

# A stock assessment for eastern Bering Sea snow crab

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*September 16, 2019*

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1. Stock: Eastern Bering Sea snow crab, *Chionoecetes opilio*.
2. Catches: trends and current levels

Retained catches increased from relatively low levels in the early 1980s (e.g. retained catch of 11.85 kt during 1982) to historical highs in the early and mid-nineties (retained catch during 1991, 1992, and 1998 were 143.02, 104.68, and 88.09 kt, respectively). The stock was declared overfished in 1999 at which time retained catches dropped to levels similar to the early 1980s (e.g. retained catch during 2000 was 11.46 kt). Retained catches have slowly increased since 1999 as the stock rebuilt, although retained catch during 2018 was low (12.51 kt) as a result of low estimated mature biomass.

Discard mortality is the next largest source of mortality after retained catch and approximately tracks the retained catch. The highest estimated discard mortality occurred during 1992 at 17.06 kt which was 16% of the retained catch. The most recent estimated discard mortality was 2.86 kt which was 23% of the retained catch.

3. Stock Biomass:

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

4. Recruitment

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

## 5. Management

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

Year	MSST	Biomass (MMB)	TAC	Retained catch	Total catch	OFL	ABC
2014/2015	73.2	129.3	30.8	30.8	34.3	69	62.1
2015/2016	75.8	91.6	18.4	18.4	21.4	83.1	62.3
2016/2017	69.7	96.1	9.7	9.7	11	23.7	21.3
2017/2018	71.4	99.6	8.6	8.6	10.5	28.4	22.7
2018/2019	63.0	123.1	12.5	12.5	15.4	29.7	23.8
2019/2020		167.3				54.9	43.9

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

Year	MSST	Biomass (MMB)	TAC	Retained catch	Total catch	OFL	ABC
2014/2015	161.38	285.06	67.9	67.9	75.62	152.12	136.91
2015/2016	167.11	201.94	40.57	40.57	47.18	183.2	137.35
2016/2017	153.66	211.86	21.38	21.38	24.25	52.25	46.96
2017/2018	157.41	219.58	18.96	18.96	23.15	62.61	50.04
2018/2019	138.89	271.39	27.56	27.56	33.95	65.48	52.47
2019/2020		368.83				121.03	96.78

## 6. Basis for the OFL

The OFL for 2019 from the chosen model (19.7) was 54.92 kt fishing at  $F_{OFL} = 1.93$  (100 % of the calculated  $F_{35\%}$ , 1.93). The calculated OFL was a 85% change from the 2018 OFL of 29.7 kt. The projected ratio of MMB at the time of mating in 2020 to  $B_{35\%}$  is 1.33.

Table 3: Metrics used in designation of status and OFL (1,000 t). ‘Years’ indicate the year range over which recruitment is averaged for use in calculation of  $B_{35}$ . ‘M’ is the natural mortality for immature crab, mature female crab, and mature male crab, respectively.

Year	Tier	BMSY	MMB	Status	FOFL	Years	M
2019/2020	3	126.1	167.3	1.33	1.93	1982-2018	0.31, 0.41, 0.3

Table 4: Metrics used in designation of status and OFL (millions of lb.). ‘Years’ indicate the year range over which recruitment is averaged for use in calculation of  $B_{35}$ . ‘Status’ is the ratio between MMB and BMSY. ‘M’ is the natural mortality for immature crab, mature female crab, and mature male crab, respectively.

Year	Tier	BMSY	MMB	Status	FOFL	Years	M
2019/2020	3	278	368.8	1.33	1.93	1982-2018	0.31, 0.41, 0.3

#### 7. Probability Density Function of the OFL

The probability density function of the OFL was characterized for all models by using maximum likelihood estimates of the OFL and associated standard errors.

#### 8. Basis for ABC

The ABC for the chosen model was 43.93 kt, calculated by subtracting a 20% buffer from the OFL as recommended by the SSC.

## A. Summary of Major Changes

1. Management: None

2. Input data:

Data added to the assessment included: 2019 Bering Sea survey biomass and length composition data, 2018 directed fishery retained and discard catch and length composition for retained and discard catch (calculated via the ‘subtraction’ method; see below), and groundfish discard length frequency and discard from 2018. Growth data were updated with 4 observations of pre- and post-molt lengths.

3. Assessment methodology:

Management quantities were derived from maximum likelihood estimates of model parameters in a size-based, integrated assessment method. Jittering was performed to identify stable model configurations. Retrospective analyses were performed for selected model configurations.

4. Assessment results

The updated estimate of MMB (February 15, 2018) was 111.41 which placed the stock at 88% of  $B_{35\%}$ . Projected MMB on February 15, 2019 from this assessment’s chosen model was 167.32 kt after fishing at the OFL, which will place the stock at 133% of  $B_{35\%}$ . Fits to all data sources were acceptable for the chosen model and most estimated population processes were credible (see discussion below).

## B. CPT May 2019 comments, SSC comments, and author response:

### Research directions

SSC comment: The SSC suggested the development of a prioritized research plan to improve the snow crab assessment and that it may be helpful to organize the plan into categories: analyses conducted within the assessment model, analyses conducted outside the model, development of alternative models (e.g., GMACS, simplified model), and collection of new data. The SSC also suggested that work that can be conducted with existing data and staff resources should be prioritized versus new work that requires new funding.

Author response (CSS): A prioritized research plan has yet to be formally written down, but a general hierarchy of needs exists. The author's current plan following the September meeting is (listed by priority):

- Develop a GMACS model for snow crab to be presented at CIE review in summer of 2020. This is the number one priority because of the desire to move to GMACS before attempting to solve model pathologies that may or may not exist when using GMACS.
- Address survey catchability and the use of BSFRF data to inform it. Given the discussion about changing assumed natural mortality and its confounding with catchability (and growth), it will be necessary to consider how to best inform catchability carefully. First, I will revisit how the BSFRF data are used to establish a mean catchability. Second, I hope to explore time-variation in catchability potentially resulting from changes in spatial distribution and environmental variation. This could address some of the spatial issues related to the fraction of the stock in the northern Bering Sea, poor fits in some years, and retrospective patterns in estimates of MMB.
- A postdoc has just been hired to develop a fully spatial assessment for snow crab using code built on the VAST framework.

These projects will consume at least the next year.

### Assessment scenarios for September 2019

The CPT made several recommendations for scenarios with the current assessment methodology to be presented in September based on analyses presented during the May 2019 CPT meeting, including a status quo model, a model with higher M, a model with linear growth for females and kinked growth for males, a model with linear growth for males and kinked growth for females, models that estimate different size distributions for male and female recruitment. The SSC agreed with these suggestions. Last year's accepted model uses kinked growth curves for both males and females, has a median prior for M of 0.23, and specifies the distribution of female and male recruitment (which are equal). The author presents 8 runs based on these recommendations:

- 18.1 – Last year's accepted model fit to last year's data.
- 19.1 – Last year's accepted model fit to this year's data.
- 19.2 – 19.1 + Hamel prior on M (0.27)
- 19.3 – 19.1 + Then prior on M (0.315)
- 19.4 – 19.1 + Linear growth for females
- 19.5 – 19.1 + Linear growth for males
- 19.6 – 19.1 + estimate different recruitment distributions by sex
- 19.7 – 19.2 + linear growth for males

A model in which both male and female growth models were specified as linear did not converge, so it is not presented here. The author's preliminary preferred model is 19.7. It should be noted that the preferred model increased the assumed mean value for the prior on natural mortality and this results in higher OFLs than if M remained the same as in 2018 (e.g. model 19.1). However, updated methodology for developing empirical estimates of natural mortality, state-space modeling that estimates time-varying natural mortality for snow crab, and closer examination of the survey data all suggest that natural mortality is higher than it has been assumed during the recent history of the snow crab assessment.

The SSC offers the following additional suggestions to the assessment author (followed by author responses):

SSC: Consider whether a higher natural mortality should be incorporated with a suitable prior or as a fixed parameter estimated outside the model.

CSS: For this round of assessment, natural mortality was incorporated with a prior, with the reasoning that allowing the model some flexibility in natural mortality will incorporate some of the uncertainty in M into derived quantities. However, once the assessment is moved to GMACS, a simulation exercise in which data are simulated with a known M and fit with GMACS could show whether or not M can be estimated reliably with the available data.

SSC: Consider the northern Bering Sea data to better understand the influence of snow crab in that area on the eastern Bering Sea assessment. Examine whether snow crab in the northern Bering Sea and higher estimates of natural mortality are linked.

CSS: The model is fit to mature biomass, which is the metric of management. Mature biomass is generally farther from the northern border of the surveyed area (Figure 1), so movement back and forth over the northern border should not be expected to influence fits to those data. Further, natural mortality for immature crab and yearly recruitment are estimated parameters, which should temper any impact of small crab moving back and forth. Again, this could be addressed via simulation once the assessment is moved to GMACS by generating data from operating models with time-varying catchability and/or time-varying natural mortality for immature crab, applying the assessment methods, and evaluating the ability of the model to estimate catchability and natural mortality (and other derived quantities used in management).

SSC: Ongoing considerations of catchability/selectivity within the survey area are also encouraged. The potential interplay of crab spatial distribution and habitat-specific catchability is intriguing. Examination of the effects of environmental conditions on snow crab spatial distribution and habitat-based catchability seems to be a potential fruitful avenue of research with existing data. Effects of temperature and survey dates on catchability of yellowfin sole may be a useful case study for comparison.

CSS: In addition to the above responses, I have explored the BSFRF data further in this document and discuss briefly plans in the immediate future for work related to this question.



## 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 2 & Figure 3). Smaller crabs tend to occupy more inshore northern regions (Figure 4) and mature crabs occupy deeper areas to the south of the juveniles (Figure 5 & Figure 6; 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

Relatively few targeted studies exist to determine natural mortality for snow crab in the Bering Sea. In one of these studies, Nevissi, et al. (1995) used radiometric techniques to estimate shell age from last molt (Figure 7). 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 NMFS Bering Sea survey. Representative samples for the 5 shell condition categories were collected from the available crab. 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; carapace width of 110 mm). 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). 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.

In recent years, the mean for the prior for natural mortality used in the eastern Bering Sea snow crab assessment was based on the assumption that longevity would be at least 20 years in a virgin population of snow crab, informed by the studies above. 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. For the base model in this assessment cycle, the means of the prior on natural mortality for immature males and females, mature males, and mature females were also set to  $0.23 \text{ yr}^{-1}$ .

In contrast to the implied natural mortalities from the methodology used above, Murphy et al. (2018) estimated time-varying natural mortality for eastern Bering Sea snow crab with a mean of 0.49 for females and 0.36 for males (based on the output of state-space models fit to NMFS survey data; Figure 8). Further, natural mortality estimates produced from empirical analyses by Then et al. (2015) and Hamel (2015) using similar assumed maximum ages as the methodology above produce natural mortalities larger than 0.23 (Table 5). Then et al. (2015) compared several major empirical estimation methods for M (including Hoenig's method) with an updated data set and found that maximum age was the best available predictor. A maximum age of 20 years corresponded to an M of ~0.315 in Then et al.'s analysis. Hamel (2015) developed priors in a similar manner to Then et al., but forced the regression of observed natural mortality onto maximum age through the intercept, which resulted in an M of ~0.27 for an assumed maximum age of 20 years.

Table 5: Empirical estimates of natural mortality for a range of methods over a range of assumed maximum ages (column header).

	23	20	17
<b>Then</b>	0.277	0.315	0.365
<b>Hoening (1983)</b>	0.19	0.212	0.257
<b>Hoening (2015)</b>	0.194	0.223	0.261
<b>Hamel</b>	0.235	0.27	0.318

In addition to the results of empirical estimates of  $M$  from updated methodologies and state-space modeling by Murphy et al. (2018), inspection of the survey data suggests that natural mortality for mature individuals is higher than assumed. A fraction of the mature population (which are assumed not to grow, given evidence for a terminal molt) are not selected in the fishery (e.g. sizes 50-80 mm; Figure 9). Consequently, all mortality observed is ‘natural’. The collapse in recruitment in the 1990s can be used as an instrument to understand natural mortality for mature individuals. The last large recruitment enters these size classes in the mid- to late-1990s and numbers of crab in these size classes return to low levels in less than 5 years. It would be useful to perform radiometric aging on old shell crab that are not selected in the fishery to better understand natural mortality for mature crab.

Natural mortality is one of the major axes of uncertainty considered in the assessment scenarios presented in this assessment. The median value of the priors used in some scenarios were changed to values resulting from assuming a maximum age of 20 years and applying Then et al.’s or Hamel’s methodology. A standard error of 0.054 was used for all priors and was estimated using the 95% CI of  $\pm 1.7$  years on maximum age estimates from dactal wear and tag return analysis in Fonseca, et al. (2008). Another potential, but unexplored, option for developing a prior is to apply all of the methods to the range of possible maximum ages, develop a probability density function for maximum age given the observed data, then calculate a weighted average of the natural mortalities using the pdf for weights and use the standard error from that weighted average to define the breadth of the 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 is now 48 g; a mature female crab of carapace width 57.5 mm was estimated to previously weigh 102 g and is now 67.7 g; and a male of carapace width 92.5 mm was previously estimated to weigh 450 g and now weighs 451 g.

## Maturity

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

crab chela to the nearest tenth of a millimeter show a similar break in chela height to the Canadian data (Rugolo et al. 2005). The probability of maturing (which is different from the fraction mature at length) is estimated within the model for both sexes as a freely estimated (but smoothed) function of length.

## **Molting probability**

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

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

## **Mating ratio and reproductive success**

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

Quantifying the reproductive potential of the female population from survey data can be difficult. 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 eye at the time of the survey. The fraction of barren females observed in the survey may not be an accurate measure of fertilization success because females may retain unfertilized eggs for months after

extrusion. To examine this hypothesis, RACE personnel sampled mature females from the Bering Sea in winter and held them in tanks until their eggs hatched in March of the same year (Rugolo et al. 2005). All females then extruded a new clutch of eggs in the absence of males. All eggs were retained until the crabs were euthanized near the end of August. Approximately 20% of the females had full clutches of unfertilized eggs. The unfertilized eggs could not be distinguished from fertilized eggs by visual inspection at the time they were euthanized. Indices of fertilized females based on the visual inspection method of assessing clutch fullness and percent unmated females may overestimate fertilized females and may not be an accurate index of reproductive success.

## Growth

Historically, little information was available on growth for Bering Sea snow crab. However, many new data points have been added in recent years (Table 7). These studies include:

1. Transit study (Rugolo unpublished data, 2003); 14 crab
2. Cooperative seasonality study (Rugolo); 6 crab
3. Dutch harbor holding study; 9 crab
4. NMFS Kodiak holding study held less than 30 days; 6 crab
5. NMFS Kodiak holding study 2016; 5 crab
6. NMFS Kodiak holding study 2017; 70 crab.
7. BSFRF/NMFS holding study 2018; 4 crab.

In the “Transit study”, pre- and post-molt measurements of 14 male crabs that molted soon after being captured were collected. The crabs were measured when shells were still soft because all died after molting, so measurements may be underestimates of post-molt width (Rugolo, pers. com.). The holding studies include only data for crab held less than 30 days because growth of crabs held until the next spring’s molting was much lower. Females molting to maturity were excluded from all data sets, since the molt increment is usually smaller. Crab missing more than two limbs were excluded due to other studies showing lower growth. Crab from Rugolo’s seasonal study were excluded that were measured less than 3 days after molting due to difficulty in measuring soft crab accurately. In general, growth of snow crab in the Bering Sea appears to be greater than growth of some North Atlantic snow crab stocks (Sainte-Marie 1995).

## Management history

### ADFG harvest strategy

Before the year 2000, the Guideline Harvest Level (GHL) for retained crab only was a harvest rate 58% of the number of male crab over 101 mm CW estimated from the survey. The minimum legal size limit for snow crab is 78 mm, however, the snow crab market generally only accepts crab greater than 101 mm. In 2000, due to the decline in abundance and the declaration of the stock as overfished, the harvest rate for calculation of the GHL was reduced to 20% of male crab over 101 mm. After 2000, a rebuilding strategy was developed based on simulations by Zheng (2002) using survey biomass estimates. The realized retained catch typically exceeded the GHL historically, resulting in exploitation rates for the retained catch on males >101mm ranging from about 10% to 80%. The estimated exploitation rate for total catch divided by mature male biomass ranged from 6% to 51% for the chosen model in this assessment (Figure 10).

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

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

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

## History of 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  $B_{MSY}$ . 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. The range of years of recruitment used to calculate biomass reference points is from 1982 to the present assessment year, minus 1.

## 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; Table 8). 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 2018 was low (12.51 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 2.86 kt which was 23% of the retained catch.

Discard from the directed pot fishery has been estimated from observer data since 1992 and has ranged from 11-55% of the magnitude of retained catch by numbers. In recent years, discards have reached 50-55% of the magnitude of retained catch because of the large year class entering the population. 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 11). Bycatch in fisheries other than the groundfish trawl fishery has historically been relatively low. Size frequency data and catch per pot have been collected by observers on snow crab fishery vessels since 1992. Observer coverage has been 10% on catcher vessels larger than 125 ft (since 2001), and 100% coverage on catcher processors (since 1992).

Several modifications to pot gear have been introduced to reduce bycatch mortality. In the 1978/79 season, escape panels were introduced to pots used in the snow crab fishery to prevent ghost fishing. Escape panels consisted of an opening with one-half the perimeter of the tunnel eye laced with untreated cotton twine. The size of the cotton laced panel was increased in 1991 to at least 18 inches in length. No escape mechanisms for undersized crab were required until the 1997 season when at least one-third of one vertical surface of pots

had to contain not less than 5 inches stretched mesh webbing or have no less than four circular rings of no less than 3 3/4 inches inside diameter. In the 2001 season the escapement for undersized crab was increased to at least eight escape rings of no less than 4 inches placed within one mesh measurement from the bottom of the pot, with four escape rings on each side of the two sides of a four-sided pot, or one-half of one side of the pot must have a side panel composed of not less than 5 1/4 inch stretched mesh webbing.

## D. Data

Updated 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 1982 to 2018 were used in this analysis (Table 8). Discard size composition data from 1992 to 2017 were estimated from observer data and then combined with retained catch size compositions to become the ‘total catch’ size composition data, which are fit in the assessment. In 2018, observer data collection changed and only total catch size composition data and retained size composition data are produced. This is a sensible step in data collection, but the current formulation of the snow crab model accepts discarded size composition data as an input. So, in 2018 the discarded size comps were calculated by subtracting the retained size comps from the total size comps. This mismatch of input data types will be addressed in the development of a GMACS model for snow crab.

The discard male catch was estimated for survey year 1982 to 1991 in the model using the estimated fishery selectivities based on the observer data for the period of survey year 1992 to 2018. The discard catch estimate was multiplied by the assumed mortality of discards from the pot fishery. The assumed mortality of discarded crab was 30% for all model scenarios. This estimate differs from the currently used strategy (since 2001) to the present by ADFG to set the TAC, which assumes a discard mortality of 25% (Zheng, et al. 2002). The discards prior to 1992 may be underestimated due to the lack of escape mechanisms for undersized crab in the pots before 1997. See Table 6 for a summary of catch data.

Table 6: Data included in the assessment. Dates indicate survey year.

Data component	Years
Retained male crab pot fishery size frequency by shell condition	1982 - 2018
Discarded Males and female crab pot fishery size frequency	1992 - 2018
Trawl fishery bycatch size frequencies by sex	1991 - 2018
Survey size frequencies by sex and shell condition	1982 - 2019
Retained catch estimates	1982 - 2018
Discard catch estimates from crab pot fishery	1992 - 2018
Trawl bycatch estimates	1993 - 2018
Total survey biomass estimates and coefficients of variation	1982 - 2019
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 Lang et al., 2018). In 1982 the survey net was changed resulting in a potential change in catchability and additional survey stations were added in 1989. Consequently, survey selectivity has been historically modeled in two ‘eras’ in the assessment (1982-1988, 1989-present: Figure 12). 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 13 & Figure 14) 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  $\leq 2$ . 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 9). 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 5) while smaller males have been more prevalent on the north west portion of the shelf (Figure 2). Females have exhibited a similar pattern (compare Figure 3 to Figure 6). In addition to changing spatially over the shelf and by size class, distributions of crab by size and maturity have also changed temporally. The centroids of abundance in the summer survey have moved over time (Figure 15 & Figure 16). 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 16).

Centroids of the catch have generally been 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. In general, the majority of catch was taken west and north of the Pribilof Islands, but this rule has had exceptions.

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

## Experimental study of survey selectivity

The Bering Sea Fisheries Research Foundation (BSFRF) has conducted supplementary surveys in the Bering Sea in which snow crab were caught during 2009, 2010, 2016, 2017, and 2018. The location and extent of

these survey varied over the years as the goal of the survey changed. In 2009, the survey consisted of 108 tows in 27 survey stations and the goal was to improve understanding snow crab densities and the selectivity of NMFS survey gear (Figure 17). In 2010, the survey area was larger and still focused on snow crab. The mature biomass and size composition data gleaned from each of these experiments (and their complimentary NMFS survey observations; Figure 18 & Figure 19) 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.

In 2016, 2017, and 2018, snow crab were not the focus of the BSFRF surveys, yet were still caught in the BSFRF gear. Comparing the ratio of the number of crab caught at length in the BSFRF gear (which is assumed to have a catchability/selectivity of 1 over all size classes) to the number of crab caught at length within the same area in the NMFS survey gear (which is assumed to have a catchability/selectivity  $\leq$  to one for at least some of the size classes) can provide an empirical estimate of /catchability/selectivity (Figure 20). Empirical estimates of catchability/selectivity vary by year and size class across the different BSFRF data sets (Figure 21). The number of snow crab used to develop estimates of numbers at length probably contribute to these differences among years (Figure 22), but there are likely other factors that influence catchability/selectivity at size of the NMFS survey gear (e.g. Somerton et al. 2013 show substrate type can influence selectivity). Further understanding the implication of these experiments is a research priority for snow crab.

## 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 (19.1), 366 parameters were estimated. Parameters estimated within the assessment included those associated with the population processes recruitment, growth, natural mortality (historically subject to a fairly informative prior), fishing mortality, selectivity (fishery and survey), catchability, and maturity (Table 10 & Table 11). Weight at length, discard mortality, bycatch mortality, and parameters associated with the variance in growth and proportion of recruitment allocated to size bin were estimated outside of the model or specified. See appendix A for a complete description of the population dynamics.



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

Retrospective analyses were performed in which the terminal year of data was removed sequentially from the model fitting. Then estimated management quantities (like MMB) were compared between the most recent model and successive ‘peels’ of the data to identify retrospective patterns. A retrospective pattern is a consistent directional change in assessment estimates of management quantities (e.g. MMB) in a given year when additional years of data are added to an assessment. Mohn’s rho (which computes the average difference between the reference case and the peels) was calculated for each retrospective analysis to quantify the retrospective patterns.

## Model selection and evaluation

Models were evaluated based on their fit to the data (Table 12), the credibility of the estimated population processes, stability of the model (Figure 23), the magnitude of retrospective patterns (Figure 24), 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 11.

## Results

Several of the models exhibited unstable behavior when jittered (Figure 23). Models appeared to ‘converge’ (i.e. returned small gradients) over a range of likelihood values and derived management quantities exhibited bimodality to some degree for several models. This bimodality has been linked to the change point growth model in the past (Turnock, 2016; Szuwalski, 2017 & 2018). The model that provided the most stable estimates of management quantities was model 19.5, in which the male growth curve was forced to be linear.

All models for which retrospective analyses were performed displayed retrospective patterns (Figure 24). Retrospective patterns suggest that a process is varying over time that is not allowed to vary within the model (e.g. catchability) or the data are incomplete (e.g. not all catch is reported). No model produced the lowest retrospective patterns for both sexes; 19.7 (Higher M and linear growth for males) performed best for males and 19.5 (Linear growth for males) performed best for females.

Below, the fits to the data and estimated population processes for all considered models are described. The data for all eight models were the same, consequently the likelihoods can be directly compared.

## 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 the time series (Figure 25). Model 19.4 (linear female growth) fit the survey biomass data somewhat better as seen through the likelihoods. The updated survey data did not increase as much as expected given previous years’ numbers at length, which caused a revision of the most recent years of MMB downward (see Figure 24). All models fits exceeded the final year of observed survey MMB (169.108 kt) and observed survey MFB (110.429 kt).

## Growth data

A range of growth curves were estimated to fit the female growth increment data (Figure 26), depending upon the assumed functional form and the prior on  $M$ . Two models produced roughly linear growth for females: 19.3 (highest  $M$ ) and 19.4 (assumed female linear growth). Presumably, with the higher  $M$ , larger individuals were able to be killed within the model more quickly, which allowed the model to accommodate larger growth increments at larger sizes. Model 19.3 produced by far the best fits to the female growth data (Table 12). It should be noted that much of the ‘fit’ improved here is to data that are outside of the size range modeled by the assessment.

Models 19.5 and 19.7 both produced linear growth curves for males, but were also both forced to be linear. All models fit the male growth data similarly (Table 12). Notably, the model in which linear growth was forced for males (19.5) had the most stable performance under the jittering analysis in terms of spread of ‘converged’ models. Model 19.7 also produced the smallest retrospective patterns for MMB of the models analyzed (Figure 24).

## Catch data

Retained catch data were fit by all models well, with no visually discernible differences among models (Figure 27). Female discard data were fit adequately given the specified uncertainty (Figure 27 & Table 12). Male discard data during the period for which data exist (early 1990s to the present) were well fit by every model with little visually discernible difference (Figure 27), though model 19.6 fit the data best as seen through the likelihoods (Table 12). Fits to the trawl data were adequate for all models given the uncertainty in the data (Figure 27).

## Size composition data

Retained catch size composition data were visually well fit by all models (Figure 28); total catch size composition data were similarly well fit (Figure 29). Retained and total catch size composition length composition data were fit similarly by most models, except 19.5 and 19.7, which both had linear growth for males and produced slightly poorer fits (e.g. neg log like 1031 vs 1025). Trawl size composition data were generally well fit, with several exceptions in certain years. Higher  $M$  allowed for slightly better fits to the trawl composition data (Figure 30 & Table 12).

Fits to size composition data for the BSFRF survey selectivity experiments produced some notable runs of positive and negative residuals for the males in particular (Figure 31). The number of males was generally underestimated by the industry survey in 2009 and overestimated by the NMFS survey, while the opposite pattern was seen for females. Fits to the 2010 survey size composition data were better than the 2009 fits.

