An assessment for eastern Bering Sea snow crab

Cody Szuwalski

September 13, 2024

Contents

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. 11.85 kt during 1982) to historical highs in 1990s (retained catches 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. 11.46 kt). Retained catches slowly increased after 1999 before dropping again in 2016. Total allowable catches were reduced with the collapse of the population in 2021, the fishery was closed for the first time in 2022, and the closure continued through 2023.

Discard mortality from the directed fishery 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. There was no discard mortality in 2023 because there was no directed fishery. Non-directed mortality continues to be very small at 0.07 kt in 2024.

3. Stock Biomass:

Observed morphometrically mature male biomass (MMB) at the time of the survey increased from low levels in the early to mid-1980s to historical highs in the 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, recently the observed MMB has declined to historical lows and the stock was declared overfished again in 2021. MMB at the time of the survey was 63.04 kt in 2024.

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 the mid 2010s and was tracked until 2018 and 2019, but disappeared from the eastern Bering Sea shelf before reaching commercial size. After the recent collapse, some sign of small crab has been observed in the survey and this year's observed immature female biomass in the survey was the highest on record.

5. Management

Table 1: Historical status and catch specifications for snow crab (1,000t). MMB 2023/2024 and after is based on functionally mature male biomass.

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	26.7	20.4	20.4	26.2	95.4	71.6
2021/2022	91.6	41.3	2.5	2.5	3.6	7.5	5.6
2022/2023	78	92.4	0	0	0.05	10.3	7.7
2023/2024	47.4	13.4	0.0	0.0	0.07	15.44	7.72
2024/2025		11.3				0.05	0.04

Table 2: Historical status and catch specifications for snow crab (millions of lbs). MMB 2023/2024 and after is based on functionally mature male biomass.

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	58.86	44.97	44.97	57.76	210.32	157.85
2021/2022	201.94	91.05	5.51	5.51	7.94	16.53	12.35
2022/2023	171.96	203.71	0	0	0.11	22.71	16.98
2023/2024	104.5	29.54	0	0	0.15	34.04	17.02
2024/2025		24.91				0.11	0.09

6. Basis for the OFL

The author-preferred OFL for 2024 was 0.66 kt fishing at $F_{OFL} = 0.05$. This OFL was based on a tier 4 sloped harvest control rule that uses the survey estimates of >101mm carapace width crab as biomass, the average of survey estimates of >101mm carapace width crab from 1982-2023 as a proxy for B_{MSY}, and natural mortality as a proxy for F_{MSY}. The tier 3 harvest control rules were not recommended because the status quo reference points are too aggressive and the modification suggested by the CPT was too conservative. Using natural mortality as a proxy for F_{MSY} within the GMACS model is not straight-forward because the total fishery selectivity curve is shifted to the right of industry-preferred males. Even if a fishing mortality rate equivalent to natural mortality was identified the assessment model exhibited a lack of fit to large males and convergence problems.

The CPT recommended model 24.1b for use in specifying the 2024/25 OFL and ABC. Tables within this document have been updated to reflect this decision.

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. 'Years' indicates the year range used in the calculation of the proxy for BMSY. 'M' is the natural mortality for mature male crab. MMB here refers to functionally mature biomass. (continued below)

Year	Tier	BMSY	MMB	Status	Proj_MMB	Proj_Status	FOFL
2024/25	3c	94.8	13.4	0.14	11.28	0.14	0

Years	M
1982-2023	0.28

7. Basis for ABC

The ABC for the author-recommended model was 0.04 kt, calculated by subtracting a 20% buffer from the OFL. This buffer accounts for scientific uncertainty not directly considered in the assessment model like retrospective patterns and model misspecification.

This OFL is likely smaller than reasonable and an addendum to this document briefly discusses bycatch issues related to setting the ABC.

A. Summary of Major Changes

1. Management:

The eastern Bering Sea snow crab population was declared overfished in October 2021 and the directed fishery was closed for the 2022 and 2023 season.

2. Input data:

Data added to the GMACS model included: 2024 eastern Bering Sea survey biomass and length composition data and non-directed discard length frequency and discard biomass from the 2023 season.

3. Assessment methodology:

Management quantities were derived from maximum likelihood estimates of model parameters in a size-based, integrated assessment method using GMACS. Retrospective analyses and jittering analyses were performed for a selection of models. An application of tier 3 methodologies are used with assessment output to calculate management quantities. A single GMACS model is presented this year with an appendix that explores the impacts of using different definitions of reference points and currencies of management on management advice. Tier 4 methodologies for calculating the OFL using observed survey data are recommended for 2024.

4. Assessment results

The author-preferred OFL is based on a tier 4 harvest control rule that uses the survey estimates of >101mm carapace width crab as biomass, the average of survey estimates of >101mm carapace width crab from 1982-2023 as a proxy for B_{MSY}, and natural mortality (equal to 0.27) as a proxy for F_{MSY}. Although the GMACS model represent the best available science on the biology of stock, the status quo reference points allow the complete removal of large males because of large numbers of small mature males and an assumed equivalency between small and large mature males. It is unclear what fraction of the small morphometrically mature males are active in reproduction. An attempted revision of tier 3 reference points to incorporate this uncertainty resulted in very conservative management. Given the lack of convincing tier 3 reference points, the author-preferred tier 4 OFL for 2024 is 0.66 kt fishing at $F_{OFL} = 0.05$.

The CPT recommended model 24.1b for use in specifying the 2024/25 OFL and ABC. Tables within this document have been updated to reflect this decision. This resulted in an OFL of 0.05 kt and an ABC of 0.04 kt. The CPT requested additional analyses related to the specification of bycatch which are now included with this document as an addendum.

B. Comments, responses and assessment summary

SSC and CPT comments + author responses from June 2024

SSC comment: The SSC requests that the Clark maximin re-analysis more closely follow the original analysis, which was carefully crafted to encompass a reasonable range of discrete stock productivities. Clark (1991) used both Ricker and Beverton Holt curves, used three curves intended to span a plausible range of steepness (0.50, 0.67, and 0.80), and excluded alternatives of 0.33 and 0.89 steepness. The SSC notes that FX% is the fishing mortality associated with an X percent reduction in spawning output per recruit (not percent reduction in stock size as shown in the draft document). It will be important to provide plots showing yield and the percent reduction in the different reproductive output measures as a function of fishing mortality. The SSC also requests that an exploitation rate be reported in addition to fishing mortality, which can be misleading because of the right-shifted selectivity curve for snow crab. This shift results in very few crab experiencing full-selection fishing mortality. Ideally, this analysis would use the parameters estimated in the GMACS operational model, rather than the snow crab research model.

This has been done to the best of my ability in the time available and is detailed in appendix A.

SSC comment: Concerning the GMACS assessment model, the SSC continues to recommend that the assessment author explore ways to incorporate the molt to maturity data in the model in a way that reflects the observation error associated with those estimates. An analysis in a GLMM modeling framework, which treats years as random effects, would provide smoother estimates, accommodate differing sample sizes by year and length, and deal appropriately with years in which data are missing. Another possibility that was suggested in the CPT report was to include the annual observed probabilities of terminal molt as data and then fit them, as in the Tanner crab assessment.

Not addressed in this document. The observation error is not considered when preparing the data that enters the assessment, so it is hard to understand how trying to consider uncertainty in the model that doesn't exist in the input data will provide meaningful results. I will try to do a better job of explaining this in my presentations. This is not to say there is no uncertainty in the probability of undergoing terminal molt, only that it is a less pressing problem than identifying appropriate reference points for snow crab.

SSC comment: The SSC recommends that this model be brought forward in the fall but requests that an additional Tier 4 model be provided for comparison, as recommended in the Simpler Modeling Workshop report and requested in the SSC's June 2023 and October 2023 Reports. This additional model would use the random effects model (REMA) to smooth survey estimates and would not decrement with natural mortality.

This is included in this document.

Previous unaddressed SSC and CPT comments (cumulative)

Each of these points has been discussed to some extent at CPT meetings and will be addressed more thoroughly when time allows.

From Sept 2023:

SSC comment: The SSC strongly supports the plans of the CPT to evaluate other metrics for reproductive output. The CPT may want to consider a multi-attribute measure of reproductive output. For example, both percent reduction in mature male biomass and percent reduction in large males could be evaluated as a function of fishing mortality.

SSC comment: Figure 23 on page 73 of the SAFE report shows the decline in CPUE over a season by statistical area and year. This represents a kind of depletion experiment, suggesting that total mortality (Z) could be estimated from the linear parameters representing each line. This might help determine spatial patterns in F, indicate the natural bounds for F and M, and assist in determining stock status.

SSC comment: Investigate whether there is information outside the assessment model (e.g., larval or post-settlement data) or in the model supporting estimated skewed sex-ratios at recruitment.

Assessment summary

Six assessment models are presented here:

- 23.1 – Last year's accepted model
- 24.1 – Last year's model fit to this year's data
- 24.1a – 24.1 + correcting an issue with indexing of molting probabilities
- 24.1b – 24.1a + using >95 mm carapace width biomass as MMB
- 24.1c – 24.1b + using SBPR% derived from analyses in appendix A

The underlying population dynamics of these models change very little (Table 7), but the way reference points and management advice is calculated changes. Recent changes to the way terminal molt is modeled resulted in the status quo reference points allowing complete removal of the large males. The updated population dynamics reflect the best available science on the biology, but the impacts on reference points is undesirable given uncertainty on the importance of large males in reproduction.

Here analyses are presented to attempt to incorporate another axis of reproductive uncertainty into the calculation of reference points (described in appendix A). Uncertainty in the stock recruit relationship is already incorporated into the SBPR reference points used for snow crab (and nearly all Alaskan stocks for which detailed assessments exist); the enclosed analysis uses the same methodology to incorporate the uncertainty around the size of reproductively active males. This analysis results in much higher target biomasses for larger males and adopting these reference points would result in a federally closed fishery.

Two alternative methodologies for providing catch advice are presented that use the observed survey biomass of >101mm carapace width males (i.e. the industry preferred size) instead of assessment model output. Natural mortality (~0.27) is used as a proxy for F_{MSY}. The first method is the tier 4 methodology outlined in the front matter of the crab SAFE documents. A harvest control rule is used and the survey biomass is decremented by natural mortality to the time of the fishery. This method would result in an OFL of 0.66 kt. The second method was requested by the SSC and is simply the product of the observed survey biomass and an exploitation rate set equal to natural mortality. This method returns an OFL of ~3.9 kt.

Although the new SBPR analyses provide a methodology consistent with current management to address reproductive uncertainty, they result in much more conservative management than historically used for snow crab (particularly in retrospect as this strategy would have declared the fishery overfished from 2014-present with closures beginning in 2018). Given the drastic change in estimated stock status, the author-preferred method for calculating the OFL is the first tier 4 method described above in which the OFL was 0.66 kt. This retains a slope in the HCR, decrements the biomass to reflect mortality before the fishery, and focuses management on the portion of the stock vulnerable to fishing. The OFL of 0.66 kt is several times the recent non-directed bycatch values, so should not constrain non-directed fisheries.

The CPT recommended the model 24.1b after the September 2024 CPT meeting, see the minutes for a justification.

C. Introduction

Studies and data relevant to key population and fishery processes are discussed below to provide background for the modeling choices made in this assessment. A model description is available on the github repository for GMACS and the files needed to reproduce these assessments also have a github repo, both of which are linked at the end of this document.

Distribution

Snow crab (*Chionoecetes opilio*) are distributed on the continental shelf of the Bering Sea, Chukchi Sea, and in the western Atlantic Ocean as far south as Maine. In the Bering Sea, snow crab are distributed widely over the shelf and are common at depths less than ~200 meters (Figure 1 for distribution over time and Figure 2 for 2024 distribution of all males). Smaller crab tend to occupy more inshore northern regions (Figure 3 & Figure 4) and mature crab occupy deeper areas to the south of the juveniles (Figure 5 & Figure 6; Zheng et al. 2001). The eastern Bering Sea population within U.S. waters is managed as a single stock; however, the distribution of the population may extend into Russian waters to an unknown degree.

Natural Mortality

Relatively few targeted studies exist to determine natural mortality for snow crab in the Bering Sea. Nevissi, et al. (1995) used radiometric techniques to estimate shell age from last molt (Figure 7). The total sample size was 21 male crab (a combination of Tanner and snow crab) from a collection of 105 male crab 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 crab with SC4 (very old shell) and SC5, was 4.95 years (range: 2.70 to 6.85 years). Given the small sample size, this maximum age may not represent the 1.5% percentile of the population that is approximately equivalent to Hoenig's method (1983). Tag recovery evidence from eastern Canada revealed observed maximum ages in exploited populations of 17-19 years (Nevissi, et al. 1995, Sainte-Marie 2002). A maximum time at large of 11 years for tag returns of terminally molted mature male snow crab in the North Atlantic has been recorded since tagging started about 1993 (Fonseca, et al. 2008). Fonseca, et al. (2008) estimated a maximum age of 7.8 years post terminal molt using data on dactal wear.

In recent years, the mean for the prior for natural mortality used in the eastern Bering Sea snow crab assessment was based on the assumption that longevity would be at least 20 years in an unfished 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). 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 produced natural mortalities larger than 0.23 (Table 5). Then et al. (2015) compared several major empirical estimation methods for M (including Hoenig's method) with an updated data set and found that maximum age was the best available predictor. A maximum age of 20 years corresponded to an M of ~0.315 in Then et al.'s analysis. Hamel (2015) developed priors in a similar manner to Then et al., but forced the regression of observed natural mortality onto maximum age through the intercept, which resulted in an M of ~0.27 for an assumed maximum age of 20 years.

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

	23	20	17
Then	0.277	0.315	0.365
Hoenig (1983)	0.19	0.212	0.257
Hoenig (2013)	0.194	0.223	0.261
Hamel	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 8). 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 (0.271). A standard error of 0.0054 was used for initial priors and was estimated using the 95% CI of +-1.7 years on maximum age estimates from dactal wear and tag return analysis in Fonseca, et al. (2008). 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.

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; Figure 9). 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 (see Richar and Foy, 2022 for details).

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). Mature male snow crab that do not molt 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.

Mating ratio and reproductive success

Bering Sea snow crab 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 crab, which are nearly 100% mature. Male snow crab are sperm conservers, using less than 4% of their sperm at each mating and females also can 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 would 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, some aspect of female reproduction is likely also an important indicator of reproductive potential of the stock.

Clutch fullness is recorded for the females measured in the survey (Figure 10). 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 even then the proportion of barren females was low (Figure 11). 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 crab 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 crab that molted soon after being captured were collected. The crab 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 crab 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). Crab in their first few years of life may molt more than once per year, however, the smallest crab included in the model are approximately 4 years old and would be expected to molt annually.

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 a proxy for 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 the B_{MSY} proxy. 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 the B_{MSY} proxy (Zheng et al. 2002).

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

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 crab 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, as is the case for snow crab. The range of years of recruitment used to calculate biomass reference points is from 1982 to the present assessment year, minus 1. However, recent analyses suggest SPR-based reference points do not provide a meaningful constraint on the snow crab fishery when the probability of having undergone terminal molt is specified to reflect observations in the survey. This is because a large fraction of the population matures (and ceases growing) at a size smaller than is harvested by the fishery.

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, the fishery was closed for the first time in 2022 following the collapse observed in 2021.

Discard mortality from the directed fishery 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. There was no discard mortality in 2022 because there was no directed fishery.

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 12). 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 2023 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 were 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 years 1982 to 1991 in the model using the estimated fishery selectivities based on the observer data for the period of survey year 1992 to 2023. 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 6 for a summary of catch data.

Table 6: Data included in the assessment. Dates indicate survey year. The 2020 survey was cancelled due to the pandemic.

Data component	Years
Retained male crab pot fishery size frequency by shell condition	1982 - 2023
Discarded Males and female crab pot fishery size frequencey	1992 - 2023
Trawl fishery bycatch size frequencies by sex	1991 - 2023
Survey size frequencies by, maturity, sex and shell condition	1982 - 2019, 2021 - 2024
Retained catch estimates	1982 - 2023
Discard catch estimates from crab pot fishery	1992 - 2023
Trawl bycatch estimates	1993 - 2023
Total survey abundance estimates and coefficients of variation	1982 - 2019, 2021 - 2024
2009 study area biomass estimates, CVs, and size frequencey for BSFRF and NMFS tows	2009
2010 study area biomass estimates, CVs, and size frequencey for BSFRF and NMFS tows	2010

Survey biomass and size composition data

Estimates of of the numbers of crab by sex and size from the annual eastern Bering Sea (EBS) bottom trawl survey conducted by NMFS (e.g. Figure 13 & Figure 14; see Lang et al., 2018 for materials and methods; see the most recent tech memo for detailed description) are used to calculate the primary indices of abundance used in this assessment. 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. Biomass and abundance of crab in several size groups are currently at or near all-time lows (Figure 15 & Figure 16).

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. All old shell crab of both sexes were assumed to be mature. New shell crab were demarcated as any crab with shell condition index <= 2. The biomass of new and old shell mature individuals was calculated by multiplying the vector of numbers at length by weight at length. These vectors were then summed by sex to provide the input for assessment (Table 10). Input sample sizes are specified as 200 for both sexes and maturity states for all years of survey size composition data given the very large number of sampled crab (see tech memo for numbers).

Spatial distribution of survey abundance and catch

Snow crab are distributed widely over the eastern Bering Sea shelf, but their density and the extent of their distribution has changed over time (Figure 1 & Figure 2). 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 5 & Figure 6) while smaller males have been more prevalent on the northern portion of the shelf (Figure 3 & Figure 4). The centroids of abundance for male crab sized 45-85 mm carapace width have moved over time (Figure 17). 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 & Figure 20). This is possibly due to the proximity to port and practical constraints of meeting delivery schedules. Unstandardized CPUE (hereafter just 'CPUE') in the fishery has varied over time and an increase in average CPUE occurred after rationalization (Figure 21 & Figure 22). The change in CPUE in a given spatial area within a season can reflect the impact of the fishery on the population in that area. Declines in CPUE can be seen by spatial area over time within a season (Figure 23), and the mean weekly change in CPUE is -11.6 (Figure 24). Total catch in an area is negatively correlated with the change in CPUE–that is, higher catches in an area are related to larger declines in CPUE (Figure 24).

The observed distribution of large males during the summer survey and the fishery catch have historically differed, 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 25). 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, but 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 <= to 1 for at least some of the size classes) can provide an empirical estimate of catchability/selectivity (Figure 26). Empirical estimates of catchability/selectivity vary by year and size class across the different BSFRF data sets (Figure 27 & Figure 28). The number of snow crab used to develop estimates of numbers at length likely contribute to these differences among years (Figure 29), 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 empirical estimates of selectivity are used are priors on estimated selectivity in the currently used assessment model.

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 is used to set an acceptable biological catch (ABC) that is less than or equal to the OFL, which in turn provides a ceiling to the TAC set by the state process.

Model description

Recently, the Generalized Model for Assessing Crustacean Stocks (GMACS) was adopted as the assessment platform for snow crab after a demonstration that GMACS could effectively reproduce the dynamics of the status quo model and offered structural improvements. GMACS is an integrated, size-structured model developed using automatic differentiation software developed as a set of libraries under C++ (ADModel Builder). ADModel Builder can estimate a large number of parameters in a non-linear model using automatic differentiation software extended from Greiwank and Corliss (1991) and developed into C++ class libraries.

The snow crab population dynamics model tracks the number of crab of sex s, maturity state m, during year y at length l, $\mathrm{N}_{s,m,y,l}$. 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 132.5 mm carapace width, with 5 mm size classes. For the author-preferred model, 407 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), and catchability. The yearly probability of undergoing terminal molt, weight at length, discard mortality, bycatch mortality, variance in growth increment, and parameters associated with proportion of recruitment allocated to size bin were estimated outside of the model or specified. See the GMACS repo linked at the end of this document to peruse the control files that specify the populations 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 a selected number of models here. Retrospective analyses were also performed here in which the terminal year of data was removed sequentially from the model fitting process. 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.

Only a single population dynamics model is presented here, with the differences among the model runs related to data inputs and assumptions about reference points or currency of management. A correction was made in the indexing of the probability of undergoing terminal molt for male crab. The probabilities measured in 2019 (for example) occurred as a result of processes that happened in 2018, but in the 2023 assessment the 2019 data were input as informing the process in 2019. This revision means that only model 24.1a, 24.1b, and 24.1c should be under consideration for provision of management advice.

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 models converged with updated data and the overall fit to the data improved from model 24.1 to 24.1a (Table 11). Retrospective patterns were relatively small compared to historical patterns (Figure 30). Jittering analyses produced larger scatter than expected in management quantities with only a single model converging to the lowest negative log likelihood (Figure 31; three models are shown to demonstrate changes in the reference points and management advice, but only one model configuration exists). The source of these convergence issues is unclear, but under investigation. Below, the fits to the data and estimated population processes are identical for the models available for consideration in management (24.1a, 24.1b, 24.1c). Consequently, the contribution of likelihood components to the objective function (Table 11), parameter estimates, and standard deviations (Table 12) are identical for these models.

Fits to data

Survey biomass data

Fits to the survey morphometrically mature male biomass improved for recent years with the revision of the probability of undergoing terminal molt in model 24.1a, but fits earlier in the time series degraded (Figure 32 & Figure 33).

Growth data

No differences existed in the estimates of the relationship between pre- and post-molt increment among the models for consideration in management (Figure 34). The resulting size-transition matrices for males appears to be broadly consistent with studies on crab growth (e.g. Herbert et al., 2001; Figure 35).

Catch data

Catch data were fit well for all models (Figure 36).

Size composition data

Most years of retained and total catch size composition data were visually well fit (Figure 37 & Figure 38). In some years, more crab were estimated in the largest size bins than observed (e.g. 1992, 2005, 2009). Predictions of female discards in the directed fishery were right-skewed for some years, potentiallly reflecting unmodeled time-variation in the availability of females to the directed fishery (Figure 39). Estimated size composition of the catch in non-directed fisheries was the least well fit of the catch sources, but the models were fairly consistent in their fits (Figure 40 & Figure 41). Residuals for the author-preferred model can be seen in (Figure 42, Figure 43, Figure 44, Figure 45, and Figure 46).

Size composition data for the NMFS survey were generally acceptably fit and fits were visually similar for most data sources in most models in most years (Figure 47, Figure 48, Figure 49, Figure 50, Figure 51, Figure 52, Figure 53 & Figure 54). Poor fits often occurred at the smallest size bins, which is likely related to the interplay of poor and variable selectivity at small sizes with pseudocohorts (i.e. groups of similarly sized crab used in place of 'cohort' because we cannot age crab) that were first observed (and subsequently persisted) at larger sizes (Figure 55, Figure 56, Figure 57, Figure 58, Figure 59, Figure 60, Figure 61 & Figure 62). Predicted mature male size compositions displayed rather conspicuous lack of fit to the larger size bins from 2022 to 2024 (Figure 61). This resulted in fewer large males predicted than observed for this period of time (Figure 63).

Estimated population processes and derived quantities

Estimated population processes and derived quantities varied little among presented models given the similarity of their formulation. One exception is MMB estimates, which had different definitions for different models (Figure 64). Models 23.1, 24.1, and 24.1a all use morphometrically mature male biomass as the currency for MMB and have a similar (but not identical) scale and trends. Models 24.1b and 24.1c use mature males >95mm carapace width as the currency of management and differ in the SBPR% used to define the minimum stock size threshold (24.1b = 35%; 24.1c = 45%, based on appendix A). Using the larger males as a currency of management results in more pessimistic perception of the status of the stock, with model 24.1b estimating the stock was beneath MSST since 2014 with a brief increase above it in 2019.

The number and biomass of crab that are commercially preferred (>101 mm carapace width) are two of the most important figures to come out of the assessment because they are directly related to the calculation of the OFL. The raw time series of commercially preferred males biomass is one of the time series considered in the state strategy and comparing the survey estimates to the assessment model estimates can provide context for the impact of selecting among models. Given only one population dynamics model is presented for consideration here, there is only a single time series available to compare to the observations (Figure 63). The assessment estimates of industry preferred biomass is somewhat higher on average than the observations due to the incorporation of the BSFRF survey selectivity information. However, in the last three years, the estimates are slightly smaller than the observed biomass, owing in part to the predicted size composition data. It is important to note that the commercially preferred biomass is not a quantity to which the model fits; this is purely a derived quantity.

The scale and shape of the survey selectivity curves are all similar since moving to using the BSFRF data directly as priors on survey selectivity at size rather than as an additional survey (Figure 65). Over all, estimates of survey selectivity for males mostly stayed within the implied uncertainty of the CVs associated with the BSFRF priors with small departures at smaller sizes (Figure 66). Retained and total fishery selectivity estimates for males were nearly identical for all models, but capture selectivity in the directed fishery varied among models (Figure 67).

Estimated fully-selected fishing mortality in the directed and non-directed fleets were slightly lower in the models with updated probability of undergoing terminal molt (Figure 68). Estimates of fully-selected fishing mortality are quite high in some years, and this is partially related to the shape of the total fishery selectivity curve (Figure 67). These fishing mortalities can be translated to exploitation rates by dividing the number of crab greater than a given size removed during the fishing season by the number of crab present at the beginning of the fishing season (the fishing season is effectively instantaneous; Figure 69). These calculated exploitation rates are lower than the ~100% fully-selected fishing mortality, but still high (Figure 70).

The specified probabilities of undergoing terminal molt are calculated as the proportion of new shell crab by size that are mature based on chela height (Richar and Foy, 2022; Figure 71). These proportions are used to divide the survey data into ‘mature’ and ‘immature’ data to calculate size compositions that are input into the assessment. Higher probabilities of terminally molting at smaller sizes results in much more of the population ceasing to grow beneath the size at which they would be harvested in the directed fishery. This has large impacts on estimated SBPR-based reference points, which will be discussed below.

Patterns and scale in recruitment by sex changed slightly when updating the probability of terminal molt data (Figure 72). The addition of the survey data resulted in an increase in the estimated male recruitment of the most recent three years. No clear relationship exists between the calculated mature male biomass (the currency of which changes among models) and recruitment (Figure 73).

Estimated average natural mortality was very similar to the input prior for all models (~0.27) (Figure 74). Estimated mortality events in 2018 and 2019 were most intense for immature females and males, but even the lower mortalities for mature crab resulted in >80% of crab dying.

F. Calculation of the OFL

Methodology for OFL

Tier 3

Historically, 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 spawning-biomass-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 to the stock 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:

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

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

In addition to the status quo tier 3 control rule, two variations were tested here that vary in what the currency of management is (i.e. morphometrically mature biomass vs. >95mm carapace width mature male biomass) and the percentage of unfished biomass to be used as a management target. The status quo SBPR reference points are based on 35% of unfished biomass that resulted from Clark's original analyses; a scenario is presented here that uses 45% based on analyses specific to snow crab biology and that incorporate additional uncertainty around the reproductively active portion of the stock (see appendix A).

Calculated tier 3 OFLs ranged from 0.05 to 20.15 kt (Table 13). Differences in OFLs were a result of differences in estimated MMB, the currency used for MMB, and the SBPR% used. Correcting the probability of terminal molt (model 24.1) decreased the OFL from 20.15 to 19.60 kt, of which only 7.9 kt is retained. Using 'functional mature biomass' (i.e. >95mm carapace width mature male biomass) as the currency of management resulted in closures of the directed fishery (i.e. zero retained catch). Using the snow crab specific SBPR% derived from the analyses in appendix A also resulted in the closure of the directed fishery, but with an even lower status determination.

Tier 4

Two tier 4 OFLs were calculated based on the survey biomass estimates of males >101mm carapace width. The first mirrors the tier 4 control rule defined in the introduction to the crab SAFE documents which is very similar to the tier 3 HCR defined above. However, in the tier 4 HCR, an average biomass over 1982-2023 was used as the biomass target and natural mortality was used as the fishing mortality target. The observed survey biomass was decremented by 7 months of natural mortality before the calculated F_{OFL} was applied to the stock to produce the OFL. This method produced an OFL of 0.66 kt (Table 14). The second method was simply the product of the observed survey biomass estimates of males >101mm carapace width smoothed using REMA (Figure 75) and the natural mortality translated to an exploitation rate. The OFL from this method was 3.92 kt.

G. Calculation of the ABC

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

Author recommendations

Recent changes to the population dynamics model used for snow crab aligned the GMACS model with the best available science on reproductive biology. However, all of the large males can be removed from the population using that model and status quo reference points, which seems like an undesirable outcome. This assessment attempted to address this outcome by incorporating the uncertainty in contribution to reproduction of mature male crab by size into the reference points.

Appendix A outlines the methodology used to do this. It provides rationale for using a larger currency of management than morphometrically mature crab (e.g. >95mm carapace width males) and identifies a proportion of the unfished spawning biomass per recruit (SBPR%) that integrates over the uncertainty in reproductive contribution. This proportion is much larger than if one assumes small crab are reproductively identical to large males. The new SBPR% and use of >95mm carapace width male biomass as the management currency are ideologically consistent with the existing management framework, but they result in much more conservative outcomes than historical management. Applying model 24.1b retrospectively, the stock would have been declared overfished in 2014 (Figure 69).

Conflicting anecdotes exists for the importance of large males in the reproductive dynamics of snow crab. It is difficult to make the case that status quo management is 'working' to provide high, sustained levels of biomass of large males on which to fish. After the collapse in 1999 from periods of historical highs, fishing mortalities were greatly decreased and the stock rebuilt, but to levels much lower than those observed in the 1990s (Figure 69). As fishing pressure was ramped up again, the stock began to decline again, this time to a much lower 'bottom' than in the 2000s, exacerbated by a marine heatwave in 2018 and 2019. The end result is a stock of commercially preferred males for which the 8 lowest observed survey biomasses occurred in the last 8 years.

At the same time, immature female biomass observed in the survey during 2024 was the highest ever observed. A portion of these females would have been spawned during a time when large male biomass was very low (~2019/2020). The largest estimated recruitments on record also came at times when large male abundances were relatively low (Figure 72). Recruitment for snow crab has been linked to environmental conditions (e.g. Szuwalski et al., 2021) and females store sperm, so it might be the case that large males are not that important in reproduction, provided environmental conditions are 'good'. The small males observed in the survey during 2022 also seem to be surviving and making their way through the size classes, so an argument might be made to allow a small fishery to alleviate some of the financial burden the industry is suffering while banking on the incoming recruits to backfill.

Another point for consideration is that large males might be necessary to produce more large males if there is density dependence in the probability of terminally molting (which has been suggested in eastern Canada; Mullowney and Baker, 2021). In Alaska, there does appear to be a increase in the probability of maturing at size for a male crab when densities of large males are higher (compare 2021 to 1991 in Figure 76, for example and refer to the appendix of the May 2024 snow crab assessment document). In addition to the potential for plasticity in size at maturity, there is also an unexplored potential for genetic changes if only small males are reproducing. So, even if the small mature males could sustain the population, it's not clear that the population produced would have the qualities needed to support the production of large biomasses of large males that the fishery captures.

In light of these points, precaution seems appropriate. The author-recommended OFL is 0.66 kt, based on the "4_author" scenario (Table 14), a sloped harvest control rule that decreases the proportion of the F_{MSY} proxy that is applied to the stock as biomass declines. It does not consider fishery selectivity and applies the fishing mortality to all crab >101 mm carapace width. This control rule would have closed the fishery in the last 3 years, but not before that, which is more consistent with State management than the tier 3 models presented.

In the future, a tier 4 harvest control rule could be applied within the GMACS model, but an equivalent fishing mortality to natural mortality would have to be calculated with consideration for the estimated fishery selectivity. There was not time to accomplish this during this assessment cycle. Even if there were time, the estimates of large male biomass from GMACS were considerably lower than the survey observations, due to poor fits to the survey size composition (i.e. the model underpredicted the proportion of the mature biomass in the largest size classes), which would be useful to address before using GMACS and a modified tier 4 rule. Convergence problems seen through the jittering analyses further strengthen the recommendation to use a survey biomass-based tier 4 harvest control rule this year, but with the intention of using the GMACS model in the future.

The CPT ultimately recommended model 24.1b for use in setting the OFL and ABC (see the meeting minutes for details).

H. Data gaps and research priorities

Knowing how active small morphometrically mature males are in reproduction would provide a clearer path to management. This is a difficult question to answer by dive surveys in the way eastern Canadians were able to in their protected and shallower bays. The Bering Sea is larger, deeper, and stormier. Manned or un-manned submersibles with video equipment might be a more realistic, but expensive, method for collecting this information in the Bering Sea. Experimental evaluation of the prospect of density dependence in terminal molt processes would also shed light on the importance of preserving large males in the population. The largest observation of immature females in the survey occurred during 2024 and would have spawned sometime in the last 5-6 years, which was a period of historically low large male biomass and may also have a link to density dependence or environment, both of which should be explored.

Data weighting continues to be a topic that is acknowledged as important to modeling outcomes, but secondary to finding an appropriate model and harvest control rule configuration. A thorough examination of the data streams in the assessment including reconstructing historical time series (rather than appending a year of data to the existing data file) and reevaluating the data sets to which the assessment is fit (e.g. should immature crab or very large crab also be fit) may be useful.

I. Ecosystem considerations

See the ESP for snow crab specific indices of environmental variation that may be relevant to stock dynamics (Appendix B).

J. Supplemental information

Input and output for the models described here can be found at https://github.com/szuwalski/snow_2024_9.

GMACS code and documentation can be found at: https://github.com/GMACS-project.

K. References

Chilton, E.A., C.E. Armisted and R.J. Foy. 2009. Report to industry on the 2009 Eastern Bering Sea crab survey. AFSC Processed Report 2009-XX.

Clark, W.G. 1991. Groundfish exploitation rates based on life history parameters. Can. J. fish. Aquat. Sci. 48: 734-750.

Conan, G.Y. and Comeau, M. 1986. Functional maturity and terminal molt of male snow crab. Can J. Fish Aqaut Sci. 43(9):

Dawe, E.G., D.M. Taylor, J.M. Hoenig, W.G. Warren, and G.P. Ennis. 1991. A critical look at the idea of terminal molt in male snow crab (Chionoecetes opilio). Can. J. Fish. Aquat. Sci. 48: 2266-2275.

Ennis, G.P., Hooper, R.G. Taylor, D.M. 1988. functional maturity in smalle male snow crab. Can J Fish Aquat Sci. 45(12):

Ernst, B, J.M.(Lobo) Orensanz and D.A. Armstrong. 2005. Spatial dynamics of female snow crab (Chionoecetes opilio) in the eastern Bering Sea. Can. J. Fish. Aquat. Sci. 62: 250-268.

Fonseca, D. B., B. Sainte-Marie, and F. Hazel. 2008. Longevity and change in shell condition of adult male snow crab Chionoecetes opilio inferred from dactyl wear and mark-recapture data. Transactions of the American Fisheries Society 137:1029-1043.

Fournier, D.A. and C.P. Archibald. 1982. A general theory for analyzing catch-at-age data. Can.J.Fish.Aquat.Sci. 39:1195-1207.

Greiwank, A. and G.F. Corliss(eds). 1991. Automatic differentiation of algorithms: theory, implementation and application. Proceedings of the SIAM Workshop on the Automatic Differentiation of Algorithms, held Jan. 6-8, Breckenridge, CO. Soc. Indust. And Applied Mathematics, Philadelphia.

Hamel, O. 2015. A method for calculating a meta-analytical prior for the natural mortality rate using multiple life history correlates. ICES Journal of Marine Science. 72: 62-69.

Hoenig, J. 1983. Empirical use of longevity data to estimate mortality rates. Fish. Bull. 82: 898-903.

Lang, C. A., J. I. Richar, and R. J. Foy. 2019. The 2018 eastern Bering Sea continental shelf and northern Bering Sea trawl surveys: Results for commercial crab species. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-386, 220 p.

McAllister, M.K. and Ianelli, J.N. 1997. Bayesian stock assessment using catch-at-age data and the sampling importance resampling algorithm. Can. J. Fish. Aquat. Sci. 54(2): 284-300.

Mcbride (1982). Tanner crab tag development and tagging experiments 1978-1982. In Proceedings of the International Symposium of the Genus Chionoecetes. Lowell Wakefield Fish. Symp. Ser., Alaska Sea Grant Rep. 82-10. University of Alaska, Fairbanks, Alaska. Pp. 383-403.

Methot, R. D. 1990. Synthesis model: An adaptable framework for analysis of diverse stock assessment data. Int. N. Pac. Fish. Comm. Bull. 50:259-277.

Murphy, J.T. Rugolo, L.J., Turnock, B.J. 2018. Estimation of annual, time-varying natural mortality and survival for Eastern Bering Sea snow crab (Chionoecetes opilio) with state-space population models. Fish Res 205: 122-131.

Murphy, J.T. Rugolo, L.J., Turnock, B.J. 2017. Integrating demographic and environmental variables to calculate an egg production index for the Eastern Bering Sea snow crab (Chionoecetes opilio). Fisheries Research. 193: 143-157.

Murphy, J. T., A. B. Hollowed, J. J. Anderson. 2010. Snow crab spatial distributions: examination of density-dependent and independent processes. Pp. 49-79. In G. Kruse, G. Eckert, R. Foy, G. Kruse, R. Lipcius, B. St. Marie, D. Stram, D. Woodby (Eds.), Biology and management of Exploited Crab Populations Under Climate Change. Alaska Sea Grant Program Report AK-SG-10-01, University of Alaska Fairbanks, AK. Doi:10.4027/bmecppc.2010.19

Myers, R.A. 1998. When do environment-recruitment correlations work? Reviews in Fish Biology and Fisheries. 8(3): 285-305.

Nevissi, A.E., J.M. Orensanz, A.J.Paul, and D.A. Armstrong. 1995. Radiometric Estimation of shell age in Tanner Crab, Chionoecetes opilio and C. bairdi, from the eastern Bering Sea, and its use to interpret indices of shell age/condition. Presented at the International symposium on biology, management and economics of crab from high latitude habitats October 11-13, 1995, Anchorage, Alaska.

NPFMC (North Pacific Fishery Management Council). 2007. Environmental Assessment for Amendment 24. Overfishing definitions for Bering Sea and Aleutian Islands King and Tanner crab stocks. North Pacific Fishery Management Council,Anchorage, AK, USA..

NPFMC (North Pacific Fishery Management Council). 2000. Bering Sea snow crab rebuilding plan. Amendment 14. Bering Sea Crab Plan Team, North Pacific Fishery Management Council,Anchorage, AK, USA..

NPFMC 1998. Bering Sea and Aleutian Islands Crab FMP. Bering Sea Crab Plan Team, North Pacific Fishery Management Council, P. O. Box 103136, Anchorage, Ak 99510.

Orensanz, J.M., J. Armstrong, D. Armstrong and R. Hilborn. 1998. Crustacean resources are vulnerable to serial depletion - the multifaceted decline of crab and shrimp fisheries in the Greater Gulf of Alaska. Reviews in Fish Biology and Fisheries 8:117-176.

Otto, R.S. 1998. Assessment of the eastern Bering Sea snow crab, Chionoecetes opilio, stock under the terminal molting hypothesis. In Proceedings of the North Pacific Symposium on Invertebrate Stock Assessment and Management. Edited by G.S. Jamieson and A. Campbell. Can. Spec. Publ. Fish. Aquat. Sci. 125. pp. 109-124.

Parada, C., Armstrong, D.A., Ernst, B., Hinckley, S., and Orensanz, J.M. 2010. Spatial dynamics of snow crab (Chionoecetes opilio) in the eastern Bering Sea–Putting together the pieces of the puzzle. Bulletin of Marine Science. 86(2): 413-437.

Paul, A.J., J.M. Paul and W.E. Donaldson. 1995. Shell condition and breeding success in Tanner crab. Journal of Crustacean Biology 15: 476-480.

