

# A draft assessment for eastern Bering Sea snow crab

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**Appendix A: Population dynamics model**

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 1990s (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, and retained catch during the 2020/2021 was the highest in the last 6 years (20.41 kt). However, total allowable catches were slashed with the collapse of the population in 2021 and retained catches from the 2021/2022 season were the lowest on record (2.48 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 during that year. The most recent estimated discard mortality was 1.16 kt which was 47% of the retained catch.

3. Stock Biomass:

Observed mature male biomass (MMB) at the time of the survey increased from an average of 161.68 kt in the early to mid-1980s to historical highs 1990s (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 1999 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, after 2011, the stock declined and the observed MMB at the time of survey dropped to 63.21 kt in 2016. Recently, MMB was increasing again as a large recruitment moved through the size classes, but that recruitment has since disappeared and the observed mature male biomass at the time of the 2022 survey was 37.5 kt, a new all-time low and 40% less than the previous all-time low seen in the 2021 survey.

4. Recruitment

Estimated recruitment shifted from a period of high recruitment to a period of low recruitment in the mid-1990s (corresponding with a late 1980s fertilization). A large year class recruited to the survey gear in 2015 and was tracked until 2018 and 2019, but it appears to have since disappeared from the eastern Bering Sea shelf before reaching commercial size.

## 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
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	123.1	12.5	12.5	15.4	29.7	23.8
2019/2020	56.8	167.3	15.4	15.4	20.8	54.9	43.9
2020/2021	76.7	144.29	20.4	20.4	26.2	95.4	71.55
2021/2022	98.2	50.6	2.5	2.5	3.6	7.5	5.6
2022/2023		96.7				4.0	3.0

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

Year	MSST	Biomass (MMB)	TAC	Retained catch	Total catch	OFL	ABC
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	125.22	368.83	33.95	33.95	45.86	121.03	96.78
2020/2021	169.09	318.1	44.97	44.97	57.76	210.32	157.74
2021/2022	216.49	111.55	5.51	5.51	7.94	16.53	12.35
2022/2023		213.19				8.82	6.61

## 6. Basis for the OFL

The OFL for 2022 from the author-preferred model (22.1ab) was 3.98 kt fishing at  $F_{OFL} = 0.67$  (30% of the calculated  $F_{35\%}$ , 2.26). The calculated OFL was an -47% change from the 2021 OFL of 7.5 kt. The projected ratio of MMB at the time of mating in 2023 to  $B_{35\%}$  is 0.39 under no directed fishing and 0.35 fishing at the  $F_{OFL}$ .

Table 3: Metrics used in designation of status and OFL (1,000 t). Status represents the status of the population after the completed fishing year and is used for overfished declarations. Proj\_Status represents the status of the fishery projected to after the coming fishery removes the OFL and is used in the harvest control rule. 'Years' indicates the year range over which recruitment is averaged for use in calculation of B35. 'M' is the natural mortality for immature crab, mature female crab, and mature male crab, respectively. (continued below)

Year	Tier	BMSY	MMB	Status	Proj_Status	FOFL	Years
2022/2023	3b	196.4	96.7	0.49	0.35	0.67	1982-2021

M
0.29, 0.29

## 7. Probability Density Function of the OFL

The probability density function of the OFL is not presented here.

## 8. Basis for ABC

The ABC for the chosen model was 2.98 kt, calculated by subtracting a 25% buffer from the OFL as recommended by the SSC.

## A. Summary of Major Changes

### 1. Management:

The eastern Bering Sea snow crab population was declared over-fished in October 2021 and a rebuilding plan is currently being formalized.

### 2. Input data:

Data added to the assessment included: 2022 eastern Bering Sea survey biomass and length composition data, 2021 directed fishery retained and discard catch, length composition for retained and discard catch, and groundfish discard length frequency and discard from 2021.

### 3. Assessment methodology:

Management quantities were derived from maximum likelihood estimates of model parameters in a size-based, integrated assessment method. Only GMACS models are presented with updated data, following the adoption of GMACS as the new assessment platform for snow crab by the SSC in June 2022. Jittering was performed for the author-preferred model. An application of tier 4 methodologies for calculating the OFL are also included. Incorporating the new data in the integrated model resulted in appreciable changes in estimated survey catchability, which increased the estimated scale of the population and had direct effects on the calculated OFL.

### 4. Assessment results

The updated estimate from the author-preferred model of MMB on February 15, 2022 was 96.67 kt which placed the stock at 49% of  $B_{35\%}$ . Projected MMB on February 15, 2023 from this year's author preferred model is 68.44 kt after fishing at the OFL, which would place the stock at 35% of  $B_{35\%}$ .

## B. Comments, responses and assessment summary

### SSC and CPT comments + author responses

*SSC comment: The SSC strongly recommends that the urgency of accounting for snow crab in the northern Bering Sea requires that analysts prioritize working towards a model-based survey index that incorporates the NBS data*

The fishery interacts primarily with males larger than 101 mm carapace width, but the mean fraction of commercially-sized individuals in the northern Bering Sea during the limited number of years for which we have data is less than one percent (Table 5). Historically, the observed commercial biomass has not been near the NBS boundary (Figure 1). Further, currents are generally such that if there were any mature biomass in the NBS, the larvae originating from the NBS would be unlikely to contribute to the biomass in the EBS. Given the lack of fishery impacts in the NBS, current discussion about the appropriate currency of management, other pressing issues in the assessment model (e.g. treatment of maturity data and BSFRF experimental selectivity data), and uncertainty around the connection between the biomass in the NBS and the EBS, developing indices of extrapolated data for the NBS should remain low priority. Continued monitoring of the NBS to assess the fraction of the stock with which the fishery interacts, however, will be important under rapidly shifting environmental conditions.

Table 5: Statistics related to the number of commercial males in the northern Bering Sea. The first column is the number of stations in the NBS with crab >101 mm carapace width. The second column is the total number of stations in the EBS and NBS that reported >101 mm carapace width crab. The third column is the percent of the total area-swept abundance in the NBS. The mean fraction of the abundance over years of available data was 0.68%.

Year	NBS.stations.w..crab	Total.stations.with.crab	Percent.in.the.NBS
2010	0	197	0
2017	1	157	0.1
2018	1	151	0.1
2019	8	156	1.3
2021	4	165	0.9

*SSC comment: The SSC highlights the importance of assessing the current definition of male snow crab maturity given the possibility of snow crab maturing at smaller sizes and the sensitivity of reference points to assumptions about growth and maturity, as previously illustrated by the author*

I agree, but did not have time to redo my previous analyses with updated data.

*SSC comment: The SSC strongly recommends including uncertainty intervals on estimates of biomass and abundances*

Included.

*SSC comment: The SSC continues to request an explanation for why the GMACS model estimates such a skewed sex-ratio for recruitment*

The potential reasons in the past given include potential differences in growth, spatial distribution, and maturity. More importantly, the fishery interacts with the large males and management is based on mature male biomass. Consequently, understanding the dynamics of MMB and commercially-sized males should be the primary focus of the assessment in order to provide appropriate management advice. If, for some currently unknown reason (given the data available), the dynamics of the females appear to be different than that of the males, making assumptions that force the dynamics to be the same can impede the modeling of

the dynamics of the portion of the stock with which the fishery interacts and on which the overfishing level is based. The retrospective patterns seen in previous assessments when males and female recruitment had 50/50 sex ratios are an example of this.

*SSC comment: The SSC recommends that the author work with BSFRF to summarize observations from harvesters*

Fishery catch-per-unit-effort provided by the State of Alaska are included in this assessment document.

*SSC comment: SSC requests to see Tier 4 calculations with the value for M (not including the elevated values in 2018-2019) from the last accepted model as a fall back for specifications*

Tier 4 calculations are now included. However, using morphometrically mature male biomass (the current currency of management) in the tier 4 HCR results in the calculated OFL exceeding the estimated biomass of commercially targeted males in some years, which would seem to disqualify it from consideration. So, if tier 4 rules are to be pursued, a discussion needs to be had (or continued) about an appropriate currency of management.



## Assessment summary

Five assessment models are presented here:

- 21.1 – Last year’s accepted model (status quo) fit to last year’s data
- 21.g – Last year’s GMACS model fit to last year’s data with a prior on M similar to 21.1
- 22.1 – 21.g fit to this year’s data
- 22.1a – 22.1 with alternate configuration of estimation of initial size comps in which all parameters are freely estimated rather than estimating an ogive and a scaling parameter. This model is from the mode of the jittering analysis with the larger OFL
- 22.1ab – 22.1a from the mode of the jittering analysis with the smaller OFL

GMACS was accepted as the official model for assessing eastern Bering Sea snow crab by the SSC June of 2022 on the basis of better fits, projection capabilities, and improved convergence, transparency, and reproducibility. Following this adoption, only GMACS models are presented with updated data in this assessment cycle. Model 22.1ab is the author’s preferred model from those presented based on improvements in fits to size composition data from adjusting the way the initial numbers at size are estimated and more realistic estimates of fishing mortality in recent years. However, updating the data produced some consequential changes in estimates of population processes compared to the GMACS model accepted in June. For example, survey catchability decreased from ~0.7 in 21.g to ~0.4 in 22.1ab, the estimated probability of having undergone terminal molt increased slightly at smaller sizes, and fits to recent size composition data deteriorated.

In addition to the lowest observed mature male biomass on record reported this year (~40% lower than last year), a few other concerning signals arose around the population dynamics in the previous two years. The observed probability of having undergone terminal molt was much higher for smaller sizes in 2021 than historically observed (Figure 2) and the lowest average clutch fullness scores ever were observed in 2022. Beyond biological concerns, the fishery posted the lowest catch per unit efforts ever observed in the 2021/2022 season.

Models 22.1a and 22.1ab resulted from jittering analyses and represent the models associated with the modes of a bimodal distribution of management quantities. The two modes had similar average objective function values (approximately -23204 vs. -23200) but fairly large differences in the calculated OFLs (~10 kt vs. ~4 kt). The author-preferred model (22.1ab) presented here is based on a model within the cloud of jittered models that produced an OFL of ~ 4 kt because the model associated with the 10 kt OFL produced unreasonably high estimates of fishing mortality in the 2020/2021 directed fishery (i.e. removal of >99% of commercial crab).

A draft manuscript describing efforts at explaining the recent collapse of snow crab is included with this assessment (see appendix B and C). Based on the currently available data, high temperatures and densities of crab and the resulting metabolic demand appear to have contributed to mortality events that precipitated the collapse of eastern Bering Sea snow crab. Although not quite as extreme, similar temperatures to 2018 were experienced by the snow crab population in 2003. Mortality in this period was elevated, but not as high as in 2018 and 2019, presumably as a result of lower crab densities. This information paired with projections from Szuwalski et al. 2020 may help inform selection of mortality and recruitment scenarios for rebuilding analyses (see appendix D).

A tier 4 harvest control rule was applied to four measures of male biomass observed in the survey (morphometrically mature male biomass, legal male biomass [ $>78$  mm carapace width],  $>95$  mm carapace width crab, and commercial biomass [ $>101$  mm carapace width]) and adoption of a tier 4 rule using any of these metrics would result in a closure of the fishery. Using morphometrically mature biomass and legal biomass both do not seem to be viable options because in some years they would have set the OFL at a value greater than the survey estimate of the total amount of commercial biomass in the Bering Sea.

The author’s preferred model is 22.1ab given the available options, but several concerning issues arose with this model when updating the data. Given the current status of the stock, concerns around model output, changes in biological processes, and poor fishery performance, caution in management is likely warranted. A discussion of other modeling options and/or alternative buffers may be useful at the plan team meeting.

## 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 3 & Figure 4 for 2021 distribution). Smaller crabs tend to occupy more inshore northern regions (Figure 5) and mature crabs occupy deeper areas to the south of the juveniles (Figure 6 & Figure 7; 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 8). 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 National Marine Fishery Service (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 dactyl 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.

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 9). 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 6). 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 6: 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	0.271	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 10). 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.

The median value of the priors used in this assessment are set equal to values resulting from assuming a maximum age of 20 years and applying Hamel’s methodology. A standard error of 0.054 was used for initial 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). Mortality events in 2018 and 2019 are estimated as additional mortality parameters applied by sex and maturity state to allow the model to fit recent population trends.

## Weight at length

Weight at length is calculated by a power function, the parameters for which were recalculated by the Shellfish Assessment Program 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 most years starting from the 1989 survey (Otto 1998). Mature male biomass referenced throughout this document refers to a morphometrically mature male (i.e. large-clawed). A maturity curve for males was estimated using the average fraction mature based on chela height data and applied to years of survey data to estimate mature survey numbers that do not have chela height data available. 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 showed a clear break in chela height at small and large widths and 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 a freely estimated (but smoothed) function of length for both sexes within the assessment model.

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 morphometrically 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, which are nearly 100% mature. 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.

Clutch fullness is recorded for the females measured in the survey (Figure 11). However, 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 crab at the time of the survey may have a full clutch of eggs that are unfertilized, resulting in overestimation of reproductive potential. Barren females may be a more obvious indication of low reproductive potential and increased in the early 1990s, decreased in the mid-1990s, then increased again in the late 1990s. The highest levels of barren females coincided with periods of high fishing mortality, but the even then the proportion of barren females was low (Figure 12). The average clutch fullness score was the lowest on record and the proportion of females with full clutches was the smallest on record from the 2022 NMFS survey. Biennial spawning is another confounding factor in determining the reproductive potential of snow crab. Laboratory analyses 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, NMFS 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.

## Growth

Several studies are available to estimate the growth per molt of male and female snow crab in the Bering Sea (Table 8). These studies include:

1. Transit study (2003); 14 crab
2. Cooperative seasonality study; 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 (L. 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. Crab missing more than two limbs were excluded due to other studies showing lower growth. Crab from the seasonal study were excluded that were measured less than 3 days after molting due to difficulty in measuring soft crab accurately (L. Rugolo, pers. comm.). 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 58% harvest rate 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 et al. (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 Alaska Department of Fish and Game (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).

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

Where  $TMB$  is the total mature biomass and  $TMB_{BMSY}$  is the  $TMB$  associated with maximum sustainable yield. 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 stock productivities (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-1990s (retained catches during 1991, 1992, and 1998 were 143.02, 104.68, and 88.09 kt, respectively; Table 9). 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 slowly increased after 1999 as the stock rebuilt. However, retained catch in the most recent year was 2.48 kt, the lowest on record following the collapse of 2021.

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.

Discard from the directed pot fishery has been estimated from observer data since 1992 and has ranged from 11-100% of the magnitude of retained catch by numbers. In recent years, discards have reached 50-100% 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 mortality rates for the directed fishery are assumed to be 30%. 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 13). Bycatch in fisheries other than the groundfish trawl fishery has historically been relatively low. Discard mortality rates from non-directed fisheries are assumed to be 80%. 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 required on pots used in the snow crab fishery to prevent ghost fishing. Escape panels consist 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 provisions 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 2021 were used in this analysis (Table 9). 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, from 2018 onward the discarded size compositions were calculated by subtracting the retained size compositions from the total size compositions. This mismatch of input data types will be addressed in an upcoming data overhaul for the assessment.

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 2021. 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 strategy used since 2001 to the present by ADFG to set the TAC, which assumes a discard mortality of 25% (Zheng, et al. 2002). The discards prior to 1992 may be underestimated due to the lack of escape mechanisms for undersized crab in the pots before 1997. See Table 7 for a summary of catch data.

Table 7: Data included in the assessment. Dates indicate survey year.

Data component	Years
Retained male crab pot fishery size frequency by shell condition	1982 - 2021
Discarded Males and female crab pot fishery size frequency	1992 - 2021
Trawl fishery bycatch size frequencies by sex	1991 - 2021
Survey size frequencies by, maturity, sex and shell condition	1982 - 2022
Retained catch estimates	1982 - 2021
Discard catch estimates from crab pot fishery	1992 - 2021
Trawl bycatch estimates	1993 - 2021
Total survey abundance estimates and coefficients of variation	1982 - 2022
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

Estimates from the annual eastern Bering Sea (EBS) bottom trawl survey conducted by NMFS serve as the primary index of abundance in this assessment (see Lang et al., 2018). Additional survey stations were added in 1989, which could alter the interpretation of catchability coefficient for the survey. Consequently, survey selectivity has been historically modeled in two ‘eras’ in the assessment (1982-1988, 1989-present). All survey data in this assessment used measured net widths instead of the fixed 50 ft net width based on Chilton et al.’s (2009) survey estimates. Carapace width and shell conditions were measured and reported for snow crab caught in the survey. Numbers of crab in several size groups are currently at or near all-time lows (Figure 14 & Figure 15).

Mature biomass for males and females at the time of the survey were the primary indices of population size fit to here. In the status quo assessment, total survey numbers were input to the model via the .DAT file (e.g. Figure 16), 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 proportions of mature males at length were 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 input for assessment (Table 10).

The NMFS summer surveys were canceled in 2020 due to the coronavirus pandemic, which presents challenges in understanding the recent stock dynamics.

## 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 southwest portion of the shelf (Figure 6) while smaller males have been more prevalent on the northwest portion of the shelf (Figure 3). Females have exhibited a similar pattern (compare Figure 4 to Figure 7). 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 17 & Figure 18). Centroids of mature female abundance early in the history of the survey were 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 18).

Fishing effort has generally been south of 58.5 N, even when ice cover did not restrict the fishery moving farther north (Figure 19). 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. Fishing effort in 2020 was located farther north than usual as a result of higher CPUEs (Figure 20).

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 surveys varied over the years as the survey goals changed. In 2009, the survey consisted of 108 tows around 27 survey stations and the goal was to improve understanding snow crab densities and the selectivity of NMFS survey gear (Figure 21). 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 22 & Figure 23) 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 suggests 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  $\leq 1$  for at least some of the size classes) can provide an empirical estimate of catchability/selectivity (Figure 24). Empirical estimates of catchability/selectivity vary by year and size class across the different BSFRF data sets (Figure 25 & Figure 26). The number of snow crab used to develop estimates of numbers at length likely contribute to these differences among years (Figure 27), but other factors may also influence catchability/selectivity at size of the NMFS survey gear (e.g. Somerton et al. 2013 show substrate type can influence selectivity). The assessments presented either treat these data as an additional survey with selectivity nested within the NMFS survey or directly as priors on survey selectivity (see appendix A for details).

The assessment model estimates a vector that represents the ‘availability’ of crab to the BSFRF experiments (see appendix A for a discussion of how this is modeled). Availability in this case means how much of the population was in the area surveyed in the BSFRF experiments. Some candidate models in the past had an ‘empirical’ availability specified, rather than estimated. Because the size composition of the total NMFS survey and the size composition of the NMFS survey stations associated with the BSFRF experiments are known, the ‘empirical availability’ can be directly calculated simply by dividing the size composition of the subset of stations within the BSFRF survey area by the size composition of all the NMFS summer survey stations.

## 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 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 status quo 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. Recently, the Generalized Model for Assessing Crustacean Stocks (GMACS) was adopted as the assessment platform after a demonstration that GMACS could effectively reproduce the dynamics of the status quo model and offered structural improvements.

The snow crab population dynamics model tracked the number of crab of sex  $s$ , maturity state  $m$ , during year  $y$  at length  $l$ ,  $N_{s,m,y,l}$ . 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 author-preferred model, 431 parameters were estimated. Parameters estimated within the assessment included those associated with the population processes recruitment, growth, natural mortality (subject to an informative prior and two years of additional ‘mortality events’ estimated in 2018 and 2019), fishing mortality, selectivity (fishery, survey, and BSFRF experiments), catchability, and maturity. Weight at length, discard mortality, bycatch mortality, and parameters associated with proportion of recruitment allocated to size bin were estimated outside of the model or specified. See appendix A for a more complete description of the population dynamics.

A ‘jittering’ approach has been historically used to explore the impact of different starting values on the assessment output (Turnock, 2016). Jittering was implemented for the first time this year for a GMACS model for snow crab using recently developed functionality. Retrospective analyses were performed in which the terminal year of data was removed sequentially from the model fitting for the author-preferred model. Then time series of estimated MMB were compared between the most recent model and successive ‘peels’ of the data to identify retrospective patterns. A retrospective pattern is a consistent directional change in assessment estimates of management quantities (e.g. MMB) in a given year when additional years of data are added to an assessment.

## Model selection and evaluation

Models were evaluated based on their fit to the data, evidence of non-convergence, the credibility of the estimated population processes, and the strength of the influence of the assumptions of the model on the outcomes of the assessment.

## Results

All GMACS models converged with the addition of the new data with maximum gradient components of 0.009 or smaller. The author-preferred model displayed positive retrospective patterns (Figure 28). Retrospective patterns suggest that a process is varying over time that is not allowed to vary within the model (e.g. catchability or maturity) or the data are incomplete (e.g. not all catch is reported). Jittering analyses revealed bimodality in model output and a model from each mode is presented here (Figure 29). The two modes had similar average objective function values (approximately -23204 vs. -23200) but fairly large differences in the calculated OFLs (~10 kt vs. ~4 kt). The author-preferred model (22.1ab) presented here belongs to the cloud of jittered models that produced an OFL of ~ 4 kt. Model 22.1ab is the author-preferred model in spite of slightly poorer fits (particularly to recent male size composition data) than models from the other cloud in the jitter analysis because those models produced unreasonable estimates of fishing mortality in recent years.

Below, the fits to the data and estimated population processes are described for all considered models that include the most recent data (see contribution of likelihood components to the objective function in Table 11 and parameter estimates and standard deviations in Table 12).

## **Fits to data**

### **Survey biomass data**

Fits to the survey mature male biomass were fairly similar for all GMACS models for the majority of years in the time series (Figure 30 & Figure 31) with the same data. However, differences in the estimated survey MMB in the final four years existed. Model 22.1a fit 2019 and 2022 well, but fit 2021 poorly. Model 22.1ab fit 2021 and 2022 well, but fit 2019 worse than model 22.1a. Differences in fit among the models were also seen around the transition from survey era 1 to survey era 2. Small differences in negative log likelihoods existed among models (Table 11).

### **Growth data**

Small differences existed in the estimates of the relationship between pre- and post-molt increment in the GMACS models, with model 22.1ab estimating slightly larger growth increments for males at size than the other models with updated data. The status quo model historically estimated growth outside of the model and specified it because of convergence issues (Figure 32).

### **Catch data**

All catch data were well-fit by all models, with few visually discernible differences among GMACS models (Figure 33). Small differences in male discards were apparent in the models representing the modes of the jittered model, with 22.1a overestimating discards in 2020 and model 22.1ab underestimating discards in 2019. Existing differences in fit were amplified in the objective function by the small CVs placed on the different sources of catch data (Table 11).

### **Size composition data**

Most years of retained and total catch size composition data were visually well fit by all models (Figure 34 & Figure 35). Key differences among models occurred at the beginning and end of the time series. Model 21.g and 22.1 (both GMACS models) overestimated the proportion of animals in the largest size bins in 1982-1984. Model 22.1a and 22.1ab addressed this issue by using an alternate method for estimating the initial size composition. The other obvious change in model fits arose at the end of the time series (particularly 2019-2021) with the addition of new data to the GMACS model. More variability was seen among the fits to the bycatch size composition data, but the general shapes of the predicted size compositions were similar within years (Figure 36).

Fits to size composition data for the BSFRF survey selectivity experiments produced some runs of positive and negative residuals for the males in particular (Figure 37). 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 acceptably fit and fits were visually similar for most models in most years (Figure 38, Figure 39, Figure 40 & Figure 41). Some of the largest departures occurred for immature males and females in 2019-2022. For males, a potential reason this occurred is the large difference in the probability of terminally molting observed in 2021 compared to other years (Figure 2) and the use of a single estimated ogive over all years in the assessment. The distribution of residuals for male and female survey composition data for the author-preferred model varied by sex. Size composition data for females tended to be overestimated for larger size classes (Figure 42), whereas a pattern for males was less clear (Figure 43).

## Estimated population processes and derived quantities

Estimated population processes and derived quantities varied among models and the GMACS models with updated data produced populations with more pronounced declines in MMB (Figure 44). Model 22.1 and 22.1a had almost identical trends from 1989-present, but diverged during 1982-1988 as a result of differences in estimated catchability during that era. Uncertainty in estimates of MMB during the first survey era (1982-1988) was larger than in later years (Figure 45). Estimated MMB at the time of mating in the past several years was distinctly different for the models representing the two modes of bimodality from the jittering analysis. Model 22.1a estimates of MMB declined continually from 2017 to 2020, but estimates from model 22.1ab declined in 2018, rose in 2019, then continually declined to the present. The trend of estimated MMB in these models is closely related to the estimates of additional mortality in 2018 and 2019. Model 22.1ab estimated very little additional mortality for mature males in 2019, which allowed the increase in MMB. Model 22.1a, however had the highest estimates of additional mortality for mature males in 2019 and these differences in estimated MMB and additional M had large consequences for the fishing mortality estimated in 2020 (see below). Estimated fishing mortality in the recent past was above  $F_{35\%}$  during 2020 for all models (Figure 46).

Estimates of selectivity and catchability varied among models (Figure 47). In era 1 (1982-1988), selectivity curves all had similar shapes, but the catchability coefficients ranged from  $\sim 0.2$  to  $\sim 0.9$  between males and females. In era 2 (1989-present), catchability ranged from  $\sim 0.4$  -  $\sim 0.7$  for males; for females, estimated catchability was much lower ( $< 0.4$ ) for all GMACS models than the historically assumed 1 in the status quo model. The models with updated data estimated catchabilities closer to the catchability implied by the BSFRF experiments (Figure 26). The 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 48).

Small differences in the estimated shape of the curve representing the probability of having undergone terminal molt existed among models (Figure 49). The GMACS models (except 22.1ab) generally estimated slightly lower probabilities of having undergone terminal molt for male crab in the 85-100 mm carapace width range than the status quo model. In general, model 22.1ab estimated the highest probabilities of having undergone terminal molt at size across models. No models estimated a probability of having undergone terminal molt similar to the observed probability of new shell male crab having undergone terminal molt - estimated probabilities were somewhat lower than the observed probabilities in the middle size ranges (Figure 2).

Trends in estimated fishing mortality in the directed fishery were similar for all models, though the scale differed (Figure 50). GMACS models 22.1 and 22.1a estimated unreasonably high fishing mortalities in 2020 with  $> 99\%$  of the exploitable males being captured. Estimates of  $F$  during 2020 from model 22.1ab were more reasonable, but still high (exploitation rates  $\sim 85-90\%$ ). Total and retained fishery selectivity was similar for all GMACS models (Figure 50). Estimated size at 50% selection in the trawl fishery varied across models more than selectivity in the directed fishery (Figure 50). Size at 50% selection for discarded females was similar for all models (Figure 50). Predicted mortalities from discards and bycatch were very small relative to estimated fishing mortality associated with the directed fleet.

Patterns in recruitment by sex varied somewhat among models, particularly with respect to the size and timing of the recent large pseudocohort (Figure 51). Generally, the models estimated a period of high recruitment 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 2014. The addition of the new data advanced the peak of recent estimated recruitment one year, from 2015 to 2016. This change may be related to the need for the model to accommodate the large difference between the observed probability of having undergone terminal molt in 2021 and the estimated values from the assessment. Recruitment entering the model was placed primarily in the first three size bins (Figure 51).

Estimated natural mortality ranged from 0.27 to 0.29 for immature and mature crab (Figure 52). Estimated mortality events in 2018 and 2019 were most intense for immature females and mature males, but even the less 'intense' mortality events for mature females and immature males resulted in  $> 80\%$  of crab dying, except for model 22.1ab, which estimated almost no additional mortality for mature males in 2019 and very little for immature females.

## F. Calculation of the OFL

### Methodology for OFL

#### Tier 3

The tier 3 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 and constant recruitment 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 over the last 8 years.

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). To determine the  $F_{OFL}$ , the population is projected to the time of fishing for the upcoming fishery under no fishing. If the MMB at that time exceeds 25% of  $B_{35\%}$ , a fishery can occur and the  $F_{OFL}$  is calculated as:

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

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).

#### Tier 4

Tier 4 OFLs were calculated based on four time series of male biomass of different sizes of observed crab in the survey and decremented by six months of natural mortality. Natural mortality was specified as 0.27 based on an assumed maximum age of 20 years and Hamel’s (2015) analyses. The four time series used were morphometrically mature males (based on chelae height data), legal males (>78 mm carapace width), males >95 mm carapace width, and commercial sized males (>101 mm carapace width). The FMP is not explicit about what measure of biomass is to be used in a tier 4 rule, but states that ‘biomass’ should be a ‘measure of the productive capacity of the stock, such as spawning biomass or fertilized egg production’. It also states ‘a proxy of ‘B’ (biomass) may be used’ (e.g. mature male biomass). Although morphometrically mature male biomass is the historically used currency of management for snow crab, alternative measures may be useful to explore.

A tier 4 proxy for  $B_{MSY}$  for each time series was calculated as the average of the time series from 1982 to present. The  $F_{OFL}$  was calculated using the same control rule as for the tier 3 rule above, but replacing natural mortality for  $F_{35\%}$  and the tier 4  $B_{MSY}$  proxy for  $B_{35\%}$ . Given tier 4 rules have not been used in the recent past, time series of the OFLs that would have resulted from applying this harvest control rule to the available data in all years were calculated for context.

## Calculated OFLs and interpretation

### Tier 3

Calculated OFLs ranged from 3.98 to 10.32 kt (Table 13). Differences in OFLs were a result of differences in estimated MMB, calculated  $B_{35\%}$  (which ranged from 183.15.9 - 196.38 kt),  $F_{35\%}$  (which ranged from 1.37 - 2.26  $\text{yr}^{-1}$ ), and  $F_{OFL}$  (which ranged from 0.28 - 0.67  $\text{yr}^{-1}$ ; Table 13).

### Tier 4

Calculated tier 4 OFLs for 2022/2023 were all 0 kt and the adoption of a tier 4 rule would result in a closure of the fishery. The calculated OFLs using the currently employed currency of management (morphometrically mature male biomass) and legal biomass would have exceeded the biomass of the commercially viable snow crab in the Bering Sea in some years based on the historical analysis (Figure 53). Consequently, neither of these harvest control rule definitions seem appropriate for use with snow crab.

## G. Calculation of the ABC

The acceptable biological catch (ABC) was set by subtracting a 25% buffer from the OFL to account for scientific uncertainty, as recommended by the SSC.

### Author recommendations

Model 22.1ab is the author's preferred model among the integrated models presented based on improvements in fits to size composition data from adjusting the way the initial numbers at size are estimated and more reasonable estimates of fishing mortality than other models. However, the output of this model includes consequential changes in estimates of population processes compared to the GMACS model accepted in June: survey catchability decreased from  $\sim 0.7$  in 21.g to  $\sim 0.5$  in 22.1, the estimated probability of having undergone terminal molt increased at smaller sizes, and fits to recent male size composition data are poor. The bimodality in this model is also a point for concern, and models from the other mode fit the data slightly better, but do so by estimating unreasonable fishing mortality. In addition to modeling issues, the observed survey MMB declined by 40% compared to last year, the observed probability of having undergone terminal molt was much higher than historically seen for smaller sizes in 2021, average clutch fullness was the lowest on record, and the median fishery CPUE in 2021 was the lowest observed (Figure 54). The sum of these observations suggest that uncertainty related to the modeling and management of eastern Bering Sea snow crab is currently high.

In spite of this uncertainty, the stock is now under a rebuilding plan and a model is required for the projection analyses. Appendix D uses model 22.1ab as the basis for projections. Although some concerns exist with the recent dynamics of this model, it is still useful as a projection model because the key driver of uncertainty in future trajectories is projected recruitment and natural mortality. Estimated parameters for growth, maturity, and selectivity (which are the key drivers of population dynamics) are relatively similar among models. See Appendix D for further discussion.

## H. Data gaps and research priorities

Incorporating maturity data into the assessment and more appropriately incorporating the BSFRF data into the assessment to inform survey selectivity and catchability should be high priorities moving forward and may address some of the lack of fit in recent years. A male-only model may also be useful to consider in order to focus on the portion of the stock the fishery interacts with and reduce the number of uncertainties

and assumptions required by modeling both sexes. An enumeration of the ramifications of management with an F35% that can allow all males of industry-preferred size to be harvested needs to be performed, with particular attention paid to the appropriateness of the use of morphometrically mature males as the currency of management and the relative contribution to reproduction of males by size. A more thorough evaluation of the best way to re-weight size composition would be useful given the variety of shapes of the survey selectivity curves resulting from changes in the weighting of survey size composition data. Further consideration of the way in which the probability of having undergone terminal molt may be useful. It appears as though fewer old shell males are observed in the 60-80 mm carapace width size ranges than would be expected given observed estimates of having undergone terminal molt of ~20-40% for that size range (Figure 2 & Figure 57).

## **I. Ecosystem considerations and fishery performance**

The most important ecosystem consideration for snow crab in the EBS centers around what happened to the 2015 pseudocohort. It was observed for 4 years before being halved from the 2018 survey to the 2019 survey. In 2020, no survey occurred, and we grappled with two hypotheses for the decline in 2019—did the crab move or did the crab die? The 2021 survey data suggest that the crab died—they did not reappear in the EBS 2021 or 2022 NMFS survey and they were not found in the NBS. It is possible the crab moved off of the shelf into deeper waters, but data to support or refute this are sparse. NMFS performs a EBS slope survey in some years, but there have generally been very few snow crab observed in these surveys and the area of the slope relative to the shelf is much smaller (Figure 55 & Figure 56). No slope survey was not performed in 2020 or 2021. If the trend of few crab on the slope was maintained and a mortality event(s) is the only remaining culprit for the declines seen in 2018 and 2019, what was the cause of mortality?