Size composition data for the NMFS survey were generally well fit and fits were visually similar for all models (Figure 32 & Figure 33). The distribution of residuals for male and female survey composition data for the chosen model varied by sex. Size composition data for females tended to be overestimated for larger size classes (Figure 34), whereas a pattern for males was less clear (Figure 35). Models with higher  $M$  or estimated variability around the growth increment fit the survey composition data better for most size composition data sources according to the likelihoods (Table 12).

## Estimated population processes and derived quantities

Estimated population processes and derived quantities varied among models. Projected MMB for 2019 ranged from 123.07 to 174.87 kt (Figure 36). For the author preferred model (19.7), estimated fishing mortality in the recent past has been below  $F_{35\%}$ , save the years 2014-2015, which exceeded  $F_{35\%}$  (Figure 37). Estimated MMB has been less than  $B_{35\%}$  since 2011, and estimates suggest that the population may have been beneath

MSST in the recent past (Figure 37). However, the most recent estimated MMB reversed this trend and estimated MMB is currently near  $B_{35\%}$  for the chosen model.

Estimates of selectivity and catchability varied among models (Figure 38). Estimated catchability in both eras was lower for males than for females. In era 1 (1982-1988), catchability ranged from 0.42 - 0.53 for males; for females, it ranged from 0.69 - 0.75. In era 2 (1989-present), catchability ranged from 0.7 - 0.83 for males; for females, it was 1 for all models. Estimated size at 50% selection in the survey gear for era 1 ranged from ~40 mm to ~42 mm for both females and males. Size at 50% selection in the survey gear during era 2 ranged from 36 mm to 38 mm for females and 35 mm to 39 mm for males. BSFRF 'availability' curves varied from 2009 to 2010 and among models, with the availability of crab to the experimental survey generally increasing in 2010 (Figure 39).

In general, the shape of the curve representing the probability of maturing for both sexes was consistent, but the magnitude of the probabilities varied slightly. For all models, the probability of maturing by size for female crab was ~50% at ~47.5 mm and increased to 100% at ~60mm (Figure 40). The probability of maturing for male crab was ~15% to 20% at ~60 mm and increased sharply to 50% at ~97.5mm, and 100% at 107.5 mm. The region from 60 mm to 90 mm male carapace width displayed the largest differences in estimates of the probability of maturing among models.

Estimated fishing mortality in the directed fishery was similar for all models, except for in the most recent years. In those year, the 2018 model (18.1) estimated lower fishing mortality, which is probably related to lower estimates of MMB compared to models with 2019 data (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 110 - 111 mm (Figure 41). Size at 50% selection for discarded females was similar for all models (Figure 41).

Patterns in recruitment by sex were similar for all models (Figure 42). A period of high recruitment was observed in which 3 large male cohorts passed through the population during the 1980s and into the early 1990s. Following that, a period of low recruitment persisted from the early 1990s to 2013. All models indicated a large (relative to the past) recruitment to the survey gear occurred around 2013. Recruitment entering the model was placed primarily in the first three size bins, except for model 19.6 (Figure 42). Although model 19.6 (estimating separate distributions for recruitment by sex) fit the data better overall than 19.1, the differences among the estimated recruitment by sex did not change. 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 (not shown).

Estimated natural mortality ranged from 0.27 to 0.33 for immature crab, 0.26 to 0.34 for mature male crab, and 0.34 to 0.48 for mature females (Table 11).

## 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 Tier 3 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  $\alpha$  determines the slope of the descending limb of the harvest control rule (set to 0.1 here).

## Calculated OFLs and interpretation

OFLs calculated from maximum likelihood estimates of parameters in the suite presented models ranged from 29.74 to 66.07kt (Table 13). Differences in OFLs were a result of differences in estimated MMB (see above), calculated  $B_{35\%}$  (which ranged from 121.27 to 142.77kt, Table 13),  $F_{35\%}$  (which ranged from 1.22 to 2.48  $\text{yr}^{-1}$ , Table 13), and  $F_{OFL}$  (which ranged from 1.04 to 2.48  $\text{yr}^{-1}$ , Table 13). Changes in the prior on M strongly influenced the resulting reference points.

## G. Calculation of the ABC

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

## Author recommendations

When considering overall fit, retrospective patterns and stability of the model under jittering, there is no clear winner among the presented scenarios. Model 19.3 (highest M) fit the data best, model 19.7 (high M + linear male growth) had the smallest retrospective patterns for males, and model 19.5 was the most stable under jittering. Among the models presented, the key choices are between natural mortality priors and functional forms of growth.

Natural mortality should be higher than assumed in the past, given empirical meta-analyses and survey data for mature individuals not selected by the fishery. However, given confounding with other parameters and the large impact on management advice, it may be wise to chose a more precautionary prior for M the assessment until other confounded processes are explored more fully.

The question of using a linear growth curve or kinked growth curve does not have a clear answer. It makes sense that maturing individuals would grow less. It has been noted in previous assessments that growth data from maturing individuals were thrown out because the increments were smaller than others. However, the current growth function does not capture this process because it is kinked at a specific size and the molt to maturity occurs over a range of sizes. The kinked growth curve has also been a sources of model instability to this point. A potentially more realistic growth model would be one that fits two growth curves: one for immature crab and one for maturing crab. However, this would require the growth increment data to be split between ‘immature’ and ‘maturing’ growth increments, which are not currently available.

Given these observations, the author preferred model is 19.7. Natural mortality should be higher than previously assumed and the instability of the kinked growth curve overshadows any perceived (though potentially misguided) realism introduced.

## H. Data gaps and research priorities

### Methodology

Moving to GMACS is currently the highest priority for the snow crab assessment.

### Data sources

Efforts should continue to incorporate as many raw data sources as possible in the assessment. Estimating parameters outside of the model and inputting them as ‘known’ artificially decreases the uncertainty represented in the standard errors of management quantities. In addition to pulling as much data into the model as possible, continuing to standardize and automate the creation of data files from the survey and catch databases would be very useful given the short time frame of the assessment cycle, but this is currently difficult for the catch data. Procuring all available growth data (including previously excluded points and information about maturity state) would facilitate implementing a more sensible ‘kinked’ growth curve.

### Modeling and weighting

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

It is not clear in practice which parameters can be reliably estimated with the currently available data and assessment model. Different weightings of likelihood components can have drastic impacts on the management advice provided from an assessment. A close look at the way CVs, sample sizes, and other weighting factors are calculated and their influence on assessment results could provide better understanding of how well the model is balanced. Simulations may be useful to understand both the estimability of the parameters in the current model with the current data and the impact of the weights assigned to different data sources. Standardization of the weighting schemes would also improve readability of the code (for example, some size composition data have both ‘weights’ and ‘sample sizes’).

## Scientific uncertainty

Natural mortality exerts a large influence over estimated management quantities and population processes, but is poorly known. Tagging studies targeted at estimating natural mortality could be useful to the assessment 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 regardless of the centroid of large male abundance? The answer to this question could influence priors on catchability.) Lacking tagging studies, studies aimed at aging old shell crab protected from the fishery by selectivity could provide better estimates of maximum age for use in empirical estimates of  $M$ .

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

Previous analyses suggest that retrospective patterns may be a problem for the snow crab assessment (Szuwalski and Turnock, 2016; Szuwalski, 2017), which was supported by this analysis. Retrospective patterns can result from unaccounted for time-varying processes in the population dynamics of the model (Hurtado et al., 2015). The retrospective patterns in MMB for snow crab appears to be at least partially a result of large estimates of survey MMB in 2014 and 2018. The large estimated survey MMB may have caused by a change in catchability during those years and focused research on time-variation in important population processes for snow crab should be pursued to confront retrospective biases. Efforts to address catchability and the spatial dynamics of the snow crab fishery are currently underway.

## I. Ecosystem Considerations

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

Checking the new estimates of recruitment against the winter PDO (from Szuwalski and Punt, 2013) showed that the relationship has broken down with the addition of new data (which is a common phenomenon; Myers 2001). However, the PDO is highly correlated with the Arctic Oscillation (AO) and the AO is significantly correlated with estimated snow crab recruitment (Figure 43). Negative values of the AO are associated with high pressure in the polar region and greater movement of polar air into lower latitudes. This relationship may be another clue in the search for mechanistic explanations for changes in snow crab recruitment.

Regime-based management strategies have been evaluated for snow crab, but found that only small improvements in long-term yield are derived from changing the target reference points based on a change point algorithm and those changes come at a higher risk of overfishing (Szuwalski and Punt, 2012). Given the uncertainty around whether or not the environment or the fishery precipitated changes in recruitment, the

precautionary principle guides managers to assume it is the fishery. Spatial analyses of recruitment, mature biomass, environmental drivers, and the impact of the fishery may provide insight to the population dynamics of snow crab, but modeling techniques capable of fully-spatial stock assessment are only recently feasible. The most recent large recruitment events will likely divide the recruitment time series into three periods and present an intriguing opportunity for further study of the relationship between environmental variables and recruitment success.

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## Appendix A: Model structure

### Population dynamics

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

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

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

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

The dynamics after the initial year were described by:

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

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

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

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

estimated subject to constraints (see Table 10; 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  $\delta_y$  was the mid point of the fishery (all fisheries were assumed to occur concurrently and the midpoint was based on the directed fishery, which accounts for the vast majority of the fishing mortality) and  $w_{s,l}$  was the weight at length  $l$  for sex  $s$ . Trawl data and discard data were entered into the model with an assumed mortality of 80% and 30%, respectively. Fully-selected fishing mortality parameters for fishery  $f$  were estimated as a logged average over a given time period ( $F_{avg}^{log}$ ) with yearly deviations around that mean ( $F_{dev,y}^{log}$ ).

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

## Likelihood components

Three general types of likelihood components were used to fit to the available data (Table 14). 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  $\lambda_x$  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 14 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  $x$ ,  $\lambda_x$  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 14 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  $x$ ,  $\lambda_x$  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 14 for descriptions, weighting factors, and translated standard deviations).

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

Table 7: Observed growth increment data by sex

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

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

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Table 8: Observed retained catches, discarded catch, and bycatch.  
Discards and bycatch have assumed mortalities applied.

Survey year	Retained catch (kt)	Discarded females (kt)	Discarded males (kt)	Trawl bycatch (kt)
1982	11.85	0.02	1.27	0.37
1983	12.16	0.01	1.24	0.48
1984	29.94	0.01	2.76	0.51
1985	44.45	0.01	4.01	0.44
1986	46.22	0.02	4.25	1.88
1987	61.4	0.03	5.52	0.01
1988	67.79	0.04	5.82	0.67
1989	73.4	0.05	6.68	0.78
1990	149.1	0.05	15.21	0.6
1991	143	0.06	12	1.88
1992	104.7	0.12	17.06	1.78
1993	67.94	0.08	5.32	1.76
1994	34.13	0.06	4.03	3.54
1995	29.81	0.02	5.75	1.34
1996	54.22	0.07	7.44	0.92
1997	114.4	0.01	5.73	1.47
1998	88.09	0.01	4.67	1.01
1999	15.1	0	0.52	0.61
2000	11.46	0	0.62	0.53
2001	14.8	0	1.89	0.39
2002	12.84	0	1.47	0.23
2003	10.86	0	0.57	0.76
2004	11.29	0	0.51	0.95
2005	16.77	0	1.36	0.36
2006	16.49	0	1.78	0.83
2007	28.59	0.01	2.53	0.43
2008	26.56	0.01	2.06	0.27
2009	21.78	0.01	1.23	0.63
2010	24.61	0.01	0.62	0.17
2011	40.29	0.18	1.69	0.16
2012	30.05	0.03	2.32	0.22
2013	24.49	0.07	3.27	0.12
2014	30.82	0.17	3.52	0.16
2015	18.42	0.07	2.96	0.16
2016	9.67	0.02	1.31	0.08
2017	8.6	0.02	1.93	0.02
2018	12.51	0.02	2.86	0.02

Table 9: Observed mature male and female biomass (1000 t) at the time of the survey and coefficients of variation.

Survey year	Female mature biomass	Female CV	Mature male biomass	Male CV	Males >101mm (kt)	Males >101mm (million)
1982	144.4	0.15	176.8	0.14	33.34	60.91
1983	90.13	0.2	161.6	0.13	38.09	70.09
1984	42.32	0.19	177.7	0.12	88.73	151.8
1985	6.12	0.2	71.84	0.11	43.39	72.84
1986	15.74	0.18	89.81	0.11	46.7	77.91
1987	122.6	0.16	194.6	0.11	74.44	128.6
1988	169.9	0.17	259.4	0.15	104.7	173.1
1989	264.2	0.25	299.2	0.11	92.31	158.9
1990	182.9	0.19	443.8	0.14	224.7	386.4
1991	214.9	0.19	466.6	0.15	292.2	452.9
1992	131.4	0.18	235.5	0.09	143.9	227.3
1993	132.1	0.16	183.9	0.1	78.11	126.7
1994	126.2	0.15	171.3	0.08	44.78	72.57
1995	168.7	0.14	220.5	0.13	37.75	65.18
1996	107.3	0.14	288.4	0.12	87.57	155.2
1997	103.8	0.2	326.8	0.1	168.7	280.6
1998	72.73	0.25	206.4	0.09	126.7	209.7
1999	30.89	0.21	95.85	0.09	52.53	85.2
2000	96.46	0.52	96.39	0.14	41.88	69.83
2001	77.24	0.28	136.5	0.12	41.51	70.69
2002	30.22	0.28	93.17	0.23	36.56	64.16
2003	41.71	0.31	79.07	0.12	32.57	55.61
2004	50.16	0.26	79.57	0.14	35.99	57.42
2005	64.85	0.17	123.5	0.11	40.67	63.26
2006	51.93	0.18	139.3	0.26	71.13	120.9
2007	55.89	0.22	153.1	0.15	73.62	127.5
2008	57.15	0.19	142	0.1	66.56	113.6
2009	52.16	0.21	148.2	0.13	78.92	129.9
2010	98.01	0.18	162.8	0.12	88.35	138.3
2011	175.8	0.18	167.1	0.11	94.67	147.6
2012	149.4	0.2	122.2	0.12	53.17	85.35
2013	131.4	0.18	97.46	0.12	42.93	71.79
2014	119.7	0.19	163.5	0.16	81.39	138.8
2015	85.13	0.17	80.04	0.12	35.77	56.11
2016	55.39	0.21	63.21	0.11	21.96	36.51
2017	106.8	0.21	83.96	0.13	20.52	35.02
2018	165.9	0.18	198.4	0.17	26.75	48.08
2019	110.4	0.2	169.1	0.17	28.12	51.27

Table 10: Parameter bounds and symbols

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

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





Table 12: 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	18.1	19.1	19.2	19.3	19.4	19.5	19.6	19.7
Recruitment deviations	70.18	76.44	73.97	71.51	77.46	77.56	72.88	75.39
Initial numbers old shell males small length bins	4.62	4.56	4.52	4.47	4.58	4.59	4.46	4.54
ret fishery length total fish length (ret + disc)	320.96	324.51	323.97	323.91	324.8	333.85	321.1	332.48
female fish length survey length trawl length	920.93	1026.1	1025.41	1025.39	1026.73	1031.87	1017.57	1030.93
2009 BSFRF length	241.32	250.83	250.1	247.63	247.19	250.85	251.65	250.13
2009 NMFS study area length M multiplier prior maturity smooth growth males growth females	4293.05	4420.93	4373.35	4399.53	4458.89	4420.38	4418.77	4375.12
2009 BSFRF biomass	300.15	334.82	326.69	323.85	334.72	331.99	344.82	323.33
2009 NMFS study area biomass	-92.24	-91.85	-92.65	-93.44	-82.19	-91.96	-91.58	-90.12
cpue q retained catch	-75.15	-74.48	-75.19	-74.77	-70.48	-74.56	-74.07	-74.44
	77.61	79.37	59.43	43.27	80.69	79.53	85.17	61.1
	43.65	46.55	43.9	41.08	45.2	51.25	48.41	47.66
	140.07	140.59	139.96	139.09	140.8	140.91	137.36	139.69
	394.96	367.22	365.5	333.96	390.95	367.43	367.15	365.66
	0.47	0.57	0.43	0.28	4	0.55	0.61	0.27
	0.22	0.27	0.19	0.11	9.44	0.28	0.33	0.26
	0.21	0.35	0.35	0.35	0.34	0.36	0.39	0.36
	3.65	4.53	4.55	4.59	4.57	4.98	3.13	5

Likelihood component	18.1	19.1	19.2	19.3	19.4	19.5	19.6	19.7
discard catch	116.77	96.71	100.74	105.08	97.84	107.55	40.05	112.09
trawl catch	6.95	9.81	9.44	9.14	9.73	9.55	9.79	9.11
female discard catch	4.17	4.34	4.33	4.32	4.35	4.32	4.28	4.31
survey biomass	207.32	220.47	214.63	211.66	220.48	223.98	221.62	218.62
F penalty	23.51	26.37	25.96	25.51	26.13	28.54	29.68	27.74
2010 BSFRF	9.58	7.35	6.21	6.34	10.65	7.22	7.05	7.92
Biomass 2010 NMFS	3.44	6.07	5.44	3.14	3.36	6.04	6.52	3.34
Biomass Extra	547.47	546.8	546.25	543.9	545.12	546.94	547.24	546.55
weight survey lengths first year								
2010 BSFRF	-51.66	-49.86	-50.61	-50.52	-50.33	-49.42	-49.41	-51.15
length 2010 NMFS	-64.14	-62.74	-64.22	-67.53	-65.28	-62.74	-61.66	-66.72
length smooth	2.44	2.23	2.23	2.46	1.92	2.11	2.01	0.93
selectivity smooth	0	0	0	0	0	0	0	0
female selectivity init nos	43.32	43.01	43.2	43.41	43.1	43.54	41.76	43.87
smooth constraint								
Total	7493.83	7761.87	7668.08	7627.72	7844.76	7797.49	7707.08	7703.97



Table 13: Changes in management quantities for each scenario considered. Reported management quantities are median posterior values.

Model	MMB	B35	F35	FOFL	OFL
18.1	85.84	142.8	1.22	1.04	29.74
19.1	100.5	133.7	1.24	1.24	45.47
19.2	110.8	125.2	1.71	1.71	54.07
19.3	125.7	121.3	2.48	2.48	66.07
19.4	104.5	135.2	1.3	1.3	47.77
19.5	97.41	132.9	1.31	1.31	44.18
19.6	91.75	129.7	1.37	1.37	39.57
19.7	111.4	126.1	1.93	1.93	54.92

Table 14: Likelihoods form and weighting for each likelihood component for models in the analysis (continued below)

Likelihood component	Form	18.1	19.1
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	NA	NA
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

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19.2	19.3	19.4	19.5	19.6	19.7
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
NA	NA	NA	NA	NA	NA
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	0.71	0.71	0.71
0.32	0.32	0.32	0.32	0.32	0.32
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

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Table 16: Predicted mature male (MMB), mature female (FMB), and males >101mm biomass (1000 t) and numbers (in millions) at the time of the survey from the chosen model. Columns 2-5 are subject to survey selectivity; columns 6-9 are the population values (i.e. the numbers at length are not modified by multiplying them by a selectivity curve—they are estimates of the underlying population). These are maximum likelihood estimates.

Survey year	FMB	MMB	Male >101 biomass	Male >101 (millions)	FMB	MMB	Male >101 biomass	Male >101 (millions)
1982	70.62	125.3	26.15	49.75	112.6	275.2	52.94	100.7
1983	55.72	133.5	45.99	82.08	87.39	293.2	93.13	166.2
1984	40.17	139	61.99	106.2	63.05	305.8	125.5	214.9
1985	34.73	130	61.08	103.1	54.92	286.8	123.7	208.7
1986	43.19	113.7	42.62	71.88	68.99	252.2	93.1	157
1987	103.4	113.3	34.85	60.64	167.3	253.2	76.13	132.5
1988	229.2	210.7	37.85	66.18	235.2	287.1	82.7	144.6
1989	226.1	255.1	47.41	82.7	231.4	347.5	103.6	180.7
1990	185.4	318.3	71.68	124.1	189.6	432.4	156.6	271
1991	156.7	299.2	66.13	114.9	160.4	406	144.5	251
1992	143.4	249.7	54.55	94.72	146.9	338.8	119.2	206.9
1993	148.4	210.8	75.05	127	152.2	287.2	101.2	171.3
1994	163	181.2	44.44	73.77	167.2	247.7	59.93	99.49
1995	171	202.5	40.35	71.55	175.3	275.9	54.41	96.49
1996	150.7	282.2	102.5	179.8	154.1	382.9	138.2	242.4
1997	117.6	333.7	170.1	286.1	120.2	451.9	229.4	385.8
1998	89.77	247.2	120.3	199.1	91.76	334.8	162.2	268.4
1999	72.81	151.3	57.25	96.07	74.48	205.2	77.21	129.6
2000	66.28	118.8	42.03	70.2	67.88	161.4	56.68	94.67
2001	59.53	99.58	30.86	52.32	60.92	135.3	41.62	70.57
2002	50.77	94.02	29.77	51.72	51.93	127.7	40.15	69.75
2003	42.66	99.23	40.38	68.82	43.64	134.7	54.46	92.81
2004	44.83	99.56	44.72	74.41	45.98	135.3	60.31	100.3
2005	68.94	96.6	39.02	64.78	70.92	131.5	52.62	87.36
2006	84.16	103.3	35.42	60.5	86.31	140.7	47.77	81.58
2007	84.23	129.5	49.43	85.08	86.27	176	66.67	114.7
2008	73.43	151.6	66.55	113.4	75.11	205.6	89.75	152.9
2009	61.29	162.5	80.9	135.7	62.69	220.1	109.1	183.1
2010	94.53	156.6	83.82	138.9	97.31	212.1	113	187.3
2011	117	132.2	68.32	112.5	120.1	179.2	92.13	151.7
2012	109.7	95.54	37.6	63.55	112.3	129.7	50.7	85.7
2013	94.59	80.82	27.74	48.5	96.78	109.7	37.41	65.41
2014	84.46	74.81	29.17	49.98	86.47	101.5	39.34	67.41
2015	76.09	55.14	18.15	30.83	77.89	74.93	24.48	41.58
2016	82.03	46.91	11.44	19.57	84.15	64.22	15.43	26.39
2017	124.5	62.69	11.01	19	128.1	86.61	14.85	25.62
2018	176.6	109.1	18.69	33.11	181.5	149.9	25.2	44.66
2019	173.6	195.3	55.06	97.55	177.7	266	74.26	131.6

Table 17: Maximum likelihood estimates of predicted mature male biomass at mating, mature female biomass at mating (in 1000 t), recruitment (millions) from the chosen model, and estimated fully-selected total fishing mortality. These are maximum likelihood estimates.

Survey year	Mature male biomass	Mature female biomass	Recruits	Fishing mortality
1982	214.3	87.14	191.9	0.39
1983	229.5	67.63	544.5	0.22
1984	221.8	48.79	1288	0.42
1985	191.2	42.5	5409	0.7
1986	159.6	53.38	2284	1.09
1987	146.1	129.5	1077	2.45
1988	169.1	182	463.4	2.54
1989	214.3	179.1	1196	1.88
1990	209.2	146.7	1134	4.01
1991	192.4	124.1	1800	4.65
1992	175.4	113.6	1909	3.16
1993	168.2	117.7	1584	1.81
1994	167.2	129.3	360.4	1.36
1995	197.8	135.6	281.2	1.18
1996	263	119.3	307.7	0.78
1997	258.9	92.98	422.2	1.11
1998	186.3	71	593.9	1.27
1999	153.8	57.63	301.3	0.33
2000	121.2	52.53	245.6	0.35
2001	96.18	47.15	223.4	0.69
2002	92.41	40.19	680	0.6
2003	100	33.77	1596	0.34
2004	99.84	35.58	744.3	0.32
2005	91.42	54.89	619.1	0.6
2006	99.31	66.79	282.3	0.66
2007	117	66.76	315.7	0.88
2008	143.5	58.13	2664	0.55
2009	159.9	48.51	889.3	0.34
2010	150.5	75.31	480.1	0.38
2011	107	92.81	562.4	0.91
2012	76.14	86.89	635.1	1.44
2013	65.68	74.88	486.2	1.66
2014	52.45	66.81	1216	2.45
2015	42.57	60.26	2828	2.28
2016	42.88	65.12	2754	1.57
2017	62.45	99.14	331.6	1.4
2018	111.4	140.4	222	1.05

Table 18: Maximum likelihood estimates of predicted total numbers (billions), not subject to survey selectivity at the time of the survey. These are maximum likelihood estimates.