Restrepo, V.R, G.G. Thompson, P.M. Mace, W.L. Gabriel, L.L. Low, A.D. MacCall, R.D. Methot, J E. Powers, B.L. Taylor, P.R. Wade, and J.F. Witzig. 1998. Technical guidance on the use of precautionary approaches to implementing National Standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act. NOAA Technical Memorandum NMFS-F/SPO-31.

Rugolo, L.J., D. Pengilly, R. MacIntosh and K. Gravel. 2005. Reproductive dynamics and life-history of snow crab (Chionoecetes opilio) in the eastern Bering Sea. Final Completion Report to the NOAA, Award NA17FW1274, Bering Sea Snow Crab Fishery Restoration Research.

Rodionov, S. 2004. A sequential algorithm for testing climate regime shifts. Geophysical Research Letters 21: L09204.

Sainte-Marie, B., Raymond, S., and Brethes, J. 1995. Growth and maturation of the male snow crab, Chionoecetes opilio (Brachyura: Majidae). Can.J.Fish.Aquat.Sci. 52:903-924.

Sainte-Marie, B., J. Sevigny and M. Carpentier. 2002. Interannual variability of sperm reserves and fecundity of primiparous females of the snow crab (Chionoecetes opilio) in relation to sex ratio. Can.J.Fish.Aquat.Sci. 59:1932-1940.

Somerton, D.A. and Otto, R.S. 1999. Net efficiency of a survey trawl for snow crab and Tanner crab. Fish Bull 97: 617-625.

Somerton, D.A. Weinberg, K.L., Goodman, S.E. 2013. Catchability of snow crab by the eastern Bering Sea bottom trawl survey estimated using a catch comparison experiment. Can.J.Fish.Aquat.Sci. 70: 1699-1708.

Szuwalski, C.S. 2022a. Stock assessment of Eastern Bering Sea snow crab. Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Bering Sea and Aleutian Islands Regions. 2021 Crab SAFE. North Pacific Fishery Management Council,1007 West 3rd Ave., Suite 400, L92 Building, 4th floor. Anchorage, AK 99501

Szuwalski, C.S. 2021a. Stock assessment of Eastern Bering Sea snow crab. Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Bering Sea and Aleutian Islands Regions. 2021 Crab SAFE. North Pacific Fishery Management Council,1007 West 3rd Ave., Suite 400, L92 Building, 4th floor. Anchorage, AK 99501

Szuwalski, C.S. 2021b. An exploration of assessment options for eastern Bering Sea snow crab that consider additional time-variation in population processes. North Pacific Fishery Management Council,1007 West 3rd Ave., Suite 400, L92 Building, 4th floor. Anchorage, AK 99501

Szuwalski, C.S. 2020a. Stock assessment of Eastern Bering Sea snow crab. Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Bering Sea and Aleutian Islands Regions. 2021 Crab SAFE. North Pacific Fishery Management Council,1007 West 3rd Ave., Suite 400, L92 Building, 4th floor. Anchorage, AK 99501

Szuwalski, C.S., Cheng, W., Foy. R., Hermann. A.J., Hollowed, A.B., Holsman, K., Lee, J., Stockhausen, W., Zheng, J. 2020b. Climate change and the future productivity and distribution of crab in the eastern Bering Sea. ICES J. Mar. Sci. 78(2): 502-515.

Szuwalski, C.S. 2019a. Stock assessment of Eastern Bering Sea snow crab. Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Bering Sea and Aleutian Islands Regions. 2021 Crab SAFE. North Pacific Fishery Management Council,1007 West 3rd Ave., Suite 400, L92 Building, 4th floor. Anchorage, AK 99501

Szuwalski, C.S. 2019b. A summary of model runs requested by the CPT. North Pacific Fishery Management Council,1007 West 3rd Ave., Suite 400, L92 Building, 4th floor. Anchorage, AK 99501

Szuwalski, C.S. 2018a. Stock assessment of Eastern Bering Sea snow crab. Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Bering Sea and Aleutian Islands Regions. 2021 Crab SAFE. North Pacific Fishery Management Council,1007 West 3rd Ave., Suite 400, L92 Building, 4th floor. Anchorage, AK 99501

Szuwalski, C.S. 2018b. A summary of model runs requested by the CPT. North Pacific Fishery Management Council,1007 West 3rd Ave., Suite 400, L92 Building, 4th floor. Anchorage, AK 99501

Szuwalski, C.S. 2017a. Stock assessment of Eastern Bering Sea snow crab. Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Bering Sea and Aleutian Islands Regions. 2021 Crab SAFE. North Pacific Fishery Management Council,1007 West 3rd Ave., Suite 400, L92 Building, 4th floor. Anchorage, AK 99501

Szuwalski, C.S. and Punt, A.E. 2013. Regime shifts and recruitment dynamics of snow crab, Chionoecetes opilio, in the eastern Bering Sea. Fisheries Oceanography, 22: 345-354.

Szuwalski, C.S. and Punt, A.E. 2012. Fisheries management for regime-based ecosystems: a management strategy evaluation for the snow crab fishery in the eastern Bering Sea. ICES Journal of Marine Science. 70: 955-967.

Tamone, S.L., M. Adams and J.M. Dutton. 2005. Effect of eyestalk ablation on circulating ecdysteroids in hemolymph of snow crab Chionoecetes opilio: physiological evidence for a terminal molt. Integr. Comp. Biol., 45(120), p.166-171.

Then, A. Y., Hoenig, J. M., Hall, N. G., and Hewitt, D. A. 2015. Evaluating the predictive performance of empirical estimators of natural mortality rate using information on over 200 fish species. ICES Journal of Marine Science, 72: 82–92.

Turnock, B.J. 2016. Snow crab assessment model scenarios and convergence testing. Alaska Fishery Science Center.

watson, J. 1972. Mating behavior in the spider crab, Chionoecetes opilio. J Fish REs Boar Can 29: 447-449.

Zheng, J., S. Siddeek, D. Pengilly, and D. Woodby. 2002. Overview of recommended harvest strategy for snow crab in the Eastern Bering Sea. Regional Information Report No. 5J02-03. Alaska Department of Fish and Game. Juneau, Alaska.

Zheng, J., G.H. Kruse, and D.R. Ackley. 2001. Spatial distribution and recruitment patterns of snow crab in the eastern Bering Sea. Spatial Processes and management of marine populations. Alaska sea grant college program. AK-SG-01-02, 2001.

Table 7: Key differences in assumptions of presented models.

Process	24.1	24.1a	24.1b	24.1c
Sex	Both	Both	Both	Both
Maturity	Input	Input	Input	Input
BSFRF	Prior	Prior	Prior	Prior
Survey	Estimated non-parametric	Estimated non-parametric	Estimated non-parametric	Estimated non-parametric
Growth	Linear estimated	Linear estimated	Linear estimated	Linear estimated
Natural.M	By sex and maturity + 2018/19	By sex and maturity + 2018/19	By sex and maturity + 2018/19	By sex and maturity + 2018/19
Fishery	Logistic	Logistic	Logistic	Logistic

Table 8: Observed growth increment data by sex

Male premolt length (mm)	Male growth increment (mm)	Female premolt length (mm)	Female growth increment (mm)
16.1	6.9	93.8	23.8
19.2	7.4	18.6	6.6
19.8	6.7	19.3	5.9
20	6.3	19.37	4.87
20	6.3	19.8	7.1
20.1	7.9	20.2	4.7
20.3	6.1	20.3	5.9
20.6	8.3	20.4	6
20.7	7	20.4	6.3
20.7	8.5	20.6	4.5
21	6.8	20.7	6.3
21.23	5.18	20.7	6.7
21.9	6.5	20.8	6.5
22.2	5.9	20.8	6.5
23.48	4.79	20.8	6.8
24	8.3	21.25	7.48
25.2	7.6	21.4	6.6
25.6	5.8	21.6	6.1
25.9	5.2	21.94	6.77
26	6.2	22	6.2
29.9	10	22.2	7.5
30.3	10	22.3	7.1
30.7	9.8	22.8	6.8
44.2	14.5	22.8	7.4
44.7	12.6	22.9	5.7
56.5	13.5	23	8.2
57	13	23.09	6.17
57.63	10.97	24.2	6.7
58.7	13.8	24.2	7.2
59.3	15.8	24.4	6.3
60.3	14.8	25.2	6.8
60.8	17.6	25.4	6.3
62.3	19.5	25.5	9.1
64	20.7	25.5	7.4
64.7	18	25.7	6.8
67.6	18.4	25.9	6.8
67.9	17.4	26	7.1
74.5	19.4	26.2	6.4
79.9	17.9	26.4	5.4
89.8	20.2	26.5	7.4
89.9	22.2	26.9	7.5
89.9	22.4	26.9	7.6
93.8	23.8	27.4	7.7
		27.5	7.3
		28.1	6.4
		28.2	8.02
		28.2	7.6
		28.7	8.4
		28.7	7.3
		29	7.7

Male premolt length (mm)	Male growth increment (mm)	Female premolt length (mm)	Female growth increment (mm)
		29.1	9.3
		29.4	7.3
		29.5	8.9
		30.9	7.5
		32.8	12.1
		34.9	9.9
		35.3	12.3
		38.3	12.6
		38.9	14.1
		41	14.8
		42.1	12.5
		44.2	15.3
		44.3	15
		44.8	14.9
		45.2	14.4
		46.9	13.5
		47	14.4

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)	Non-directed bycatch (kt)
1982	11.85	1.27	0.02	0.37
1983	12.16	1.24	0.01	0.47
1984	29.94	2.76	0.01	0.5
1985	44.45	4.01	0.01	0.43
1986	46.22	4.25	0.02	0
1987	61.4	5.52	0.03	0
1988	67.79	5.82	0.04	0
1989	73.4	6.68	0.05	0.1
1990	149.1	15.21	0.05	0.71
1991	143	12	0.06	1.5
1992	104.7	17.06	0.12	2.28
1993	67.94	5.32	0.08	1.57
1994	34.13	4.03	0.06	2.67
1995	29.81	5.75	0.02	1.01
1996	54.22	7.44	0.07	0.66
1997	114.4	5.73	0.01	0.82
1998	88.09	4.67	0.01	0.54
1999	15.1	0.52	0	0.47
2000	11.46	0.62	0	0.41
2001	14.8	1.89	0	0.31
2002	12.84	1.47	0	0.17
2003	10.86	0.57	0	0.46
2004	11.29	0.51	0	0.63
2005	16.77	1.36	0	0.2
2006	16.49	1.78	0	0.42
2007	28.59	2.53	0.01	0.18
2008	26.56	2.06	0.01	0.18
2009	21.78	1.23	0.01	0.47
2010	24.61	0.62	0.01	0.14
2011	40.29	1.69	0.18	0.15
2012	30.05	2.32	0.03	0.22
2013	24.49	3.27	0.07	0.11
2014	30.82	3.52	0.17	0.13
2015	18.42	2.96	0.07	0.13
2016	9.67	1.31	0.02	0.06
2017	8.6	1.93	0.02	0.04
2018	12.51	2.86	0.02	0.23
2019	15.43	5.07	0.02	0.24
2020	20.41	5.8	0	0.07
2021	2.48	1.16	0	0.06
2022	NA	NA	NA	0.05
2023	NA	NA	NA	0.07

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	34.82	65.04
1983	90.13	0.2	161.6	0.13	35.09	65.57
1984	42.32	0.19	177.7	0.12	85.1	148.3
1985	6.12	0.2	71.84	0.11	43.1	73.82
1986	15.74	0.18	89.81	0.11	45.97	78.15
1987	122.6	0.16	194.6	0.11	74.29	130.8
1988	169.9	0.17	259.4	0.15	105.7	178.4
1989	264.2	0.25	299.2	0.11	92.42	162
1990	182.9	0.19	443.8	0.14	225.1	395.1
1991	214.9	0.19	466.6	0.15	278.7	439.7
1992	131.4	0.18	235.5	0.09	139	223.3
1993	132.1	0.16	183.9	0.1	77.23	127.6
1994	126.2	0.15	171.3	0.08	44.64	73.79
1995	168.7	0.14	220.5	0.13	38.18	67.3
1996	107.3	0.14	288.4	0.12	89.02	161.4
1997	103.8	0.2	326.8	0.1	171.5	290.8
1998	72.73	0.25	206.4	0.09	127.5	214.9
1999	30.89	0.21	95.85	0.09	52.04	85.72
2000	96.46	0.52	96.39	0.14	41.13	69.78
2001	77.24	0.28	136.5	0.12	39.99	69.26
2002	30.22	0.28	93.17	0.23	37.17	66.58
2003	41.71	0.31	79.07	0.12	31.53	54.97
2004	50.16	0.26	79.57	0.14	35.58	58
2005	64.85	0.17	123.5	0.11	39.85	62.96
2006	51.93	0.17	139.3	0.26	72.34	126.4
2007	55.89	0.22	153.1	0.15	74.72	132.5
2008	57.15	0.19	142	0.1	60.33	105.1
2009	52.16	0.21	148.2	0.13	77.51	129.9
2010	98.01	0.17	162.8	0.12	87.1	138.2
2011	175.8	0.18	167.1	0.11	94.38	150.1
2012	149.4	0.2	122.2	0.12	53.15	87
2013	131.4	0.17	97.46	0.12	43.13	73.64
2014	119.7	0.19	163.5	0.16	79.51	138.5
2015	85.13	0.17	80.04	0.12	35.84	57.19
2016	55.39	0.21	63.21	0.11	22	37.43
2017	106.8	0.21	83.96	0.13	20.74	36
2018	165.9	0.18	198.4	0.17	27.02	49.41
2019	110.4	0.2	169.1	0.17	28.95	53.7
2021	31.66	0.43	62.25	0.13	12.44	23.53
2022	22.44	0.41	37.5	0.15	13.49	24.59
2023	14.96	0.24	24.21	0.13	11.44	20.03
2024	40.96	0.24	63.04	0.13	17.07	29.42

Table 11: Contribution to the objective function by individual likelihood component by model. Total likelihoods from models 23.1 and 23.2 are not comparable to the other models because they still fit the BSFRF data as an extra survey. Models 23.3a and 23.3b estimate parametric survey selectivity with a prior; 23.3 specifies survey selectivity.

Component	Fishery	24.1	24.1a	24.1b	24.1c
catch	Retained	-2.38	-16.66	-16.66	-16.66
catch	Discard (male)	85.1	69.72	69.72	69.72
catch	Discard (female)	-69.66	-69.66	-69.66	-69.66
catch	Trawl	-53.41	-53.41	-53.41	-53.41
cpue	NMFS survey (era 1; females)	60.32	57.12	57.12	57.12
cpue	NMFS survey (era 2, females)	-5.09	-3.59	-3.59	-3.59
cpue	NMFS survey (era 1, males)	47.79	50.98	50.98	50.98
cpue	NMFS survey (era 2, males)	1.27	2.99	2.99	2.99
growth_inc	1	1038.76	1040.7	1040.7	1040.7
growth_inc	2	0	0	0	0
rec_dev	1	0.8	0.8	0.8	0.8
rec_dev	2	0	0	0	0
rec_dev	3	79.25	77.81	77.81	77.81
size_comp	Retained males	-3645.07	-3634.65	-3634.65	-3634.65
size_comp	Survey mature females (1982-1988)	-685.32	-683.53	-683.53	-683.53
size_comp	Survey mature females (1989-present)	-3310.34	-3312.09	-3312.09	-3312.09
size_comp	Survey mature males (1982-1988)	-582.31	-583.09	-583.09	-583.09
size_comp	Survey mature males (1989-present)	-2894.48	-2861.27	-2861.27	-2861.27
size_comp	Total males	-2643.18	-2647.49	-2647.49	-2647.49
size_comp	Discard females	-2269.96	-2270.66	-2270.66	-2270.66
size_comp	Non-directed bycatch (females)	-2542.54	-2537.19	-2537.19	-2537.19
size_comp	Non-directed bycatch (male)	-2420.8	-2418.24	-2418.24	-2418.24
size_comp	Survey immature females (1982-1988)	-628.73	-630.01	-630.01	-630.01
size_comp	Survey immature females (1989-present)	-3129.03	-3135.12	-3135.12	-3135.12
size_comp	Survey immature males (1982-1988)	-541.06	-541.67	-541.67	-541.67
size_comp	Survey immature males (1989-present)	-2871.41	-2915.9	-2915.9	-2915.9
Total	Total	-25718.77	-25761.38	-25761.38	-25761.38

Table 12: Parameter estimates and standard deviations. Only models 24.1 and 24.1a are shown because 24.1b and 24.1c are identical to 24.1a. See .CTL files for names on github repo. A fix to display the names of the parameters is on the to do list.

Parameter	24.1	SD	24.1a	SD
theta[1]	0.29	0	0.28	0
theta[2]	0.27	0	0.28	0
theta[5]	5.6	226.53	NA	NA
theta[13]	9.58	0.73	9.59	0.75
theta[14]	9.59	0.6	9.59	0.61
theta[15]	9.64	0.47	9.63	0.48
theta[16]	9.87	0.38	9.84	0.38
theta[17]	10.57	0.39	10.5	0.38
theta[18]	11.25	0.35	11.21	0.35
theta[19]	11.69	0.27	11.66	0.27
theta[20]	11.87	0.25	11.85	0.25
theta[21]	11.9	0.25	11.9	0.25
theta[22]	11.93	0.25	11.94	0.25
theta[23]	11.93	0.24	11.93	0.24
theta[24]	11.72	0.24	11.7	0.25
theta[25]	11.49	0.24	11.47	0.25
theta[26]	11.32	0.22	11.28	0.23
theta[27]	11.36	0.21	11.34	0.21
theta[28]	11.17	0.16	11.19	0.16
theta[29]	10.47	0.17	10.51	0.17
theta[30]	9.58	0.2	9.65	0.2
theta[31]	8.56	0.26	8.65	0.26
theta[32]	7.57	0.31	7.67	0.31
theta[33]	6.77	0.34	6.86	0.34
theta[34]	6.34	0.4	6.42	0.4
theta[35]	14.04	0.41	12.78	0.36
theta[36]	13.77	0.21	13.54	0.28
theta[37]	13.31	0.24	13.62	0.23
theta[38]	13.36	0.2	13.37	0.2
theta[39]	12.69	0.19	12.56	0.2
theta[40]	12.72	0.2	12.67	0.2
theta[41]	12.51	0.19	12.51	0.19
theta[42]	12.14	0.22	12.18	0.22
theta[43]	11.83	0.25	11.87	0.25
theta[44]	11.39	0.24	11.46	0.24
theta[45]	10.71	0.28	10.79	0.28
theta[46]	10.27	0.3	10.34	0.3
theta[47]	10.1	0.27	10.16	0.28
theta[48]	9.46	0.28	9.56	0.28
theta[49]	8.3	0.33	8.42	0.33
theta[50]	7.26	0.37	7.37	0.37
theta[51]	6.47	0.42	6.56	0.41
theta[52]	5.9	0.46	5.97	0.46
theta[53]	5.48	0.51	5.55	0.51
theta[54]	5.18	0.55	5.24	0.55
theta[55]	4.97	0.61	5.02	0.6
theta[56]	4.86	0.68	4.92	0.68

Parameter	24.1	SD	24.1a	SD
theta[57]	11.91	0.64	12.08	0.69
theta[58]	11.99	0.55	12.13	0.58
theta[59]	12.12	0.44	12.21	0.46
theta[60]	12.34	0.28	12.36	0.28
theta[61]	13.33	0.2	13.34	0.2
theta[62]	13.62	0.14	13.64	0.15
theta[63]	13.15	0.15	13.18	0.15
theta[64]	12.3	0.19	12.32	0.19
theta[65]	11.27	0.26	11.28	0.26
theta[66]	10.11	0.31	10.12	0.31
theta[67]	9.32	0.37	9.32	0.37
theta[68]	8.77	0.43	8.76	0.43
theta[69]	8.44	0.5	8.43	0.5
theta[70]	8.16	0.55	8.15	0.55
theta[71]	7.9	0.58	7.89	0.58
theta[72]	7.63	0.59	7.62	0.59
theta[73]	7.39	0.59	7.38	0.59
theta[74]	7.18	0.6	7.18	0.6
theta[75]	7	0.6	7.01	0.61
theta[76]	6.86	0.62	6.87	0.62
theta[77]	6.76	0.65	6.78	0.66
theta[78]	6.71	0.72	6.73	0.73
theta[79]	-13.75	4190	-13.68	211.15
theta[80]	-13.81	4190	-13.75	211.15
theta[81]	-13.99	4190	-13.9	211.15
theta[82]	-14.1	4190	-14.03	211.15
theta[83]	-13.87	4190	-13.78	211.15
theta[84]	-13.6	4190	-13.5	211.15
theta[85]	-14.49	4190	-14.38	211.15
theta[86]	-15.54	4190	-15.45	211.15
theta[87]	-16.46	4190	-16.37	211.15
theta[88]	-17.14	4190	-17.07	211.15
theta[89]	-17.63	4190	-17.55	211.15
theta[90]	-17.96	4190	-17.89	211.15
theta[91]	-18.24	4190	-18.16	211.15
theta[92]	-18.46	4190	-18.39	211.15
theta[93]	-18.65	4190	-18.58	211.15
theta[94]	-18.82	4190	-18.74	211.15
theta[95]	-18.95	4190	-18.88	211.15
theta[96]	-19.07	4190	-19	211.15
theta[97]	-19.17	4190	-19.1	211.15
theta[98]	-19.25	4190	-19.17	211.15
theta[99]	-19.3	4190	-19.23	211.15
theta[100]	-19.33	4190	-19.26	211.15
Grwth[1]	2.29	0.08	2.32	0.08
Grwth[2]	-0.22	0	-0.21	0
Grwth[4]	0.21	0.11	0.22	0.11
Grwth[5]	-0.28	0	-0.28	0
log__slx__pars[1]	4.68	0	4.68	0
log__slx__pars[2]	1.45	0.03	1.44	0.03
log__slx__pars[3]	4.23	0.01	4.23	0.01
log__slx__pars[4]	1.05	0.03	1.05	0.03

Parameter	24.1	SD	24.1a	SD
log_slx_pars[5]	4.79	0.02	4.77	0.02
log_slx_pars[6]	2.42	0.02	2.41	0.02
log_slx_pars[7]	-2.74	0.24	-3.12	0.26
log_slx_pars[8]	-2.33	0.16	-2.4	0.17
log_slx_pars[9]	-1.96	0.15	-1.92	0.15
log_slx_pars[10]	-1.21	0.13	-1.18	0.12
log_slx_pars[11]	-1.31	0.12	-1.21	0.12
log_slx_pars[12]	-1.19	0.11	-1.17	0.11
log_slx_pars[13]	-0.98	0.1	-0.95	0.1
log_slx_pars[14]	-1	0.1	-0.99	0.1
log_slx_pars[15]	-1.15	0.11	-1.14	0.11
log_slx_pars[16]	-1.14	0.11	-1.14	0.11
log_slx_pars[17]	-1.06	0.11	-1.07	0.11
log_slx_pars[18]	-1.02	0.12	-1.04	0.12
log_slx_pars[19]	-0.97	0.12	-0.99	0.12
log_slx_pars[20]	-0.84	0.11	-0.85	0.11
log_slx_pars[21]	-0.78	0.11	-0.79	0.11
log_slx_pars[22]	-0.68	0.11	-0.7	0.11
log_slx_pars[23]	-0.54	0.1	-0.56	0.1
log_slx_pars[24]	-0.43	0.1	-0.44	0.1
log_slx_pars[25]	-0.33	0.09	-0.33	0.09
log_slx_pars[26]	-0.22	0.08	-0.22	0.08
log_slx_pars[27]	-0.1	0.08	-0.11	0.08
log_slx_pars[28]	-0.04	0.11	-0.04	0.11
log_slx_pars[29]	-4.12	0.26	-4.57	0.26
log_slx_pars[30]	-4.5	0.23	-4.88	0.22
log_slx_pars[31]	-3.97	0.19	-4.19	0.2
log_slx_pars[32]	-2.22	0.14	-2.21	0.14
log_slx_pars[33]	-1.35	0.12	-1.37	0.12
log_slx_pars[34]	-0.59	0.09	-0.61	0.09
log_slx_pars[35]	-0.54	0.09	-0.57	0.09
log_slx_pars[36]	-0.74	0.11	-0.76	0.11
log_slx_pars[37]	-0.81	0.12	-0.82	0.13
log_slx_pars[38]	-0.92	0.14	-0.92	0.14
log_slx_pars[39]	-0.91	0.14	-0.91	0.14
log_slx_pars[40]	-0.87	0.14	-0.87	0.14
log_slx_pars[41]	-0.83	0.14	-0.83	0.14
log_slx_pars[42]	-0.78	0.13	-0.79	0.13
log_slx_pars[43]	-0.72	0.13	-0.72	0.13
log_slx_pars[44]	-0.63	0.12	-0.63	0.12
log_slx_pars[45]	-0.53	0.11	-0.53	0.11
log_slx_pars[46]	-0.42	0.1	-0.42	0.1
log_slx_pars[47]	-0.31	0.09	-0.31	0.09
log_slx_pars[48]	-0.2	0.08	-0.2	0.08
log_slx_pars[49]	-0.08	0.08	-0.08	0.08
log_slx_pars[50]	-0.01	0.11	-0.01	0.11
log_slx_pars[51]	-4.1	0.17	-3.9	0.21
log_slx_pars[52]	-2.97	0.11	-2.73	0.1
log_slx_pars[53]	-2.08	0.1	-2.1	0.09
log_slx_pars[54]	-1.32	0.08	-1.45	0.07
log_slx_pars[55]	-1.26	0.07	-1.3	0.07
log_slx_pars[56]	-1.14	0.06	-1.13	0.06

Parameter	24.1	SD	24.1a	SD
log__slx__pars[57]	-1.08	0.06	-1.06	0.06
log__slx__pars[58]	-1.09	0.05	-1.04	0.05
log__slx__pars[59]	-1.27	0.06	-1.22	0.06
log__slx__pars[60]	-1.33	0.06	-1.26	0.06
log__slx__pars[61]	-1.32	0.06	-1.25	0.06
log__slx__pars[62]	-1.31	0.06	-1.24	0.06
log__slx__pars[63]	-1.24	0.06	-1.21	0.06
log__slx__pars[64]	-1.03	0.06	-1.04	0.07
log__slx__pars[65]	-0.8	0.07	-0.84	0.07
log__slx__pars[66]	-0.56	0.07	-0.6	0.07
log__slx__pars[67]	-0.38	0.07	-0.41	0.07
log__slx__pars[68]	-0.25	0.07	-0.27	0.07
log__slx__pars[69]	-0.2	0.07	-0.21	0.07
log__slx__pars[70]	-0.16	0.07	-0.16	0.07
log__slx__pars[71]	-0.12	0.08	-0.13	0.08
log__slx__pars[72]	-0.1	0.11	-0.11	0.11
log__slx__pars[73]	-4.13	0.15	-4.36	0.16
log__slx__pars[74]	-3.45	0.09	-3.5	0.09
log__slx__pars[75]	-2.91	0.09	-2.95	0.09
log__slx__pars[76]	-1.31	0.07	-1.35	0.07
log__slx__pars[77]	-0.68	0.06	-0.72	0.06
log__slx__pars[78]	-0.31	0.05	-0.35	0.05
log__slx__pars[79]	-0.45	0.05	-0.47	0.05
log__slx__pars[80]	-1.05	0.07	-1.07	0.07
log__slx__pars[81]	-1.13	0.1	-1.16	0.1
log__slx__pars[82]	-1.32	0.13	-1.34	0.13
log__slx__pars[83]	-1.25	0.15	-1.26	0.15
log__slx__pars[84]	-0.92	0.15	-0.92	0.15
log__slx__pars[85]	-0.83	0.14	-0.83	0.14
log__slx__pars[86]	-0.78	0.13	-0.78	0.13
log__slx__pars[87]	-0.71	0.12	-0.71	0.12
log__slx__pars[88]	-0.62	0.12	-0.62	0.12
log__slx__pars[89]	-0.52	0.11	-0.52	0.11
log__slx__pars[90]	-0.42	0.1	-0.42	0.1
log__slx__pars[91]	-0.31	0.09	-0.31	0.09
log__slx__pars[92]	-0.2	0.08	-0.2	0.08
log__slx__pars[93]	-0.08	0.08	-0.08	0.08
log__slx__pars[94]	-0.01	0.11	-0.01	0.11
log__slx__pars[95]	4.58	0	4.58	0
log__slx__pars[96]	0.56	0.11	0.54	0.12
log__fbar[1]	0.06	0.07	-0.09	0.07
log__fbar[2]	-5.19	0.09	-5.33	0.1
log__fdev[1]	NA	NA	NA	NA
log__fdev[2]	NA	NA	NA	NA
log__foff[1]	-7.48	0.1	-7.37	0.1
log__fdov[1]	NA	NA	NA	NA
rec__dev__est	NA	NA	NA	NA
logit__rec__prop__est	NA	NA	NA	NA
m__dev__est[1]	1.74	0.12	1.76	0.12
m__dev__est[2]	0.65	0.21	0	0
m__dev__est[4]	0	0	0	0
m__dev__est[5]	2.5	0.07	2.82	0.06

Parameter	24.1	SD	24.1a	SD
m_dev_est[7]	0.88	0.35	0.95	0.33
m_dev_est[8]	1.54	0.21	1.39	0.25
m_dev_est[10]	2.68	0.26	2.54	0.21
m_dev_est[11]	1.15	1.52	1.18	1.12
m_mat_mult[1]	-0.2	0.04	-0.23	0.04
m_mat_mult[2]	0.08	0.05	0.1	0.05
sd_log_recruits	NA	NA	NA	NA
ParsOut	NA	NA	NA	NA
sd_log_ssb	NA	NA	NA	NA
sd_last_ssb	64.43	4.31	106.37	8.94

Table 13: Management quantities derived from maximum likelihood estimates by model using Tier 3 reference points. 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. The definition of MMB shifts from morphometrically mature to >95mm carapace width from 24.1a to 24.1b

Model	MMB	B35	F35	FOFL	OFL	M	avg_rec	Status
23.1	128.11	164.05	61.78	24.21	23.40	0.29	154.55	0.78
24.1	115.46	181.01	59.72	26.12	20.15	0.29	167.37	0.64
24.1a	106.52	191.81	49.63	25.07	19.60	0.28	164.98	0.56
24.1b	13.40	94.82	0.81	0.00	0.05	0.28	164.98	0.14
24.1c	13.40	121.91	0.53	0.00	0.05	0.28	164.98	0.11

Table 14: OFLs (1000t) based on survey biomass of >101 mm carapace width males (males_com). Tier '4_author' uses a harvest control rule described in the text and decrements the survey biomass by natural mortality expected between the survey and fishery. Tier '4_ssc' is the product of the exploitation rate associated with natural mortality and the survey biomass. Status represents the status of the population after the completed fishing year and can be used for overfished declarations. 'Years' indicates the year range used to calculate reference points. 'M' is the natural mortality for mature male crab.

Year	Tier	BMSY	Males_com	Status	FOFL	OFL	Years	M
2023/2024	4_author	57.27	14.58	0.25	0.05	0.66	1982-2022	0.27
2023/2024	4_SSC	NA	16.56	NA	0.27	3.92	NA	0.27

Table 15: Maximum likelihood estimates of mature male biomass (MMB), mature female biomass (FMB), and males >101mm biomass (1000 t) and numbers (in millions) at the time of the survey from the model which treats morphometrically mature biomass as MMB (24.1a). Columns 2-5 are subject to survey selectivity; columns 6-9 are the population values.

Survey year	FMB	MMB	Male >101 biomass	Male >101 (millions)	FMB	MMB	Male >101 biomass	Male >101 (millions)
1982	95.39	121.3	32.08	57.75	179.2	289.6	54.45	100.3
1983	72.43	136.3	37.75	65.46	136	324.9	61.88	110.5
1984	55.73	164.6	55.88	92.88	104.7	378.8	88.07	151.8
1985	46.34	182.1	62.49	101.1	87.09	418.2	96.14	161.8
1986	51.22	195.8	58.64	95.65	96.27	463.2	90.94	154.2
1987	105	226.5	62.94	103	198.1	543.6	97.94	166.6
1988	204.5	267.1	76.59	126.1	390.9	638.4	119.7	204.3
1989	273.3	279.6	107.9	177.3	489.8	666.7	150.1	253.7
1990	250.2	292	134.8	224	459.6	678.7	188.9	322.6
1991	207.3	295.5	155.4	243.9	384	644.9	209.2	338.4
1992	167.1	271.8	122.8	194.7	309.9	614.7	166.7	272.3
1993	140.1	227.5	80.71	131.3	258.2	553.2	111.4	186.5
1994	129.1	189.6	45.07	74.61	235.2	508.1	63.37	108
1995	134.9	206.7	47.28	80.41	242.6	560.8	67.78	118.4
1996	149	243.9	80.9	135.8	268.3	613	114.5	197.5
1997	145.5	264.1	126.2	205.2	266.2	596.9	173.8	290.8
1998	125.3	239.1	122.6	192.6	232.3	516.1	165.3	267.5
1999	100.4	165.4	71.98	112.6	187.3	376.4	97.16	156.9
2000	82.82	130.8	54.19	84.4	153.2	301.5	73.04	117.6
2001	79.3	104.4	38.93	61.88	144.3	249.3	53.23	87.41
2002	77.68	88.06	30	49.66	141.9	216.3	42.18	71.94
2003	69.29	87.33	38.62	63.38	127.9	202.5	53.61	90.48
2004	62.69	96.58	44.74	69.38	114.8	216.6	59.97	96.02
2005	75.35	95.66	37.44	57.63	132.2	227.4	50.07	79.66
2006	111.5	106.9	32.5	52.89	196.6	274.4	45.04	75.56
2007	114.7	136.3	47.35	77.96	209.8	345.3	65.99	111.8
2008	99.91	159.1	62.62	100	185.2	382.3	85.49	140.8
2009	85.26	154.6	71.14	114.4	157.3	358.4	97.53	161.7
2010	96.01	201.1	112.9	172.9	170.1	412.3	149.4	235.8
2011	130.6	159.5	80.24	123.9	231.8	343.4	107	170.4
2012	131.5	121.4	44.18	71.34	240.7	295.6	60.86	101.3
2013	115.9	117.7	38.46	65.13	214.4	294.1	54.76	95.22
2014	101	107.5	37.74	62.9	186.1	264.2	53.1	91
2015	94.54	91.53	27.01	44.32	173.2	233	37.74	63.81
2016	92.55	82.83	19.21	32.15	167.4	222.7	27.2	46.81
2017	132.9	127.8	22.26	37.2	229.3	353.1	31.49	54.14
2018	262.8	203.5	27.29	46.96	445	584	39.39	69.5
2019	135.7	142.2	29.19	52.62	230.6	388.4	43.62	80.08
2020	46.43	100.5	13.9	25.47	79.46	285	21.23	39.57
2021	35.93	69.05	6.74	11.73	61.63	202.6	9.97	17.81
2022	29.73	52.27	5.22	8.87	50.59	153.3	7.58	13.27
2023	29.97	44.77	4.33	7.18	51.04	131.2	6.18	10.6
2024	33.92	49.98	3.52	5.89	57.9	150.2	5.06	8.74

Table 16: Maximum likelihood estimates of mature male biomass (MMB), mature female biomass (FMB), and males >95mm biomass (1000 t) and numbers (in millions) at the time of the survey from the model which treats morphometrically mature biomass as MMB (24.1a). Columns 2-5 are subject to survey selectivity; columns 6-9 are the population values.

Survey year	FMB	MMB	Male >95 biomass	Male >95 (millions)	FMB	MMB	Male >95 biomass	Male >95 (millions)
1982	95.39	121.3	57.25	116.1	179.2	289.6	108.3	225.7
1983	72.43	136.3	63.58	125.6	136	324.9	117.3	240.1
1984	55.73	164.6	85.34	161.4	104.7	378.8	151.2	299.4
1985	46.34	182.1	91.39	168.4	87.09	418.2	158.1	306.9
1986	51.22	195.8	88.52	165.5	96.27	463.2	155.1	304.7
1987	105	226.5	97.14	183.1	198.1	543.6	171.4	339.5
1988	204.5	267.1	118.1	223.3	390.9	638.4	208.9	414.2
1989	273.3	279.6	156.2	289.6	489.8	666.7	253.5	496.7
1990	250.2	292	197.8	370.2	459.6	678.7	323.5	638.6
1991	207.3	295.5	205.2	359.5	384	644.9	315.6	588
1992	167.1	271.8	167.7	299	309.9	614.7	262.8	498.2
1993	140.1	227.5	116	213.6	258.2	553.2	187.2	365
1994	129.1	189.6	71.74	137.1	235.2	508.1	120.9	244.2
1995	134.9	206.7	80.13	157.5	242.6	560.8	138.8	286.7
1996	149	243.9	126.8	242.9	268.3	613	213.1	430.4
1997	145.5	264.1	175	318.4	266.2	596.9	278	535.1
1998	125.3	239.1	160.8	280.8	232.3	516.1	246.4	457.4
1999	100.4	165.4	97.08	170.8	187.3	376.4	150.7	282.7
2000	82.82	130.8	73.28	128.7	153.2	301.5	113.8	213.3
2001	79.3	104.4	55.11	99.51	144.3	249.3	87.86	168.8
2002	77.68	88.06	46.26	87.56	141.9	216.3	77.07	154.2
2003	69.29	87.33	54.67	100.6	127.9	202.5	87.83	170.7
2004	62.69	96.58	58.25	100.6	114.8	216.6	88.72	163.3
2005	75.35	95.66	49.48	85.57	132.2	227.4	75.78	140
2006	111.5	106.9	47.53	87.9	196.6	274.4	77.27	151.4
2007	114.7	136.3	68.45	126.9	209.8	345.3	111	217.6
2008	99.91	159.1	85.46	152.9	185.2	382.3	134.2	254.9
2009	85.26	154.6	97.5	175.4	157.3	358.4	153.7	293.1
2010	96.01	201.1	137	228.1	170.1	412.3	200.2	353.5
2011	130.6	159.5	99.98	169.1	231.8	343.4	148.6	267
2012	131.5	121.4	61.35	111	240.7	295.6	97.35	186.7
2013	115.9	117.7	59.08	113	214.4	294.1	98.78	198.5
2014	101	107.5	56.27	105.9	186.1	264.2	92.68	183.9
2015	94.54	91.53	41.19	77.38	173.2	233	68.17	135.6
2016	92.55	82.83	30.84	59.34	167.4	222.7	52.24	106
2017	132.9	127.8	35.58	68.36	229.3	353.1	60.17	122
2018	262.8	203.5	46.14	91.11	445	584	80.04	165.7
2019	135.7	142.2	54.86	112.8	230.6	388.4	99.09	211.6
2020	46.43	100.5	29.82	62.98	79.46	285	55.79	121.8
2021	35.93	69.05	15.67	33.05	61.63	202.6	29.63	65.12
2022	29.73	52.27	11.59	24.09	50.59	153.3	21.61	47.07
2023	29.97	44.77	9.11	18.61	51.04	131.2	16.72	35.99
2024	33.92	49.98	7.6	15.65	57.9	150.2	14.06	30.41

Table 17: Maximum likelihood estimates of total numbers of crab (billions), not subject to survey selectivity at the time of the survey.

Survey year	Total numbers
1983	10.04
1984	11.31
1985	16.05
1986	24.61
1987	24.32
1988	22.09
1989	17.68
1990	15.14
1991	15.73
1992	16.08
1993	15.41
1994	14.93
1995	12.86
1996	10.39
1997	8.403
1998	7.282
1999	6.715
2000	6.394
2001	5.725
2002	6.487
2003	7.311
2004	12.4
2005	11.49
2006	9.697
2007	7.93
2008	8.57
2009	12.26
2010	10.29
2011	8.976
2012	7.635
2013	8.301
2014	8.056
2015	17.61
2016	28.22
2017	39.11
2018	30.49
2019	10.12
2020	3.294
2021	4.663
2022	5.637
2023	10.37
2024	13.37

Table 18: Maximum likelihood estimates of functionally mature male biomass at mating, male recruitment (billions), and fully-selected total fishing mortaltiy.

