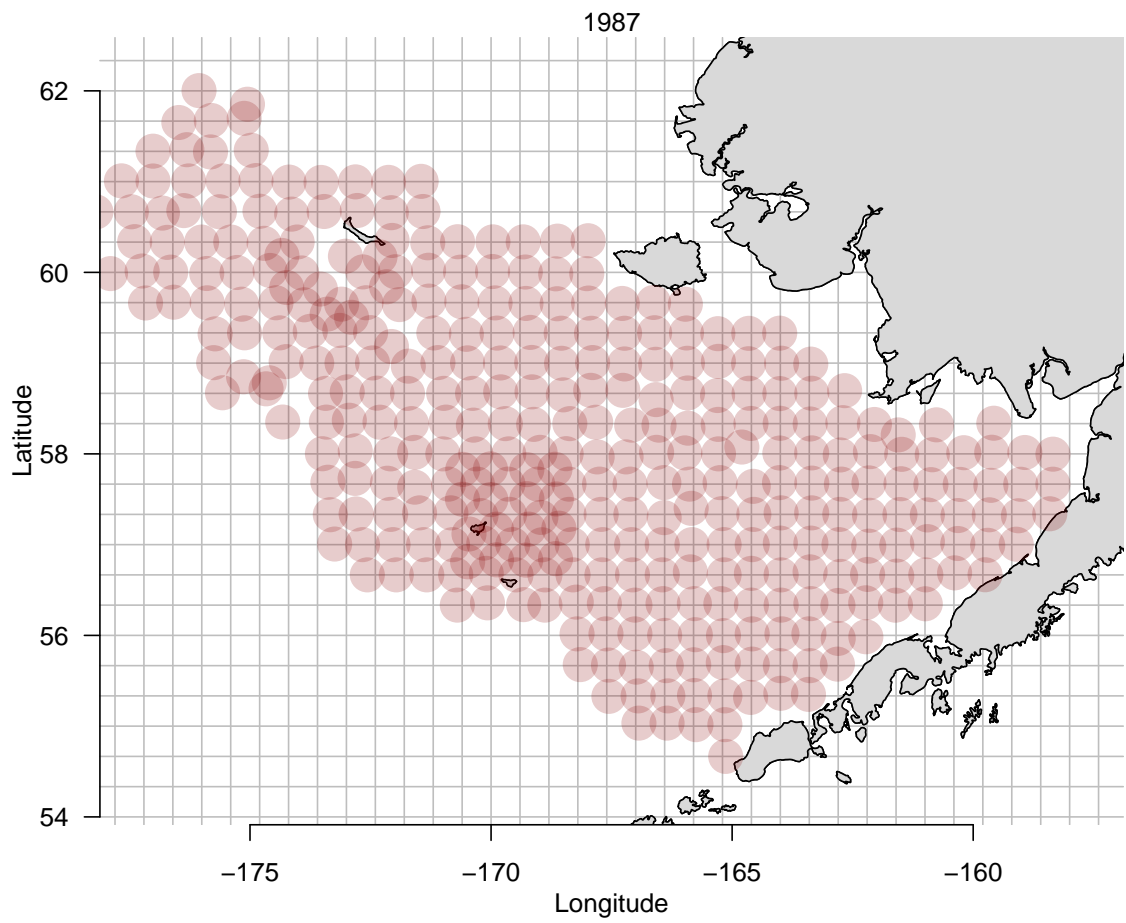


Figure 8: Distribution of survey locations in 1987

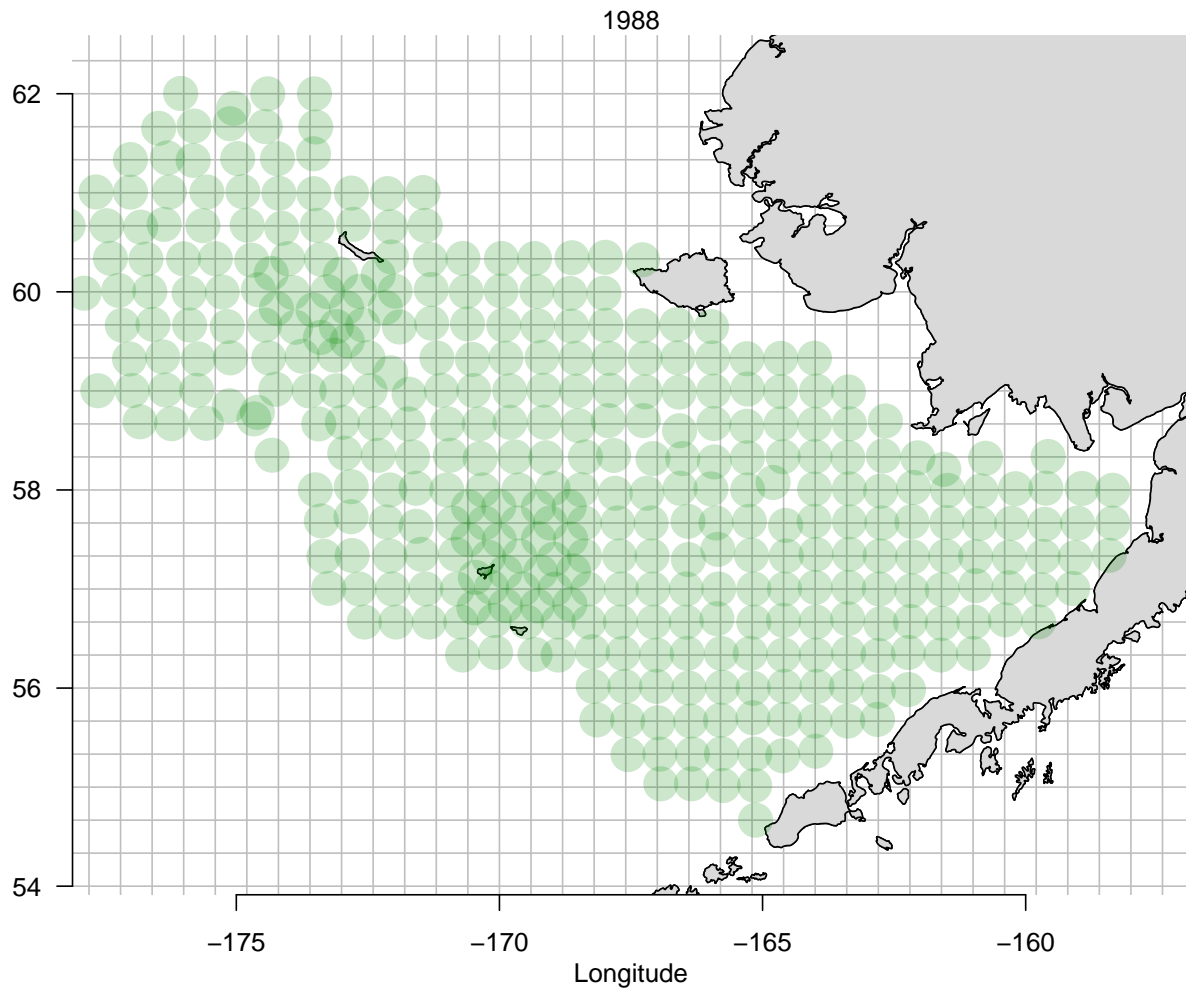


Figure 9: Distribution of survey locations in 1988

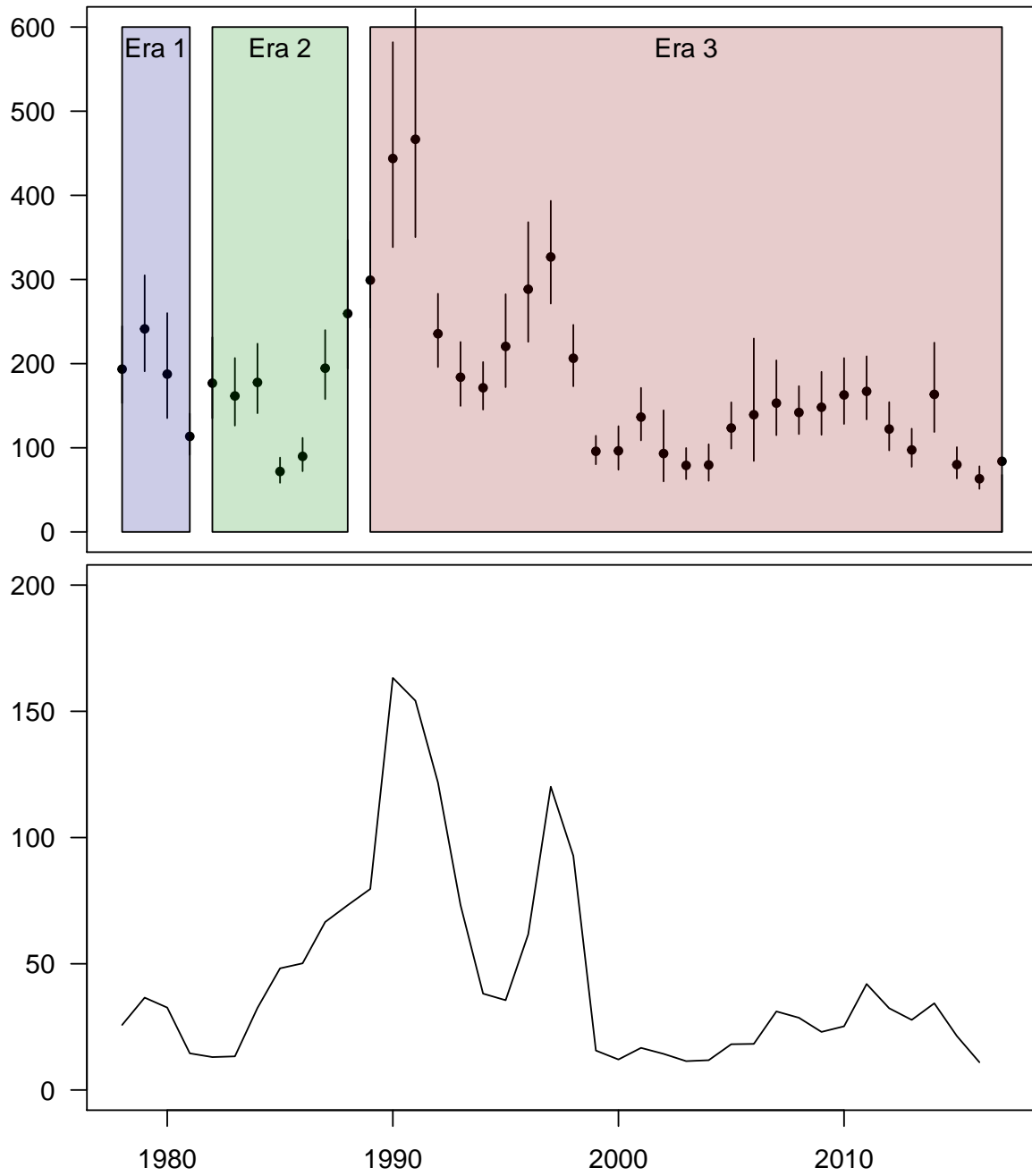


Figure 10: Divisions of survey data for estimation of q (MMB shown for reference) and total catches