Survey year	Total numbers
1982	4.843
1983	5.28
1984	5.901
1985	7.484
1986	14.99
1987	15.03
1988	15.27
1989	11.36
1990	9.486
1991	8.037
1992	13.15
1993	12.18
1994	10.79
1995	8.166
1996	6.103
1997	4.644
1998	4.364
1999	4.218
2000	3.494
2001	2.928
2002	2.894
2003	4.052
2004	5.747
2005	5.935
2006	5.462
2007	4.3
2008	3.521
2009	6.082
2010	5.582
2011	4.66
2012	3.936
2013	3.571
2014	3.399
2015	5.681
2016	11.73
2017	13.34
2018	10.2
2019	7.706

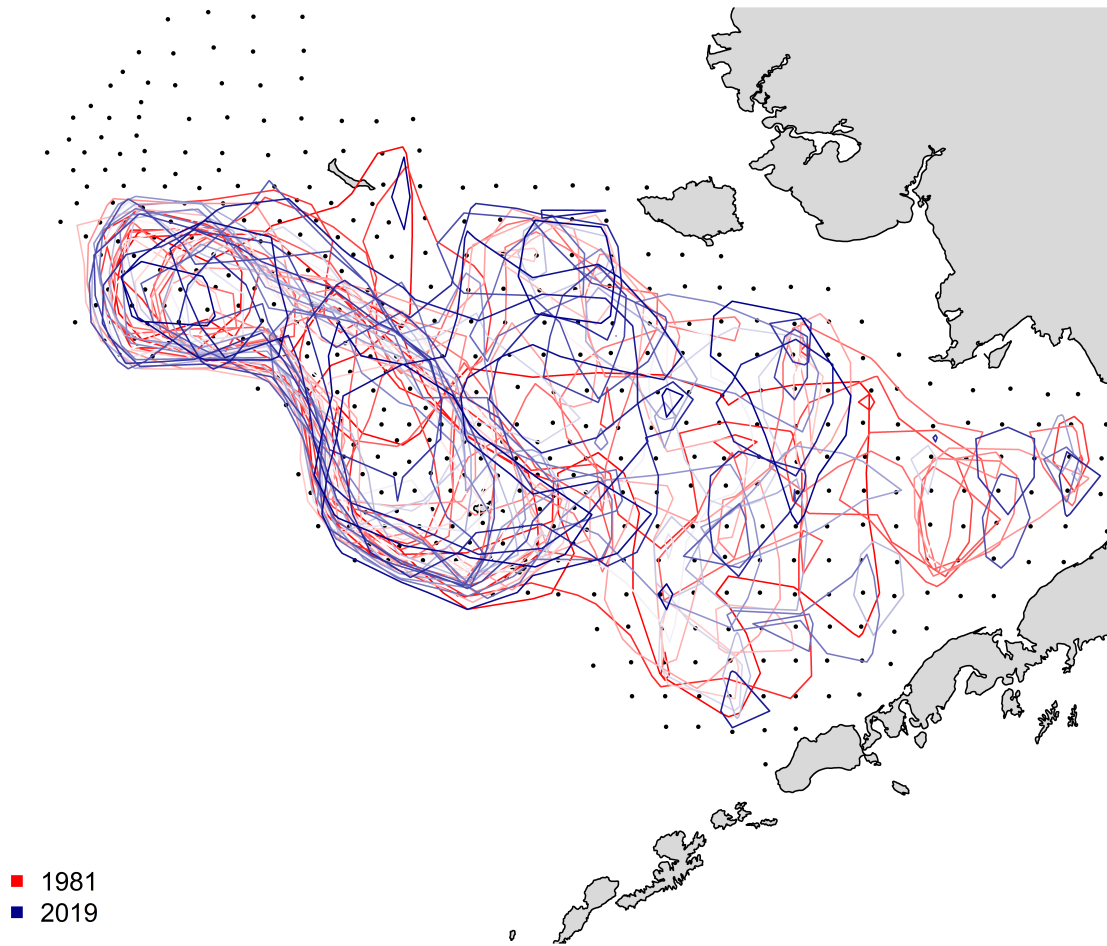


Figure 1: Kernel densities over time of greater than 77 mm carapace width males in the survey. Plotted contours are the lines that contain 99th quantile of the stations at which crab were observed in a given year. Colors are a gradient from red to blue, with red starting at 1981 and blue ending at 2019. Black points are survey stations.

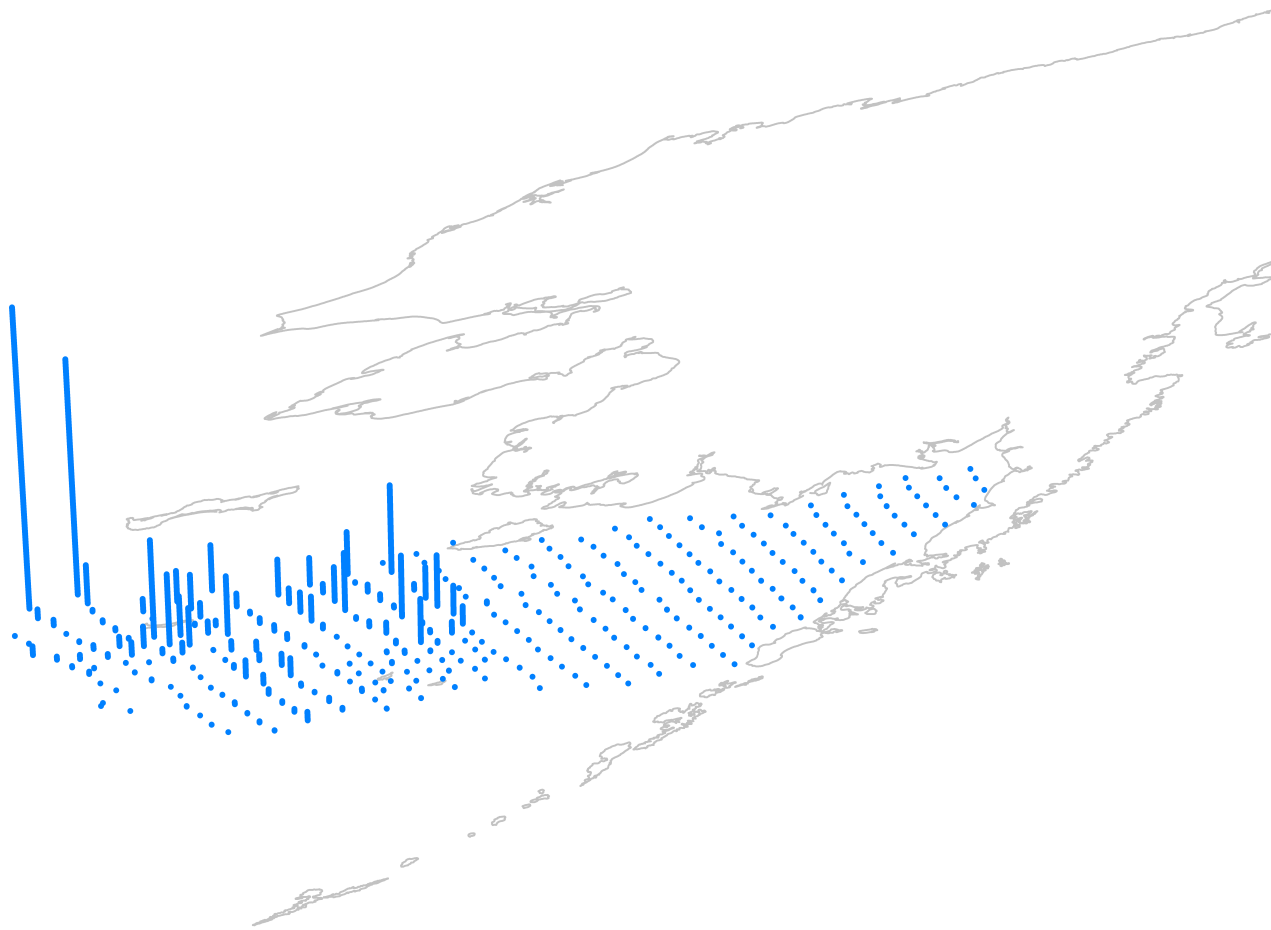


Figure 2: Observed relative density of all males at the time of the 2019 NMFS summer survey



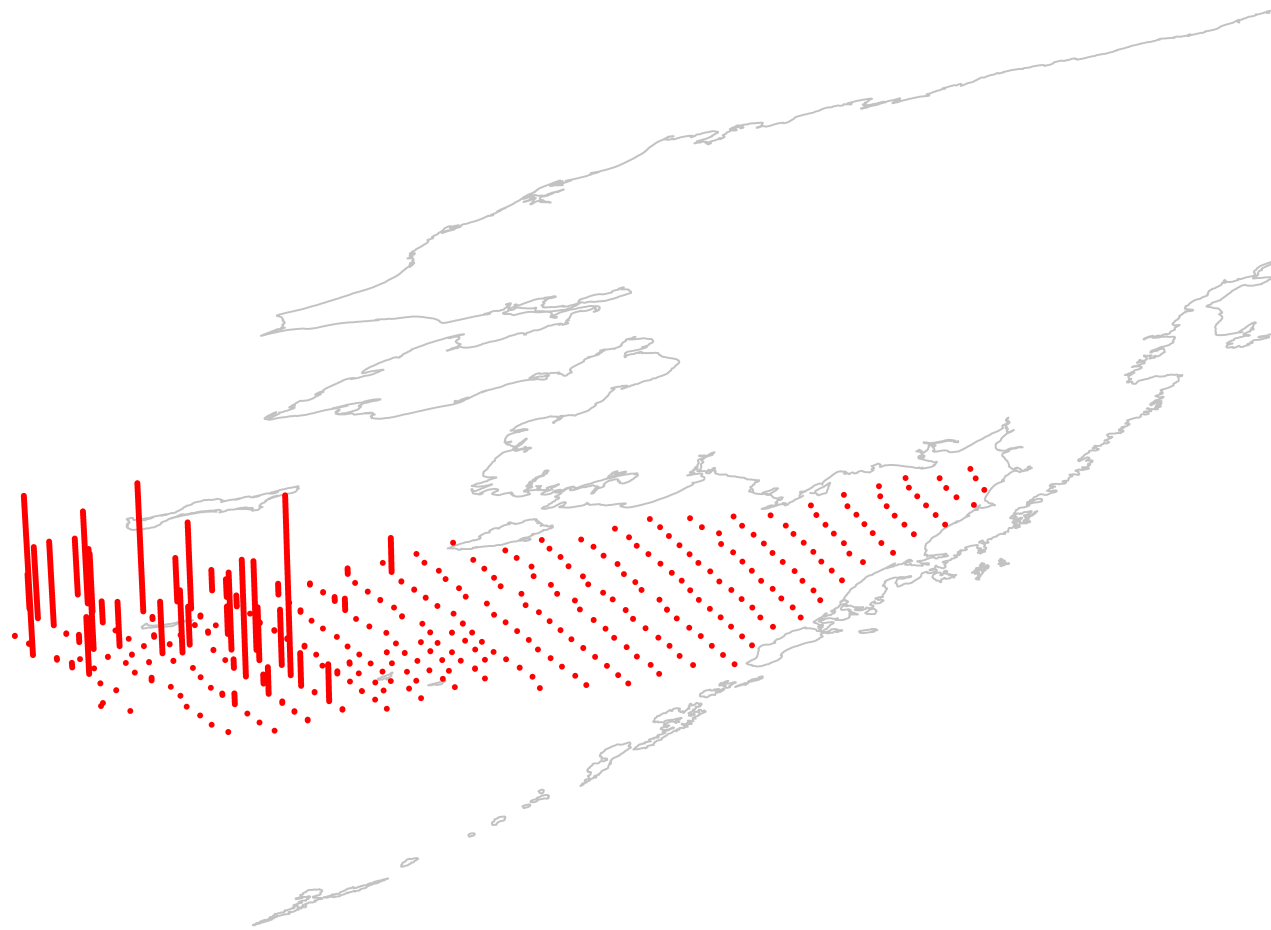


Figure 3: Observed relative density of all females at the time of the 2019 NMFS summer survey

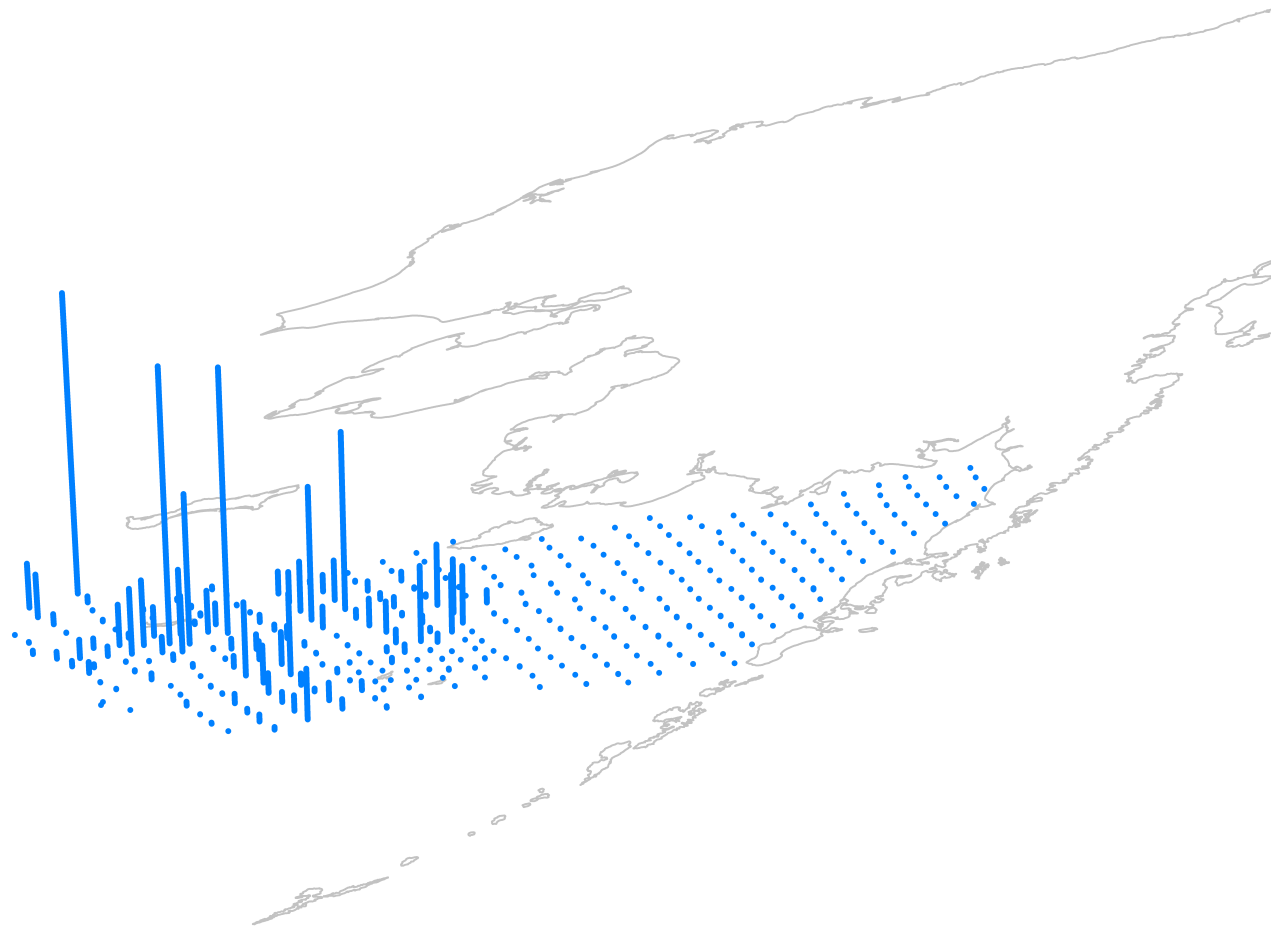


Figure 4: Observed relative density of males  $>77\text{mm}$  carapace width at the time of the 2019 NMFS summer survey

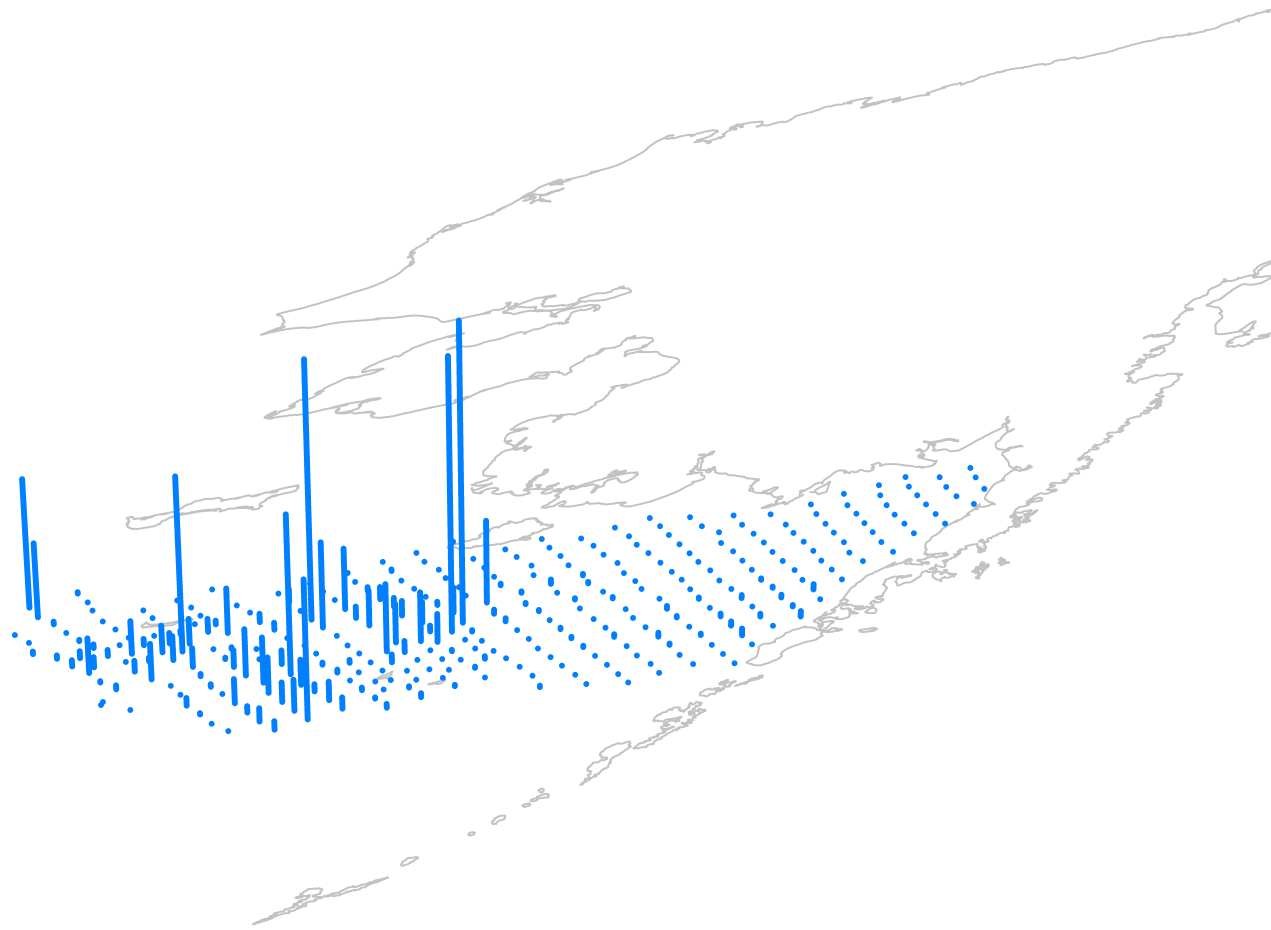


Figure 5: Observed relative density of males  $>101\text{mm}$  carapace width at the time of the 2019 NMFS summer survey

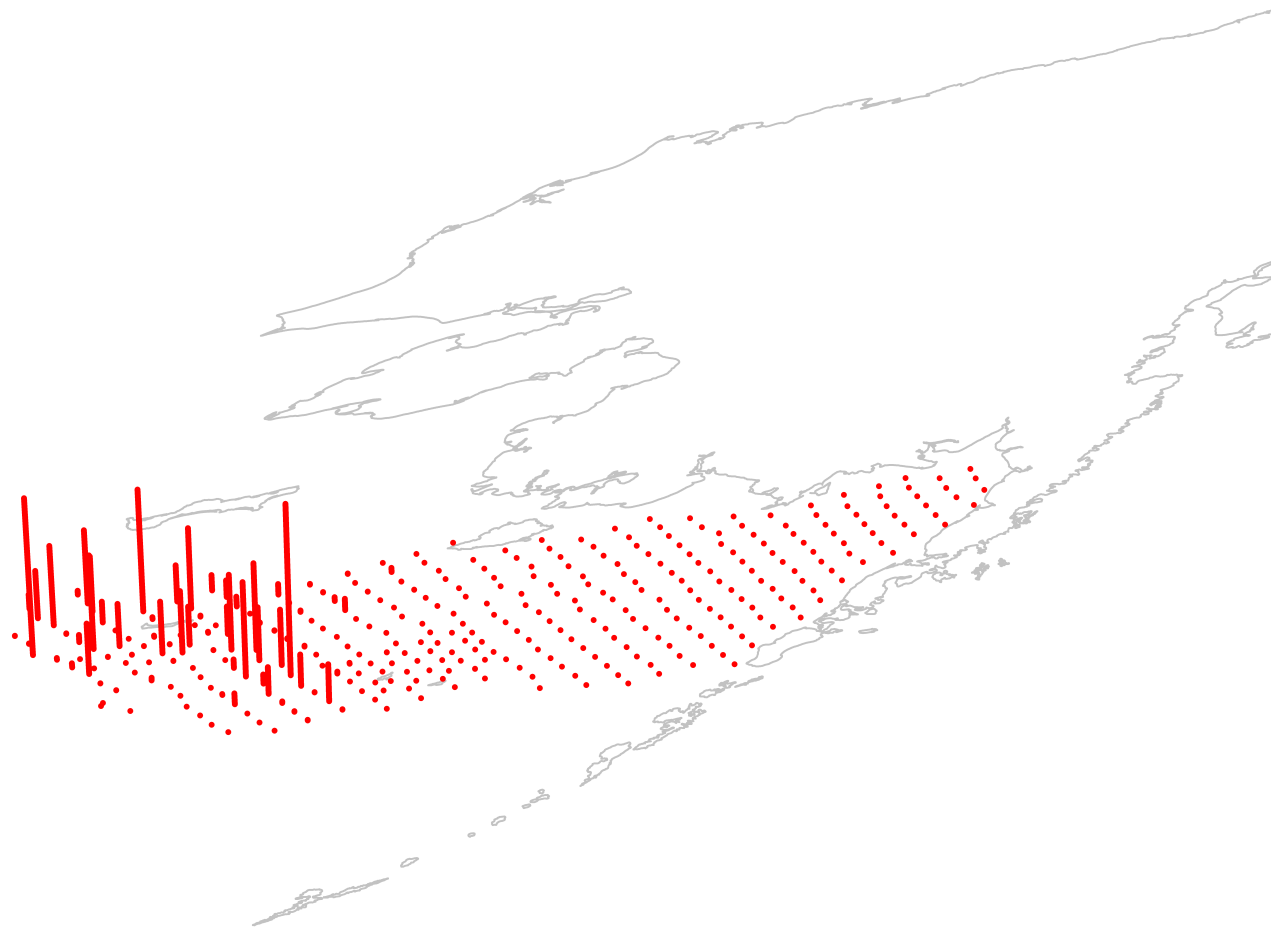


Figure 6: Observed relative density of mature females at the time of the 2019 NMFS summer survey

Shell condition	CW (mm)	Age (years)	Error (years)	Coordinates	Depth (m)	Species
0+	121	0.05	0.26	59°20'N, 171°49'W	43	<i>C. opilio</i>
0+	110	0.11	0.27	59°20'N, 171°49'W	43	<i>C. opilio</i>
0+	132	0.11	0.19	59°20'N, 171°49'W	43	<i>C. opilio</i>
1	118	0.15	0.26	59°20'N, 171°49'W	43	<i>C. opilio</i>
1	130	0.23	0.27	59°20'N, 171°49'W	43	<i>C. opilio</i>
1	116	0.25	0.24	59°20'N, 171°49'W	43	<i>C. opilio</i>
2+	93	0.33	0.28	57°00'N, 167°43'W	42	<i>C. bairdi</i>
2+	122	0.42	0.26	57°00'N, 167°43'W	42	<i>C. bairdi</i>
2+	97	0.66	0.30	59°00'N, 171°47'W	46	<i>C. opilio</i>
2+	123	0.78	0.32	59°00'N, 171°47'W	46	<i>C. opilio</i>
2+	121	0.85	0.27	57°00'N, 167°43'W	42	<i>C. opilio</i>
2+	66	1.07	0.29	59°00'N, 171°47'W	46	<i>C. opilio</i>
3	117	0.92	0.34	59°00'N, 171°47'W	46	<i>C. opilio</i>
3	69	1.04	0.28	59°00'N, 171°47'W	46	<i>C. opilio</i>
3	78	1.10	0.30	59°00'N, 171°47'W	46	<i>C. opilio</i>
4	100	4.43	0.33	57°21'N, 167°45'W	39	<i>C. opilio</i>
4	93	4.89	0.37	58°20'N, 171°38'W	52	<i>C. bairdi</i>
4	100	6.60	0.33	57°00'N, 167°43'W	42	<i>C. opilio</i>
5	111	2.70	0.44	58°60'N, 169°12'W	28	<i>C. opilio</i>
5	100	4.21	0.34	59°00'N, 171°47'W	46	<i>C. bairdi</i>
5	110	6.85	0.58	58°60'N, 169°12'W	28	<i>C. opilio</i>

Figure 7: Radiometric estimates of shell age in male snow and tanner crabs collected during the NMFS survey of 1992. Reproduced from Ernst et al. 2005's presentation of Nevissi et al. 1995.

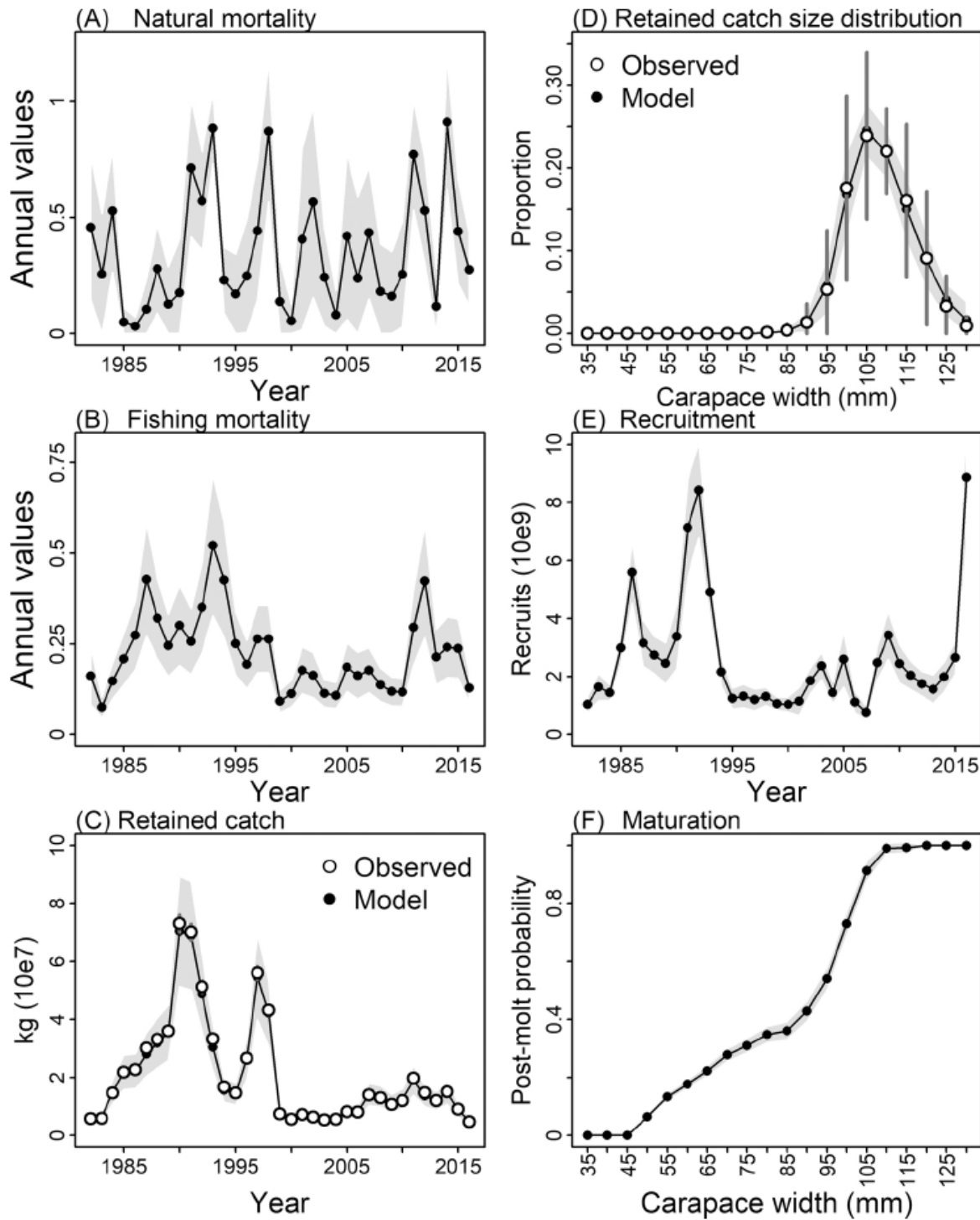


Figure 8: Murphy et al.'s (2018) estimates of natural mortality (and time-variation in  $M$ ) from a state-space modeling framework.