Survey year	Mature male biomass	Male recruits	Fishing mortality
1982	71.89	3.15	0.48
1983	75.34	3.06	0.41
1984	81.47	3.35	0.78
1985	74.11	3.08	1.13
1986	71.55	1.03	1.19
1987	71.34	2.53	1.49
1988	90.82	0.22	1.31
1989	117.2	1.43	1.14
1990	83.25	3.7	2.55
1991	78.75	3.01	2.35
1992	77.53	1.25	2.33
1993	83.57	0.29	1.4
1994	58.45	0.09	1.27
1995	69.5	0.14	1.11
1996	97.5	0.52	1.15
1997	103.4	0.86	1.45
1998	101.4	0.2	1.27
1999	105.1	0.29	0.24
2000	79.42	0.56	0.28
2001	51.67	1.75	0.67
2002	44.36	1.29	0.66
2003	52.74	2.56	0.36
2004	56.62	1.3	0.33
2005	40.64	0.33	0.75
2006	39.27	0.39	0.84
2007	49.59	1.12	1.02
2008	72.3	1.4	0.66
2009	82.21	0.22	0.41
2010	137	0.46	0.27
2011	79.67	0.44	0.76
2012	46.15	1.27	1.16
2013	48.92	1.31	1.16
2014	38.67	8.6	1.62
2015	32.15	6.27	1.37
2016	29.36	0.52	0.82
2017	36.47	0.07	0.68
2018	13.94	0.12	2.31
2019	51.89	0.09	1.08
2020	22.96	1.69	3.14
2021	20.2	1.66	0.58
2022	17.16	4.69	0
2023	13.4	3.01	0

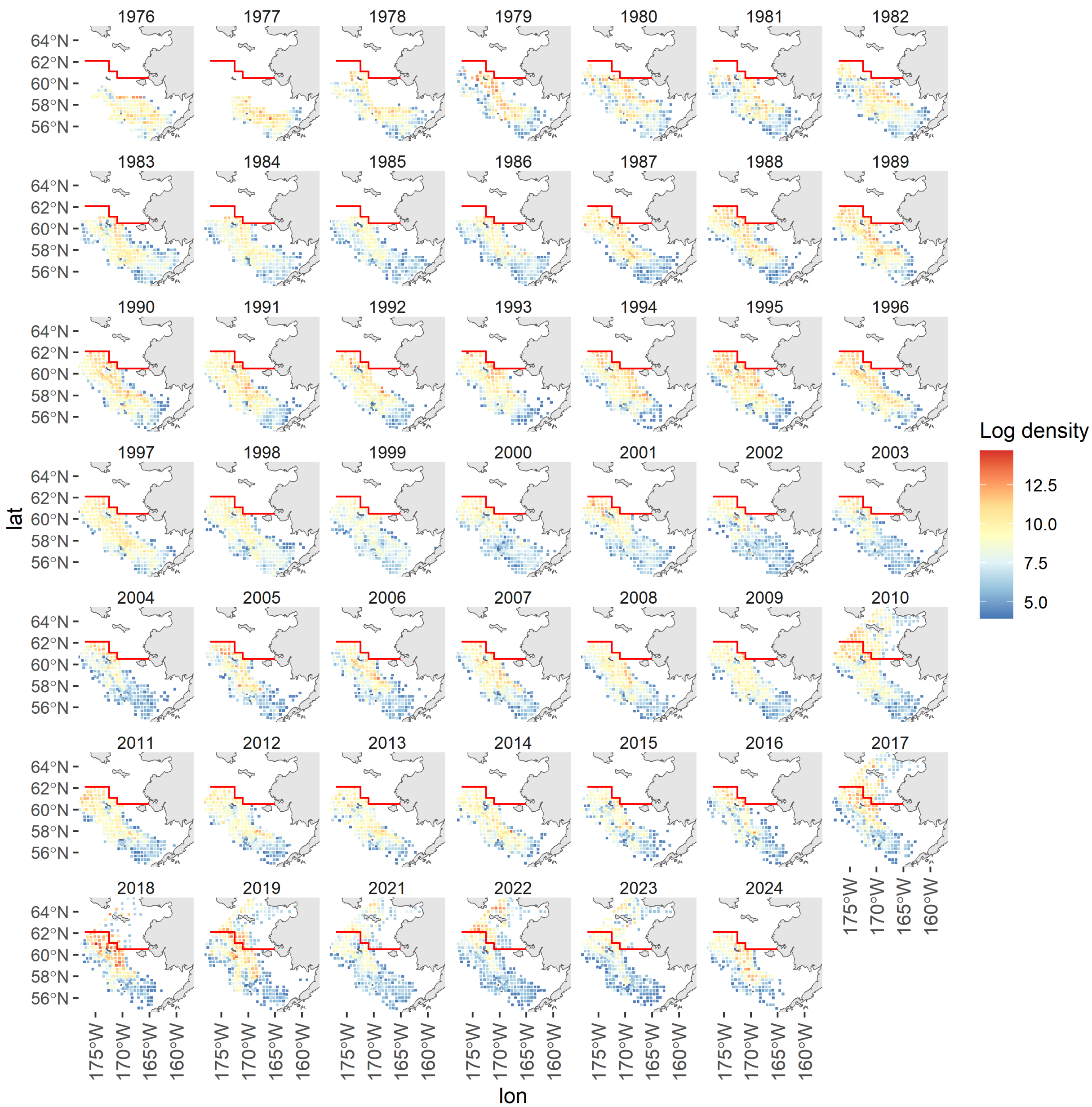

Figure 1: Observed relative density of all males over time during the NMFS summer survey. Each colored square in a facet represents a survey tow. Red line is the border between the EBS and NBS.

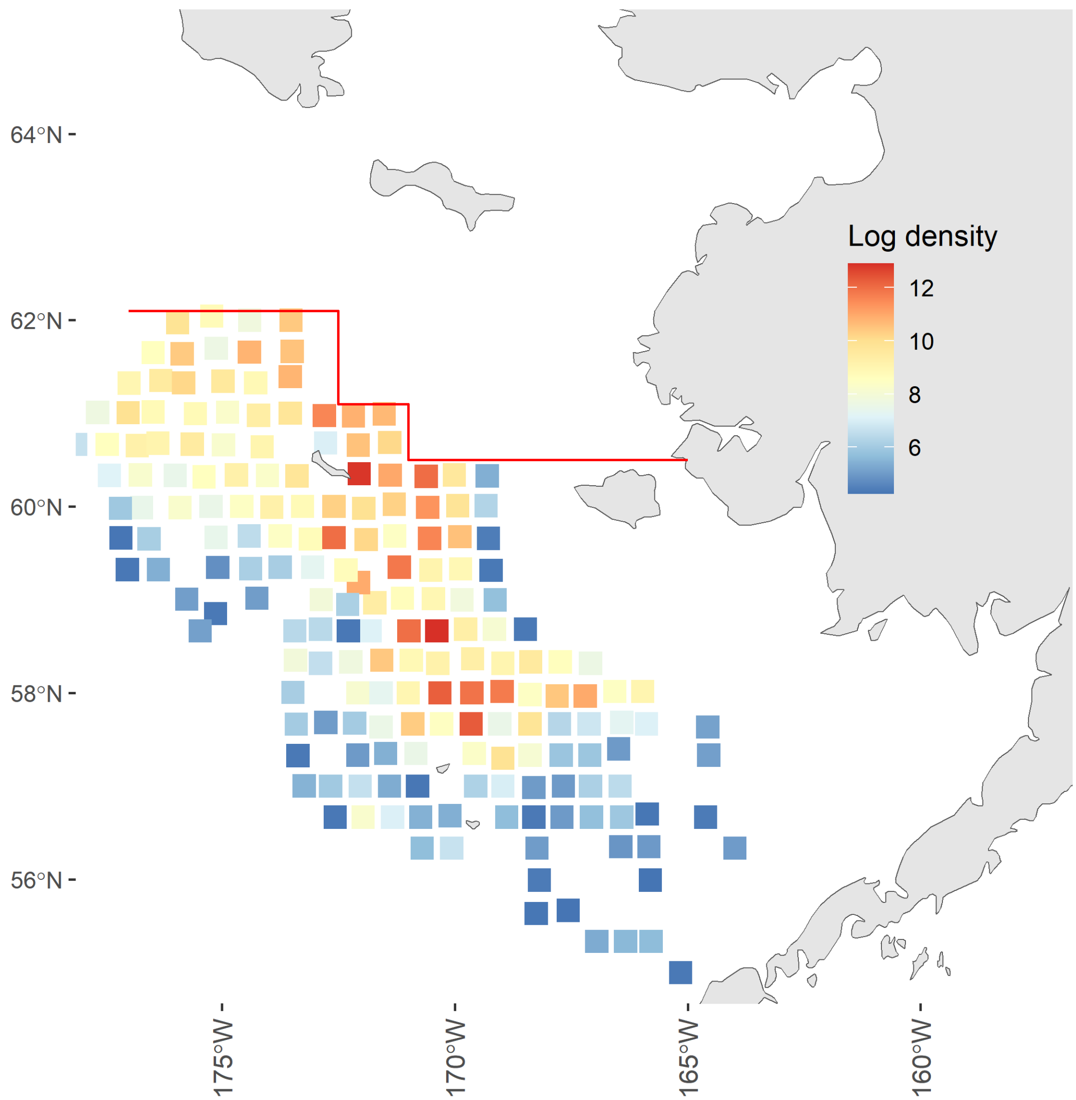

Figure 2: Observed relative density of all males at the time of the 2022 NMFS summer survey. Each colored square in a facet represents a survey tow. Red line is the border between the EBS and NBS.

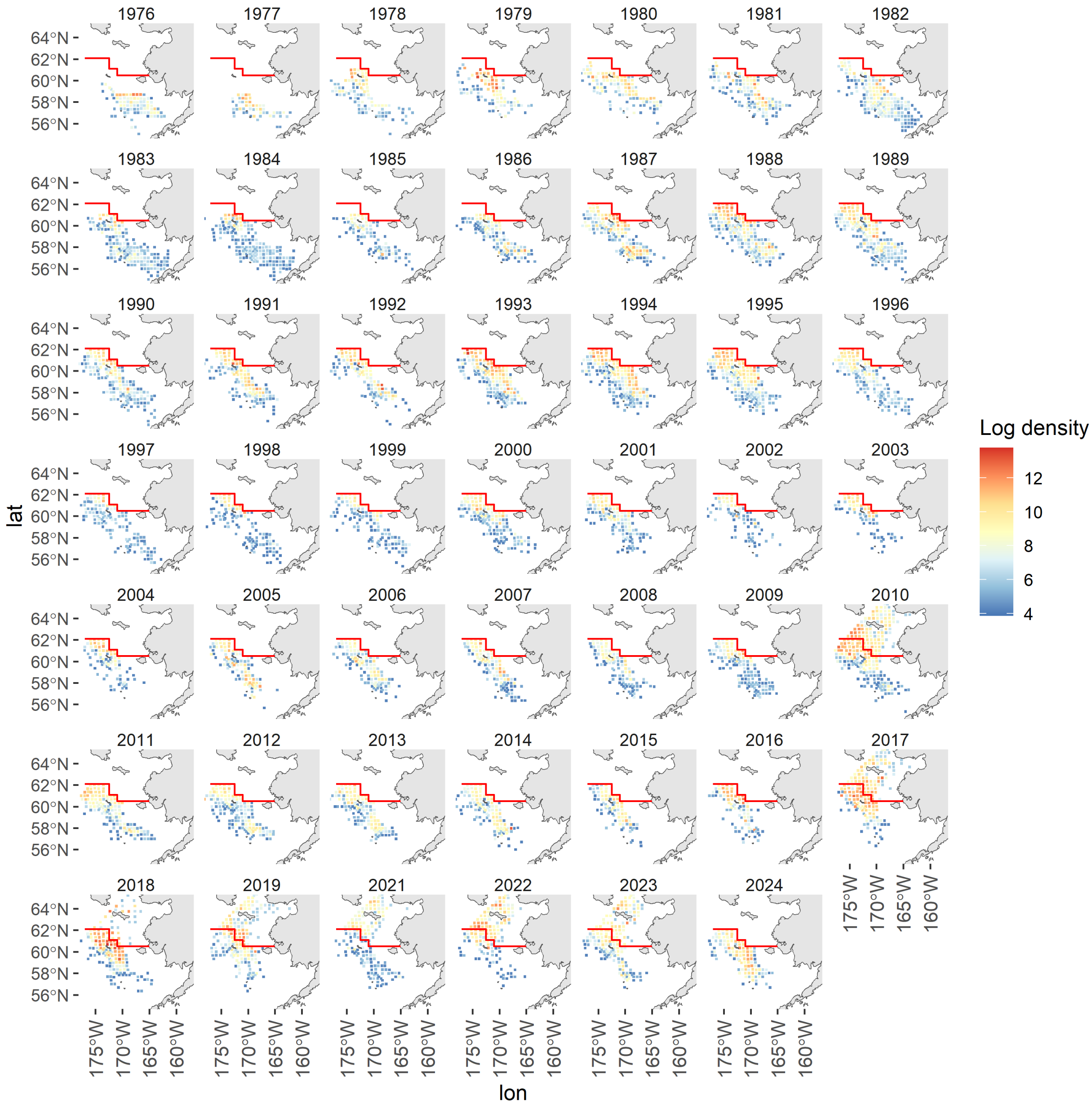

Figure 3: Observed relative density of 45-55 mm carapace width males over time during the NMFS summer survey. Each colored square in a facet represents a survey tow. Red line is the border between the EBS and NBS.

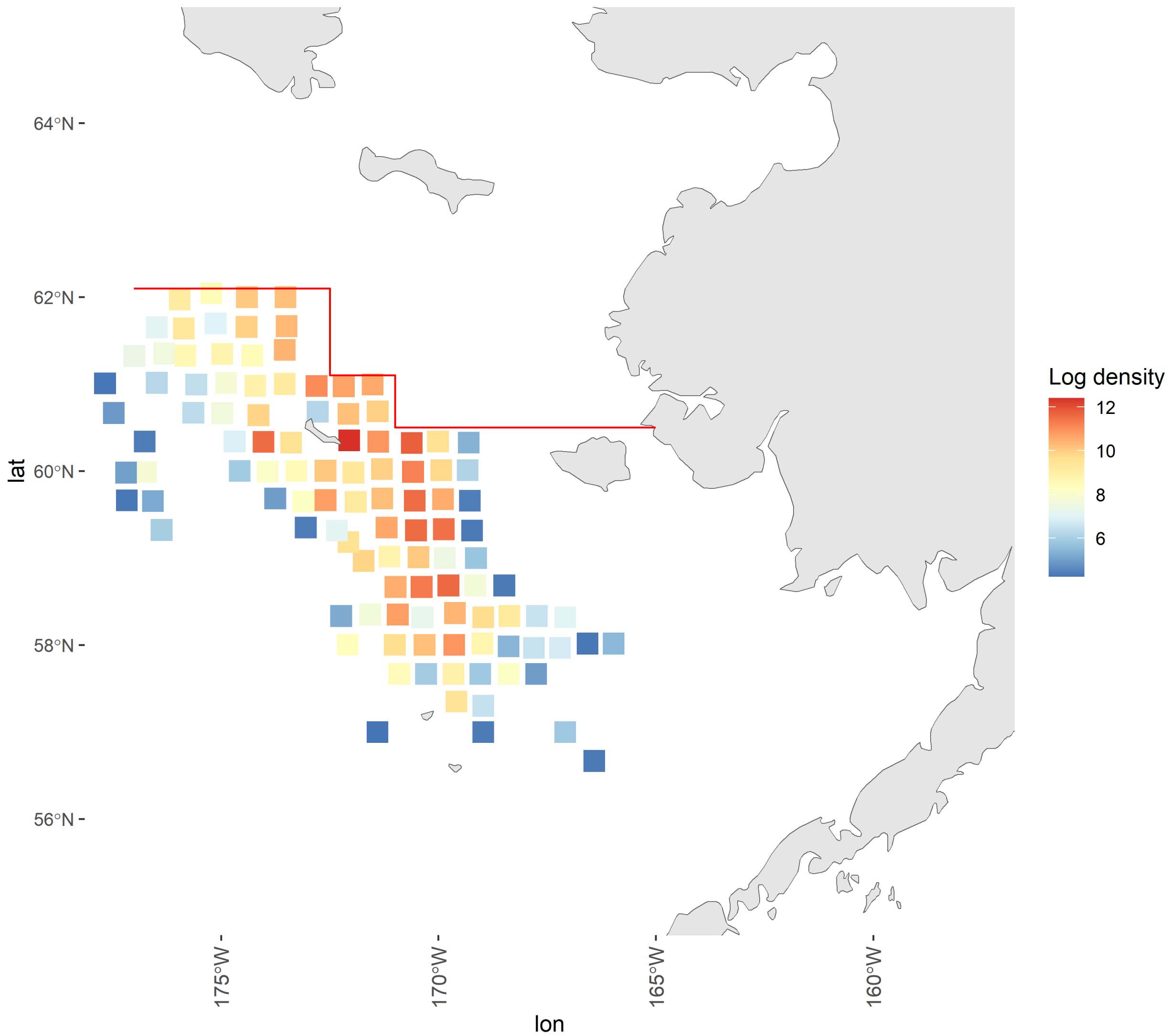

Figure 4: Observed relative density of males 45-55 mm carapace width at the time of the 2023 NMFS summer survey. Each colored square in a facet represents a survey tow. Red line is the border between the EBS and NBS.

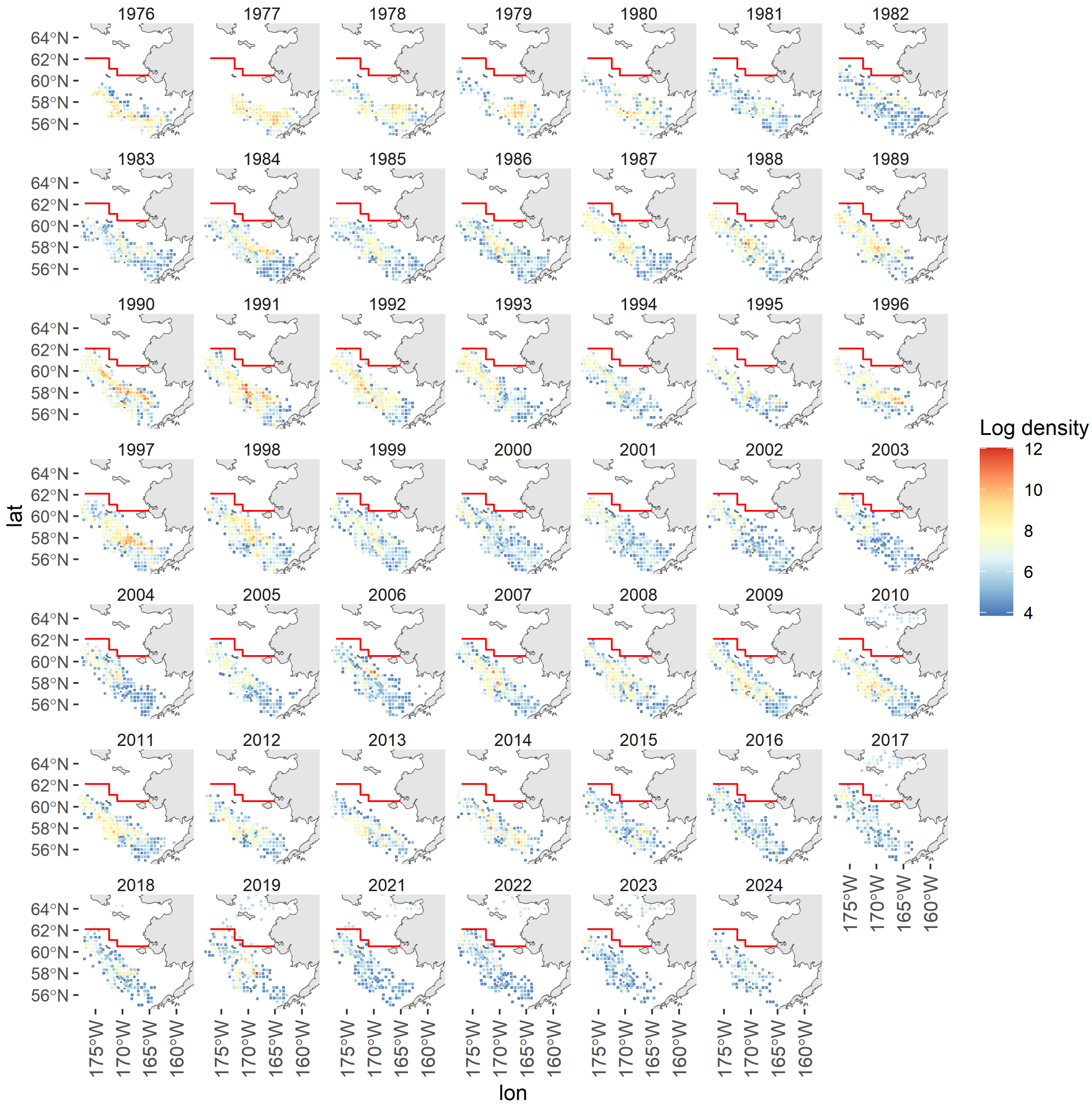

Figure 5: Observed relative density of >101 mm carapace width males over time during the NMFS summer survey. Each colored square in a facet represents a survey tow. Red line is the border between the EBS and NBS.

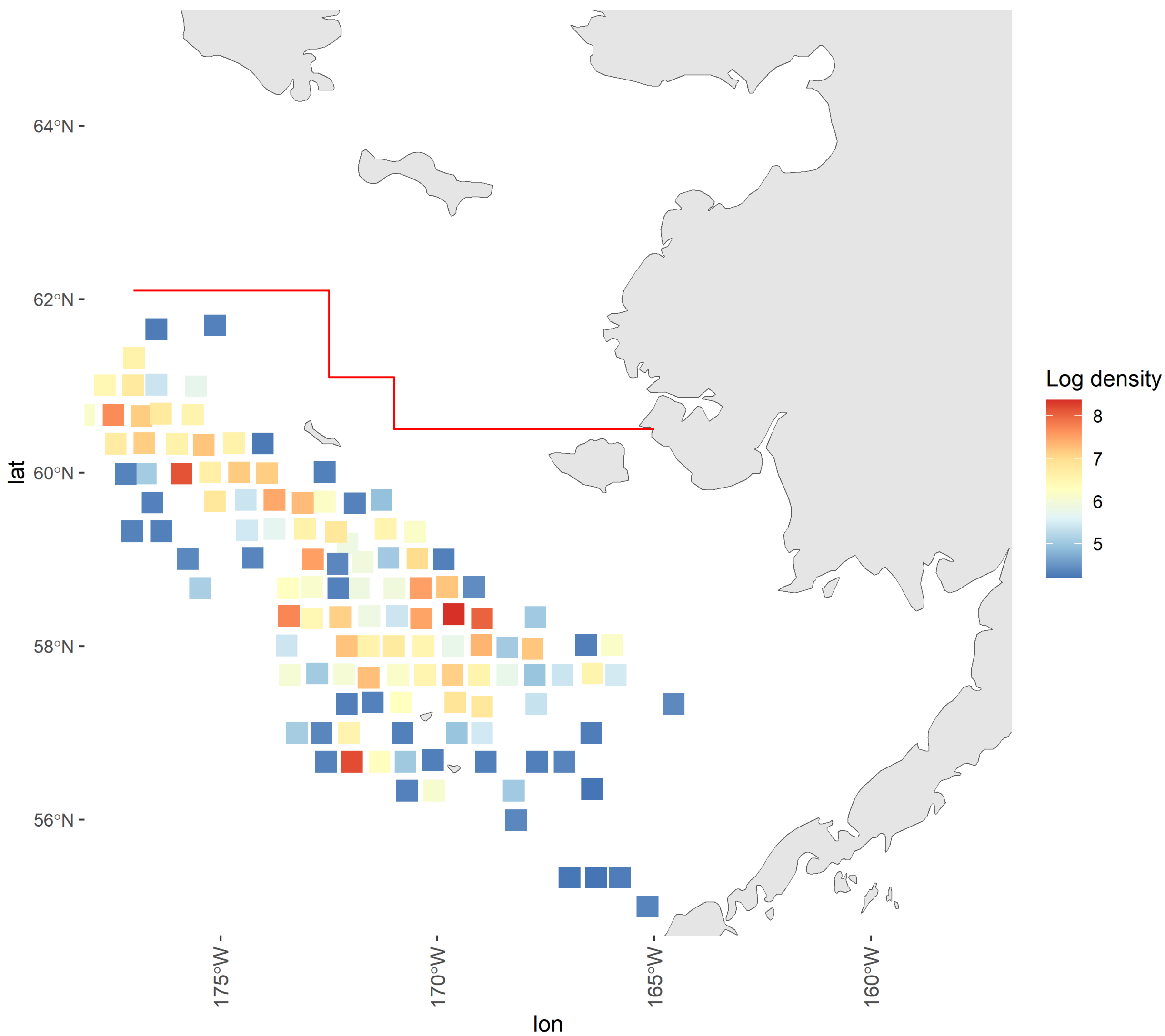

Figure 6: Observed relative density of males >101 mm carapace width at the time of the 2023 NMFS summer survey. Each colored square in a facet represents a survey tow. Red line is the border between the EBS and NBS.

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	*C. opilio*
0+	110	0.11	0.27	59°20′N, 171°49′W	43	*C. opilio*
0+	132	0.11	0.19	59°20′N, 171°49′W	43	*C. opilio*
1	118	0.15	0.26	59°20′N, 171°49′W	43	*C. opilio*
1	130	0.23	0.27	59°20′N, 171°49′W	43	*C. opilio*
1	116	0.25	0.24	59°20′N, 171°49′W	43	*C. opilio*
2+	93	0.33	0.28	57°00′N, 167°43′W	42	*C. bairdi*
2+	122	0.42	0.26	57°00′N, 167°43′W	42	*C. bairdi*
2+	97	0.66	0.30	59°00′N, 171°47′W	46	*C. opilio*
2+	123	0.78	0.32	59°00′N, 171°47′W	46	*C. opilio*
2+	121	0.85	0.27	57°00′N, 167°43′W	42	*C. opilio*
2+	66	1.07	0.29	59°00′N, 171°47′W	46	*C. opilio*
3	117	0.92	0.34	59°00′N, 171°47′W	46	*C. opilio*
3	69	1.04	0.28	59°00′N, 171°47′W	46	*C. opilio*
3	78	1.10	0.30	59°00′N, 171°47′W	46	*C. opilio*
4	100	4.43	0.33	57°21′N, 167°45′W	39	*C. opilio*
4	93	4.89	0.37	58°20′N, 171°38′W	52	*C. bairdi*
4	100	6.60	0.33	57°00′N, 167°43′W	42	*C. opilio*
5	111	2.70	0.44	58°60′N, 169°12′W	28	*C. opilio*
5	100	4.21	0.34	59°00′N, 171°47′W	46	*C. bairdi*
5	110	6.85	0.58	58°60′N, 169°12′W	28	*C. opilio*

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

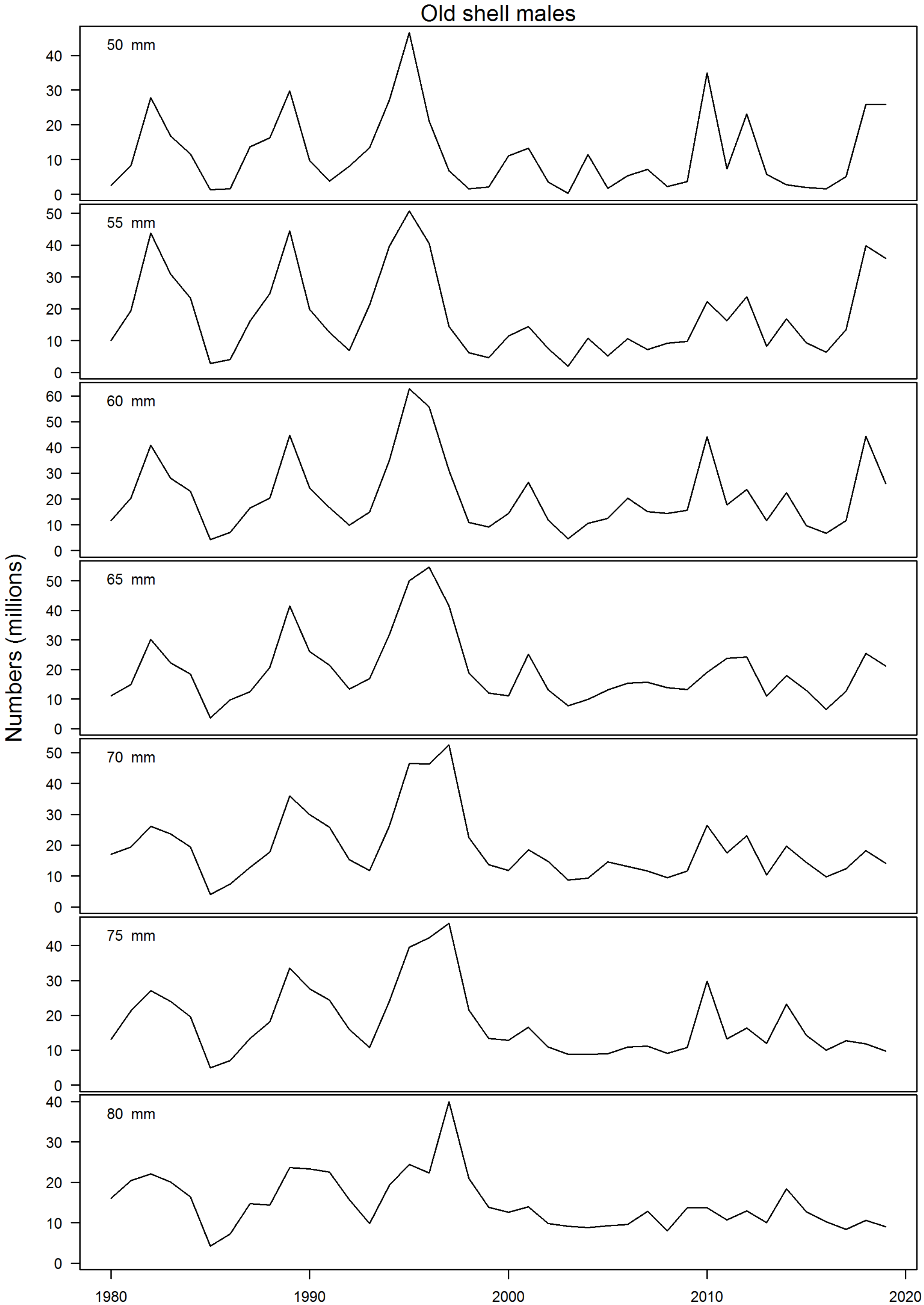

Figure 8: Observed numbers at length of old shell mature males by size class. The presented size bins are not vulnerable to the fishery, so all mortality is 'natural'. The decline in numbers in a size class after the recruitment collapse in the early 1990s demonstrates expected natural mortality for mature male individuals.

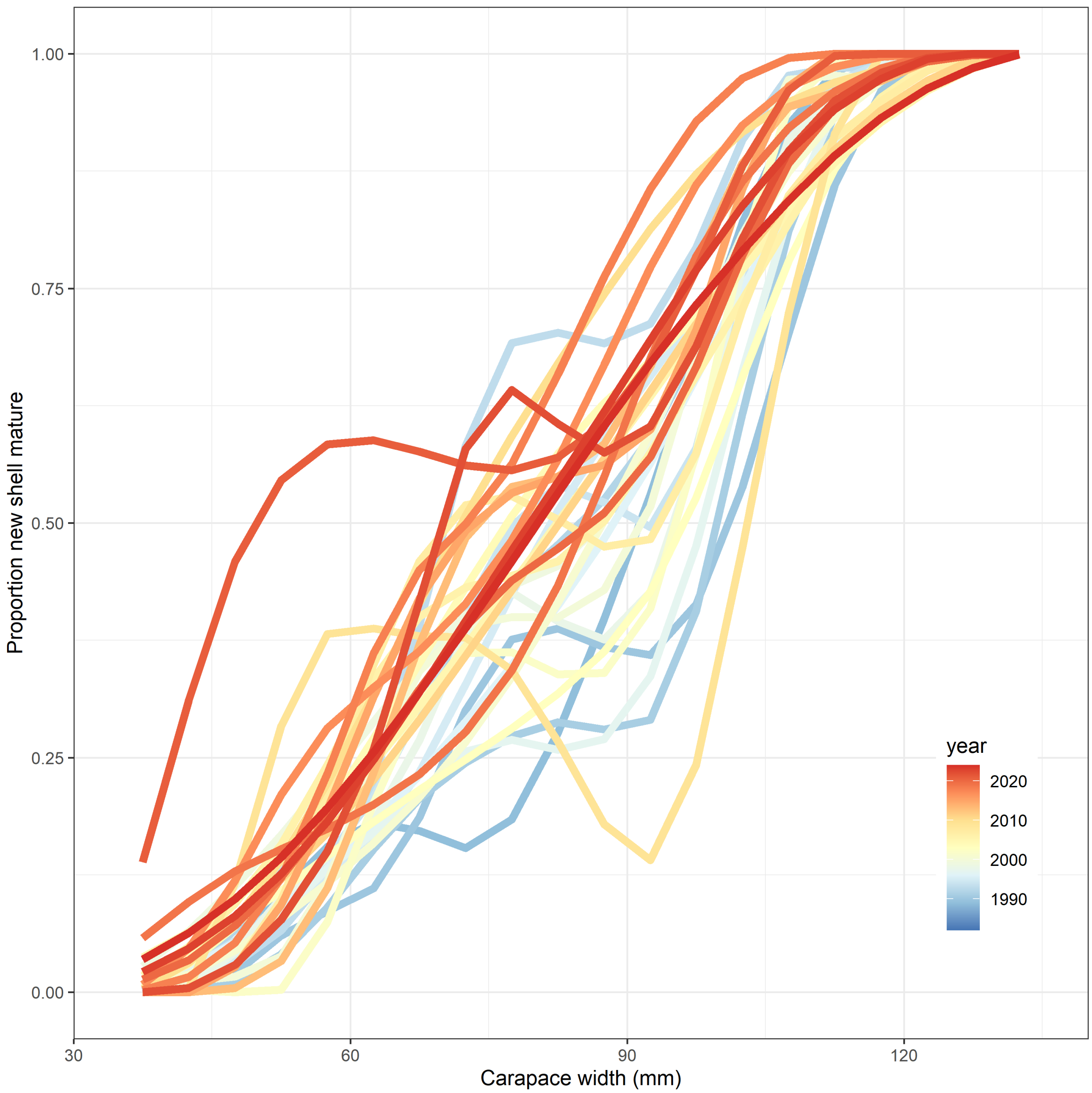

Figure 9: Observed probability of having undergone terminal molt at size for new shell male crab based on chelae height. Blue lines occurred farther back in history; red lines are most recent.

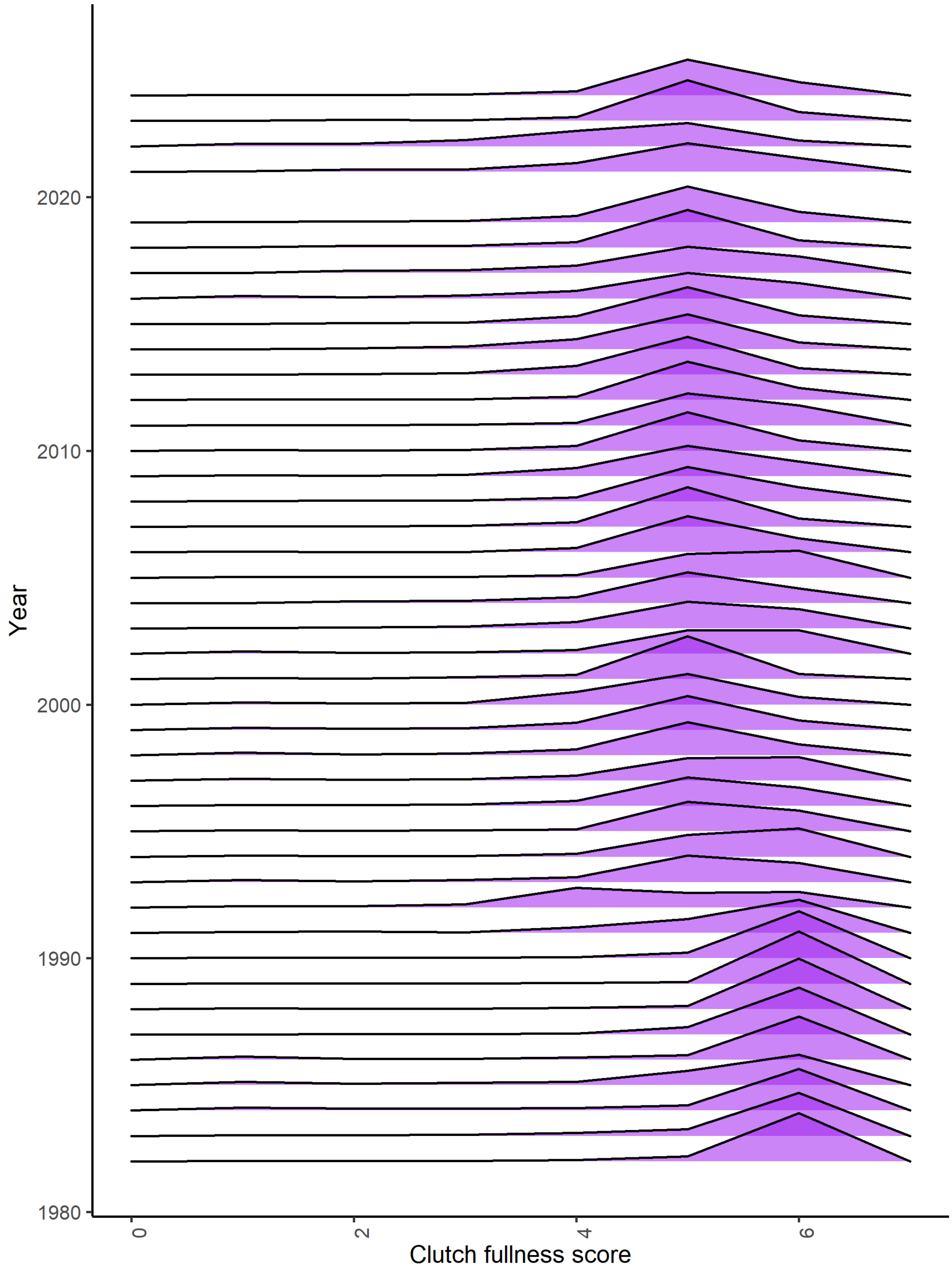

Figure 10: Clutch fullness scores from the 1982-2023 NMFS summer survey. Scores: 0 = immature, 1 = mature no eggs, 2 = trace to 0.125, 3 = 0.25, 4 = 0.5, 5 = 0.75, 6 = full of eggs; 7 = overflowing.