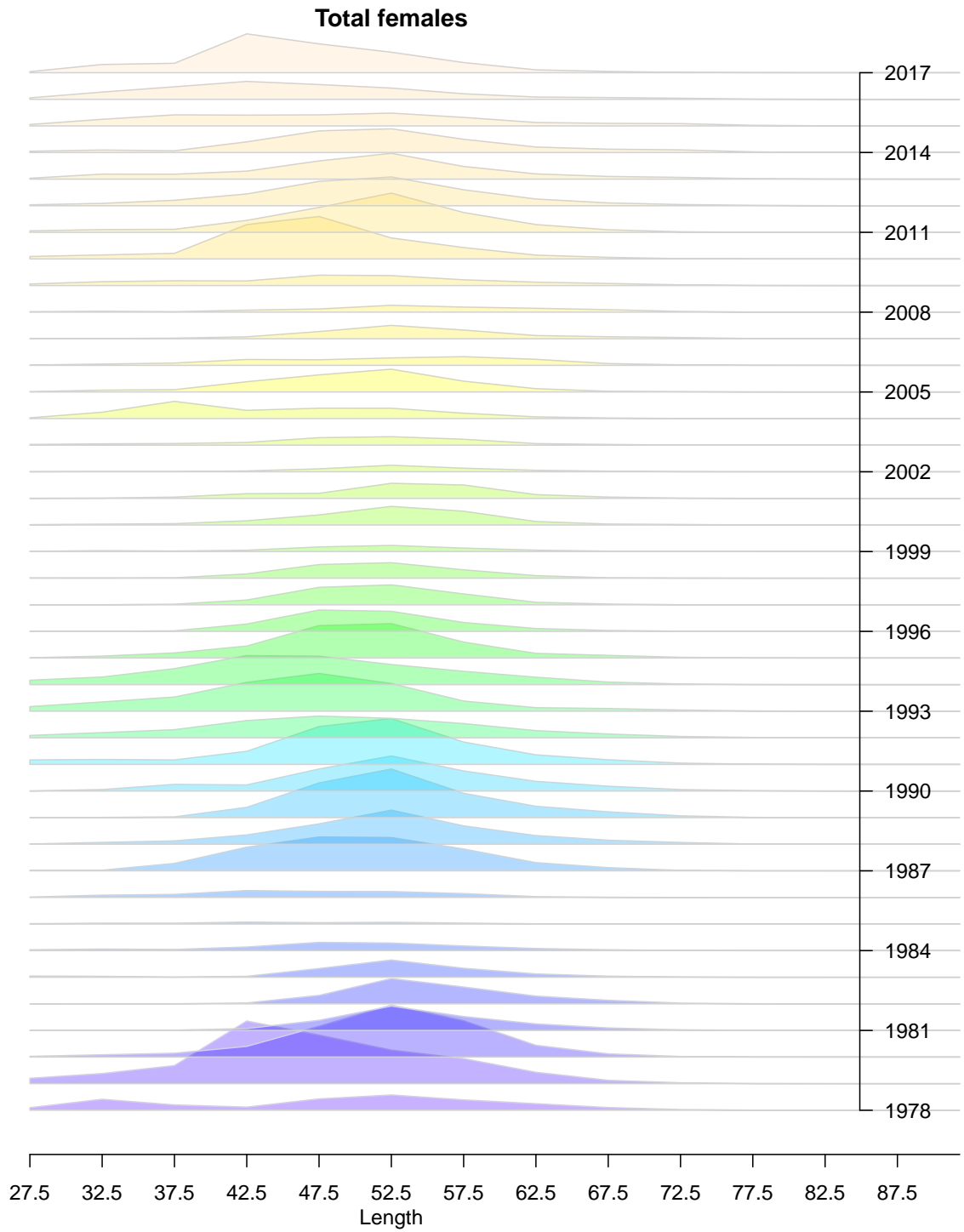


Figure 11: Observed relative numbers at length at the time of the survey

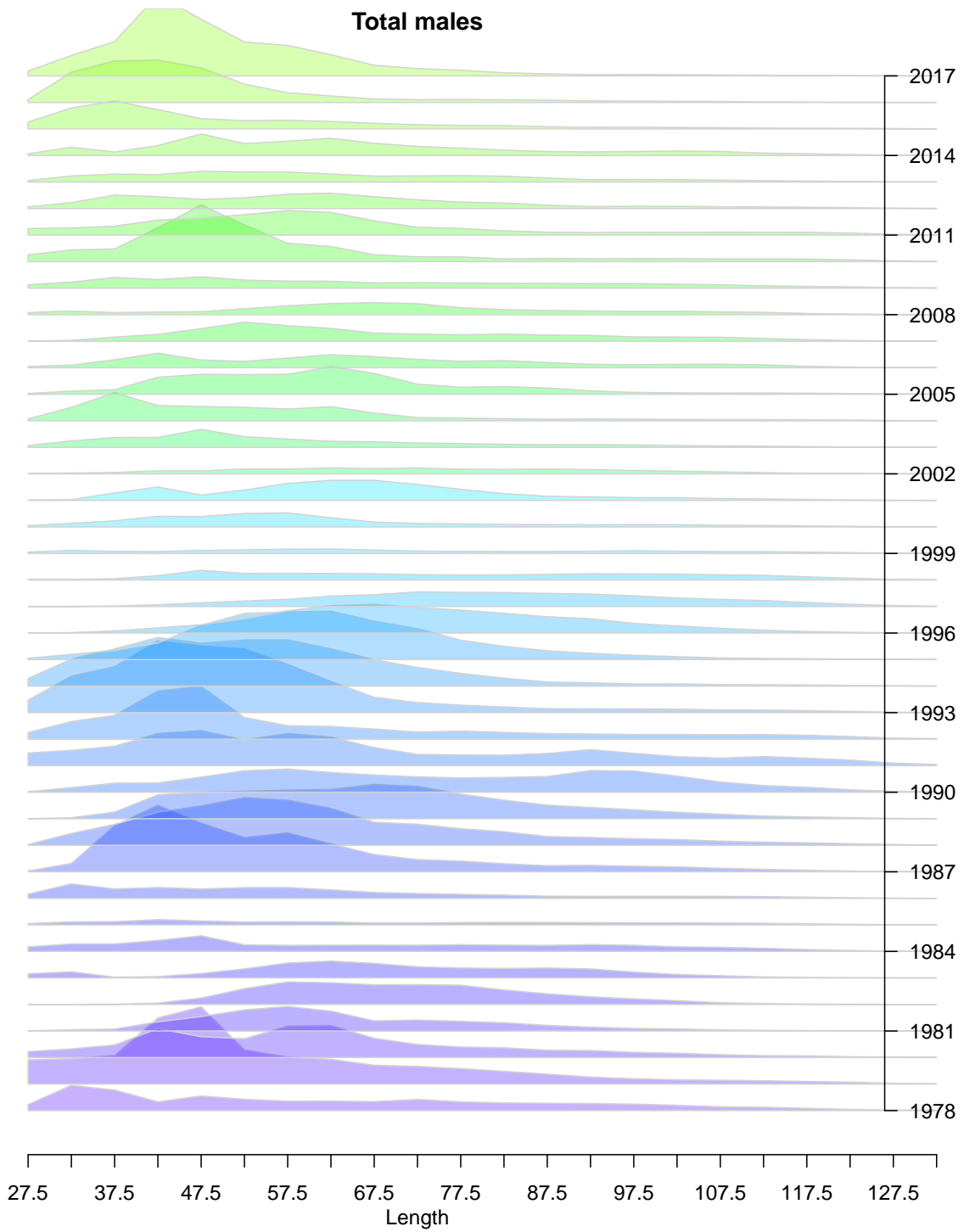


Figure 12: Observed relative numbers at length at the time of the survey

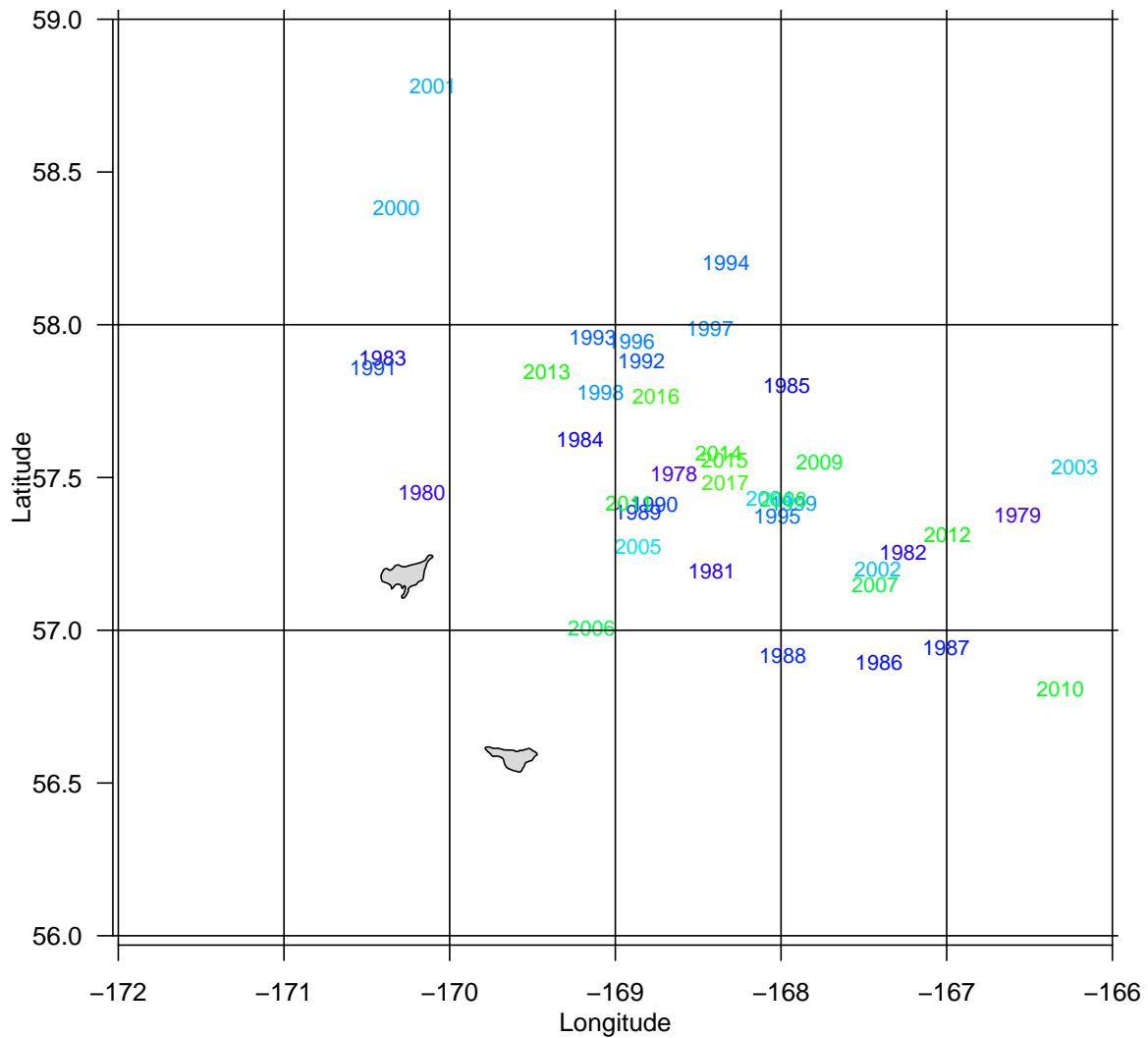


Figure 13: Centroid of mature females observed in the survey over time. Dark blue indicates years early in the time series; green are the most recent years in the time series.

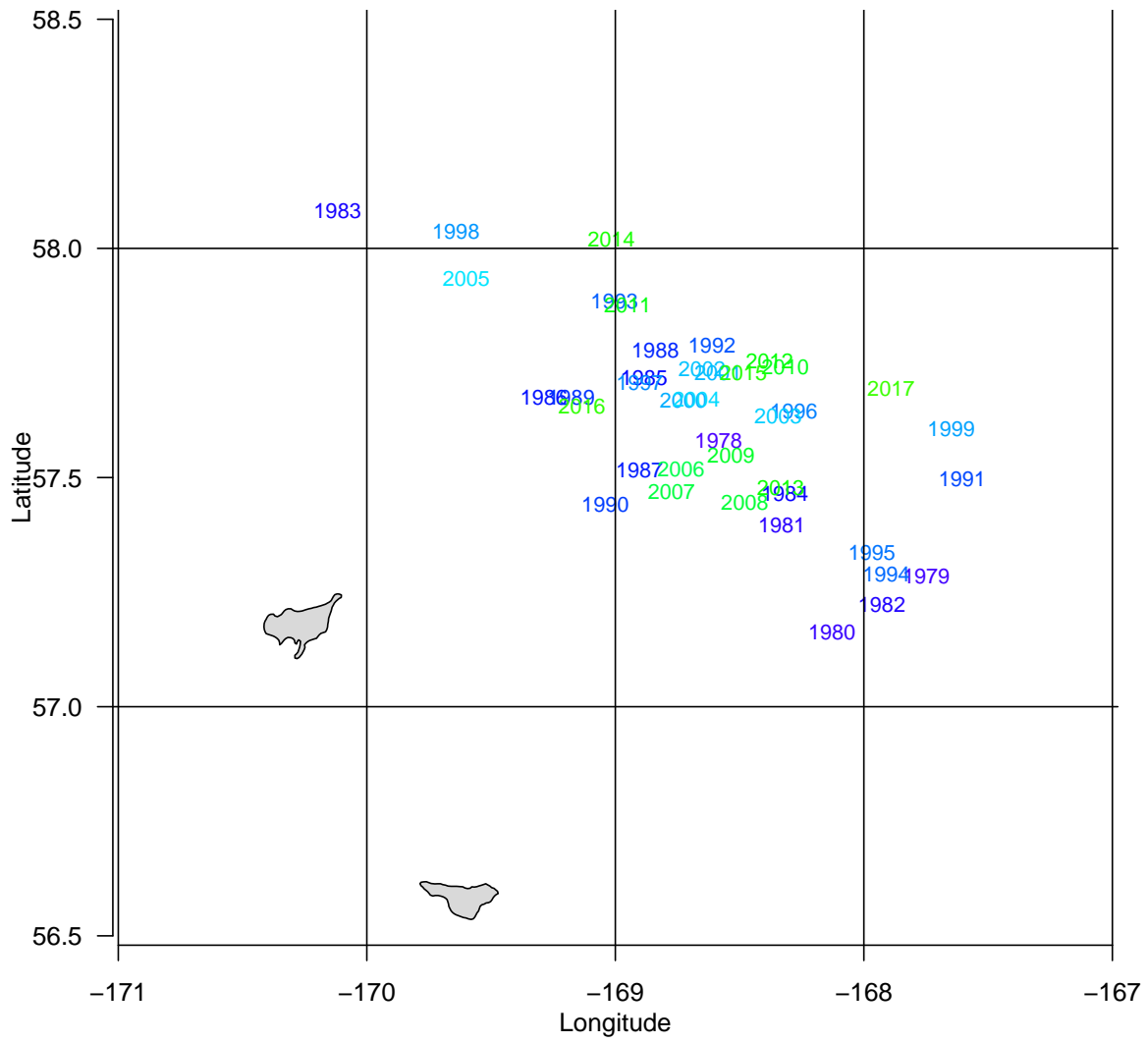


Figure 14: Centroid of large males observed in the survey over time. Dark blue indicates years early in the time series; green are the most recent years in the time series.

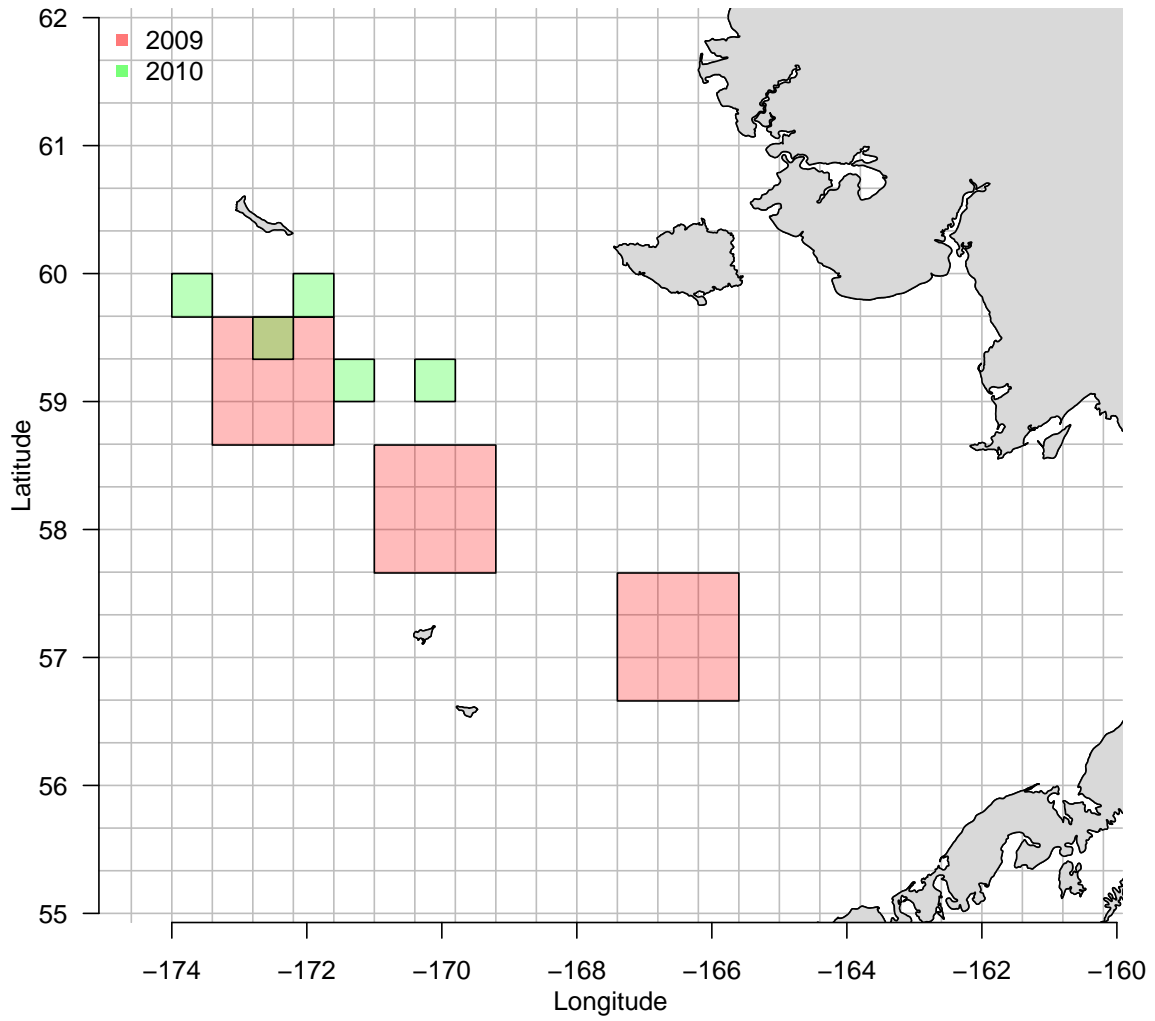


Figure 15: Location of survey selectivity experiments (2009 & 2010; this was reproduced from the 2015 SAFE; revise this figure with BSFRF data)

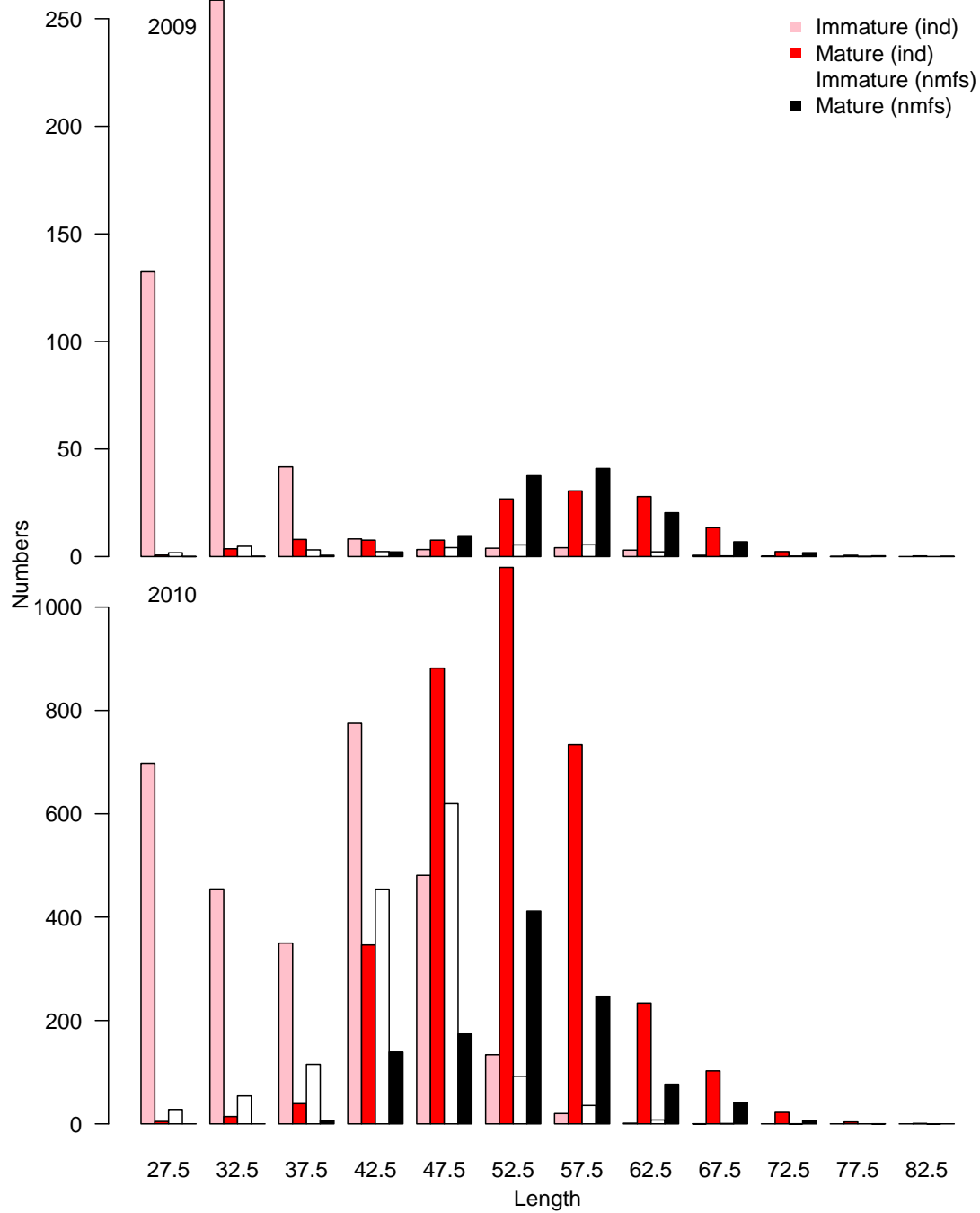


Figure 16: Raw female numbers from BSFRF survey selectivity experiments (2009 & 2010). Note a change in scale on the y-axis from 2009 to 2010