Appendix B and C outline analyses aimed at understanding the context around the recent collapse of snow crab. Given the available data, it appears that the mortality events were a function of unprecedented temperatures and high densities of crab. The investigation into the disappearance of the 2015 pseudocohort will be an on-going process. Regardless of the outcome, the disappearance underscores the importance of a yearly survey for snow crab in the Bering Sea and uninterrupted survey effort in the northern Bering Sea.

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## Appendix A: Population dynamics model

This section will be updated with the GMACS population dynamics equations when available. Until the equations are available, the basic model structure is very similar to the status quo model (below), but not identical. Appendices F, G, and H are the .DAT, .CTL, and .PRJ file used for the author preferred model.

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),  $\kappa_{s,l'}$  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 this formulation effectively specified a mean and standard deviation for a prior distribution for  $M$ ).

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

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

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

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

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

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

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

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

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

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

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

Where  $\delta_y$  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 by sex,  $S_{ind,s,l,y}$ . For some model iterations, an ‘empirical’ availability was calculated. The total NMFS survey size composition of males and females in 2009 and 2010 are known and the fraction of the NMFS survey size composition of males and females in the BSFRF experimental area are also known. Consequently, the ‘empirical availability’ can simply be calculated as the ratio of the experimental size composition to the total size composition data.

After identifying the fraction of the crab at length covered by the experimental surveys (either by estimating and ogive or inputting the empirical availability), 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.

$$S_{nmfs,s,l,y} = S_{ind,s,l,y} S_{surv,s,l,y} \quad (18)$$

For some models, survey selectivity in the second survey era (1989-present) was modeled as a non-parametric function of size (i.e. an estimated vector of parameters equal in length to the number of size classes in the model). Priors placed on the selectivity at size were based on either a weighted average of the observed selectivity from the BSFRF experiments from 2009, 2010, 2016-2018 or a generalized additive model (GAM) fit to these same data. The standard errors used in the normal likelihood to fit selectivity in the objective function were derived either from the weighted variances when calculating the averages or the standard errors generated from the fitting of the GAM.

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,  $w_{s,l}$ :

$$MMB_y = \sum_{l,v} w_{male,l} N_{male,v,mat,y,l} \quad (19)$$

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

$$w_{s,l} = \alpha_{wt,s} L_l^{\beta_{wt,s}} \quad (21)$$

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 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,  $Y_{s,l,l'}$ .

$$X_{s,l,l'} = \frac{Y_{s,l,l'}}{\sum_{l'} Y_{s,l,l'}} \quad (22)$$

$$Y_{s,l,l'} = (\Delta_{l,l'})^{\frac{L_{s,l} - (\bar{L}_l - 2.5)}{\beta_s}} \quad (23)$$

$$\hat{L}_{s,l}^{post} = \alpha_s + \beta_{s,1} L_l \quad (24)$$

$$\Delta_{l,l'} = \bar{L}_{l'} + 2.5 - L_l \quad (25)$$

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

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

$$Rec_y = e^{(Rec_{avg} + Rec_{dev,y})} \quad (26)$$

$$Pr_l = \frac{(\Delta_{1,l})^{\alpha_{rec}/\beta_{rec}} e^{-\Delta_{1,l}/\beta_{rec}}}{\sum_{l'} (\Delta_{1,l'})^{\alpha_{rec}/\beta_{rec}} e^{(-\Delta_{1,l'}/\beta_{rec})}} \quad (27)$$

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).

Three general types of likelihood components were used to fit to the available data. 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:

$$L_x = \lambda_x \sum_y N_{x,y}^{eff} \sum_l p_{x,y,l}^{obs} \ln(\hat{p}_{x,y,l}/p_{x,y,l}^{obs}) \quad (28)$$

$L_x$  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  $x$ .

Log normal likelihoods were implemented in the form:

$$L_x = \lambda_x \sum_y \frac{(\ln(\hat{I}_{x,y}) - \ln(I_{x,y}))^2}{2(\ln(CV_{x,y}^2 + 1))} \quad (29)$$

$L_x$  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  $y$ .

Normal likelihoods were implemented in the form:

$$L_x = \lambda_x \sum_y (\hat{I}_{x,y} - I_{x,y})^2 \quad (30)$$

$L_x$  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  $y$ .

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 8: 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		
23.09	29.26		



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

Table 9: 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	1.47	0.37
1983	12.16	0.01	1.43	0.47
1984	29.94	0.01	3.2	0.5
1985	44.45	0.01	4.65	0.43
1986	46.22	0.02	4.92	0
1987	61.4	0.03	6.4	0
1988	67.79	0.04	6.74	0
1989	73.4	0.05	7.74	0.1
1990	149.1	0.05	17.62	0.71
1991	143	0.06	13.9	1.5
1992	104.7	0.12	17.06	2.28
1993	67.94	0.08	5.32	1.57
1994	34.13	0.06	4.03	2.67
1995	29.81	0.02	5.75	1.01
1996	54.22	0.07	7.44	0.66
1997	114.4	0.01	5.73	0.82
1998	88.09	0.01	4.67	0.54
1999	15.1	0	0.52	0.47
2000	11.46	0	0.62	0.41
2001	14.8	0	1.89	0.31
2002	12.84	0	1.47	0.17
2003	10.86	0	0.57	0.46
2004	11.29	0	0.51	0.63
2005	16.77	0	1.36	0.2
2006	16.49	0	1.78	0.42
2007	28.59	0.01	2.53	0.18
2008	26.56	0.01	2.06	0.18
2009	21.78	0.01	1.23	0.47
2010	24.61	0.01	0.62	0.14
2011	40.29	0.18	1.69	0.15
2012	30.05	0.03	2.32	0.22
2013	24.49	0.07	3.27	0.11
2014	30.82	0.17	3.52	0.13
2015	18.42	0.07	2.96	0.13
2016	9.67	0.02	1.31	0.06
2017	8.6	0.02	1.93	0.04
2018	12.51	0.02	2.86	0.23
2019	15.43	0.02	5.07	0.24
2020	20.41	0	5.8	0.07
2021	2.48	0	1.16	0.06

Table 10: 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	0.17	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	0.17	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	0.17	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
2021	31.66	0.43	62.25	0.13	12.43	23.17
2022	22.44	0.31	37.5	0.15	13.36	23.89

Table 11: Contribution to the objective function by individual likelihood component by modeling scenario.

Component	Fishery	22.1	22.1a	22.1ab
catch	Retained	-6.6897	-8.8231	-9.1501
catch	Discard (male)	142.1084	139.3299	122.0342
catch	Discard (female)	-69.6612	-69.6608	-69.6607
catch	Trawl	-50.6422	-50.6439	-50.6438
cpue	NMFS survey (era 1; females)	51.7841	43.9095	43.6293
cpue	NMFS survey (era 2, females)	-27.6439	-30.8034	-31.2336
cpue	NMFS survey (era 1, males)	28.7505	31.6677	29.7573
cpue	NMFS survey (era 2, males)	8.7418	8.022	-5.4007
cpue	BSFRF 2009	-0.5375	-0.5799	-0.6052
cpue	BSFRF 2010	-0.5307	-1.9527	-3.6876
growth_inc	1	1020.7269	1021.2552	1016.8876
growth_inc	2	0	0	0
rec_dev	1	0.7575	0.7575	0.7575
rec_dev	2	0	0	0
rec_dev	3	86.1706	89.1284	91.2242
size_comp	Retained males	-3666.4763	-3701.8747	-3699.7386
size_comp	Survey mature females (1982-1988)	-664.0213	-688.4905	-688.4737
size_comp	Survey mature females (1989-present)	-3071.3976	-3071.9284	-3070.3273
size_comp	Survey mature males (1982-1988)	-589.1354	-595.4243	-596.1709
size_comp	Survey mature males (1989-present)	-2738.861	-2741.4501	-2721.3733
size_comp	BSFRF 2009	-175.868	-176.1576	-176.4514
size_comp	NMFS 2009	-184.5293	-184.5963	-184.6168
size_comp	BSFRF 2010	-173.8314	-173.4927	-173.4626
size_comp	NMFS 2010	-170.3389	-170.3836	-171.7761
size_comp	Total males	-2711.3257	-2711.7745	-2688.7734
size_comp	Discard females	-2282.9278	-2282.6251	-2282.1564
size_comp	Trawl bycatch (females)	-2449.8648	-2467.1116	-2466.9757
size_comp	Trawl bycatch (male)	-2360.4382	-2358.0865	-2333.903
size_comp	Survey immature females (1982-1988)	-596.184	-623.0579	-624.694
size_comp	Survey immature females (1989-present)	-2875.5278	-2876.5912	-2878.3031
size_comp	Survey immature males (1982-1988)	-573.3505	-577.3463	-577.3848
size_comp	Survey immature males (1989-present)	-2733.5207	-2733.1505	-2755.917
Total	Total	-26834.2641	-26961.9354	-26956.5897

Table 12: Parameter estimates and standard deviations from considered models.

Parameter	Model 22.1		Model 22.1a		Model 22.1ab	
	est	SD	est	SD	est	SD
theta[1]	0.28	0	0.28	0	0.29	0
theta[2]	0.28	0	0.28	0	0.28	0
theta[4]	16.23	0.12	NA	NA	NA	NA
theta[5]	5.78	198.42	21.01	1472.5	5.92	409.68
theta[13]	-0.15	0.3	10.46	0.7	10.56	0.7
theta[14]	-0.26	0.3	10.47	0.56	10.58	0.56
theta[15]	-0.01	0.3	10.56	0.44	10.67	0.44
theta[16]	0.48	0.31	11.02	0.4	11.12	0.4
theta[17]	0.99	0.29	11.68	0.37	11.79	0.37
theta[18]	1.37	0.26	12.23	0.31	12.34	0.31
theta[19]	1.42	0.24	12.6	0.27	12.67	0.27
theta[20]	1.35	0.23	12.6	0.25	12.64	0.25
theta[21]	1.39	0.23	12.43	0.25	12.52	0.25
theta[22]	1.44	0.22	12.43	0.24	12.52	0.24
theta[23]	1.32	0.22	12.44	0.24	12.49	0.24
theta[24]	1.26	0.22	12.28	0.24	12.31	0.25
theta[25]	1.27	0.2	12.17	0.25	12.2	0.25
theta[26]	1.29	0.19	12.11	0.25	12.16	0.25
theta[27]	1.11	0.2	12.18	0.24	12.27	0.24
theta[28]	0.8	0.2	12.16	0.2	12.21	0.2
theta[29]	0.22	0.23	11.87	0.21	11.84	0.21
theta[30]	-0.61	0.26	11.36	0.24	11.26	0.24
theta[31]	-1.32	0.28	10.51	0.28	10.36	0.28
theta[32]	-1.52	0.33	9.48	0.33	9.32	0.33
theta[33]	-1.43	0.36	8.53	0.36	8.38	0.36
theta[34]	0.45	0.45	7.98	0.41	7.85	0.41
theta[35]	0.64	0.36	11.82	0.46	11.89	0.46
theta[36]	1.08	0.28	11.97	0.31	12.03	0.31
theta[37]	2.35	0.33	12.73	0.29	12.78	0.29
theta[38]	2.73	0.25	13.27	0.23	13.32	0.23
theta[39]	2.04	0.22	12.65	0.21	12.73	0.21
theta[40]	1.86	0.23	12.71	0.2	12.78	0.21
theta[41]	1.61	0.25	12.61	0.2	12.7	0.2
theta[42]	1.45	0.26	12.35	0.22	12.44	0.22
theta[43]	1.23	0.25	12.16	0.24	12.25	0.24
theta[44]	0.77	0.28	11.95	0.24	12.03	0.24
theta[45]	0.43	0.31	11.55	0.28	11.63	0.28
theta[46]	0.28	0.31	11.22	0.31	11.29	0.31
theta[47]	-0.11	0.28	11.06	0.32	11.1	0.32
theta[48]	-0.71	0.29	10.54	0.34	10.48	0.34
theta[49]	-1.14	0.33	9.59	0.38	9.45	0.38
theta[50]	-1.43	0.32	8.63	0.42	8.47	0.42
theta[51]	-1.62	0.31	7.82	0.44	7.66	0.44
theta[52]	-1.74	0.3	7.21	0.47	7.07	0.47
theta[53]	-1.81	0.3	6.78	0.51	6.65	0.51
theta[54]	-1.59	0.33	6.48	0.56	6.36	0.56
theta[55]	-1.52	0.37	6.29	0.62	6.17	0.62
theta[56]	0.5	0.48	6.2	0.7	6.08	0.71
theta[57]	0.7	0.41	13.56	0.79	13.47	0.79

Parameter	Model 22.1		Model 22.1a		Model 22.1ab	
	est	SD	est	SD	est	SD
theta[58]	1.18	0.39	13.55	0.64	13.46	0.65
theta[59]	2.13	0.35	13.56	0.48	13.46	0.48
theta[60]	3.65	0.21	13.76	0.36	13.67	0.36
theta[61]	4.27	0.15	14.5	0.29	14.4	0.29
theta[62]	3.62	0.16	14.66	0.27	14.56	0.27
theta[63]	2.26	0.23	13.75	0.26	13.67	0.26
theta[64]	0.83	0.31	12.55	0.28	12.47	0.28
theta[65]	-0.22	0.3	11.4	0.33	11.31	0.34
theta[66]	-0.64	0.3	10.17	0.37	10.08	0.37
theta[67]	-0.76	0.31	9.42	0.41	9.33	0.41
theta[68]	-0.75	0.31	8.98	0.46	8.89	0.46
theta[69]	-0.75	0.31	8.73	0.52	8.63	0.52
theta[70]	-0.79	0.3	8.53	0.56	8.43	0.56
theta[71]	-0.91	0.29	8.35	0.58	8.24	0.59
theta[72]	-0.97	0.29	8.15	0.59	8.04	0.59
theta[73]	-1.02	0.29	8	0.61	7.88	0.61
theta[74]	-1.05	0.29	7.89	0.63	7.75	0.63
theta[75]	-1.1	0.3	7.8	0.67	7.66	0.66
theta[76]	-1.2	0.31	7.73	0.71	7.59	0.7
theta[77]	-1.39	0.33	7.69	0.77	7.54	0.75
theta[78]	0.05	0.42	7.67	0.84	7.52	0.83
theta[79]	0.2	0.4	-12.65	7110.5	7.15	1.27
theta[80]	0.16	0.35	-12.66	7110.5	7.12	1.17
theta[81]	0.67	0.33	-12.72	7110.5	7.05	1.05
theta[82]	1.38	0.22	-12.7	7110.5	7.14	1
theta[83]	1.7	0.17	-12.61	7110.5	7.22	1
theta[84]	0.56	0.22	-12.47	7110.5	7.36	1.02
theta[85]	-0.45	0.25	-13.68	7110.5	6.15	1.04
theta[86]	-1.13	0.26	-15	7110.5	4.84	1.06
theta[87]	-1.6	0.27	-16.04	7110.5	3.8	1.07
theta[88]	-1.83	0.27	-16.8	7110.5	3.04	1.09
theta[89]	-1.89	0.27	-17.29	7110.5	2.55	1.11
theta[90]	-1.94	0.27	-17.6	7110.5	2.24	1.14
theta[91]	-1.97	0.27	-17.84	7110.5	2	1.16
theta[92]	-2.01	0.27	-18.02	7110.5	1.82	1.18
theta[93]	-2.04	0.27	-18.16	7110.5	1.68	1.21
theta[94]	-2.08	0.27	-18.28	7110.5	1.56	1.23
theta[95]	-2.1	0.27	-18.37	7110.5	1.47	1.25
theta[96]	-2.11	0.27	-18.44	7110.5	1.4	1.28
theta[97]	-2.11	0.27	-18.49	7110.5	1.35	1.31
theta[98]	-2.11	0.27	-18.53	7110.5	1.31	1.34
theta[99]	-2.11	0.3	-18.56	7110.5	1.28	1.39
Grwth[1]	2.23	0.08	2.24	0.08	2.12	0.08
Grwth[2]	-0.22	0	-0.22	0	-0.22	0
Grwth[4]	-0.14	0.11	-0.15	0.11	-0.15	0.11
Grwth[5]	-0.3	0	-0.3	0	-0.3	0
Grwth[10]	0.03	0	0.03	0	0.03	0
Grwth[11]	0.06	0.01	0.06	0.01	0.06	0.01
Grwth[12]	0.09	0.01	0.1	0.01	0.1	0.01
Grwth[13]	0.14	0.01	0.14	0.01	0.15	0.01
Grwth[14]	0.19	0.01	0.2	0.01	0.21	0.01

Parameter	Model 22.1		Model 22.1a		Model 22.1ab	
	est	SD	est	SD	est	SD
Grwth[15]	0.2	0.01	0.21	0.01	0.21	0.01
Grwth[16]	0.23	0.01	0.24	0.01	0.24	0.01
Grwth[17]	0.27	0.02	0.28	0.02	0.3	0.02
Grwth[18]	0.26	0.02	0.27	0.02	0.3	0.02
Grwth[19]	0.23	0.02	0.24	0.02	0.28	0.02
Grwth[20]	0.24	0.02	0.25	0.02	0.32	0.02
Grwth[21]	0.4	0.02	0.41	0.02	0.5	0.02
Grwth[22]	0.81	0.02	0.81	0.02	0.85	0.02
Grwth[30]	0.04	0.03	0.05	0.04	0.05	0.04
Grwth[31]	0.05	0.02	0.06	0.02	0.06	0.02
Grwth[32]	0.36	0.04	0.38	0.05	0.36	0.04
Grwth[33]	0.79	0.02	0.79	0.02	0.78	0.02
Grwth[34]	0.92	0.01	0.92	0.01	0.92	0.01
Grwth[35]	0.95	0.01	0.96	0	0.96	0
log_slx_pars[1]	4.63	0	4.63	0.01	4.65	0.01
log_slx_pars[2]	1.56	0.03	1.57	0.03	1.58	0.03
log_slx_pars[3]	4.25	0.01	4.26	0.01	4.26	0.01
log_slx_pars[4]	0.96	0.03	0.97	0.03	0.97	0.03
log_slx_pars[5]	4.54	0.01	4.55	0.01	4.58	0.02
log_slx_pars[6]	2.21	0.03	2.19	0.03	2.23	0.03
log_slx_pars[7]	3.75	0.04	3.76	0.05	3.78	0.05
log_slx_pars[8]	1.93	0.13	2.05	0.14	2.09	0.14
log_slx_pars[9]	3.87	0.01	3.94	0.02	3.94	0.02
log_slx_pars[10]	1.02	0.05	1.25	0.05	1.25	0.05
log_slx_pars[11]	3.72	0.02	3.72	0.02	3.71	0.02
log_slx_pars[12]	1.62	0.07	1.62	0.07	1.55	0.07
log_slx_pars[13]	3.86	0.01	3.86	0.01	3.86	0.01
log_slx_pars[14]	1.32	0.03	1.31	0.03	1.32	0.03
log_slx_pars[15]	-3.89	0.94	-3.91	0.95	-3.95	0.95
log_slx_pars[16]	-3.89	0.85	-3.91	0.85	-3.95	0.86
log_slx_pars[17]	-3.89	0.75	-3.91	0.75	-3.95	0.75
log_slx_pars[18]	-3.88	0.63	-3.9	0.64	-3.95	0.64
log_slx_pars[19]	-3.86	0.52	-3.88	0.52	-3.93	0.52
log_slx_pars[20]	-3.71	0.44	-3.74	0.44	-3.79	0.45
log_slx_pars[21]	-3.36	0.41	-3.39	0.41	-3.46	0.41
log_slx_pars[22]	-2.9	0.39	-2.93	0.39	-3	0.38
log_slx_pars[23]	-2.47	0.36	-2.5	0.36	-2.55	0.37
log_slx_pars[24]	-2.02	0.35	-2.06	0.35	-2.11	0.35
log_slx_pars[25]	-1.83	0.33	-1.87	0.33	-1.97	0.33
log_slx_pars[26]	-1.63	0.32	-1.68	0.32	-1.81	0.32
log_slx_pars[27]	-1.2	0.32	-1.24	0.32	-1.43	0.32
log_slx_pars[28]	-0.83	0.32	-0.86	0.32	-1.12	0.32
log_slx_pars[29]	-0.95	0.31	-0.97	0.31	-1.19	0.3
log_slx_pars[30]	-1.43	0.3	-1.43	0.3	-1.52	0.3
log_slx_pars[31]	-1.69	0.31	-1.69	0.31	-1.71	0.31
log_slx_pars[32]	-1.81	0.32	-1.79	0.32	-1.77	0.32
log_slx_pars[33]	-1.78	0.33	-1.76	0.33	-1.71	0.33
log_slx_pars[34]	-1.6	0.37	-1.58	0.37	-1.51	0.37
log_slx_pars[35]	-1.5	0.45	-1.48	0.45	-1.4	0.45
log_slx_pars[36]	-1.42	0.59	-1.4	0.6	-1.33	0.6
log_slx_pars[37]	-3.19	1.19	-3.22	1.21	-3.11	1.21

Parameter	Model 22.1		Model 22.1a		Model 22.1ab	
	est	SD	est	SD	est	SD
log_slx_pars[38]	-3.19	1.12	-3.22	1.14	-3.11	1.14
log_slx_pars[39]	-3.24	1.02	-3.29	1.03	-3.19	1.03
log_slx_pars[40]	-3.44	0.88	-3.53	0.89	-3.44	0.89
log_slx_pars[41]	-3.67	0.85	-3.72	0.86	-3.66	0.85
log_slx_pars[42]	-2.76	0.84	-2.79	0.84	-2.74	0.84
log_slx_pars[43]	-2.24	0.84	-2.25	0.84	-2.21	0.84
log_slx_pars[44]	-1.97	0.84	-1.96	0.84	-1.92	0.84
log_slx_pars[45]	-2.05	0.85	-2	0.86	-1.97	0.86
log_slx_pars[46]	-2.29	0.88	-2.2	0.88	-2.16	0.88
log_slx_pars[47]	-2.37	0.93	-2.26	0.94	-2.23	0.94
log_slx_pars[48]	-2.37	1.01	-2.25	1.02	-2.22	1.02
log_slx_pars[49]	-2.37	1.09	-2.25	1.1	-2.22	1.1
log_slx_pars[50]	-2.37	1.16	-2.25	1.17	-2.22	1.17
log_slx_pars[51]	-2.37	1.23	-2.25	1.24	-2.22	1.24
log_slx_pars[52]	-2.37	1.3	-2.25	1.31	-2.22	1.31
log_slx_pars[53]	-2.37	1.36	-2.25	1.37	-2.22	1.37
log_slx_pars[54]	-2.37	1.42	-2.25	1.43	-2.22	1.43
log_slx_pars[55]	-2.37	1.48	-2.25	1.48	-2.22	1.48
log_slx_pars[56]	-2.37	1.53	-2.25	1.54	-2.22	1.54
log_slx_pars[57]	-2.37	1.59	-2.25	1.59	-2.22	1.59
log_slx_pars[58]	-2.37	1.64	-2.25	1.64	-2.22	1.64
log_slx_pars[61]	0	0.01	0	0.01	-0.01	0.57
log_slx_pars[62]	-0.37	0.25	-0.35	0.25	-0.37	0.32
log_slx_pars[63]	-0.68	0.22	-0.67	0.22	-0.69	0.23
log_slx_pars[64]	-0.35	0.19	-0.35	0.19	-0.36	0.19
log_slx_pars[69]	-0.38	0.22	-0.39	0.22	-0.41	0.22
log_slx_pars[70]	-0.46	0.26	-0.48	0.26	-0.52	0.26
log_slx_pars[71]	-0.53	0.27	-0.56	0.27	-0.64	0.27
log_slx_pars[72]	-0.63	0.27	-0.66	0.27	-0.77	0.27
log_slx_pars[73]	-0.55	0.3	-0.58	0.3	-0.71	0.3
log_slx_pars[74]	-0.53	0.31	-0.55	0.31	-0.7	0.3
log_slx_pars[75]	-0.57	0.29	-0.59	0.29	-0.73	0.28
log_slx_pars[76]	-0.7	0.25	-0.72	0.25	-0.82	0.26
log_slx_pars[77]	-0.79	0.24	-0.8	0.24	-0.86	0.25
log_slx_pars[78]	-0.77	0.25	-0.77	0.25	-0.81	0.26
log_slx_pars[79]	-0.7	0.27	-0.71	0.28	-0.74	0.29
log_slx_pars[80]	-0.63	0.34	-0.64	0.34	-0.67	0.37
log_slx_pars[81]	-0.56	0.47	-0.57	0.47	-0.61	0.5
log_slx_pars[82]	-0.53	0.62	-0.54	0.62	-0.59	0.64
log_slx_pars[83]	-0.48	0.54	-0.32	0.53	-0.26	0.53
log_slx_pars[84]	-1.1	0.31	-0.95	0.32	-0.89	0.31
log_slx_pars[85]	-1.39	0.28	-1.24	0.28	-1.19	0.28
log_slx_pars[86]	-0.74	0.26	-0.6	0.26	-0.55	0.25
log_slx_pars[87]	-0.47	0.16	-0.37	0.16	-0.33	0.16
log_slx_pars[88]	-0.59	0.16	-0.55	0.16	-0.51	0.16
log_slx_pars[89]	-0.62	0.18	-0.6	0.18	-0.57	0.18
log_slx_pars[90]	-0.76	0.23	-0.76	0.23	-0.73	0.23
log_slx_pars[91]	-0.69	0.35	-0.69	0.36	-0.67	0.36
log_slx_pars[92]	-0.71	0.47	-0.72	0.49	-0.7	0.49
log_slx_pars[93]	-0.71	0.62	-0.72	0.63	-0.7	0.63
log_slx_pars[94]	-0.71	0.74	-0.71	0.75	-0.7	0.75



Parameter	Model 22.1		Model 22.1a		Model 22.1ab	
	est	SD	est	SD	est	SD
log_slx_pars[95]	-0.71	0.85	-0.71	0.85	-0.7	0.85
log_slx_pars[96]	-0.71	0.94	-0.71	0.95	-0.7	0.95
log_slx_pars[97]	-0.71	1.02	-0.71	1.03	-0.7	1.03
log_slx_pars[98]	-0.71	1.1	-0.71	1.11	-0.7	1.11
log_slx_pars[99]	-0.71	1.18	-0.71	1.18	-0.7	1.18
log_slx_pars[100]	-0.71	1.25	-0.71	1.25	-0.7	1.25
log_slx_pars[101]	-0.71	1.31	-0.71	1.31	-0.7	1.32
log_slx_pars[102]	-0.71	1.37	-0.71	1.38	-0.7	1.38
log_slx_pars[103]	-0.71	1.43	-0.71	1.44	-0.7	1.44
log_slx_pars[104]	-0.71	1.49	-0.71	1.49	-0.7	1.49
log_slx_pars[107]	4.58	0	4.58	0	4.58	0
log_slx_pars[108]	0.29	0.23	0.33	0.2	0.29	0.22
log_fbar[1]	-0.95	0.08	-0.98	0.09	-0.95	0.09
log_fbar[2]	-6.5	0.09	-6.47	0.09	-6.46	0.1
log_fdev[1]	NA	NA	NA	NA	NA	NA
log_fdev[2]	NA	NA	NA	NA	NA	NA
log_foff[1]	-6.52	0.13	-5.96	0.16	-5.93	0.16
log_fdov[1]	NA	NA	NA	NA	NA	NA
rec_dev_est	NA	NA	NA	NA	NA	NA
logit_rec_prop_est	NA	NA	NA	NA	NA	NA
m_dev_est[1]	1.8	0.13	1.78	0.14	2.06	0.09
m_dev_est[2]	2.39	0.09	2.39	0.09	0	0.01
m_dev_est[3]	0	1.41	NA	NA	NA	NA
m_dev_est[4]	0.61	0.39	0.62	0.39	1.12	0.19
m_dev_est[5]	2.18	0.09	2.19	0.09	2.66	0.07
m_dev_est[6]	0	1.41	NA	NA	NA	NA
m_dev_est[7]	0.6	0.5	0.51	0.51	0.4	0.57
m_dev_est[8]	1.72	0.25	1.75	0.25	1.8	0.24
m_dev_est[9]	0	1.41	NA	NA	NA	NA
m_dev_est[10]	2.62	0.26	2.52	0.3	2.58	0.27
m_dev_est[11]	1.3	1.21	1.11	1.37	0.46	1.74
m_dev_est[12]	0	1.41	NA	NA	NA	NA
m_mat_mult[1]	0.02	0.05	0.01	0.05	0.01	0.05
m_mat_mult[2]	0.07	0.05	0.04	0.05	0.04	0.05
survey_q[1]	0.18	0.03	0.35	0.08	0.38	0.09
survey_q[2]	0.33	0.03	0.4	0.04	0.42	0.05
survey_q[3]	0.32	0.03	0.24	0.03	0.23	0.03
survey_q[4]	0.54	0.03	0.53	0.03	0.45	0.03
sd_log_recruits	NA	NA	NA	NA	NA	NA
ParsOut	NA	NA	NA	NA	NA	NA
sd_log_ssb	NA	NA	NA	NA	NA	NA
sd_last_ssb	53.6	4.45	53.86	4.47	71.97	6.07
theta[100]	NA	NA	-18.57	7110.5	1.27	1.44

Table 13: Changes in management quantities for each scenario considered. Reported management quantities are derived from maximum likelihood estimates. Reported natural mortality is for mature males, average recruitment is for males, and status and MMB were estimates for February 15 of the completed crab year.

	Model	MMB	B35	F35	FOFL	OFL	M	avg_rec	Status
1	21.sq	26.74	153.42	1.43	0.37	7.50	0.27	106.14	0.17
3	21.g	23.71	153.33	1.59	0.36	7.89	0.28	131.71	0.15
4	22.1	39.85	189.12	1.37	0.28	9.06	0.28	161.82	0.21
5	22.1a	41.21	183.15	1.50	0.32	10.32	0.28	164.02	0.23
6	22.1ab	96.67	196.38	2.26	0.67	3.98	0.29	180.36	0.49

Table 14: 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
1983	14.67
1984	13.62
1985	14.93
1986	42.43
1987	39.56
1988	32.5
1989	25.26
1990	20.48
1991	19.51
1992	21.85
1993	21.34
1994	20.55
1995	16.16
1996	12.28
1997	9.312
1998	9.069
1999	10.67
2000	8.891
2001	7.125
2002	7.38
2003	7.788
2004	15.94
2005	13.58
2006	10.44
2007	7.992
2008	7.394
2009	20.04
2010	17.08
2011	14.2
2012	13.27
2013	11.02
2014	8.631
2015	11.48
2016	40.69
2017	43.03
2018	33.91
2019	13.61
2020	3.55
2021	2.725
2022	2.069

Table 15: Maximum likelihood estimates of predicted mature male biomass at mating, male recruitment (millions) from the chosen model, and estimated fully-selected total fishing mortality.