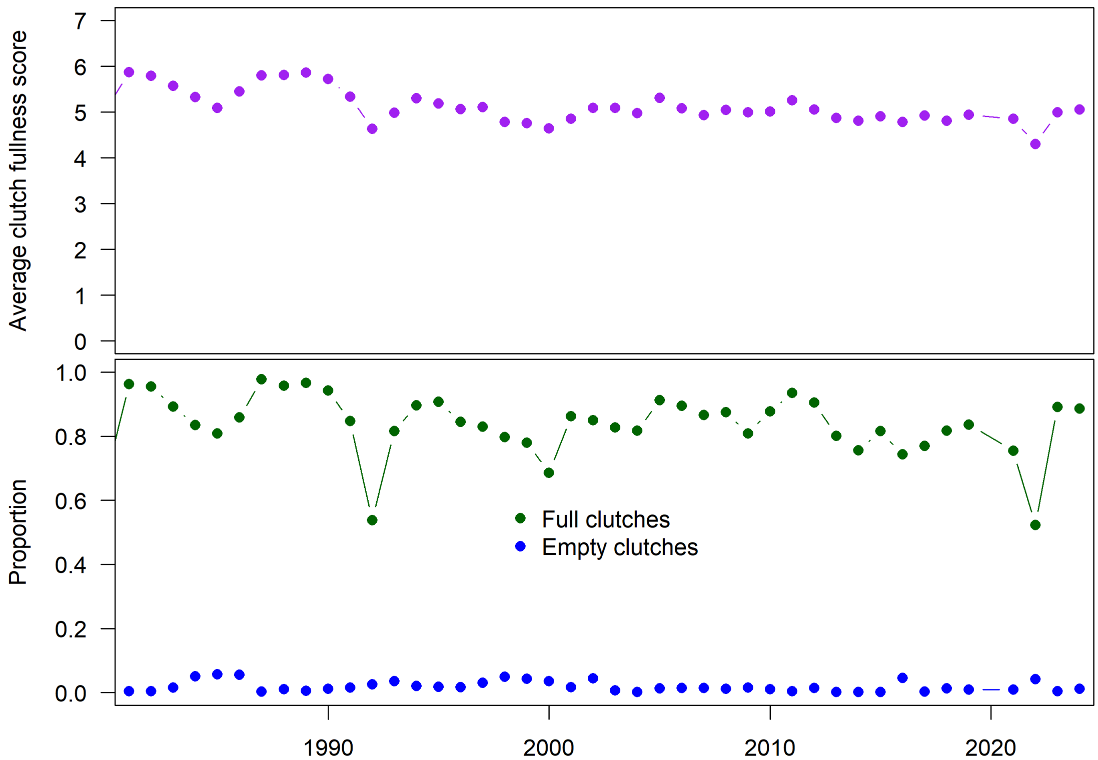

Figure 11: Time series of the average clutch fullness score (top) and the proportion of observed crab with full clutches (green) and empty clutches (blue) in the NMFS summer survey (bottom). Scores: 0 = immature, 1 = mature no eggs, 2 = trace to 0.125, 3 = 0.25, 4 = 0.5, 5 = 0.75, 6 = full of eggs; 7 = overflowing..

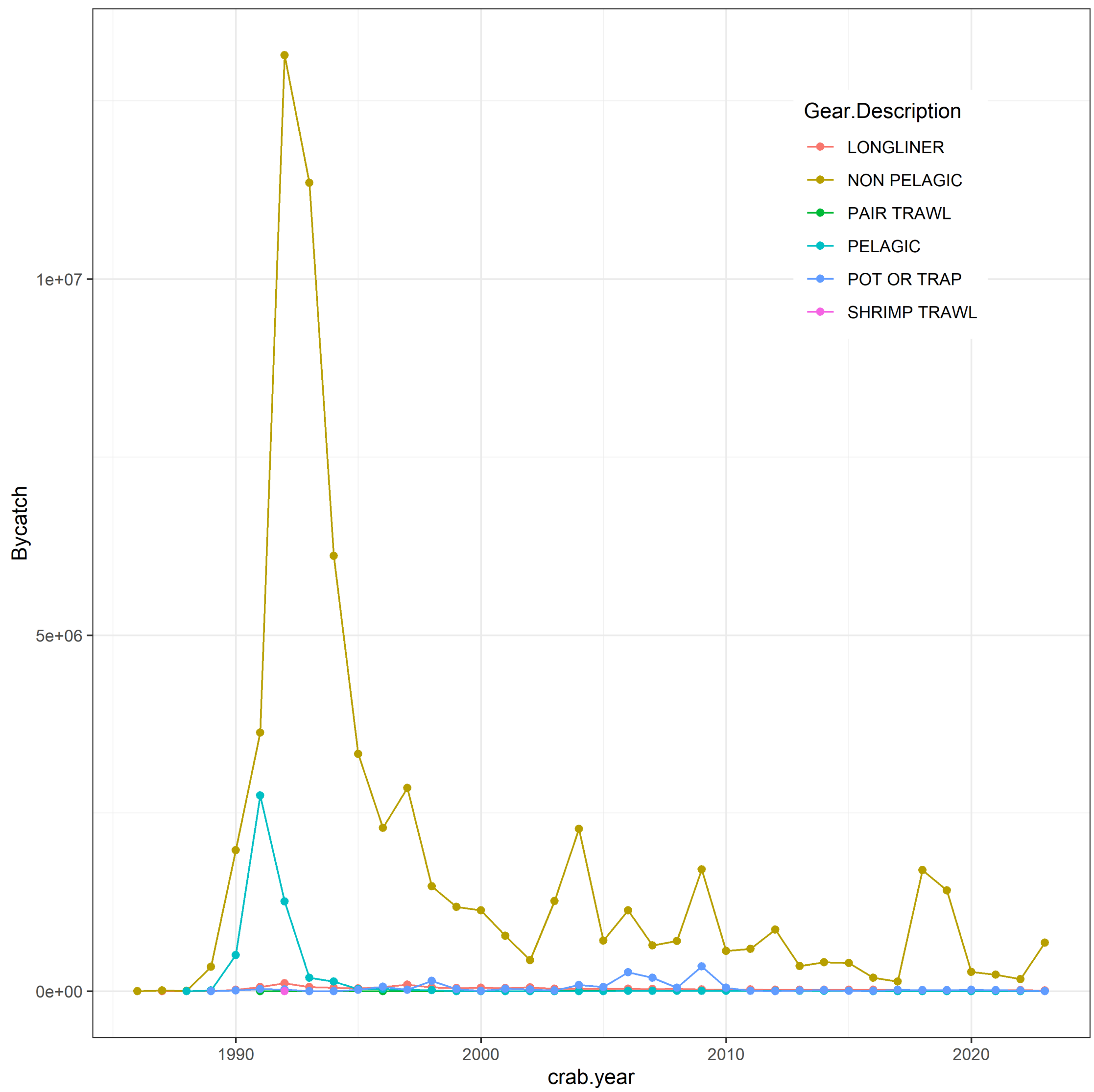

Figure 12: Time series of non-directed bycatch by gear in numbers of crab.

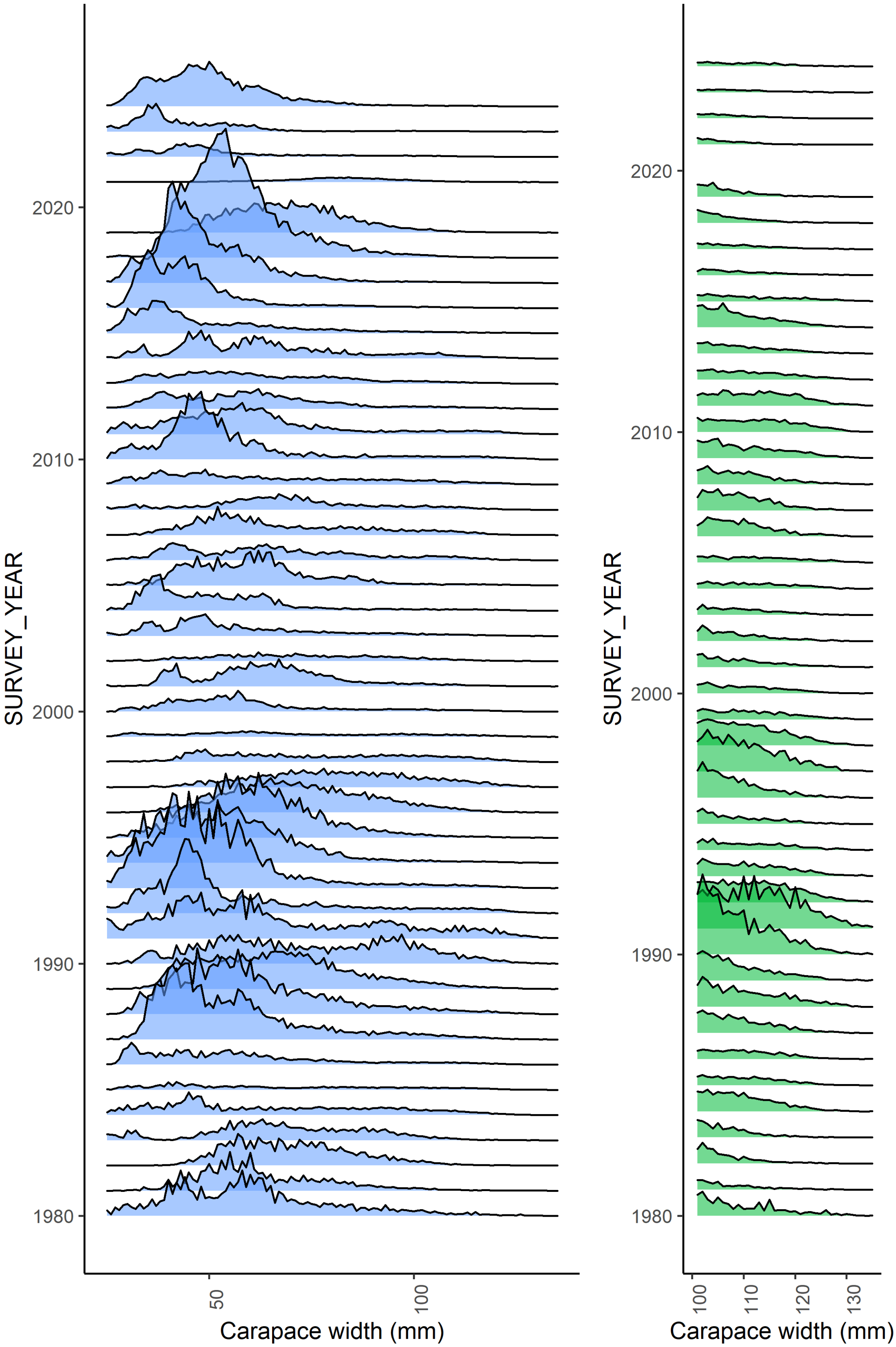

Figure 13: Raw total numbers at size of male crab observed in the survey. Blue are all numbers at size; green are males >101mm carapace width.

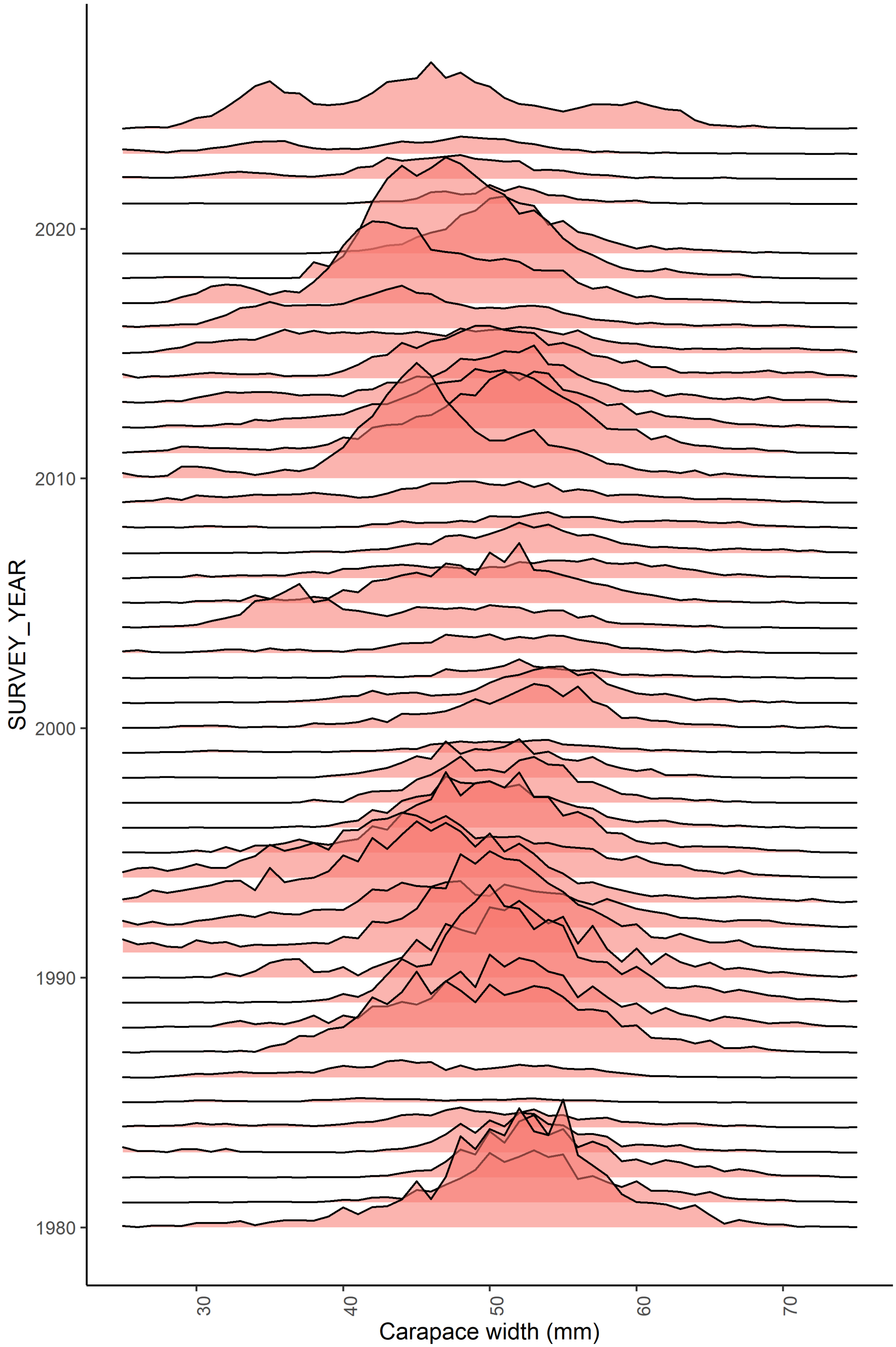

Figure 14: Raw total numbers at size of female crab observed in the survey.

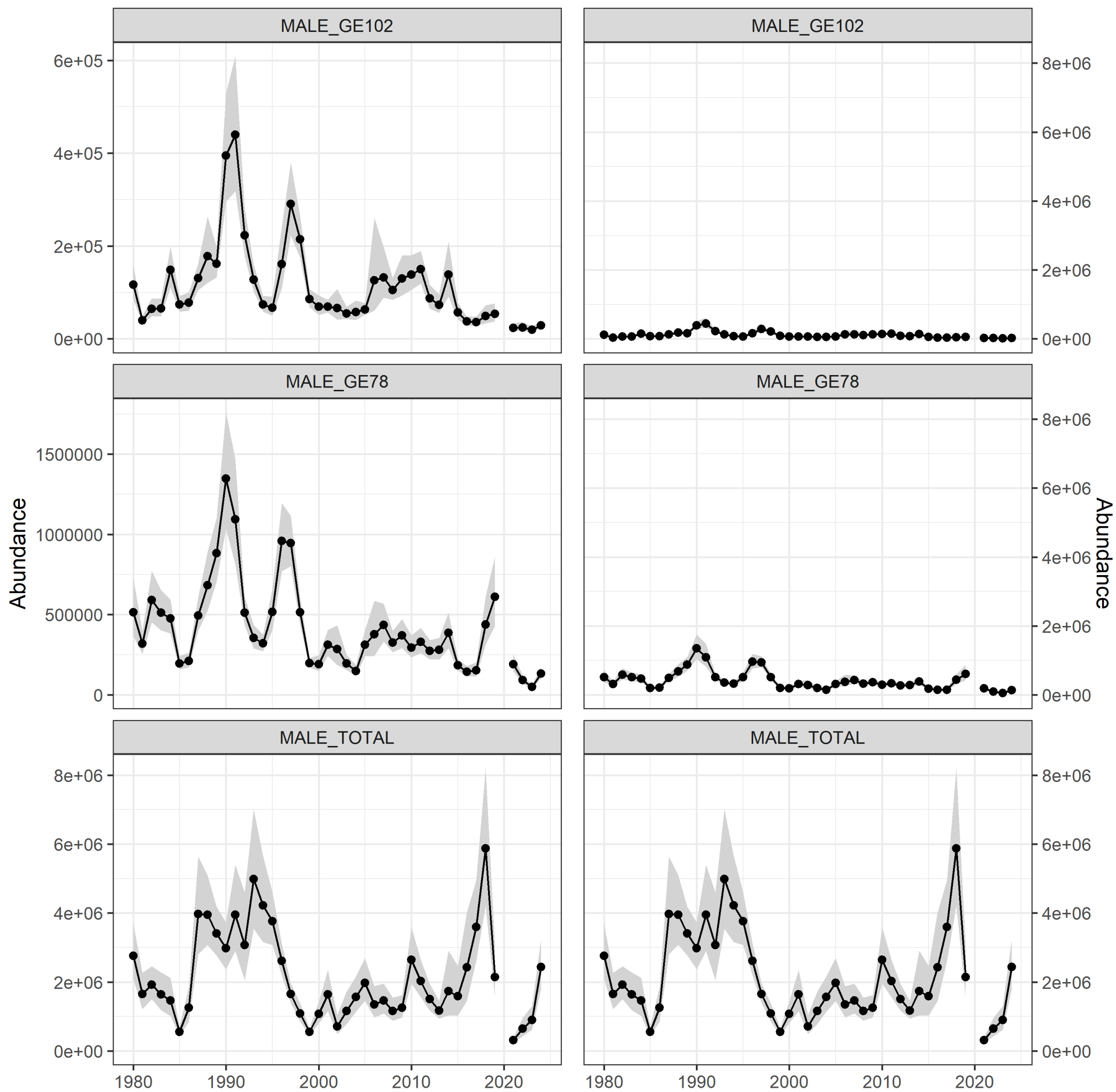

Figure 15: Abundance of males estimated from the NMFS summer survey over time for different size classes. GE102 means greater than or equal to 102 mm carapace width. Grey shading is 95th percent confidence interval. Left side allows for free y-axis; right side retains a common y-axis.

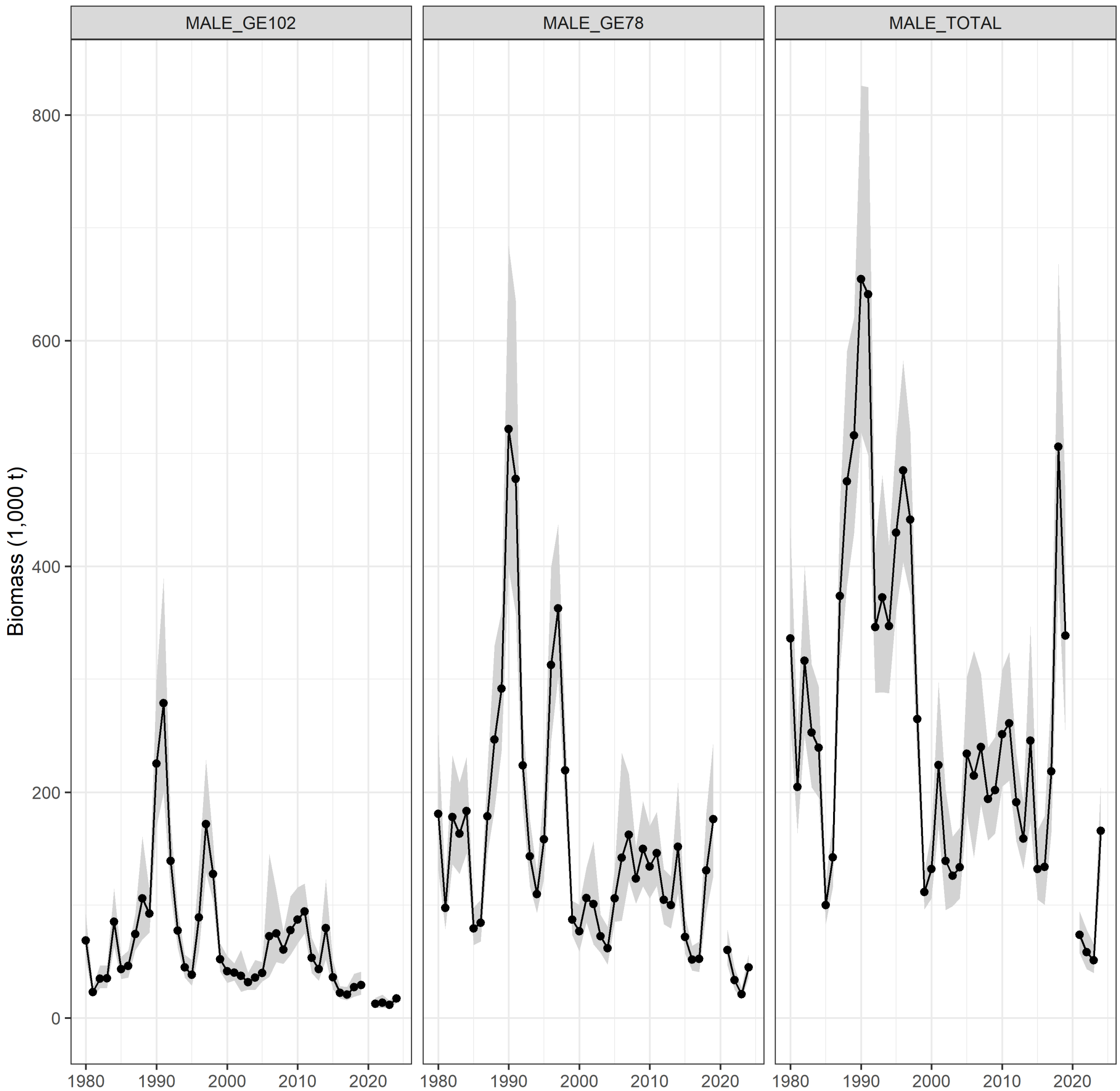

Figure 16: Biomass of males estimated from the NMFS summer survey over time for commercially relevant size classes. GE102 means greater than or equal to 102 mm carapace width. Grey shading is 95th percent confidence interval. Grey shading is 95th percent confidence interval.

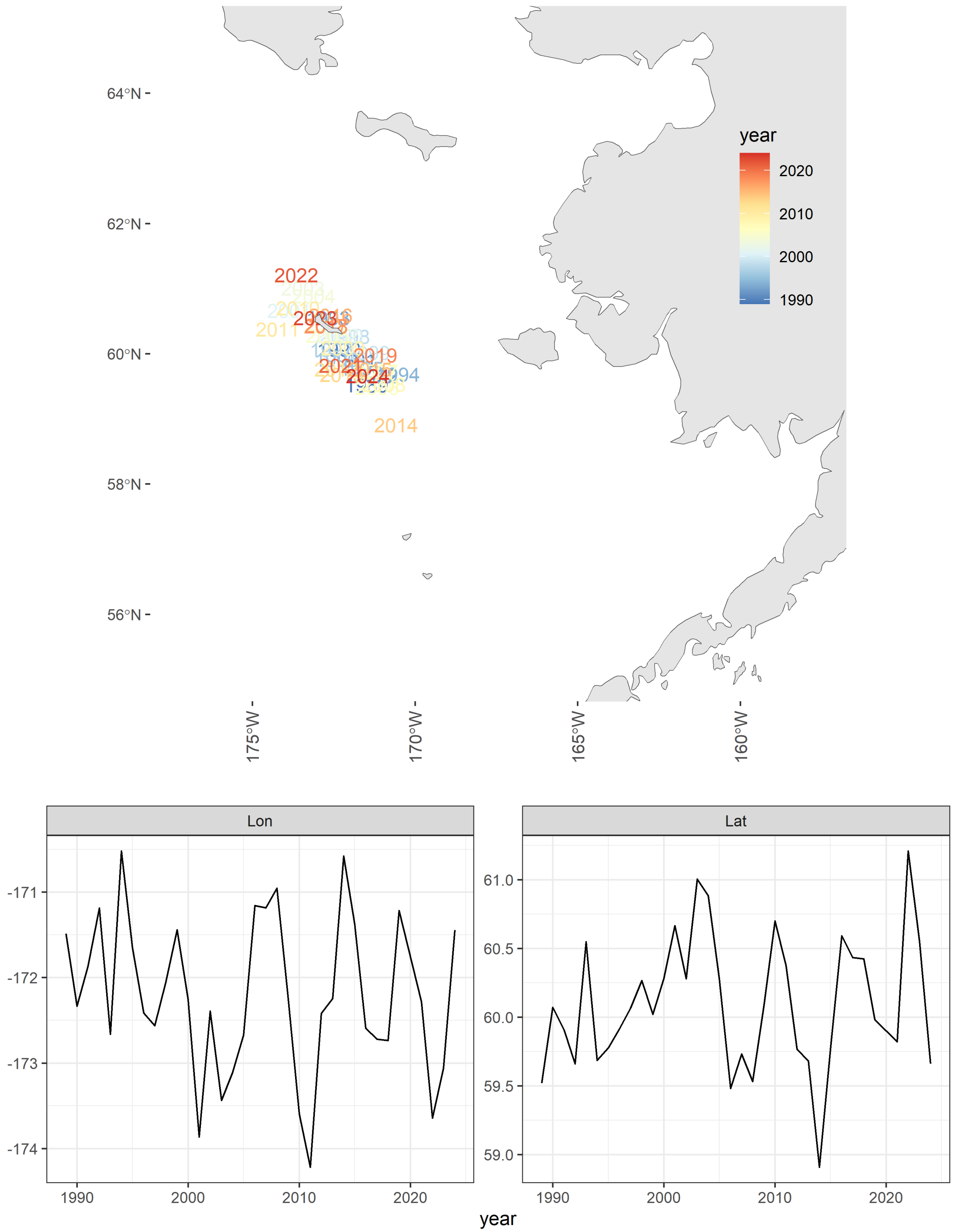

Figure 17: Centroids of abundance for males 45-85 mm carapace width. Map shows the centroid in space by year; blue colors are farther in the past. Bottom figures isolate the latidudinal and longitudinal components.

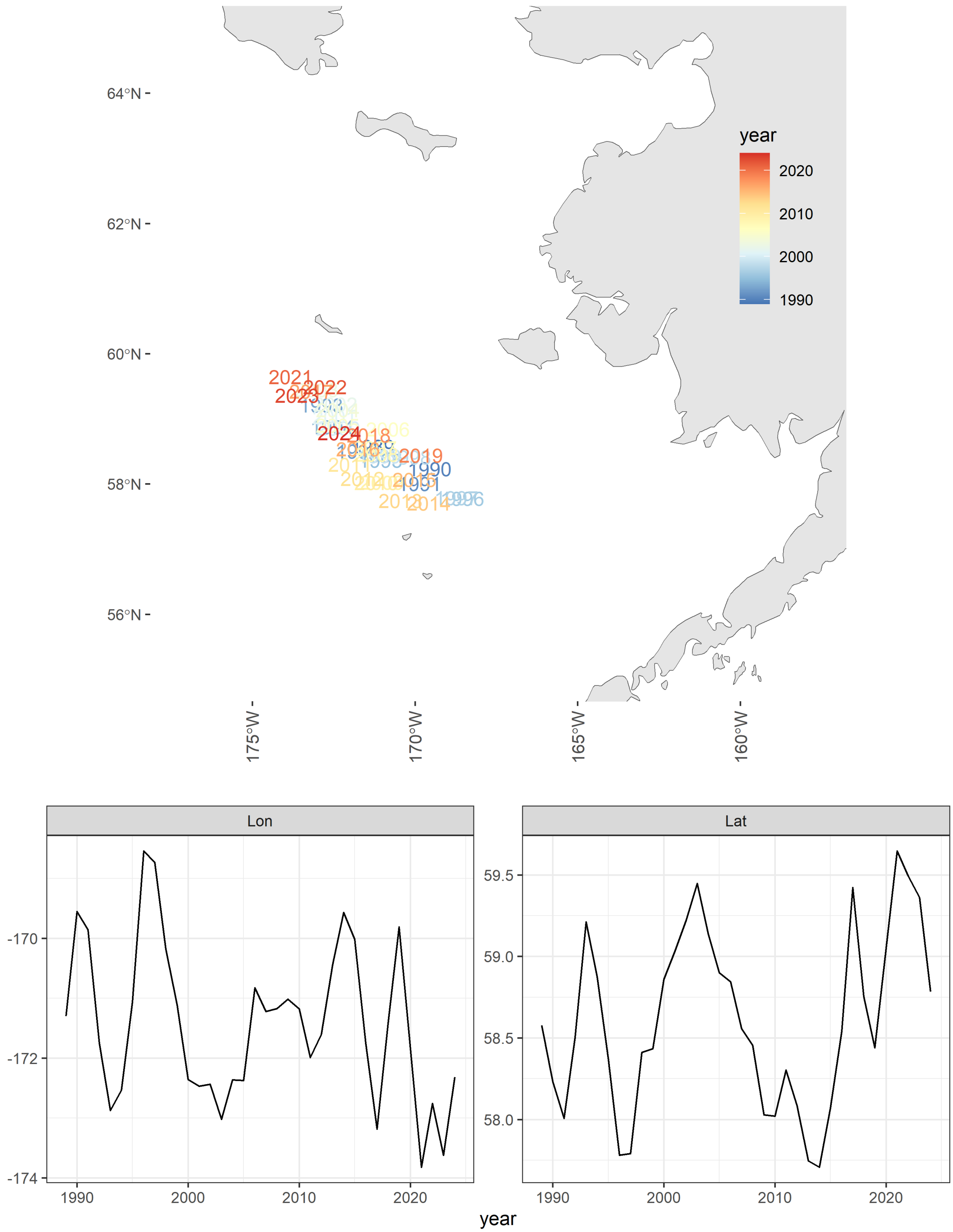

Figure 18: Centroids of abundance for males greater than 101 mm carapace width. Map shows the centroid in space by year; blue colors are farther in the past. Bottom figures isolate the latidudinal and longitudinal components.

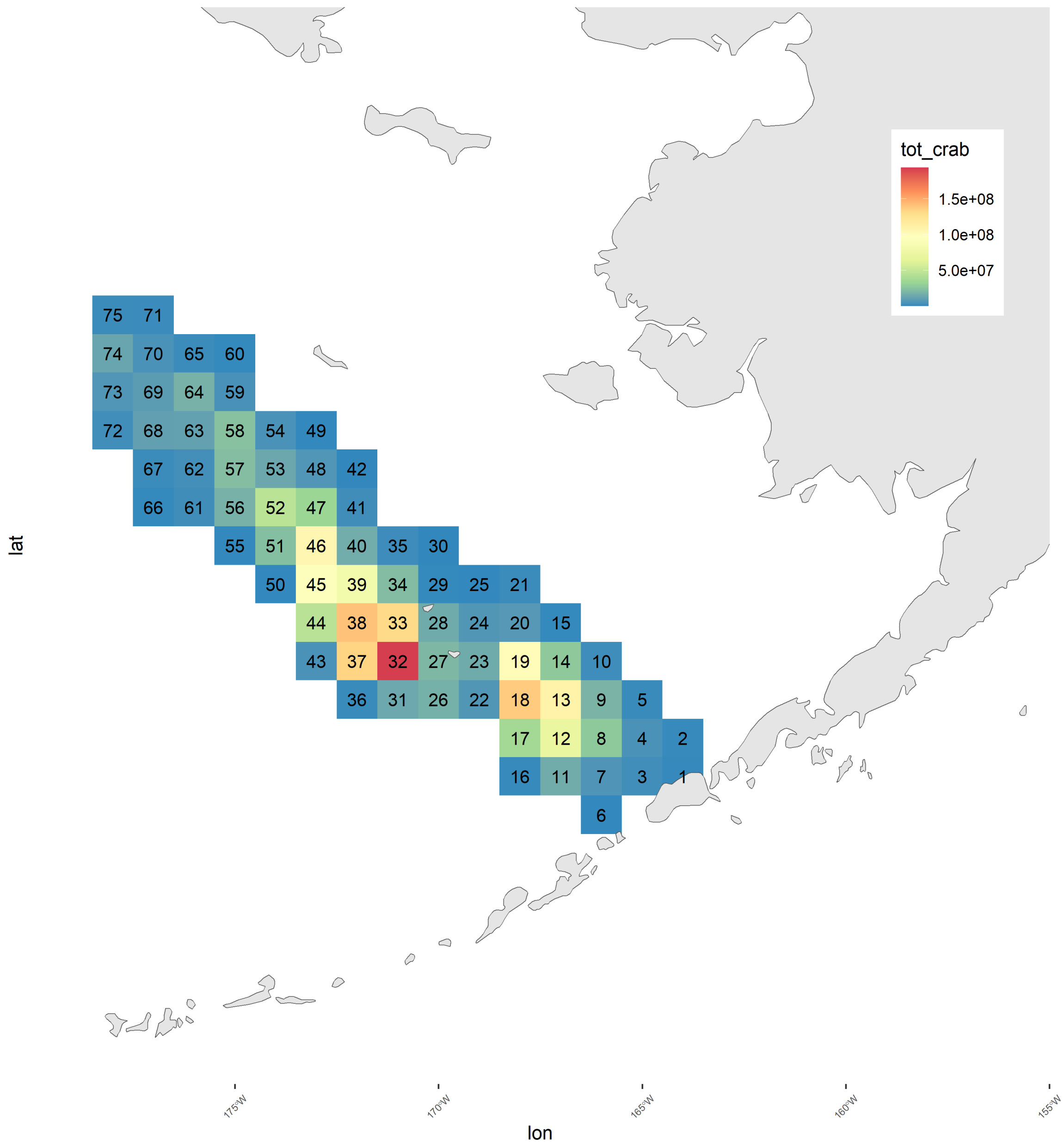

Figure 19: Distribution of effort in terms of potlifts in the directed fishery on the Bering Sea shelf summed from 1990-present. Squares are statistical areas defined by the state. Numbers are generated to give context to the following figures. Only data in areas that had three or more fishers and processors represented were used to make this figure. That accounts for 87% of the data points available.

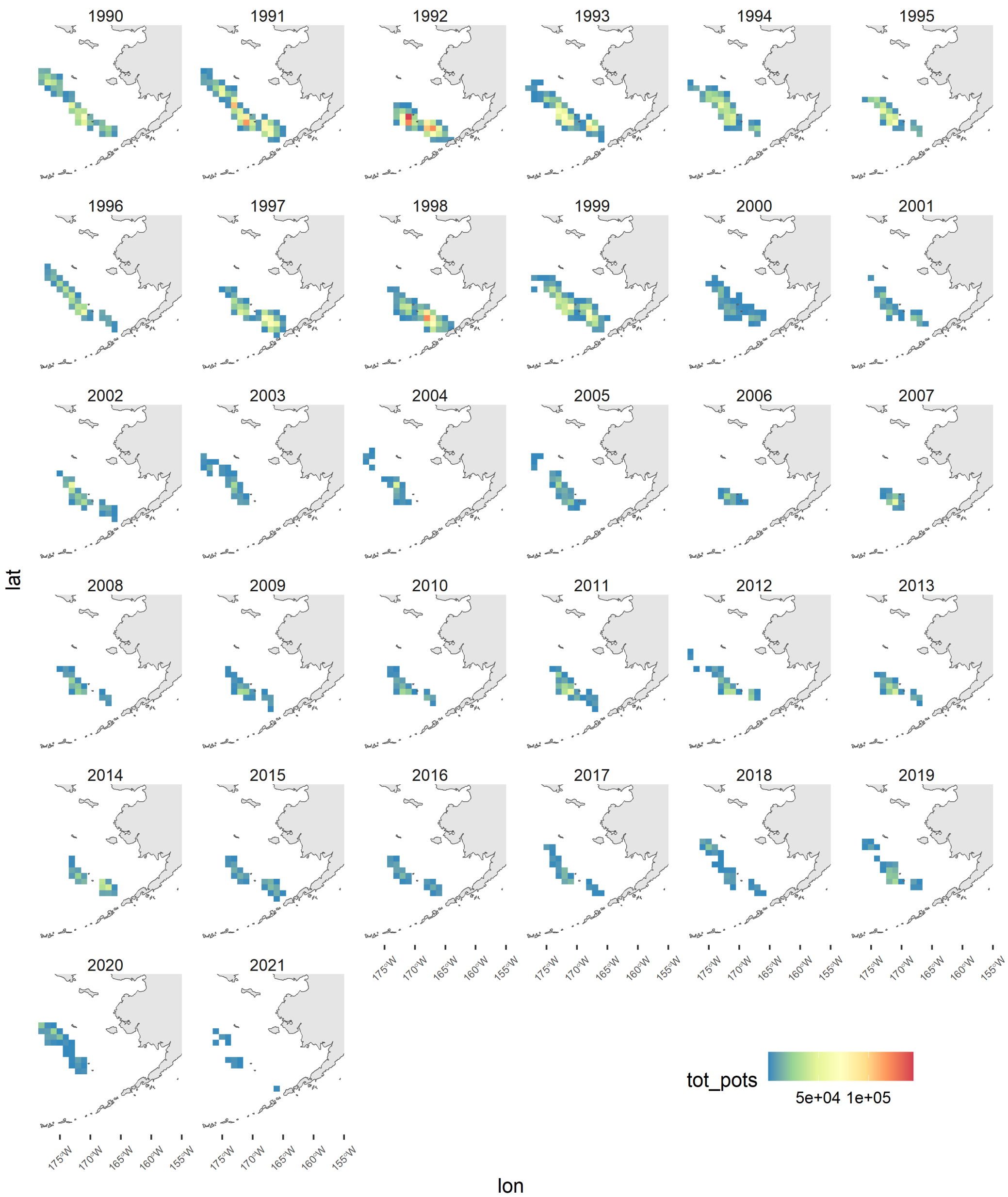

Figure 20: Yearly distribution of effort in terms of potlifts in the directed fishery on the Bering Sea shelf displayed from 1990-present.