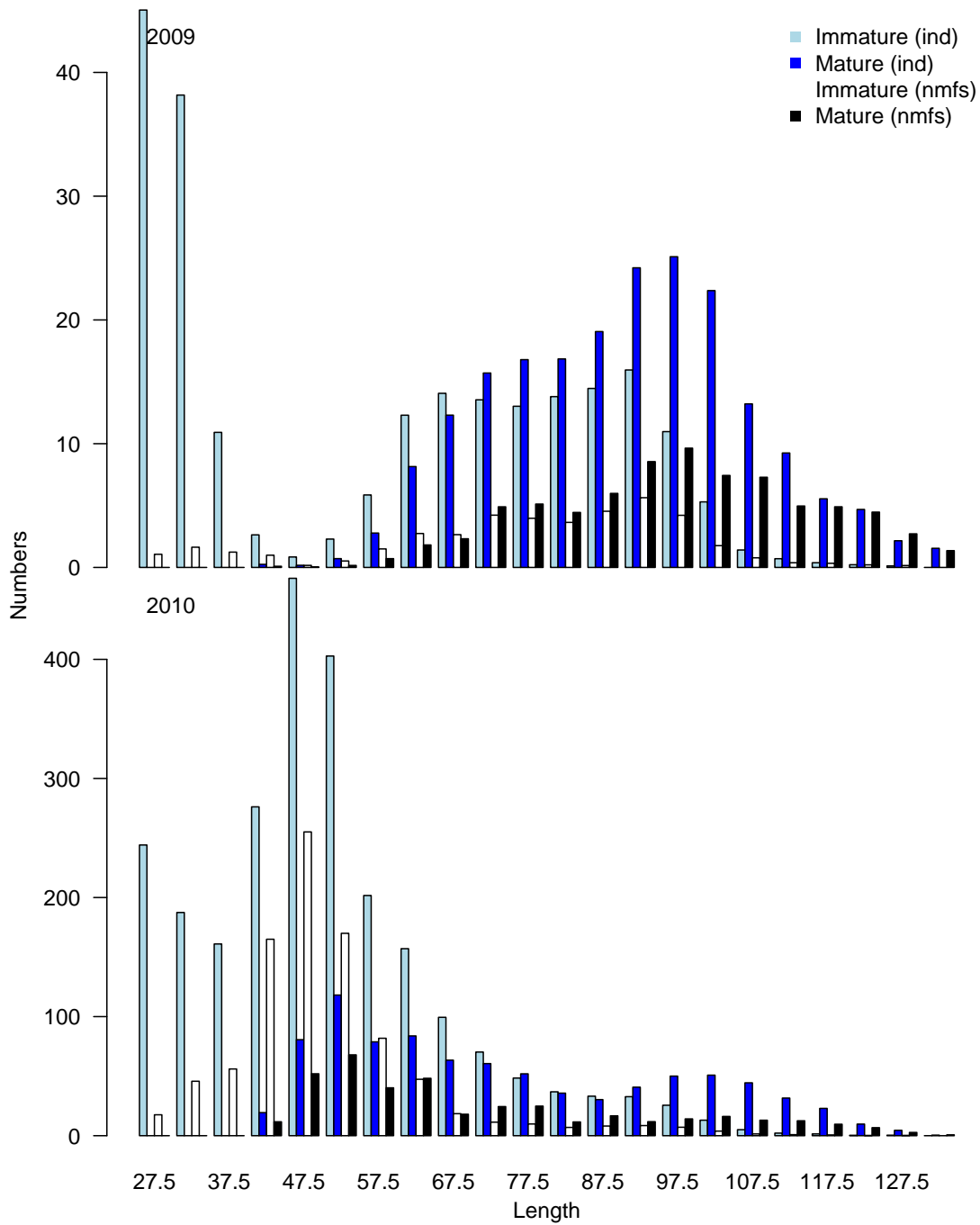


Figure 17: Raw male numbers from BSFRF survey selectivity experiments (2009 & 2010). Note a change in scale from 2009 to 2010 on the y-axis.

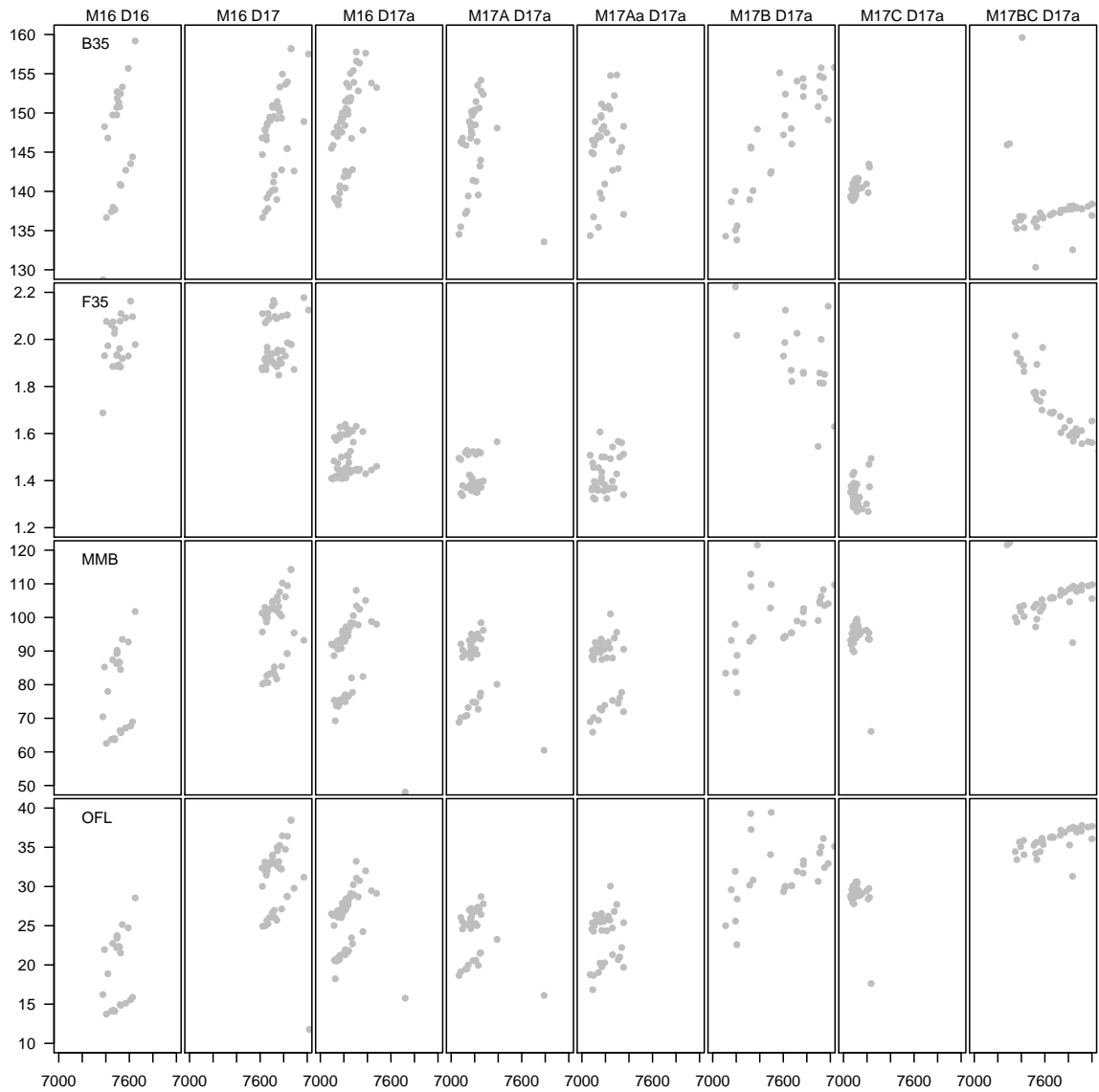


Figure 18: Management quantities after jittering all models.

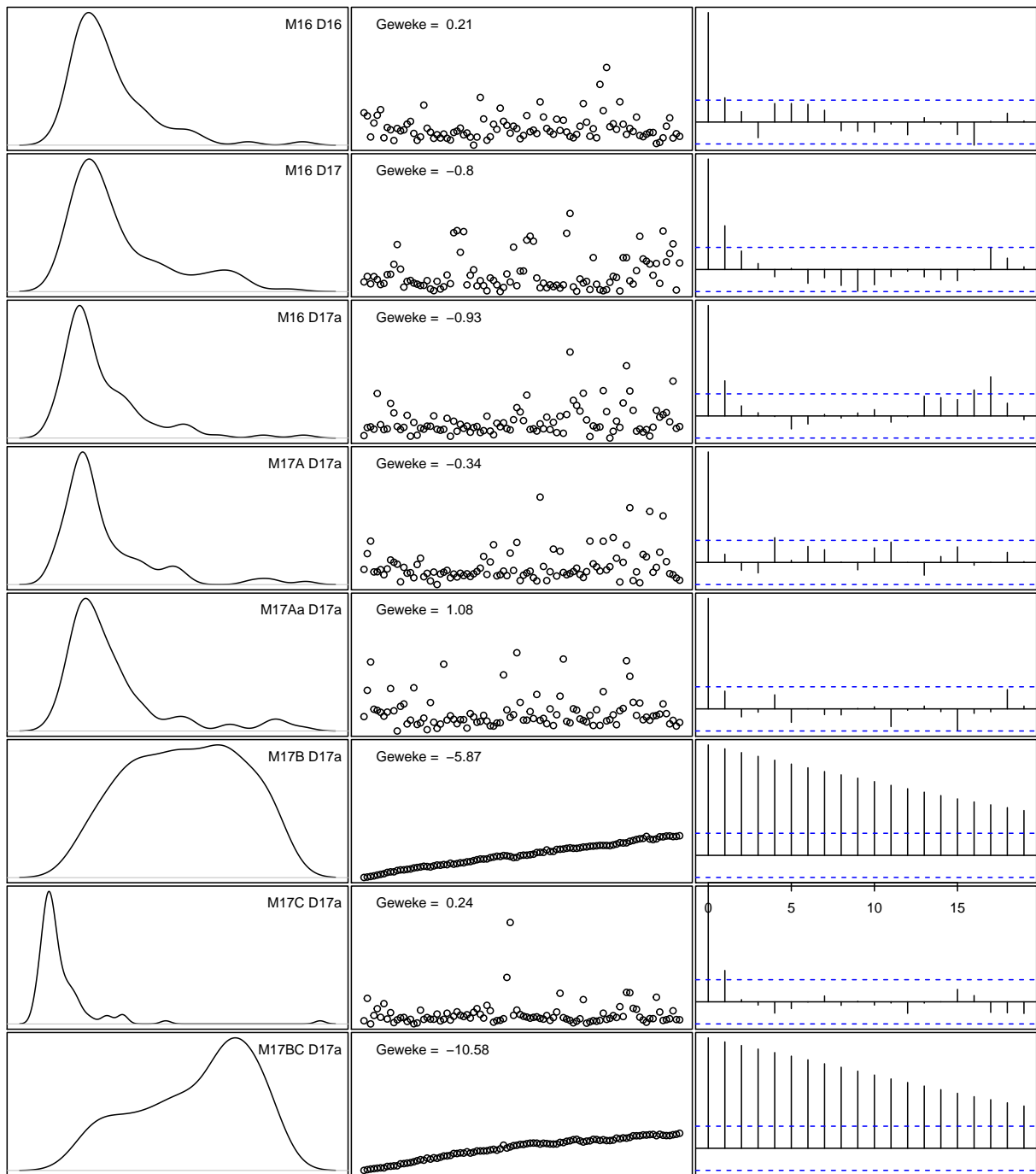


Figure 19: Basic MCMC diagnostics. Left column is the density of the value of the objective function. Middle column is the trace of the objective function. Number in the upper left of each panel is the z-score of the Geweke diagnostic. Right is the autocorrelation in the objective function value.