Survey year	Mature male biomass	Male recruits	Fishing mortality
1982	572.4	3.57	0.08
1983	549.2	2.39	0.08
1984	532	3.38	0.17
1985	485.4	5.9	0.27
1986	440.5	0.72	0.32
1987	423.3	2.35	0.47
1988	460.5	0.24	0.47
1989	511.9	0.71	0.45
1990	490.4	3.13	0.9
1991	442.5	5.24	0.92
1992	352.4	2.04	1.06
1993	306	0.32	0.78
1994	301.2	0.1	0.54
1995	348.8	0.13	0.44
1996	422.9	0.14	0.45
1997	426	2.2	0.6
1998	354.6	0.16	0.58
1999	300.1	0.38	0.12
2000	239.8	0.33	0.14
2001	195.5	2	0.28
2002	188.8	2.15	0.23
2003	198.8	1.46	0.14
2004	191.6	1.32	0.15
2005	182.7	0.19	0.29
2006	207.3	0.09	0.28
2007	248.2	0.52	0.34
2008	280.7	1.32	0.25
2009	284.3	0.18	0.17
2010	255.6	0.42	0.18
2011	189.1	0.5	0.47
2012	143.8	0.97	0.62
2013	126.8	0.22	0.69
2014	109.8	3.34	0.97
2015	98.4	23.21	0.79
2016	104.2	0.59	0.41
2017	157.2	0.16	0.33
2018	75.61	0.04	1.41
2019	190.7	0	0.78
2020	124.9	0.02	2.38
2021	96.67	0	0.49

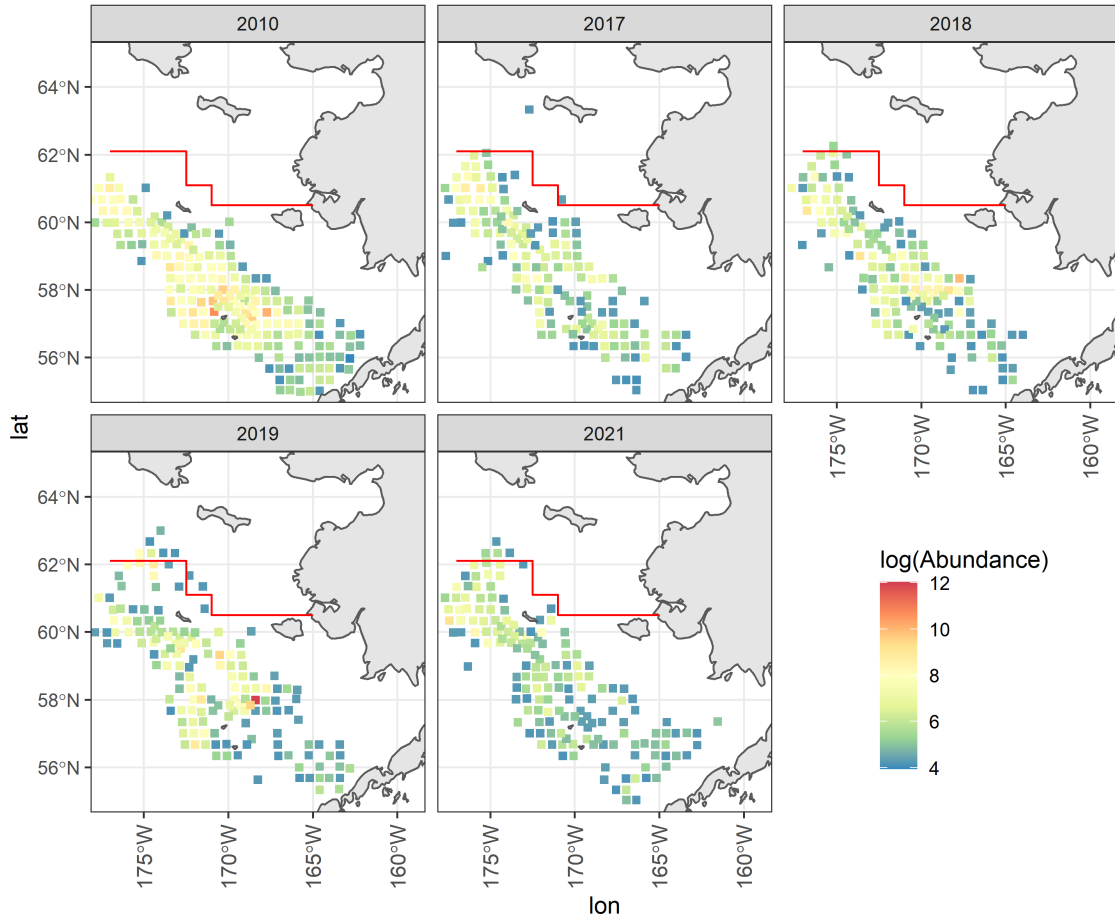


Figure 1: Abundances (in log space) of male crab with carapaced wider than 101 mm from years in which the northern Bering Sea was surveyed. The red line represents the border between the northern and eastern Bering Sea survey grids. Colored squares are survey tows in which large males were captured.

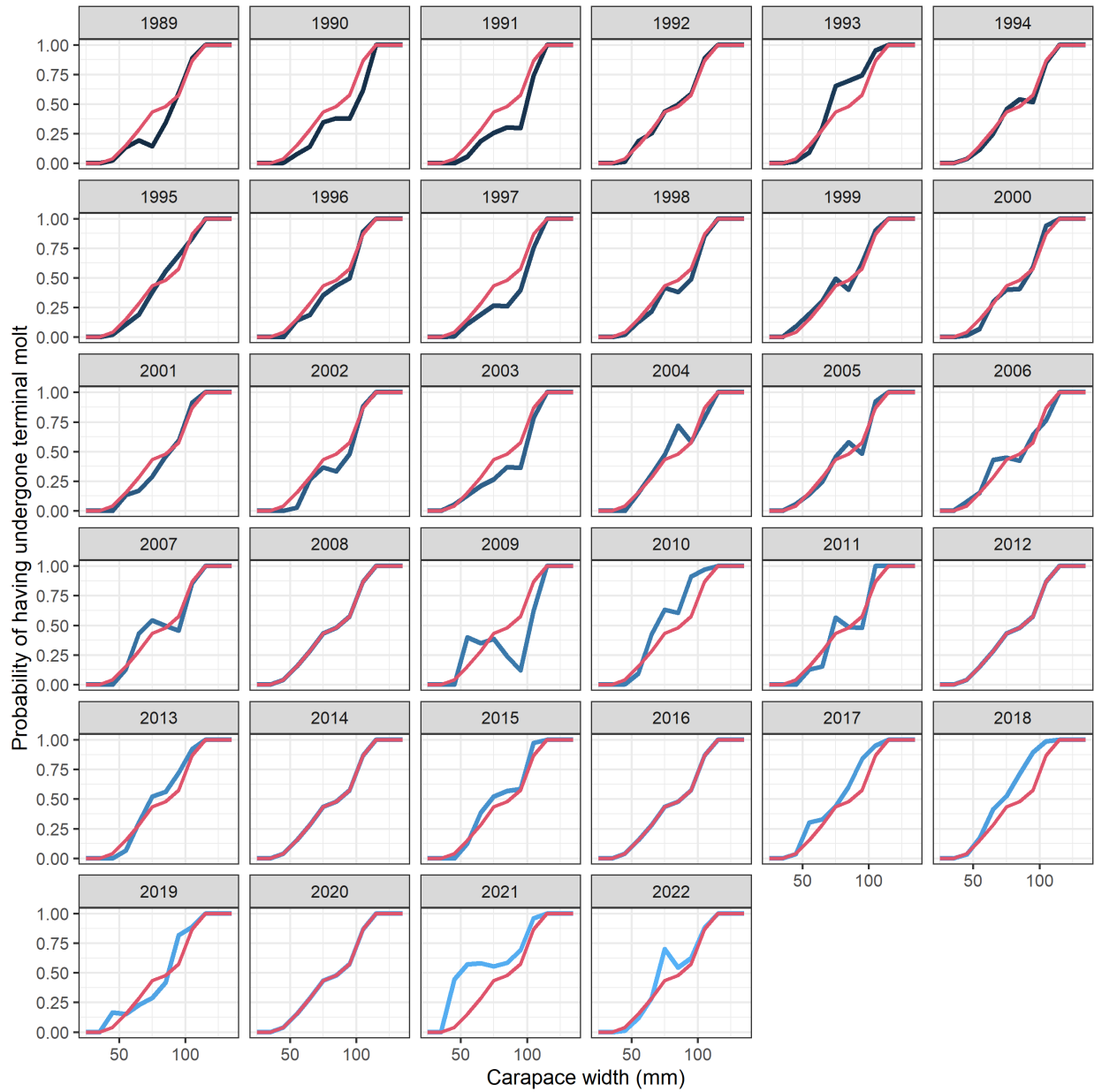


Figure 2: Observed probability of having undergone terminal molt for new shell male crab. Blue lines are the yearly data and red lines are the averages over all years.

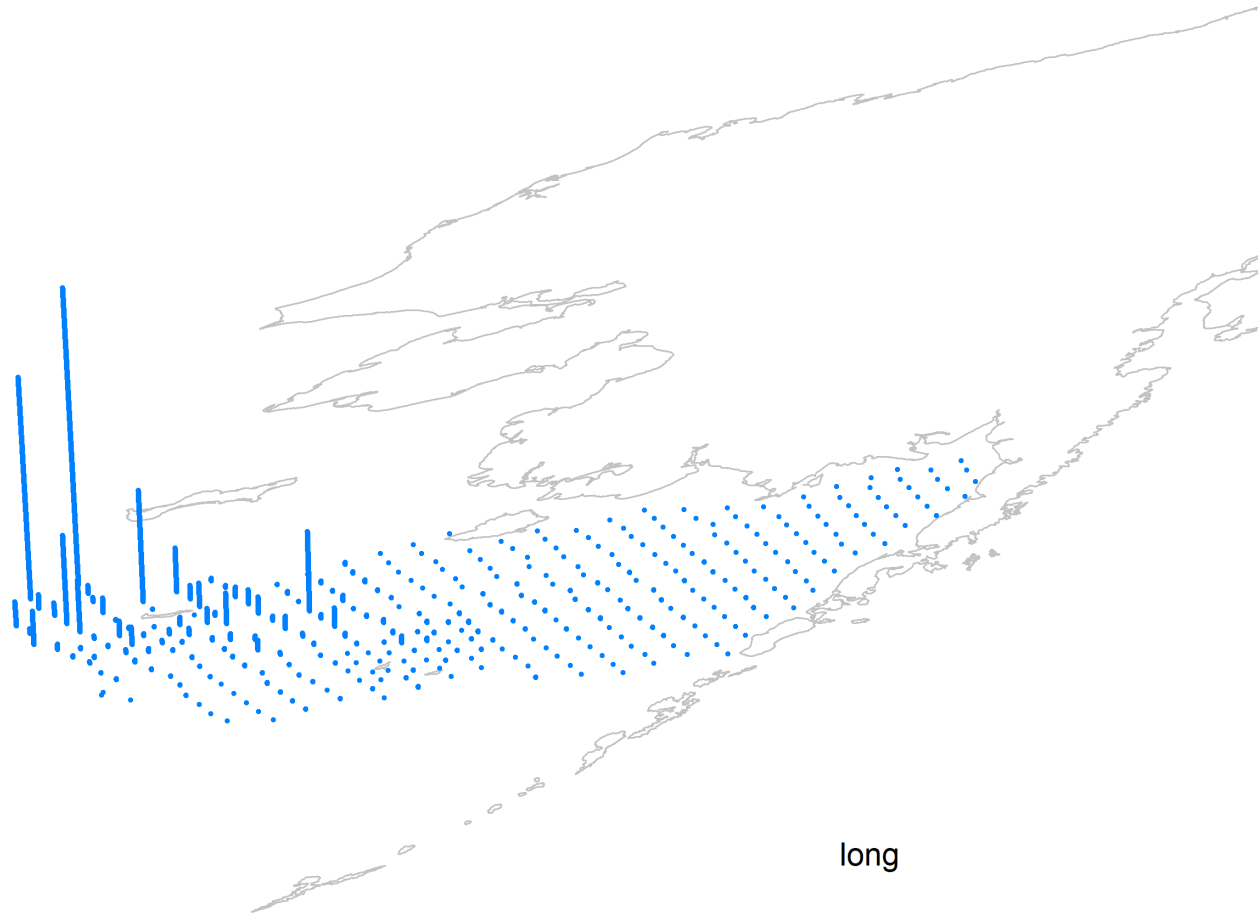


Figure 3: Observed relative density of all males at the time of the 2022 NMFS summer survey

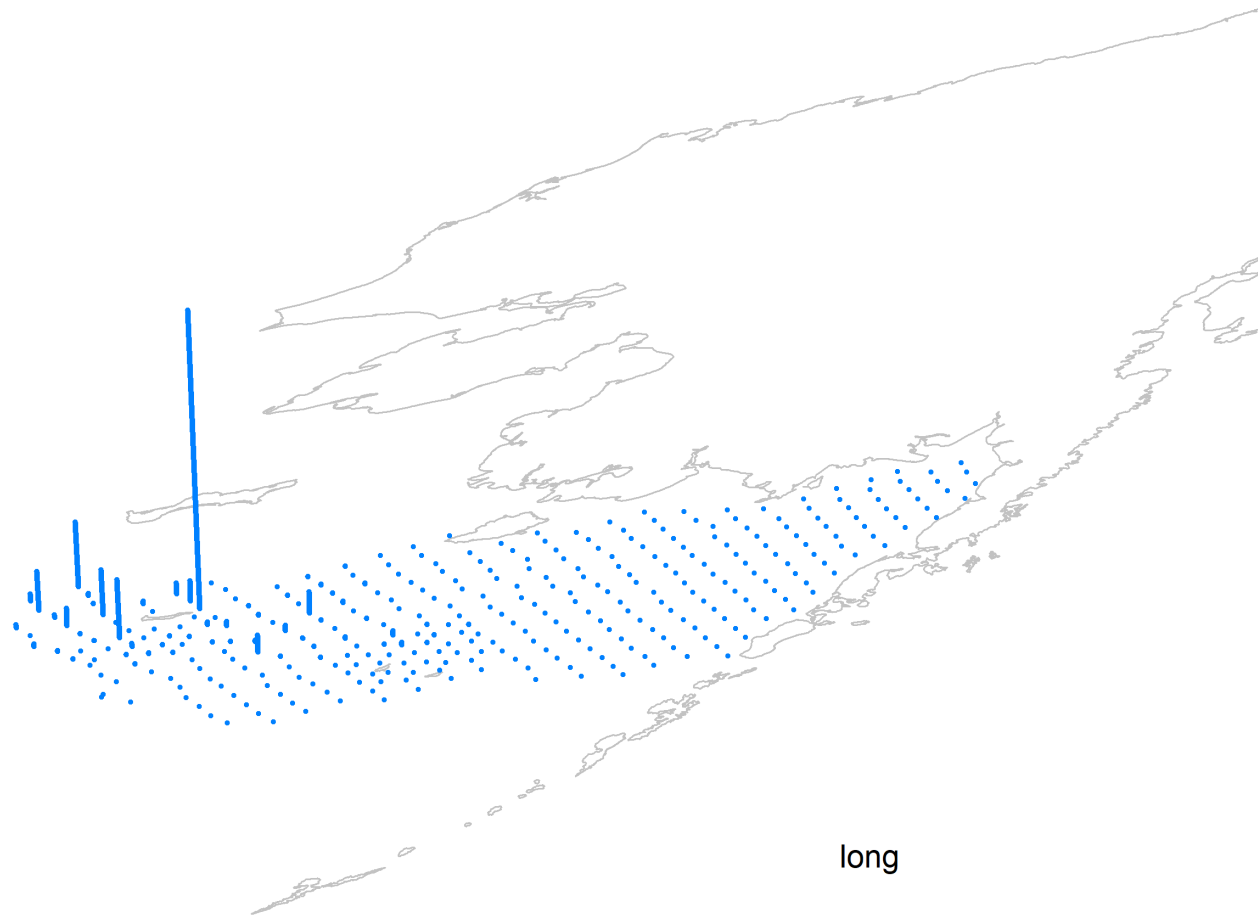


Figure 4: Observed relative density of all females at the time of the 2022 NMFS summer survey



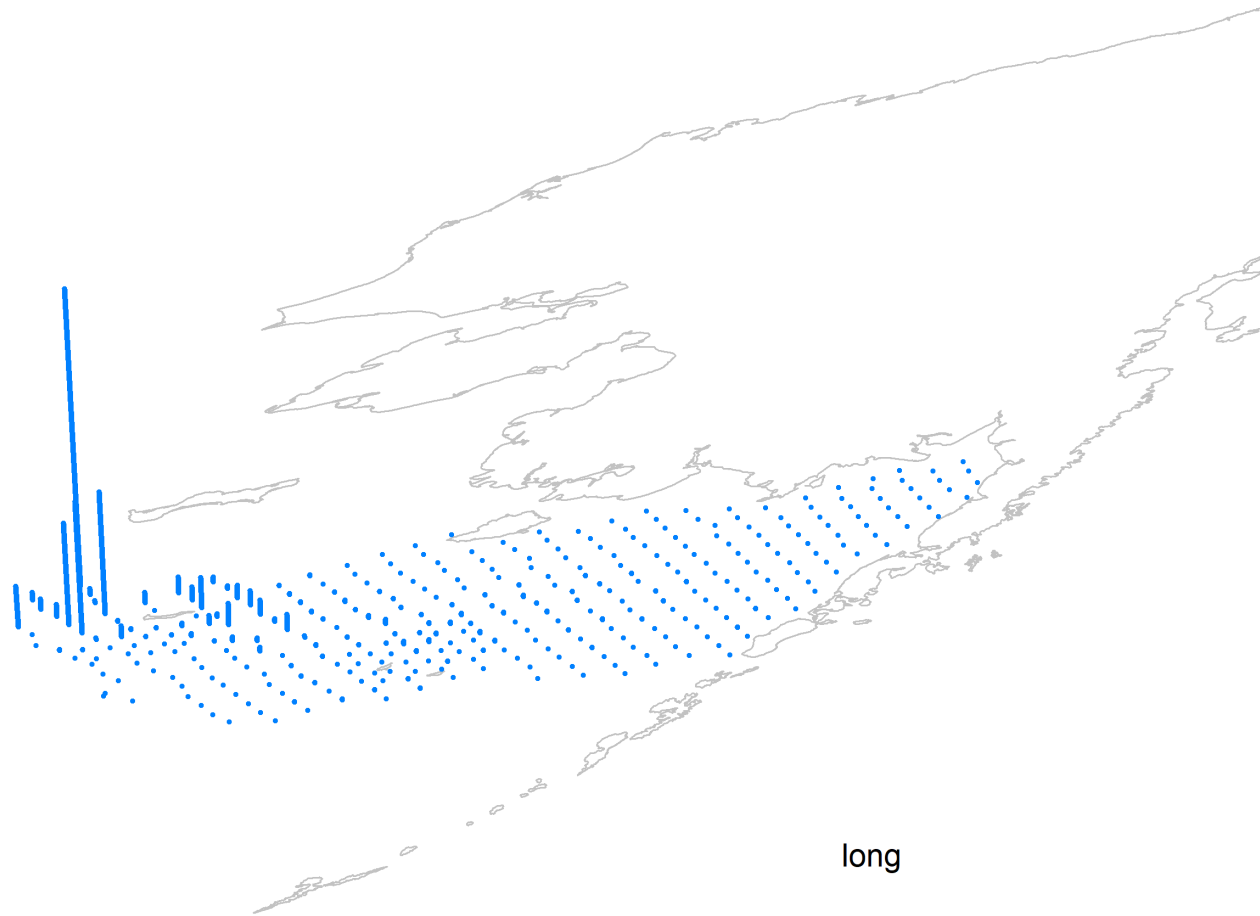
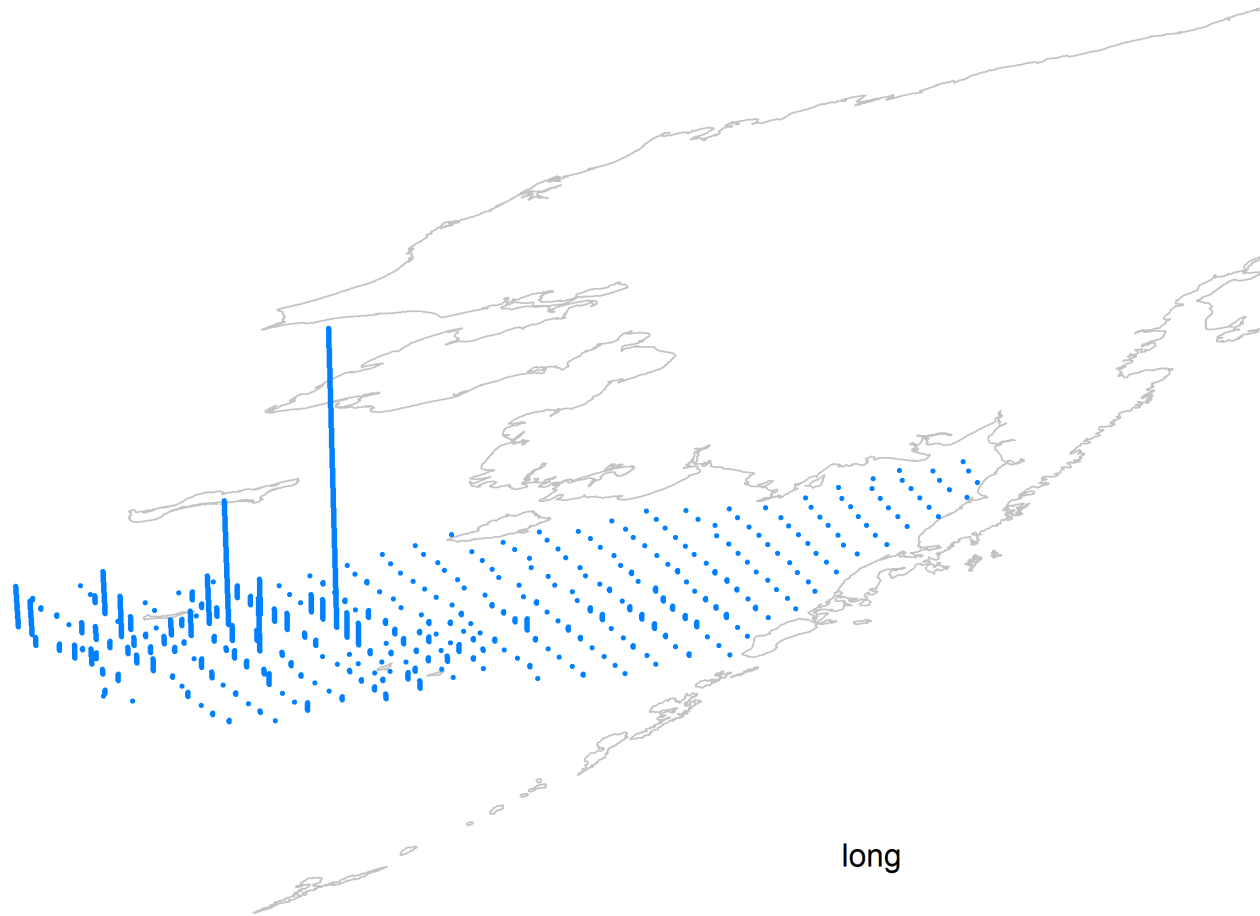


Figure 5: Observed relative density of males <70 mm carapace width at the time of the 2022 NMFS summer survey



long

Figure 6: Observed relative density of males greater than 101 mm carapace width at the time of the 2022 NMFS summer survey

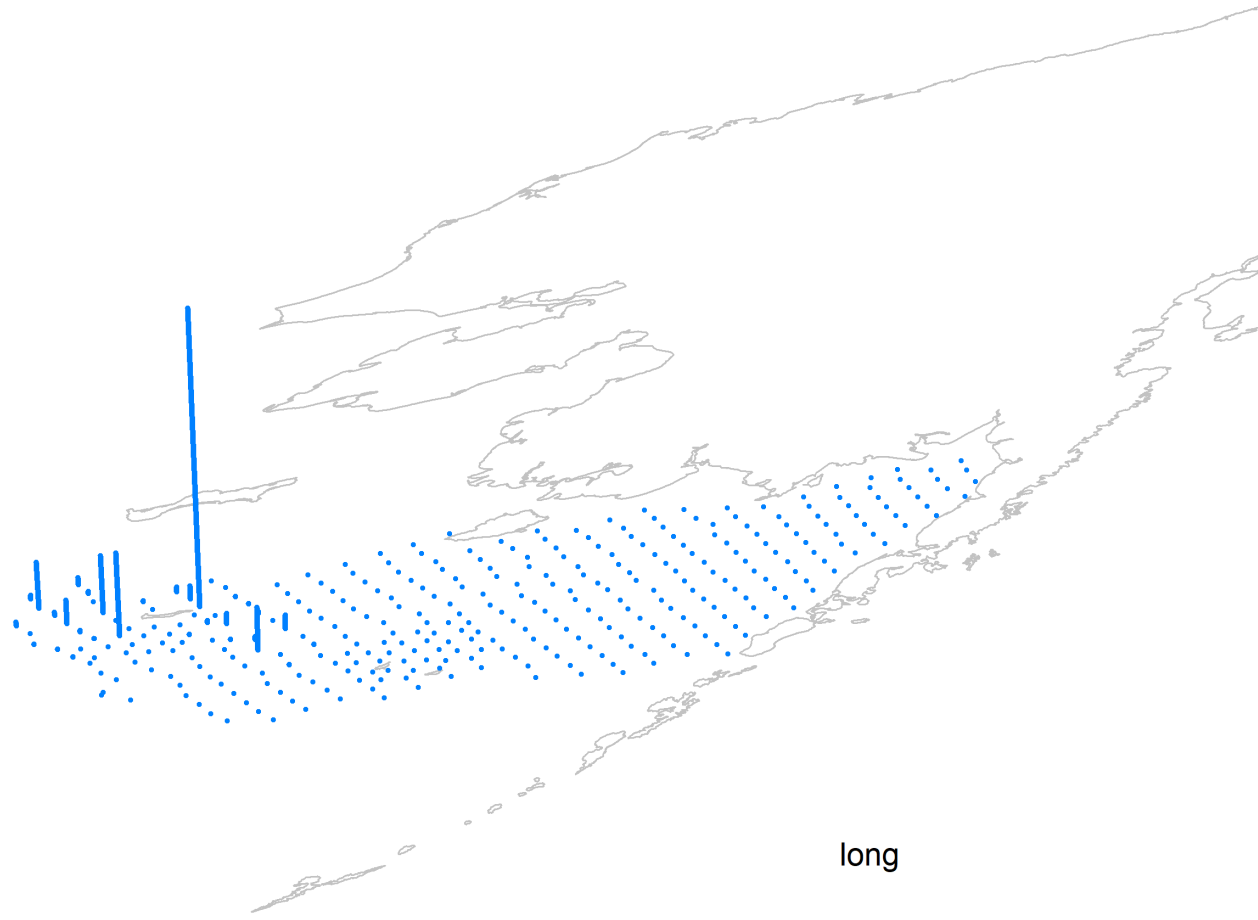


Figure 7: Observed relative density of mature females at the time of the 2022 NMFS summer survey

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 8: 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.

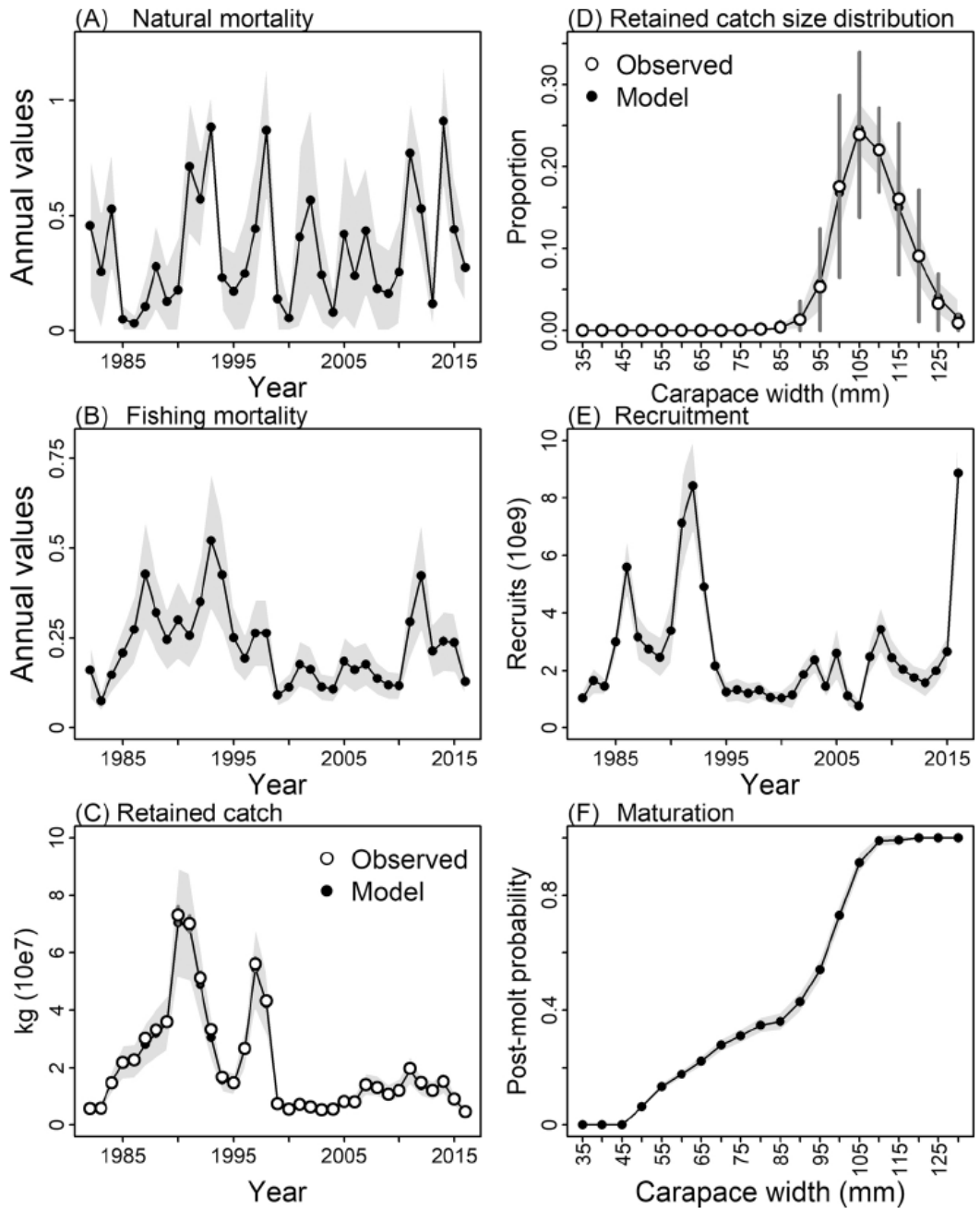


Figure 9: Estimated time-variation in natural mortality and other model output from Murphy et al. 2018.

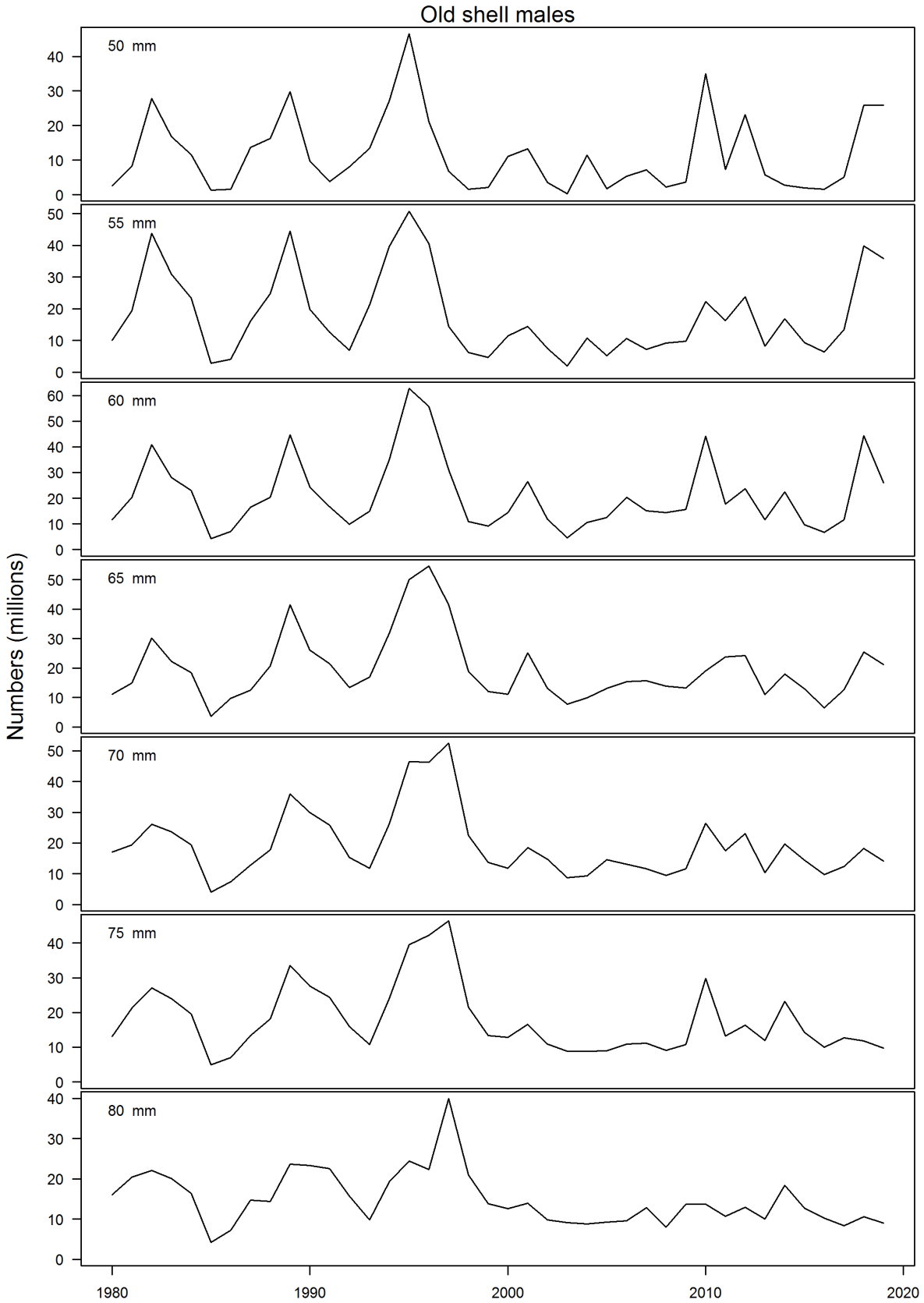


Figure 10: Observed numbers at length of old shell mature males by size class. The presented size bins are not vulnerable to the fishery, so all mortality is 'natural'. The decline in numbers in a size class after the recruitment collapse in the early 1990s demonstrates expected natural mortality for mature male individuals.