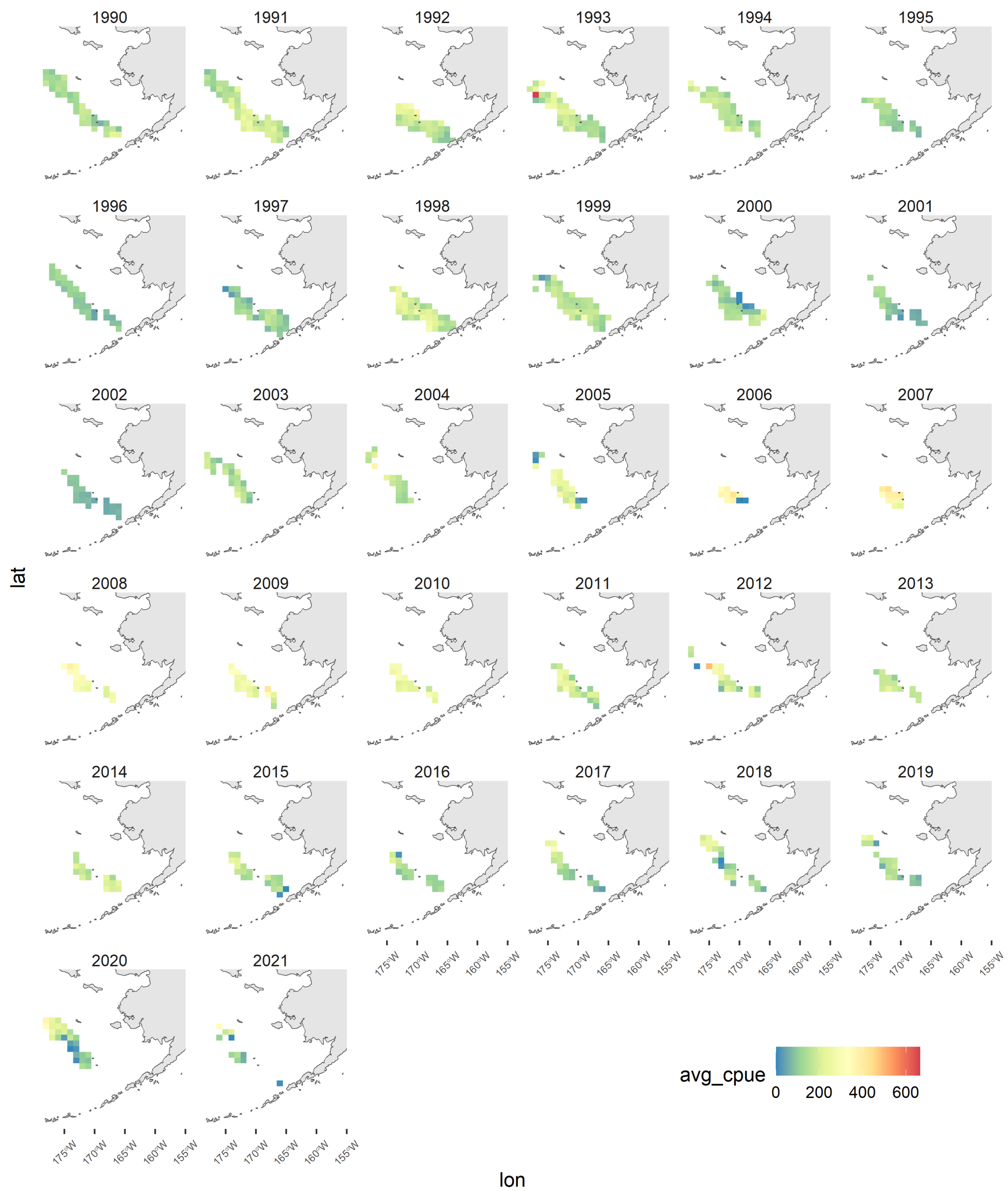

Figure 21: Yearly distribution of unstandardized catch per unit effort across from 1990-present

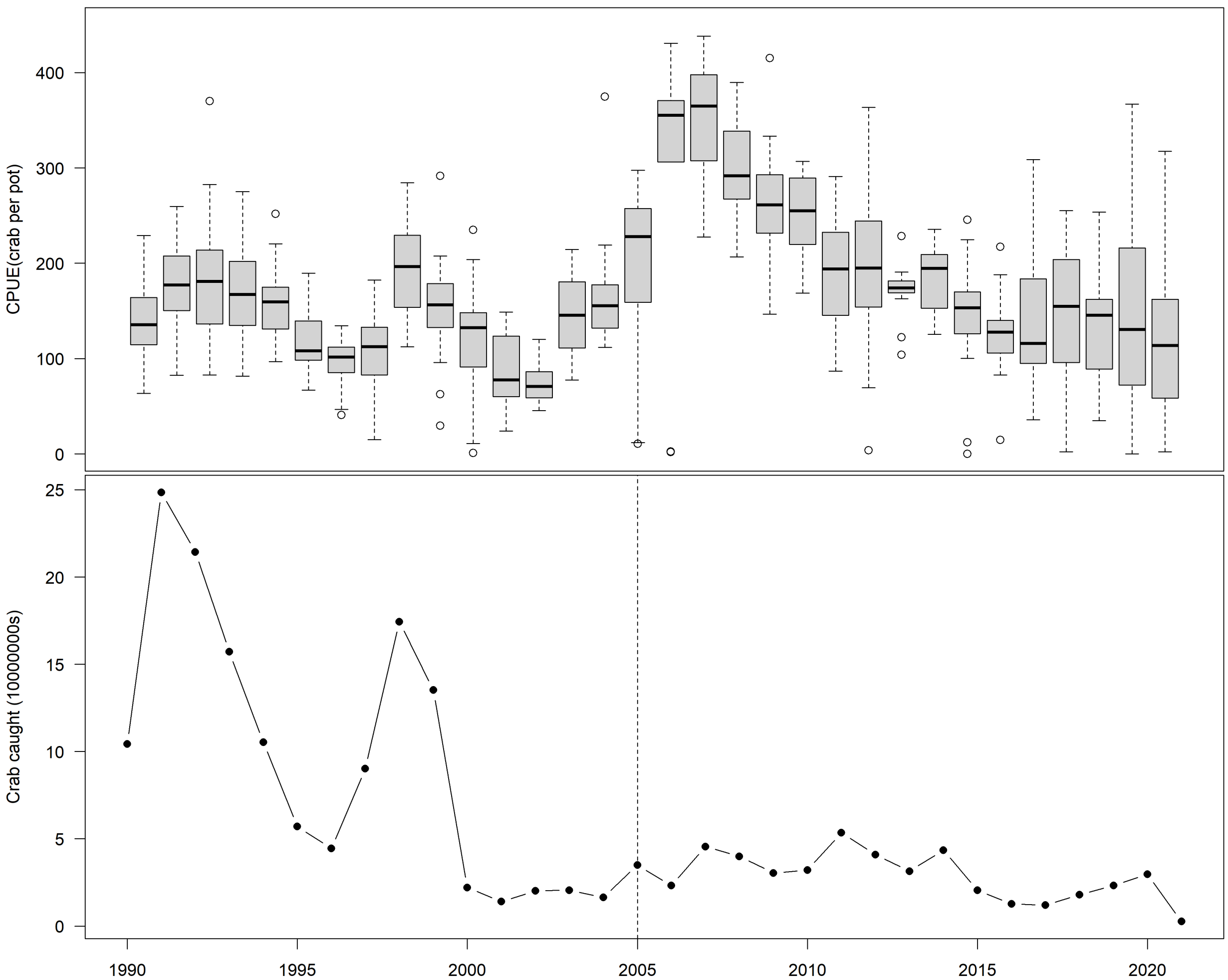

Figure 22: Unstandardized catch per unit effort in the snow crab fleet (top) and total crab caught (bottom), courtesy of Ben Daly.

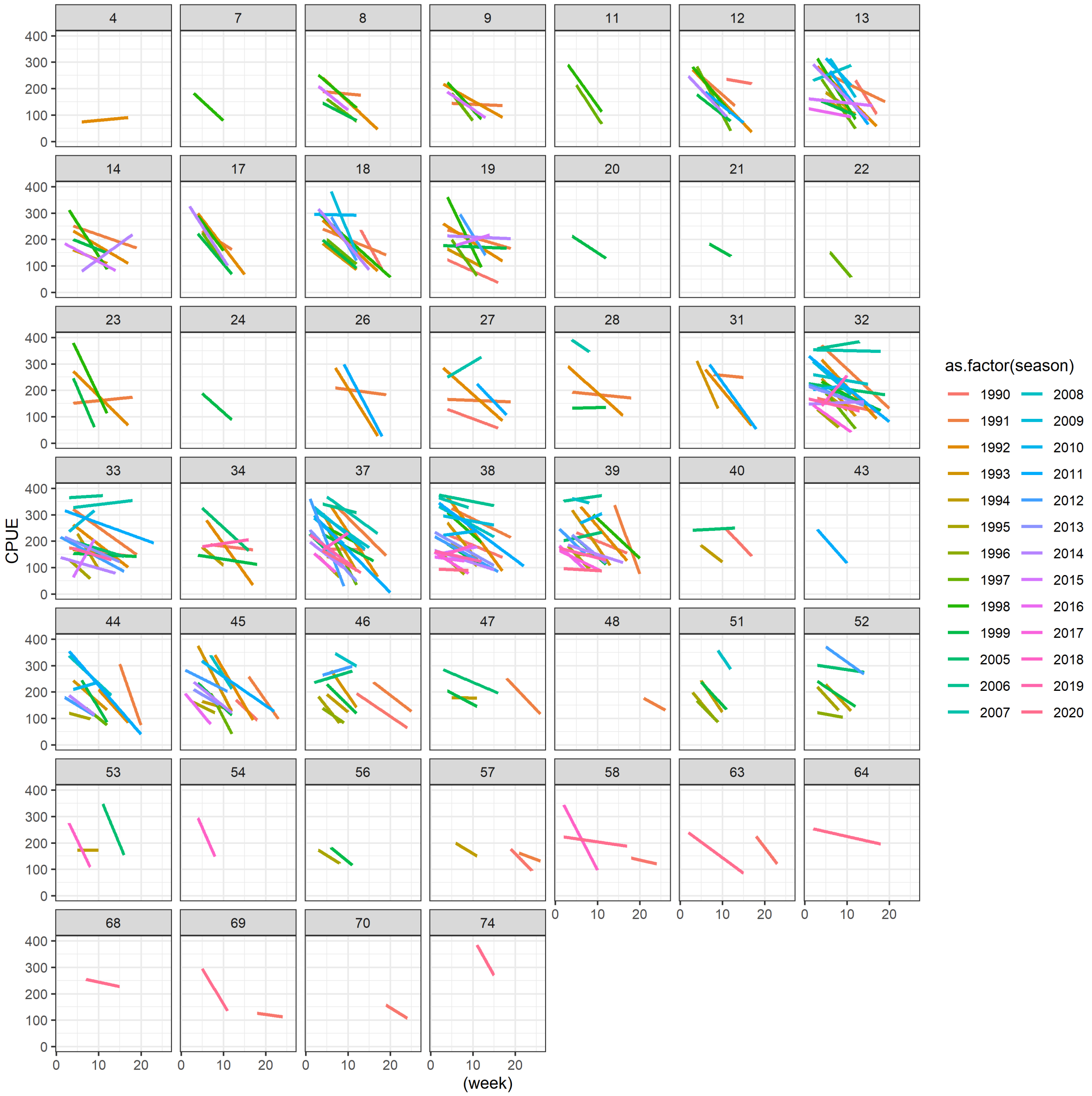

Figure 23: Trends in unstandardized CPUE by statistical area. Each line is produced from a linear model fit through observed CPUE in a given area in a given year. Trends were only fit if the data represented in an area came included 3 or more fishers and processors and only if there were at least 5 weeks of CPUE data in a given area, in a given season.

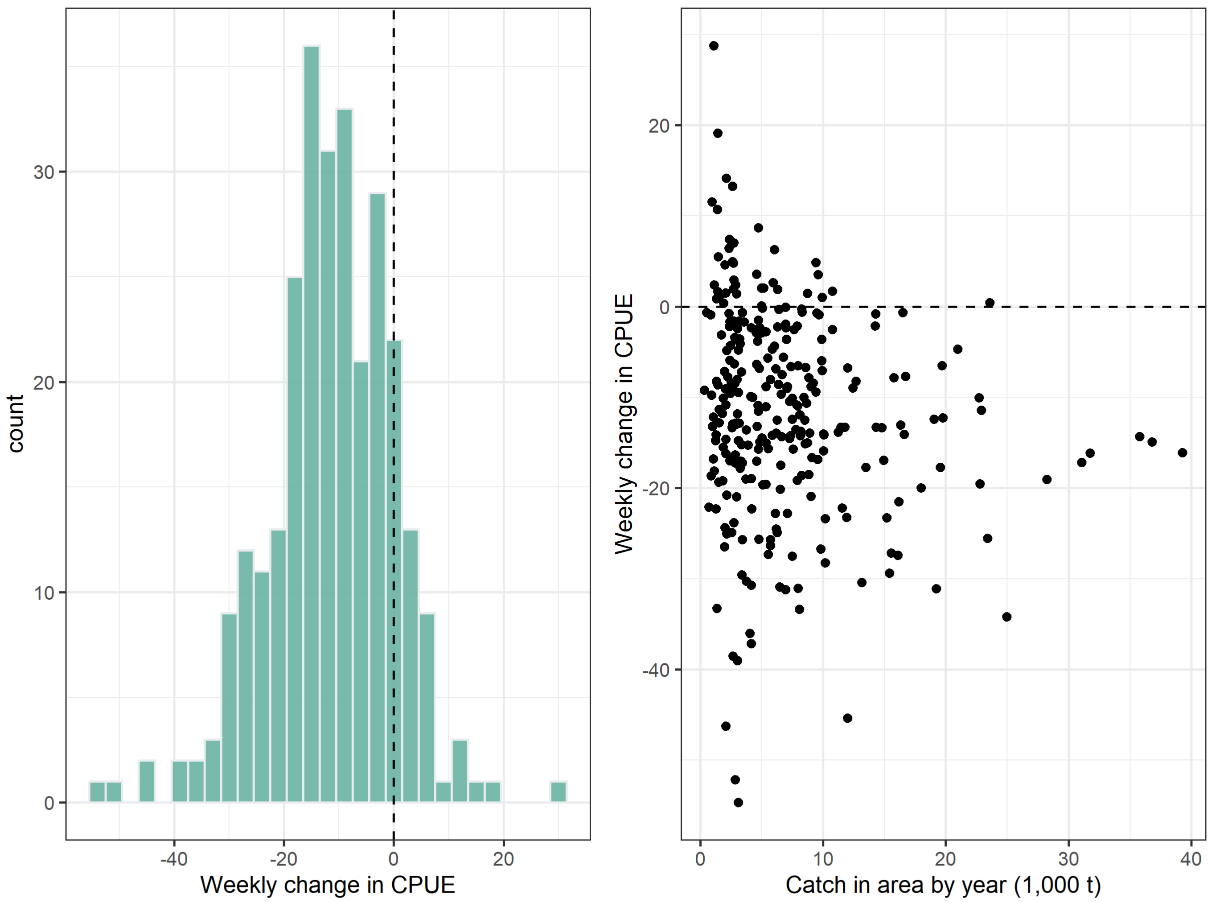

Figure 24: Distribution of the slopes of trends in inseason cpue by spatial area shown in previous figure. Slopes plotted against the catches removed in a given season and area.

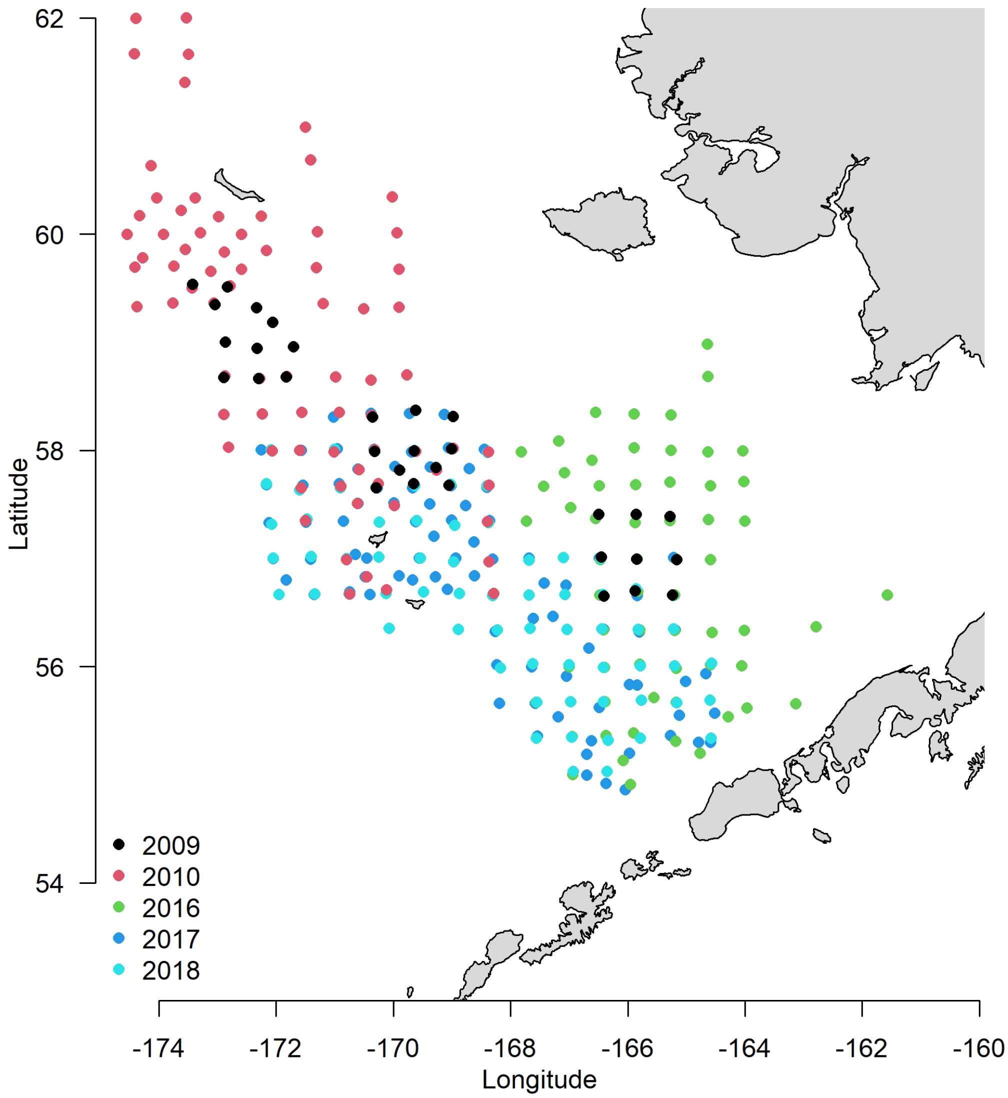

Figure 25: Location of BSFRF survey selectivity experiments that provided data used in this assessment over time.

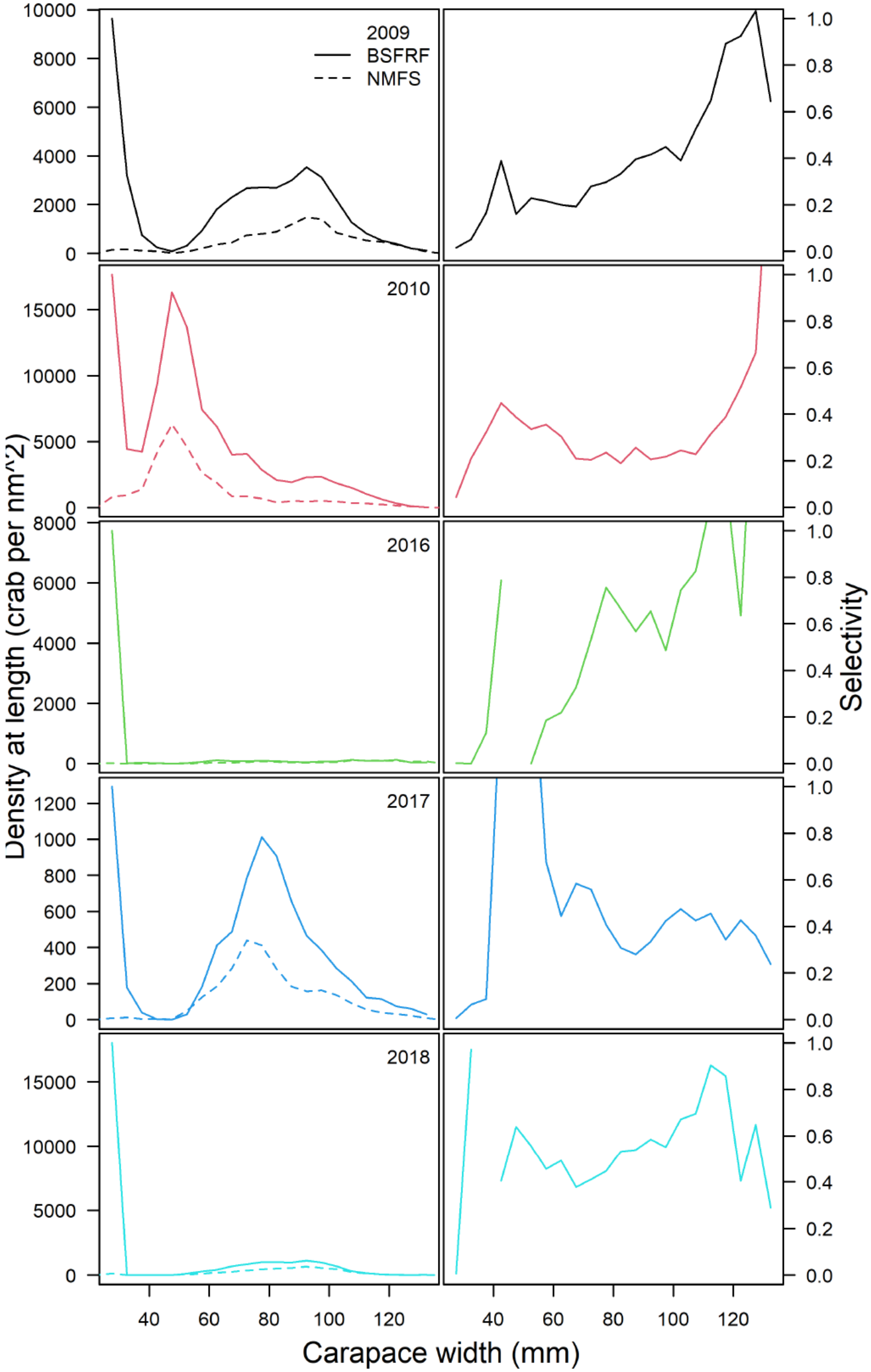

Figure 26: Observed numbers at length extrapolated from length composition data and estimates of total numbers within the survey selectivity experimental areas by year (left). Inferred selectivity (i.e. the ratio of crab at length in the NMFS gear to crab at length in the BSFRF gear.

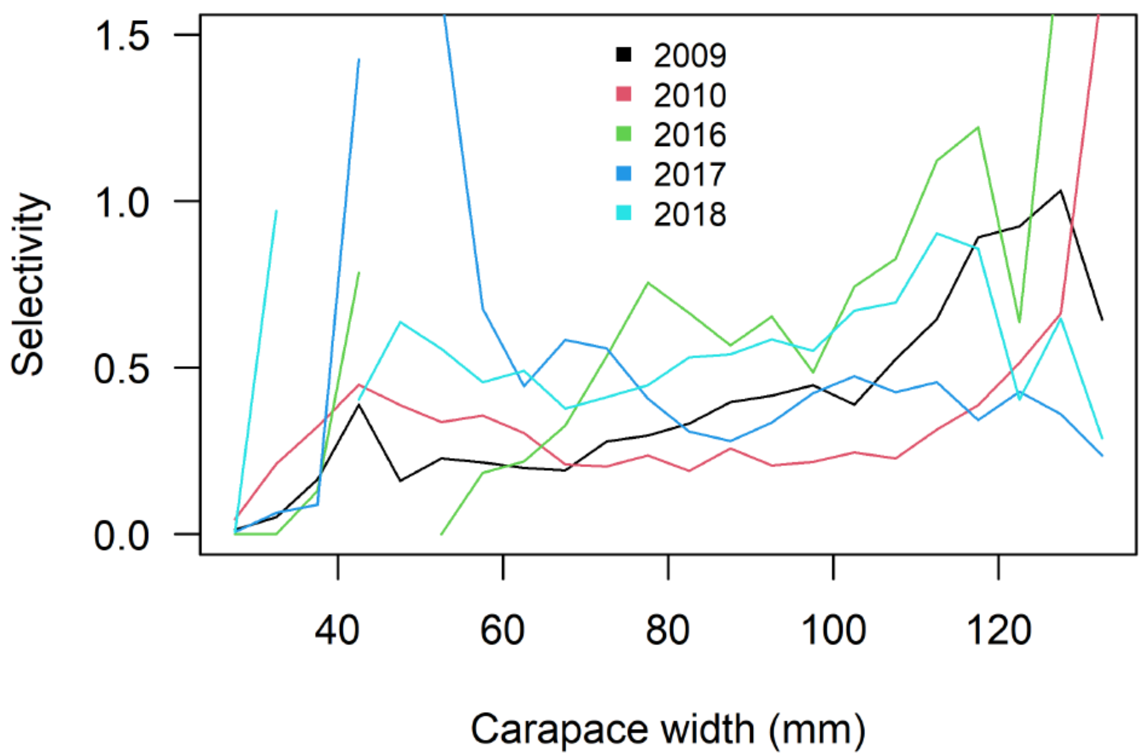

Figure 27: Inferred selectivity for all available years of BSFRF data.

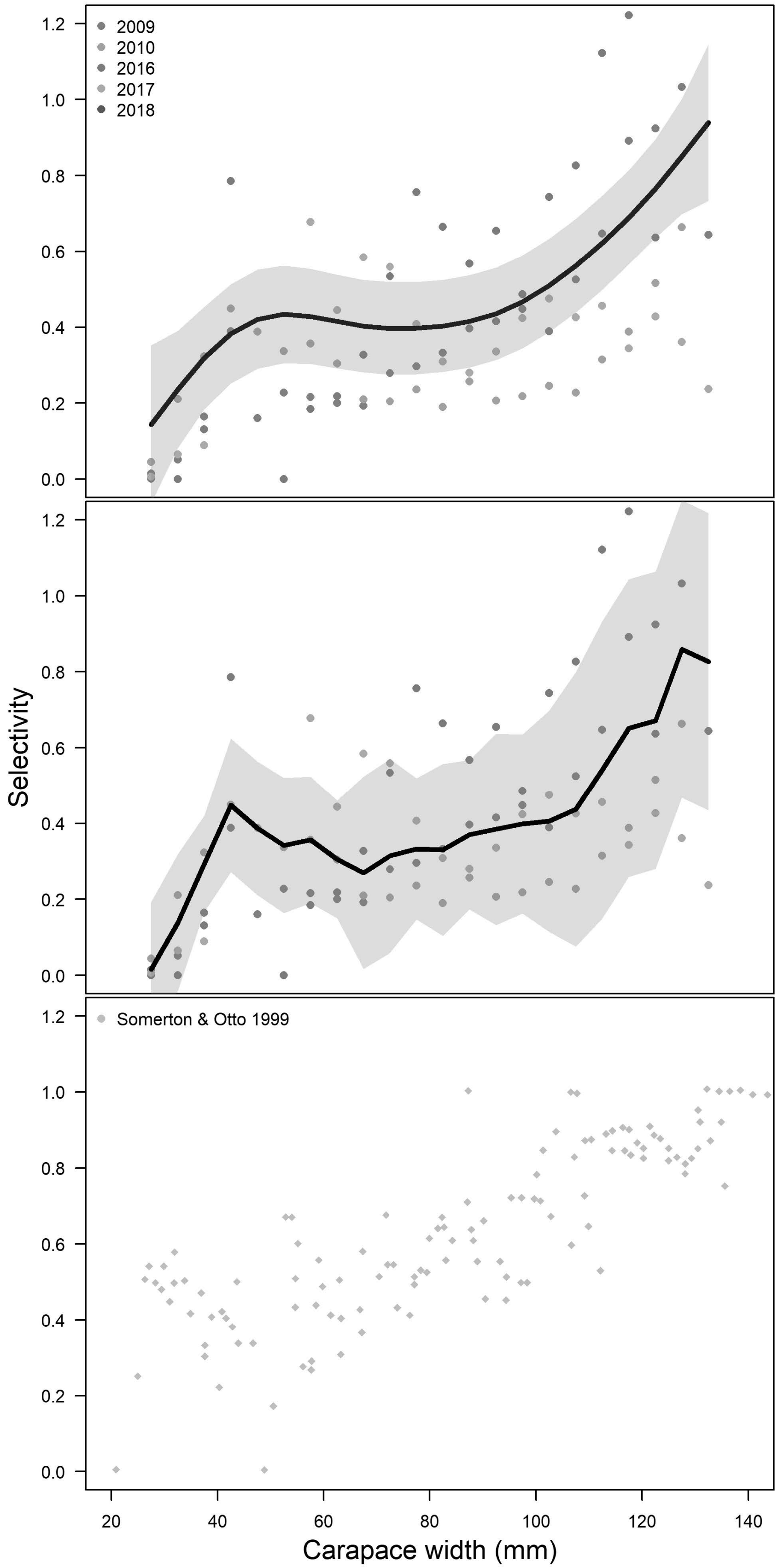

Figure 28: Inferred selectivity from BSFRF experiments with selectivity at size class estimated by generalized additive model (top). Inferred selectivity from BSFRF experiments with selectivity at size class estimated by sample size-weighted means and variances (middle). Somerton and Otto (1998) underbag experimental data. Point estimates and associated CVs from the GAM were used as priors in model series 23.3.

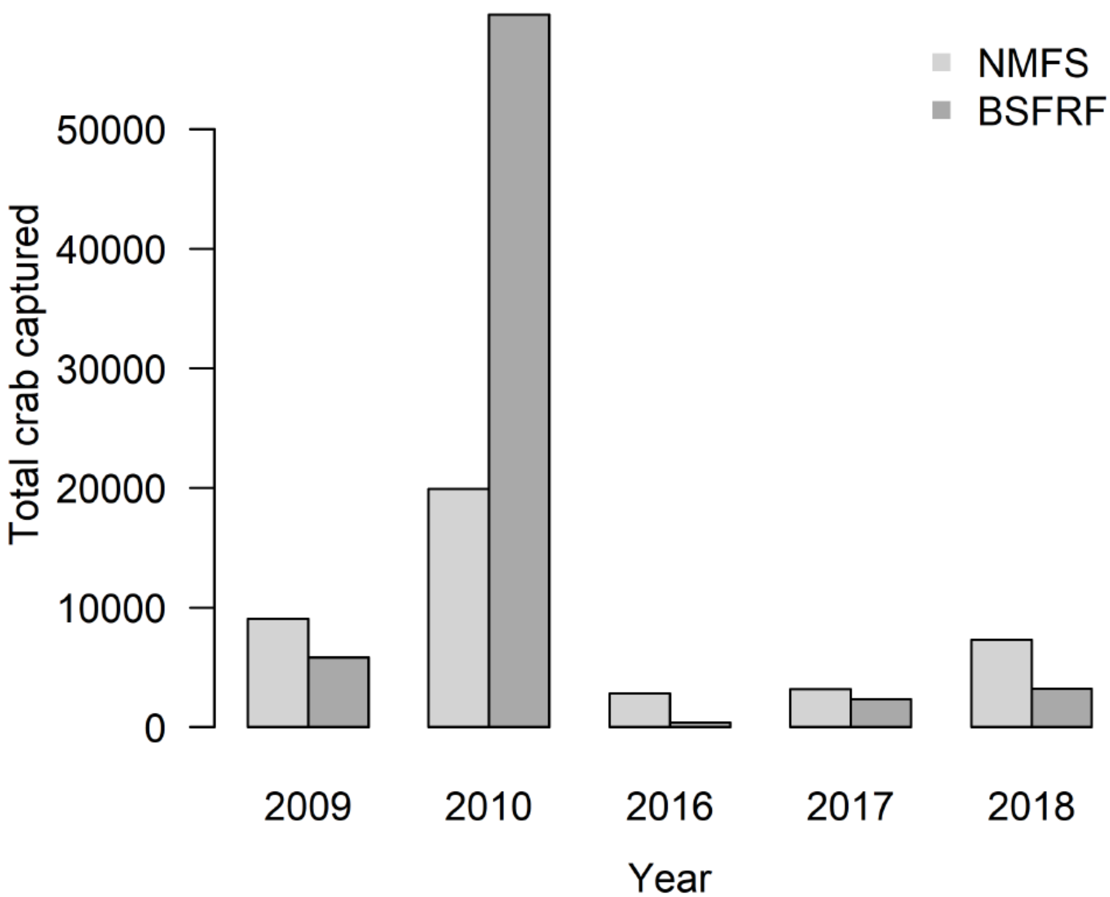

Figure 29: Number of crab collected in the BSFRF experimental areas by the NMFS survey and the BSFRF survey.

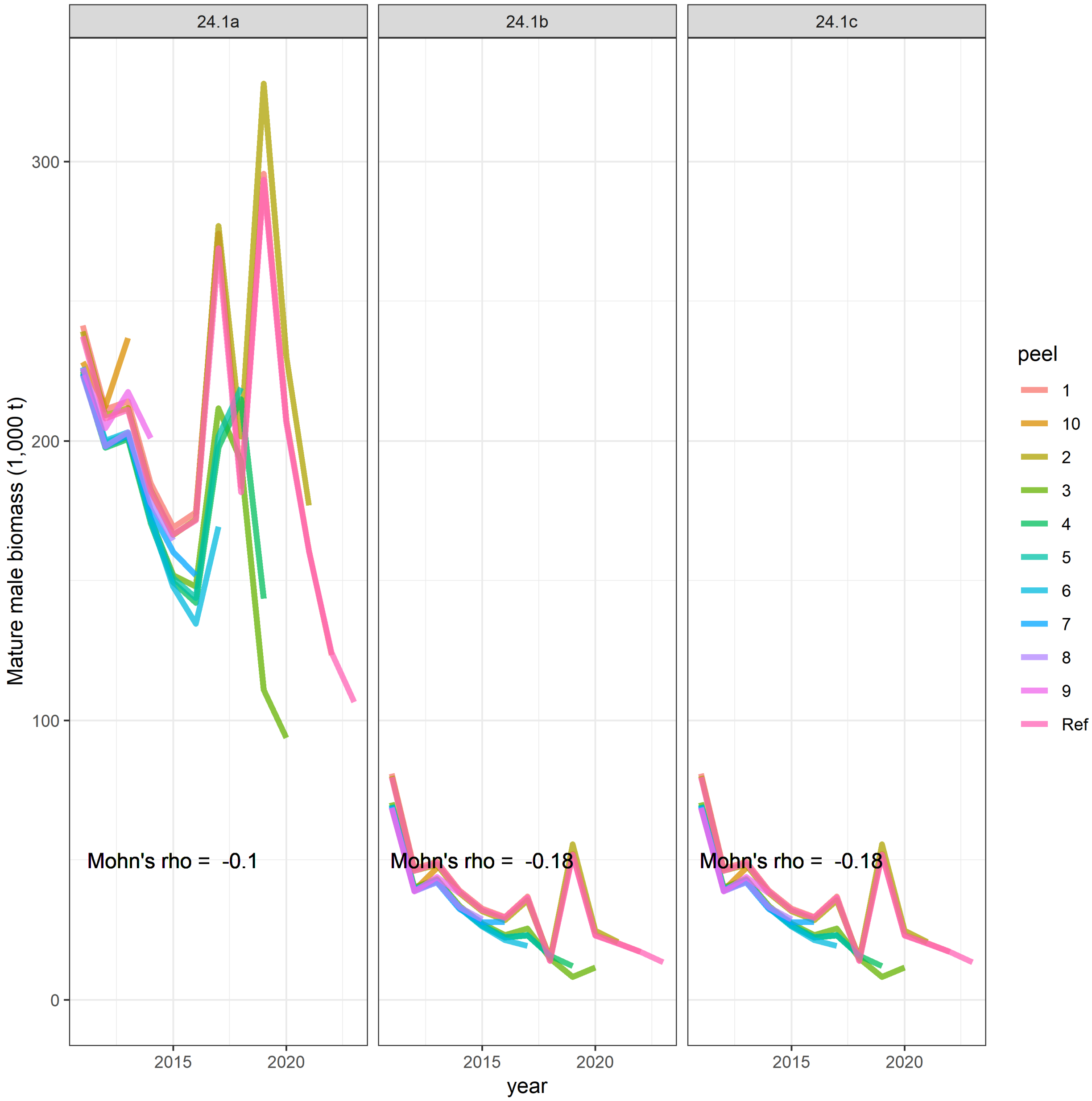

Figure 30: Retrospective patterns in estimated mature male biomass for selected models.

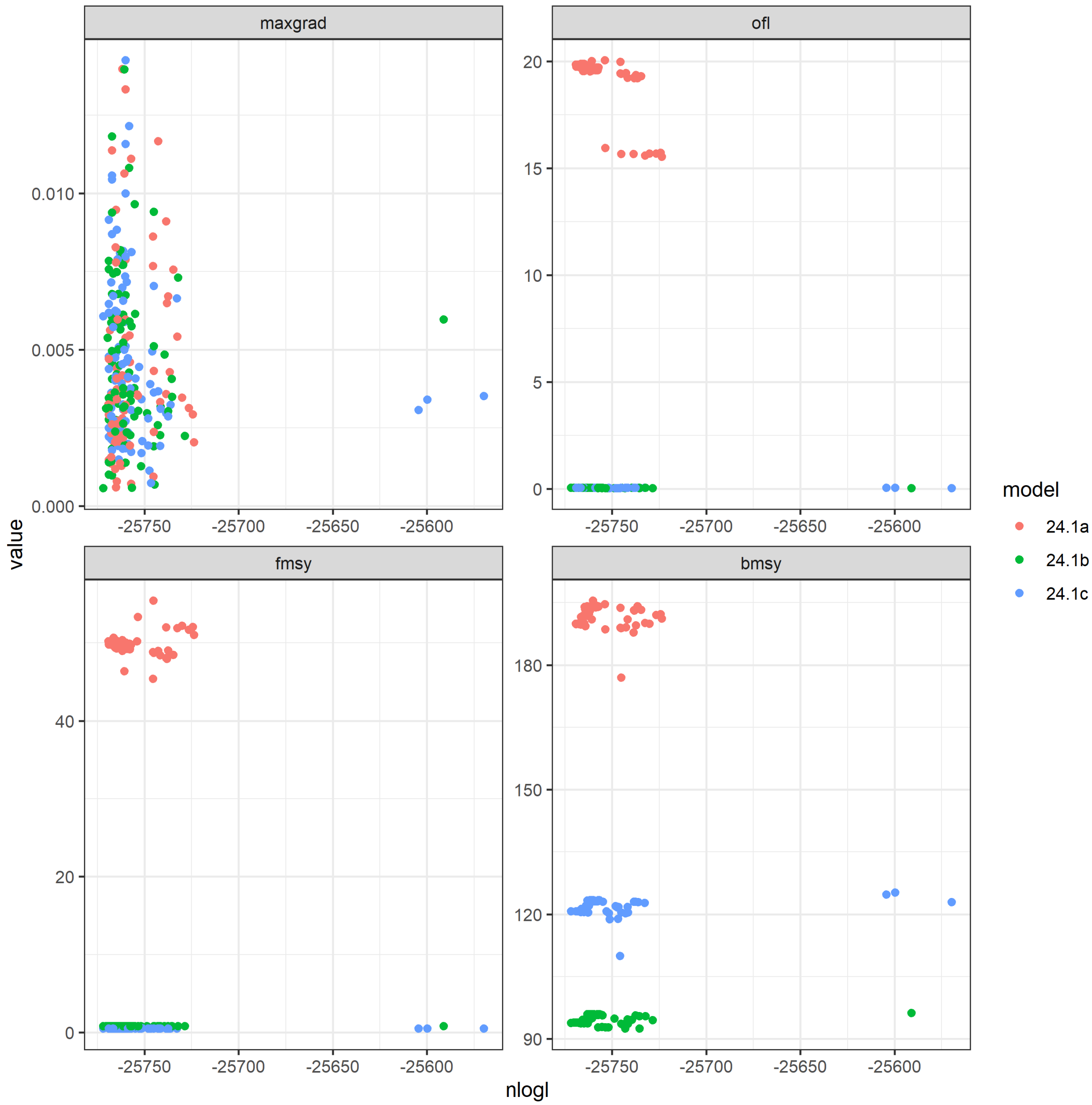

Figure 31: Output of 100 jittered model fittings for selected models. Top left is the maximum gradient component, top right is the overfishing level, bottom left is F35, and bottom right is B35. Each dot represent an instance of a jittered fitted model and are colored based on the OFL resulting from that run.