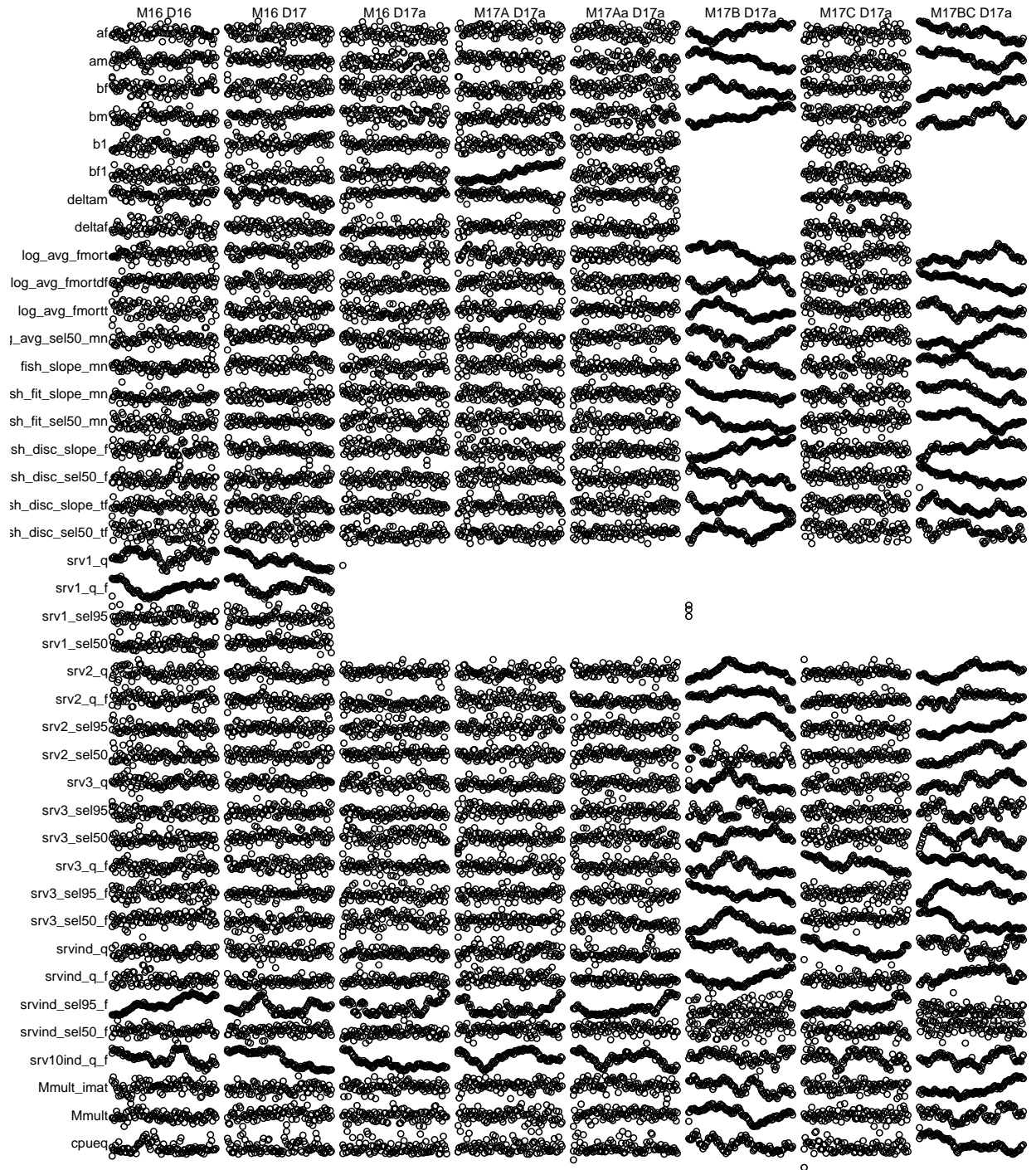


Figure 20: Traces for parameters from each model

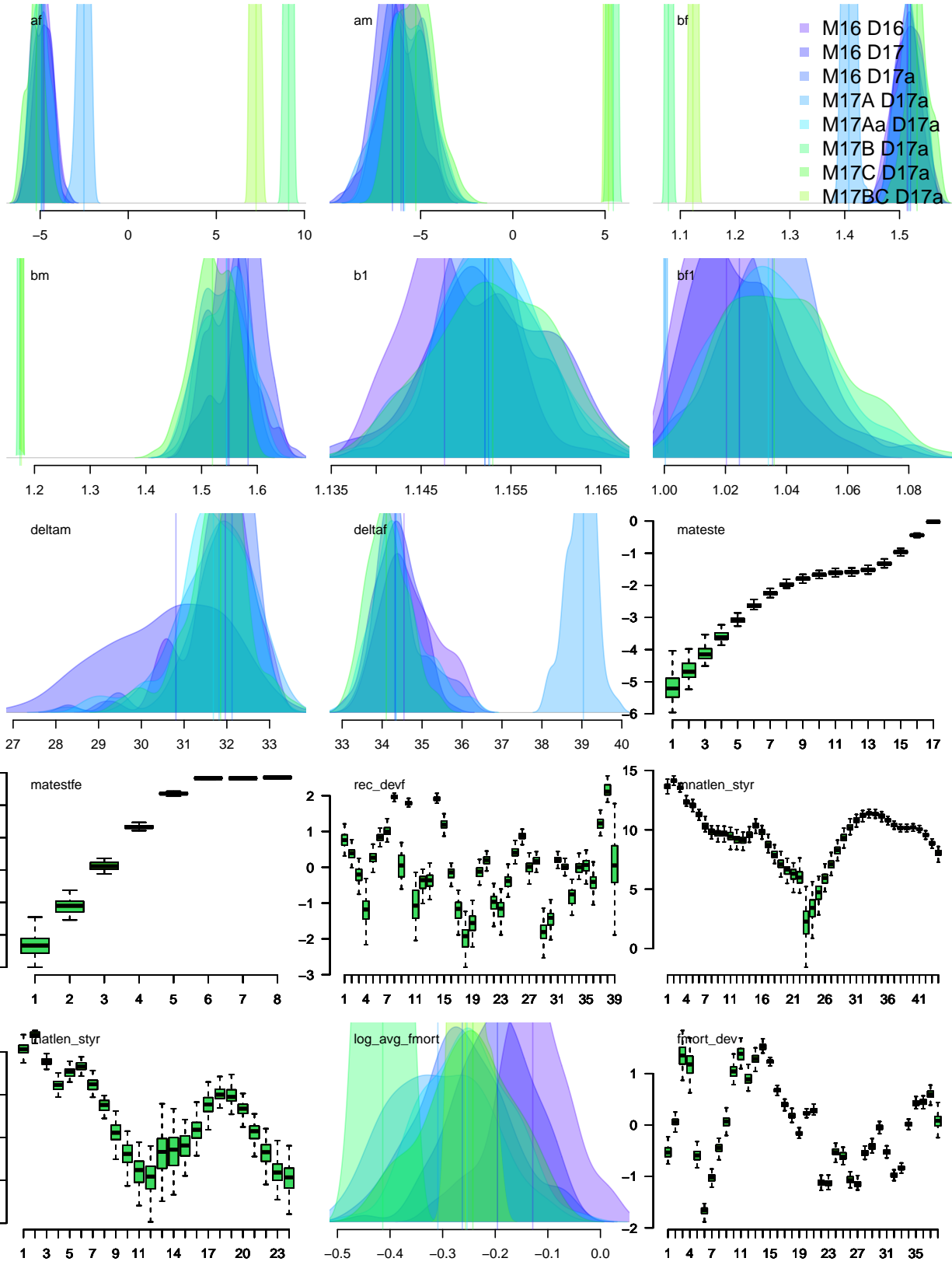


Figure 21: Posterior densities for estimated parameters by scenario

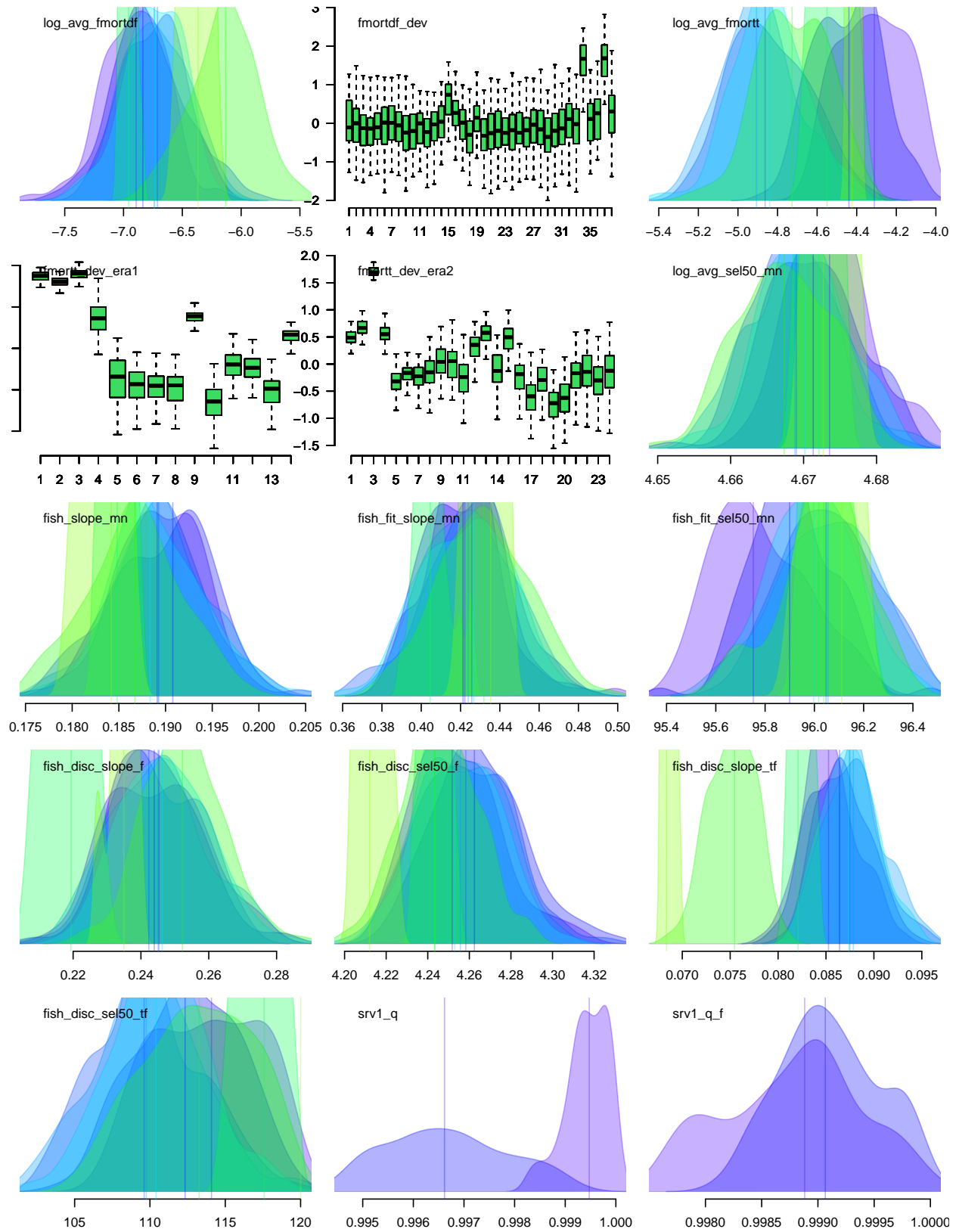


Figure 22: Posterior densities for estimated parameters by scenario

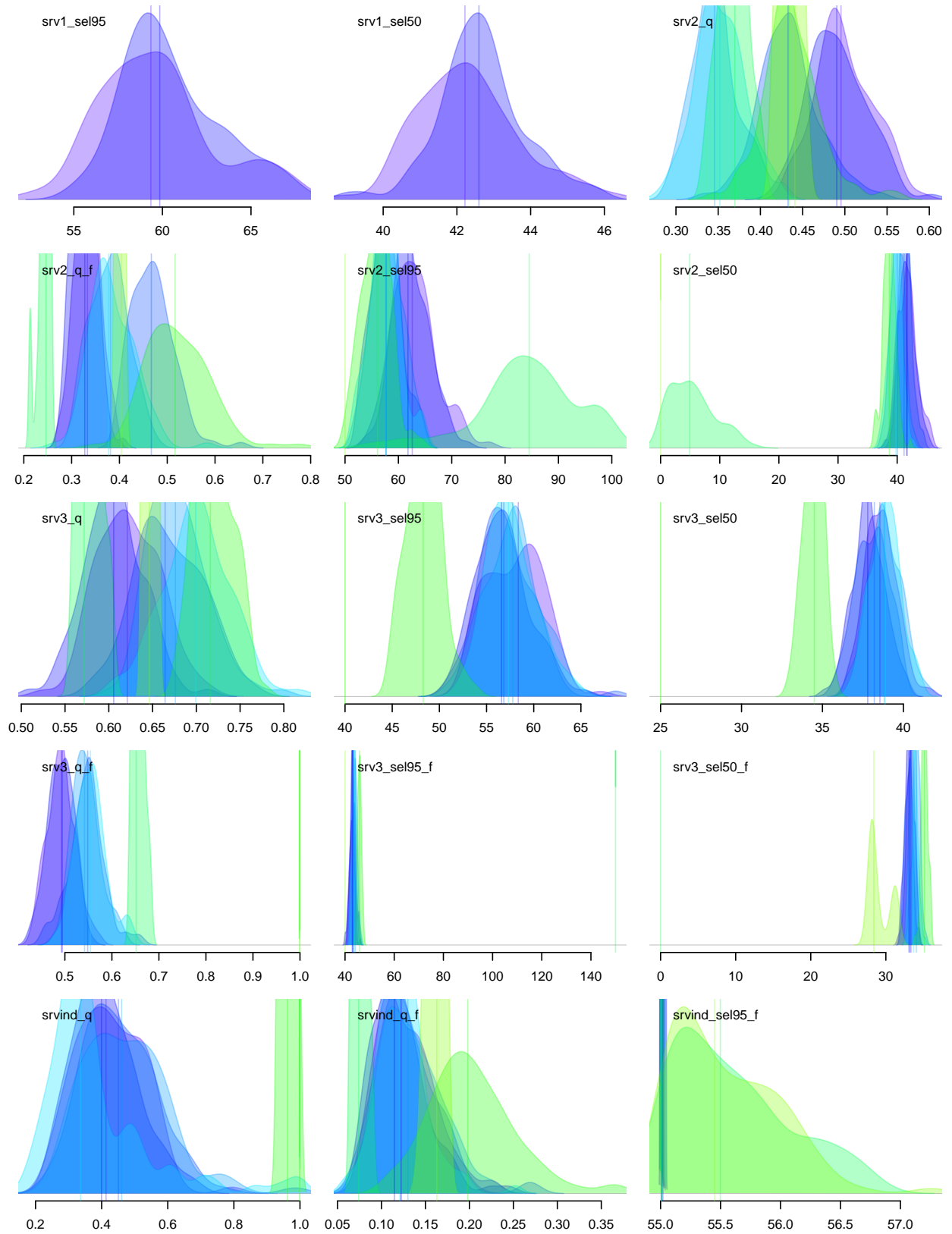


Figure 23: Posterior densities for estimated parameters by scenario

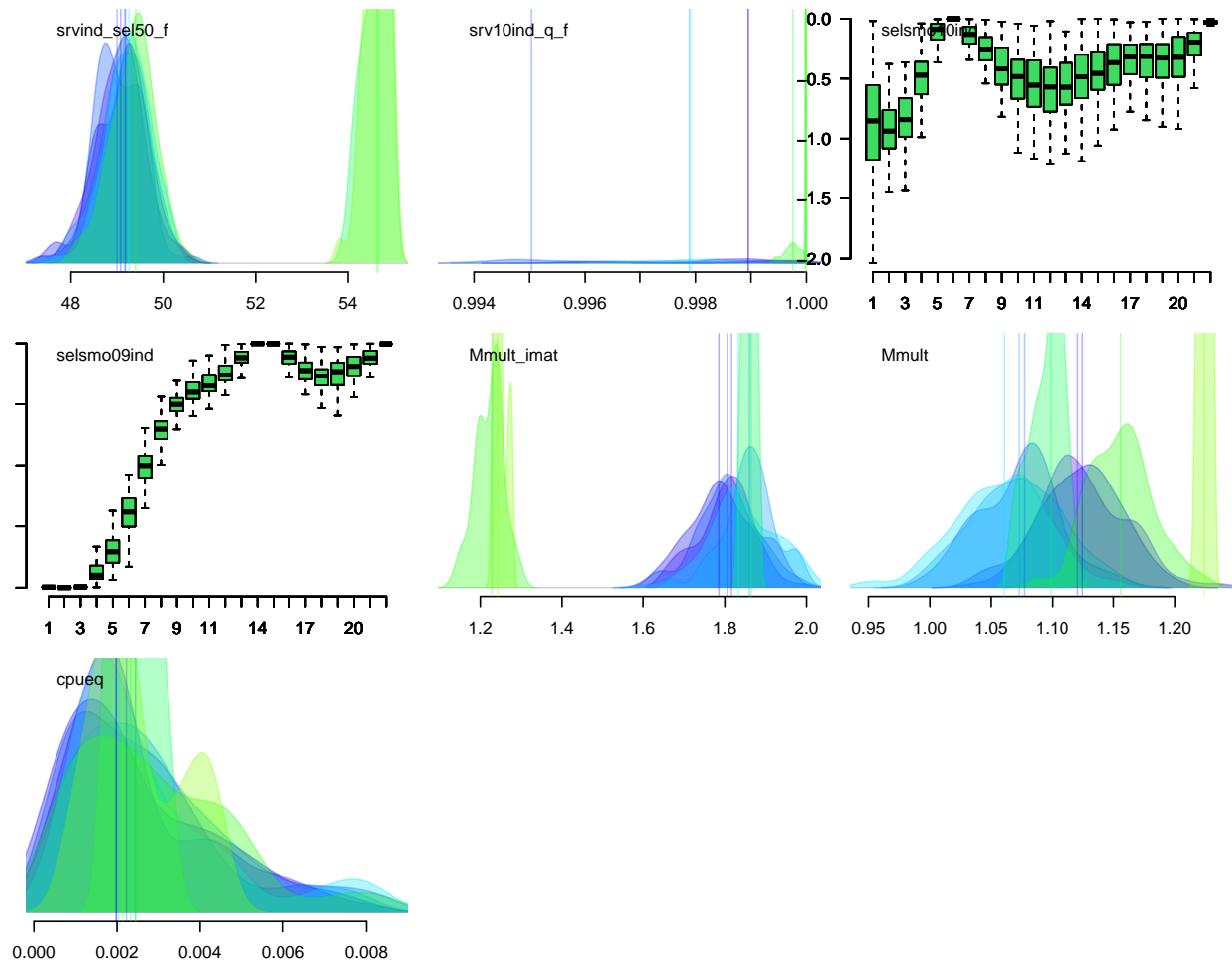


Figure 24: Posterior densities for estimated parameters by scenario

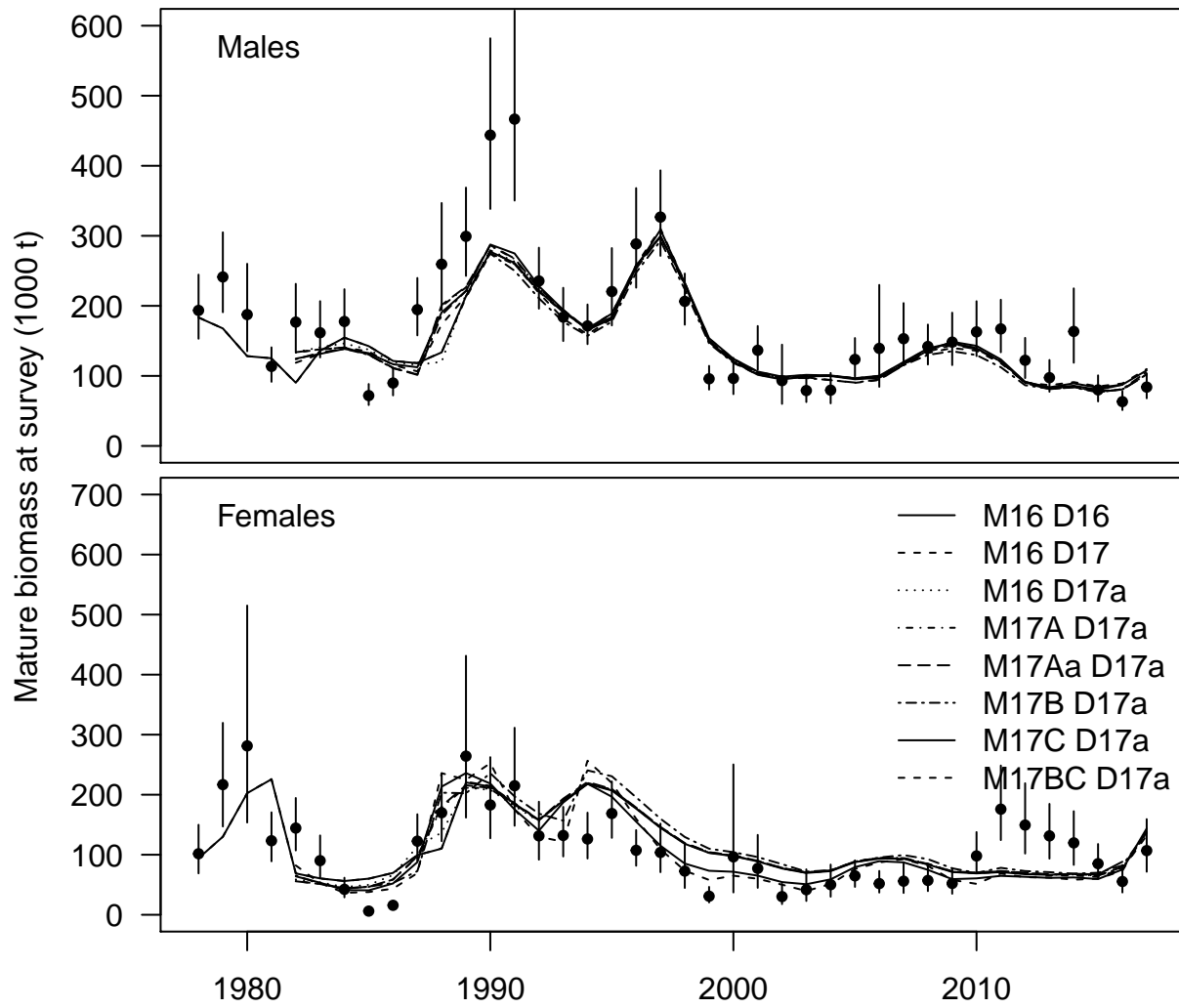


Figure 25: Model fits to the observed mature biomass at survey

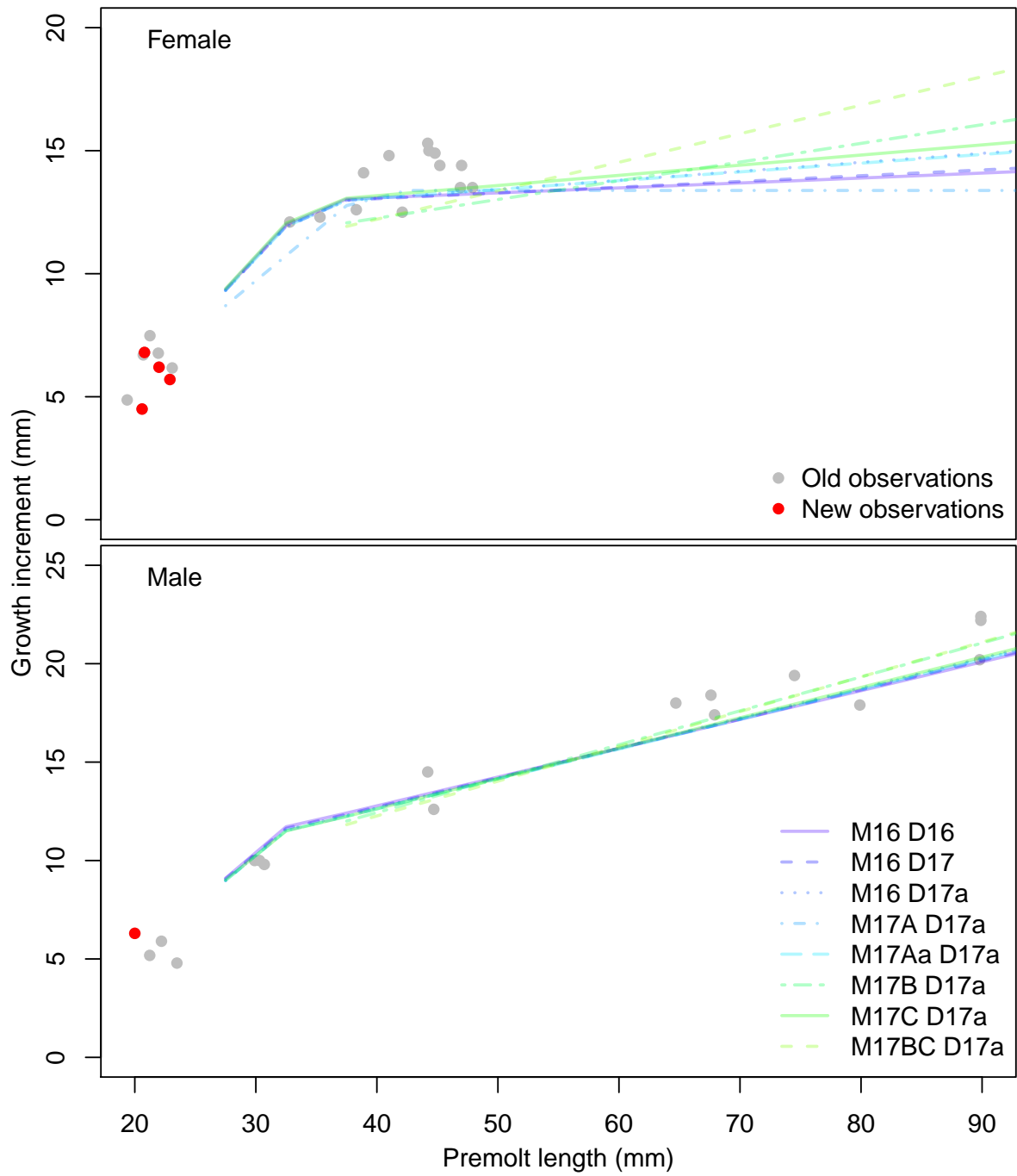


Figure 26: Model fits to the growth data