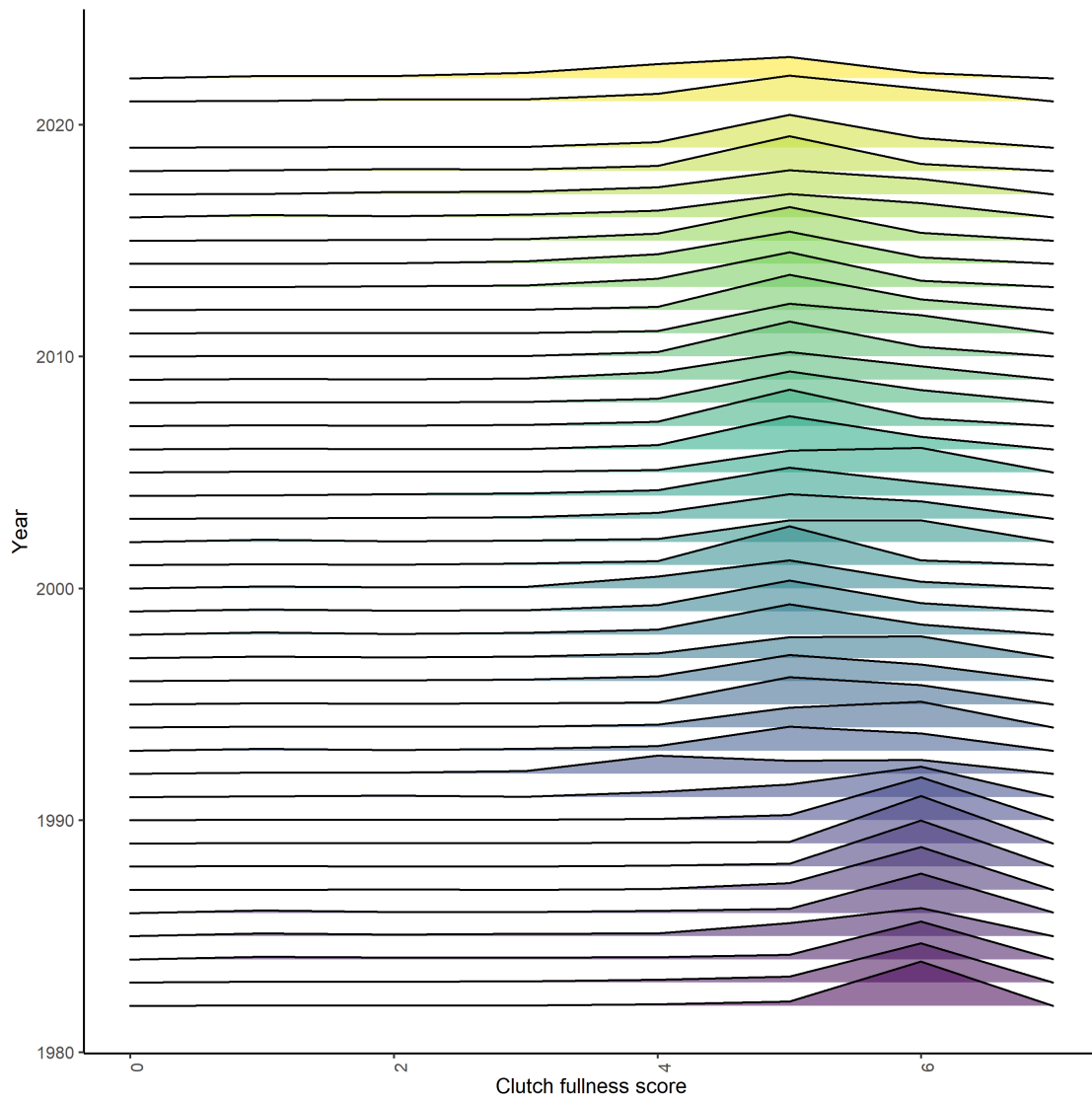


Figure 11: Clutch fullness scores from the 1982-2021 NMFS summer survey. Scores: 0 = immature, 1 = mature no eggs, 2 = trace to 0.125, 3 = 0.25, 4 = 0.5, 5 = 0.75, 6 = full of eggs; 7 = overflowing.

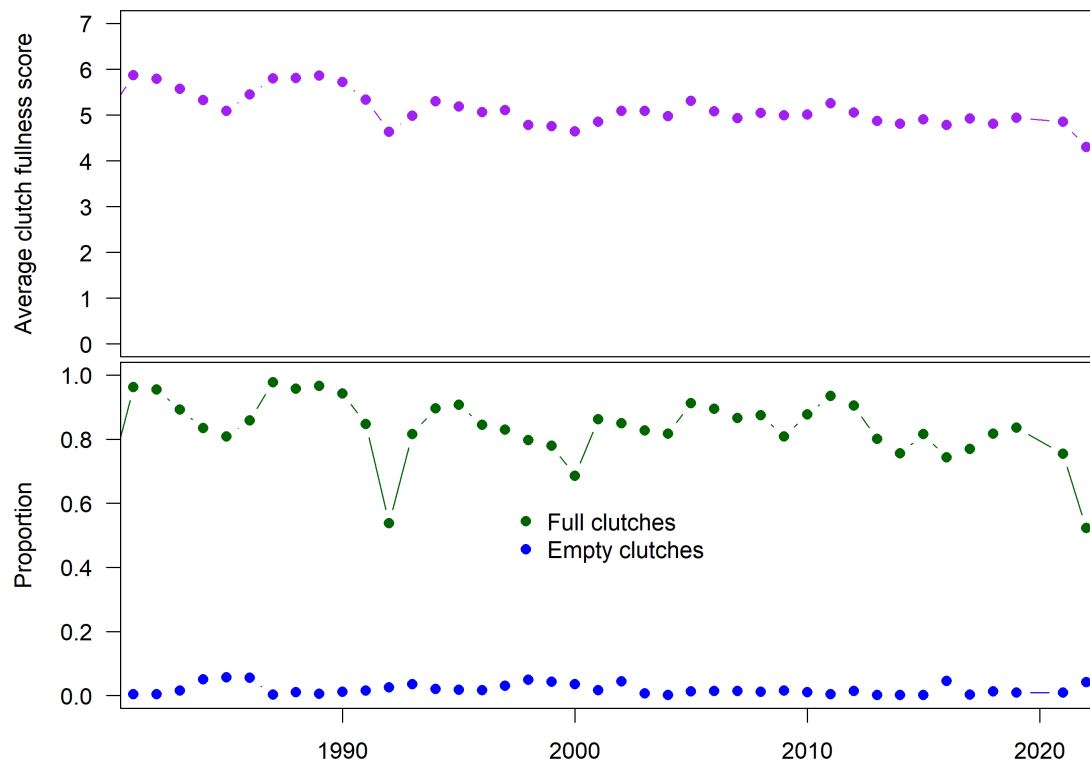


Figure 12: Time series of the average clutch fullness score (top) and the proportion of observed crab with full clutches (green) and empty clutches (blue) in the NMFS summer survey (bottom). Scores: 0 = immature, 1 = mature no eggs, 2 = trace to 0.125, 3 = 0.25, 4 = 0.5, 5 = 0.75, 6 = full of eggs; 7 = overflowing..



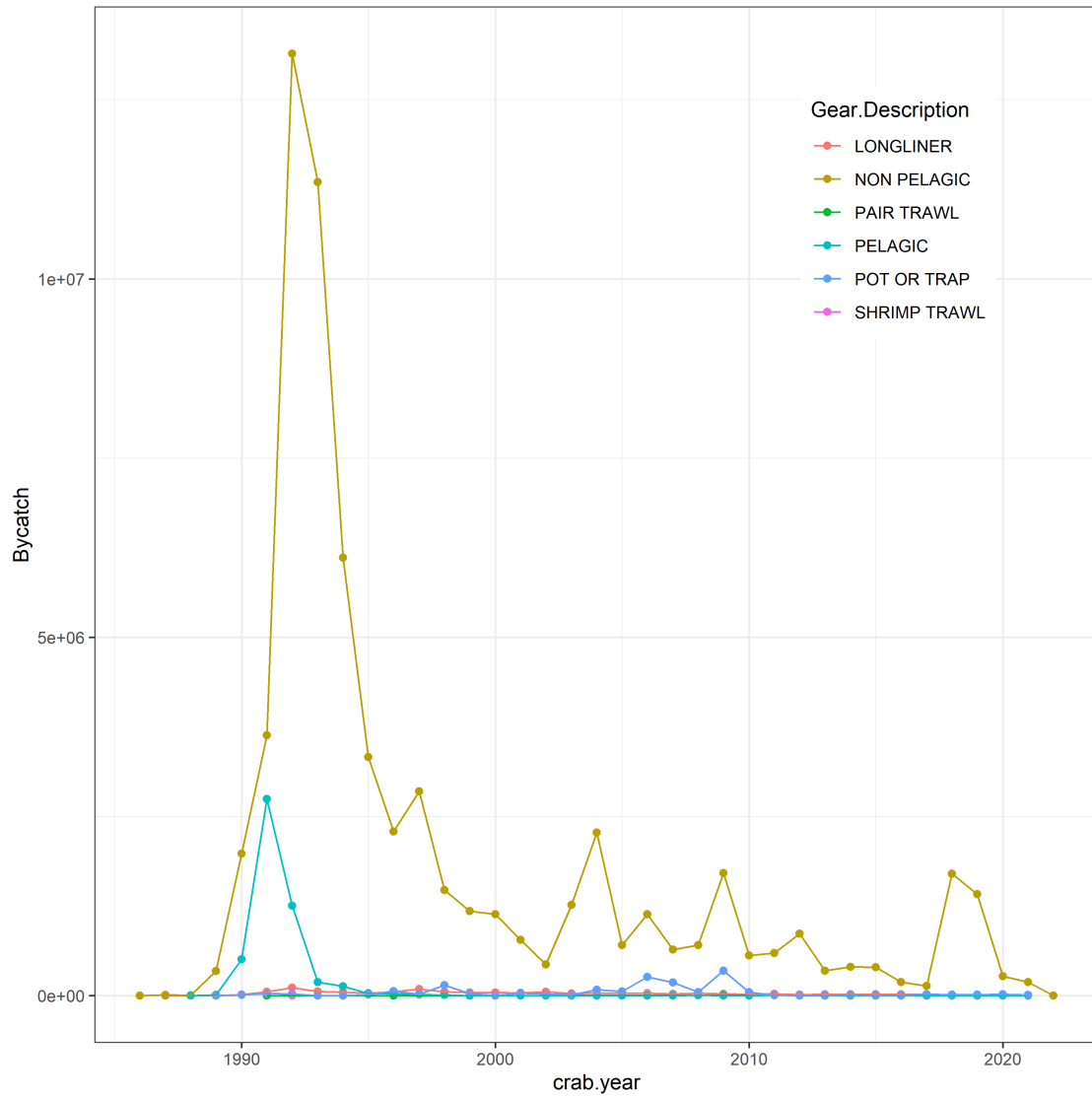


Figure 13: Time series of bycatch by gear in numbers of crab.

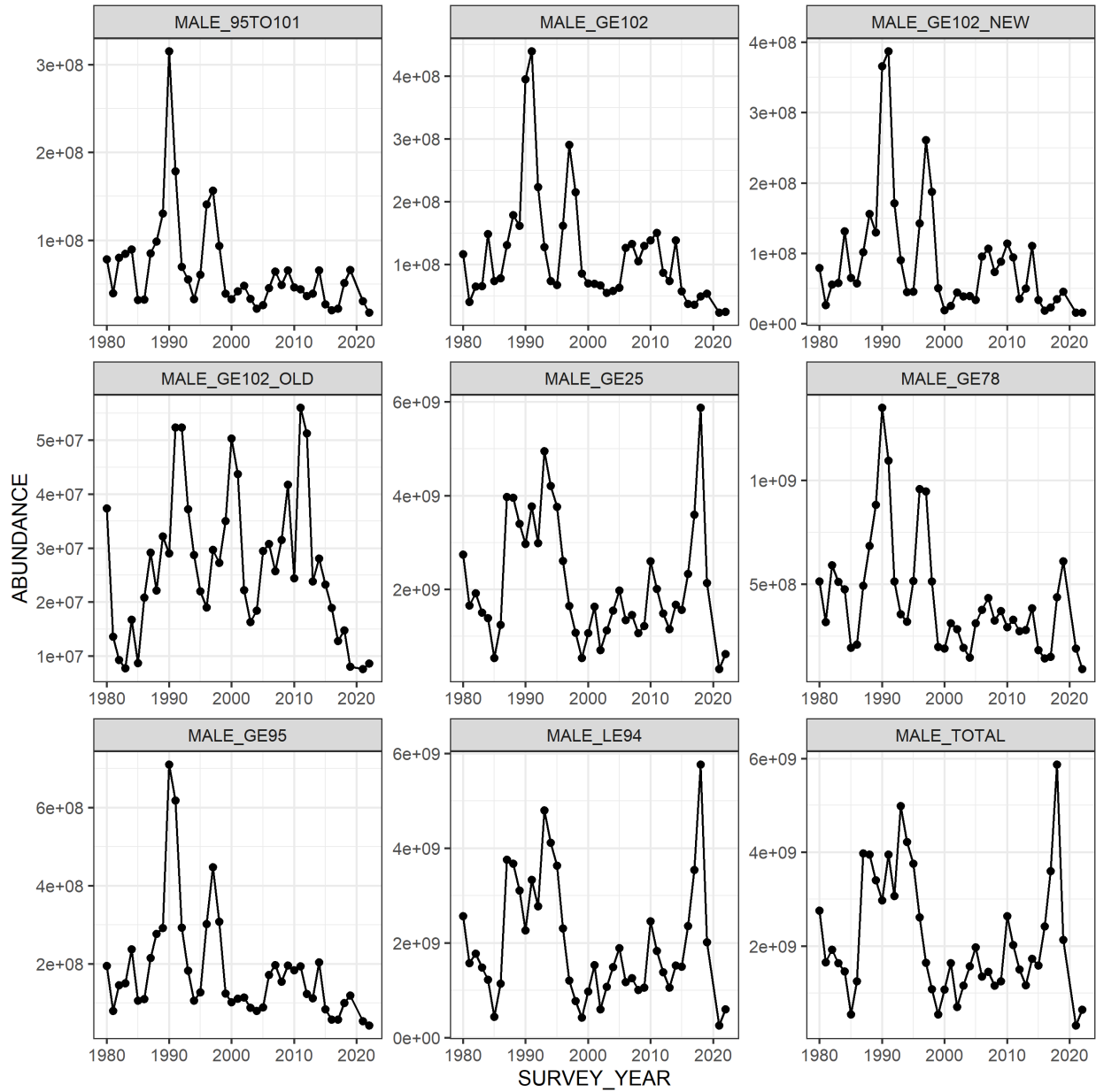


Figure 14: Abundance of males estimated from the NMFS summer survey over time for different size classes. GE102 means greater than or equal to 102 mm carapace width.

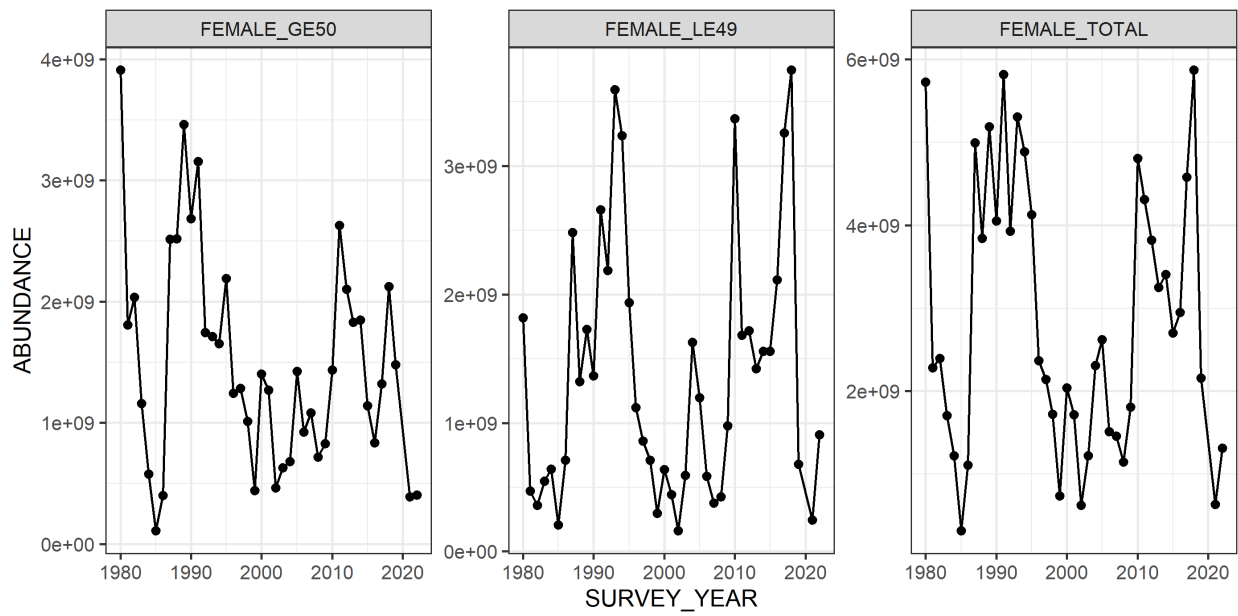


Figure 15: Abundance of females estimated from the NMFS summer survey over time for different size classes. GE50 means greater than or equal to 50 mm carapace width.

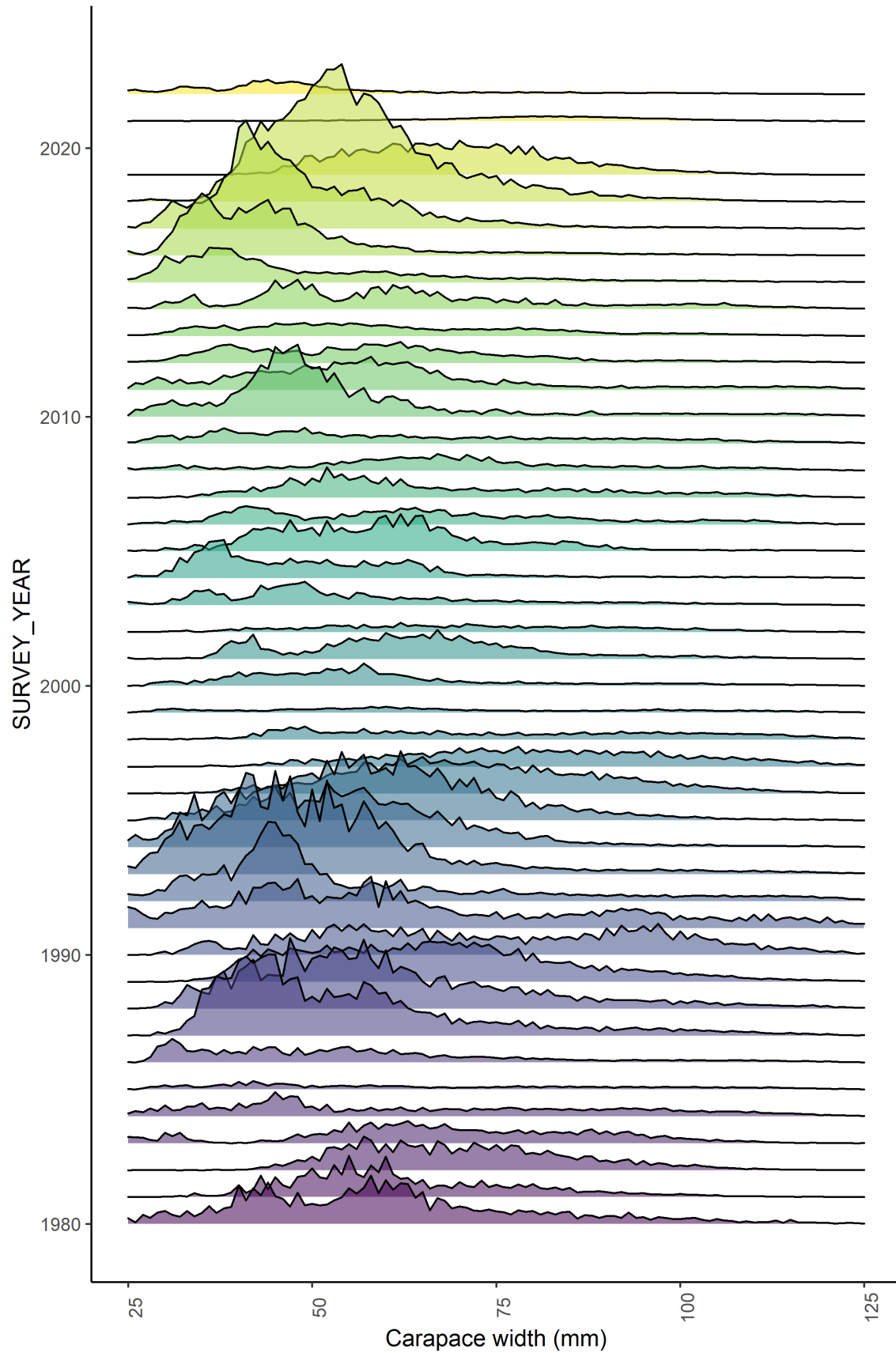


Figure 16: Raw total numbers at size of male crab observed in the survey.

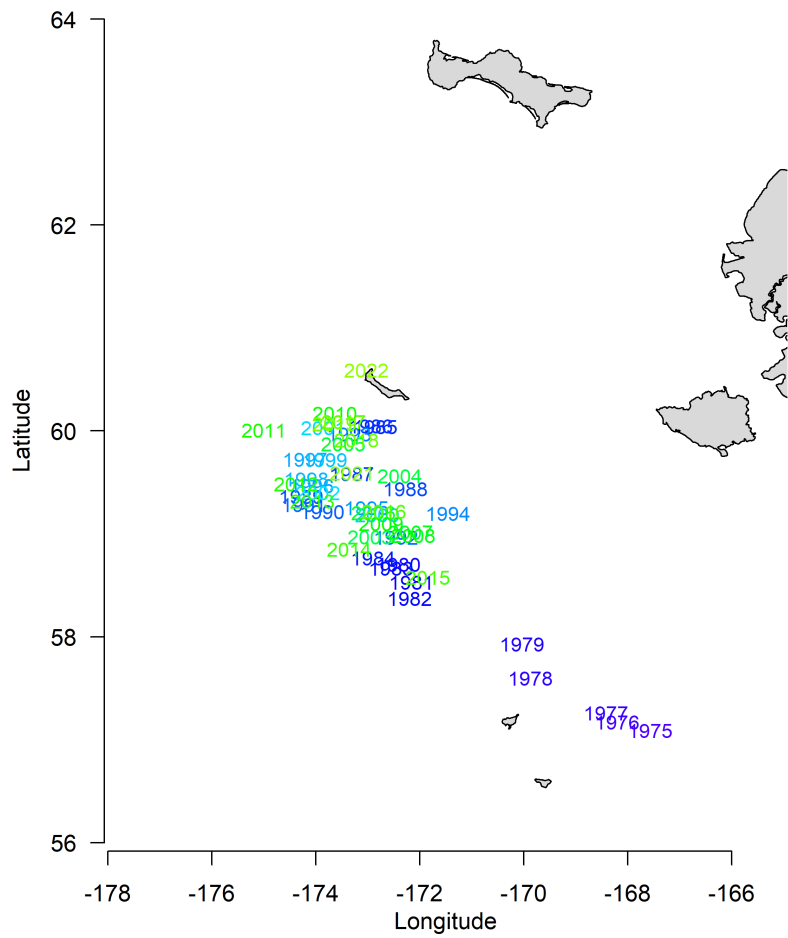


Figure 17: Centroids of abundance for mature females over time.

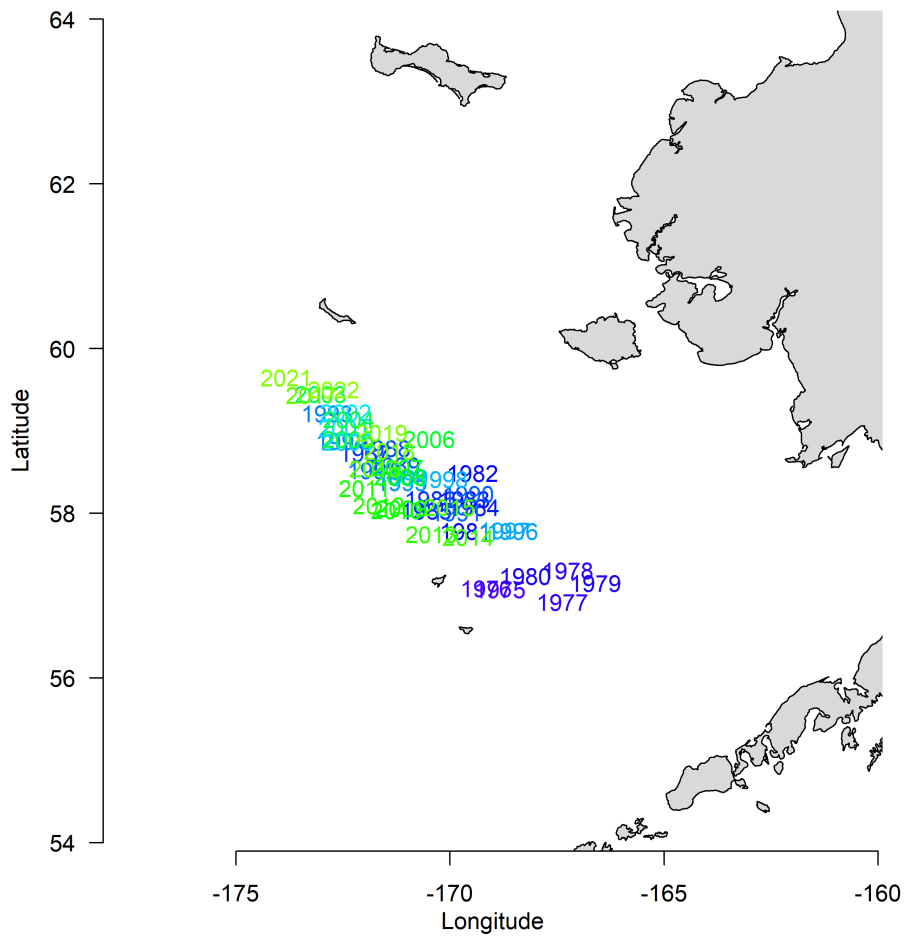


Figure 18: Centroids of abundance for males greater than 101 mm carapace width.

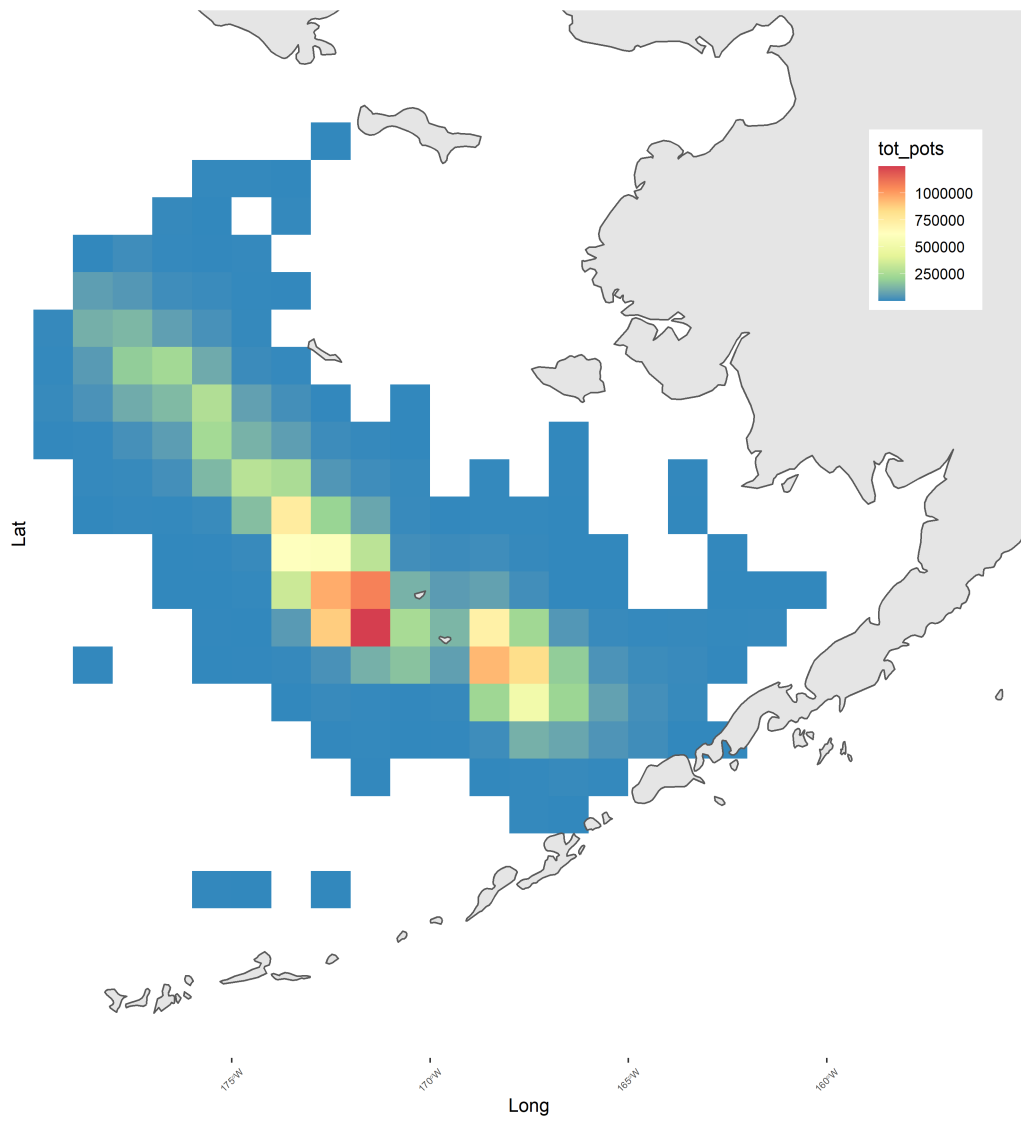


Figure 19: Heatmap of effort in terms of potlifts summed over time.

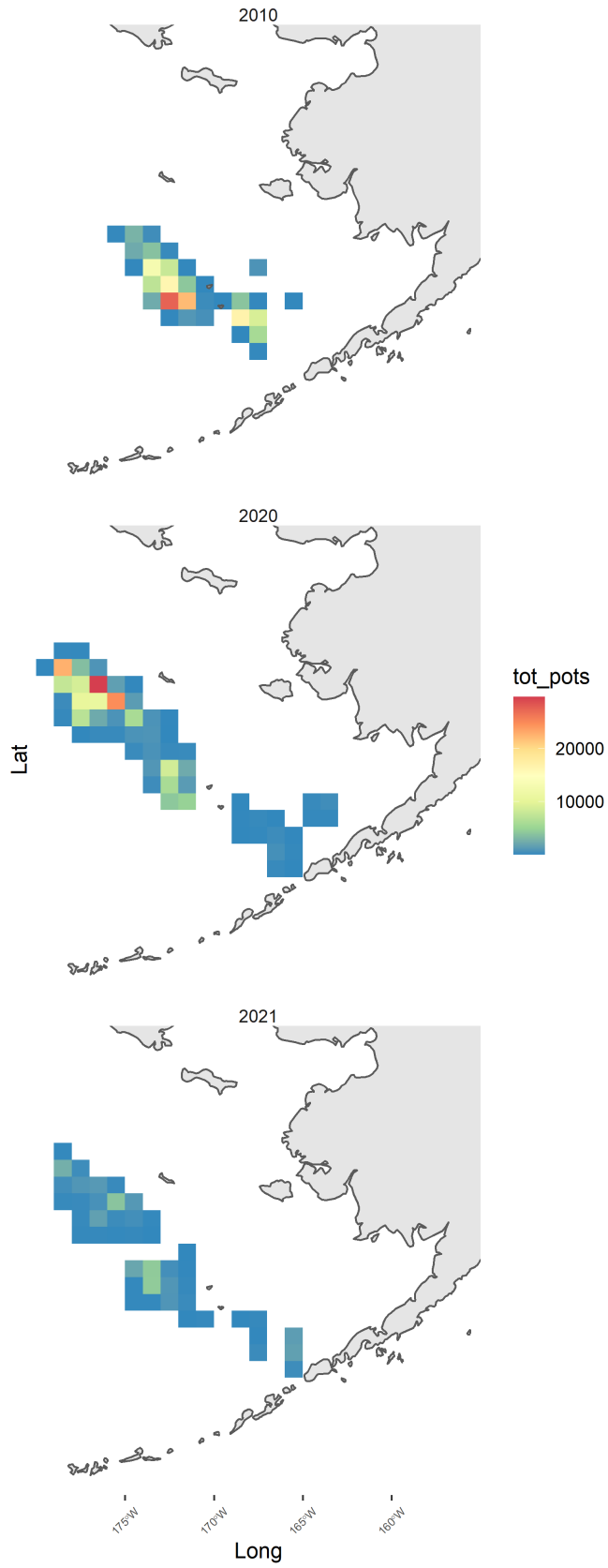


Figure 20: Spatial distribution of effort in selected years.