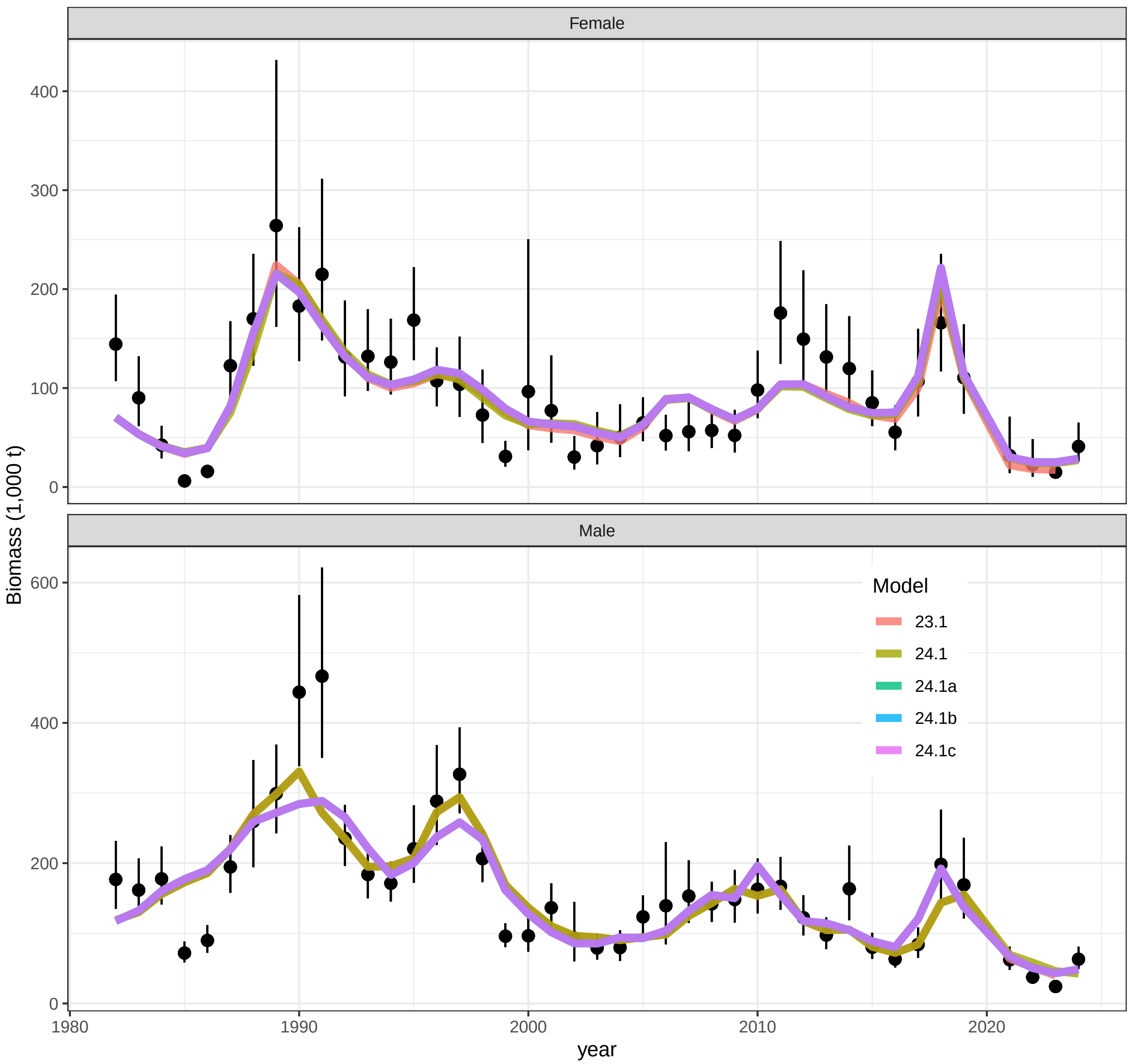

Figure 32: Model fits to the observed morphometrically mature biomass at survey.

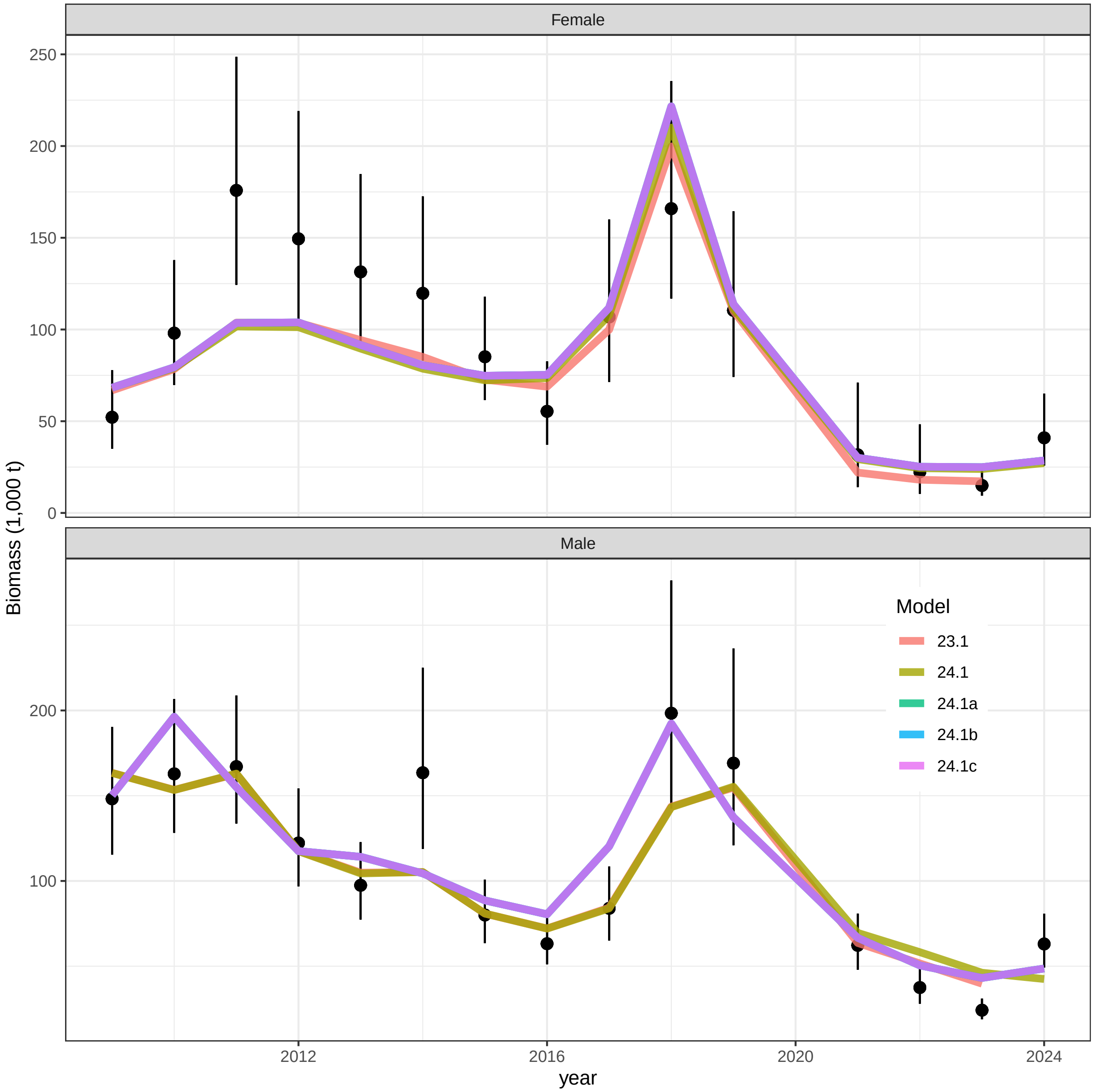

Figure 33: Model fits to the observed morphometrically mature biomass at survey 2009-present

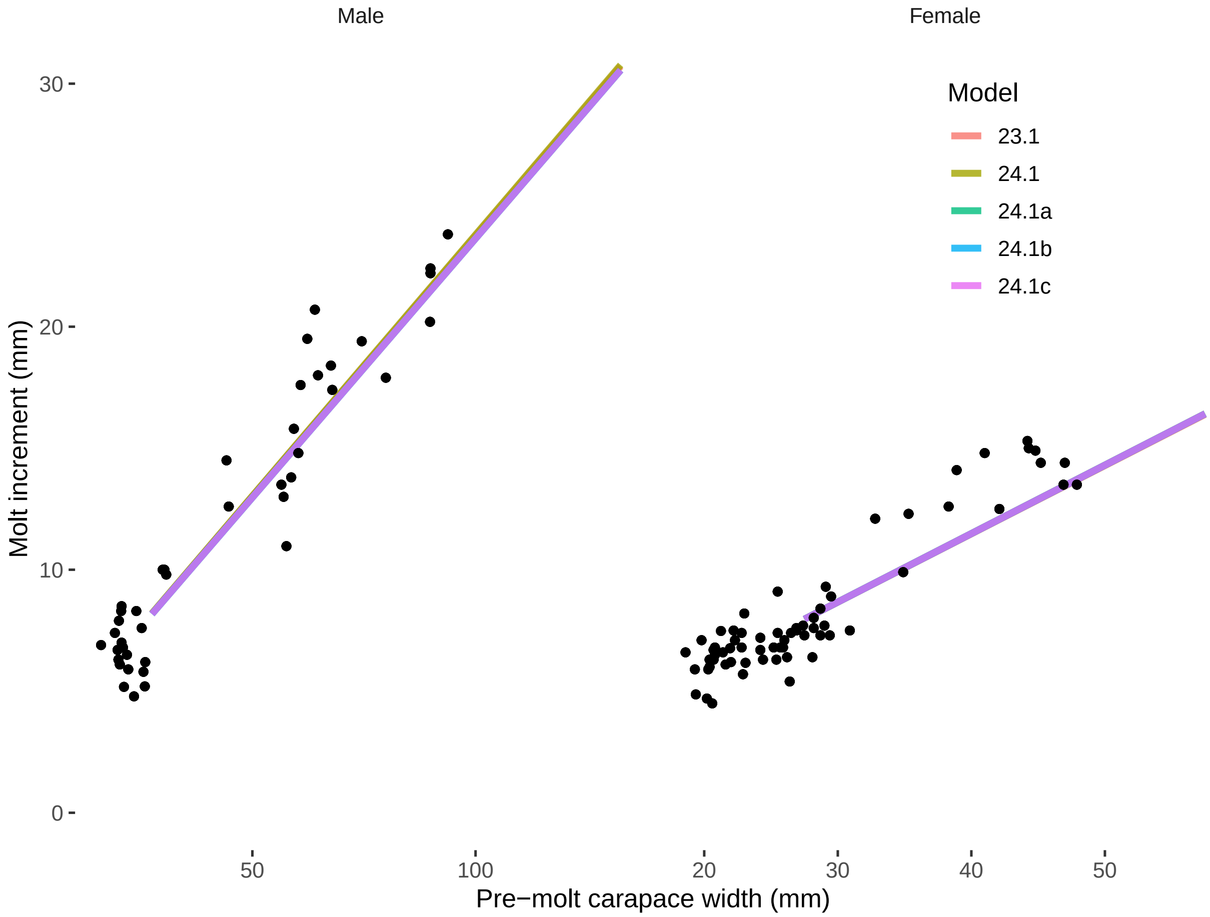

Figure 34: Model fits (colored lines) to the growth data (black dots).

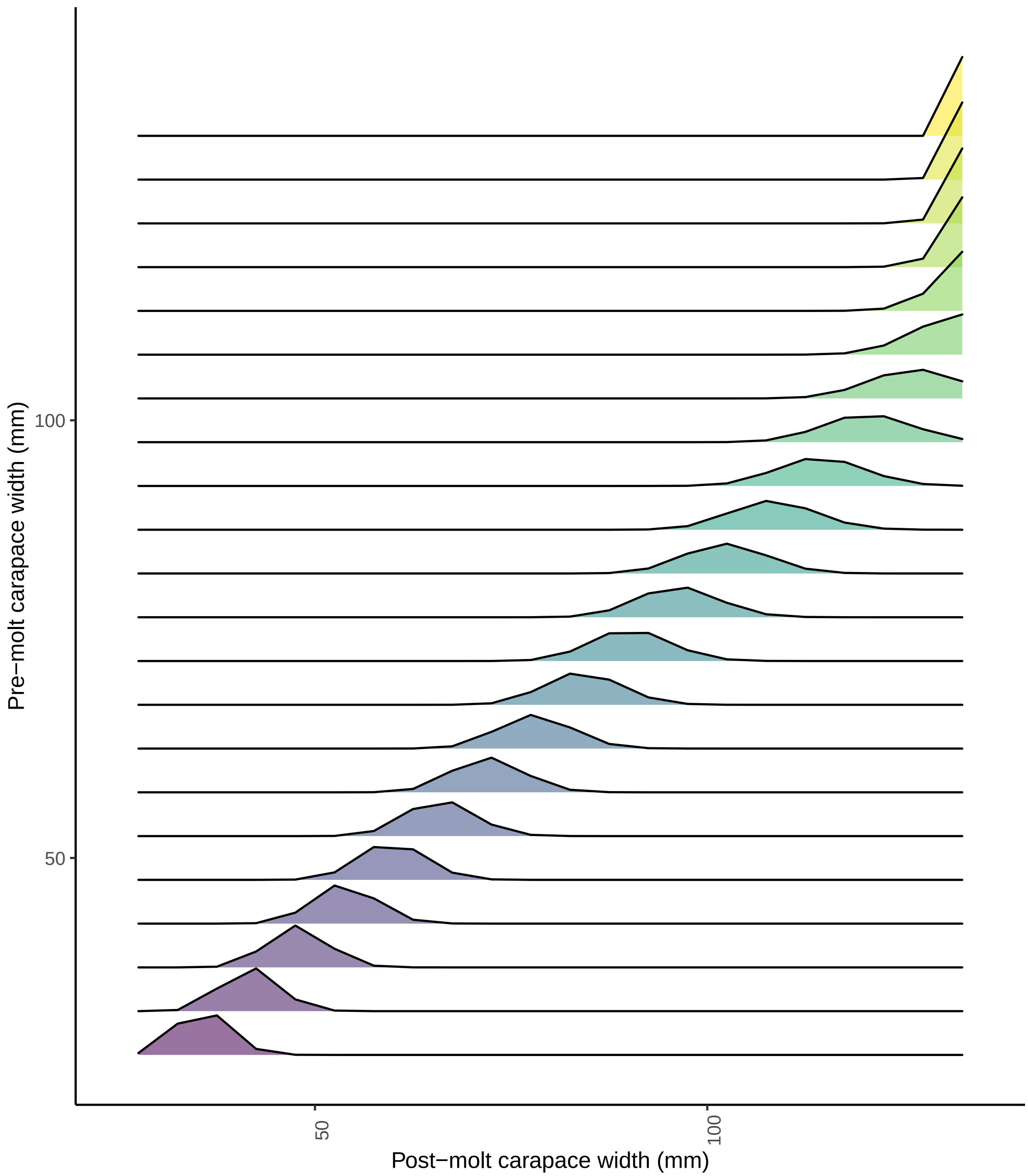

Figure 35: Size transition matrix from the author-preferred model.

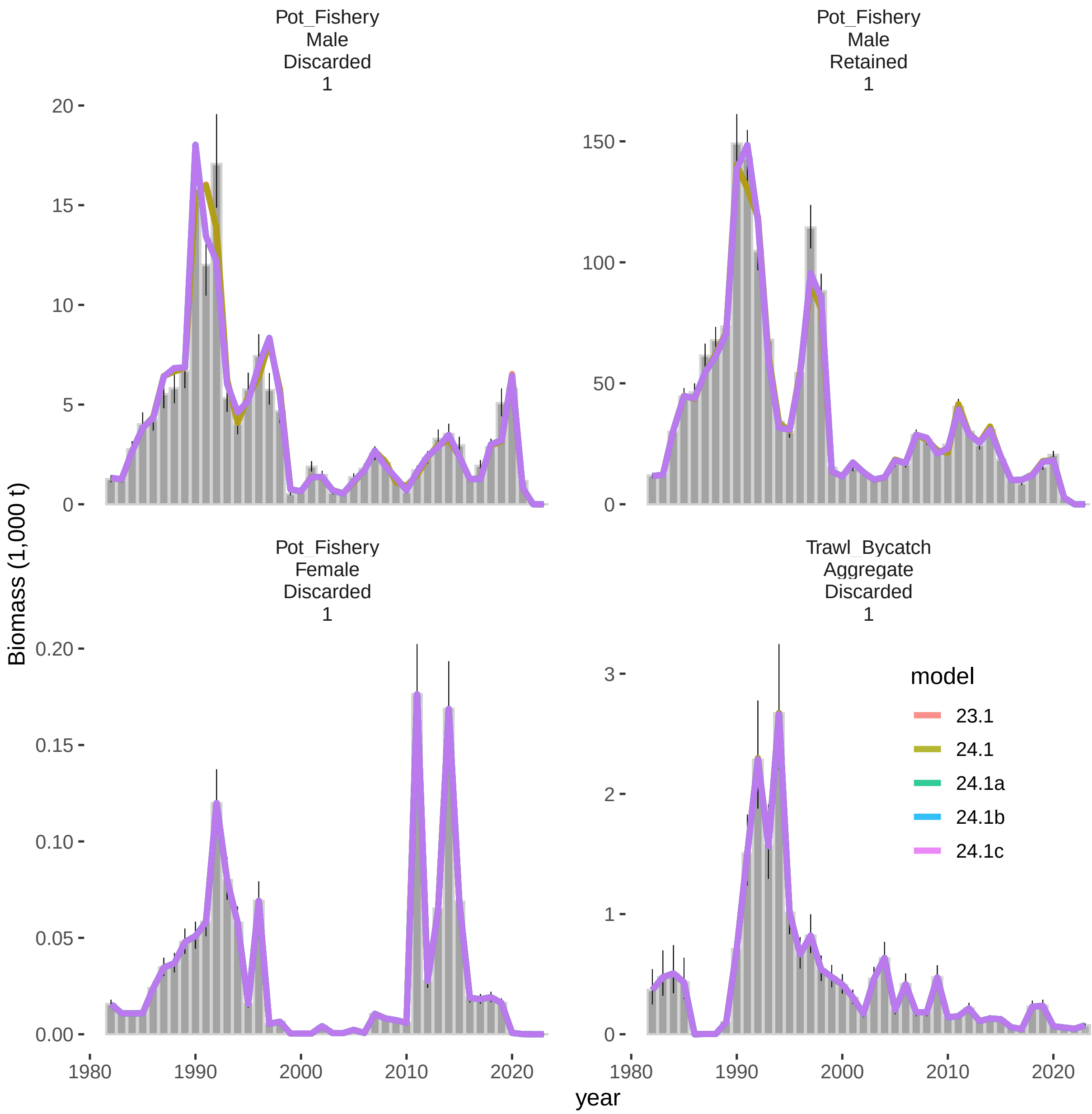

Figure 36: Model fits to catch data.

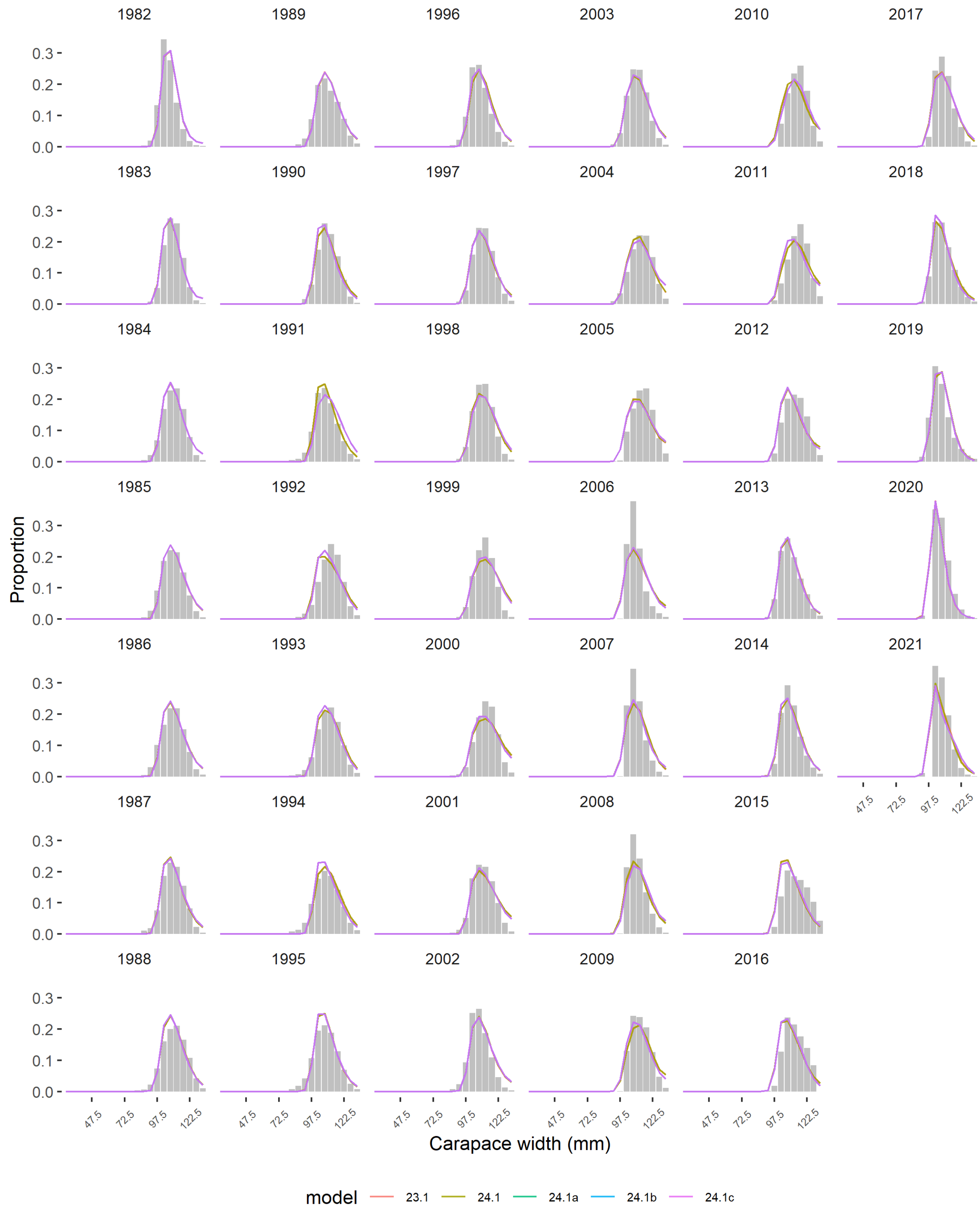

Figure 37: Model fits (lines) to the retained catch size composition data (grey bars).

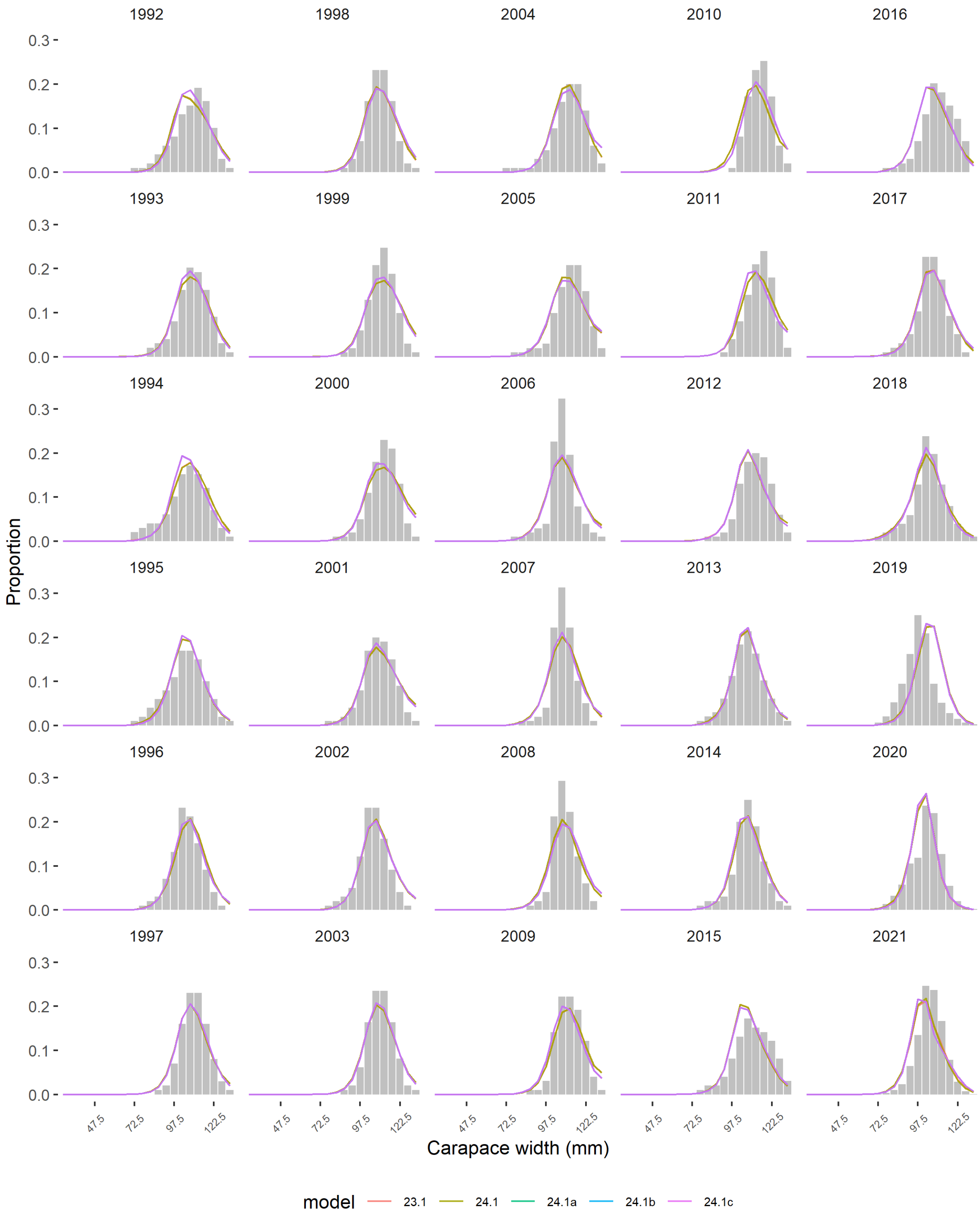

Figure 38: Model fits (lines) to the total catch size composition data (grey bars).

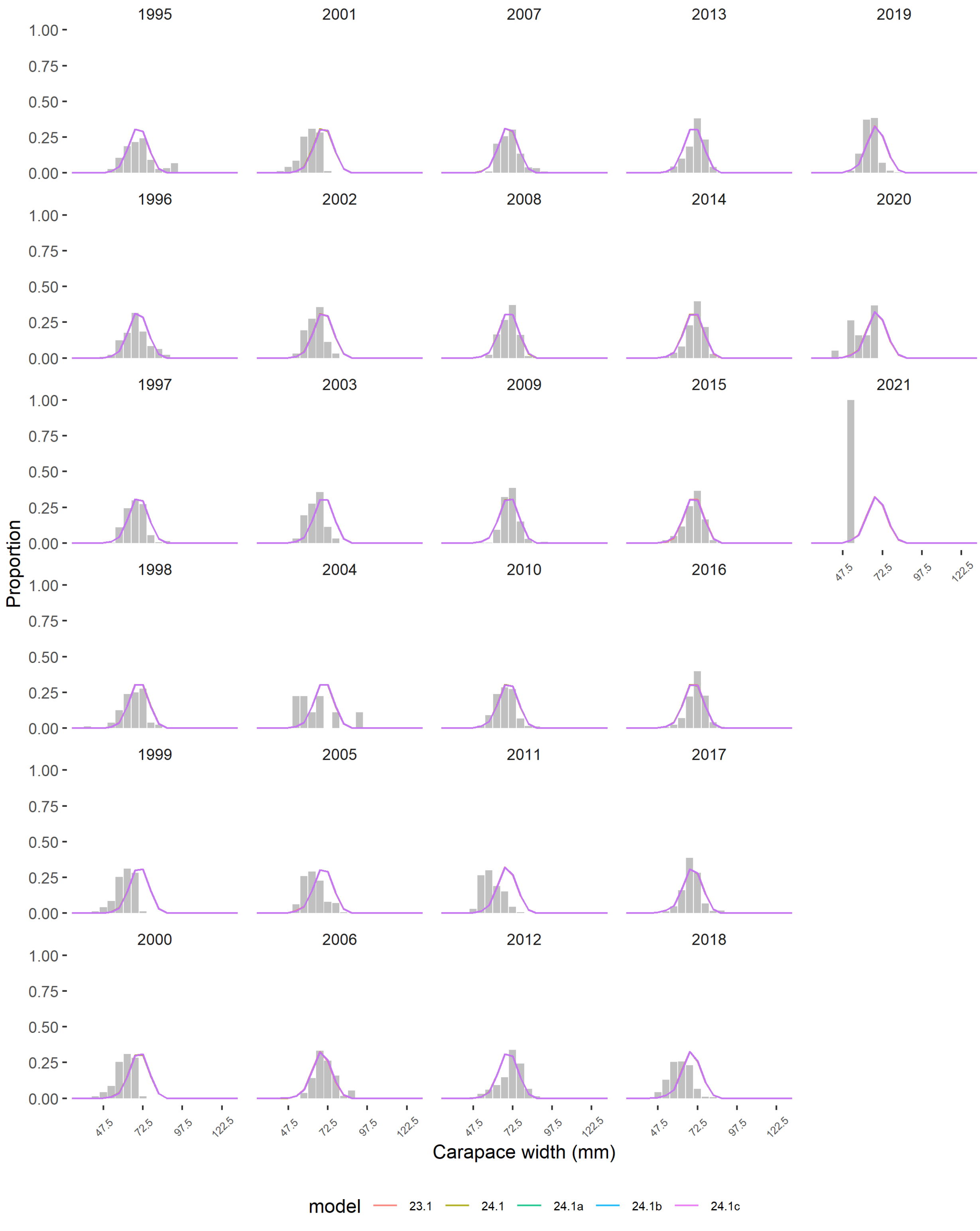

Figure 39: Model fits (lines) to the female discard size composition data (grey bars).

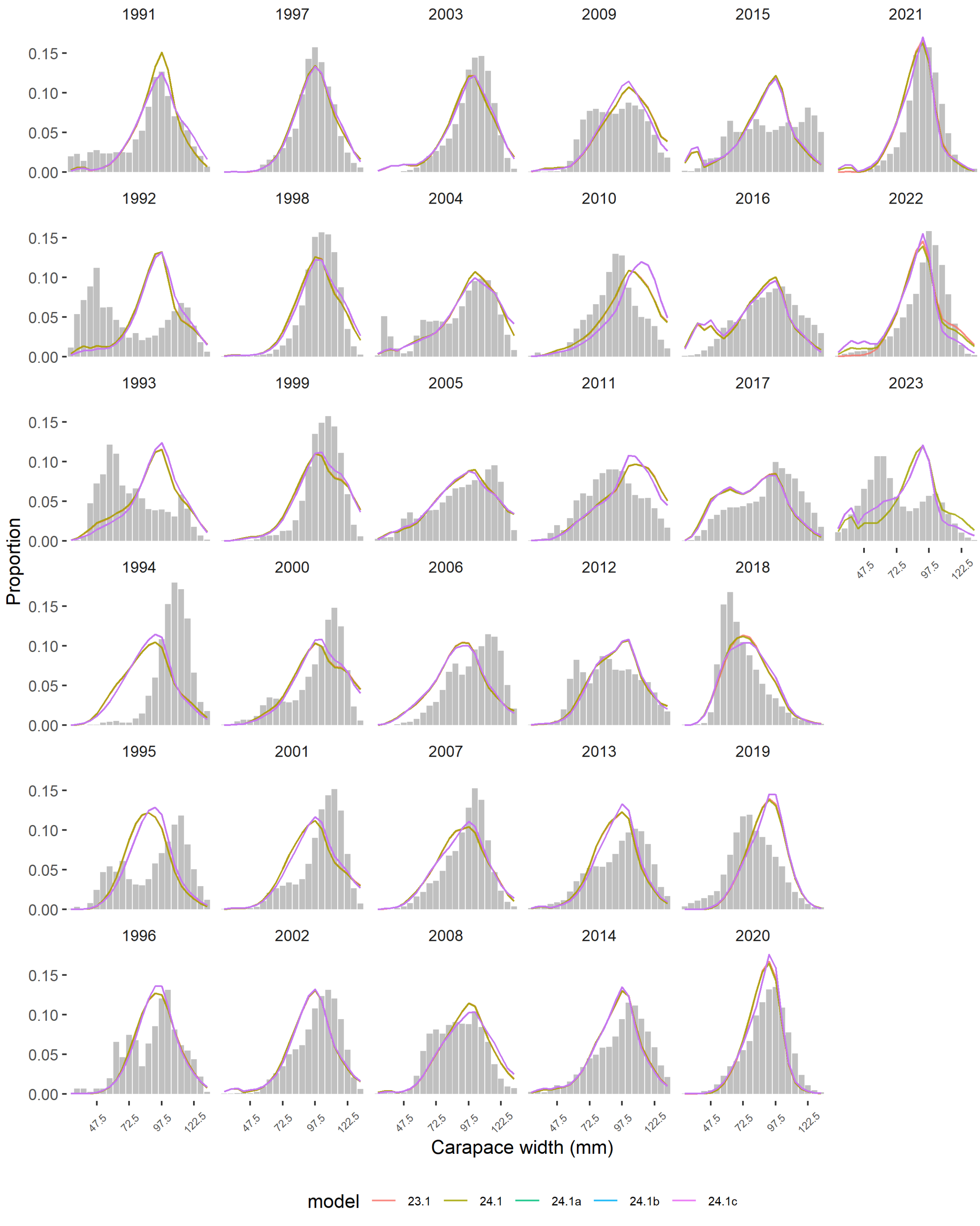

Figure 40: Model fits (lines) to the male non-directed fishery size composition data (grey bars).

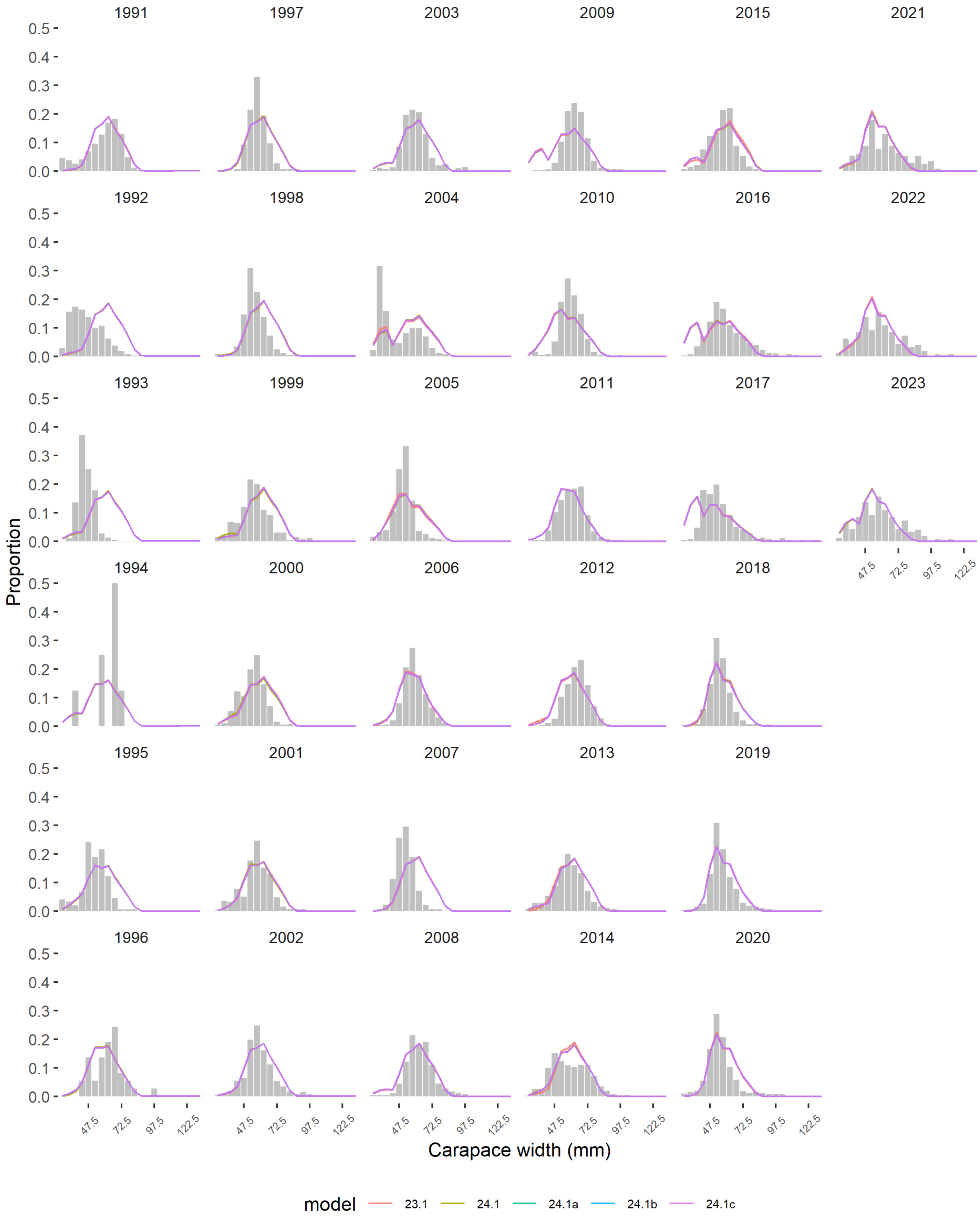

Figure 41: Model fits (lines) to the female non-directed size composition data (grey bars).

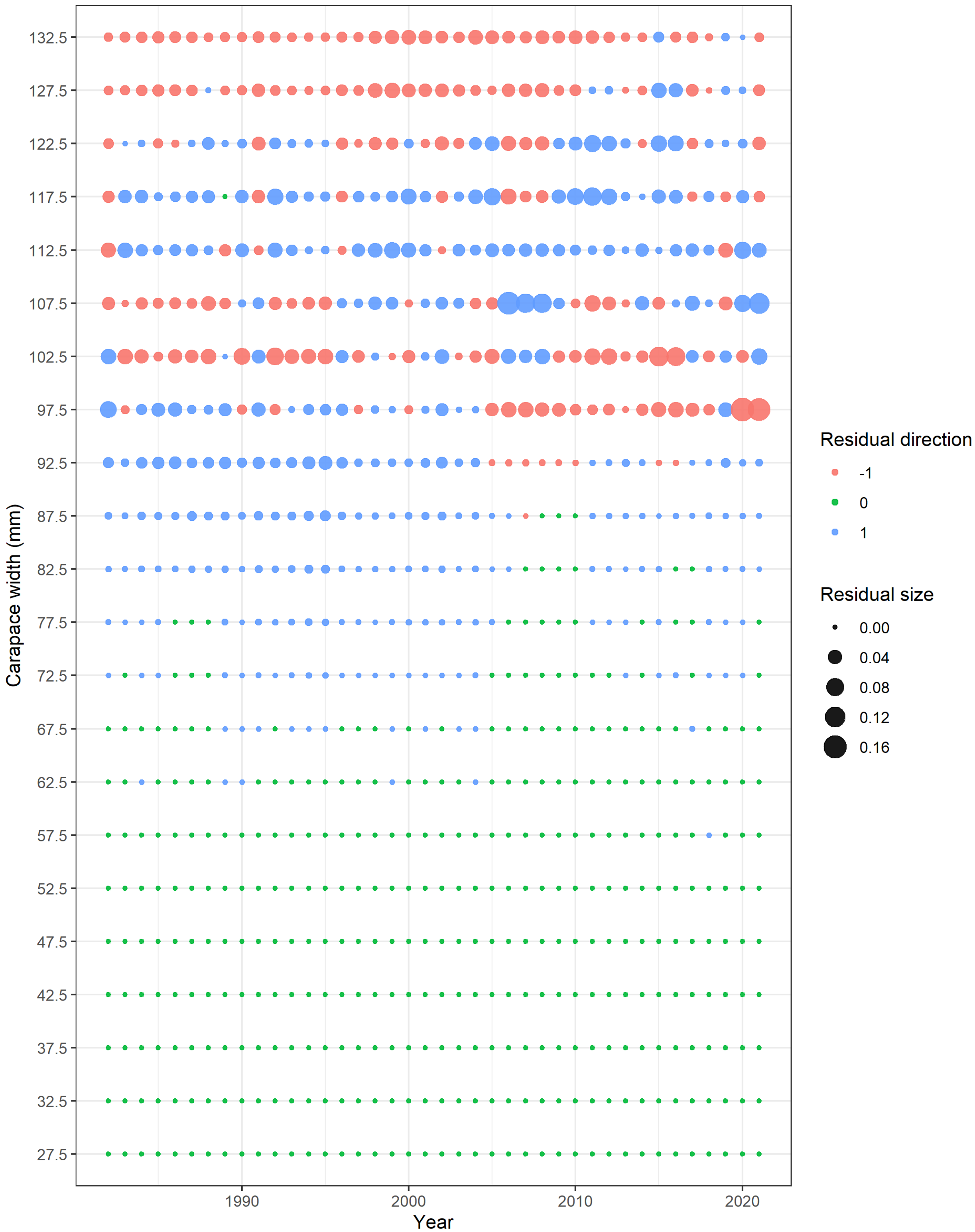

Figure 42: Residuals from chosen model for the retained catch size composition data.