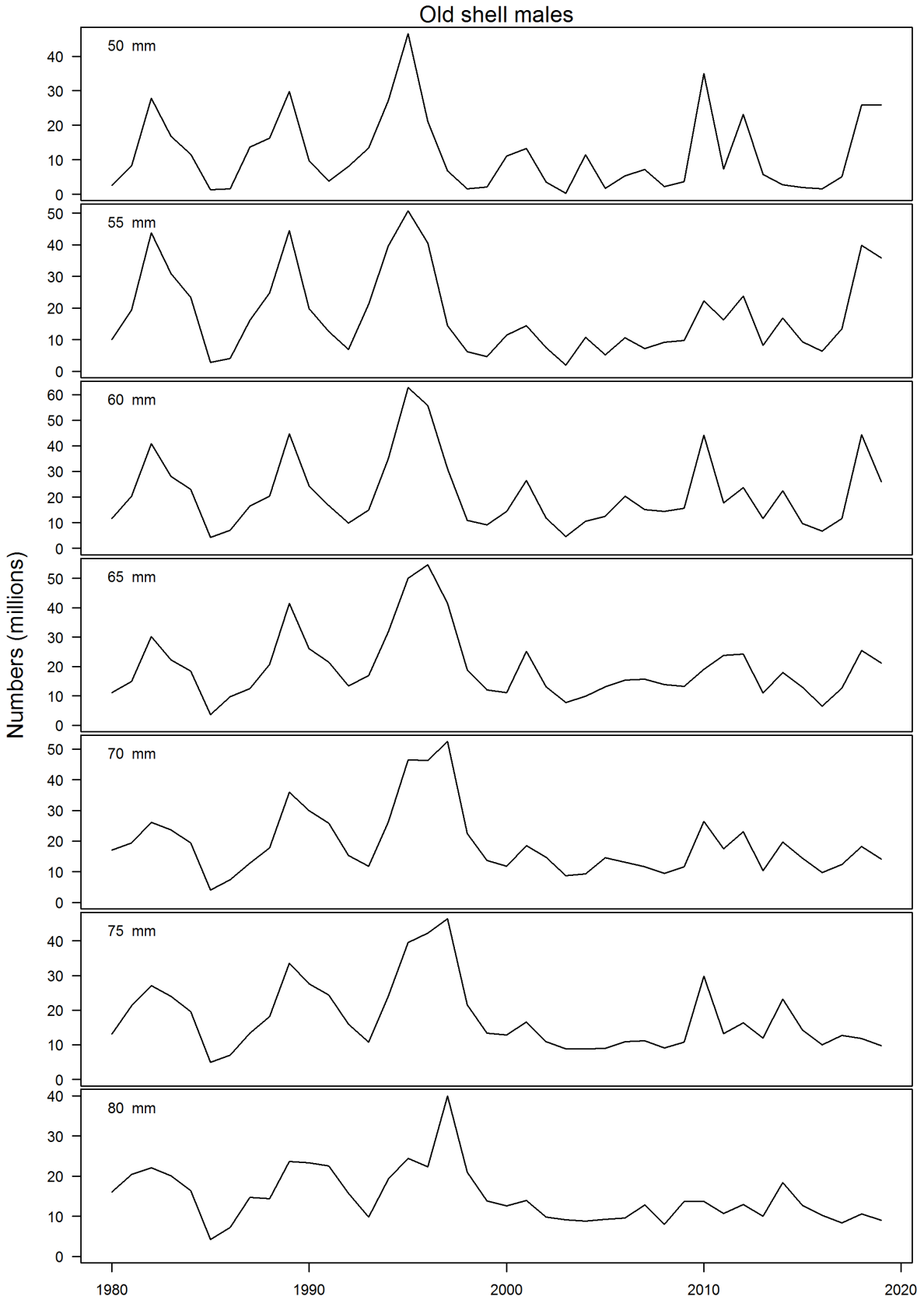


Figure 9: Observed numbers at length of old shell mature males by size class. The presented size bins are not vulnerable to the fishery, so all mortality is 'natural'. The decline in numbers in a size class after the recruitment collapse in the early 1990s demonstrates expected natural mortality for mature male individuals.

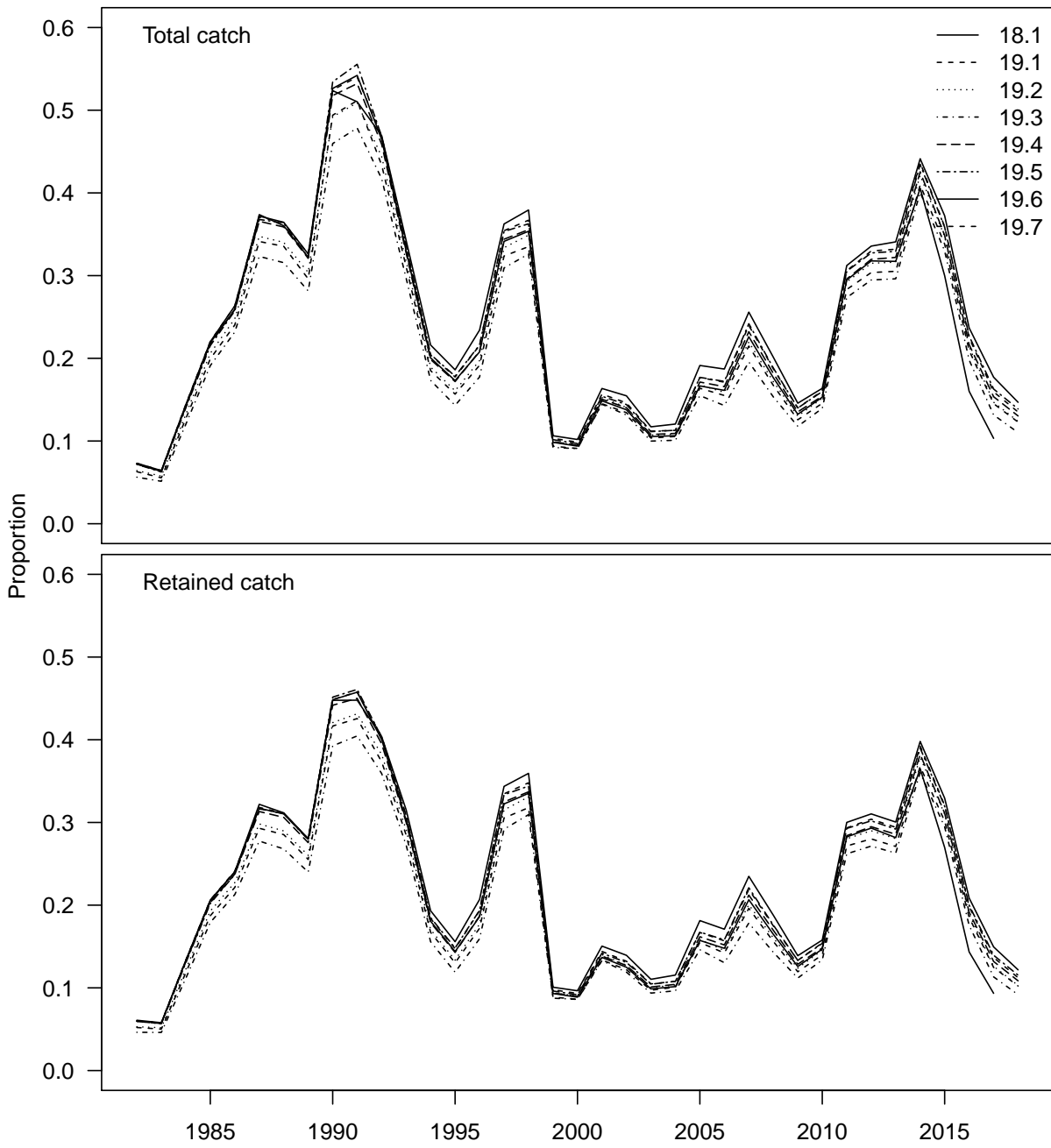


Figure 10: Model predicted ratio of catch to mature male biomass



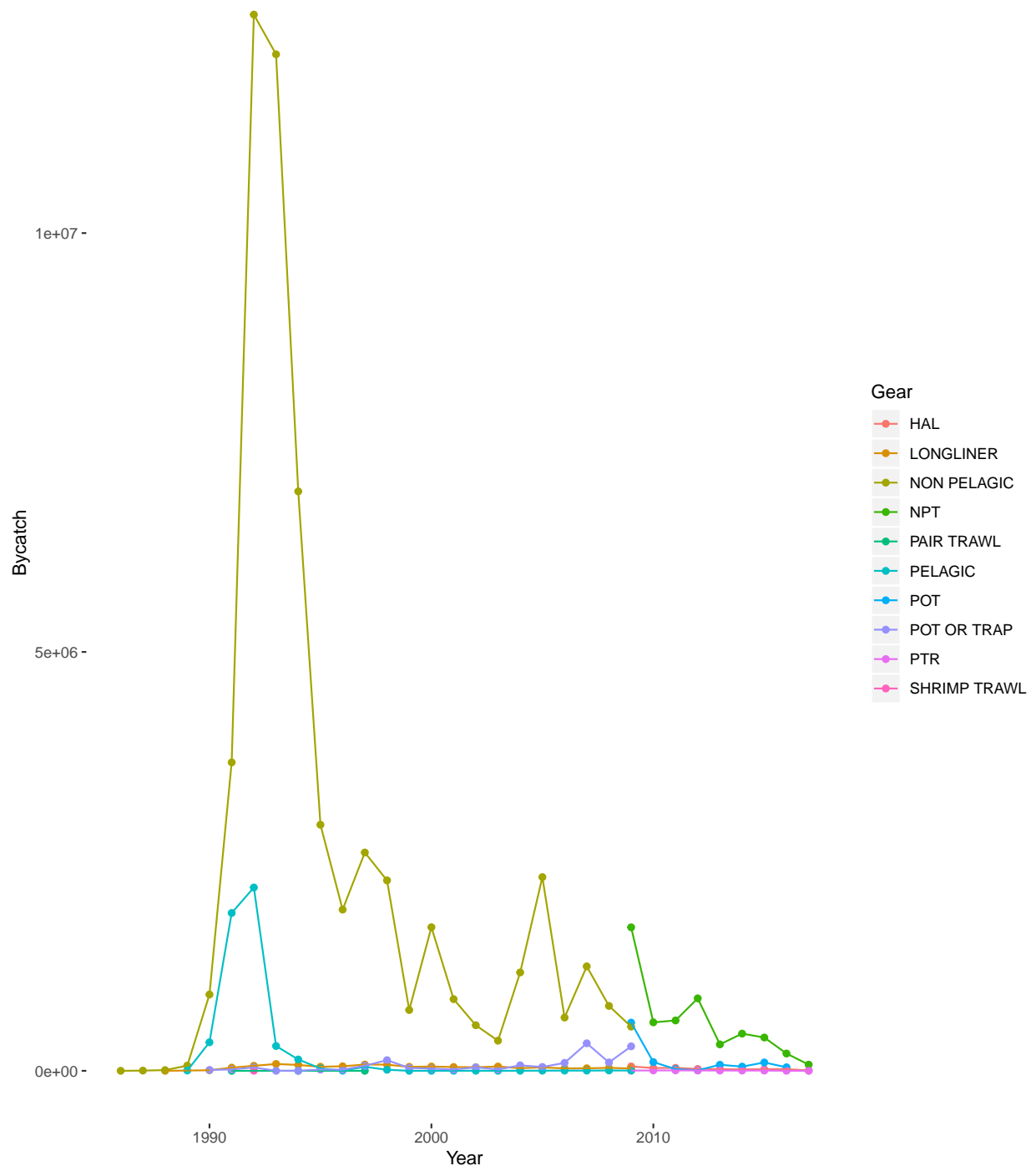


Figure 11: Bycatches in other fishing fleets.

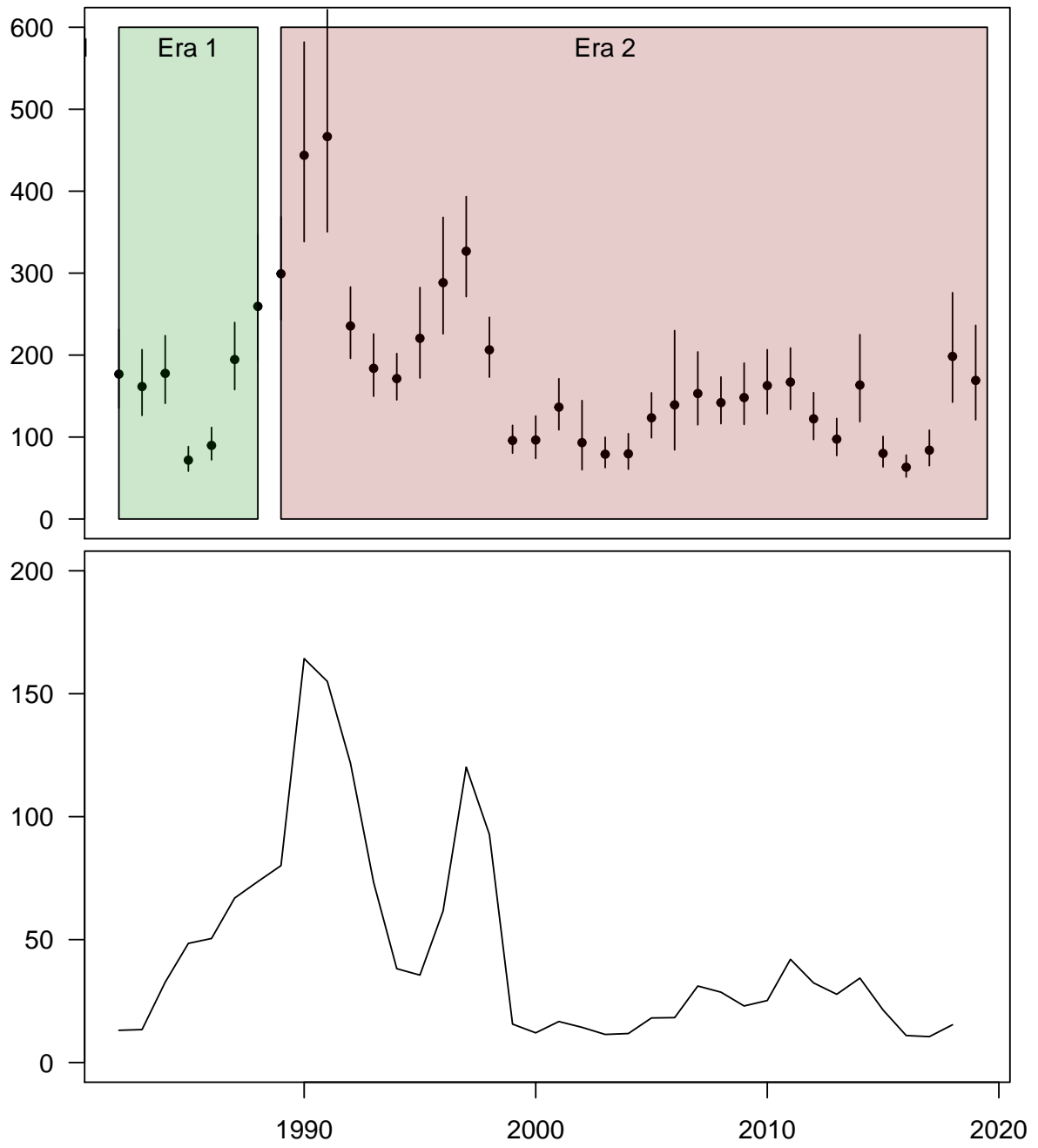


Figure 12: Divisions of survey data for estimation of  $q$  (MMB shown for reference; top) and total catches (bottom)

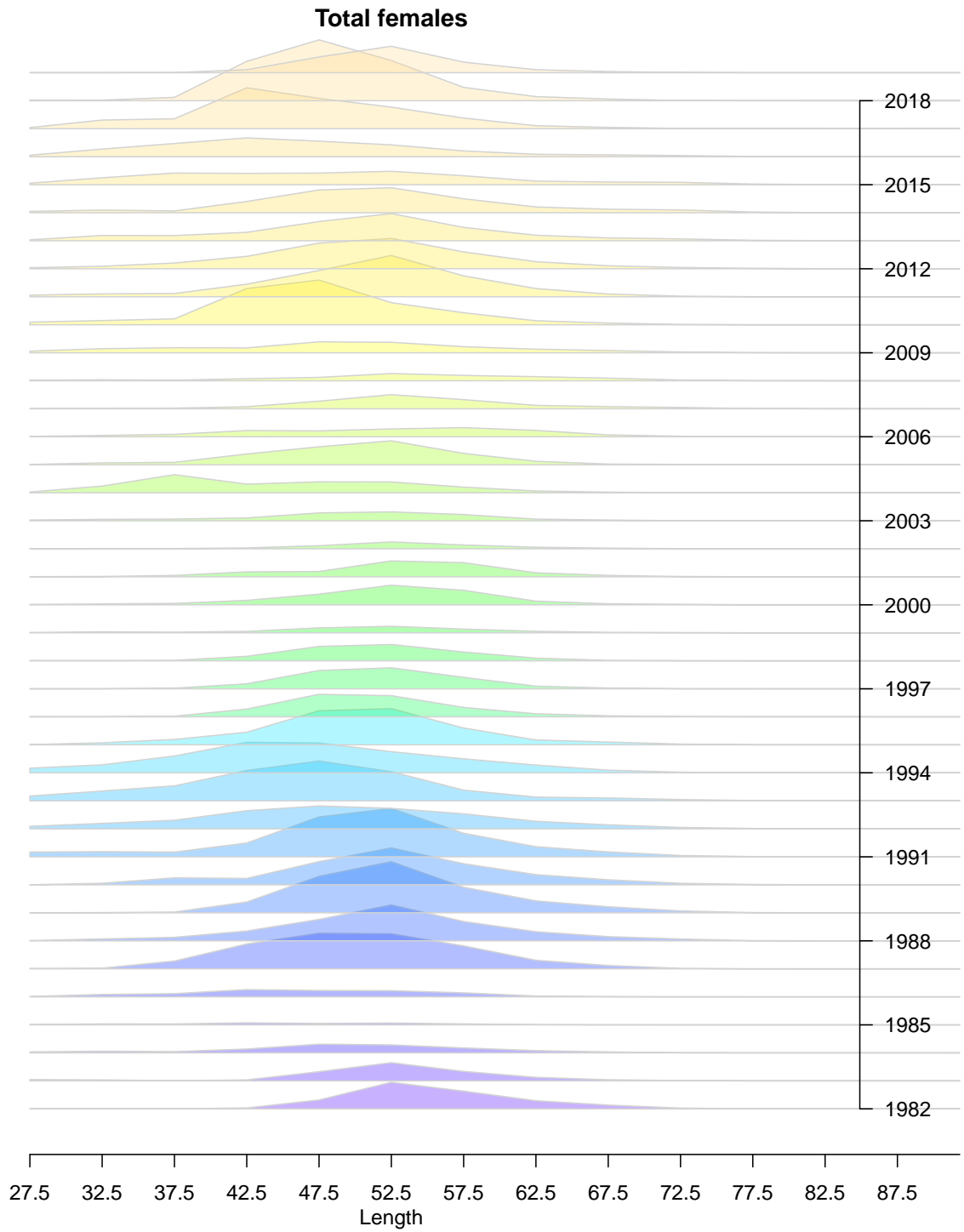


Figure 13: Observed relative numbers of females at length at the time of the survey

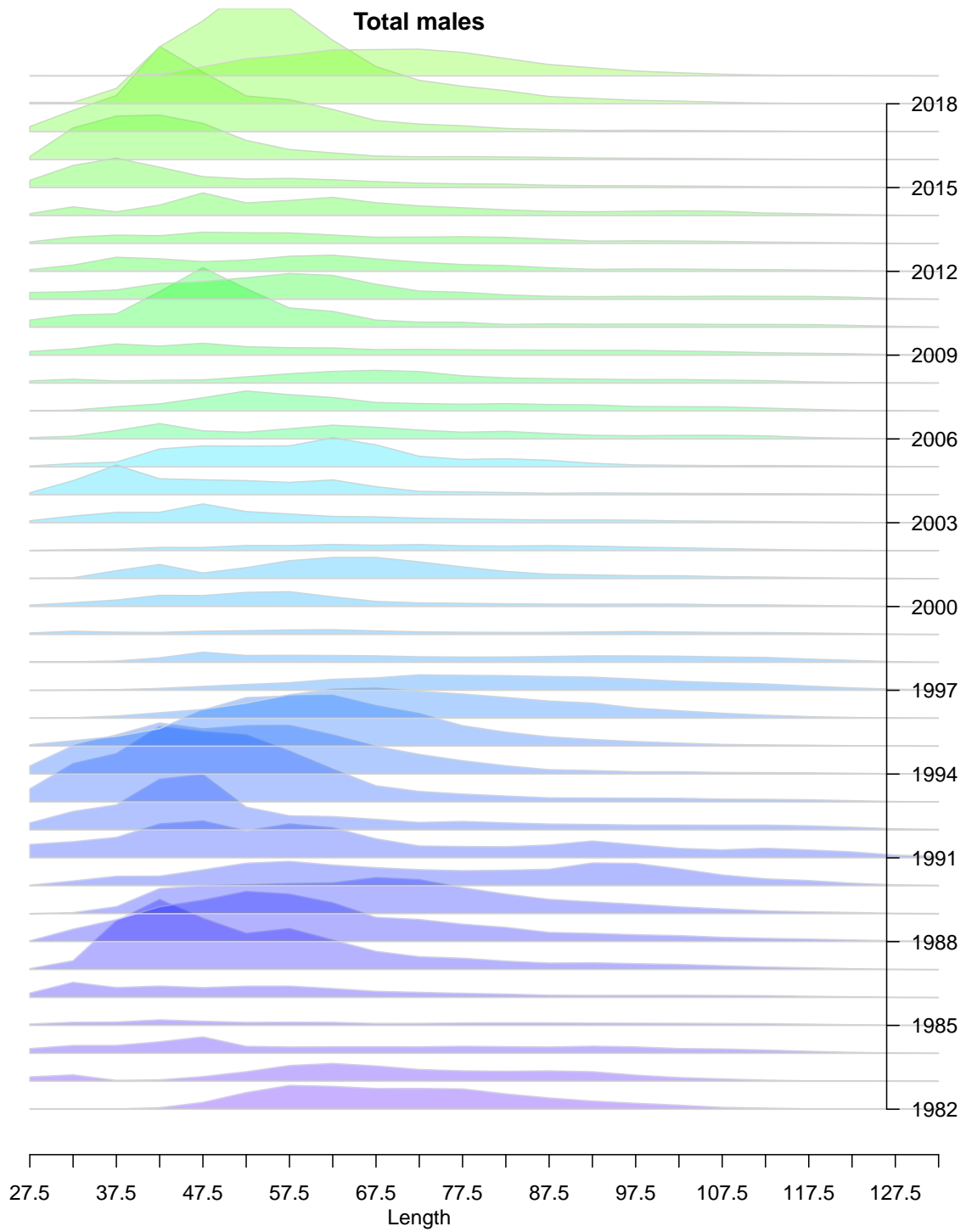


Figure 14: Observed relative numbers of males at length at the time of the survey

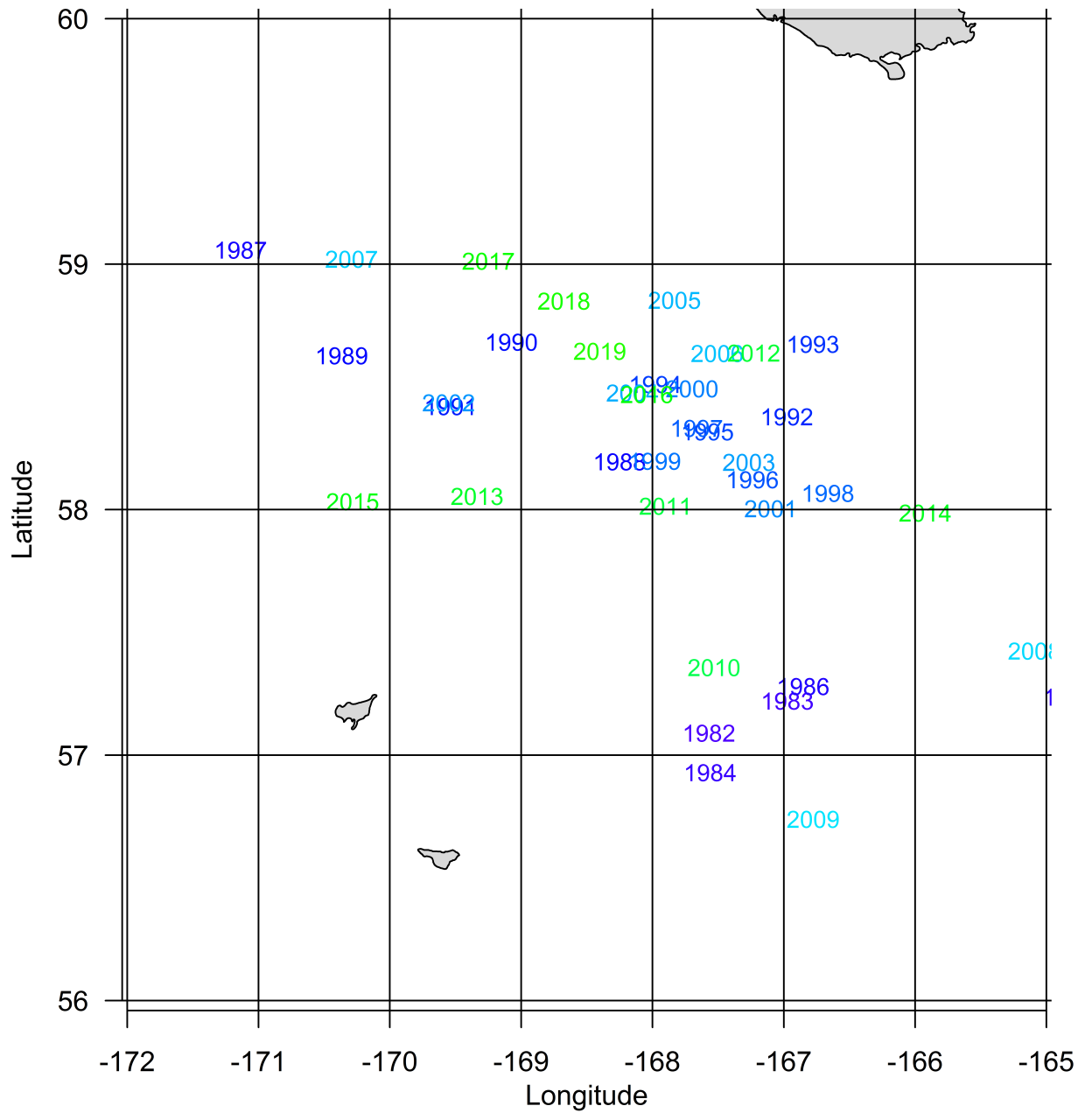


Figure 15: Centroid of mature females observed in the survey over time. Dark blue indicates years early in the time series; green are the most recent years in the time series.