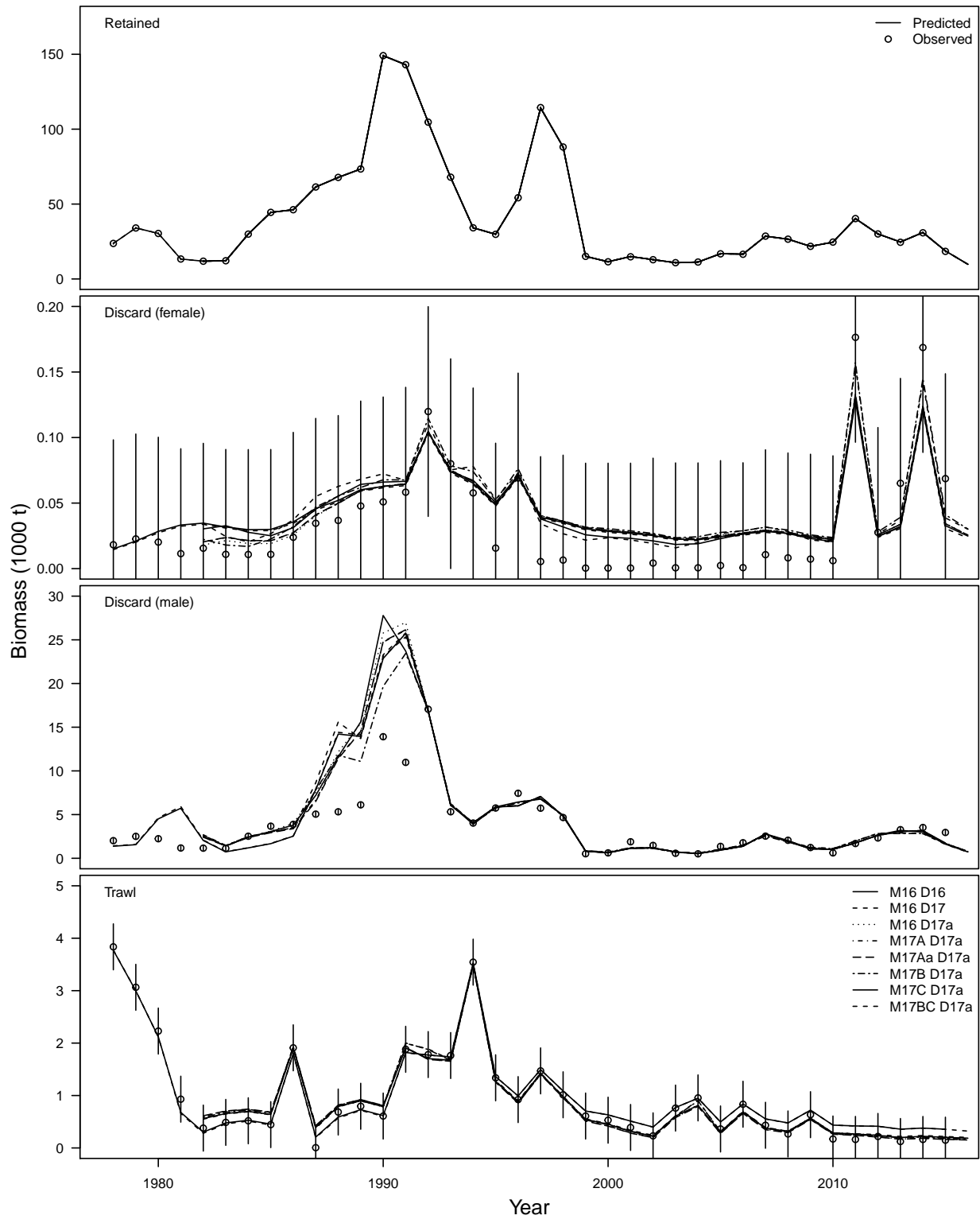


Figure 27: Model fits to catch data

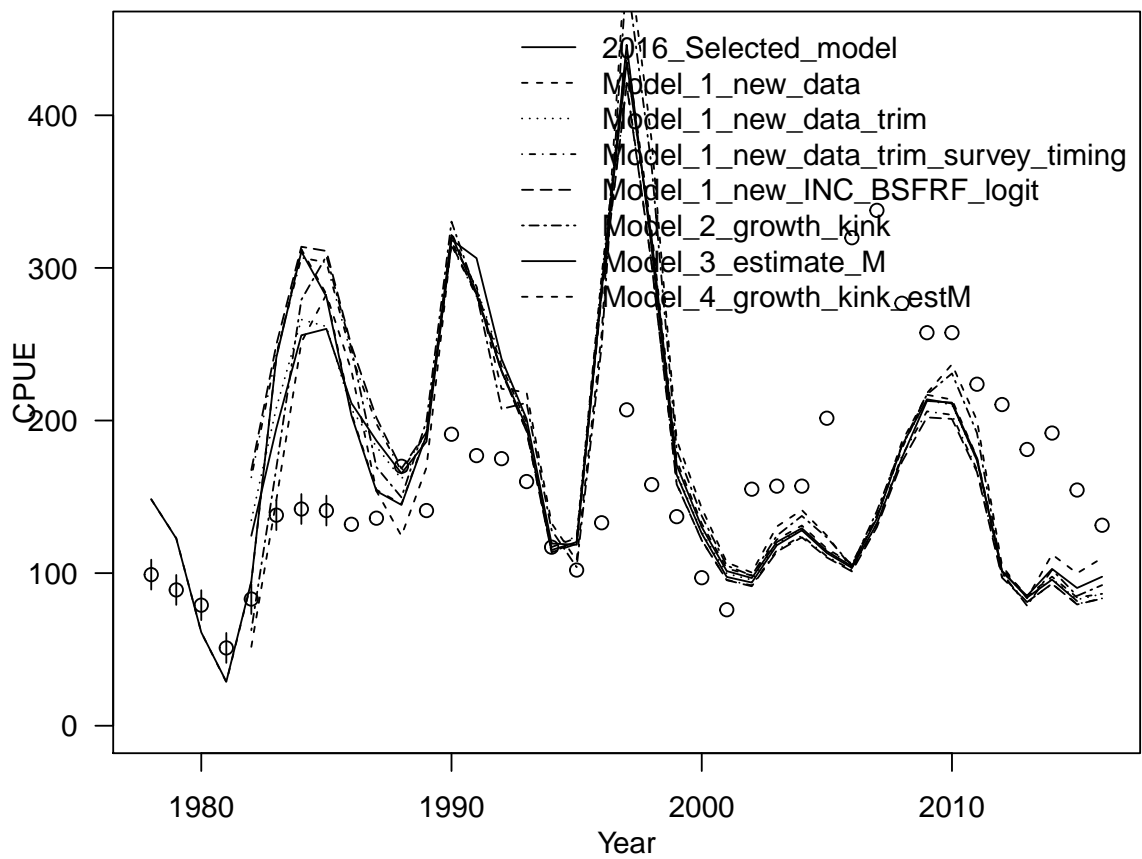


Figure 28: Model fits to pot CPUE data

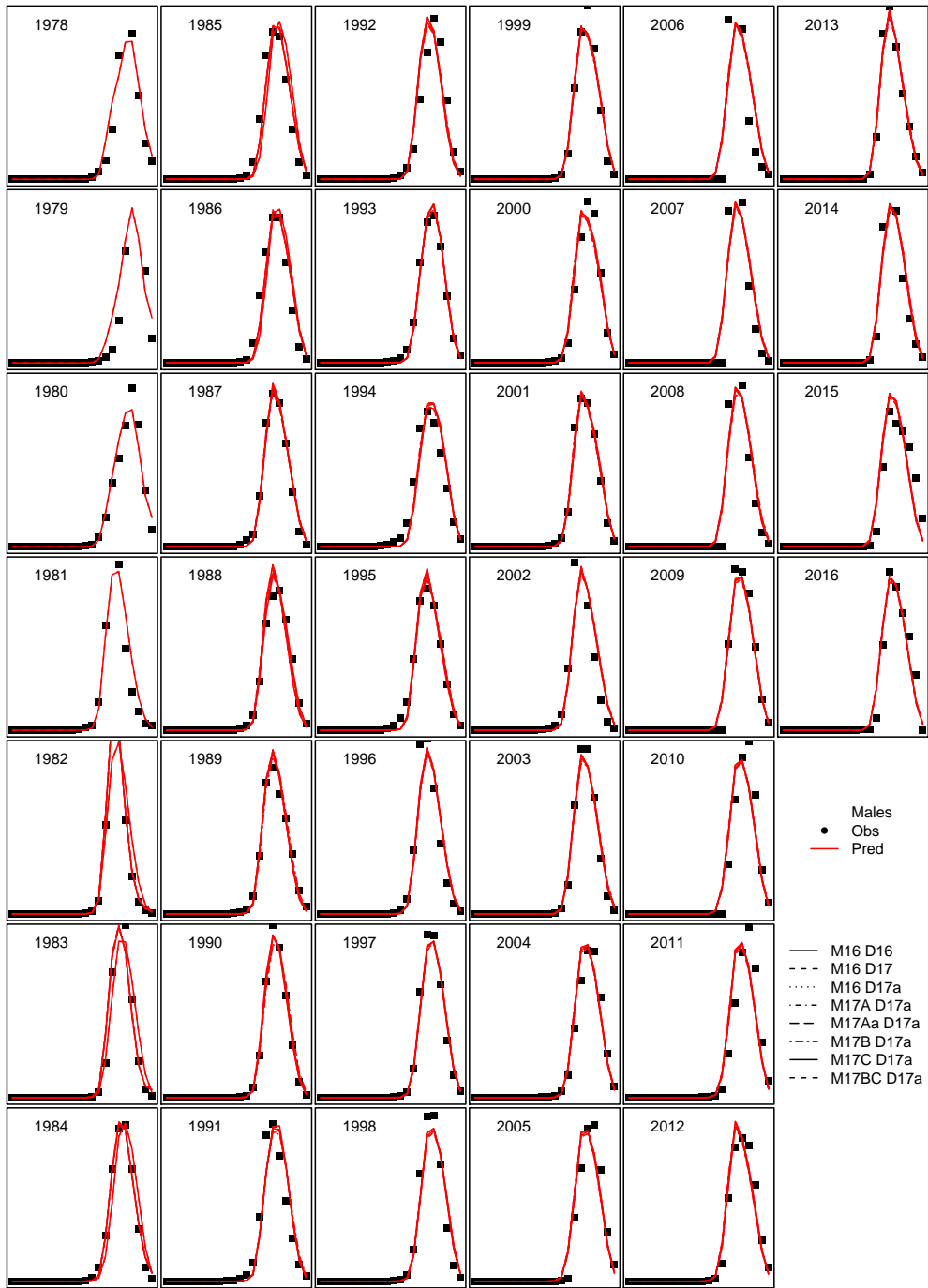


Figure 29: Model fits to retained catch size composition data

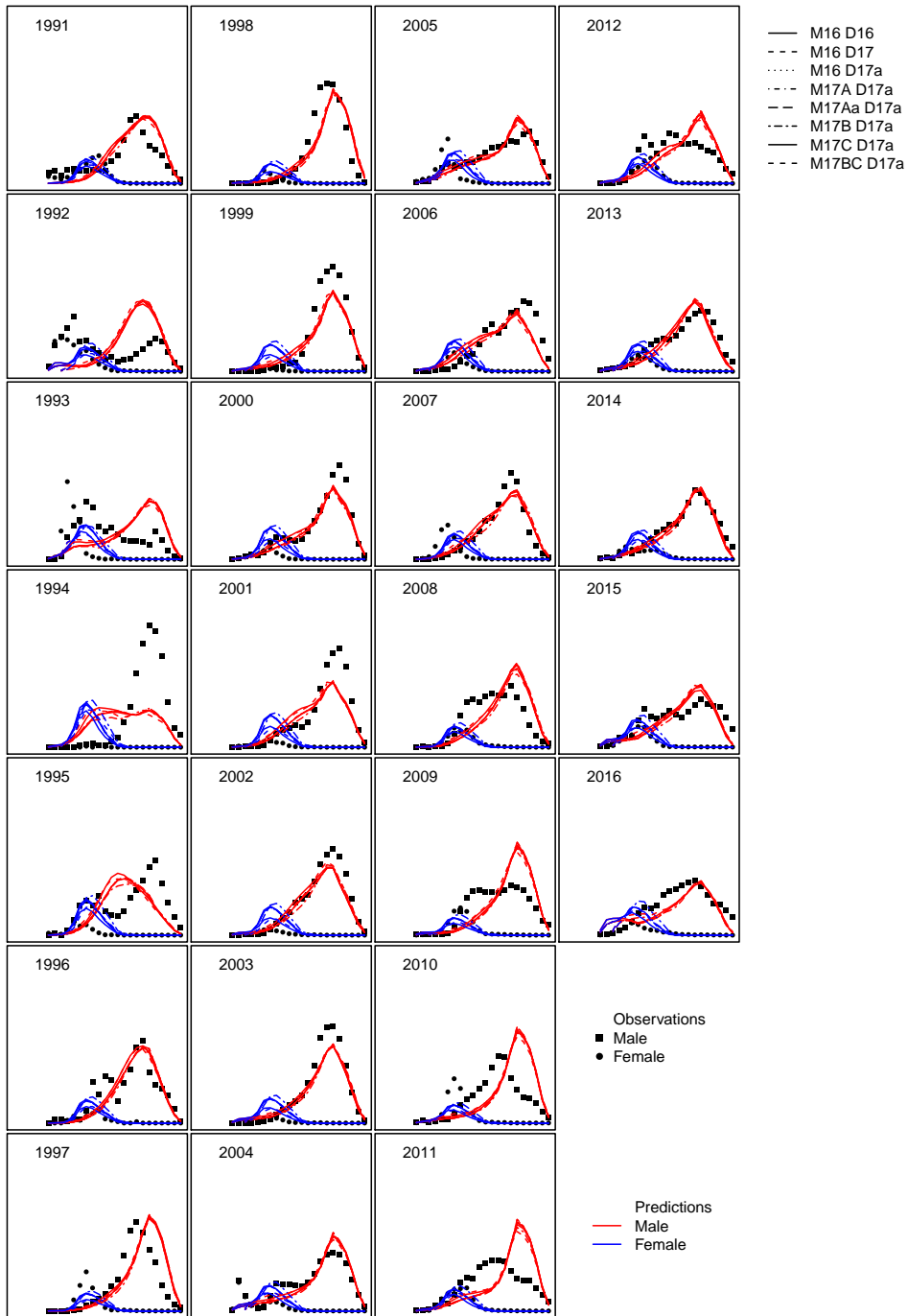


Figure 30: Model fits to trawl catch size composition data

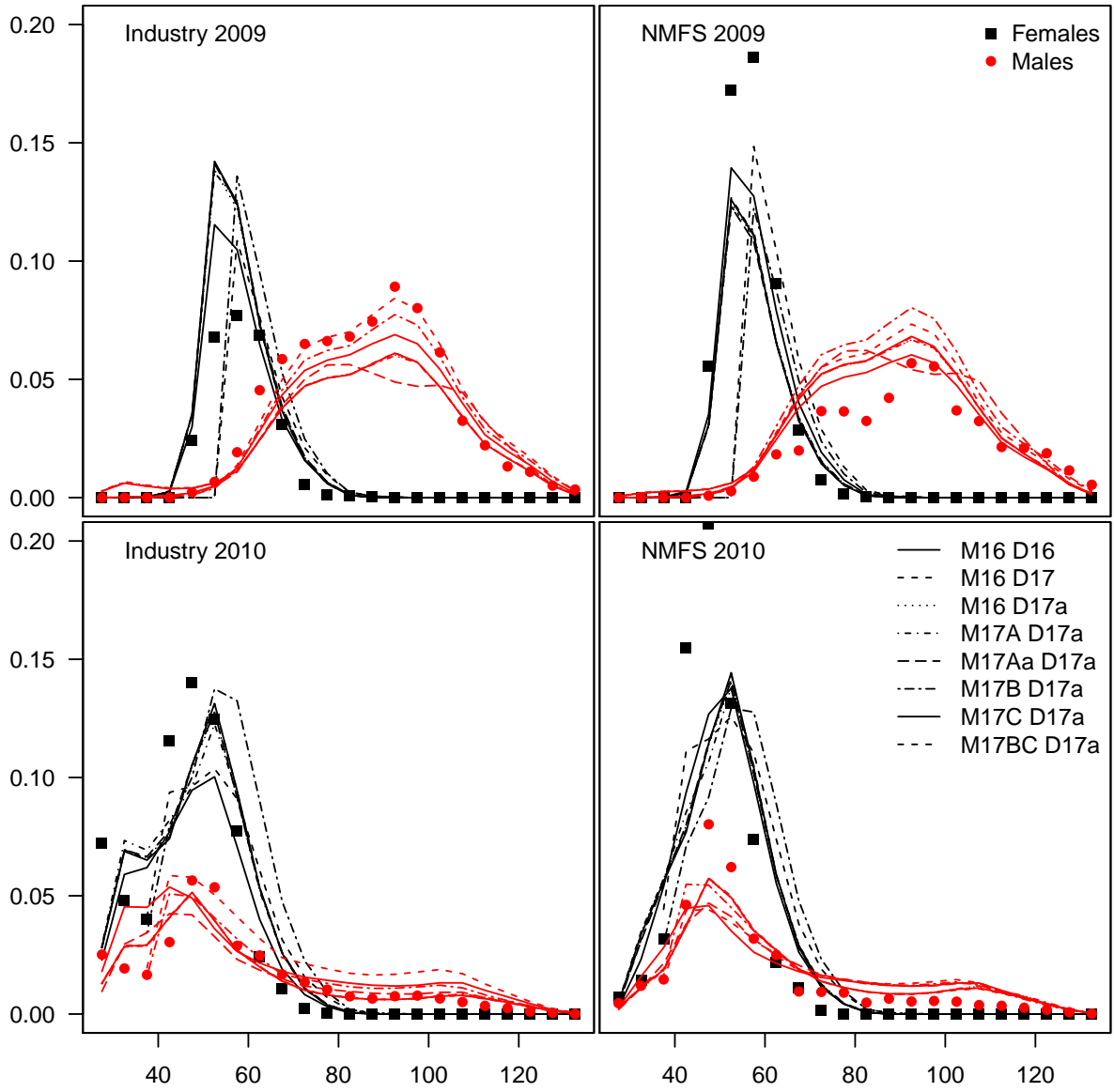


Figure 31: Model fits to size composition data from summer survey experiments (2009 & 2010)

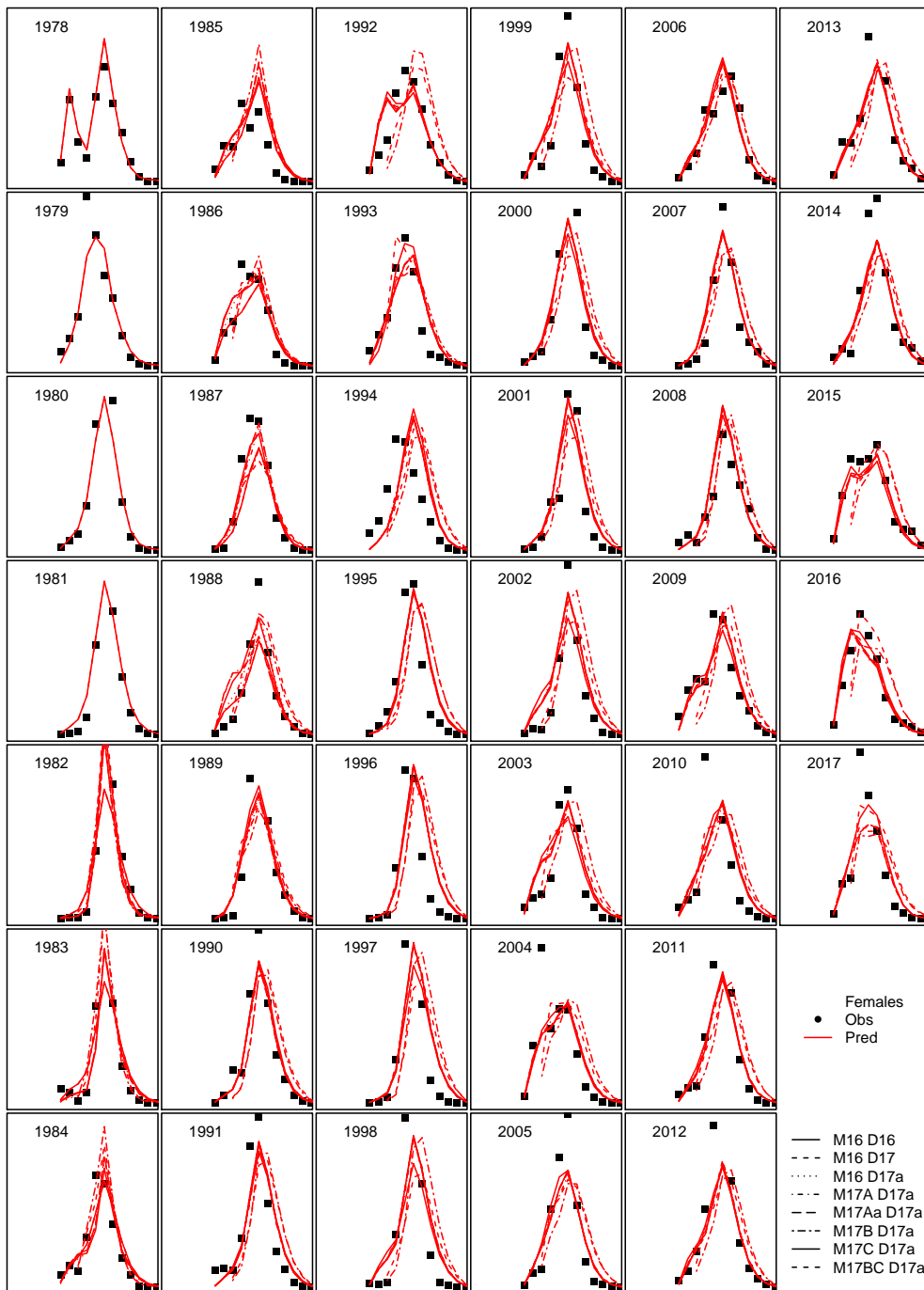


Figure 32: Model fits to female survey size composition data. Note that male and female survey selectivity proportions at length in a given year sum to 1. Consequently, the integral of predicted length compositions may appear to be different than the integral of the observed length composition data.