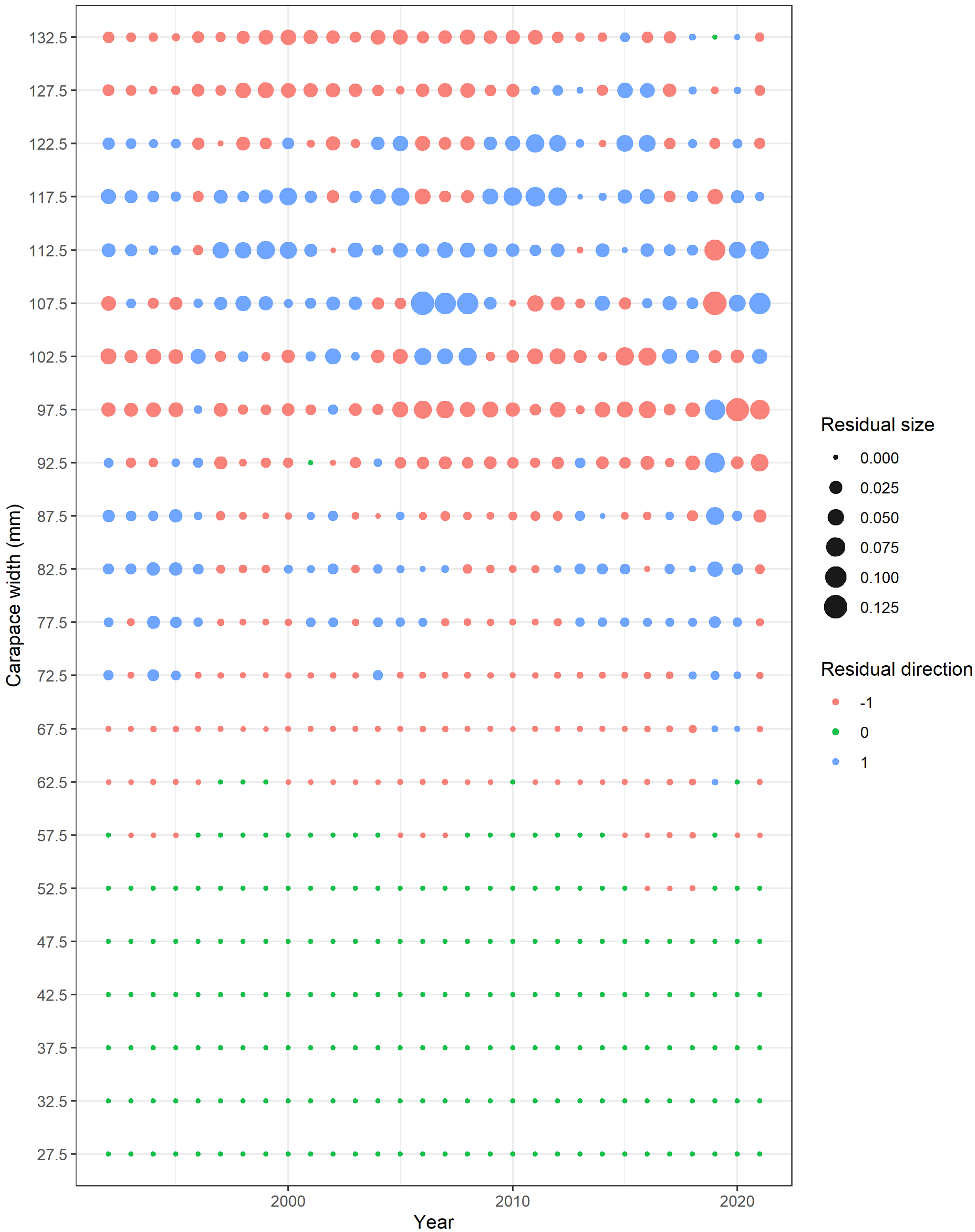

Figure 43: Residuals from chosen model for the total catch size composition data.

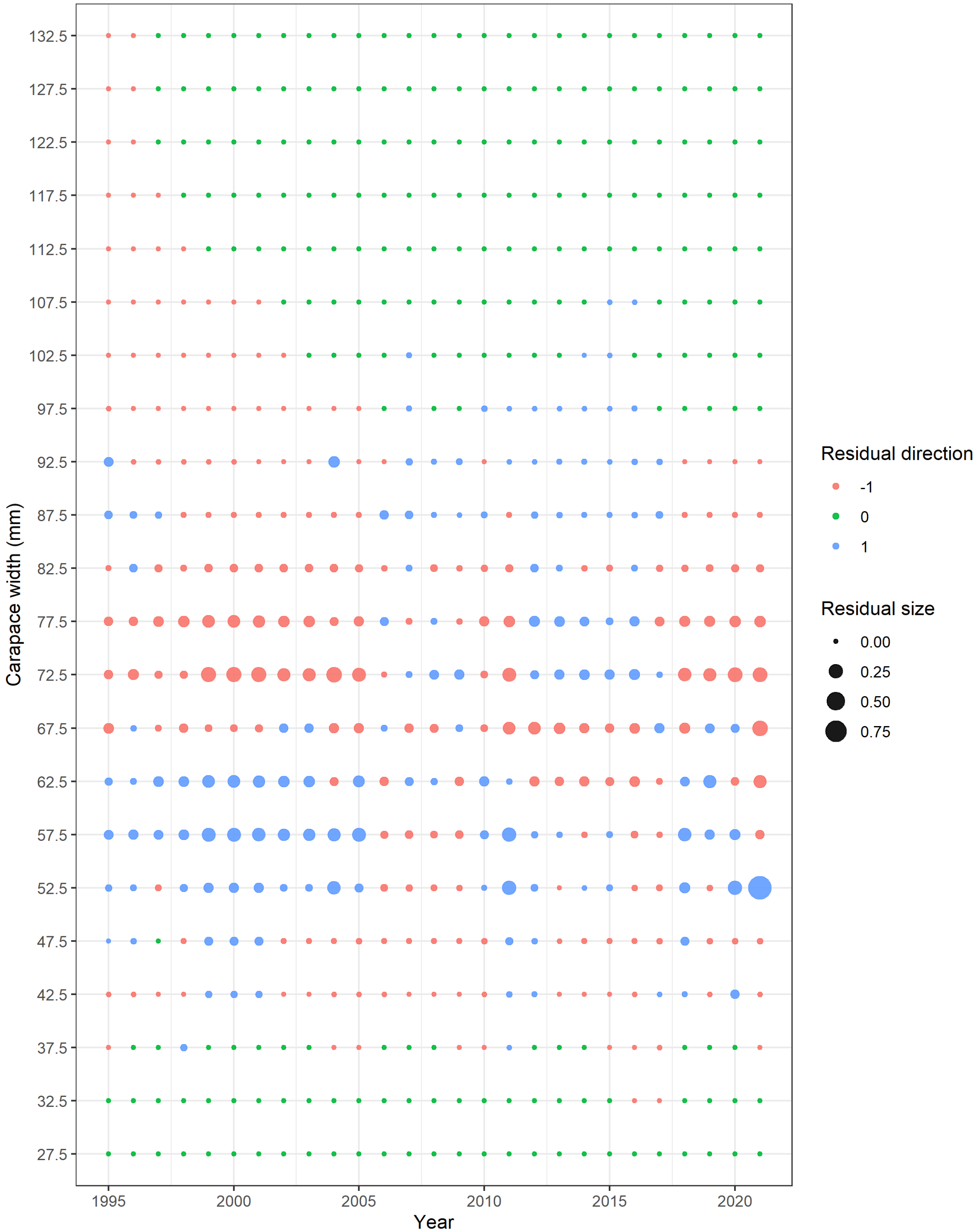

Figure 44: Residuals from chosen model for the female discard size composition data.

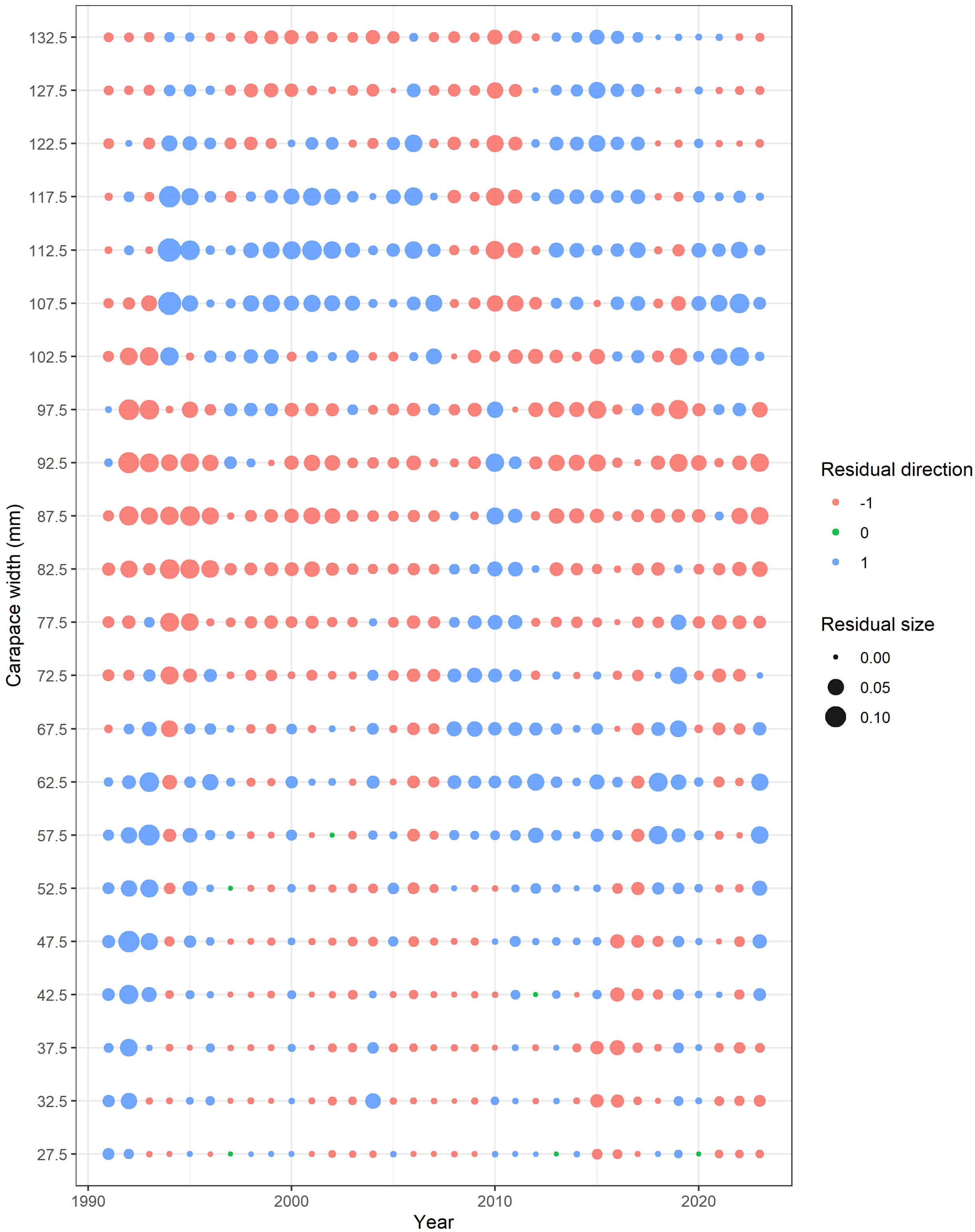

Figure 45: Residuals from chosen model for the male non-directed fishery size composition data.

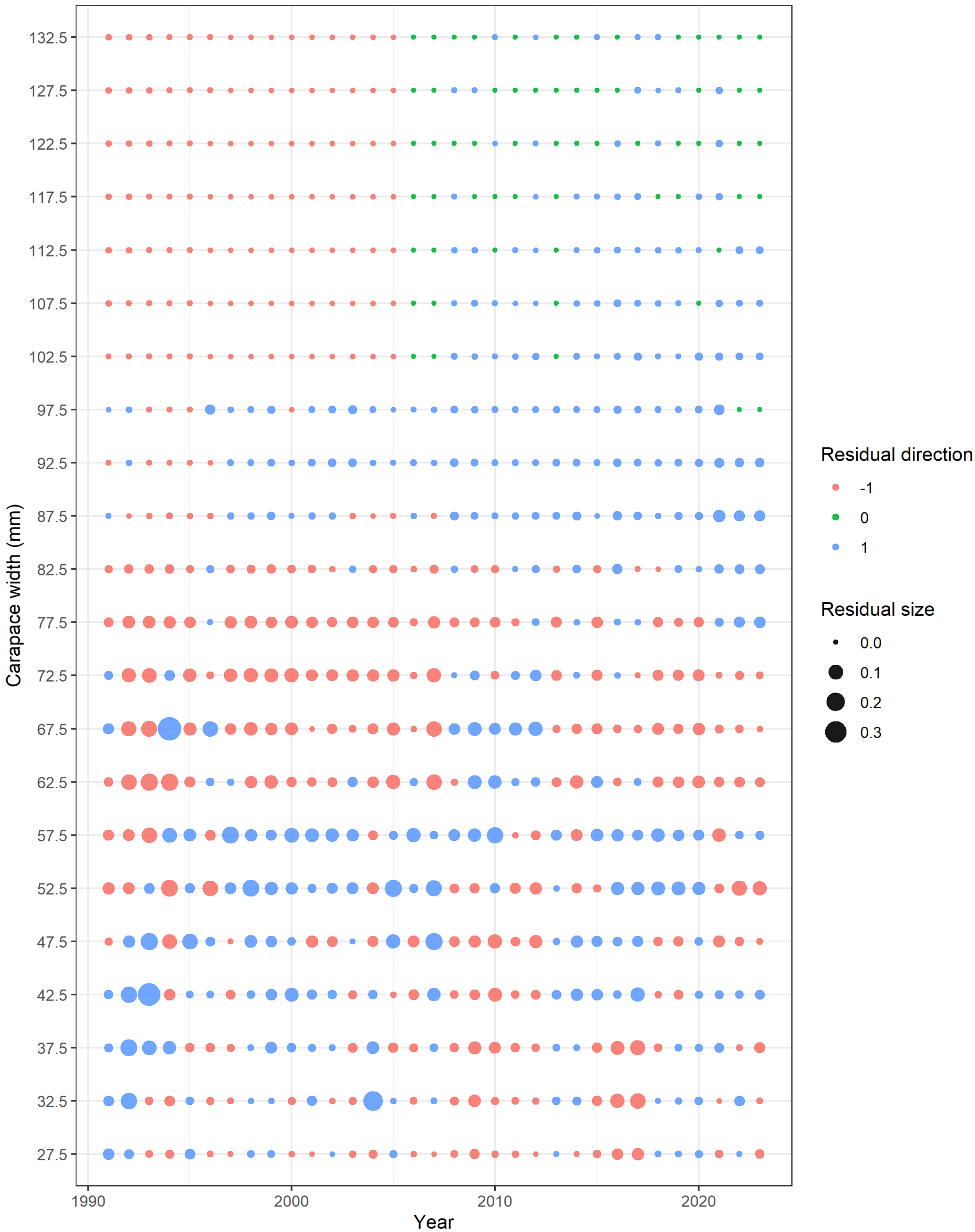

Figure 46: Residuals from chosen model for the female non-directed size composition data.

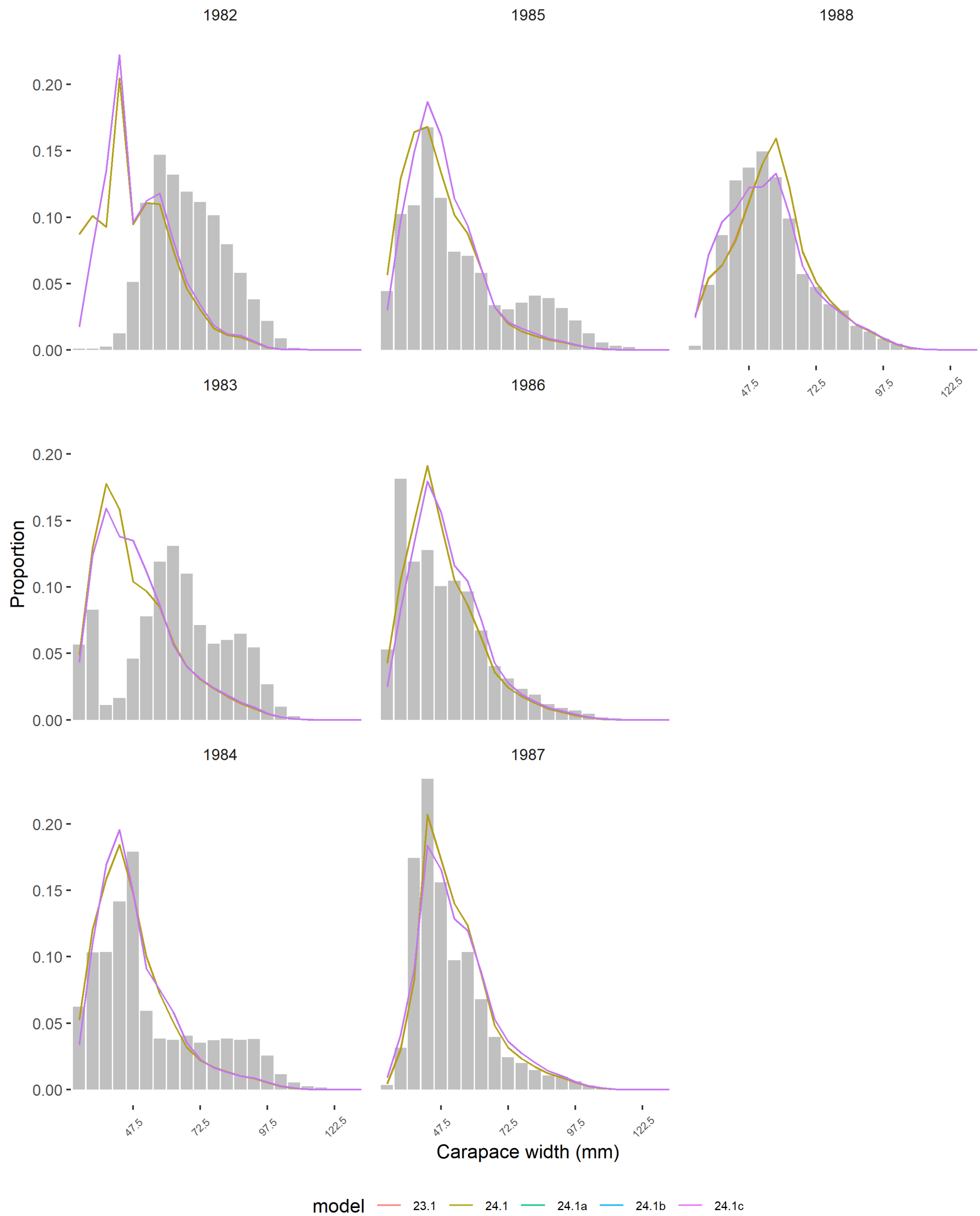

Figure 47: Model fits to immature male survey size composition data from 1982-1988.

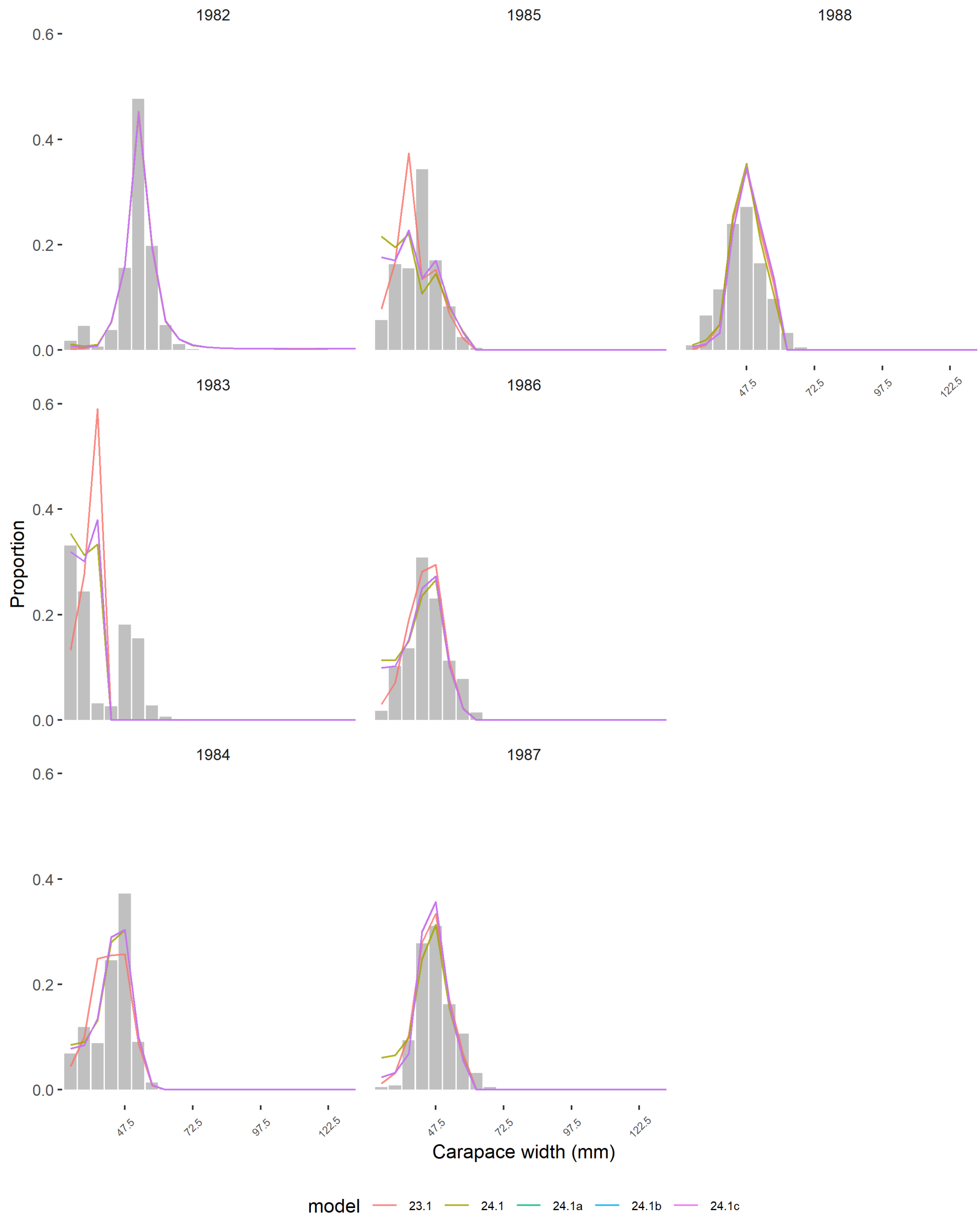

Figure 48: Model fits to immature female survey size composition data from 1982-1988.

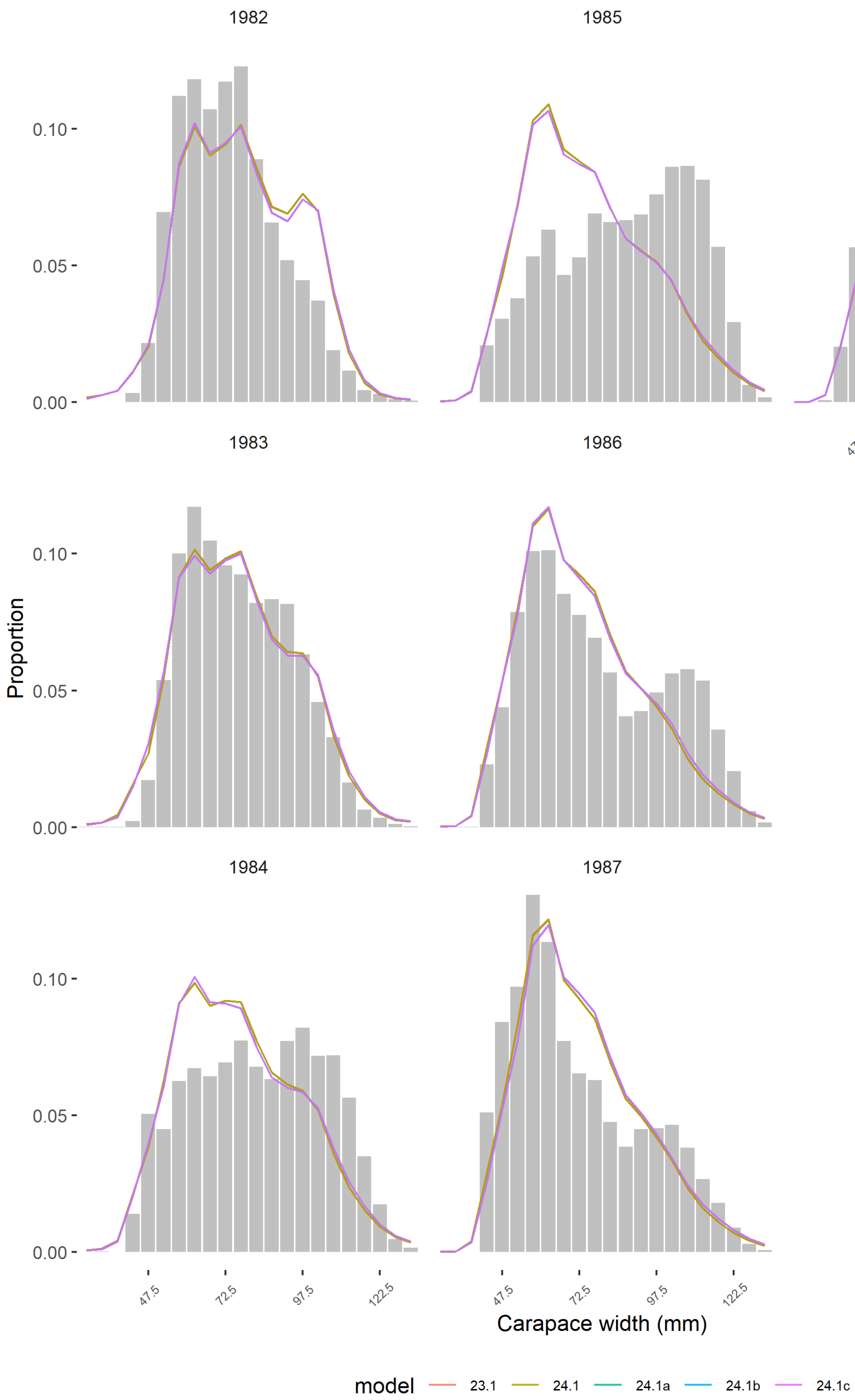

Figure 49: Model fits to morphometrically mature male survey size composition data from 1982-1988.

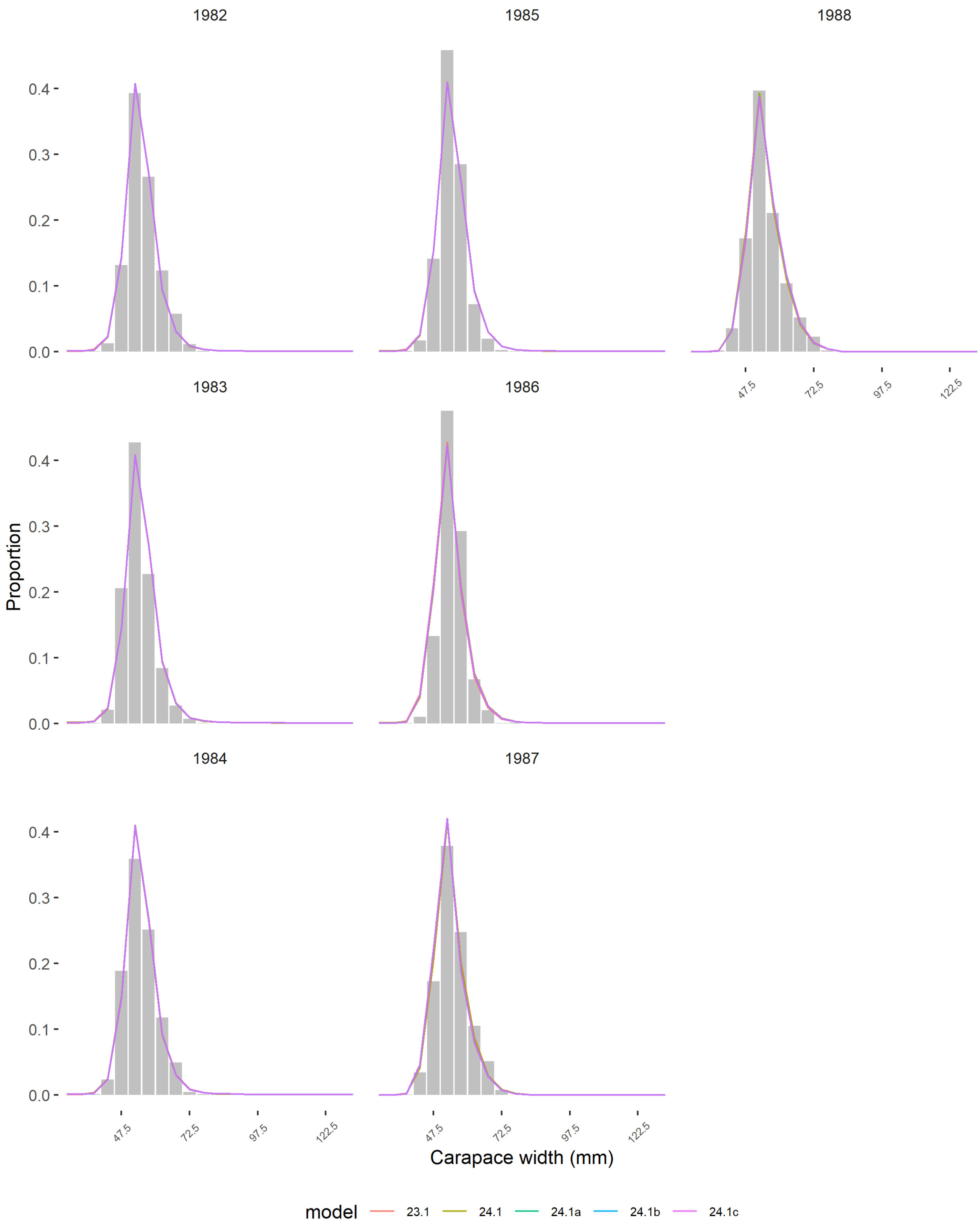

Figure 50: Model fits to mature female survey size composition data from 1982-1988.

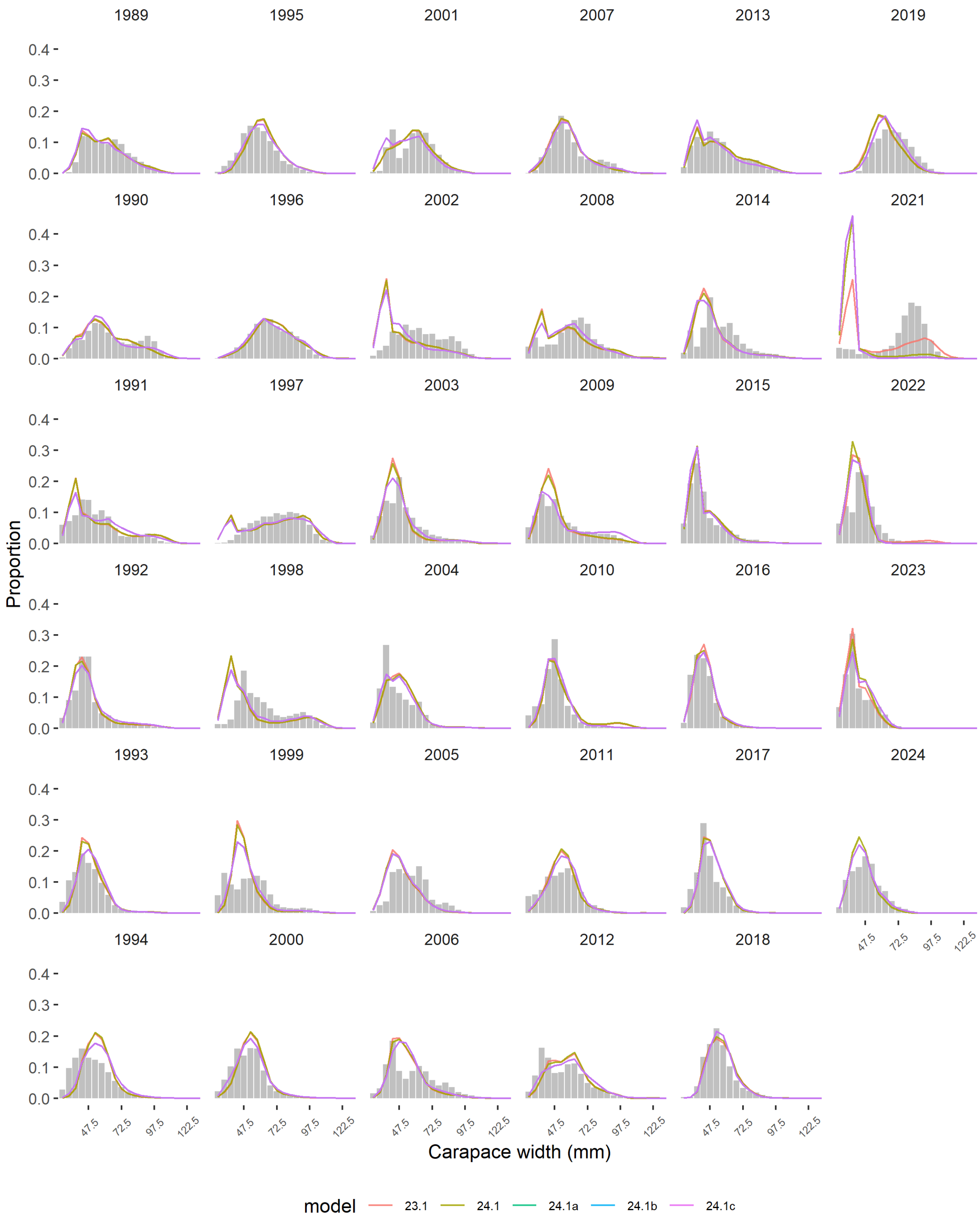

Figure 51: Model fits to immature male survey size composition data from 1989-present.

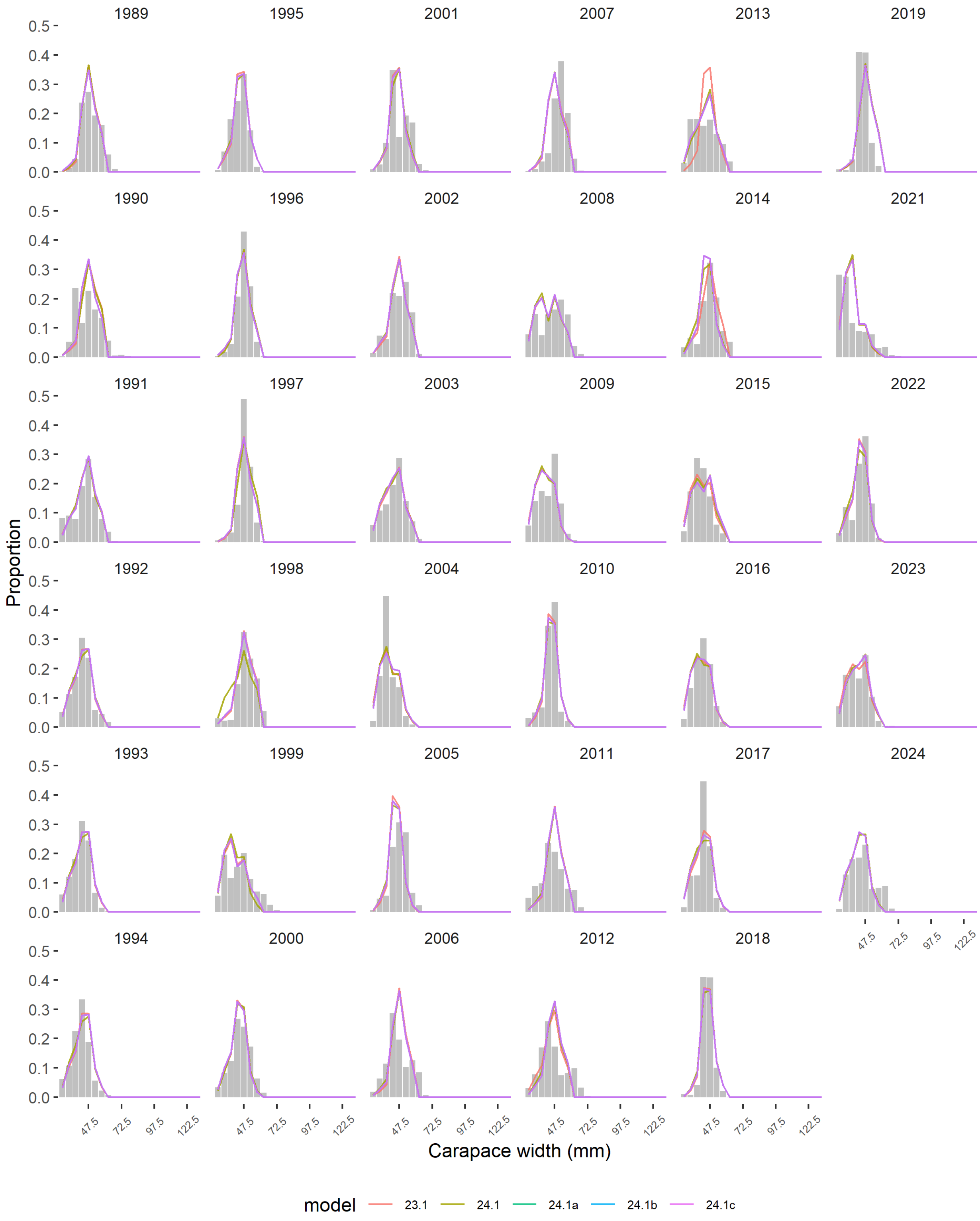

Figure 52: Model fits to immature female survey size composition data from 1989-present.