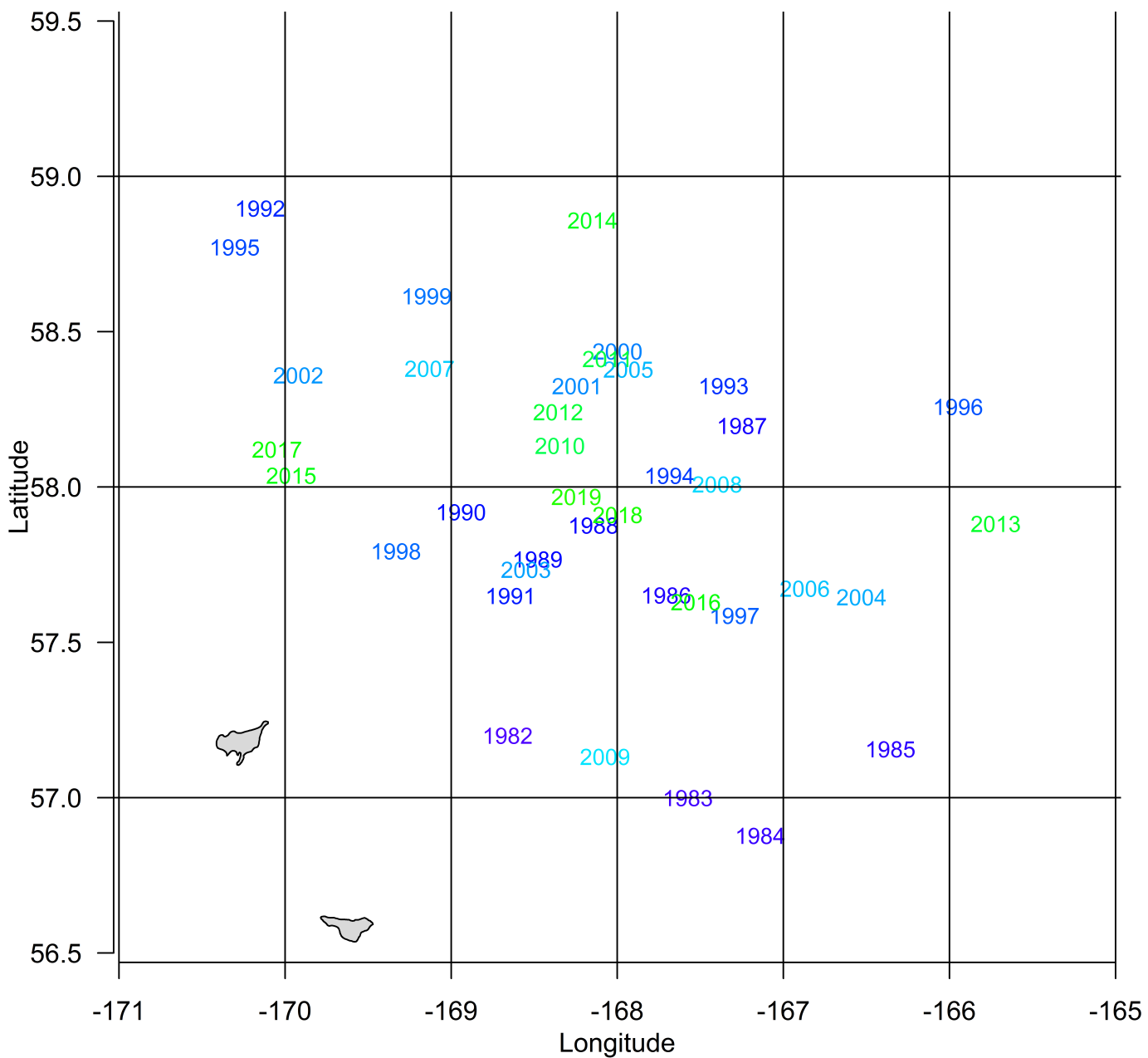


Figure 16: Centroid of large males observed in the survey over time. Dark blue indicates years early in the time series; green are the most recent years in the time series.

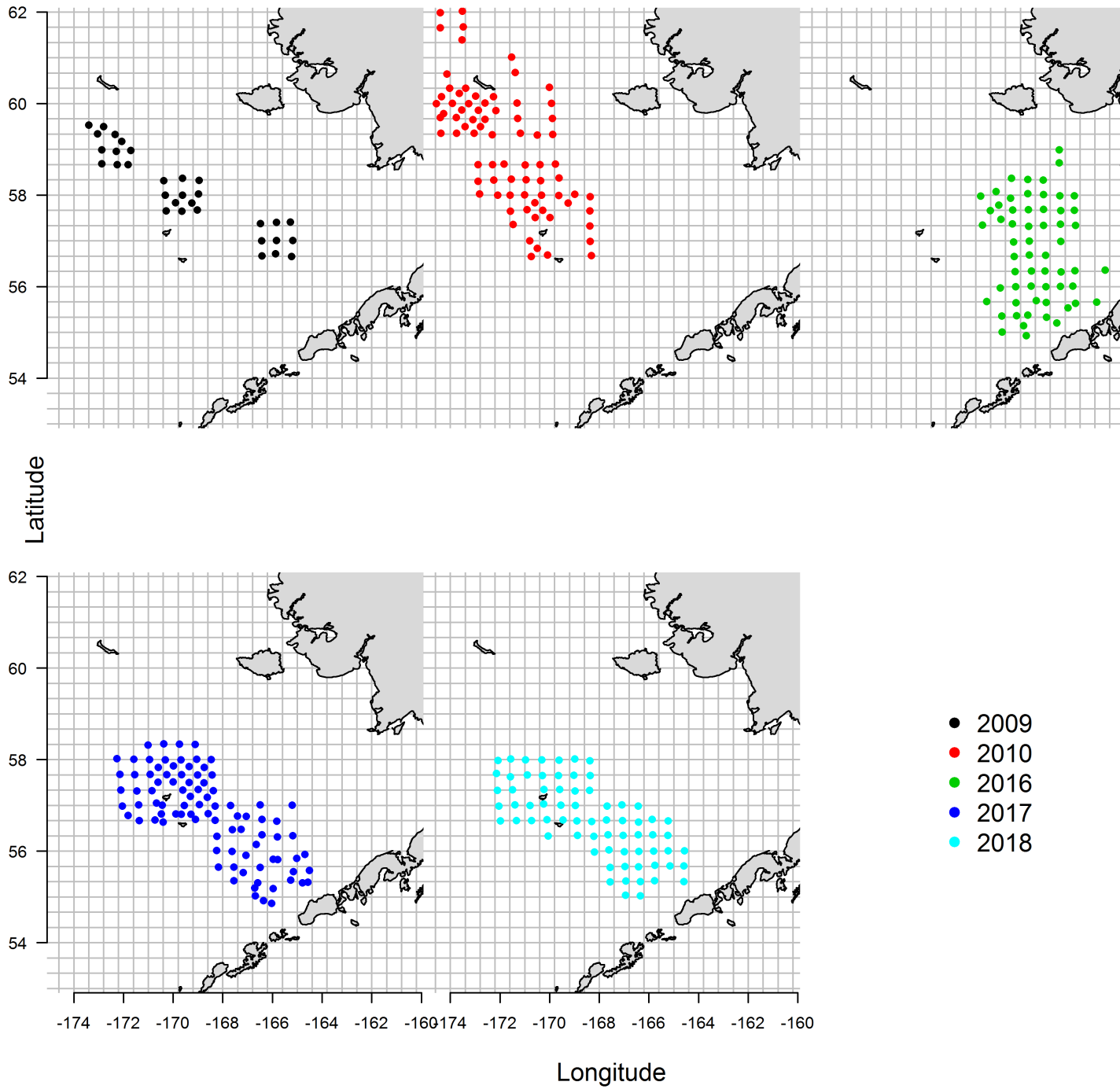


Figure 17: Location of BSFRF survey selectivity experiments.

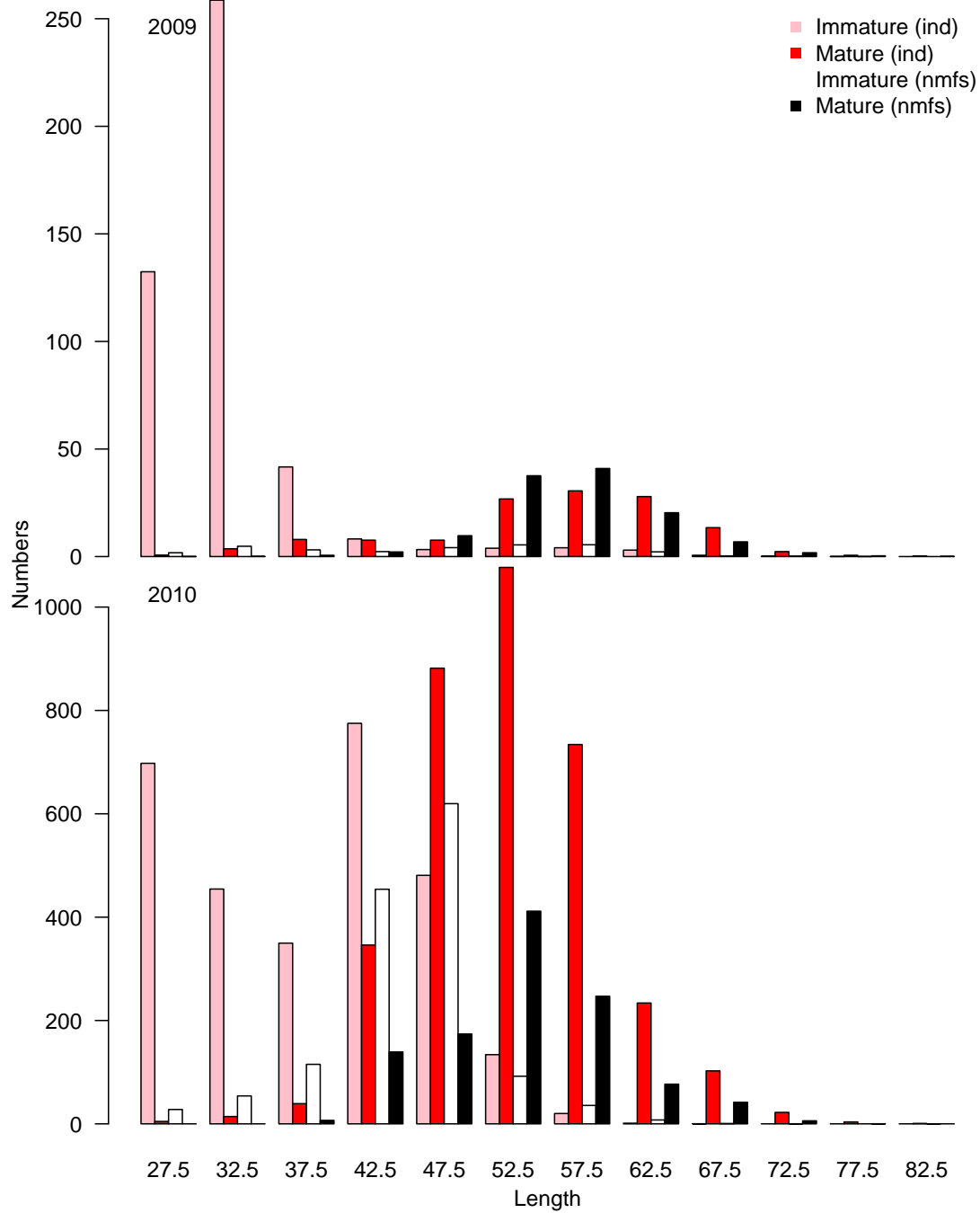


Figure 18: Raw female numbers from BSFRF survey selectivity experiments (2009 & 2010). Note a change in scale on the y-axis from 2009 to 2010



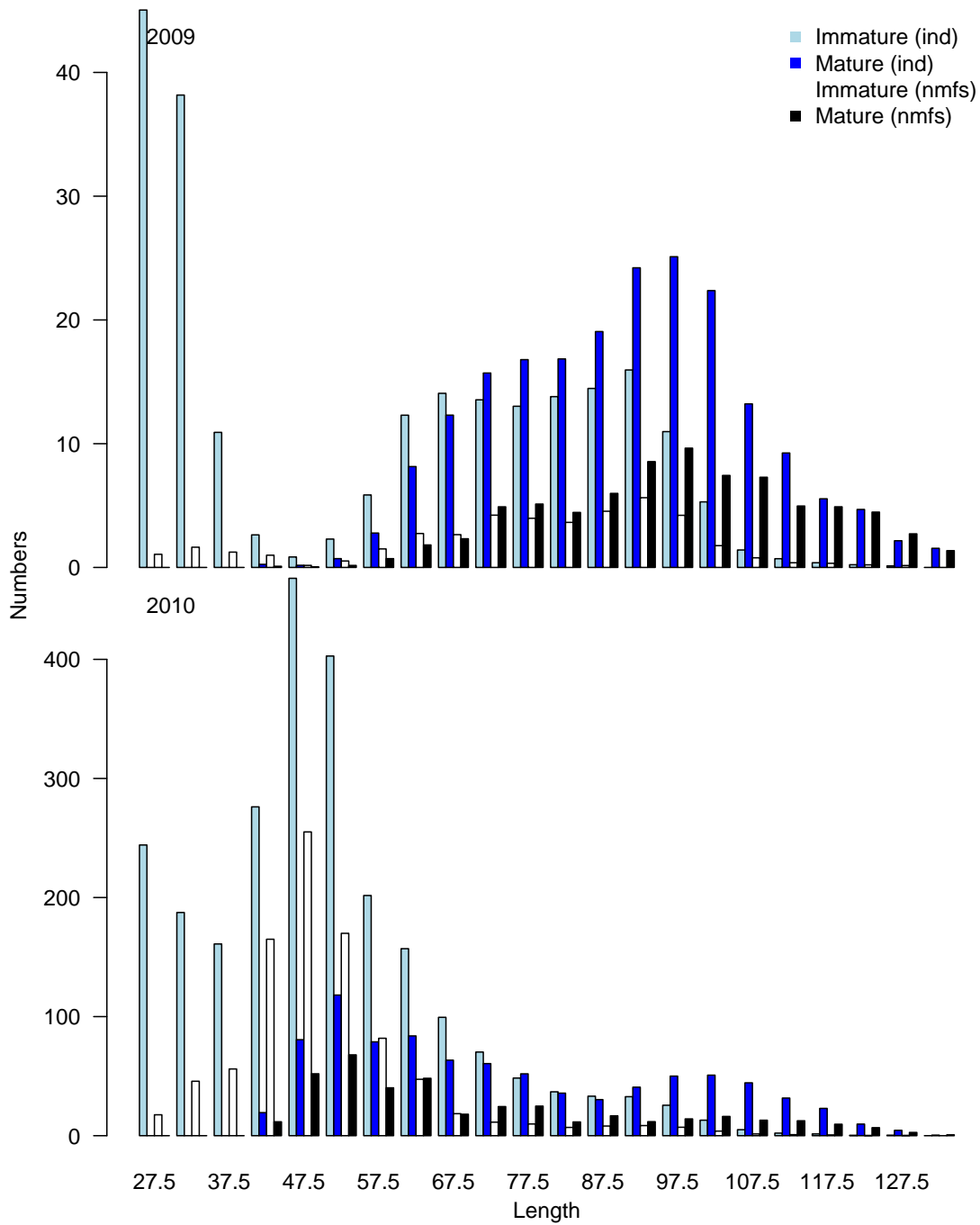


Figure 19: Raw male numbers from BSFRF survey selectivity experiments (2009 & 2010). Note a change in scale from 2009 to 2010 on the y-axis.

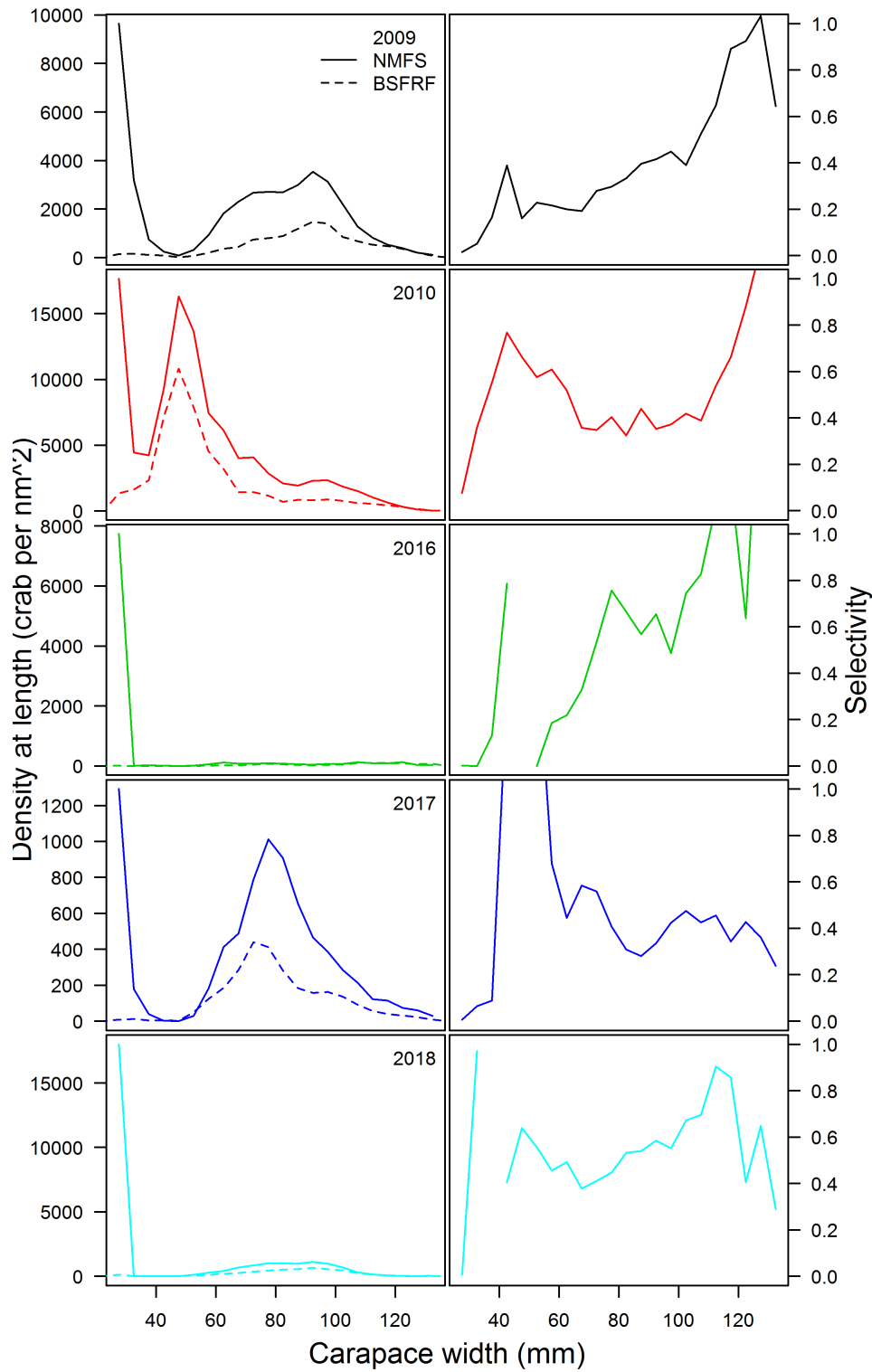


Figure 20: Observed numbers at length extrapolated from length composition data and estimates of total numbers within the survey selectivity experimental areas by year (left). Inferred selectivity (i.e. the ratio of crab at length in the BSFRF gear to crab at length in the NMFS gear).

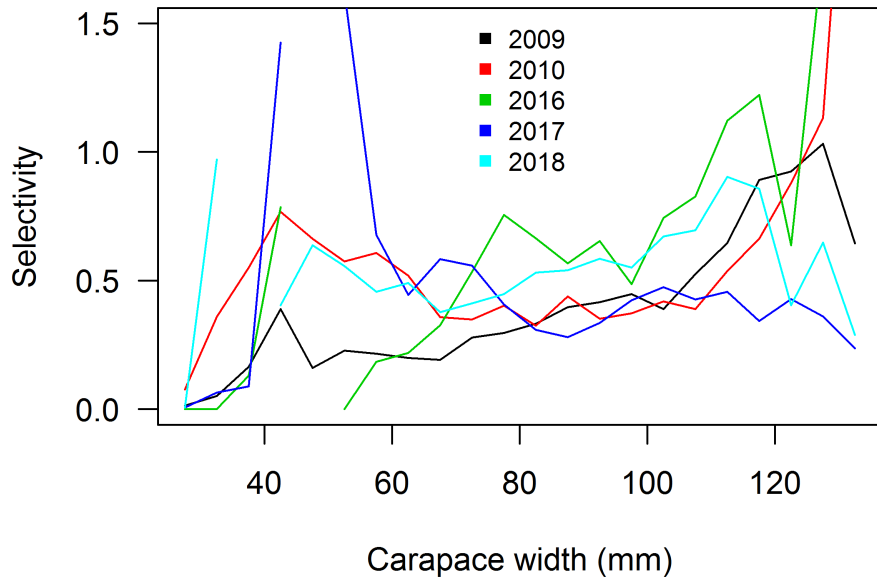


Figure 21: Inferred selectivity for all available years of BSFRF data.

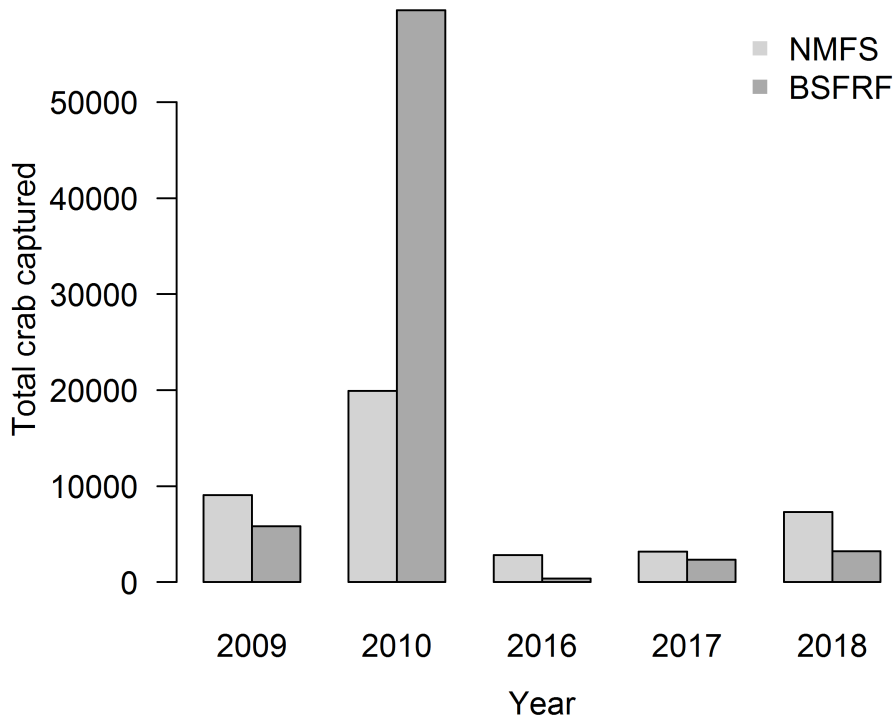


Figure 22: Number of crab from which estimates of biomass and length composition data were inferred within the survey selectivity experimental area.