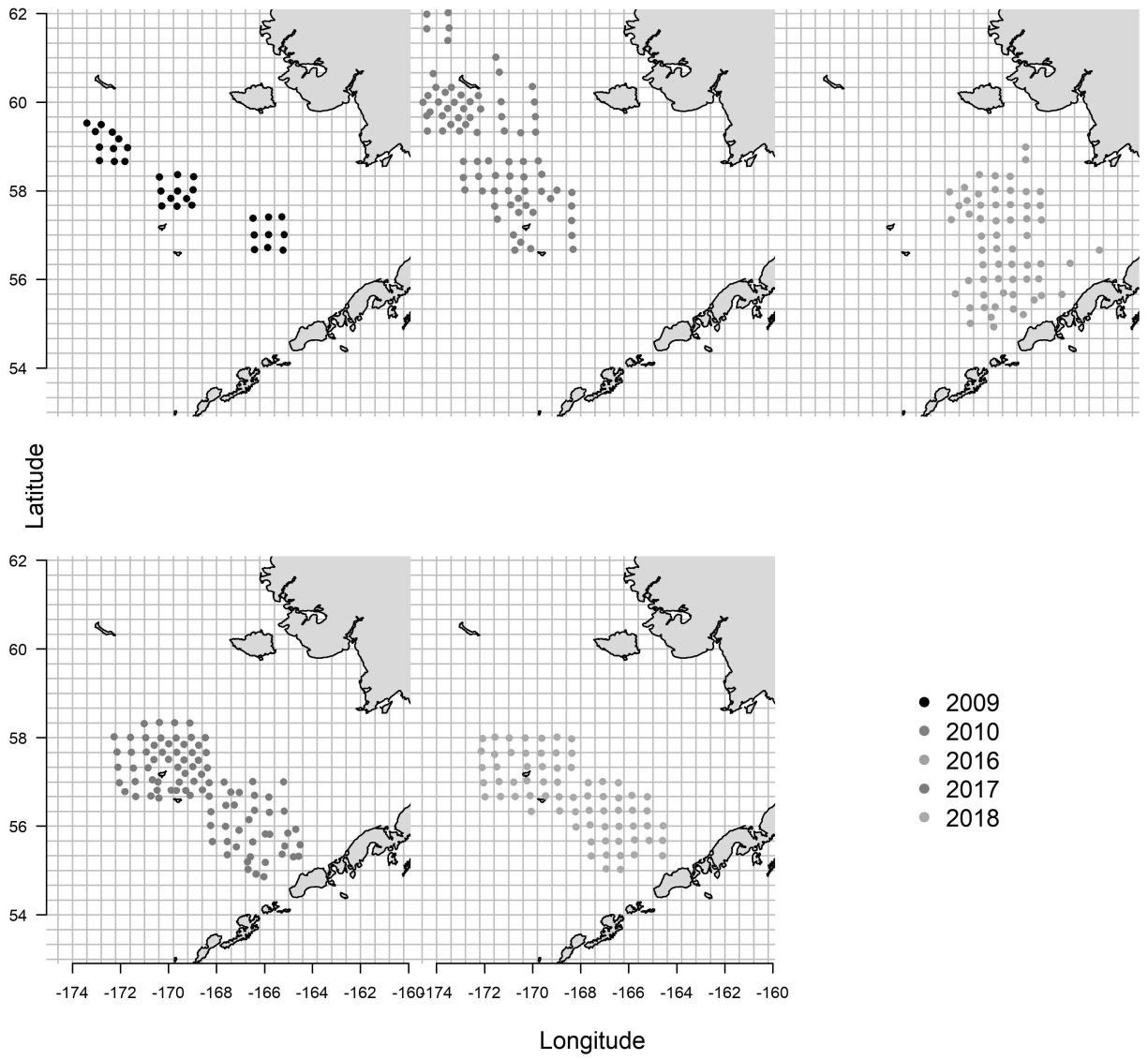


Figure 21: Location of BSFRF survey selectivity experiments.

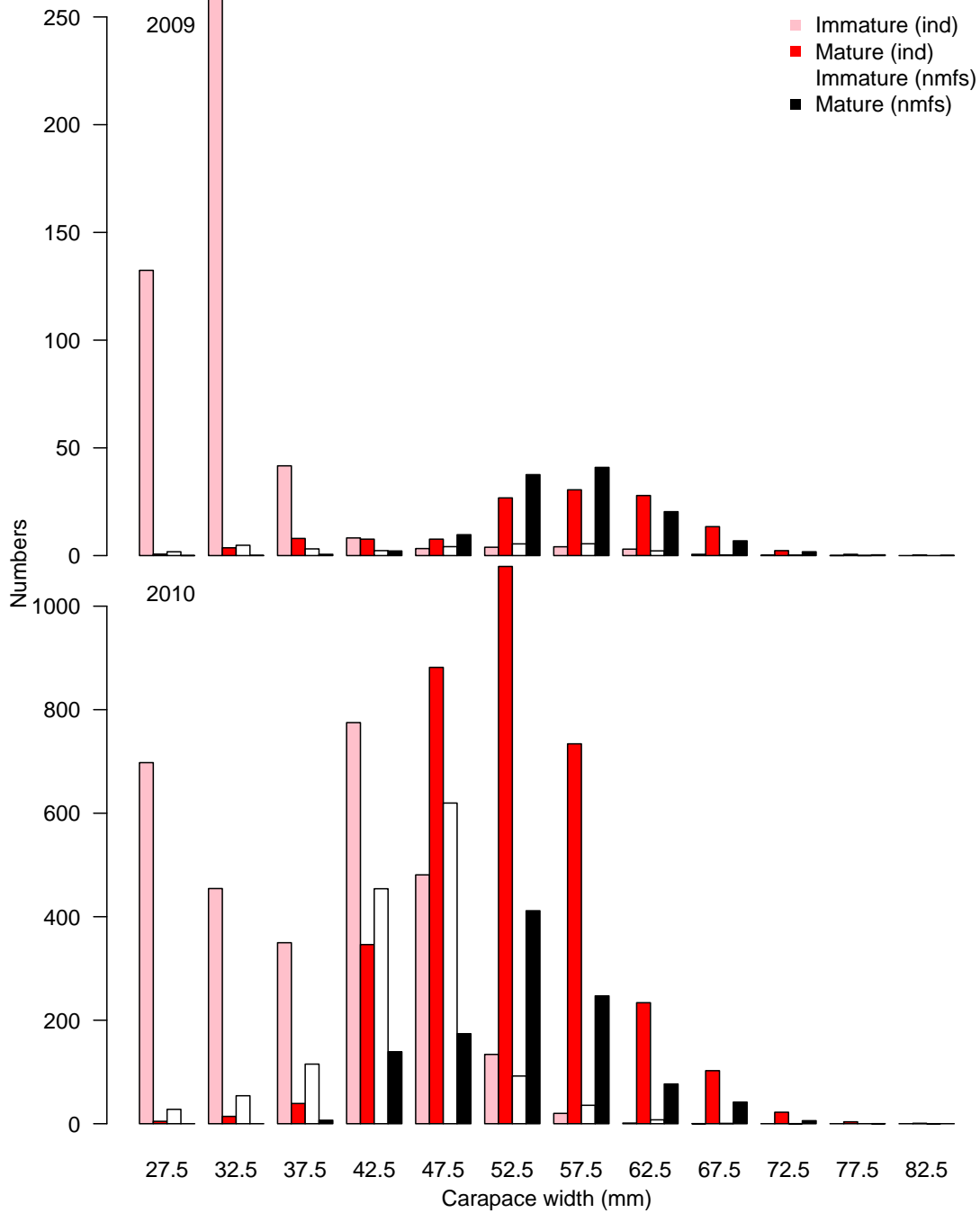


Figure 22: Raw female numbers from BSFRF survey selectivity experiments (2009 & 2010). Note a change in scale on the y-axis from 2009 to 2010

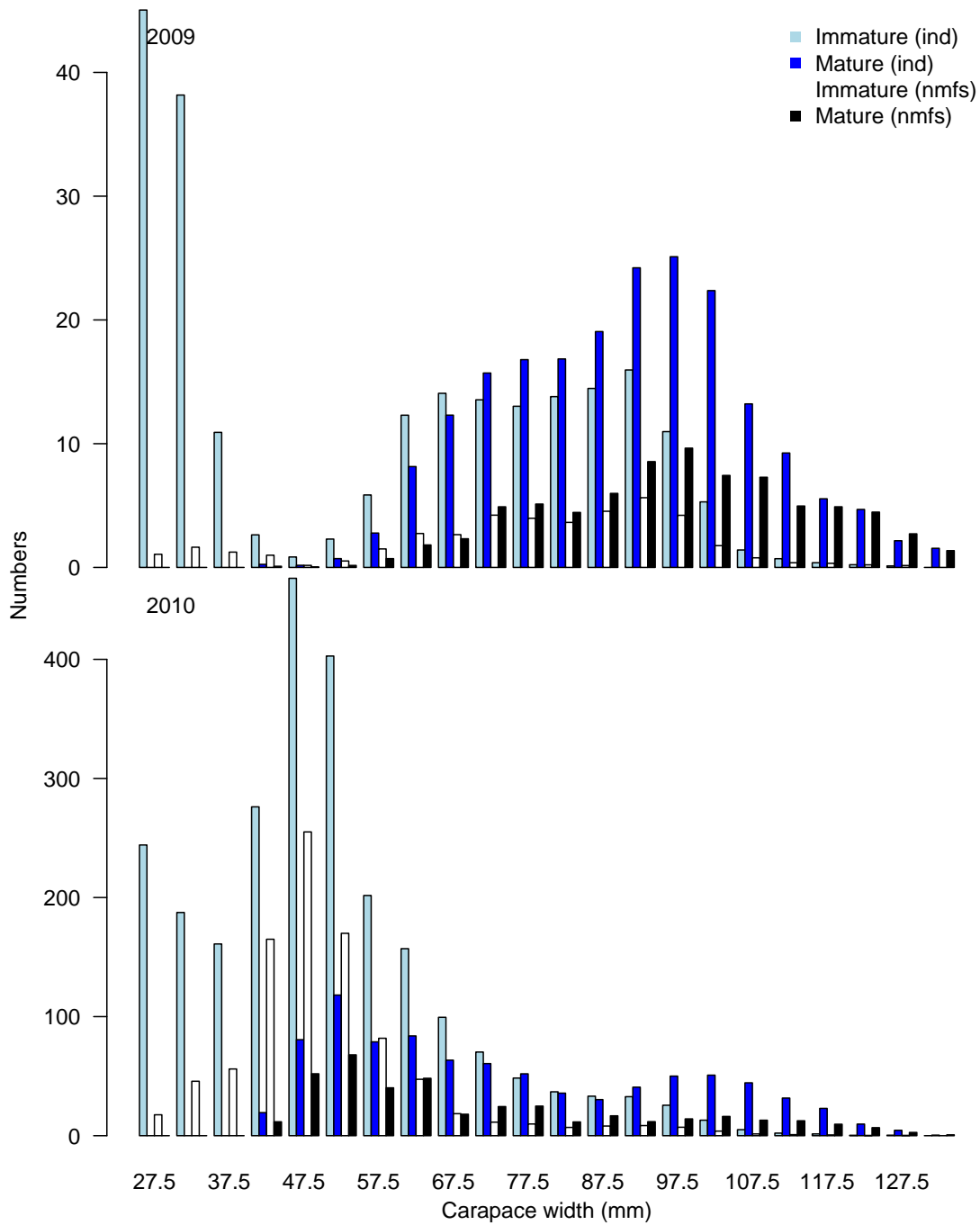


Figure 23: Raw male numbers from BSFRF survey selectivity experiments (2009 & 2010). Note a change in scale from 2009 to 2010 on the y-axis.

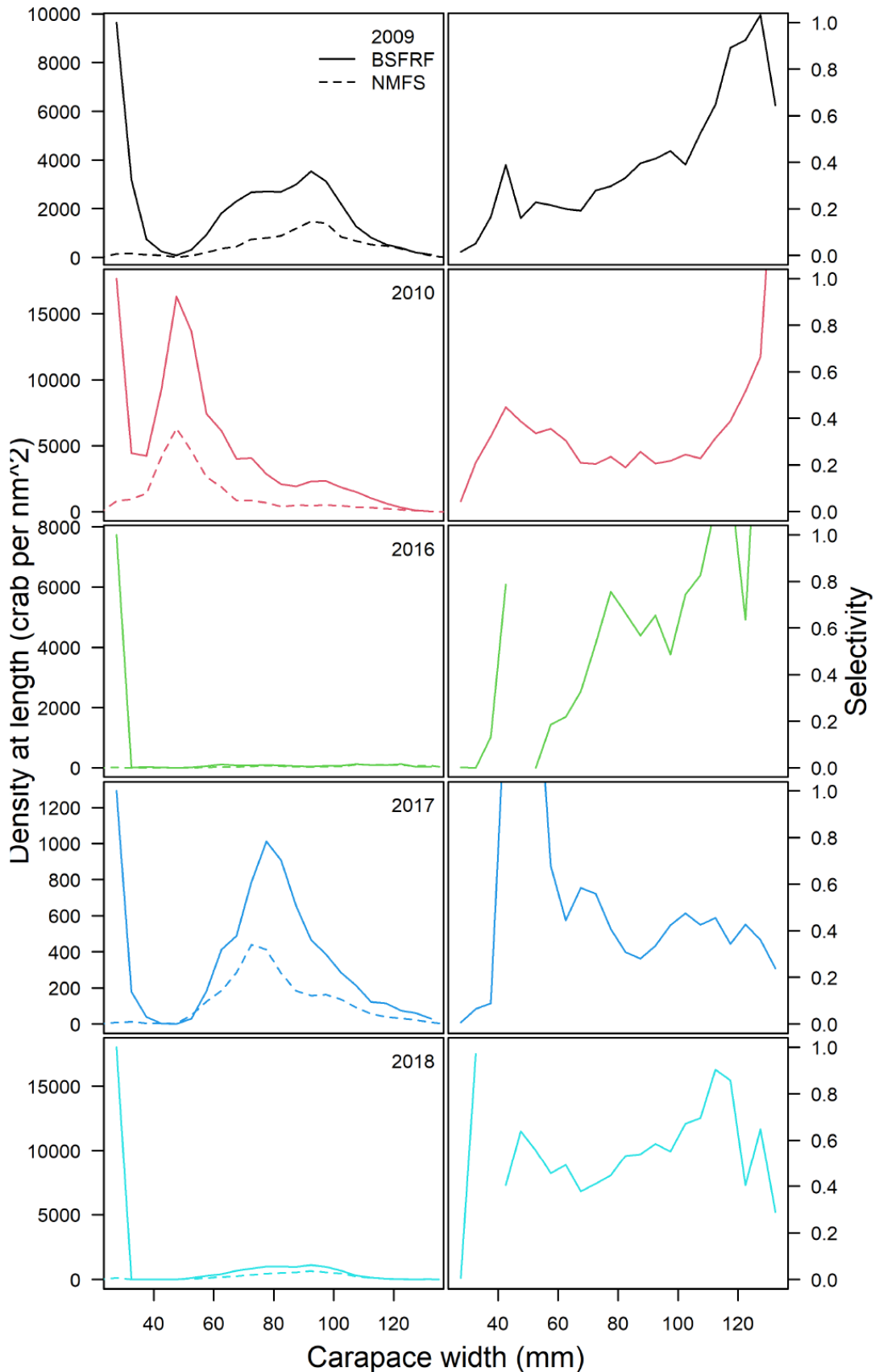


Figure 24: Observed numbers at length extrapolated from length composition data and estimates of total numbers within the survey selectivity experimental areas by year (left). Inferred selectivity (i.e. the ratio of crab at length in the NMFS gear to crab at length in the BSFRF gear).

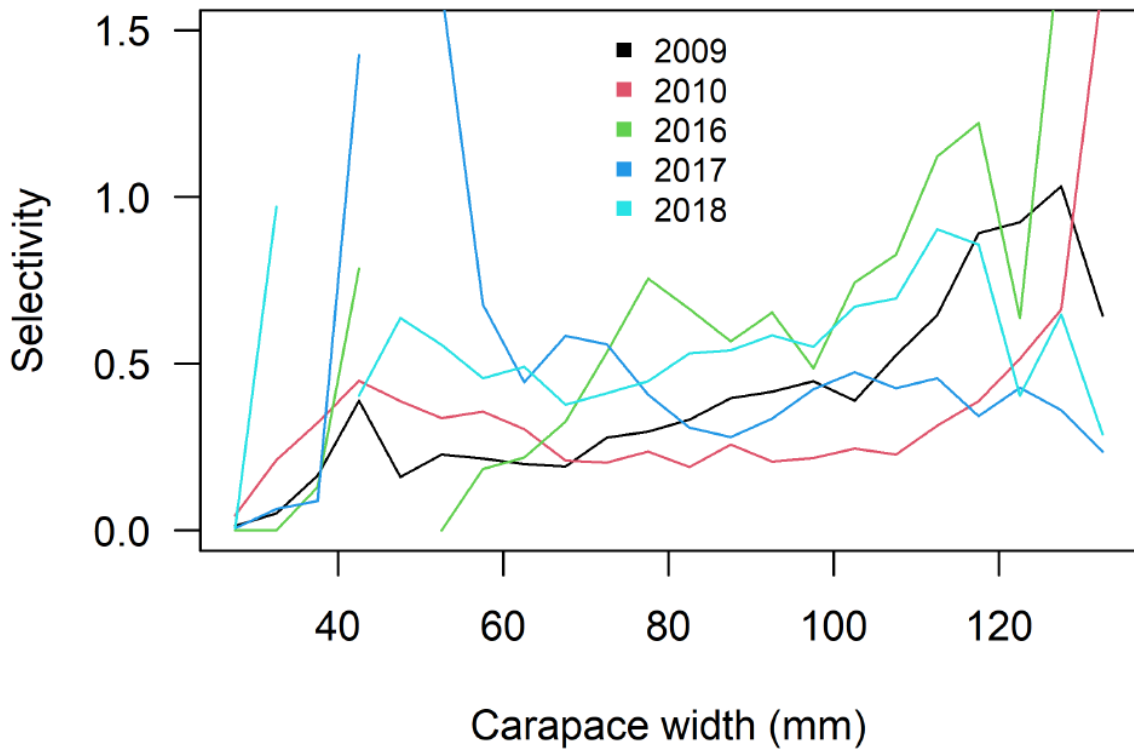


Figure 25: Inferred selectivity for all available years of BSFRF data.

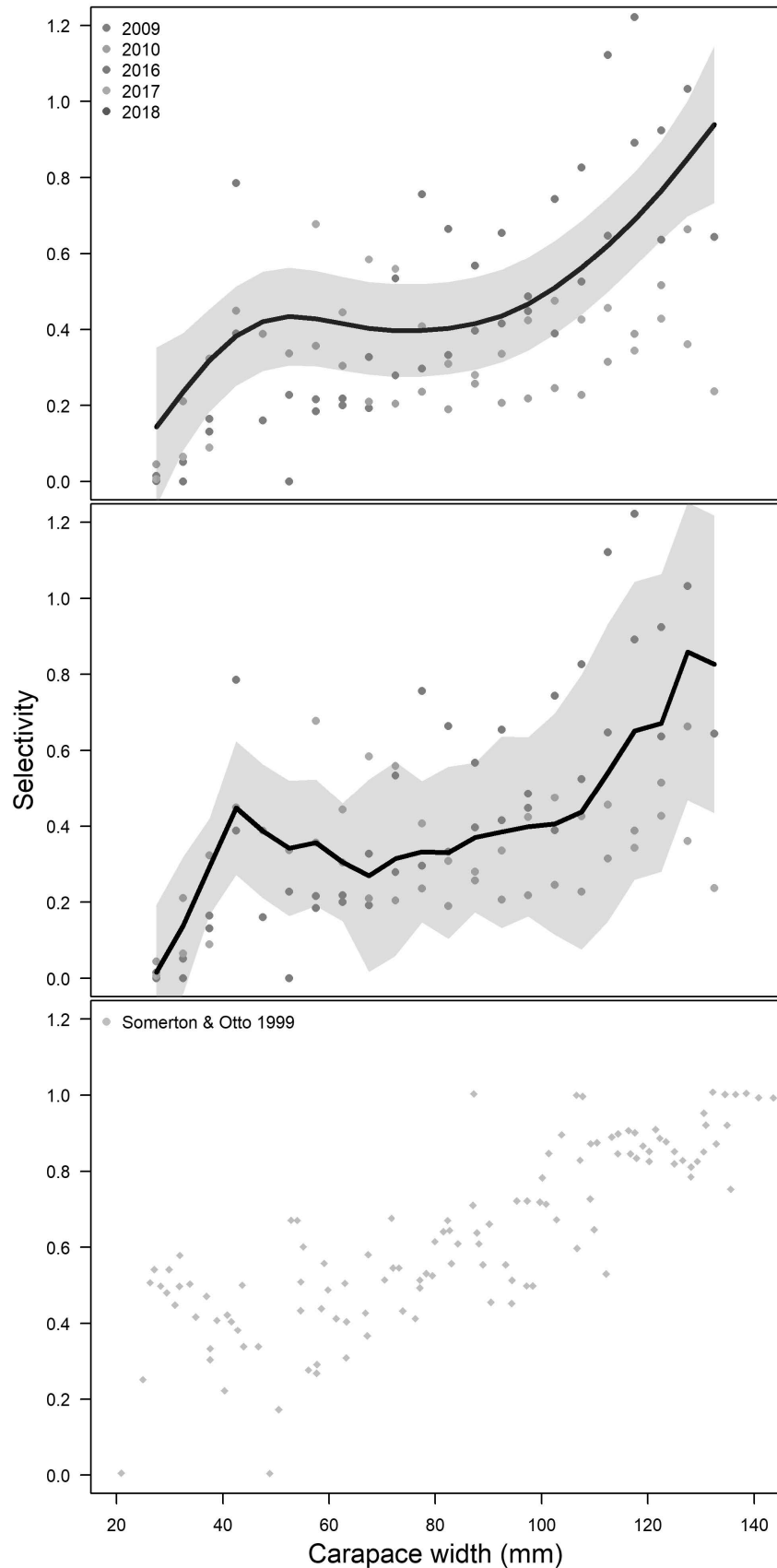


Figure 26: Implied selectivity from BSRF experiments with selectivity at size class estimated by generalized additive model (top). Implied selectivity from BSRF experiments with selectivity at size class estimated by sample size-weighted means and variances (middle). Somerton and Otto (1998) underbag experimental data.

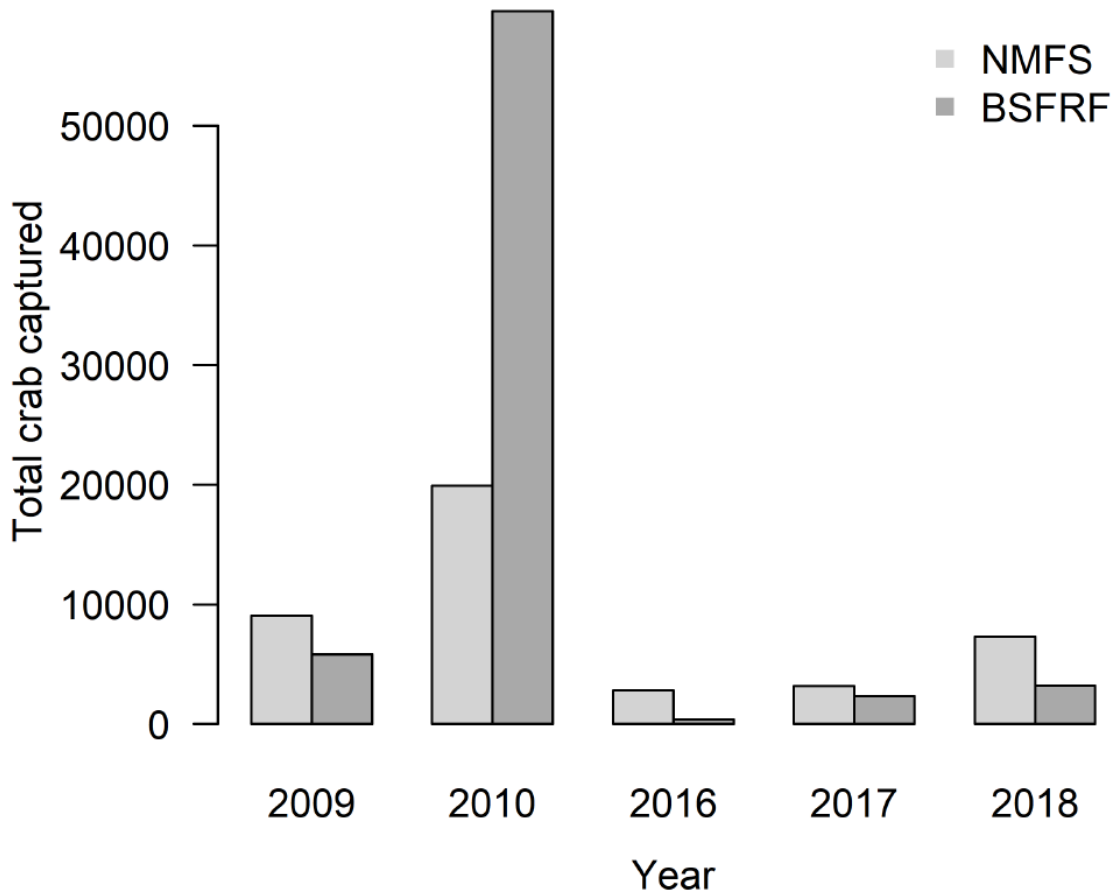


Figure 27: Number of crab from which estimates of biomass and length composition data were inferred within the survey selectivity experimental area.

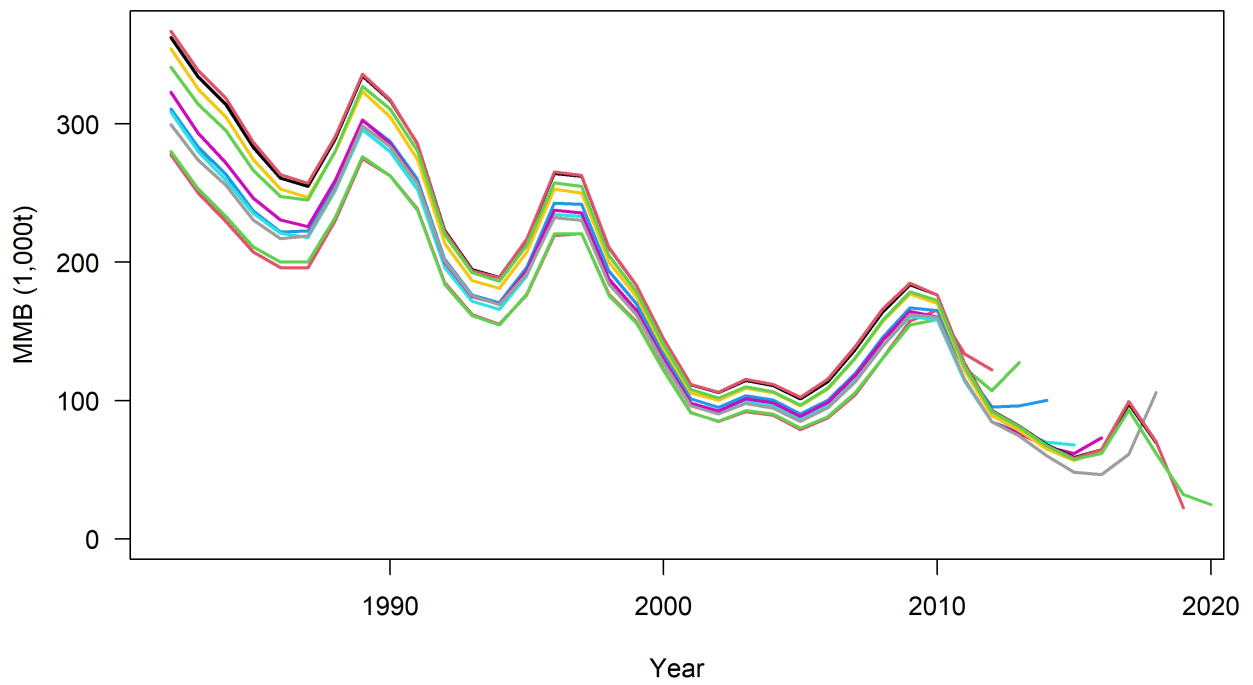


Figure 28: Retrospective patterns in estimated mature male biomass at the time of mating for the author-preferred model.



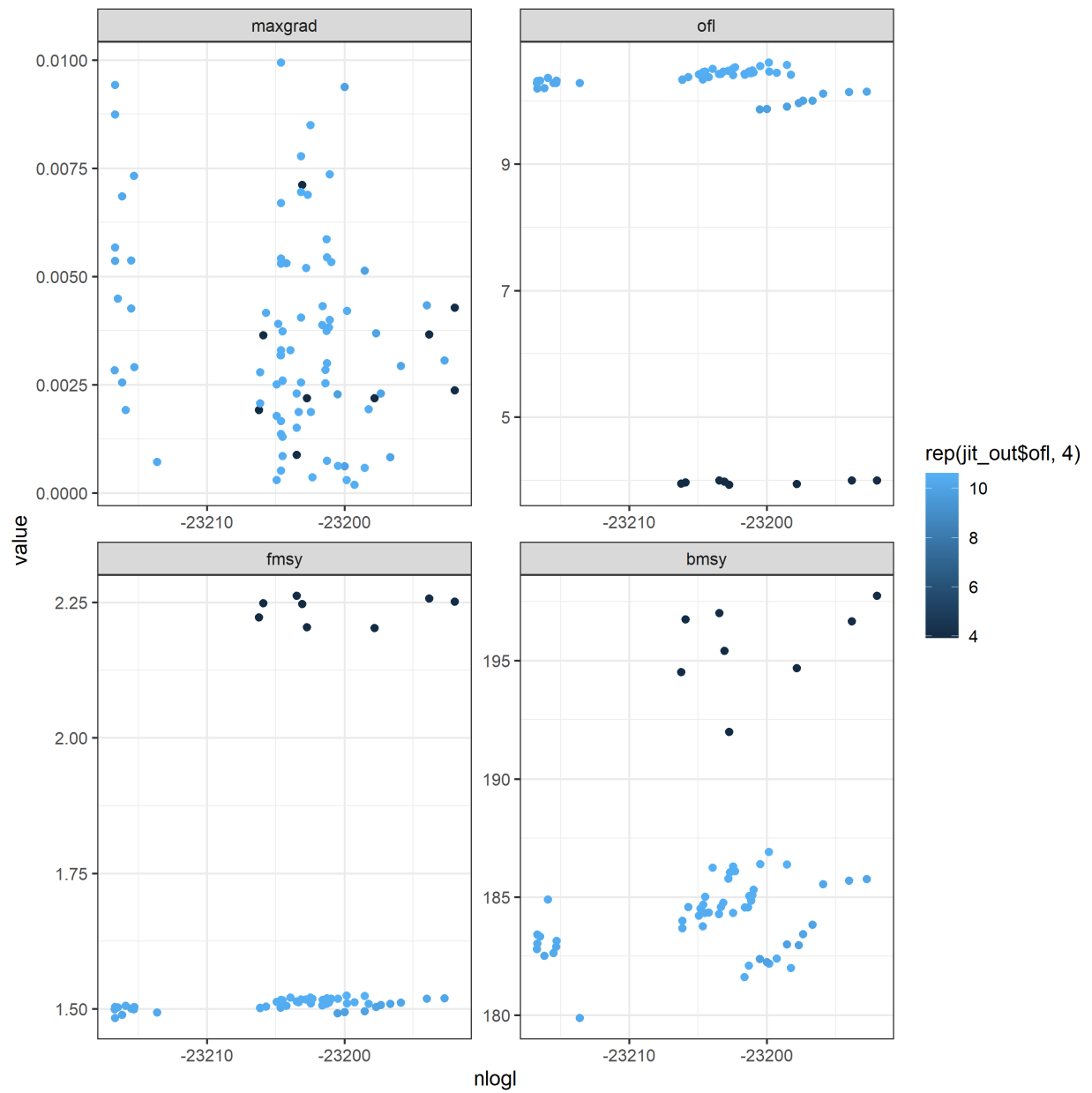


Figure 29: Output of 100 jittered model fittings for the model from which 22.1a and 22.1ab are derived. Top left is the maximum gradient component, top right is the overfishing level, bottom left is F35, and bottom right is B35. Each dot represent an instance of a jittered fitted model and are colored based on the OFL resulting from that run.