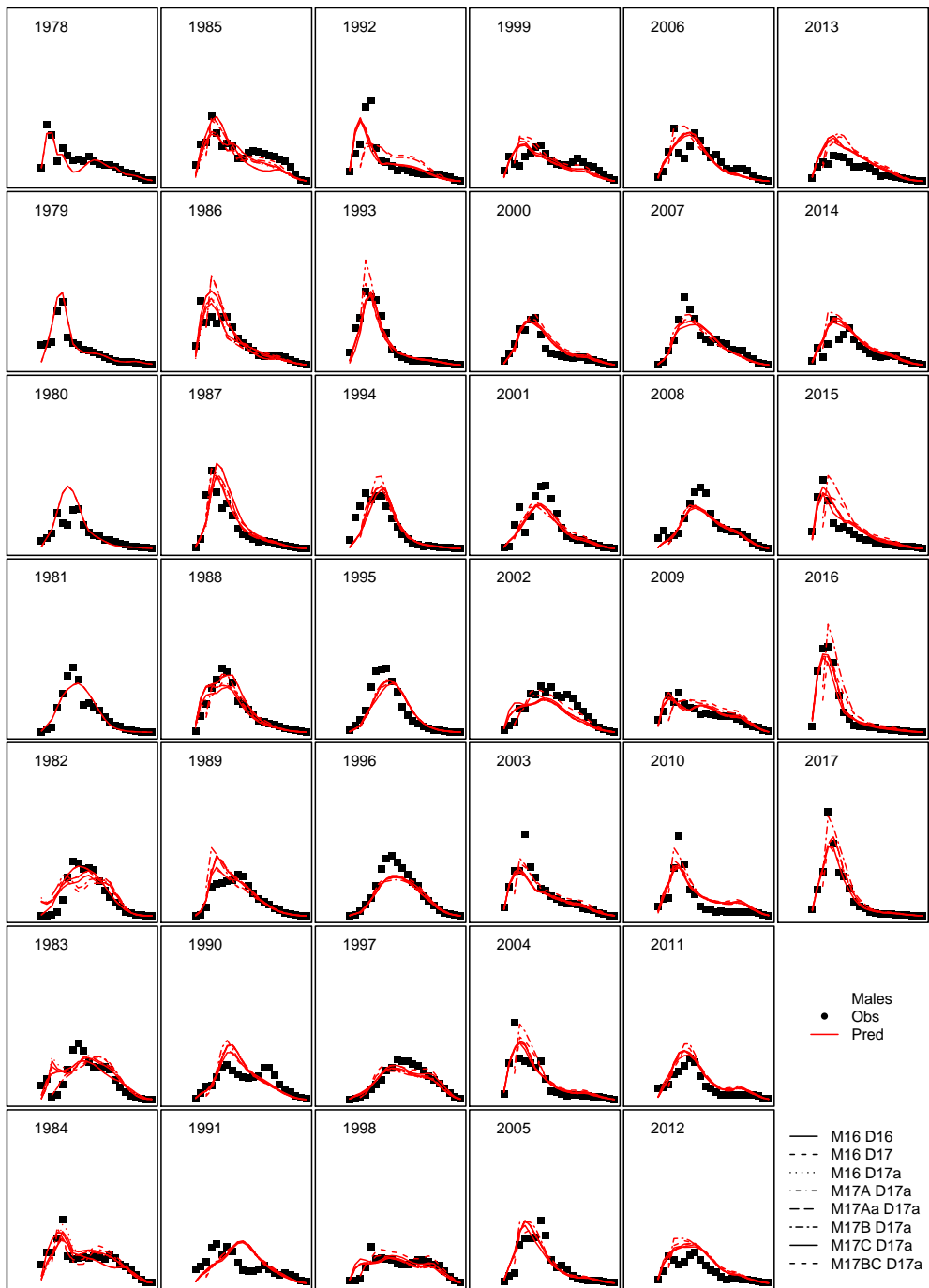


Figure 33: Model fits to male survey size composition data. Note that male and female survey selectivity proportions at length in a given year sum to 1. Consequently, the integral of predicted length compositions may appear to be different than the integral of the observed length composition data.

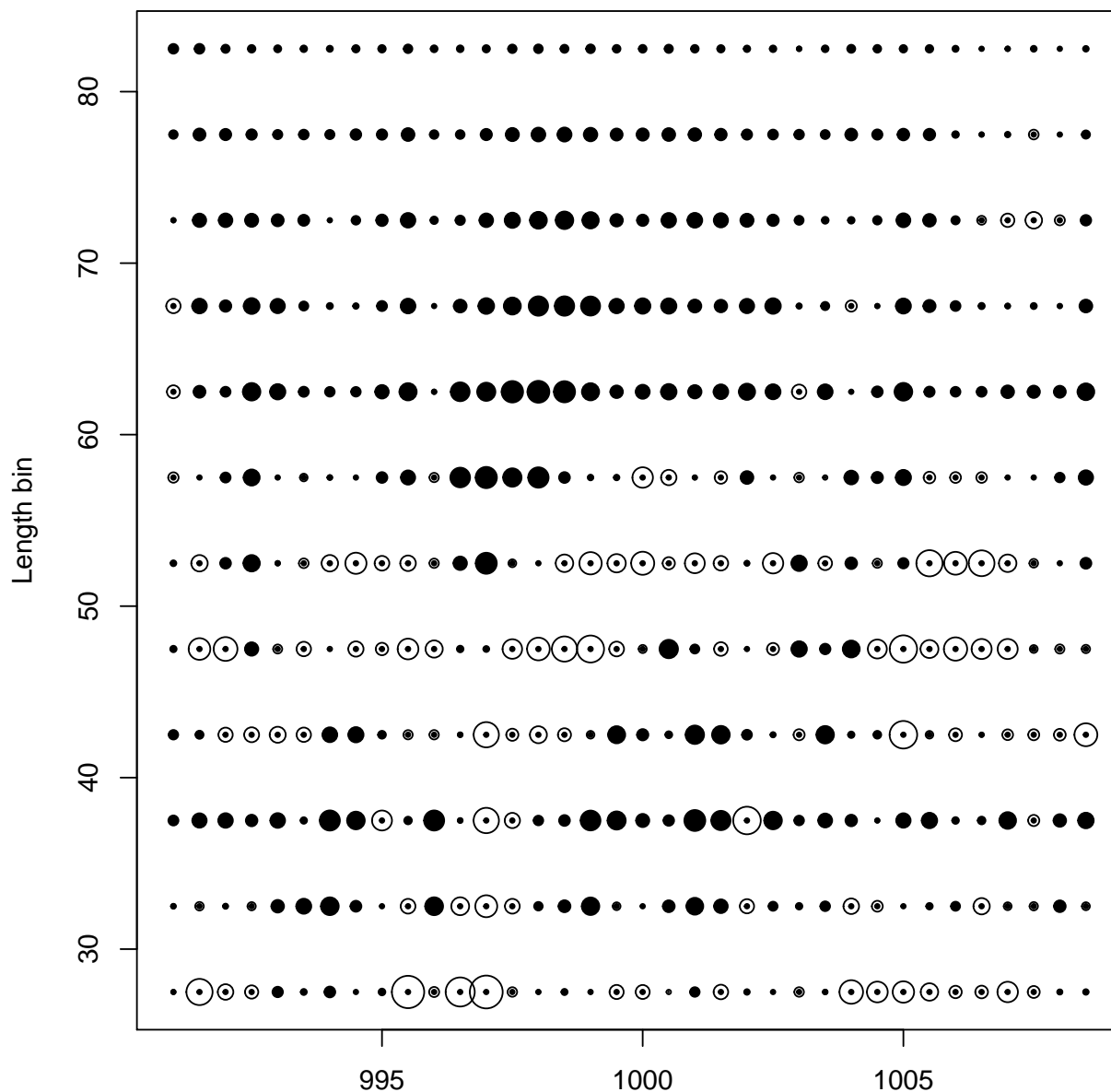


Figure 34: Residuals for female survey length proportion data for the author's preferred model (3b). Open circles are positive residuals, filled are negative, and the size of the circle is proportional to the magnitude of the residual. Stars are residuals > 5 .