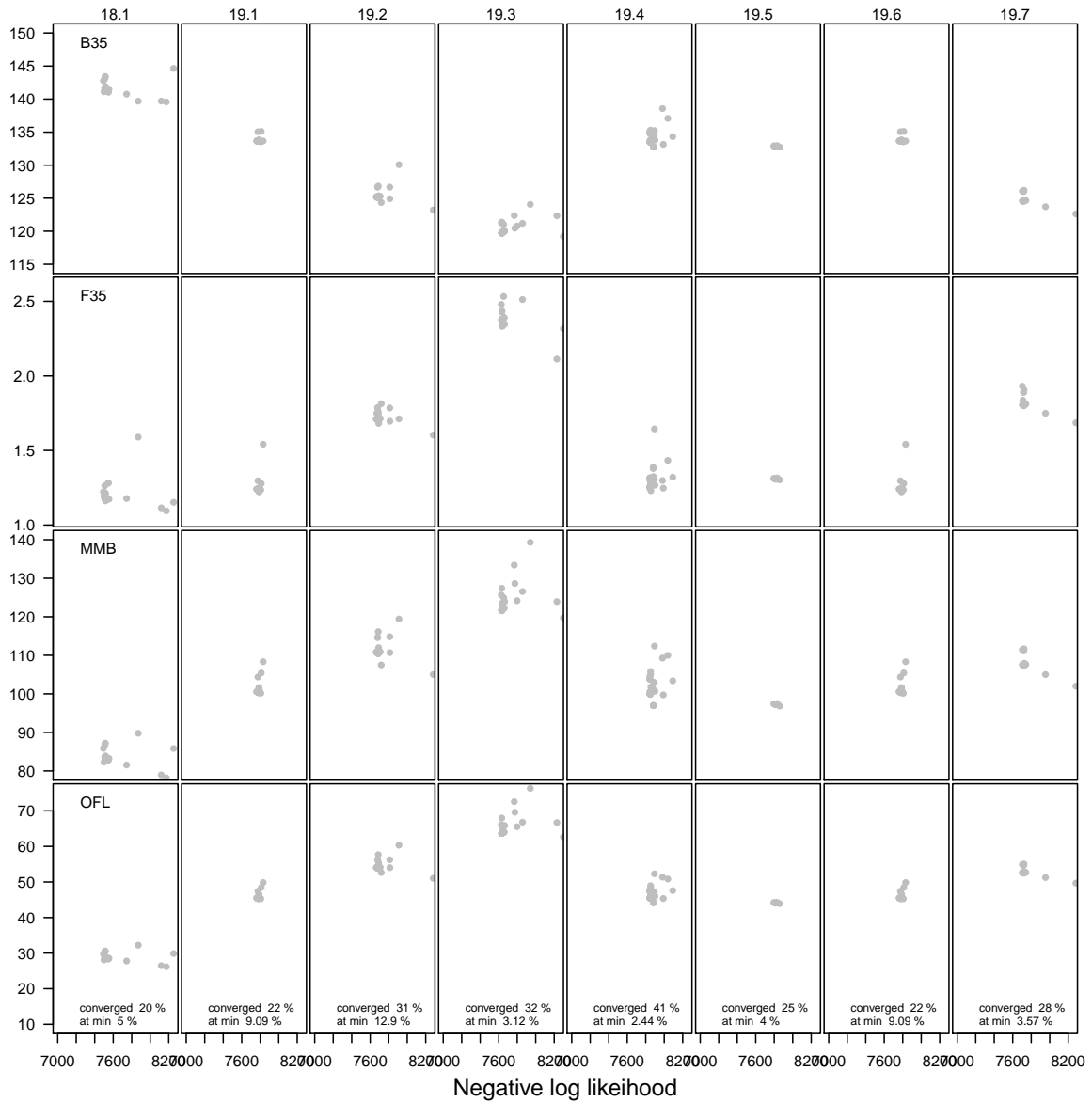


Figure 23: Management quantities after jittering selected models. ‘Converged %’ indicates the % of jittered models that had a maximum gradient component  $< 0.005$ . ‘at min %’ indicates the number of runs that converged to the minimum observed negative log likelihood

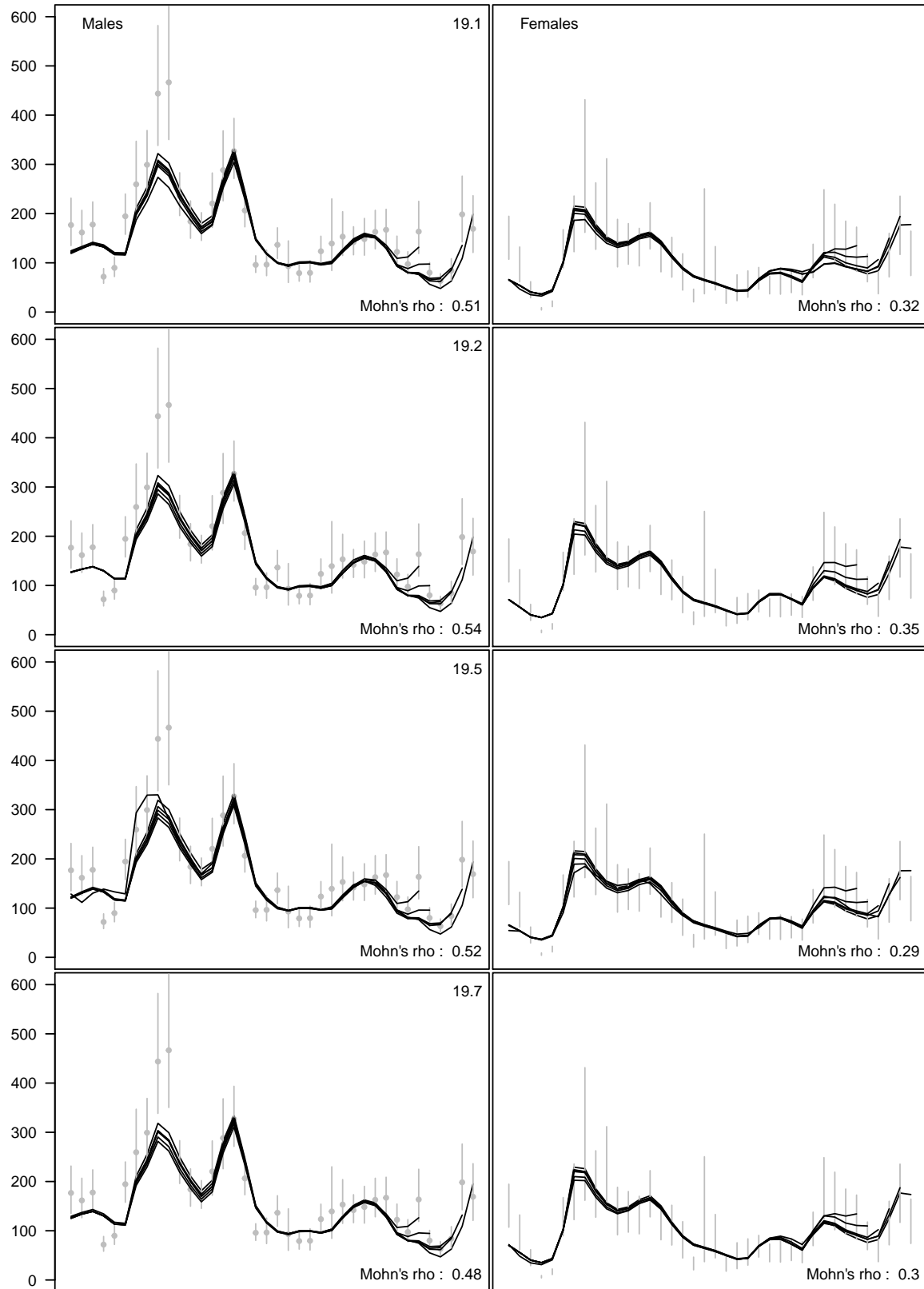


Figure 24: Retrospective analysis for selected models. Each line represents the model predictions for survey mature biomass when successively more years of data are removed from the analysis. Average difference is calculated as the mean relative error over the retrospective period (i.e. (Peeled MMB - 2019 MMB)/ 2019 MMB )