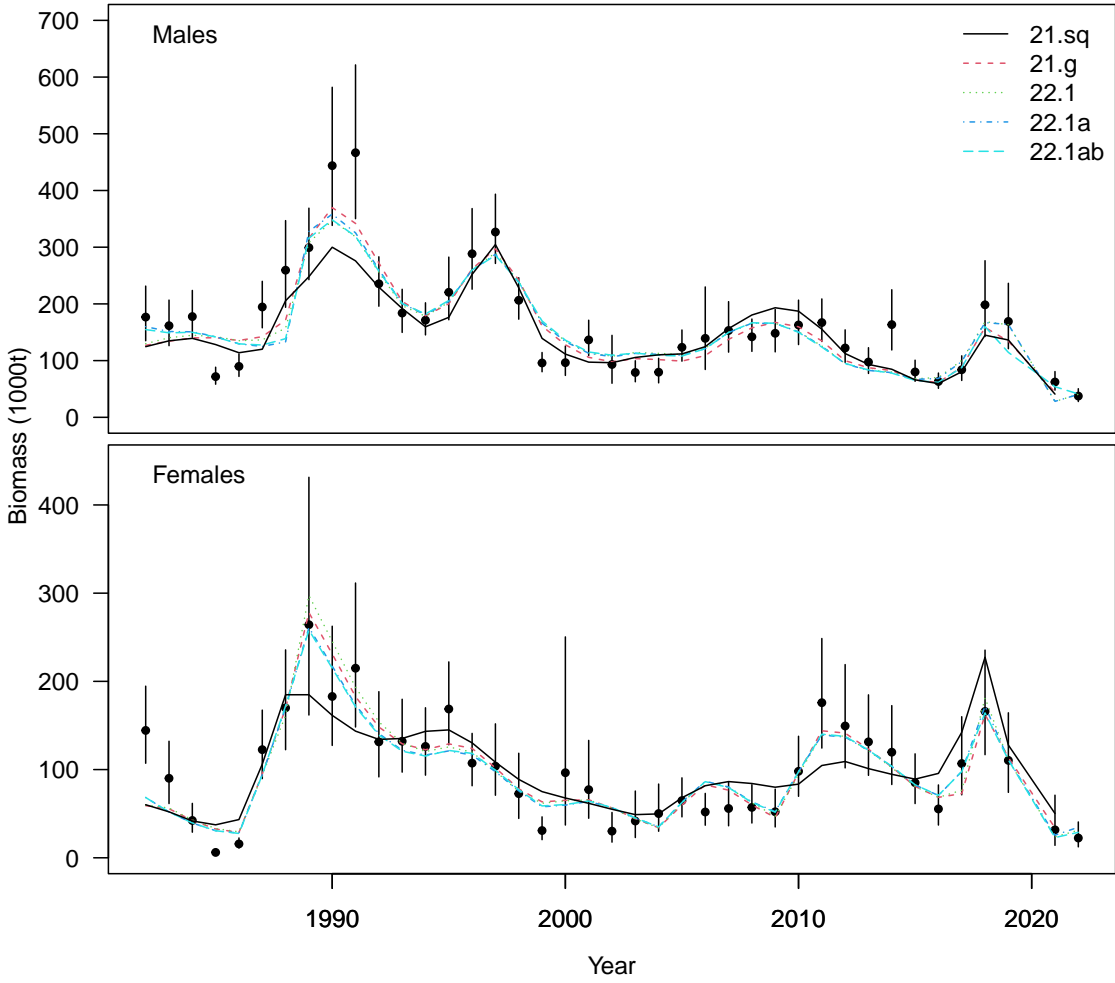


Figure 30: Model fits to the observed mature biomass at survey

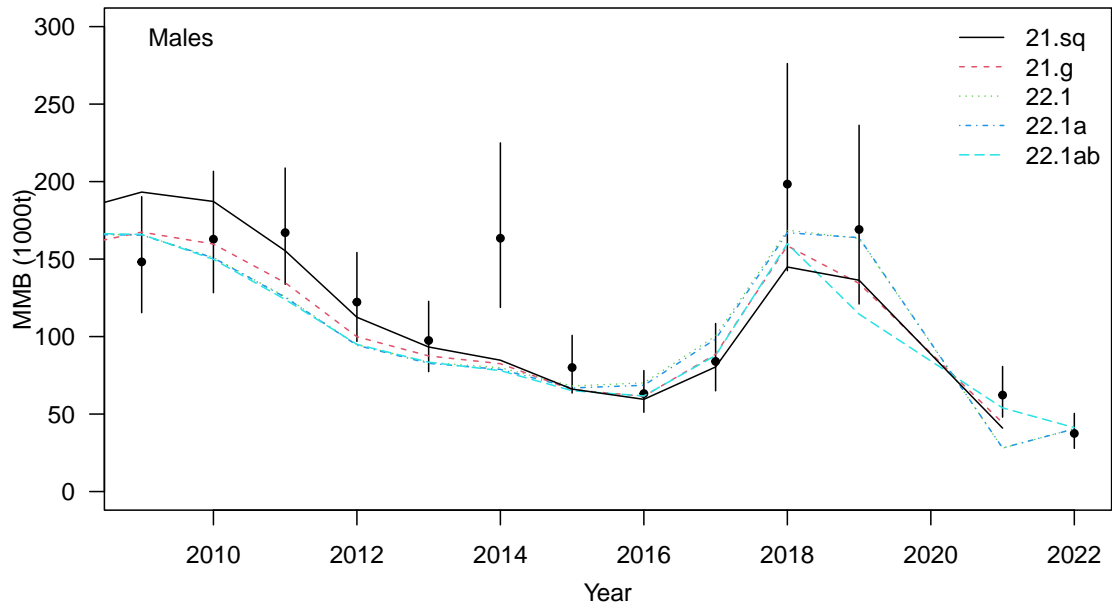


Figure 31: Model fits to the observed mature biomass at survey 2009-present

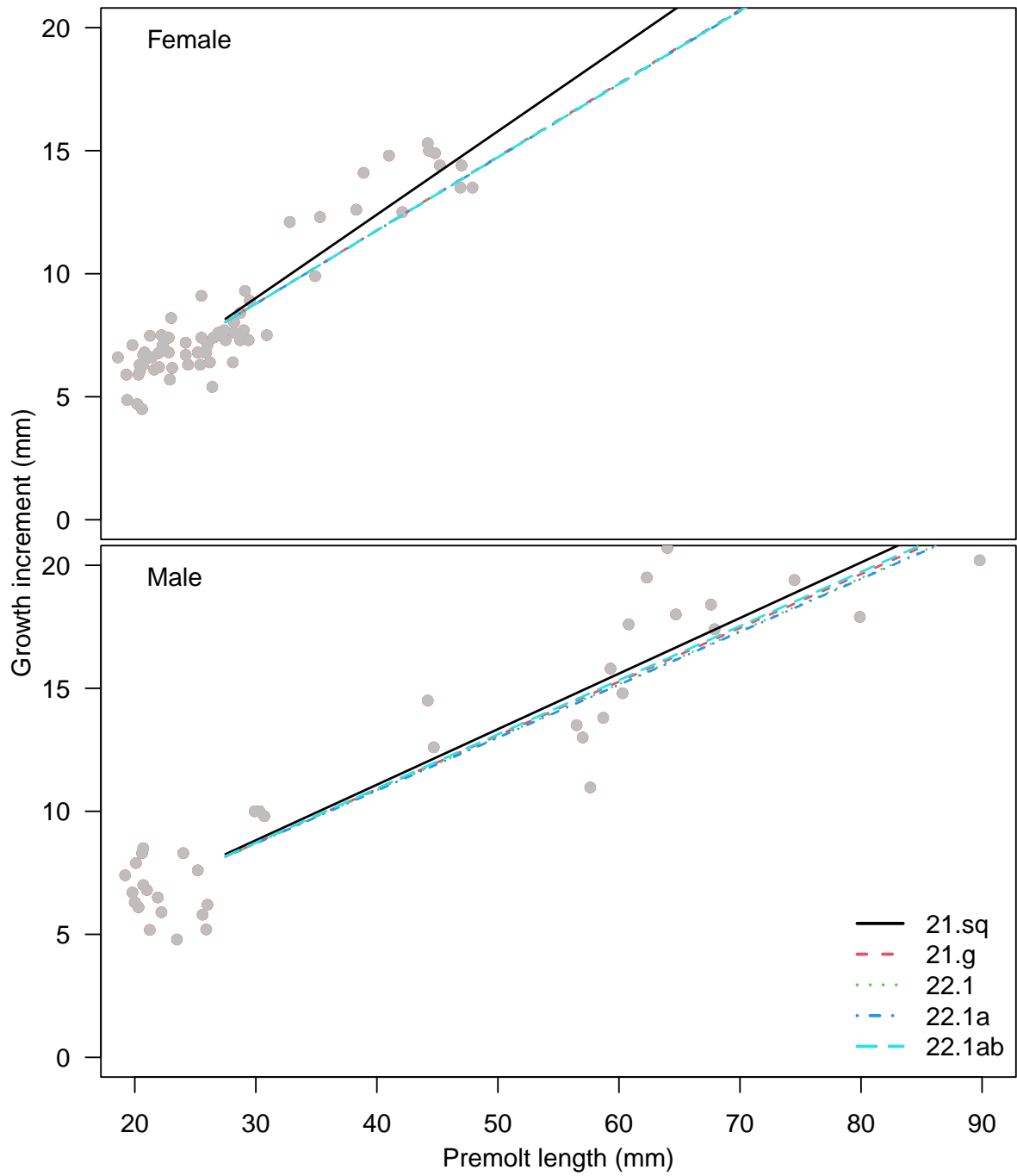


Figure 32: Model fits to the growth data

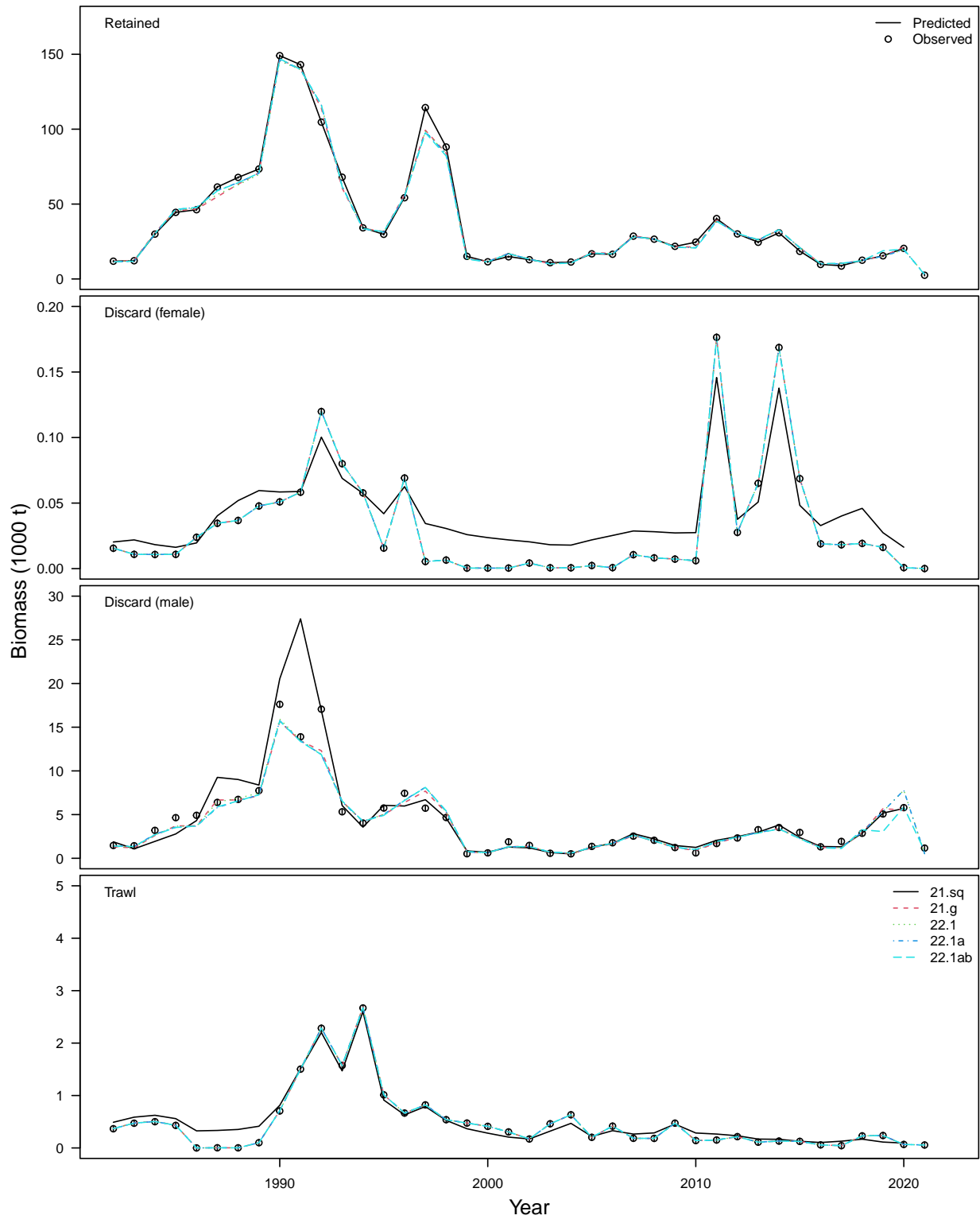


Figure 33: Model fits to catch data

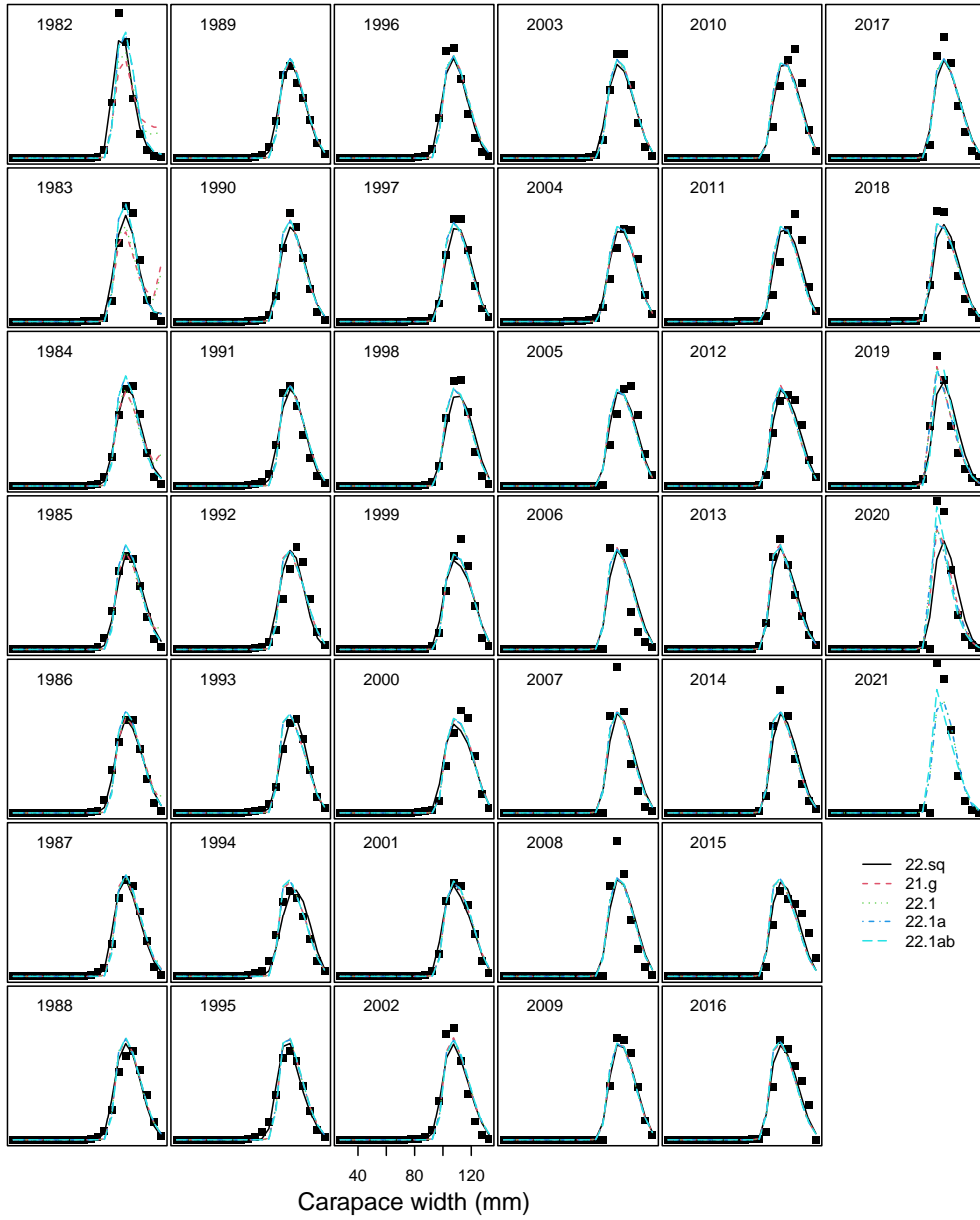


Figure 34: Model fits to retained catch size composition data

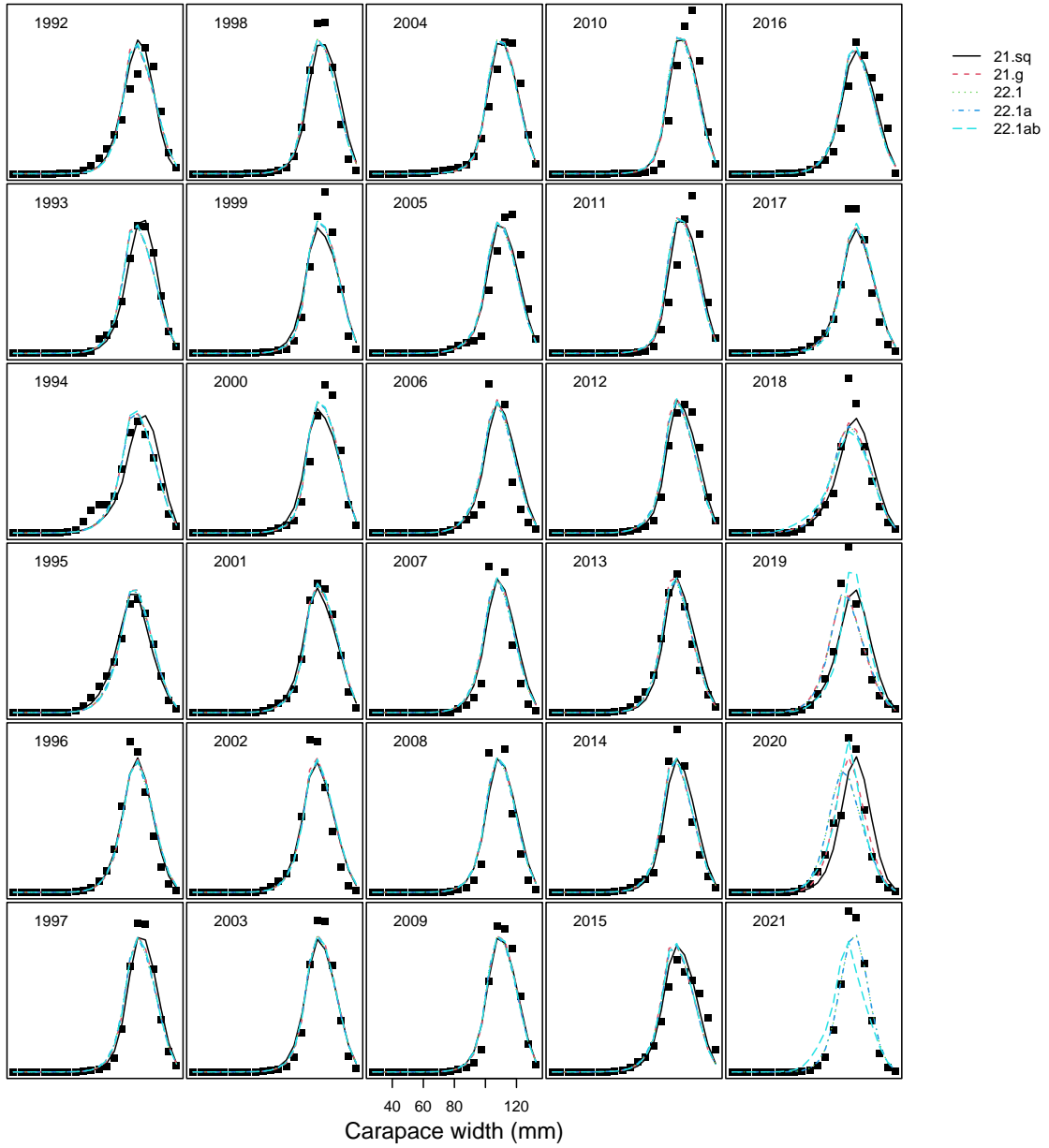


Figure 35: Model fits to total catch size composition data

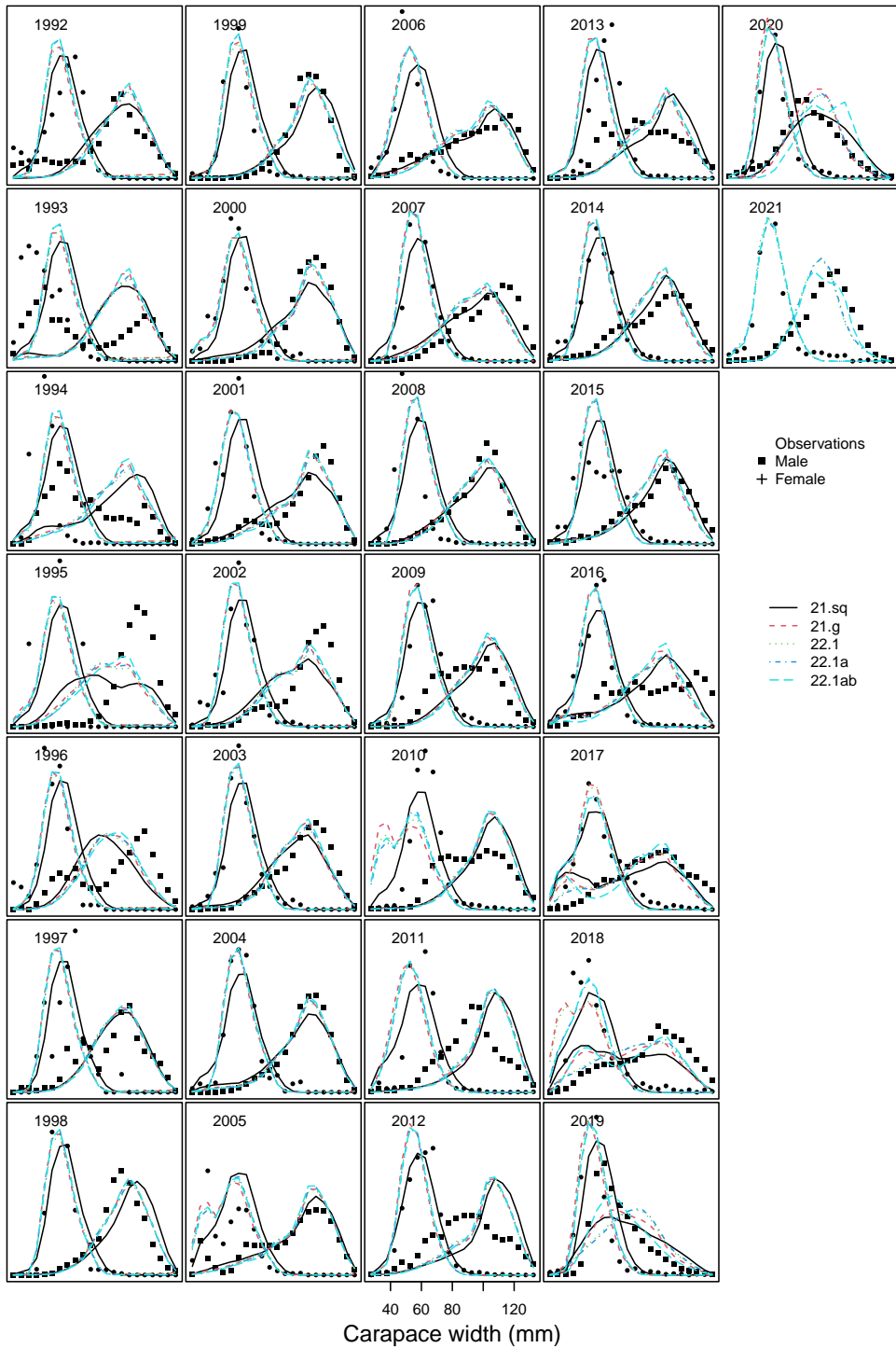


Figure 36: Model fits to trawl catch size composition data



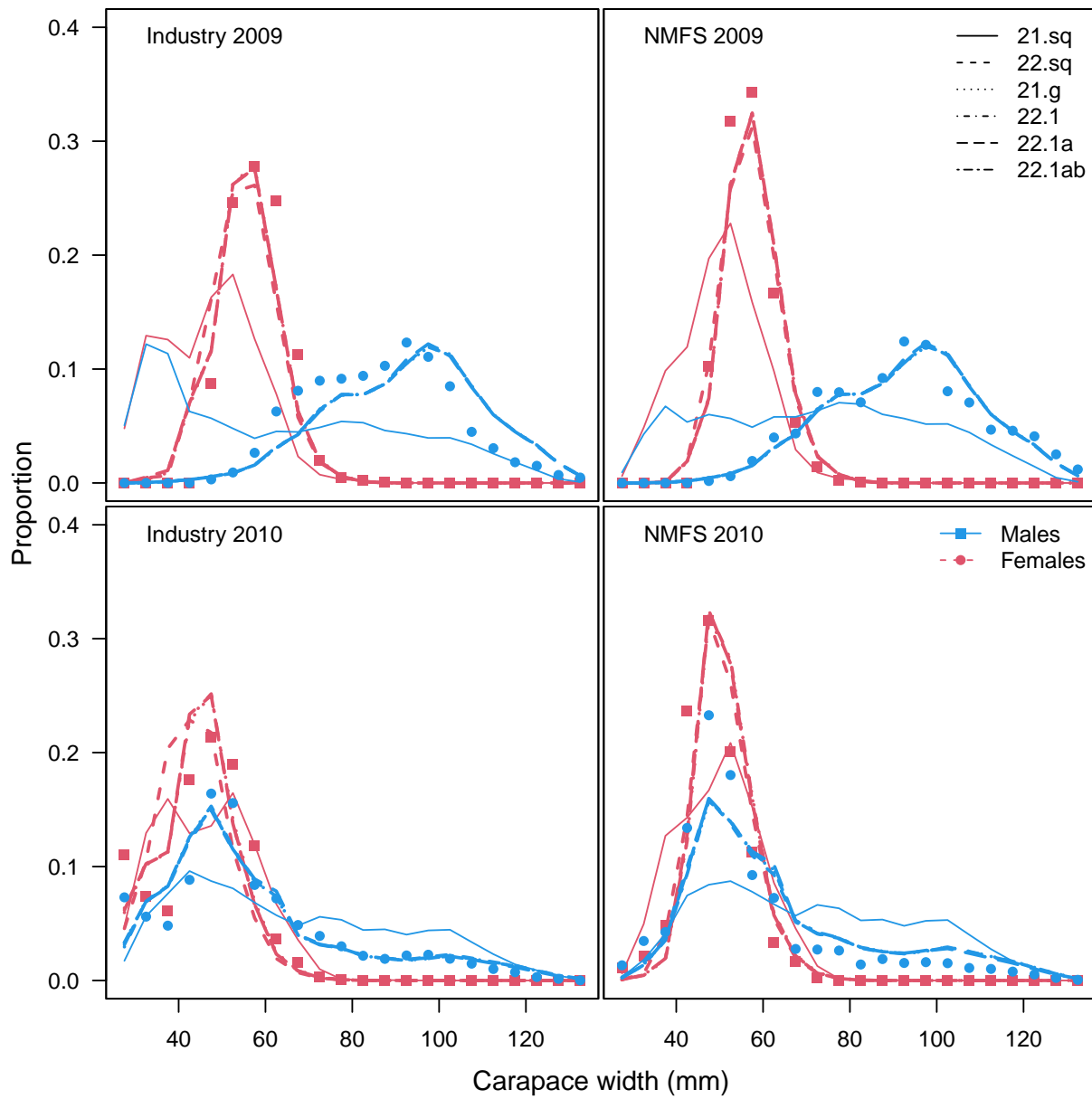


Figure 37: Model fits to size composition data from summer survey experiments (2009 & 2010)

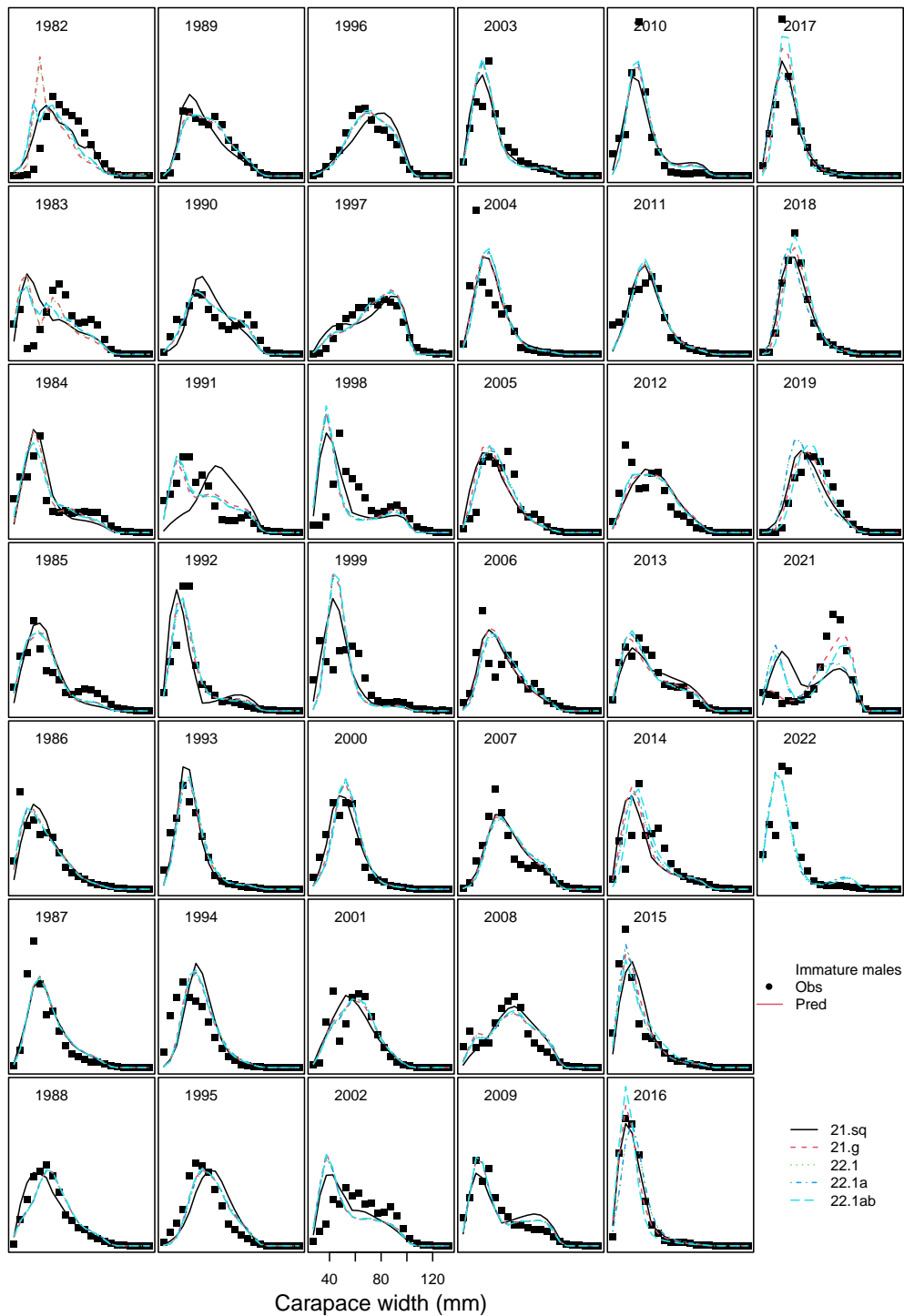


Figure 38: Model fits to immature male survey size composition data. Note that male and female survey selectivity proportions at length in a given year sum to 1. Consequently, the integral of predicted length compositions may appear to be different than the integral of the observed length composition data.