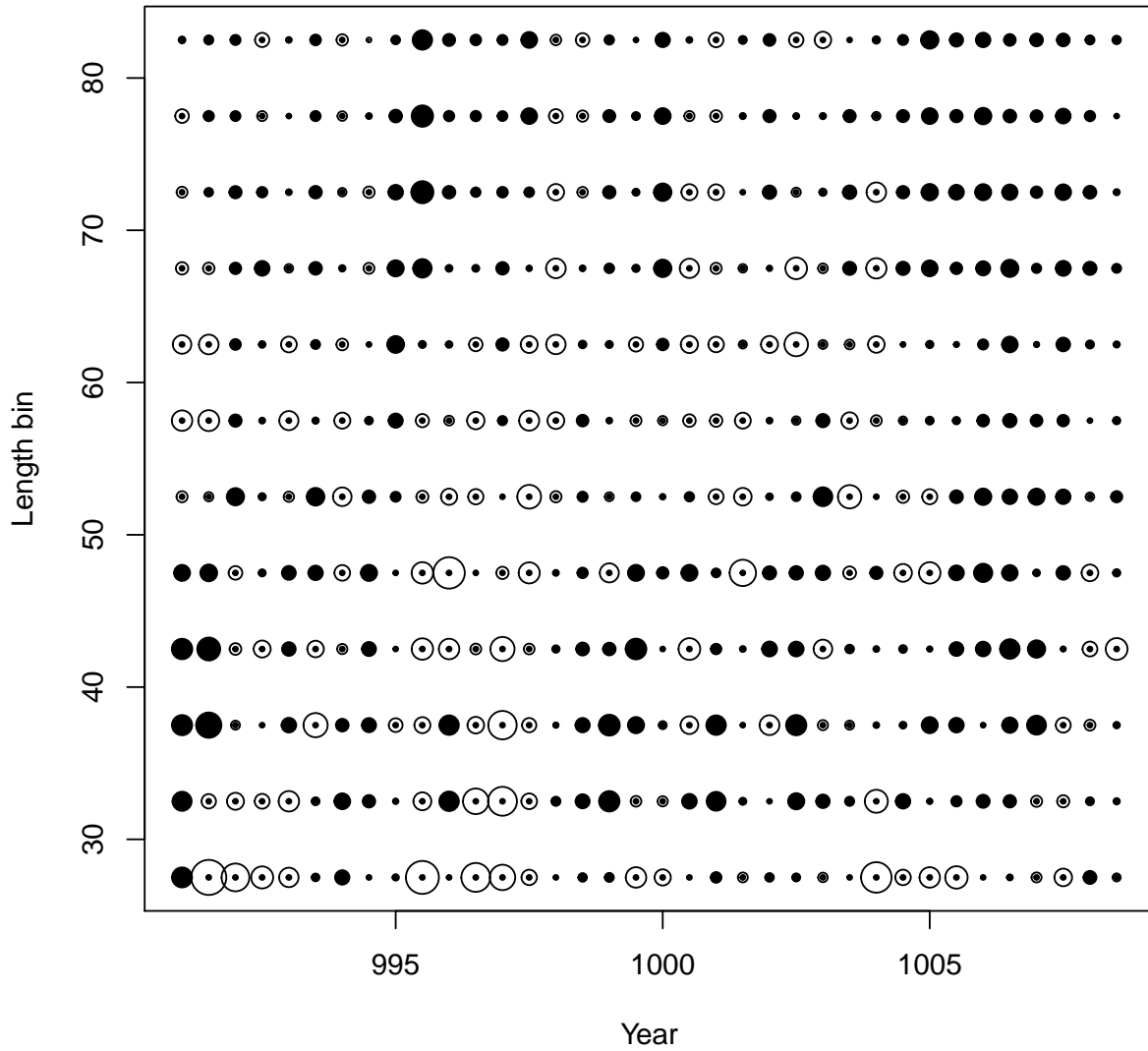


Figure 35: Residuals for male survey length proportion data for the author's preferred model (3b). Open circles are positive residuals, filled are negative, and the size of the circle is proportional to the magnitude of the residual. Stars are residuals > 5 .

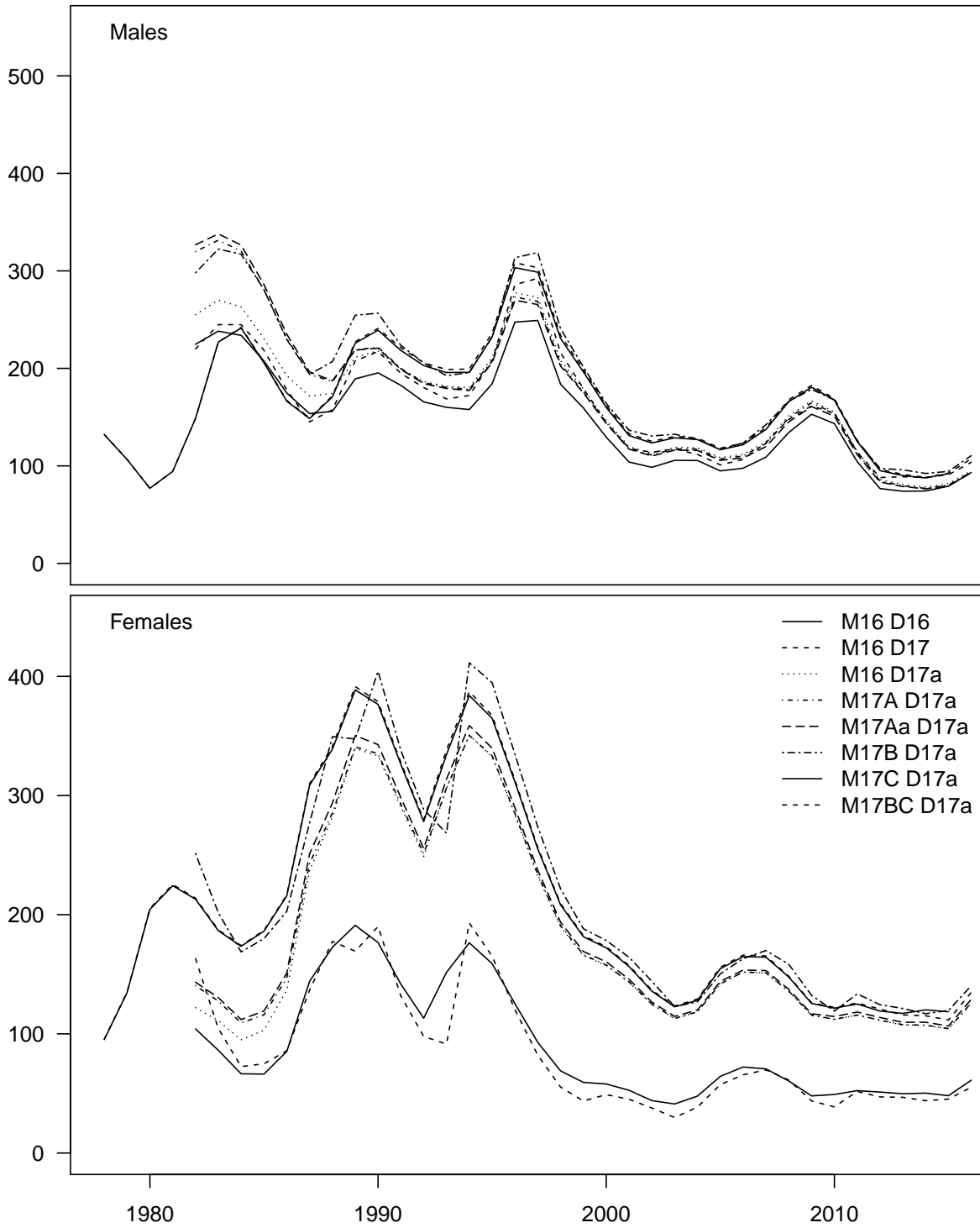


Figure 36: Model predicted mature male biomass at mating time

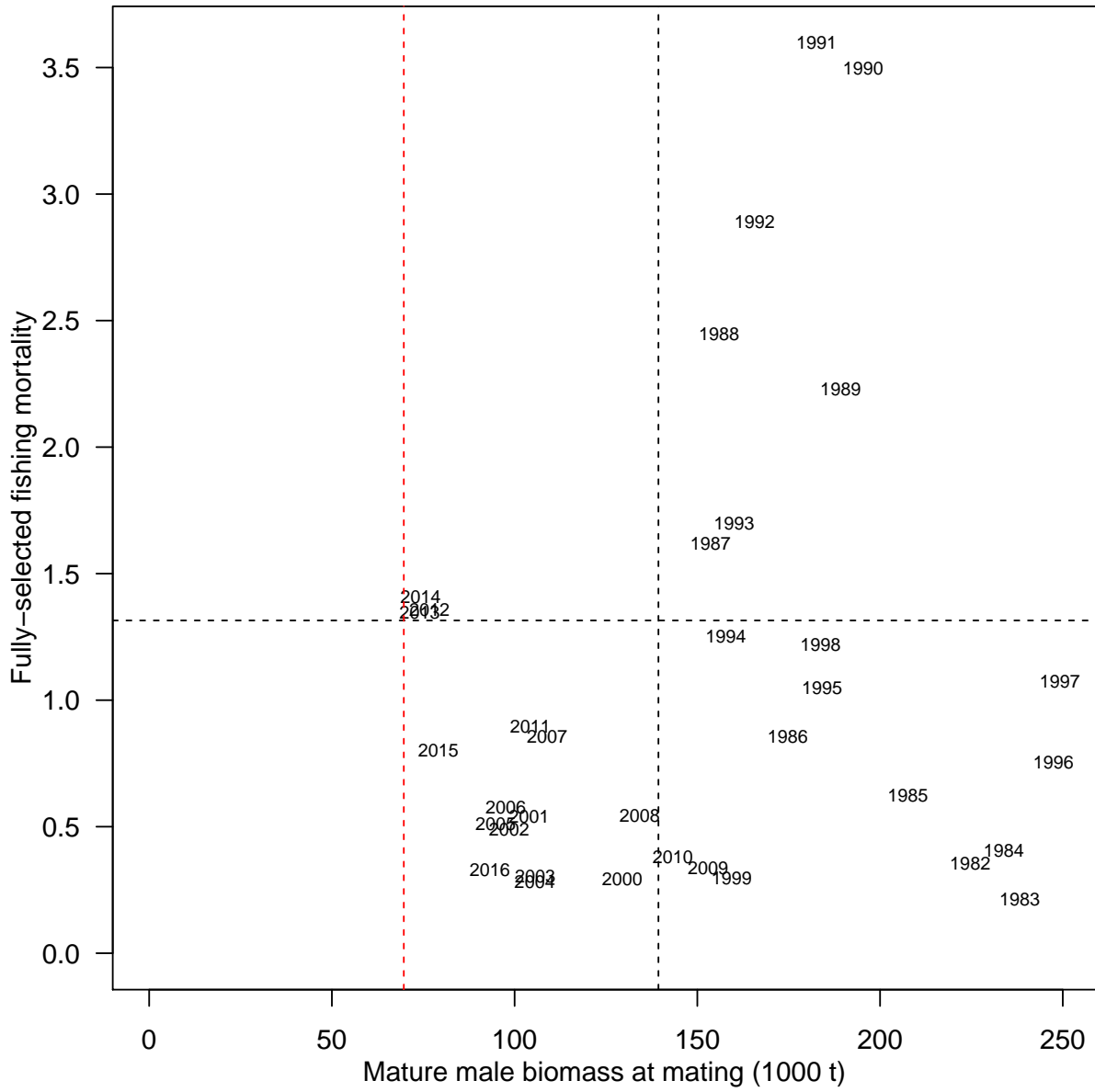


Figure 37: Kobe plot for the chosen model. Vertical dashed black line represents the median posterior value for B35; Vertical dashed red line represents the overfished level, horizontal dashed black line represents F35

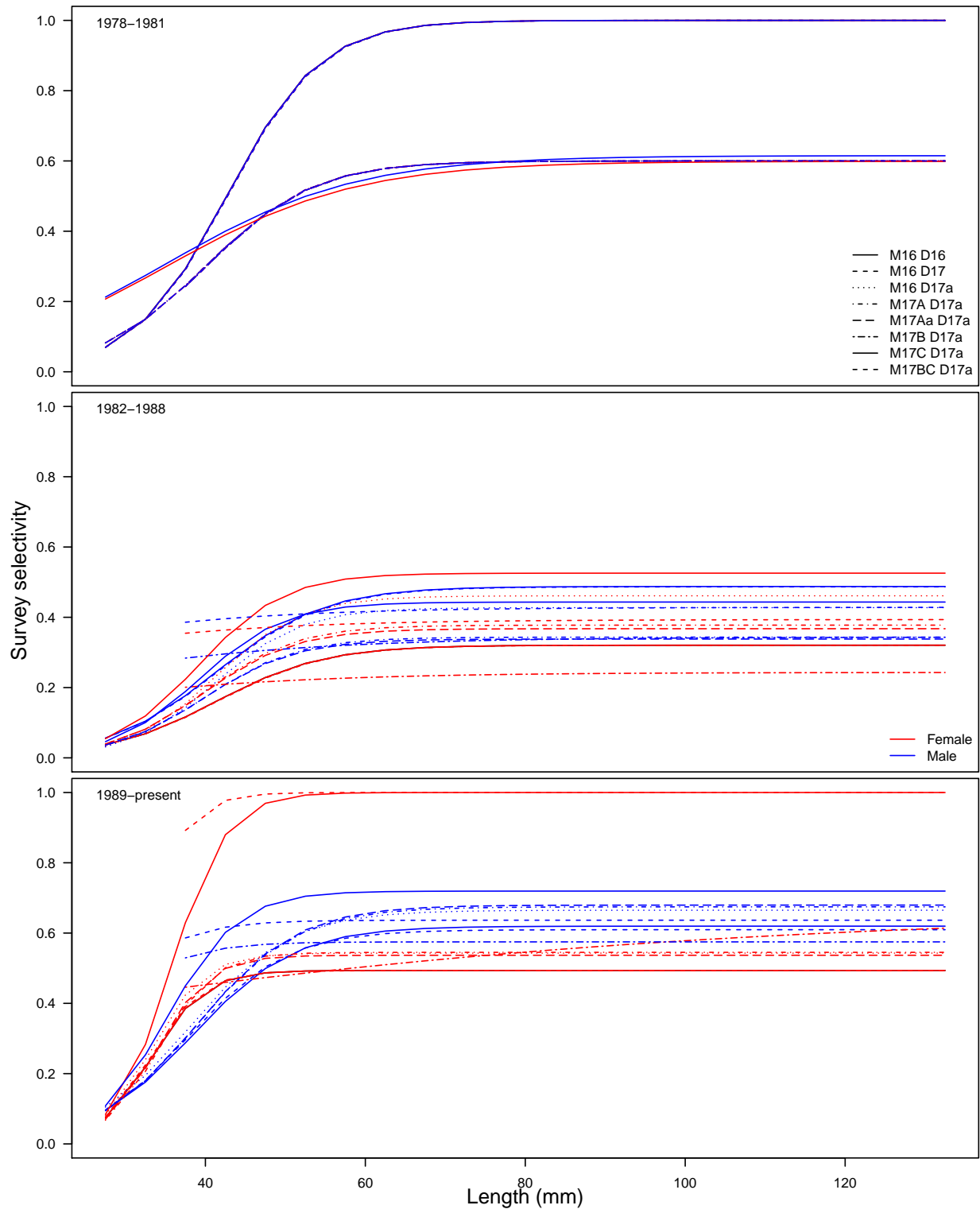


Figure 38: Estimated survey selectivity

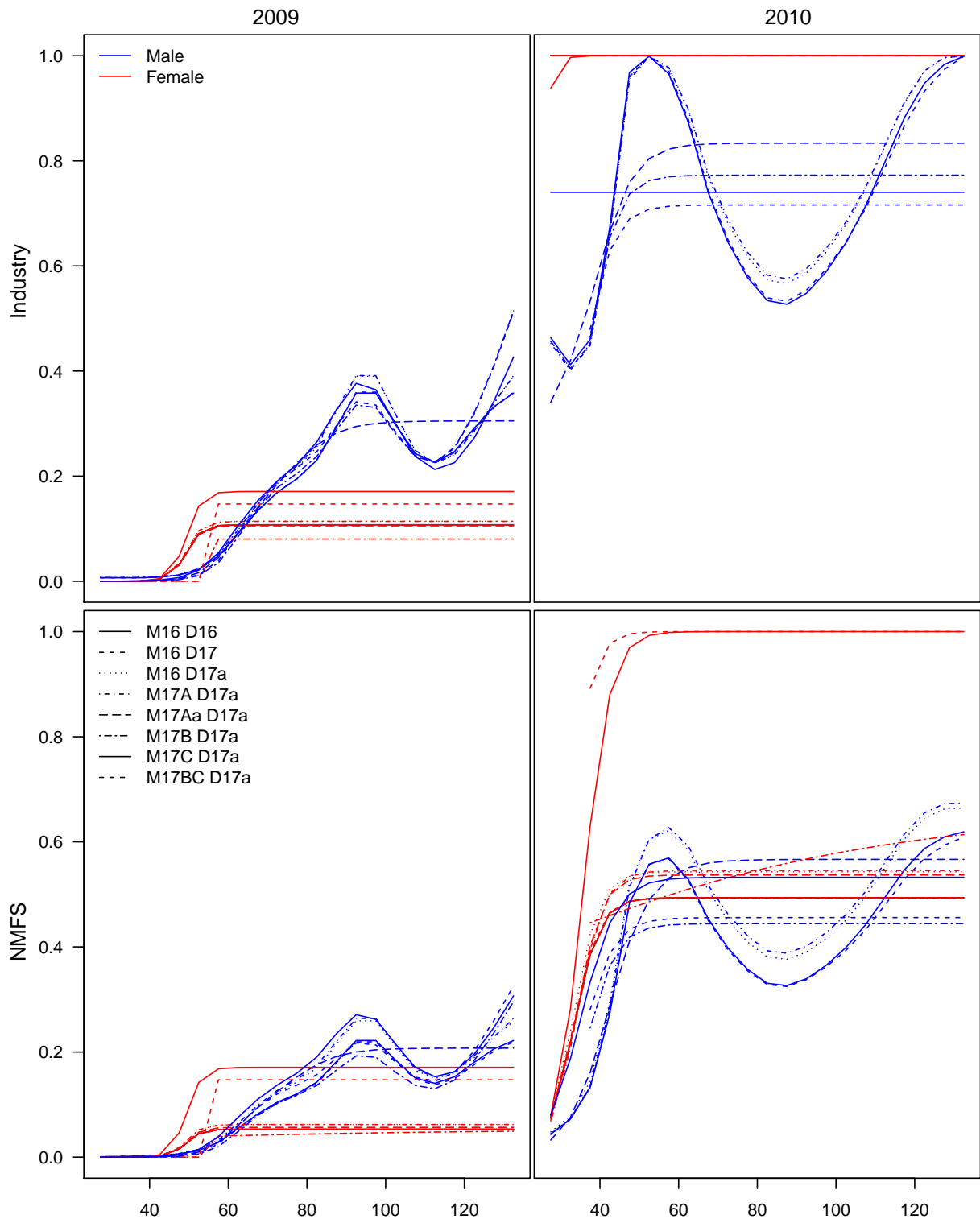


Figure 39: Estimated experimental survey selectivity (availability * survey selectivity)