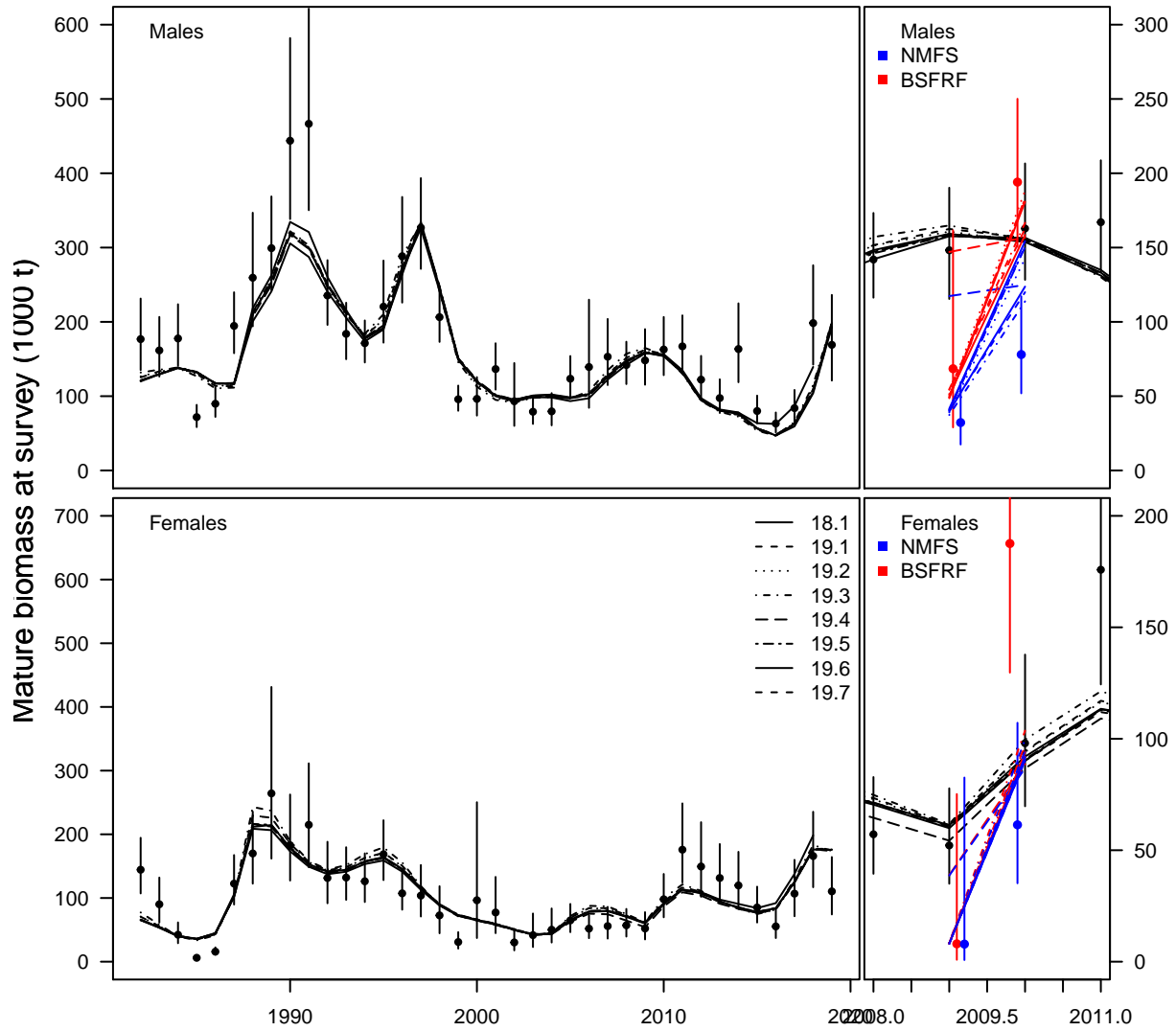


Figure 25: Model fits to the observed mature biomass at survey

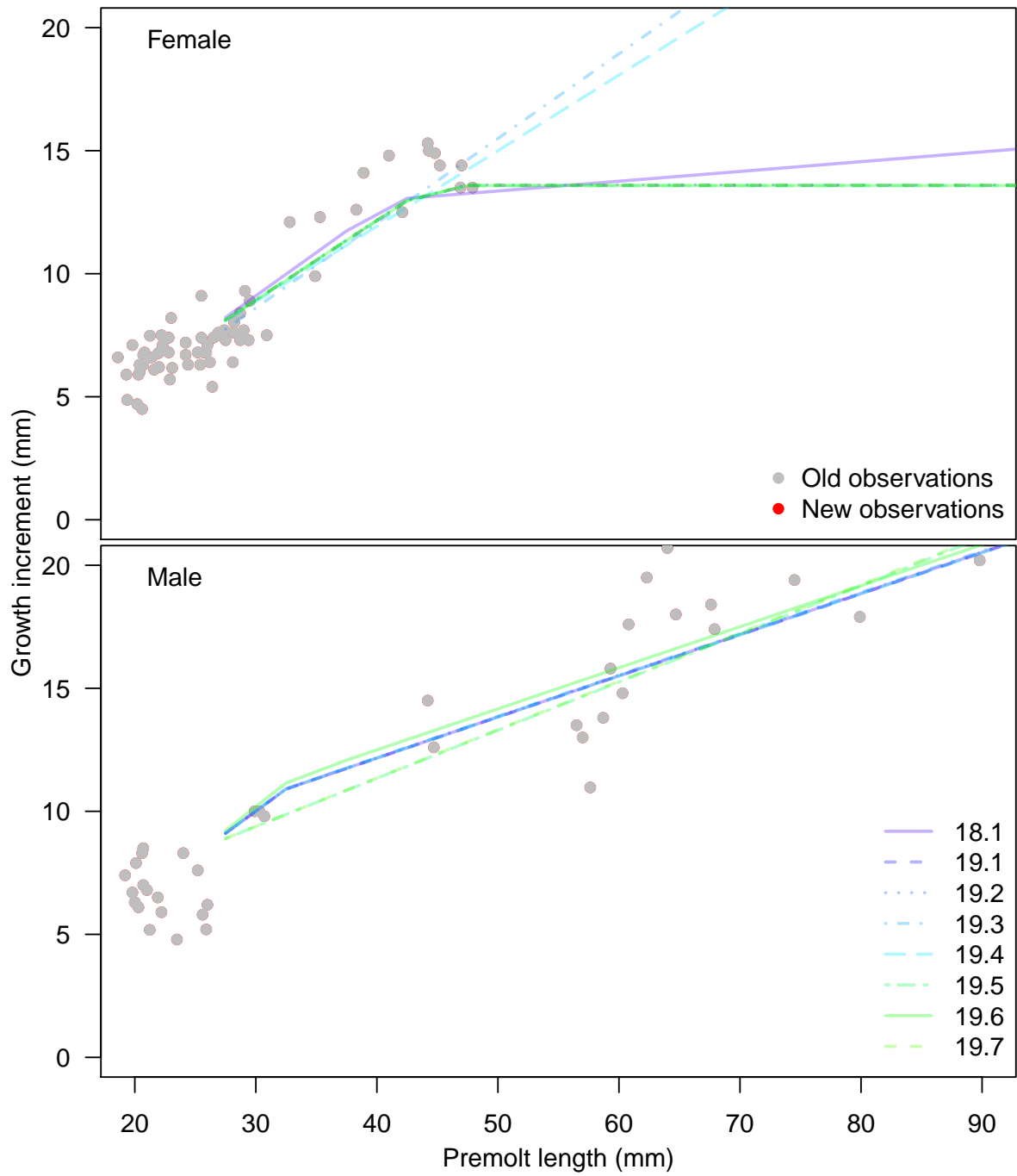


Figure 26: Model fits to the growth data

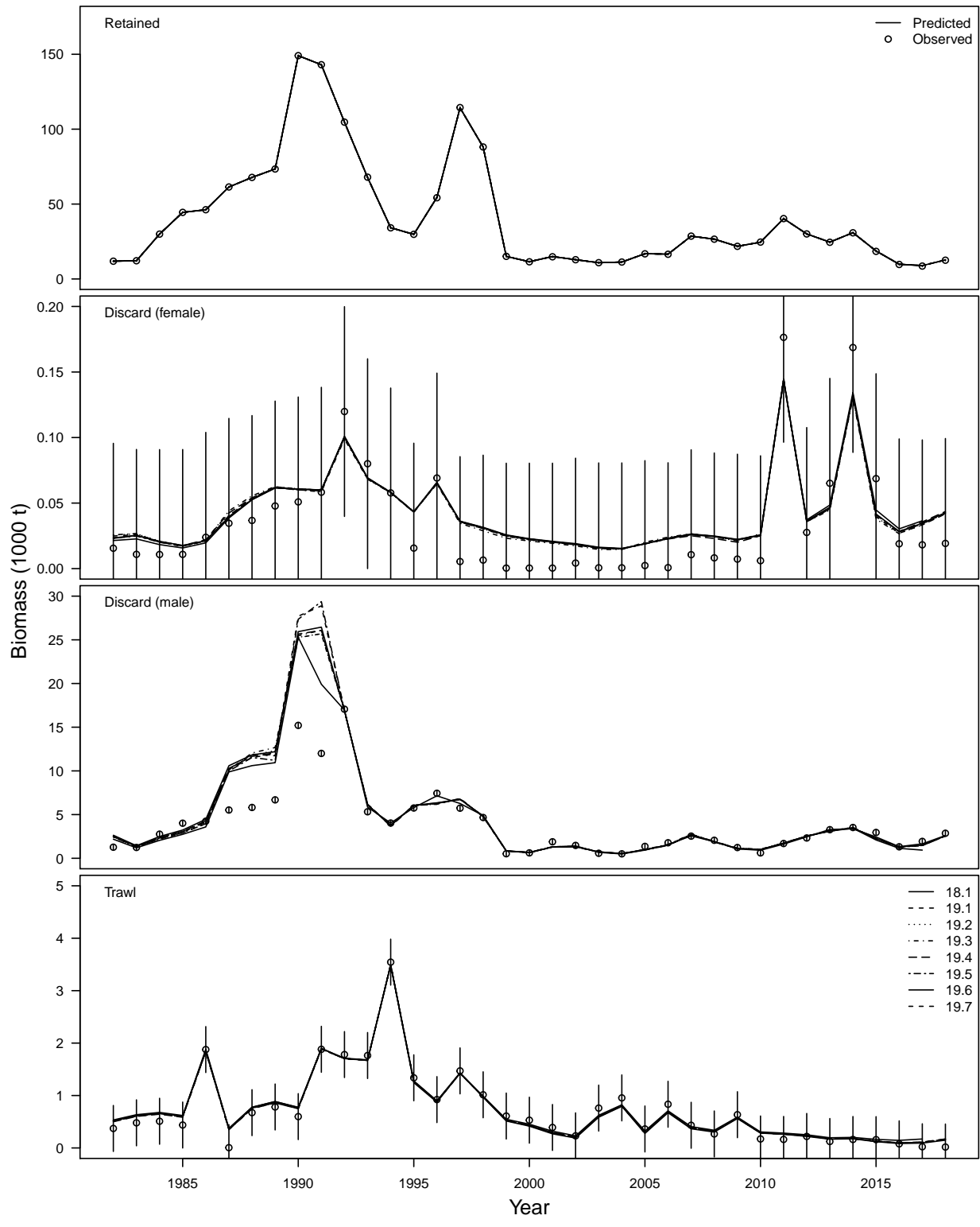


Figure 27: Model fits to catch data



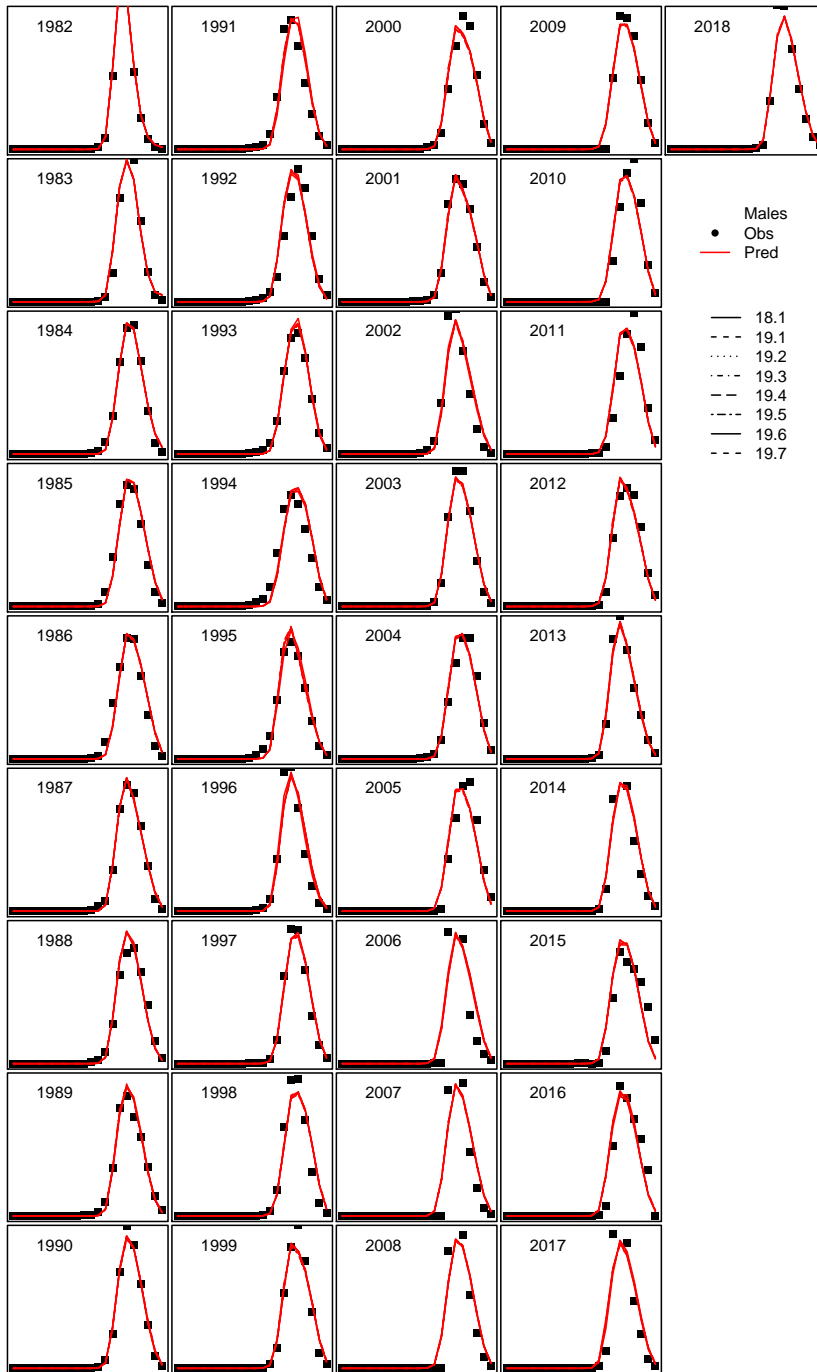


Figure 28: Model fits to retained catch size composition data

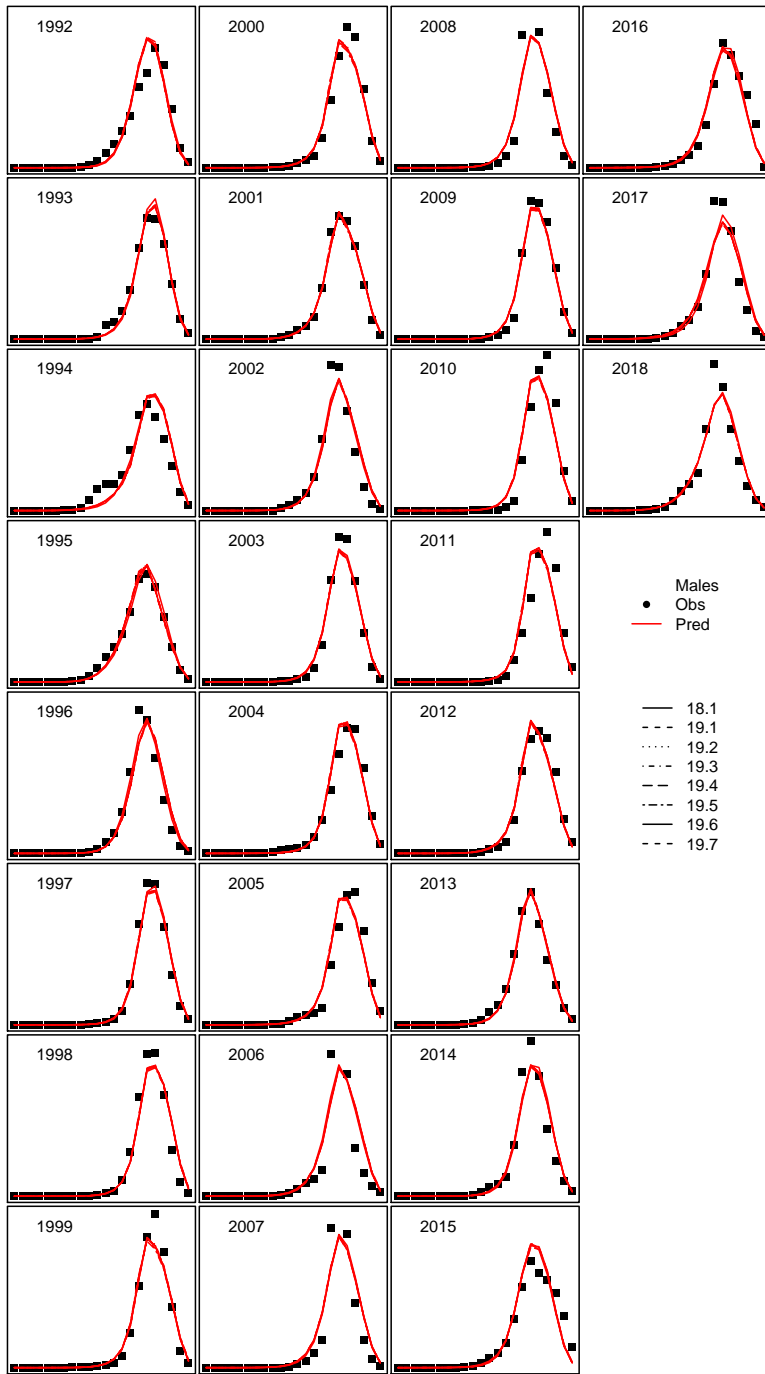


Figure 29: Model fits to total catch size composition data

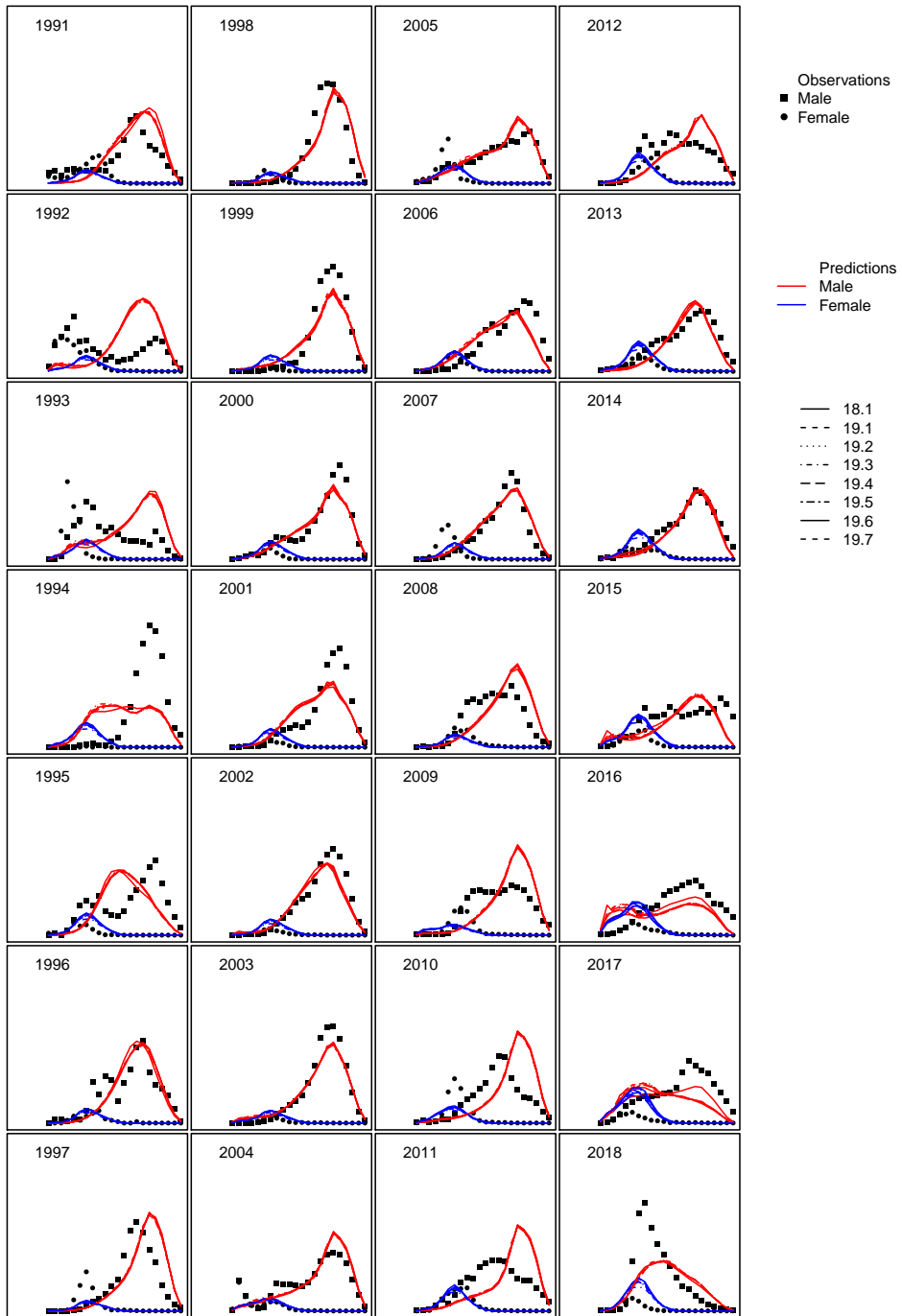


Figure 30: Model fits to trawl catch size composition data

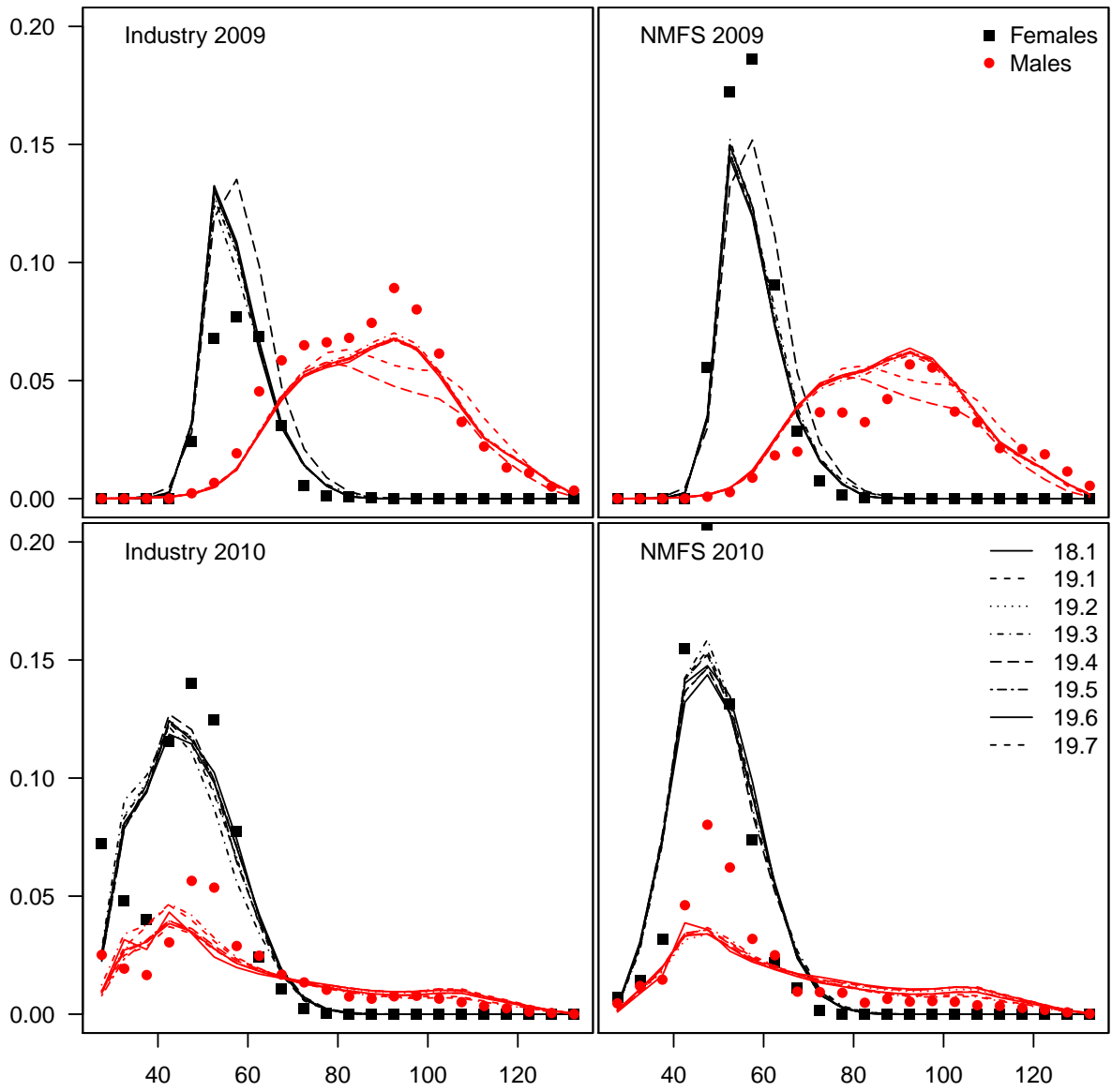


Figure 31: Model fits to size composition data from summer survey experiments (2009 & 2010)

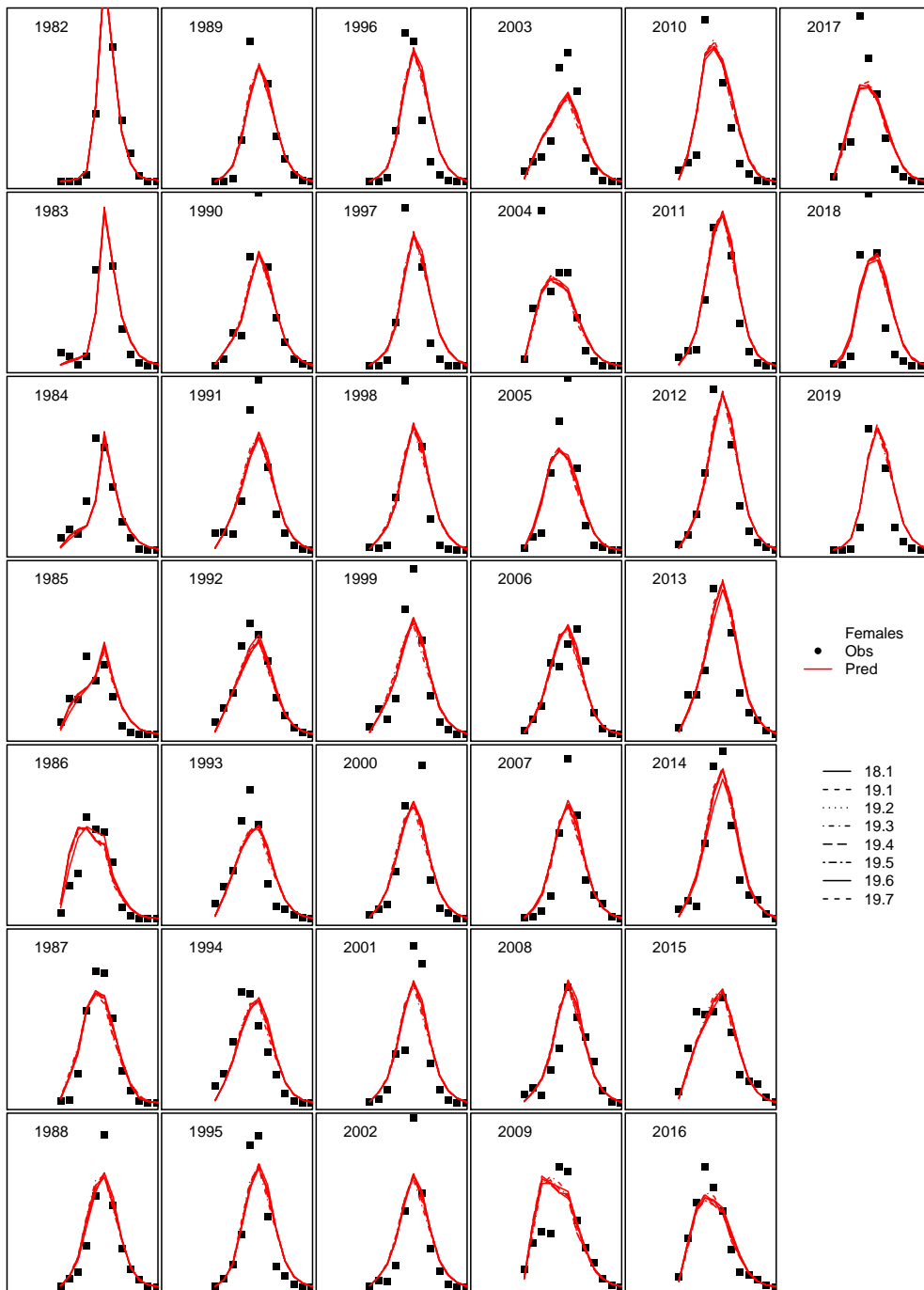


Figure 32: Model fits to female survey size composition data. Note that male and female survey selectivity proportions at length in a given year sum to 1. Consequently, the integral of predicted length compositions may appear to be different than the integral of the observed length composition data.

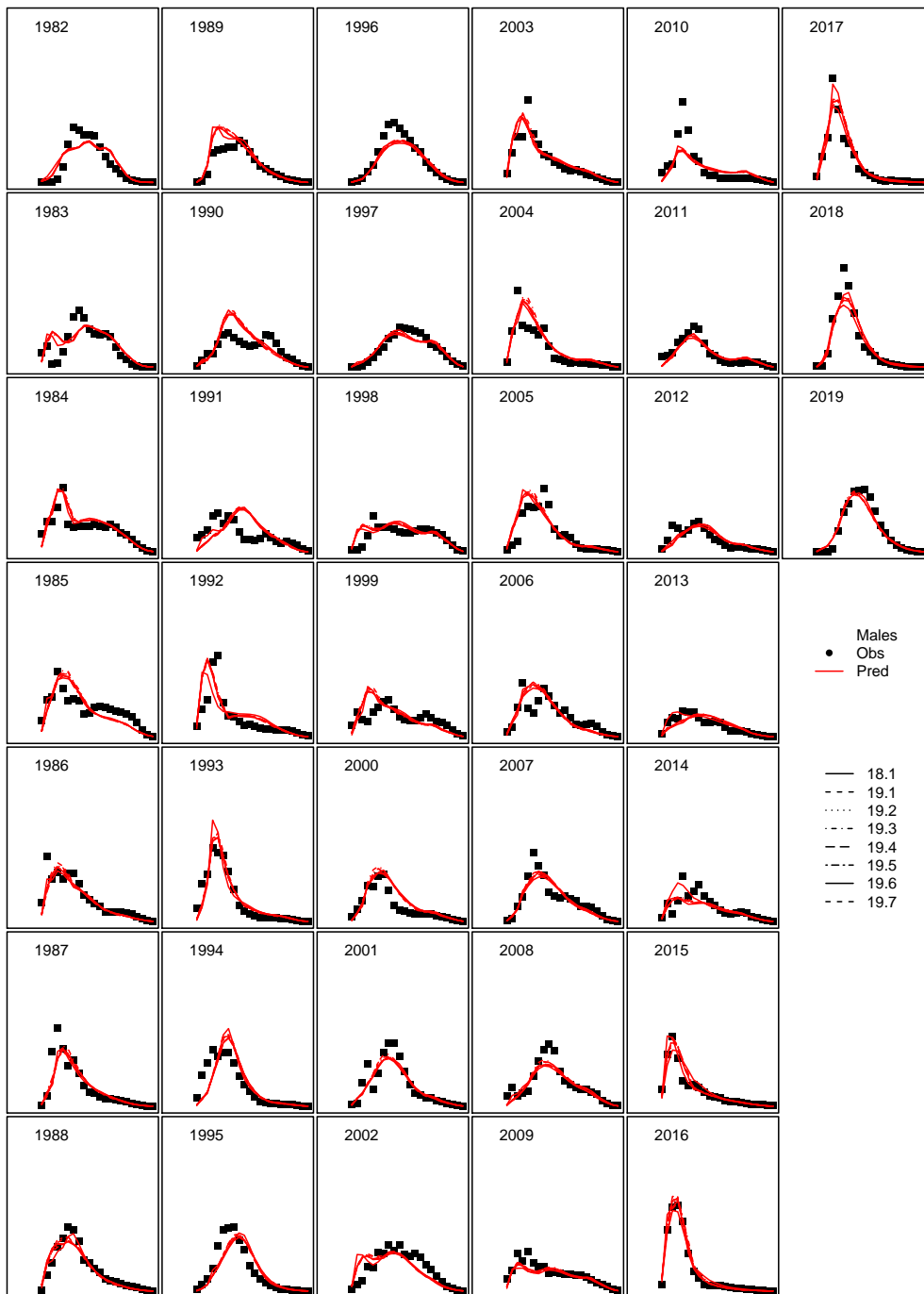


Figure 33: Model fits to male survey size composition data. Note that male and female survey selectivity proportions at length in a given year sum to 1. Consequently, the integral of predicted length compositions may appear to be different than the integral of the observed length composition data.

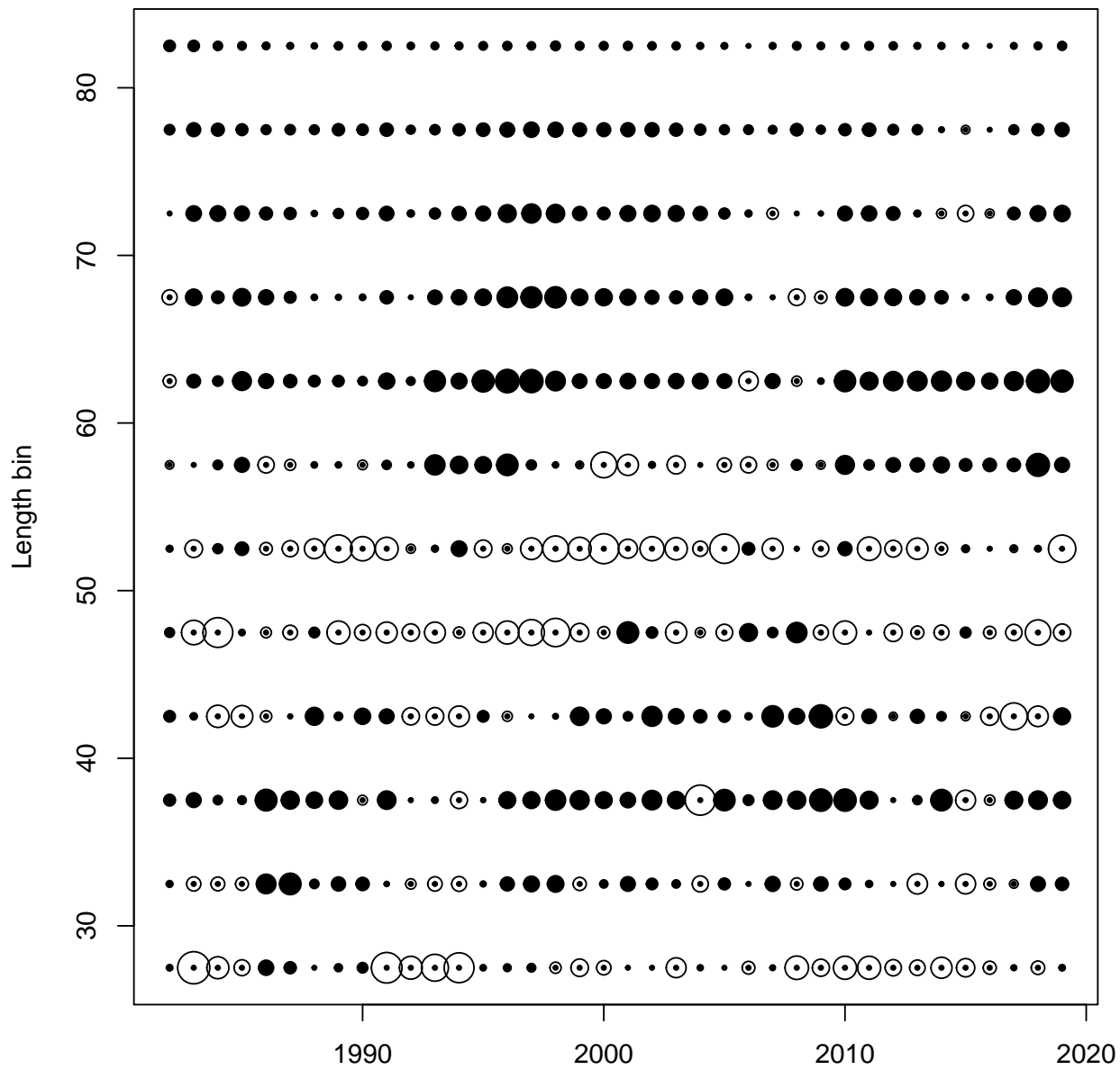


Figure 34: Residuals for female survey length proportion data for the author's preferred model (3b). Open circles are positive residuals, filled are negative, and the size of the circle is proportional to the magnitude of the residual. Stars are residuals  $> 5$ .

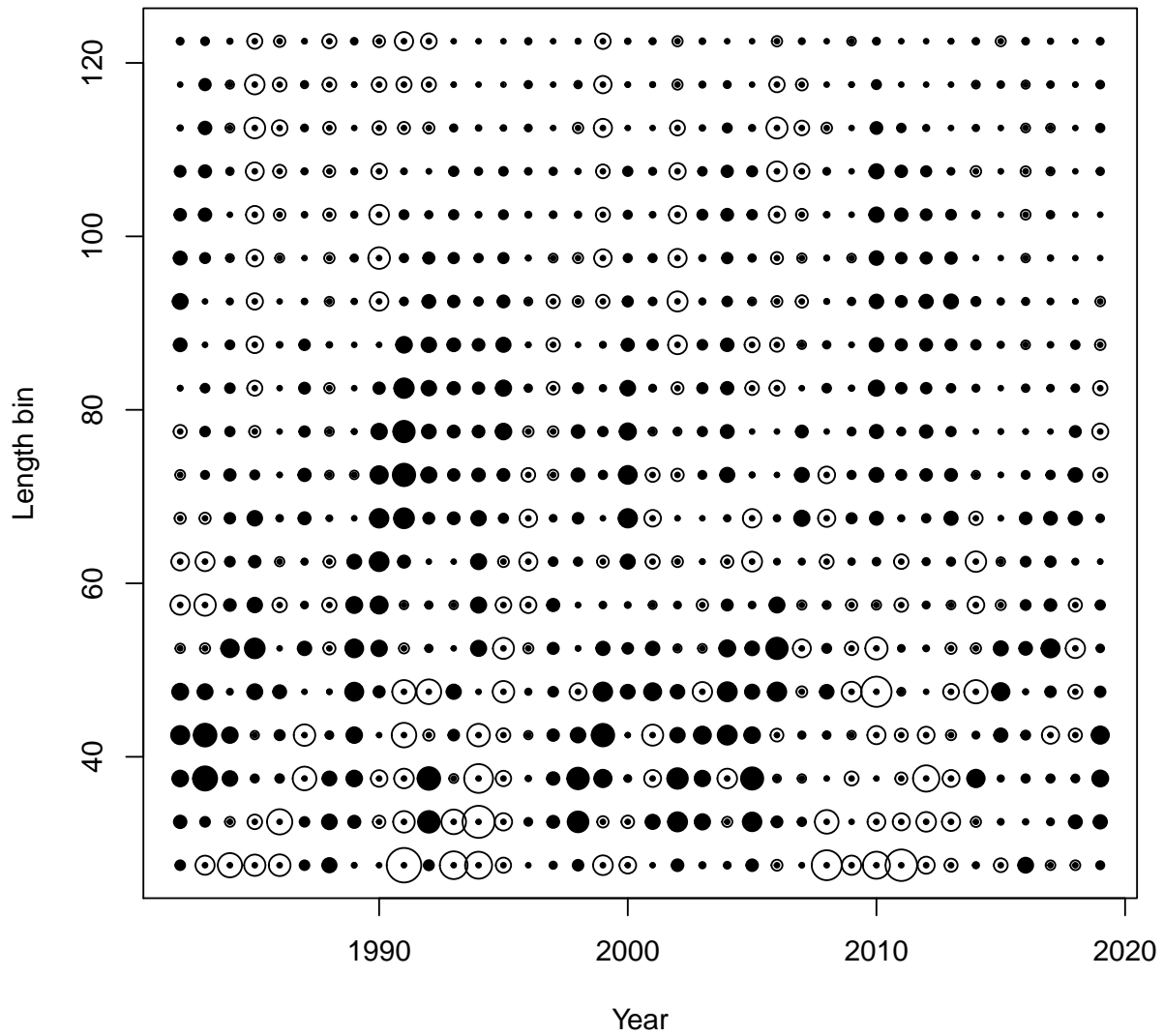


Figure 35: Residuals for male survey length proportion data for the author's preferred model (3b). Open circles are positive residuals, filled are negative, and the size of the circle is proportional to the magnitude of the residual. Stars are residuals  $> 5$ .