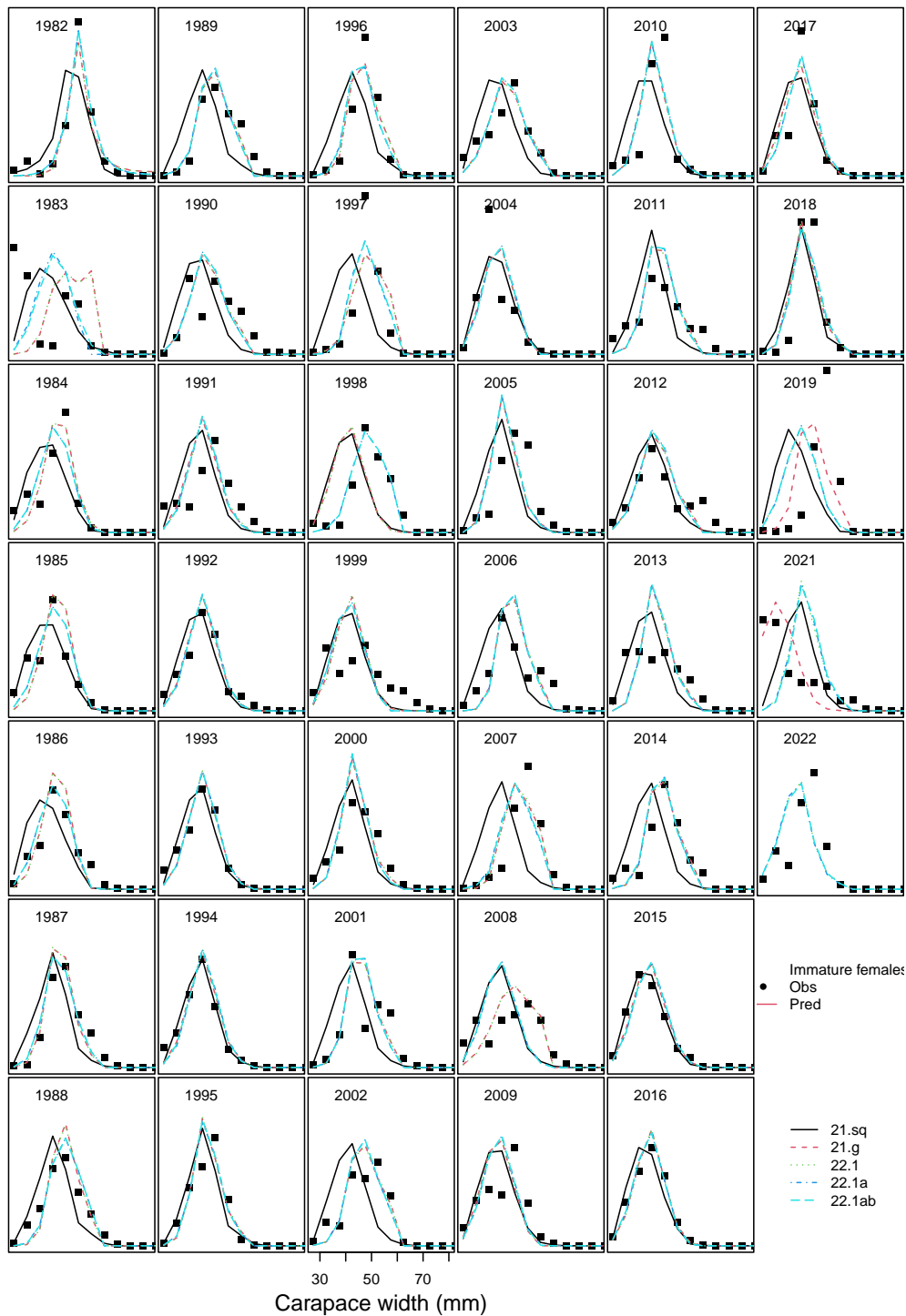


Figure 39: Model fits to immature female survey size composition data. Note that male and female survey selectivity proportions at length in a given year sum to 1. Consequently, the integral of predicted length compositions may appear to be different than the integral of the observed length composition data.

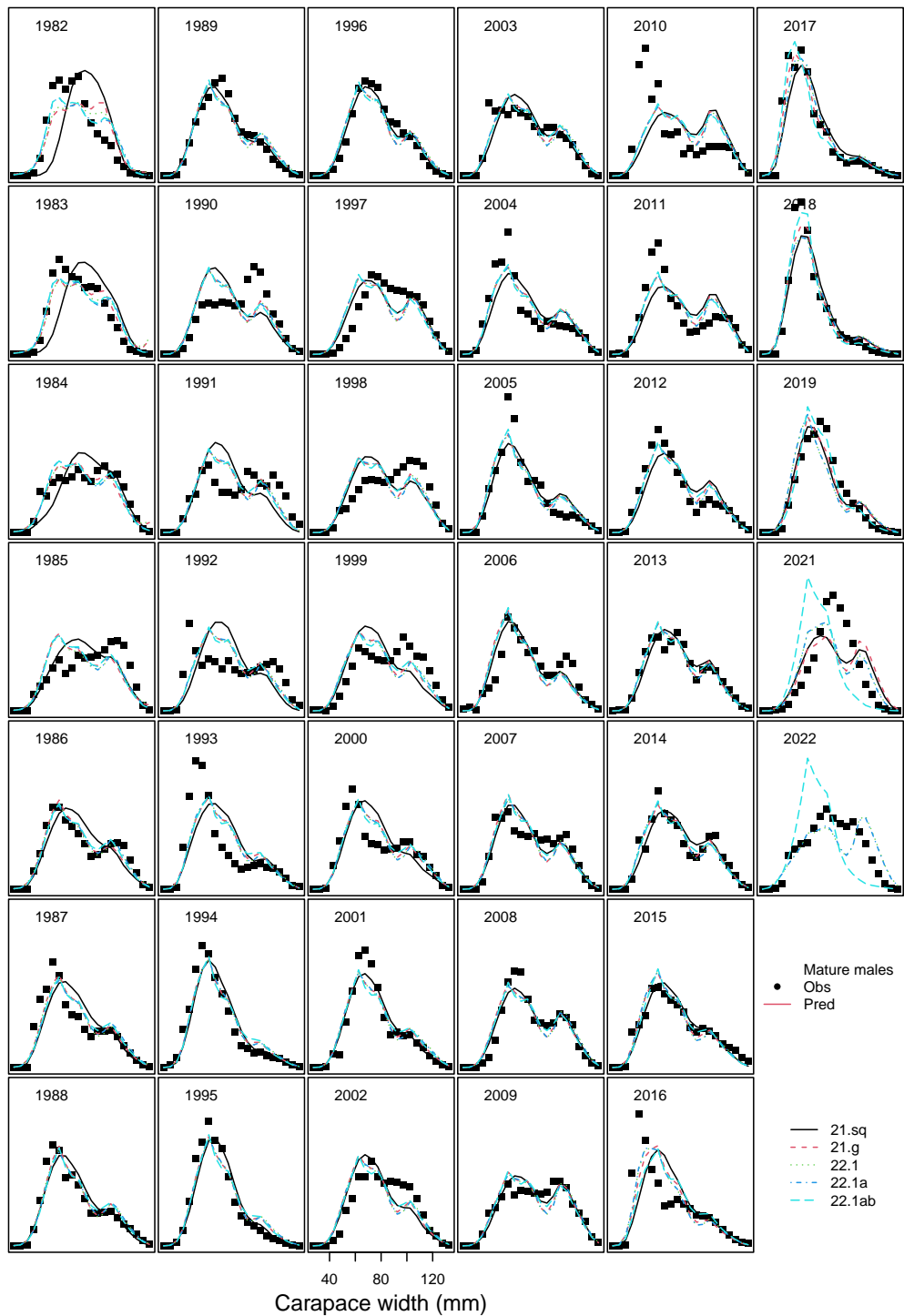


Figure 40: Model fits to mature male survey size composition data. Note that male and female survey selectivity proportions at length in a given year sum to 1. Consequently, the integral of predicted length compositions may appear to be different than the integral of the observed length composition data.

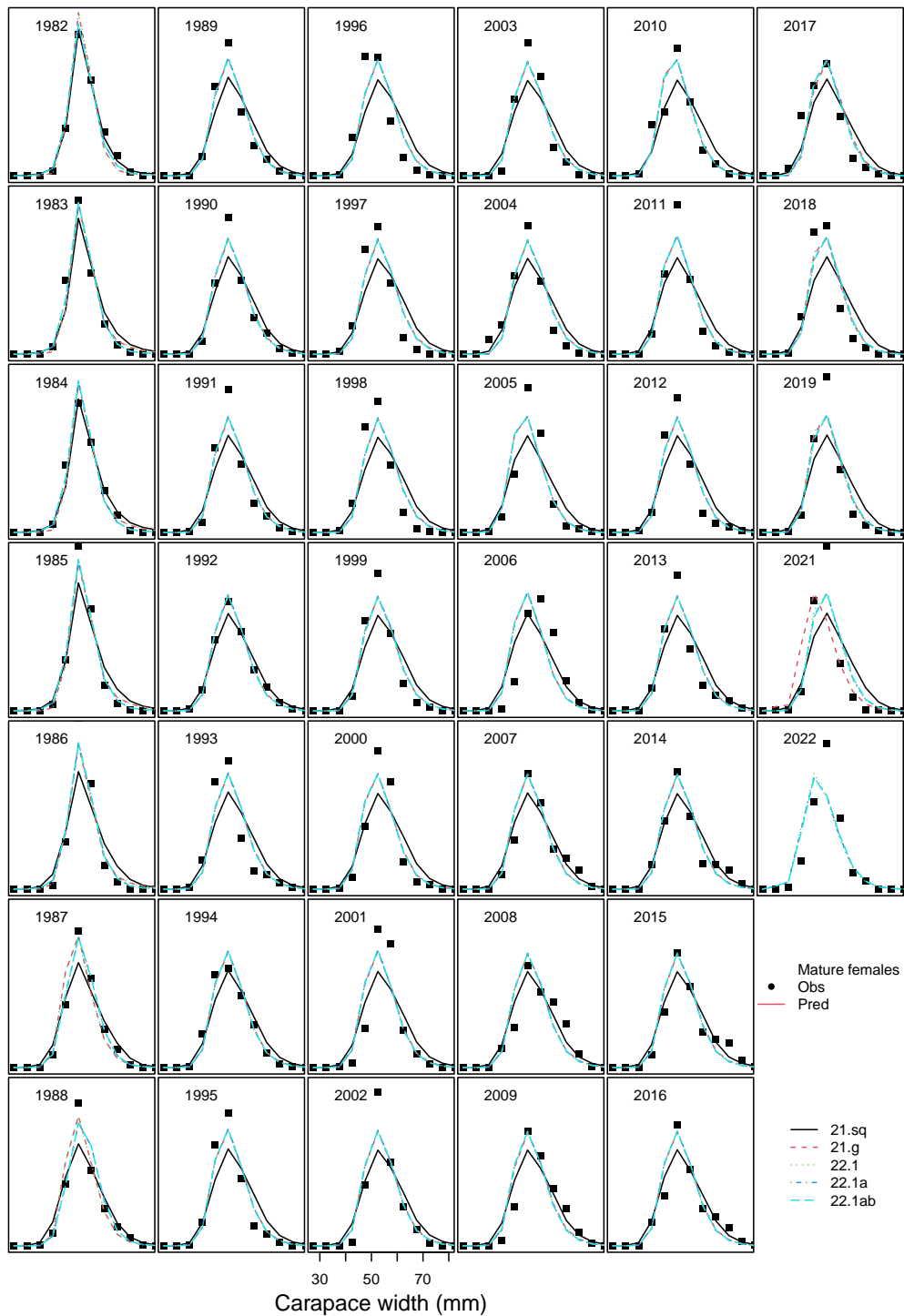


Figure 41: Model fits to mature female survey size composition data. Note that male and female survey selectivity proportions at length in a given year sum to 1. Consequently, the integral of predicted length compositions may appear to be different than the integral of the observed length composition data.

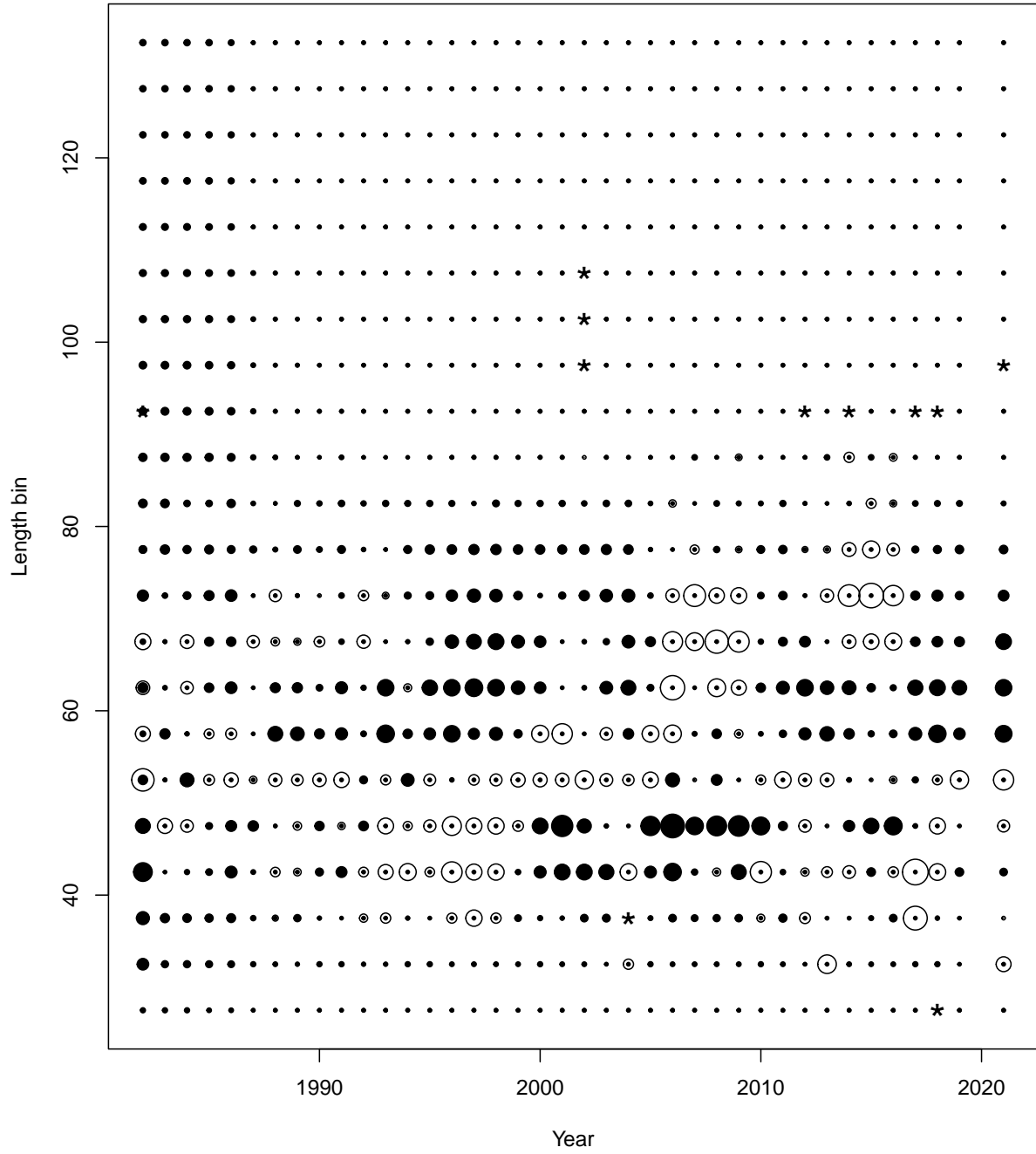


Figure 42: Residual bubble plot of the fits to the NMFS mature female for the author-preferred model. Open circles represent positive residuals; closed circles represent negative residuals.

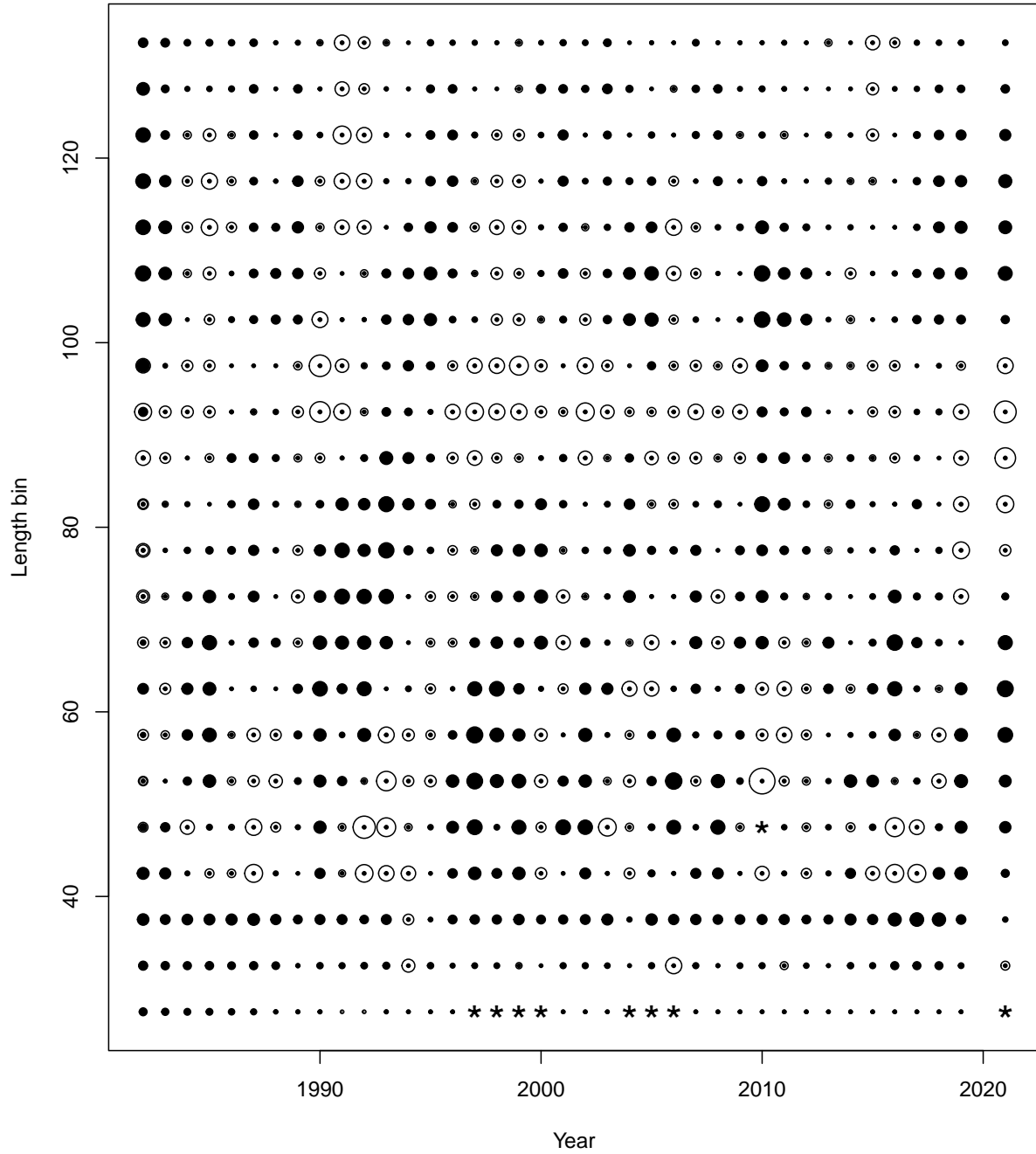


Figure 43: Residual bubble plot of the fits to the NMFS mature male for the author-preferred model. Open circles represent positive residuals; closed circles represent negative residuals.

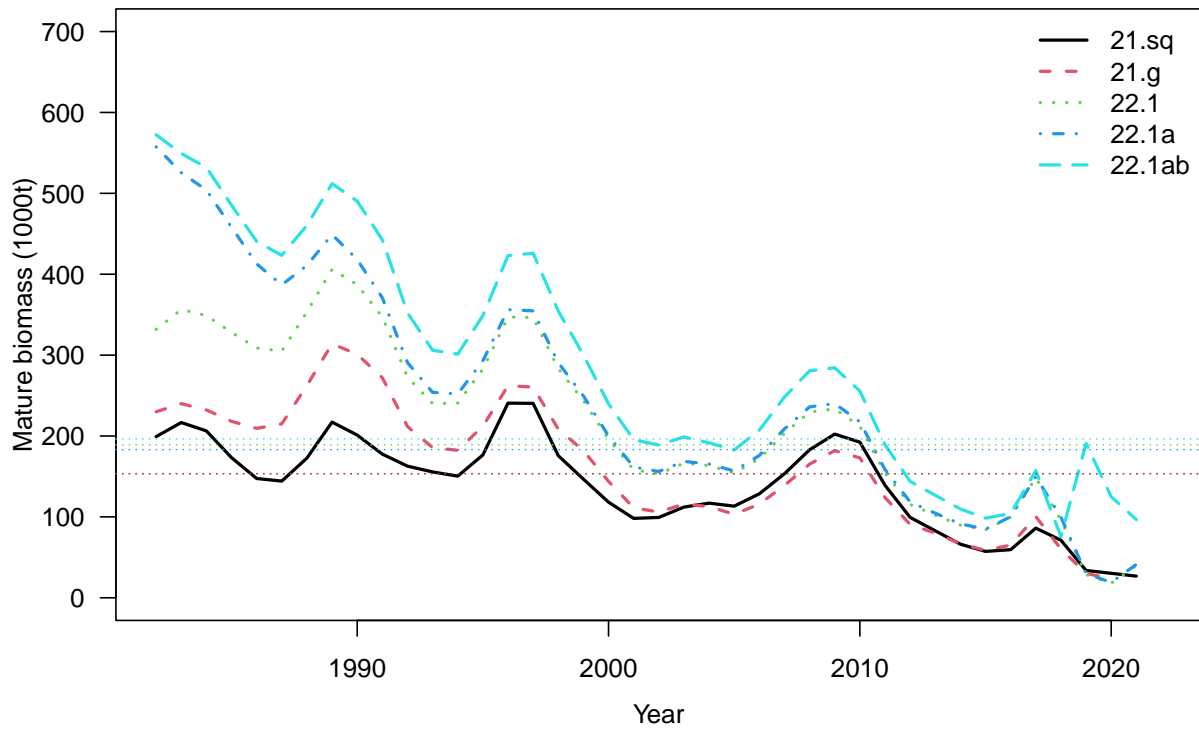


Figure 44: Model predicted mature biomass at mating time. Dotted horizontal lines are target biomasses.

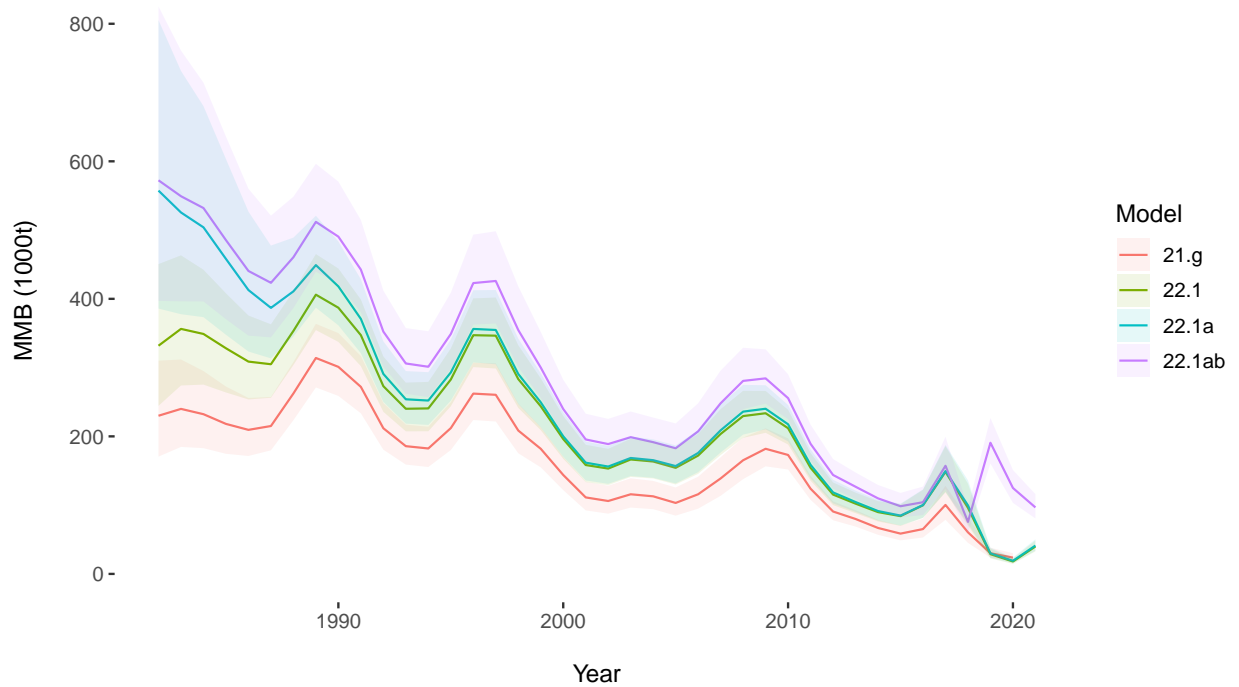


Figure 45: Trajectories of estimated MMB at the time of mating with 95% log-normal confidence intervals.



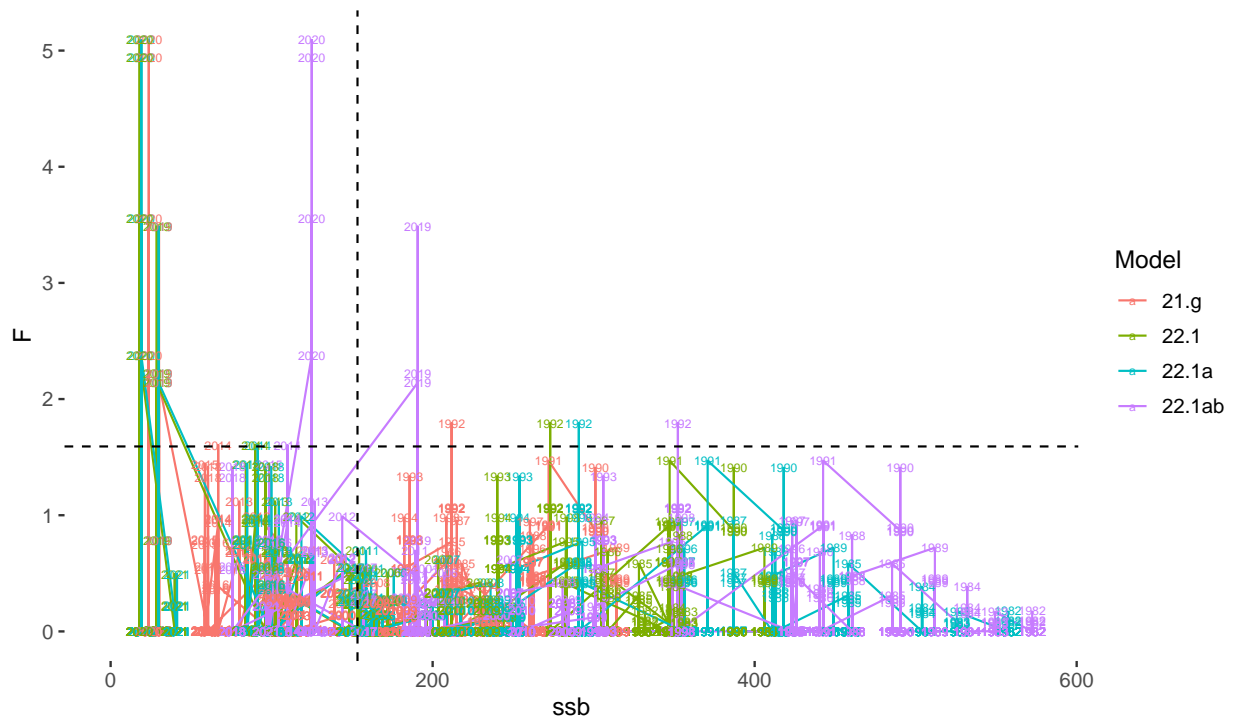


Figure 46: Kobe plots. Vertical dashed black line represents the MLE value for B35%; horizontal dashed black line represents F35%

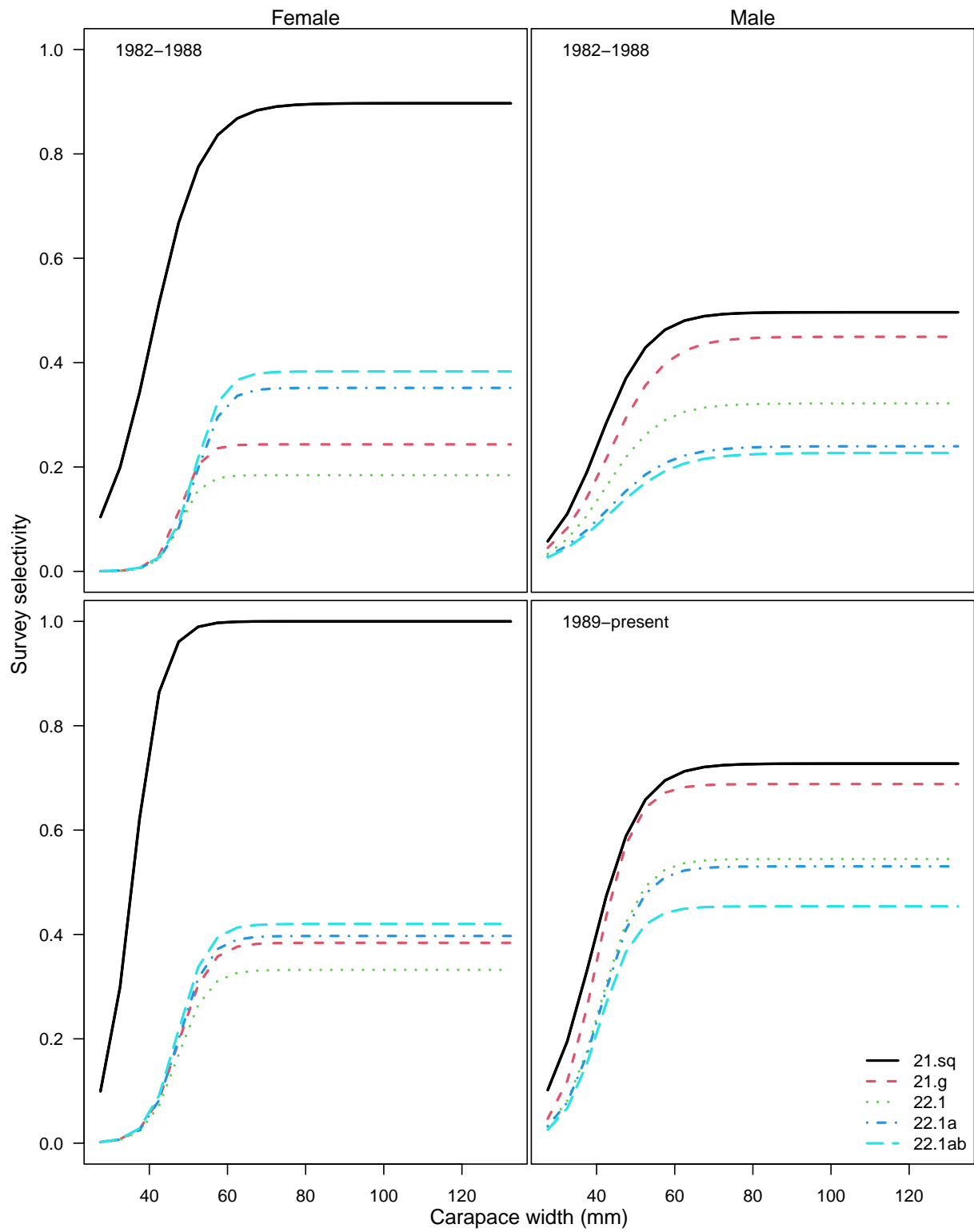


Figure 47: Estimated survey selectivity

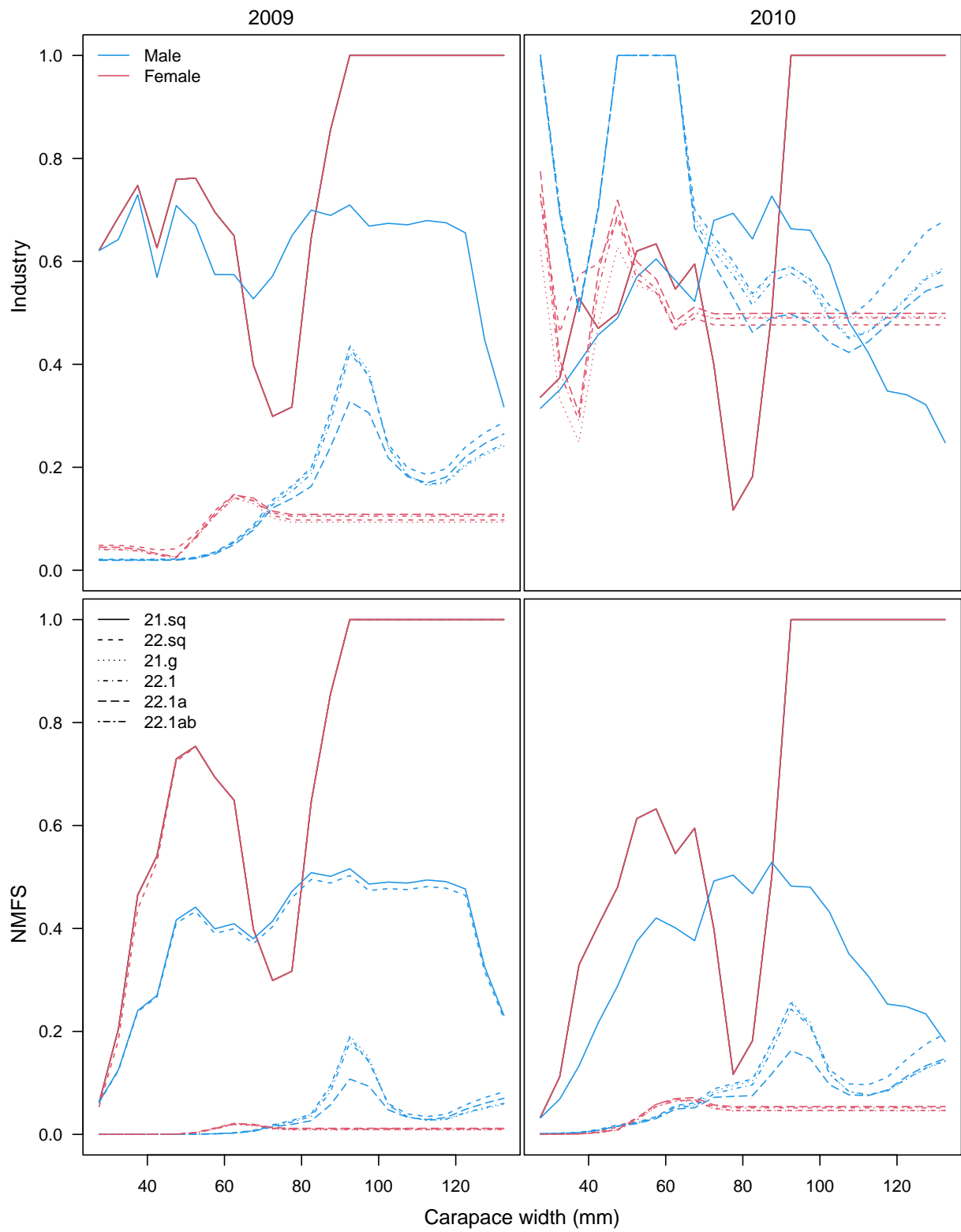


Figure 48: Estimated or specified availability (top row) and estimated experimental survey selectivity (availability \* survey selectivity; bottom row).