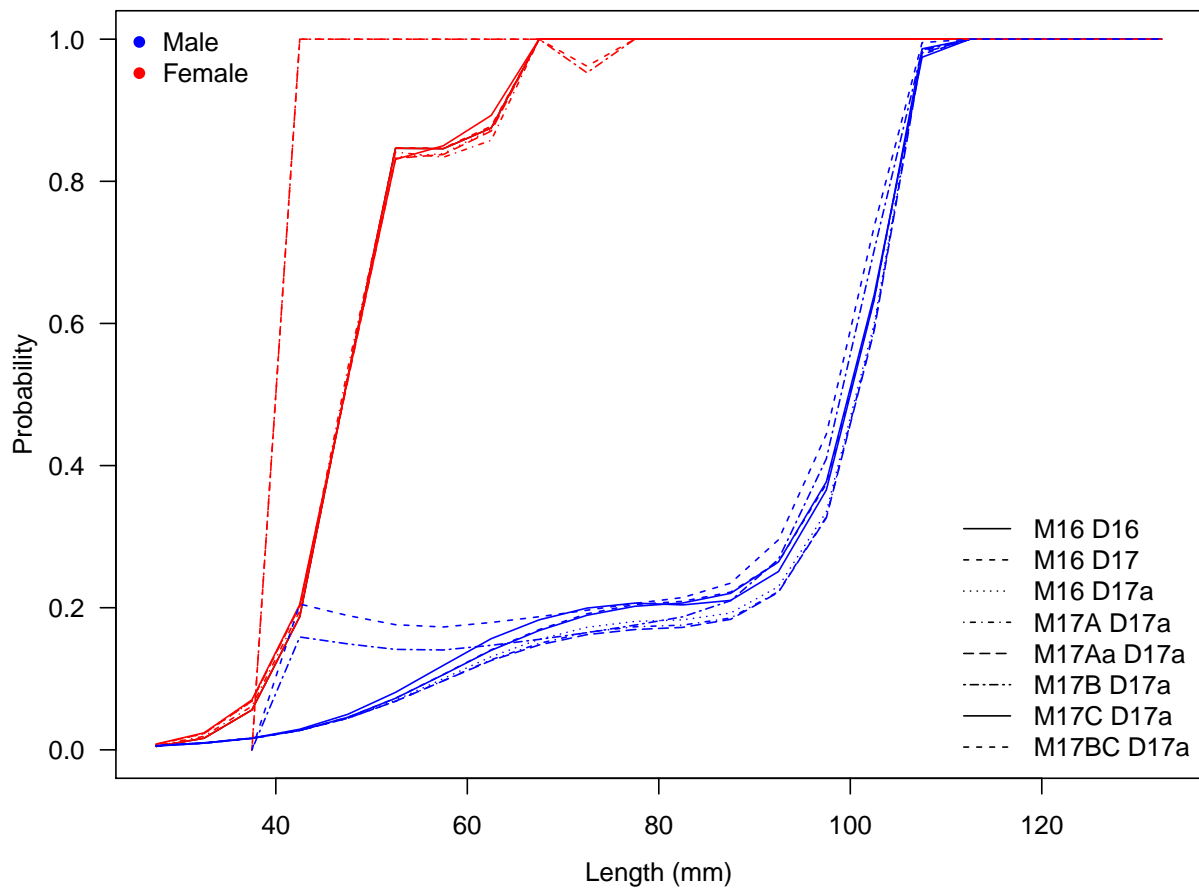


Figure 40: Estimated probability of maturing

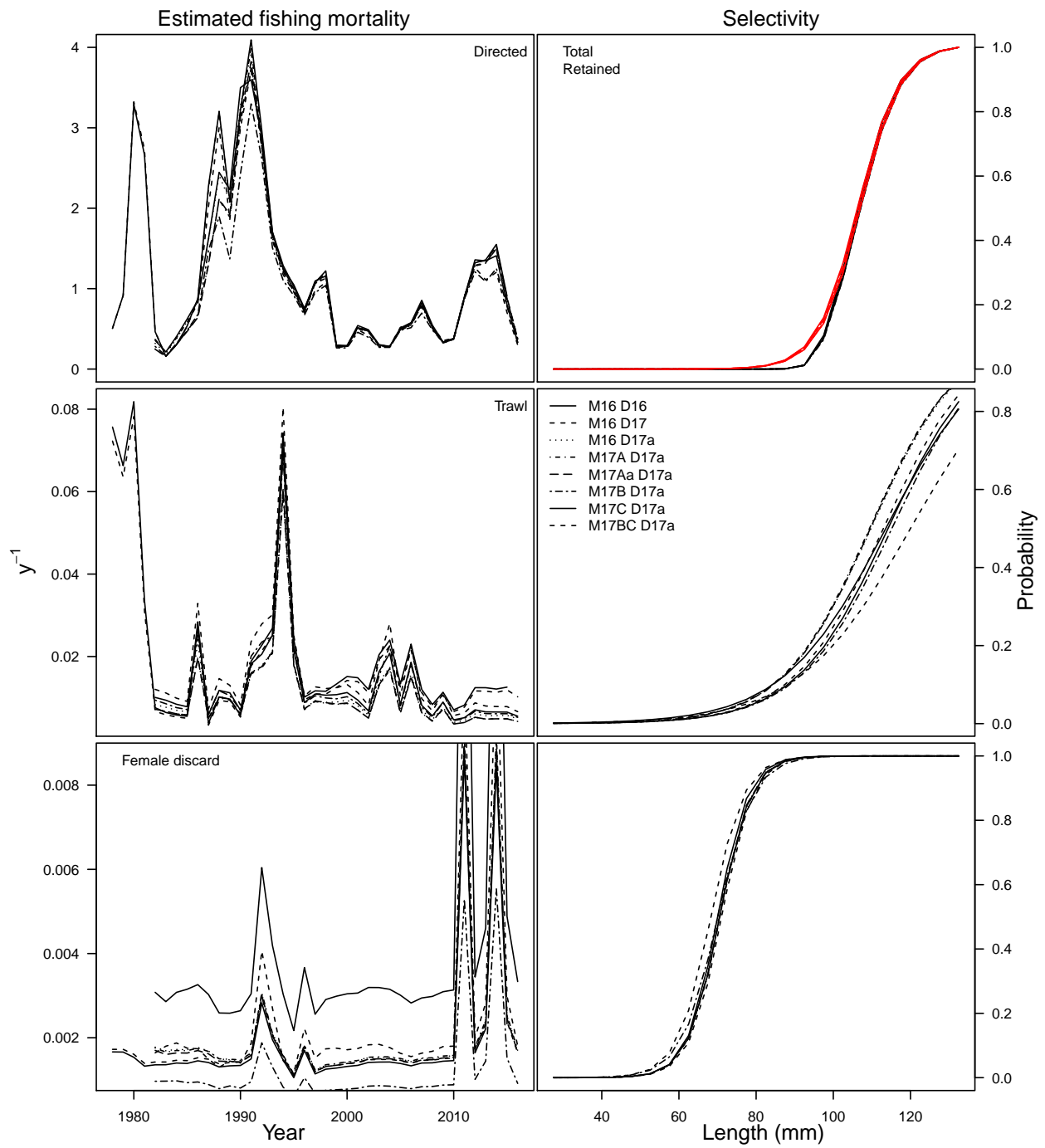


Figure 41: Model predicted fishing mortalities and selectivities for all sources of mortality

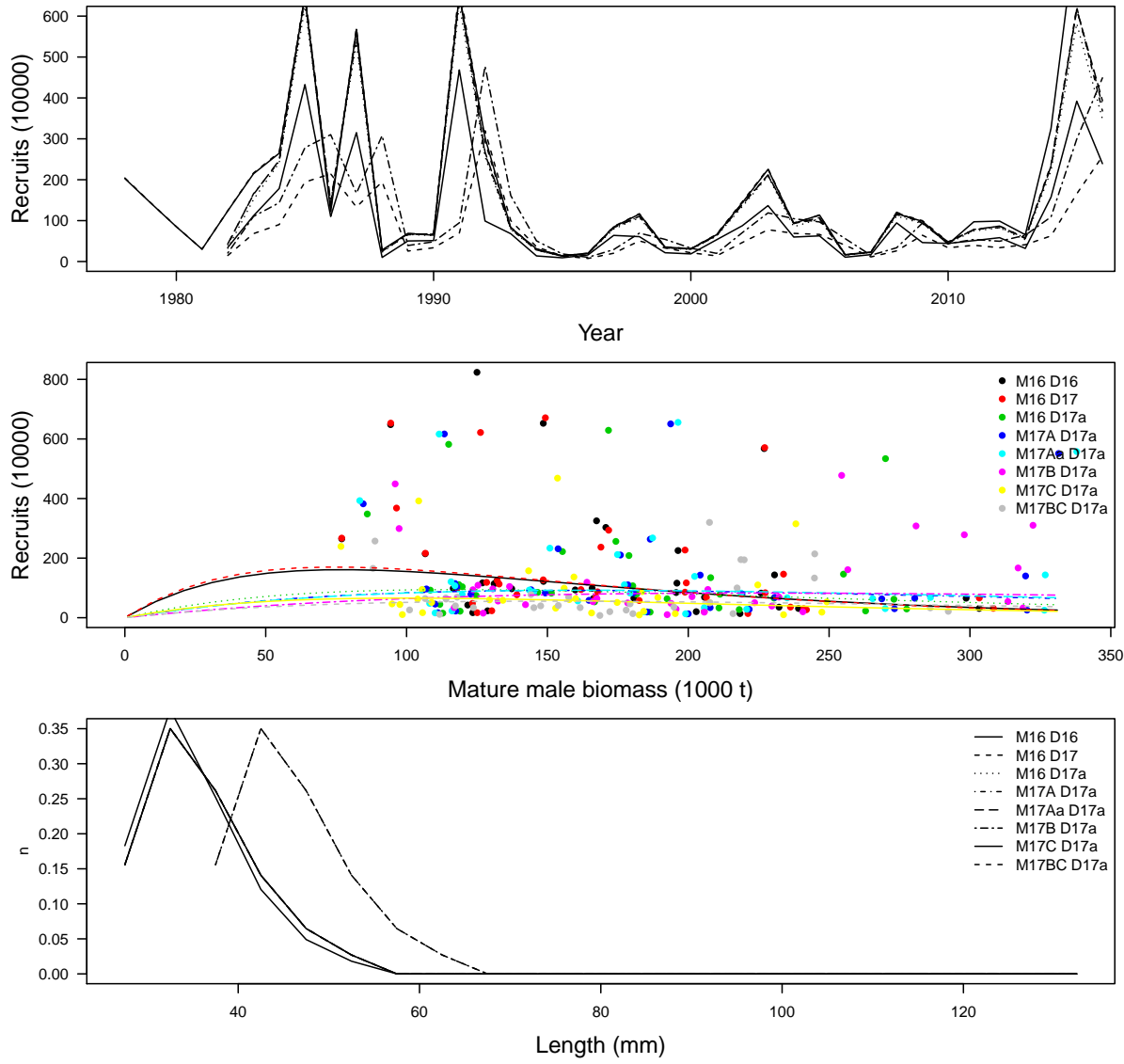


Figure 42: Estimated recruitment, fits to stock recruit curve (MMB lagged 5 years), and proportions recruiting to length bin

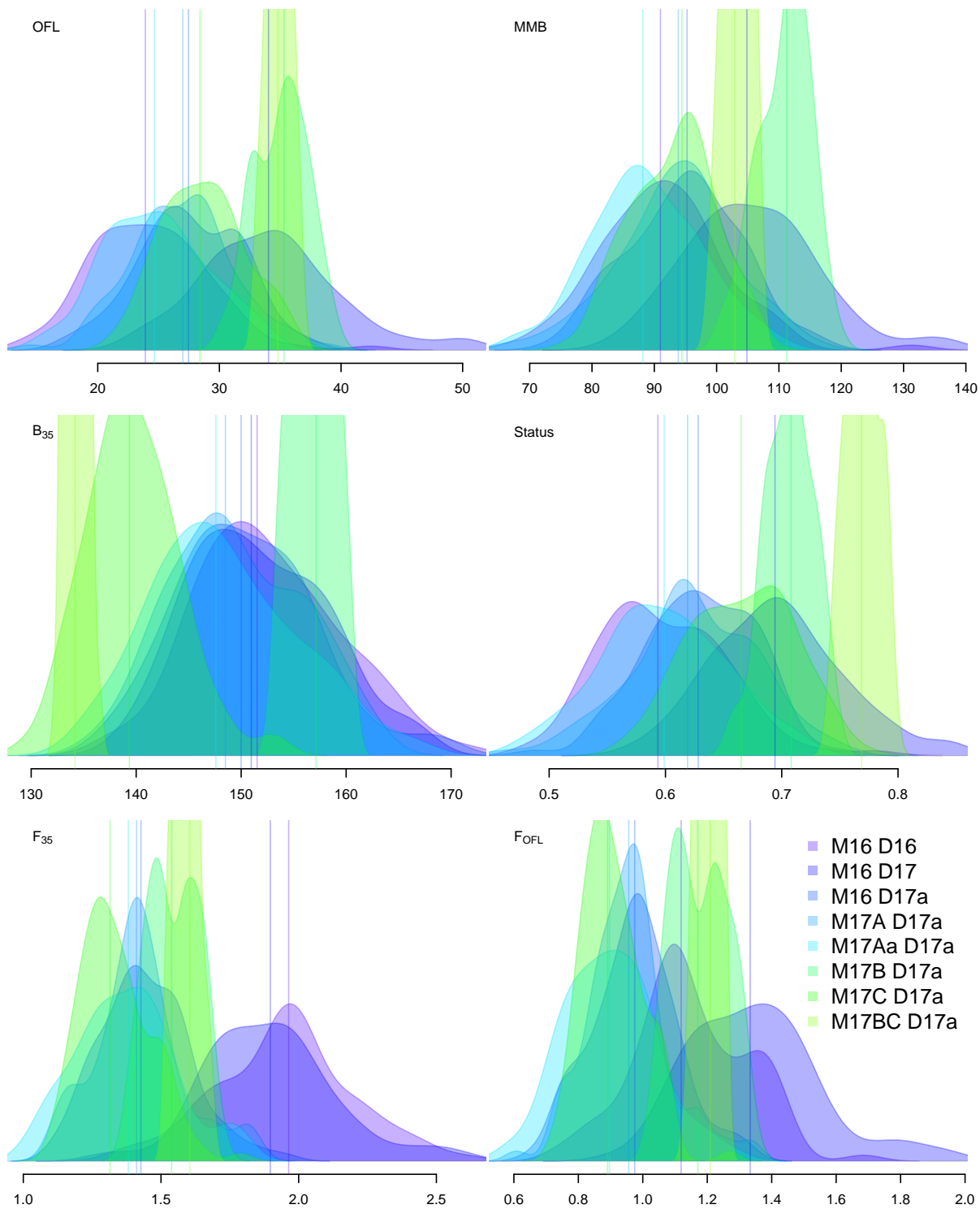


Figure 43: Posterior densities for management quantities by scenario