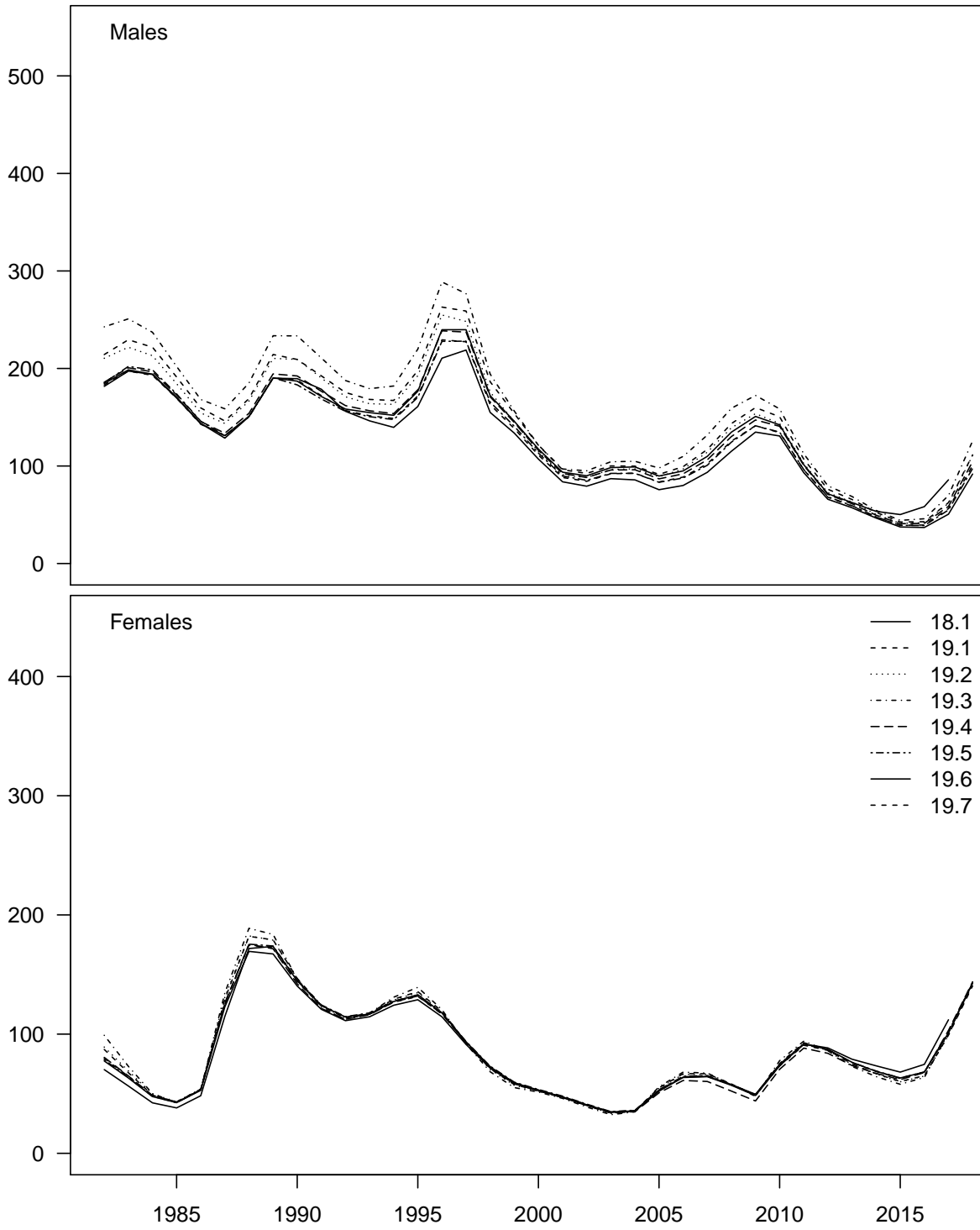


Figure 36: Model predicted mature male biomass at mating time

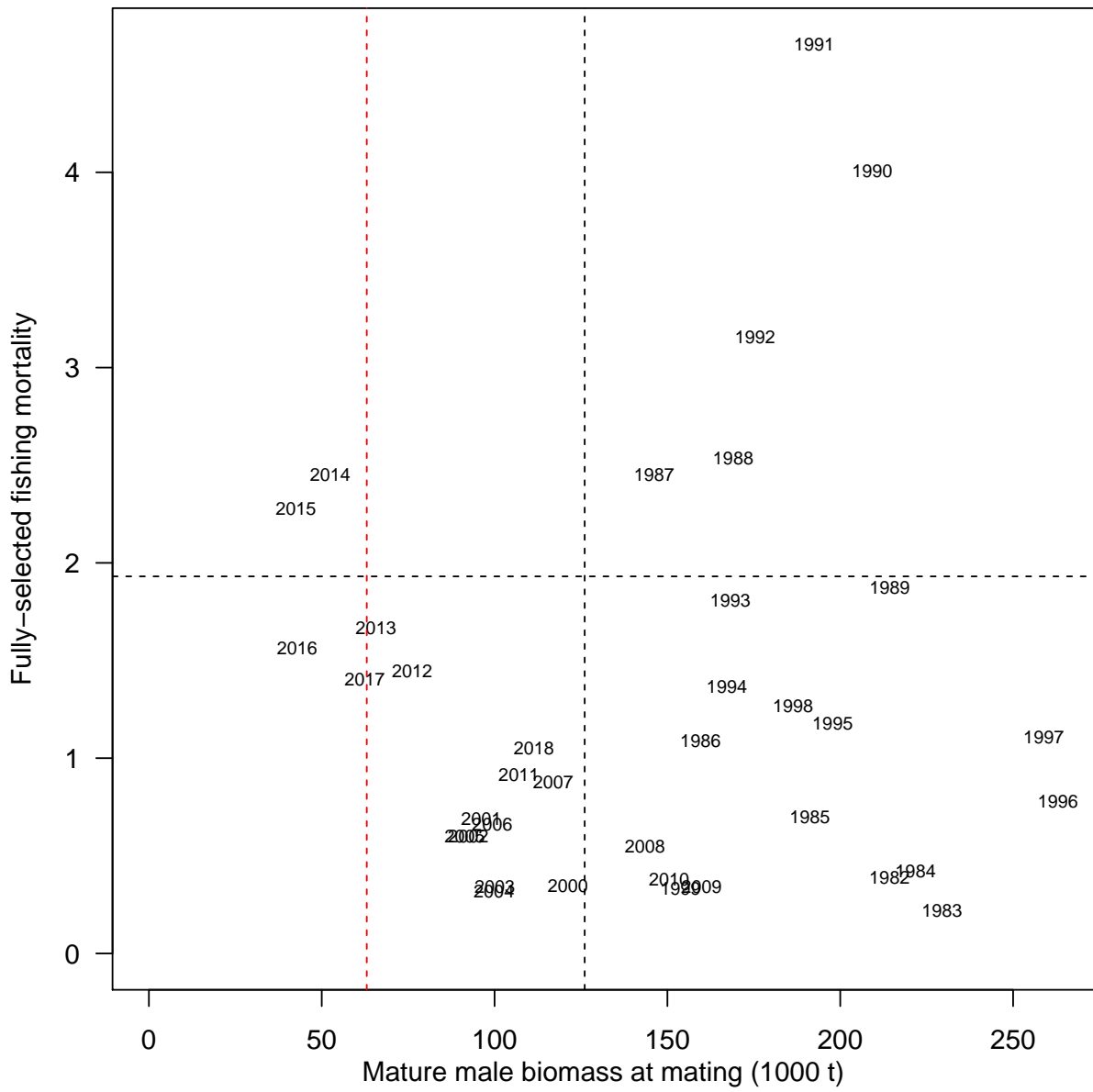


Figure 37: Kobe plot for the chosen model. Vertical dashed black line represents the MLE value for B35; Vertical dashed red line represents the overfished level, horizontal dashed black line represents F35

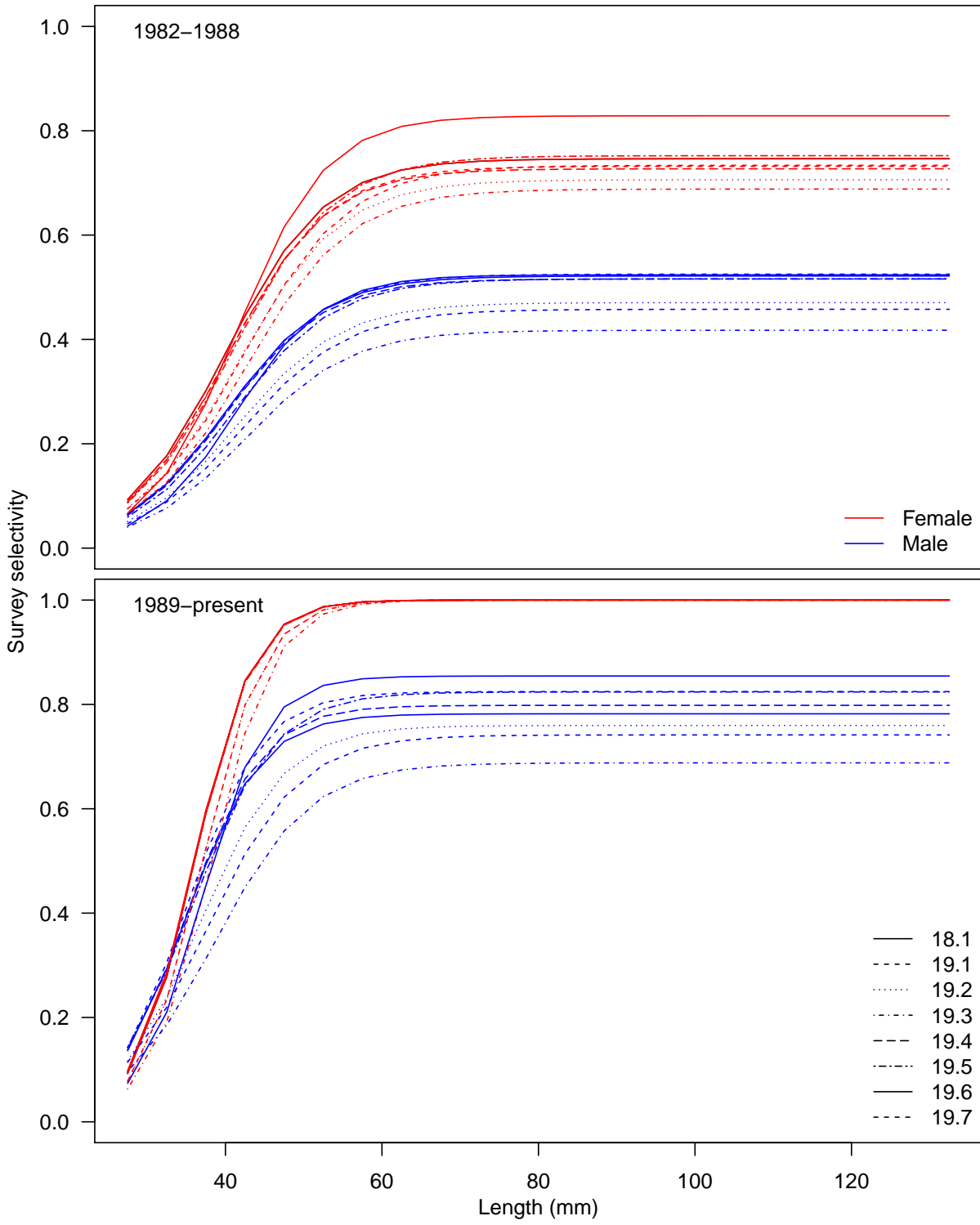


Figure 38: Estimated survey selectivity

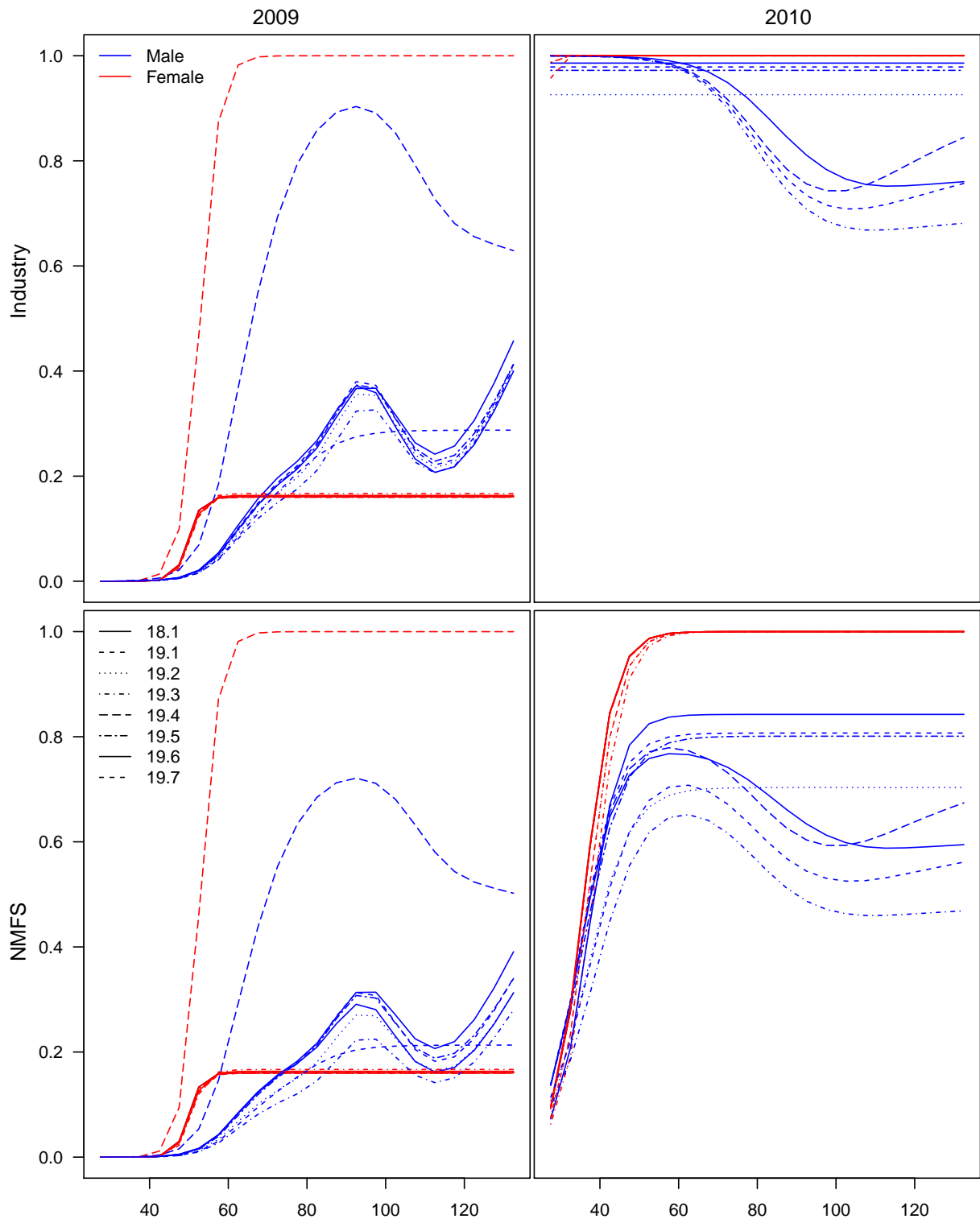


Figure 39: Estimated experimental survey selectivity (availability \* survey selectivity)

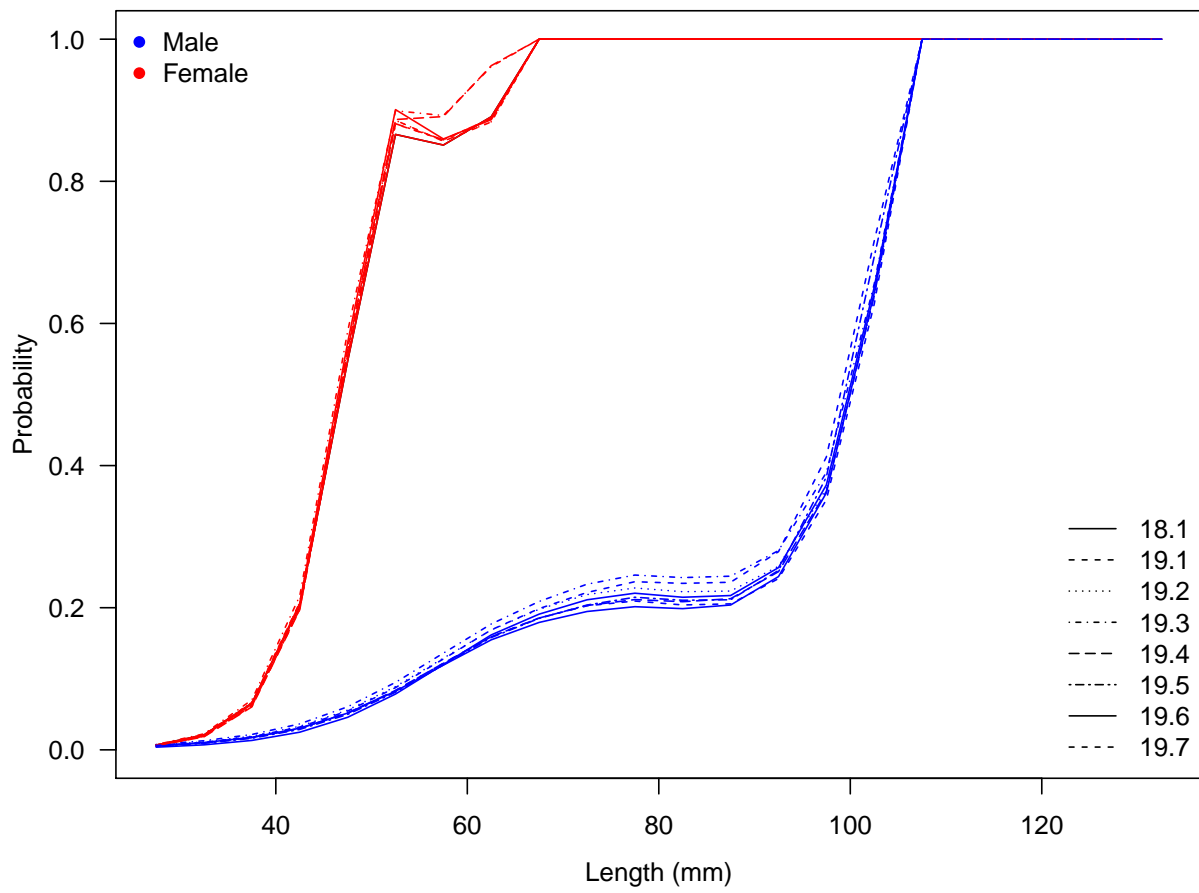


Figure 40: Estimated probability of maturing

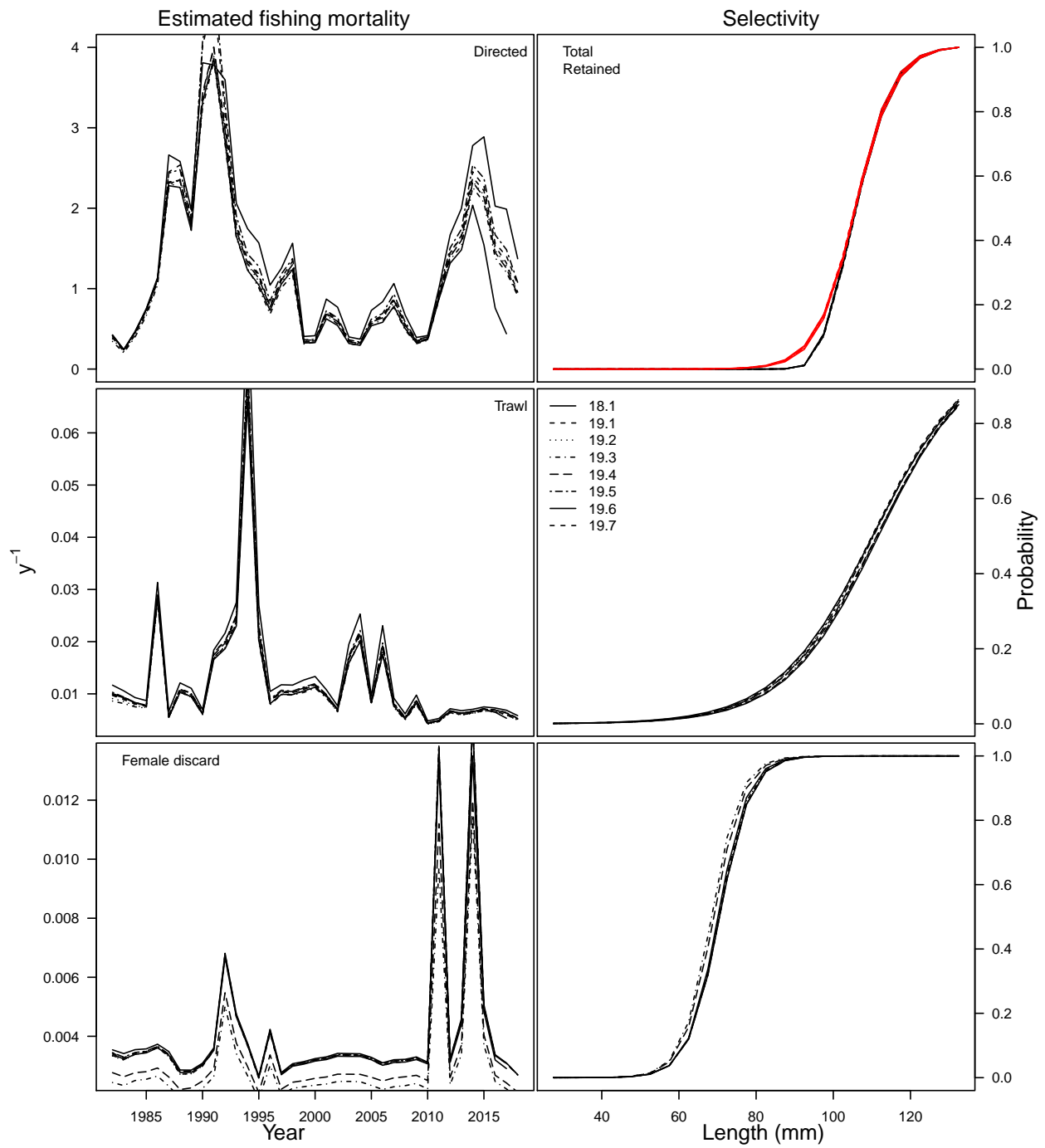


Figure 41: Model predicted fishing mortalities and selectivities for all sources of mortality

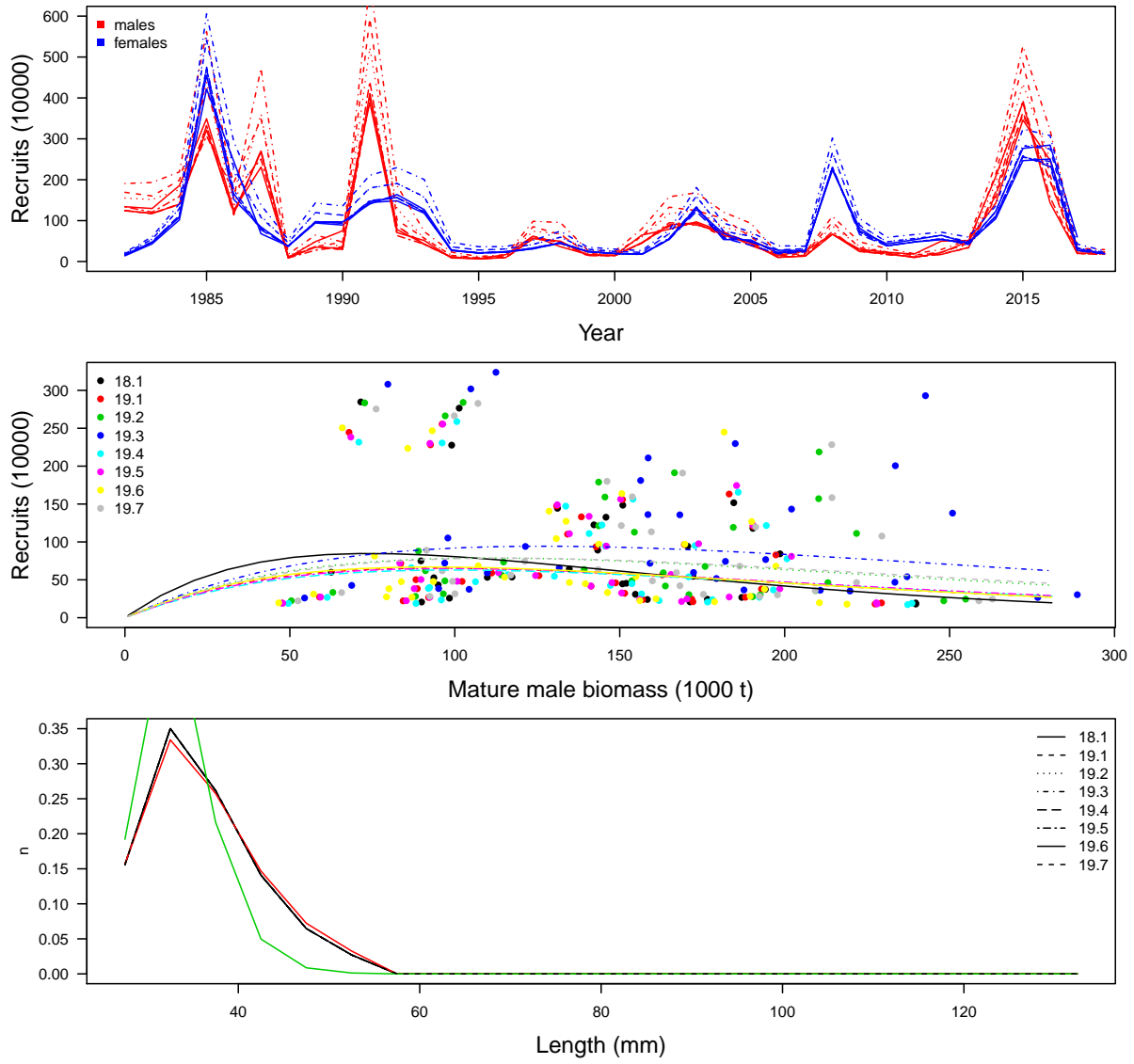


Figure 42: Estimated recruitment, fits to stock recruit curve (MMB lagged 5 years), and proportions recruiting to length bin. For bottom plot, males are red and females are green. Black lines are both sexes combined.

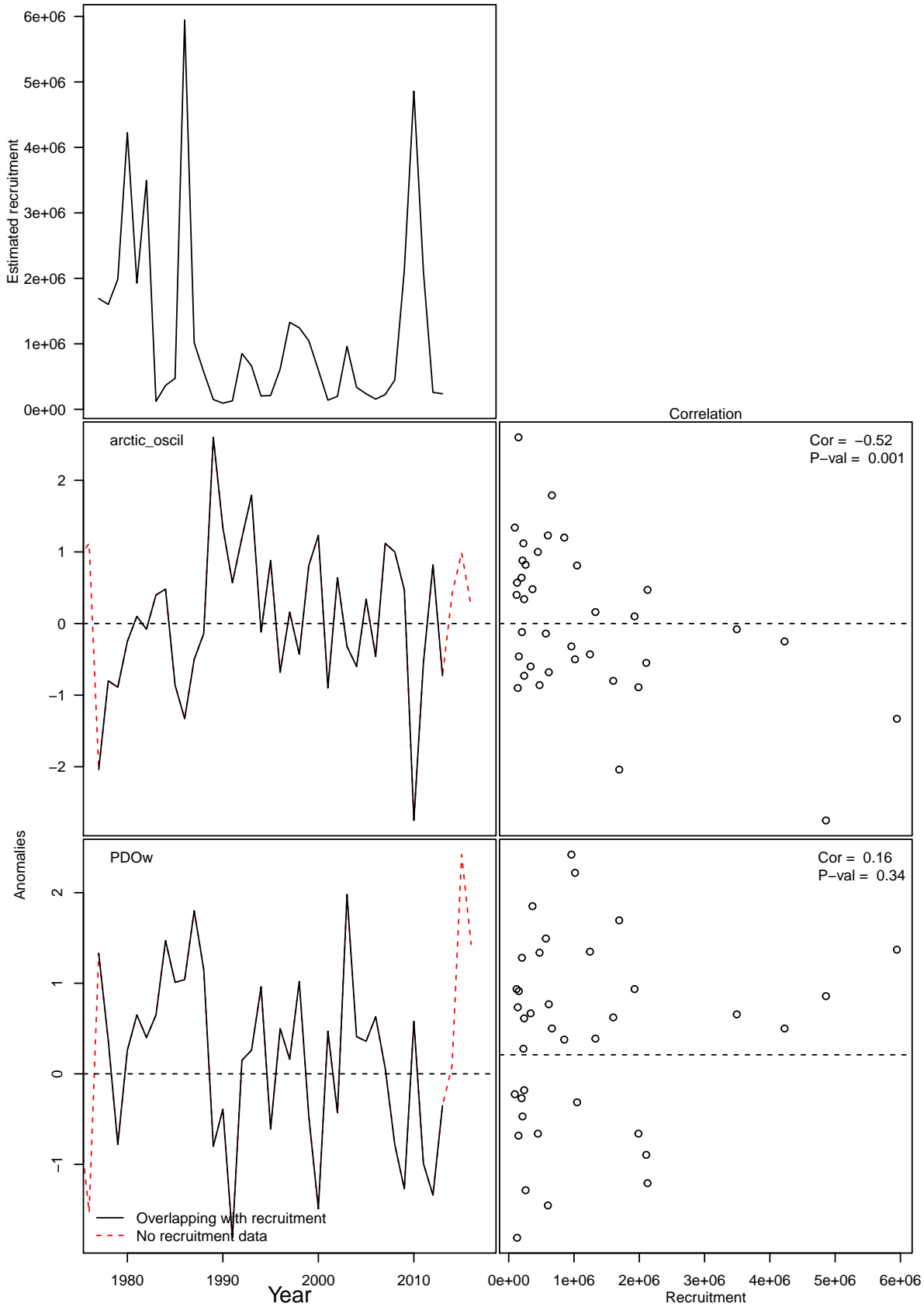


Figure 43: Comparison of estimated recruitment from the chosen model with the Pacific Decadal Oscillation and the Arctic Oscillation