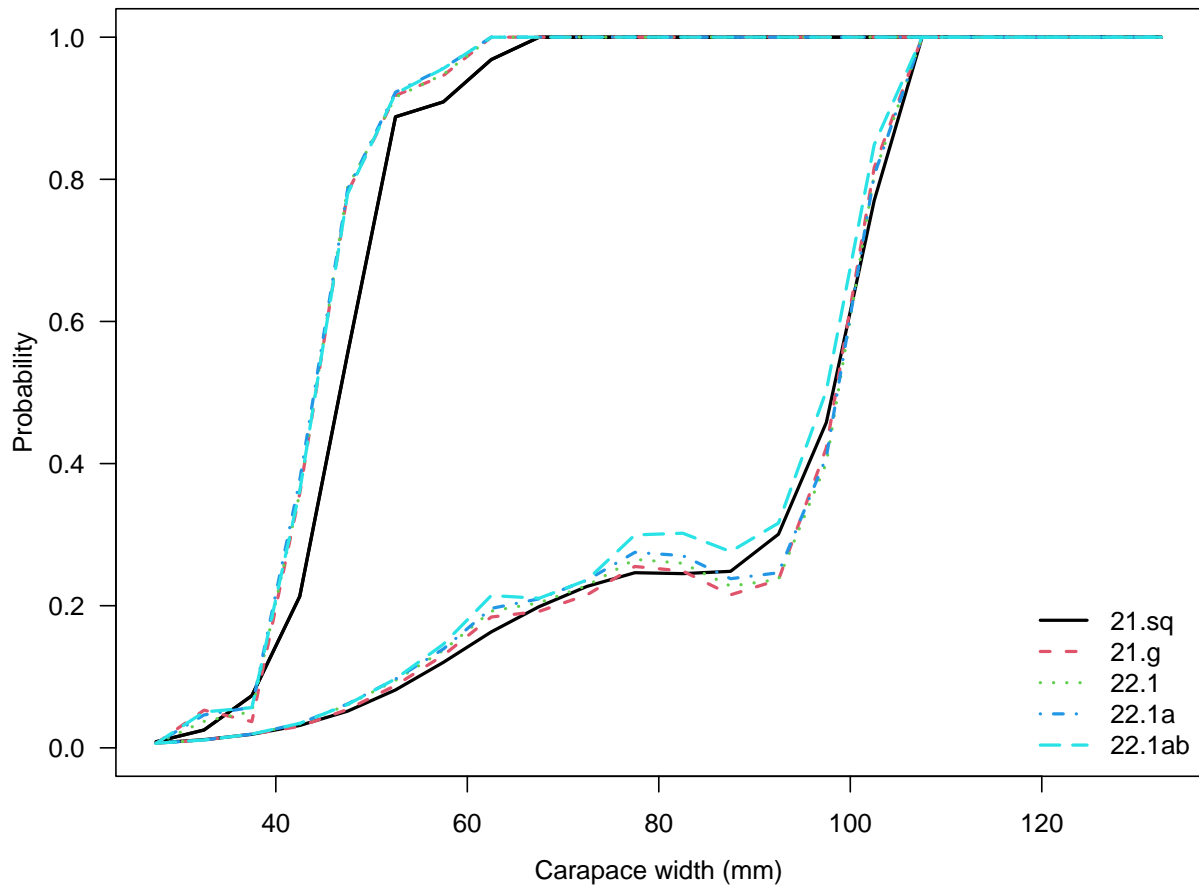


Figure 49: Estimated probability of maturing

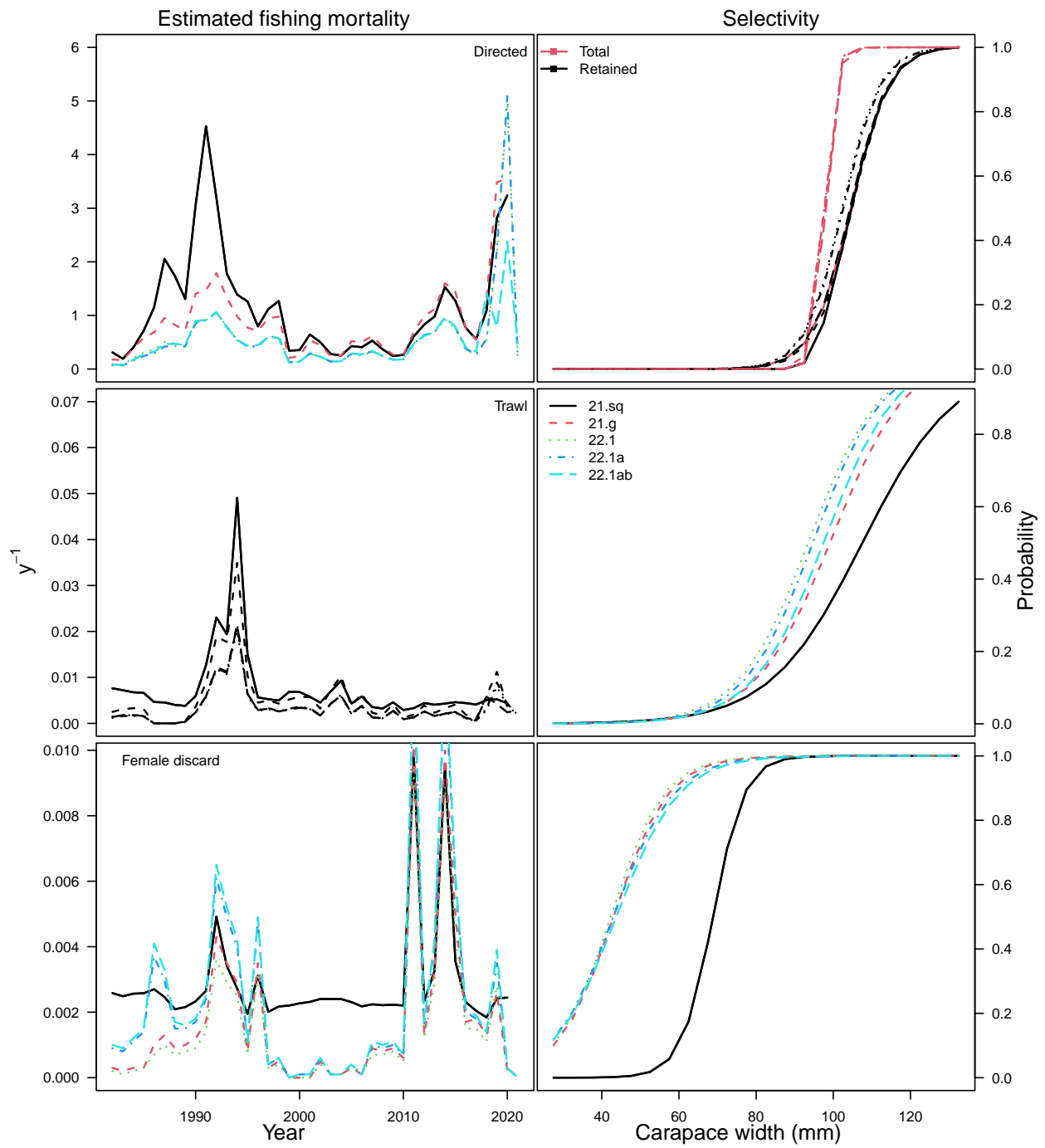


Figure 50: Model predicted fishing mortalities and selectivities for all sources of mortality

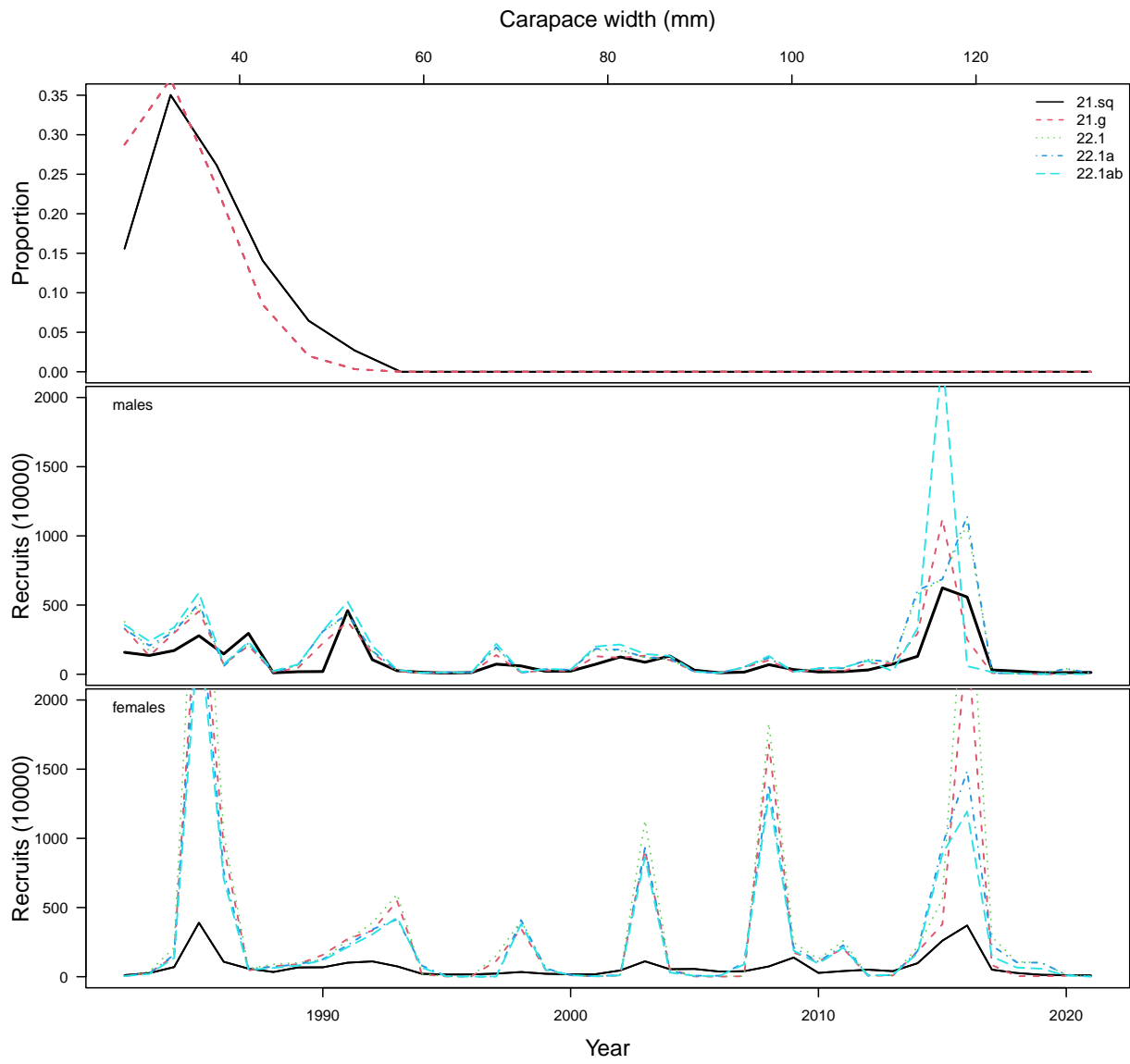


Figure 51: Estimated recruitment and proportions recruiting to length bin.

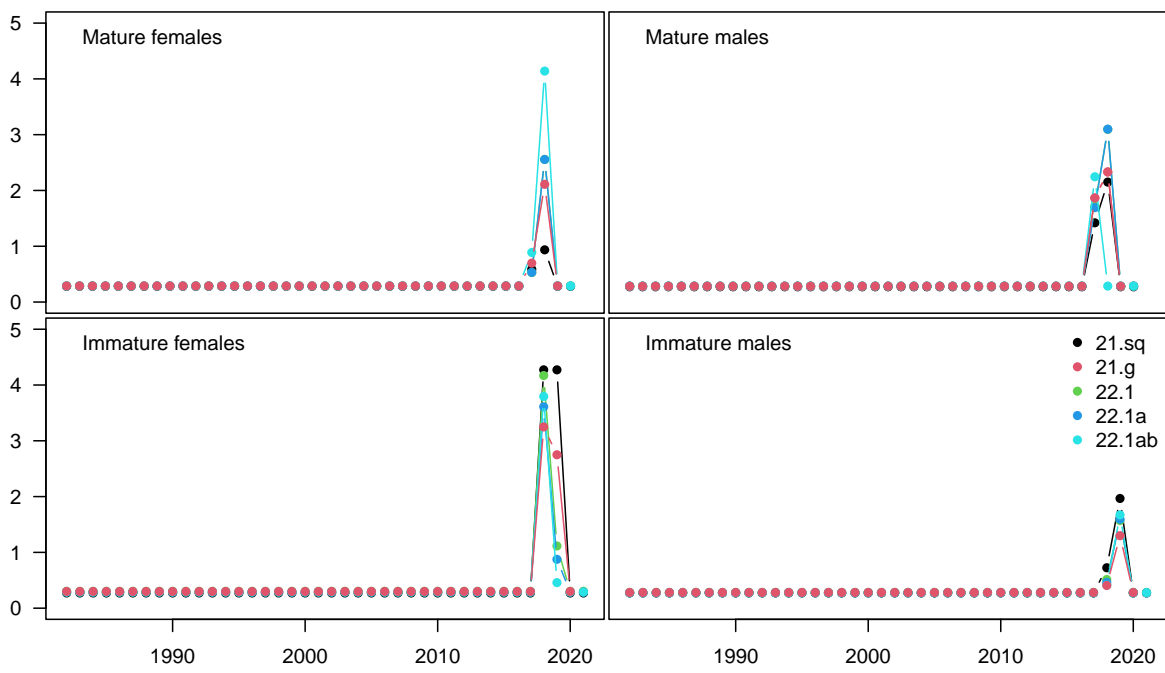


Figure 52: Estimated natural mortality by sex and maturity state.

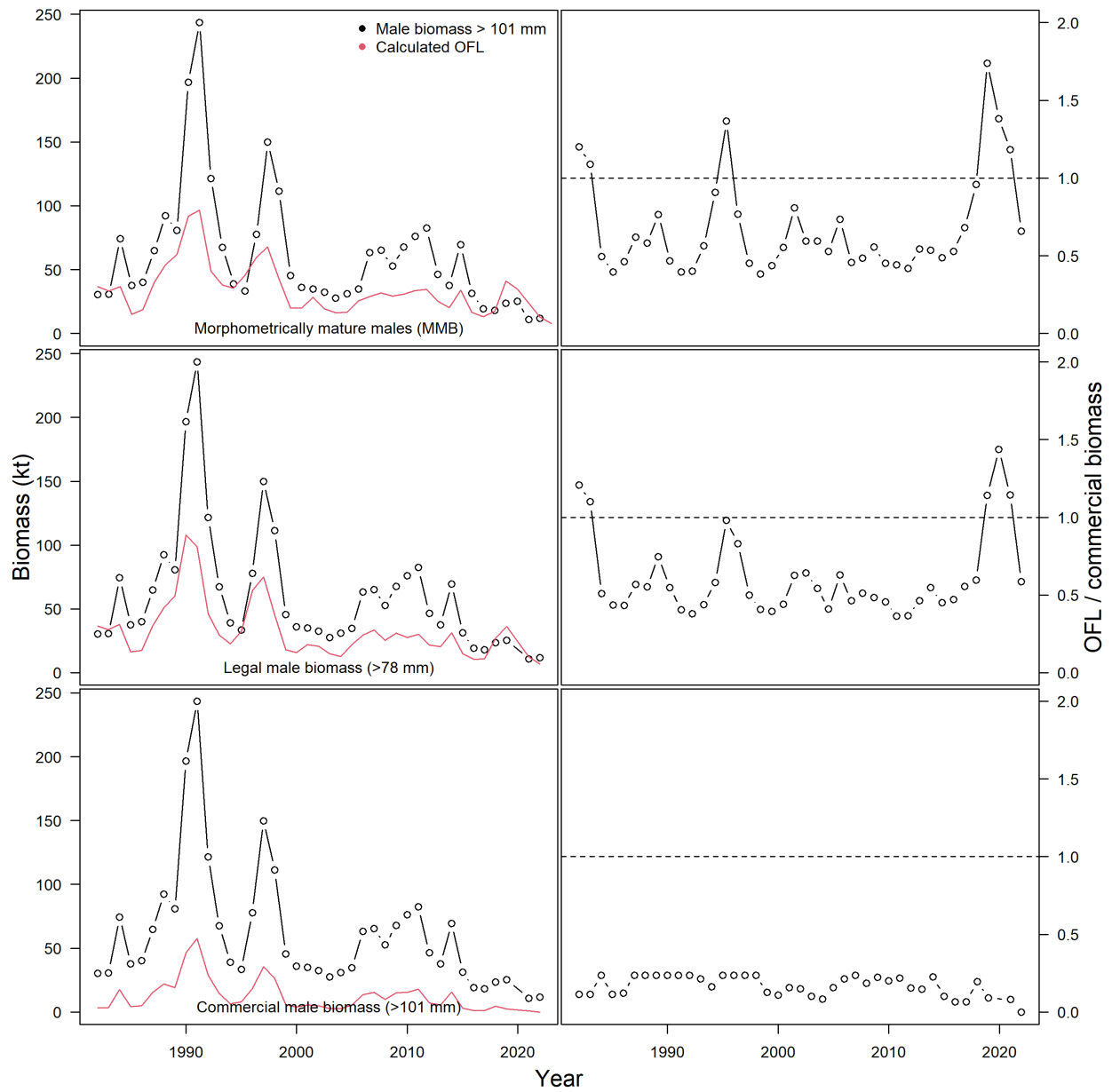


Figure 53: Application of tier 4 harvest control rules to different currencies of management for snow crab.



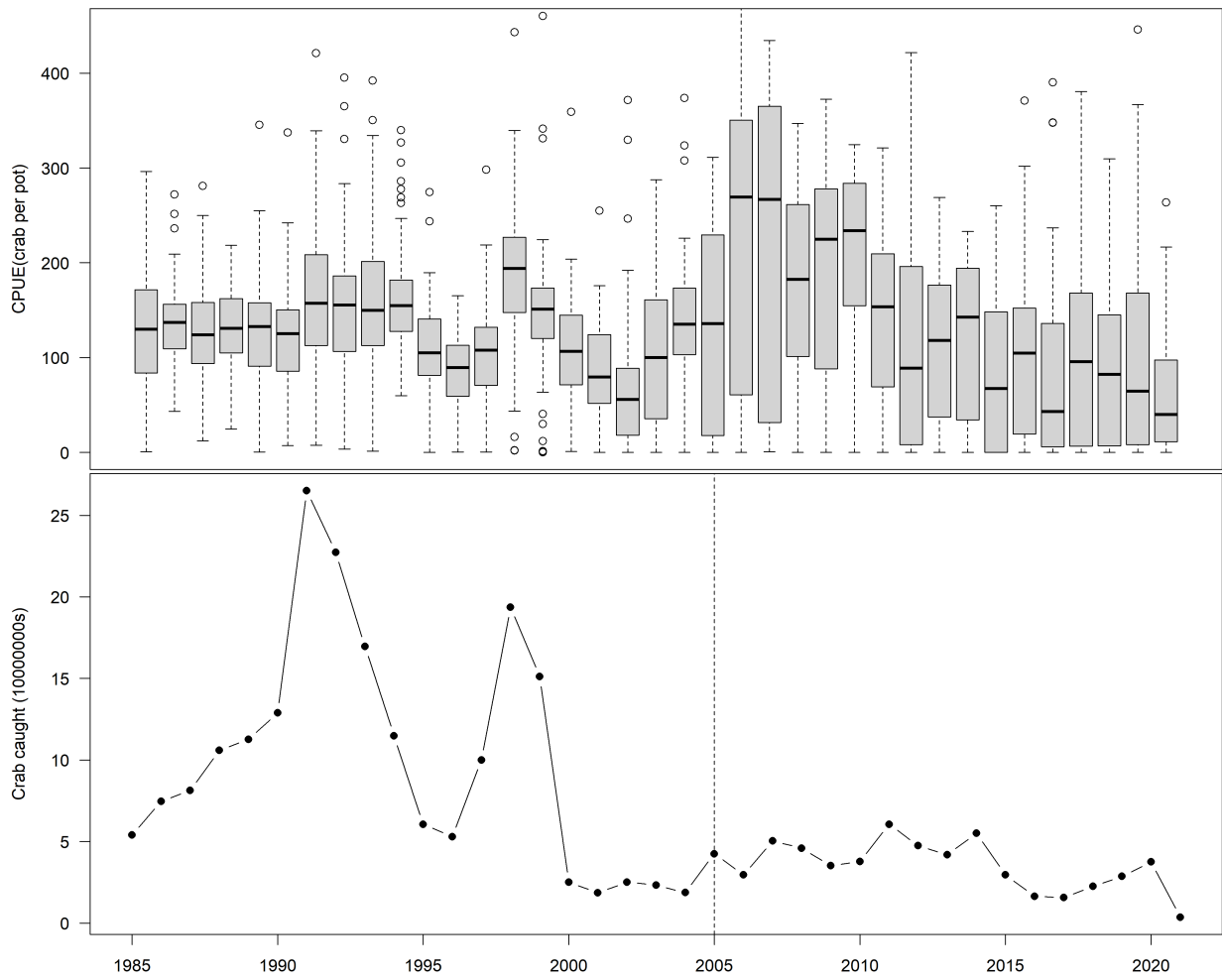


Figure 54: Catch per unit effort in the snow crab fleet, courtesy of Ben Daly.

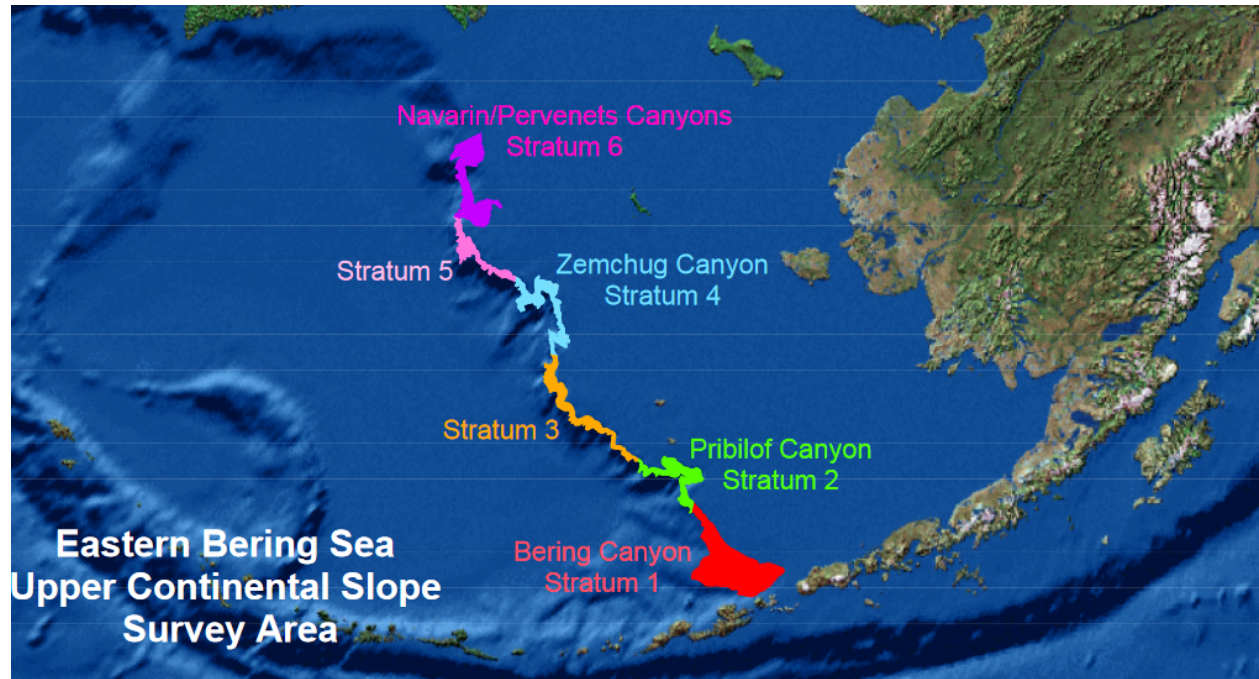


Figure 55: Location of the survey strata on the eastern Bering Sea slope.

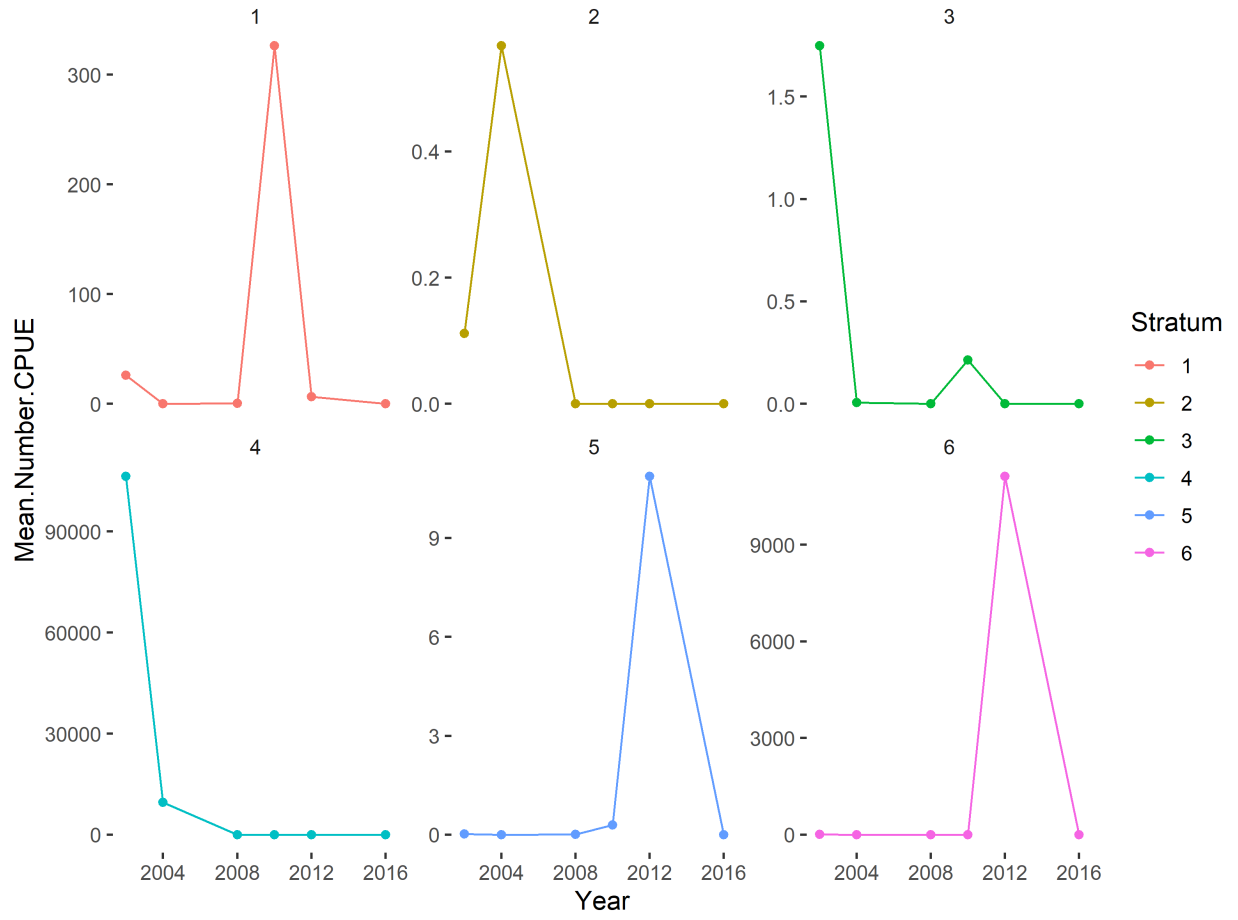


Figure 56: Mean catch per unit effort by strata over time in the EBS slope survey.

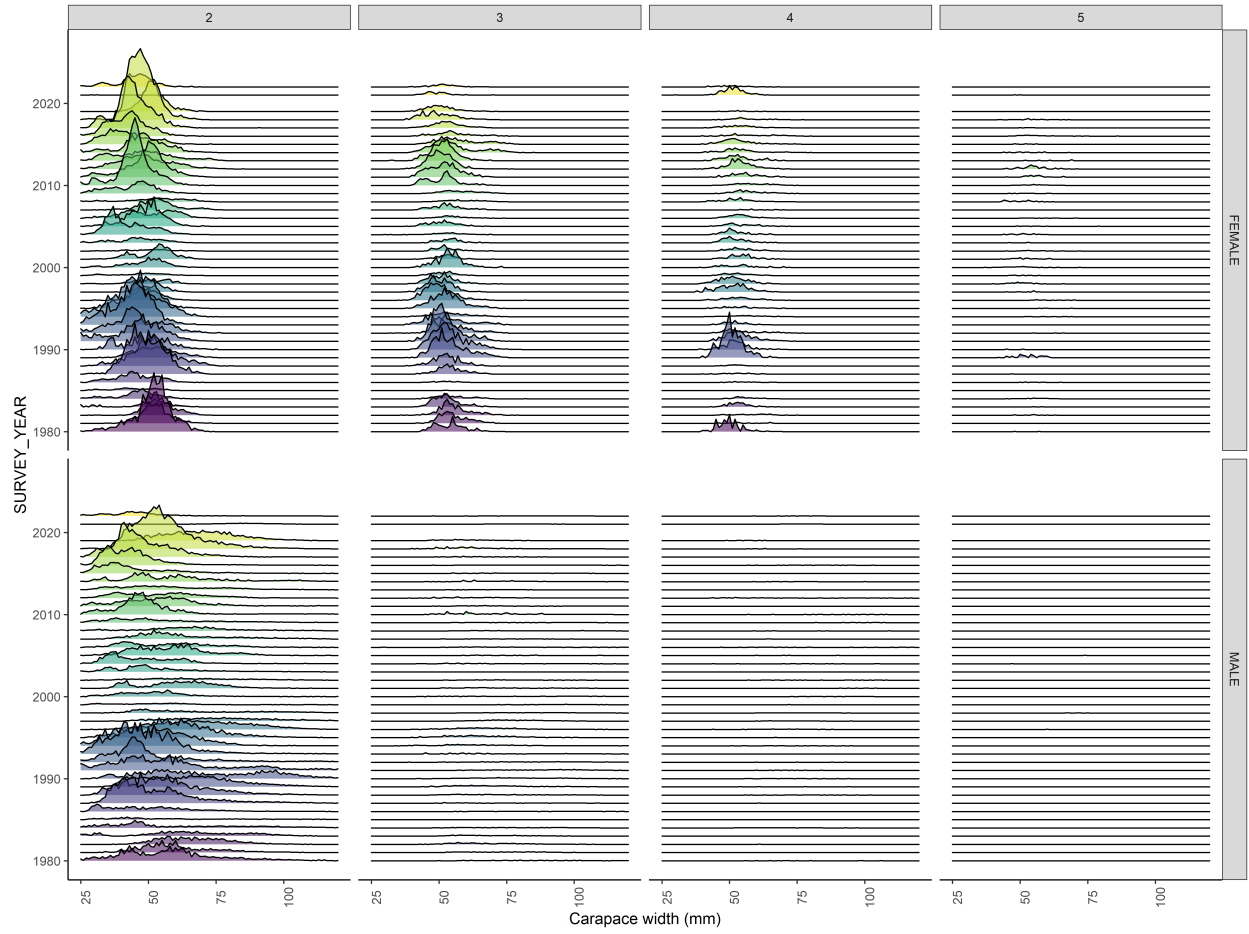


Figure 57: Relative numbers at size by shell condition and sex observed in the NMFS summer survey.