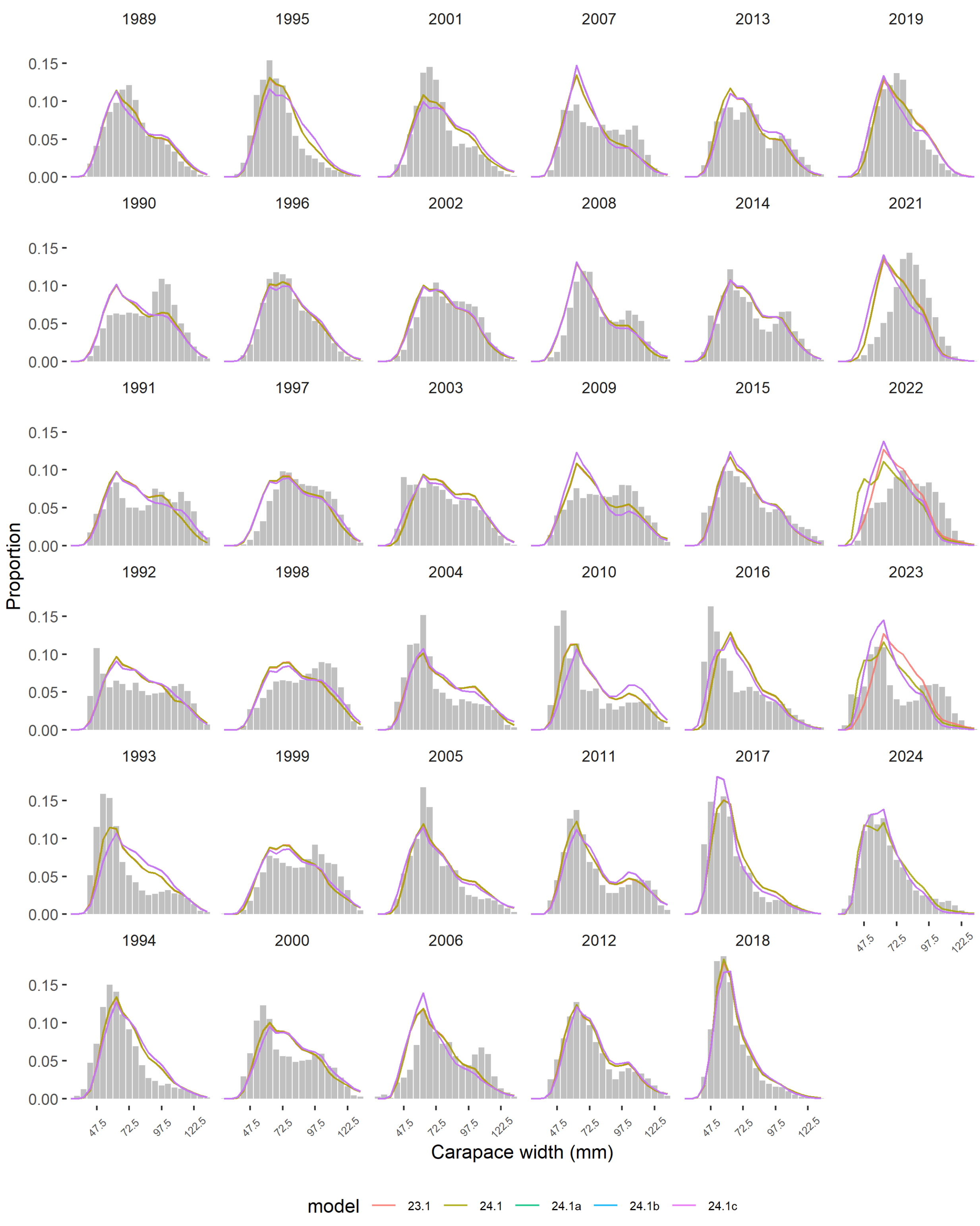

Figure 53: Model fits to morphometrically mature male survey size composition data from 1989-present.

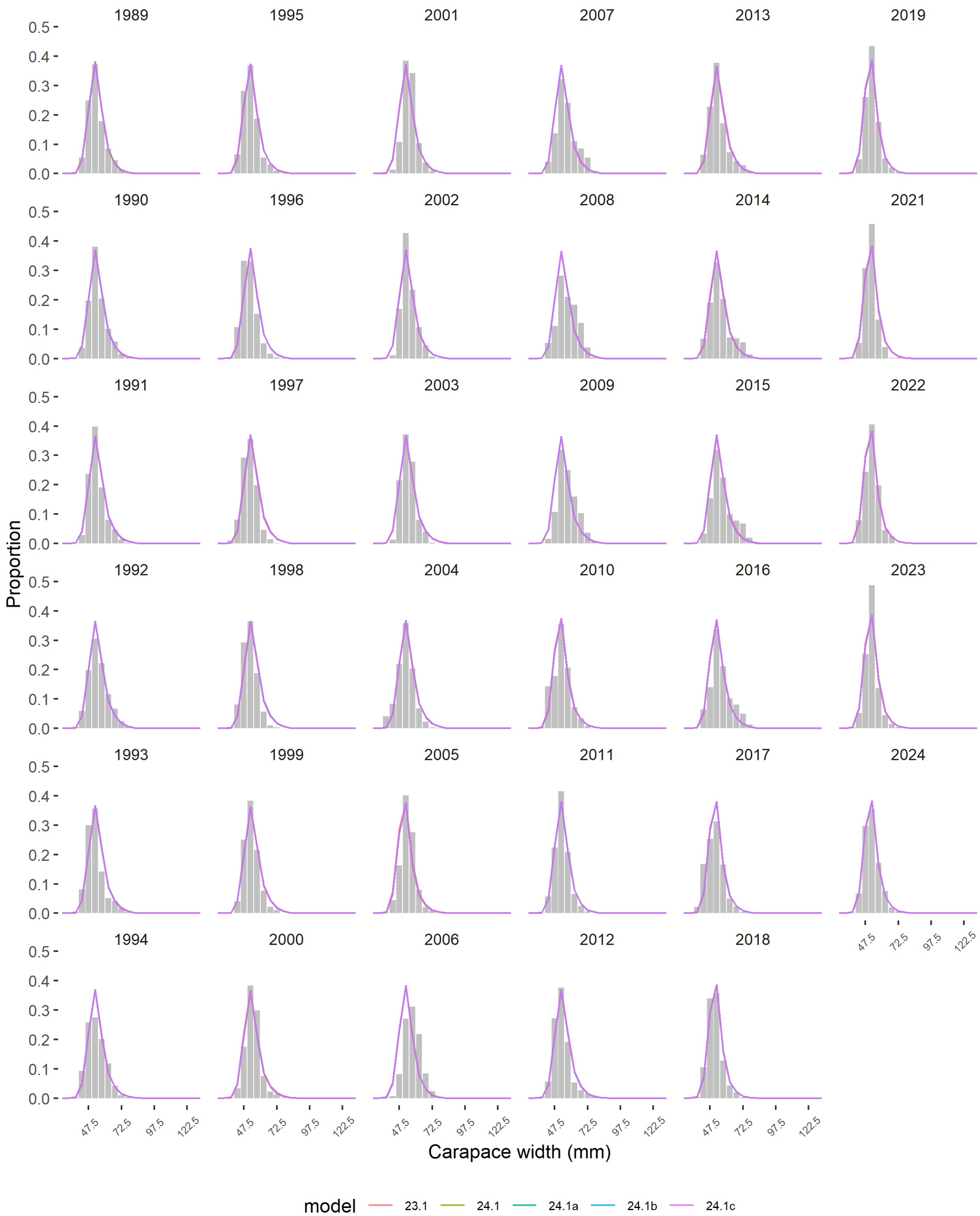

Figure 54: Model fits to mature female survey size composition data from 1989-present.

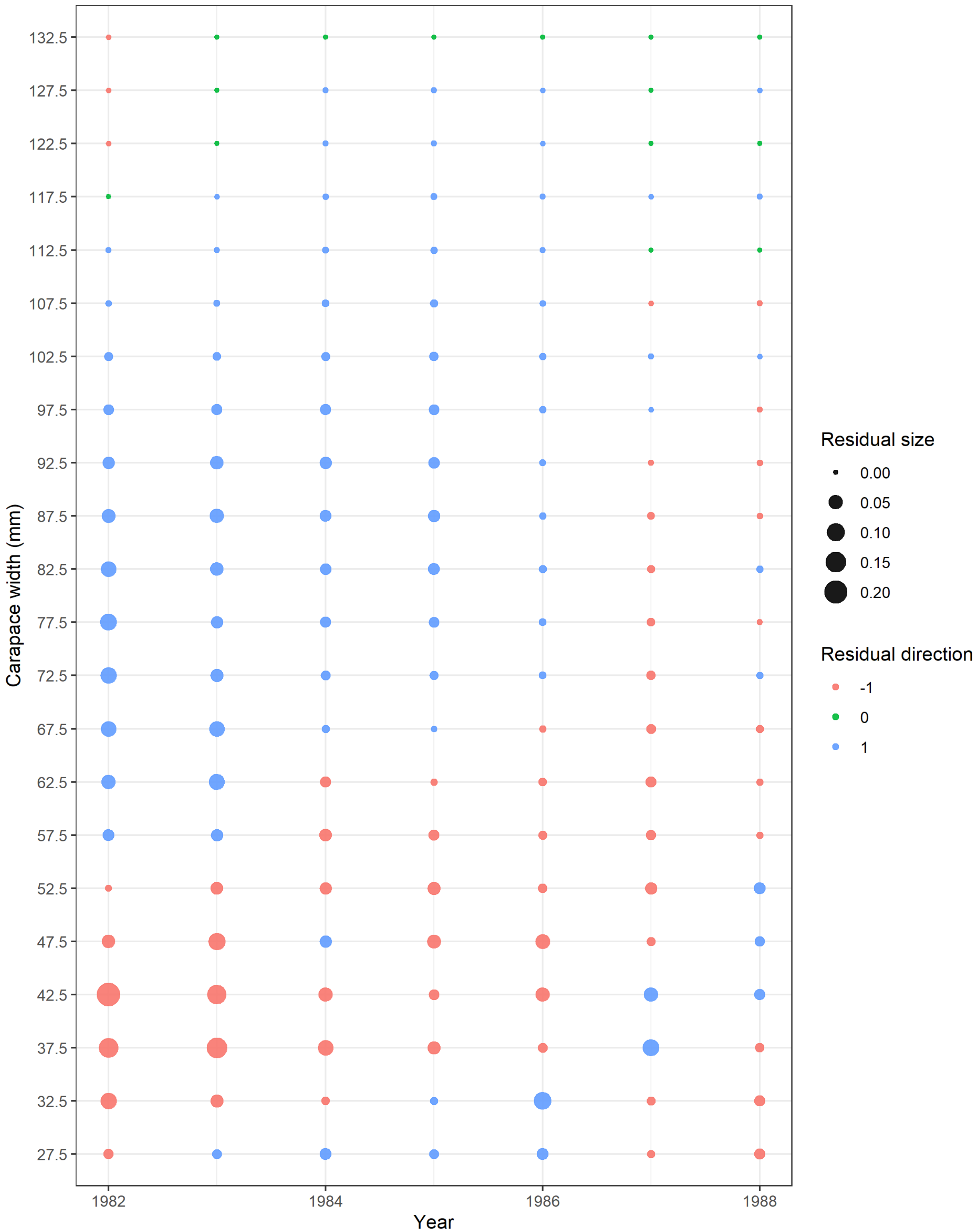

Figure 55: Residuals from chosen model for immature male survey size composition data from 1982-1988.

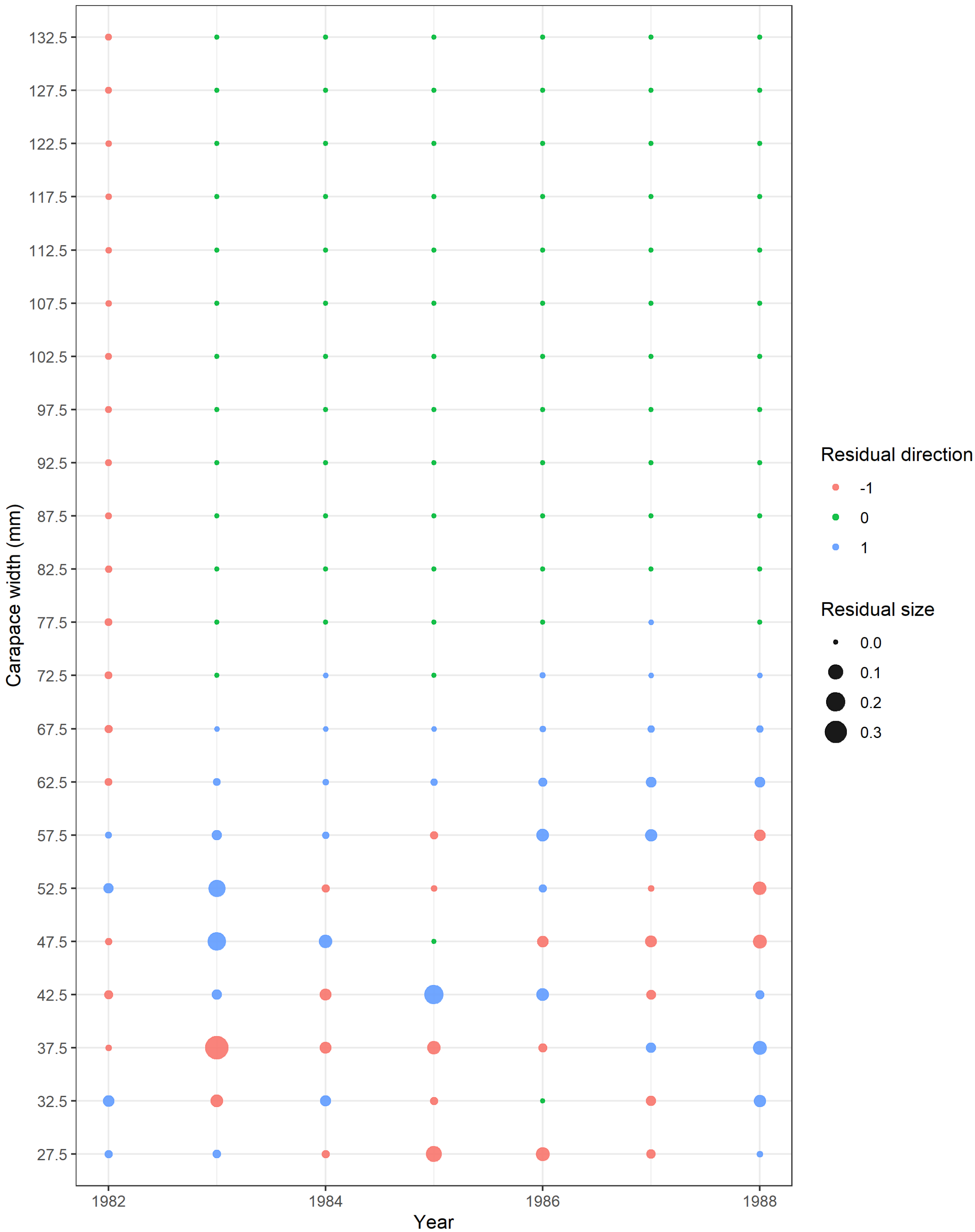

Figure 56: Residuals from chosen model for immature female survey size composition data from 1982-1988.

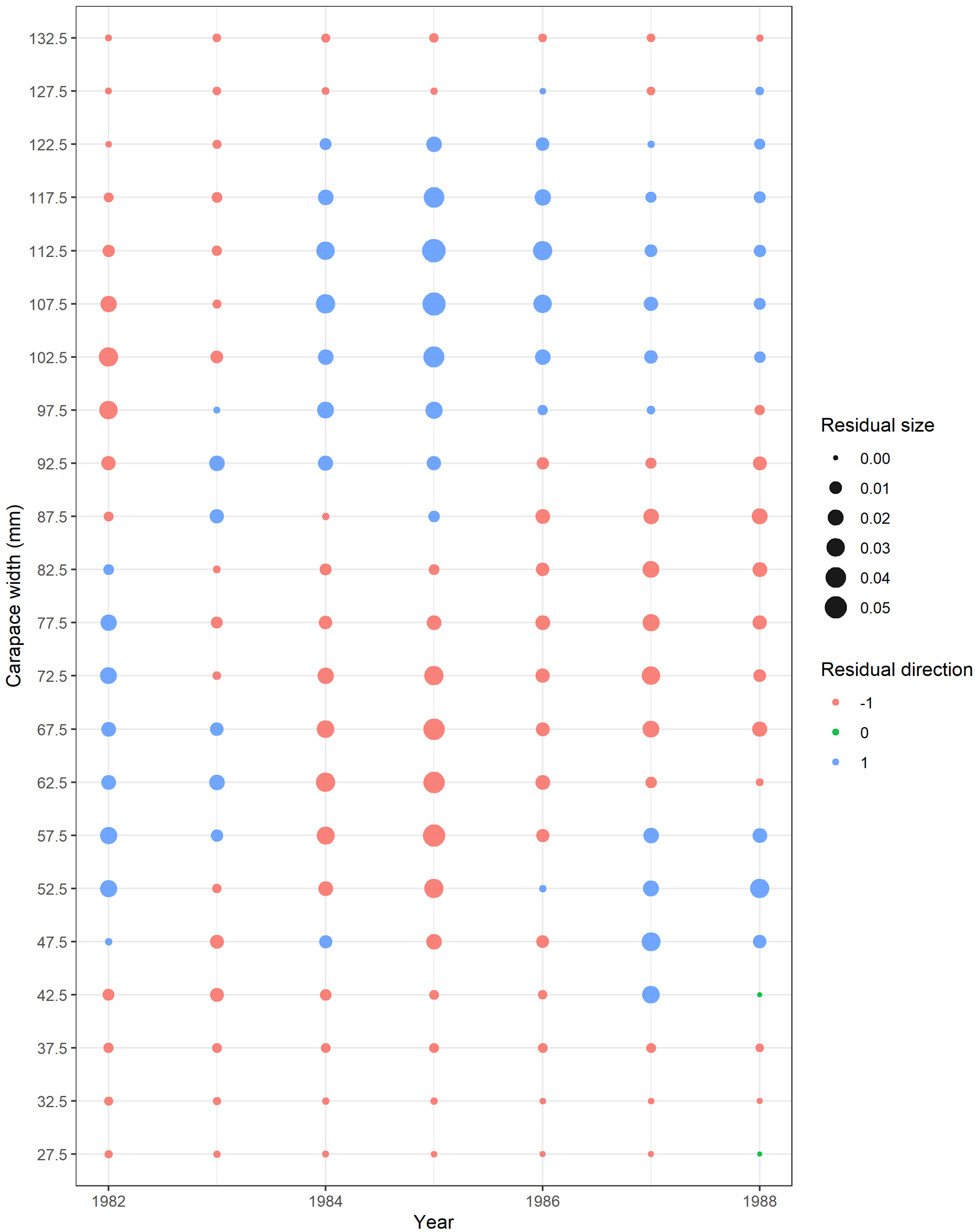

Figure 57: Residuals from chosen model for morphometrically mature male survey size composition data from 1982-1988.

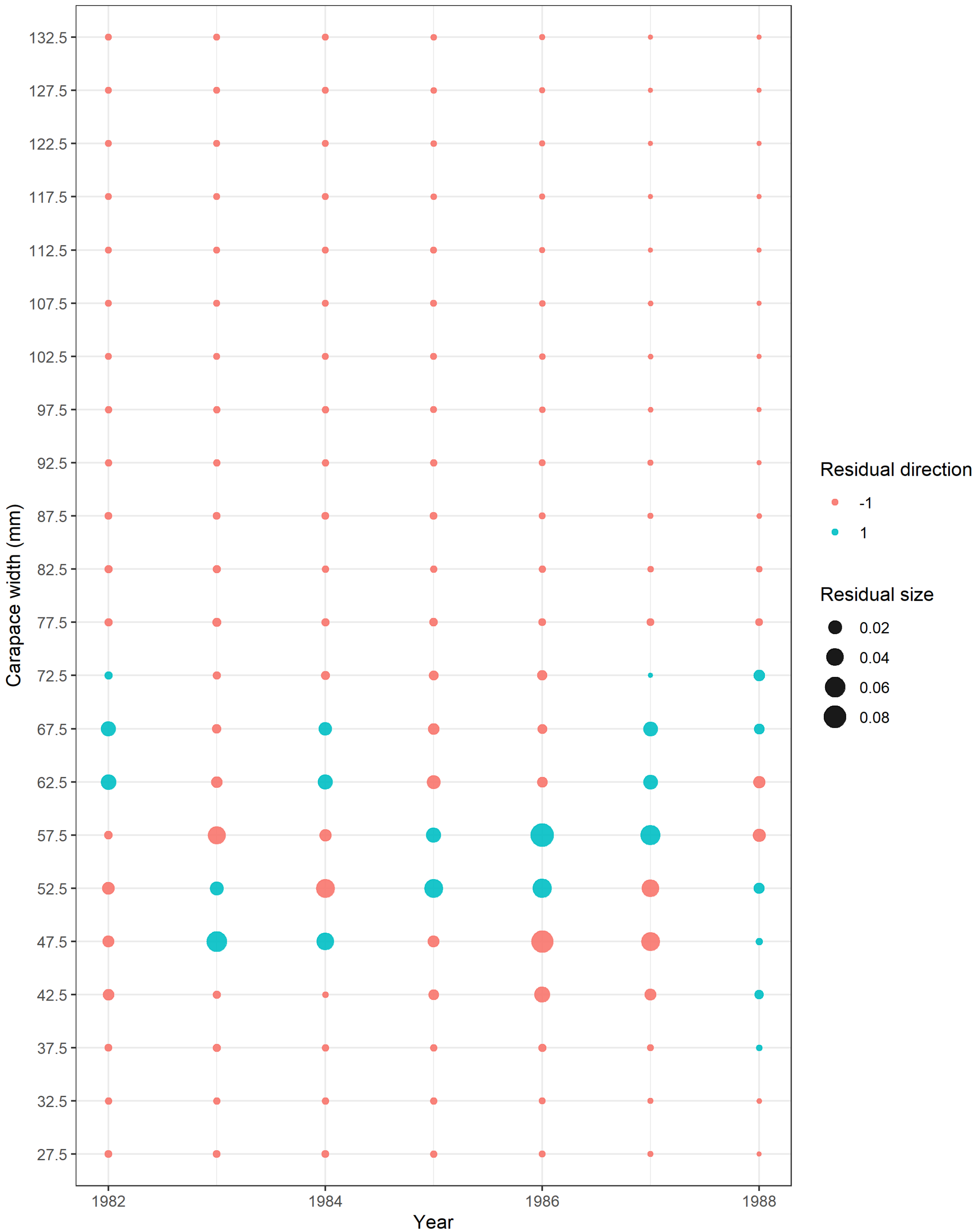

Figure 58: Residuals from chosen model for mature female survey size composition data from 1982-1988.

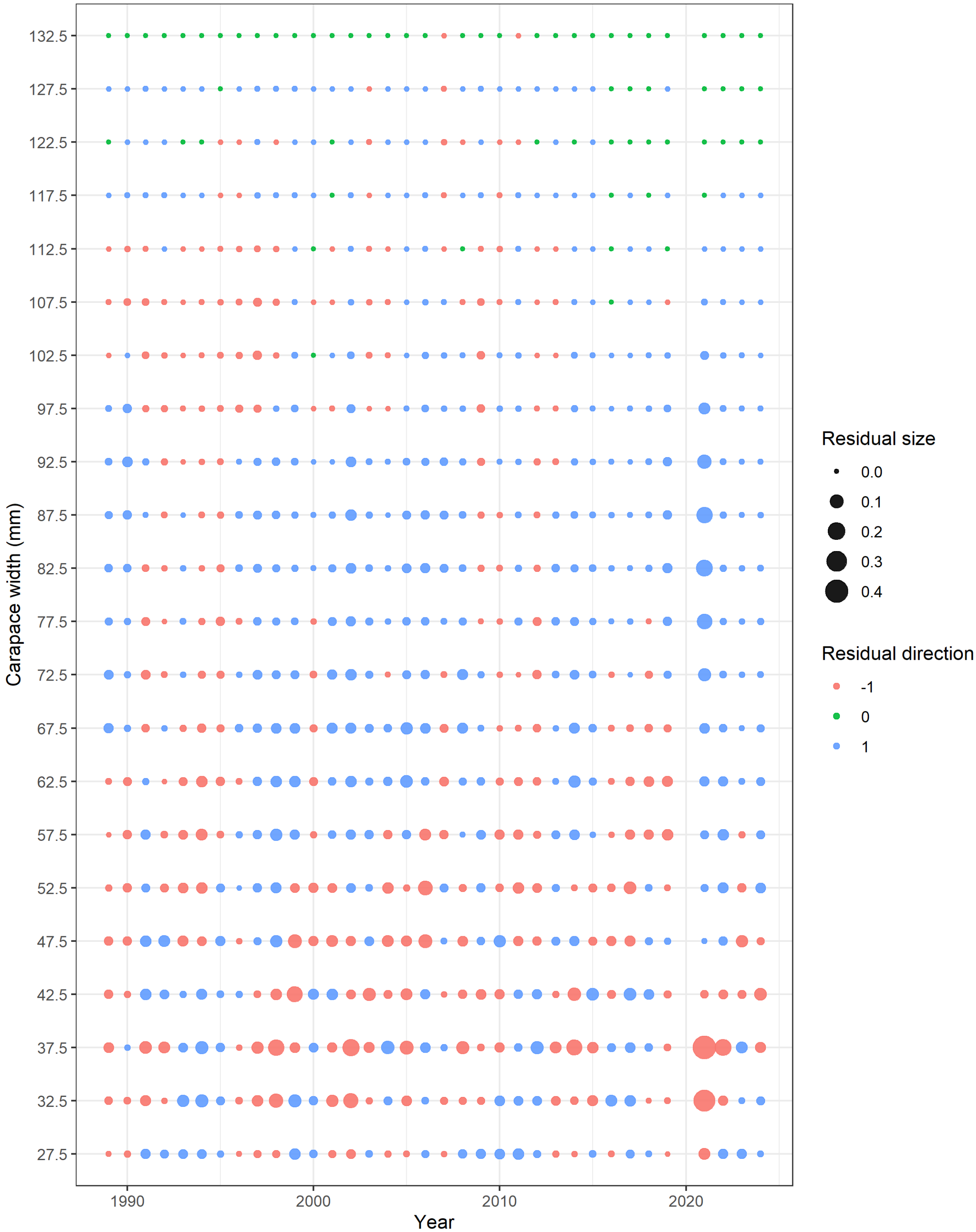

Figure 59: Residuals from chosen model for immature male survey size composition data from 1989-present.

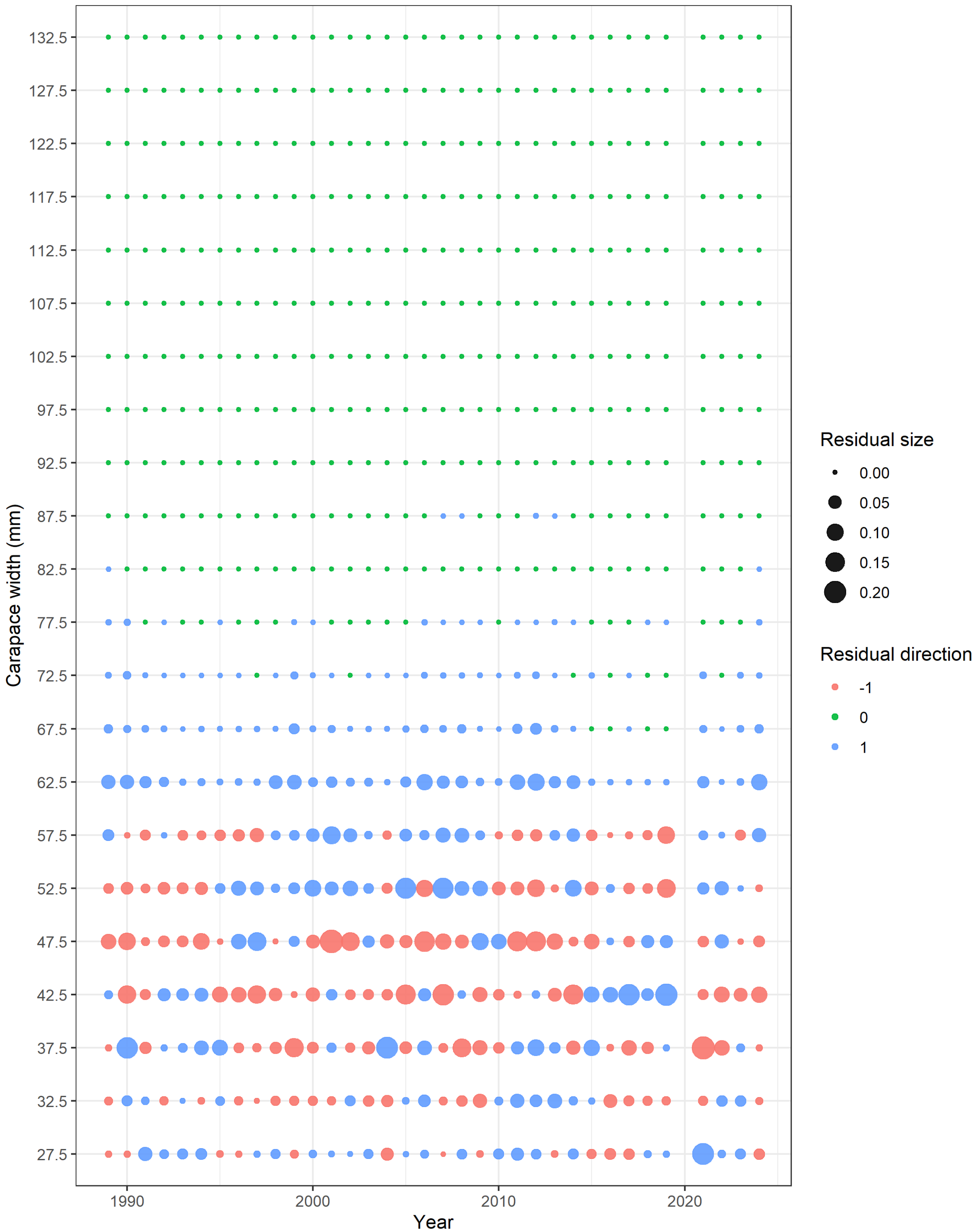

Figure 60: Residuals from chosen model for immature female survey size composition data from 1989-present.

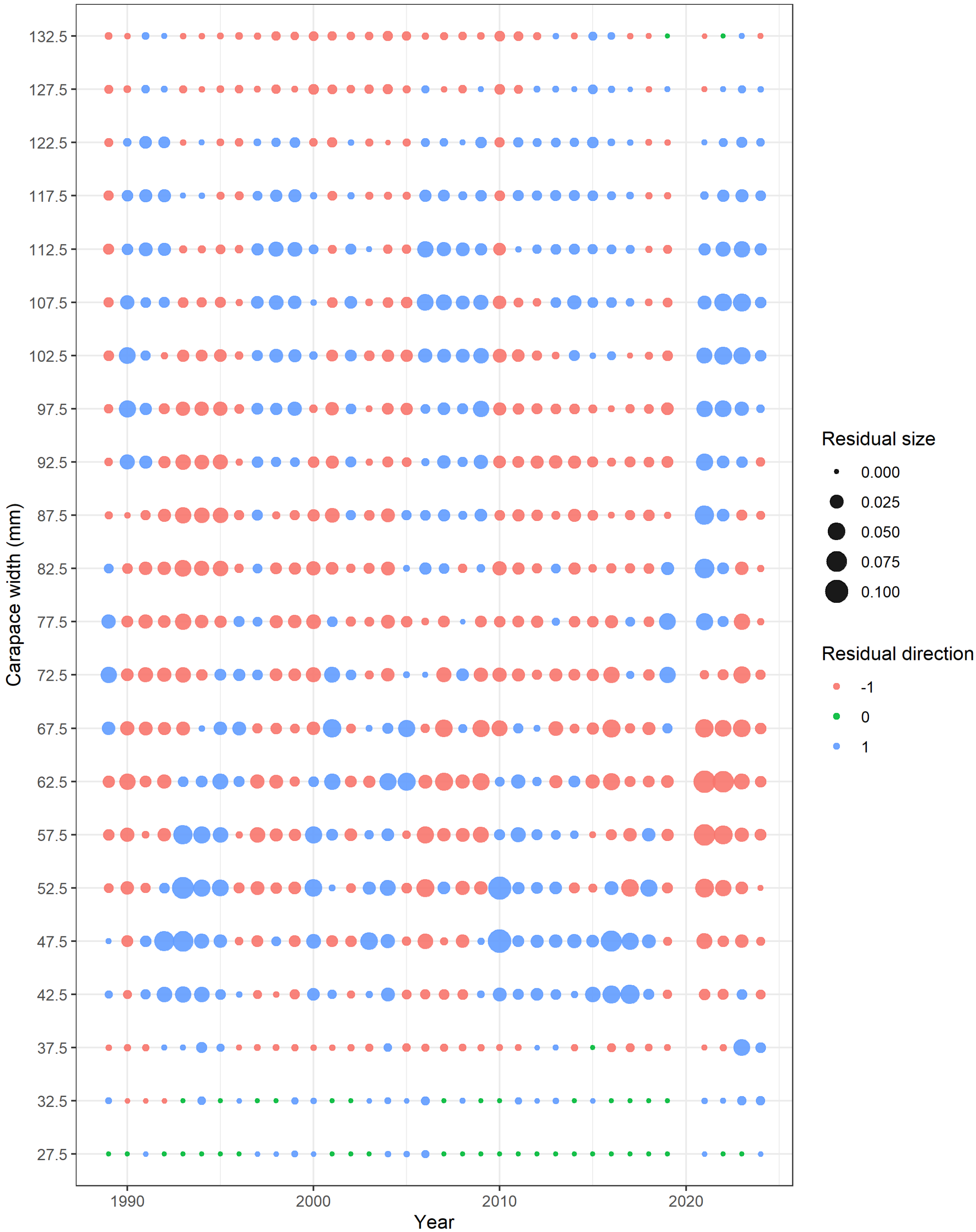

Figure 61: Residuals from chosen model for morphometrically mature male survey size composition data from 1989-present.

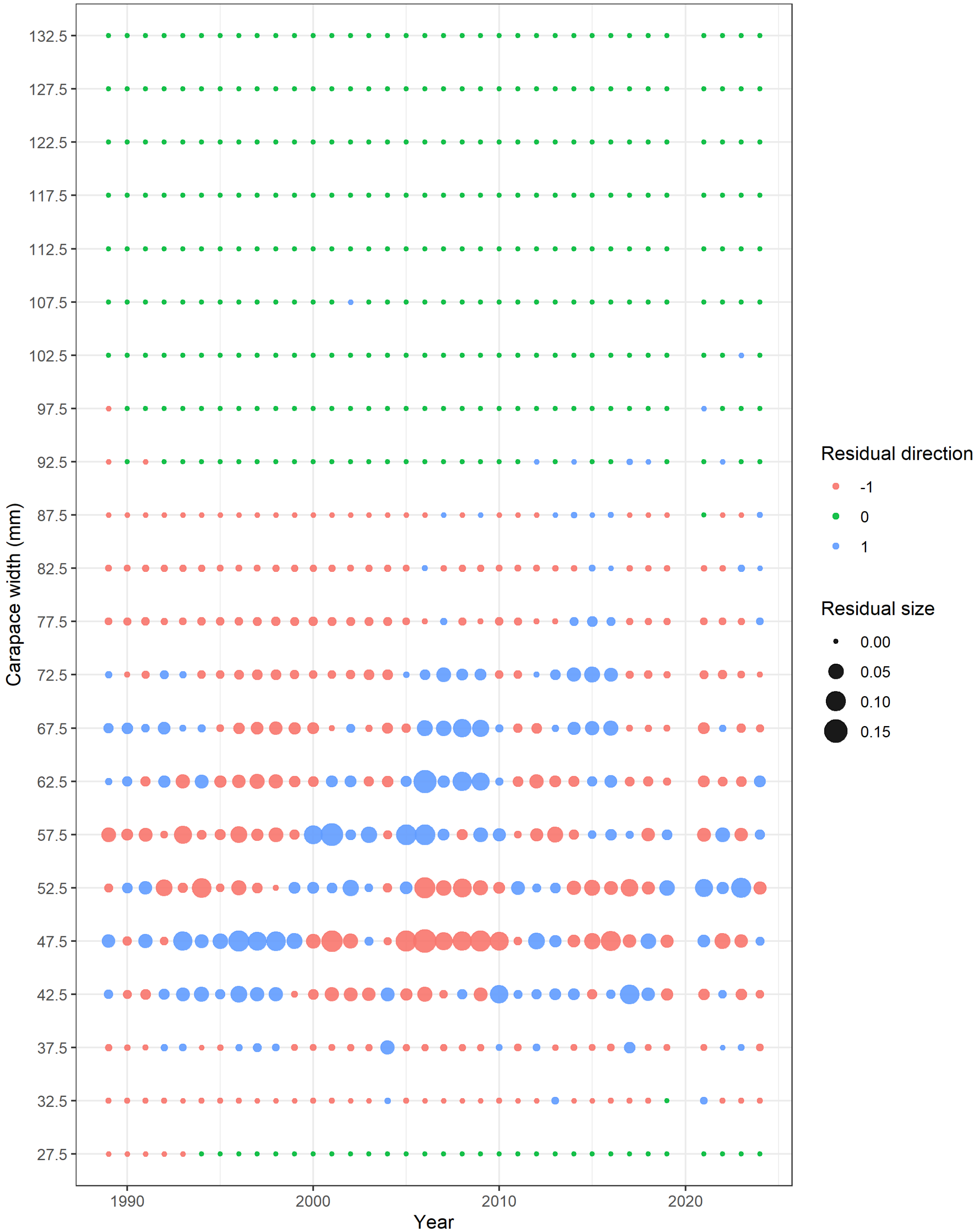

Figure 62: Residuals from chosen model for mature female survey size composition data from 1989-present.

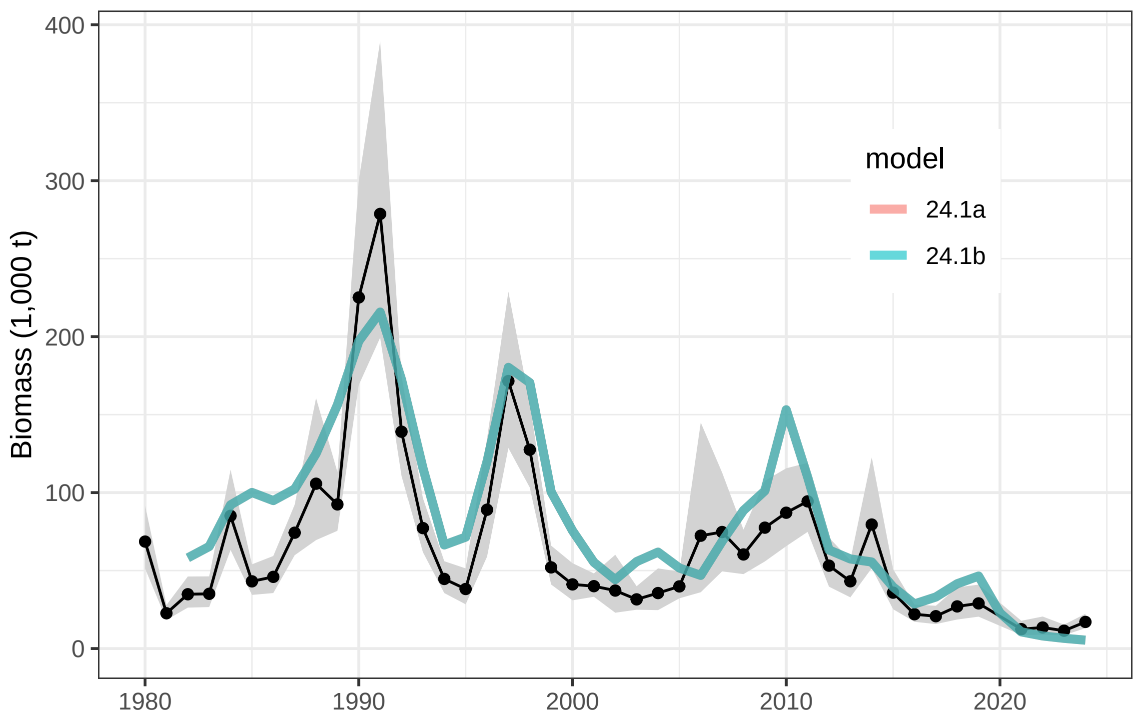

Figure 63: Estimated biomass of male crab >101mm carapace width from the survey (black line and dots with gray 95th CI) and from each model in the assessment (colored lines).

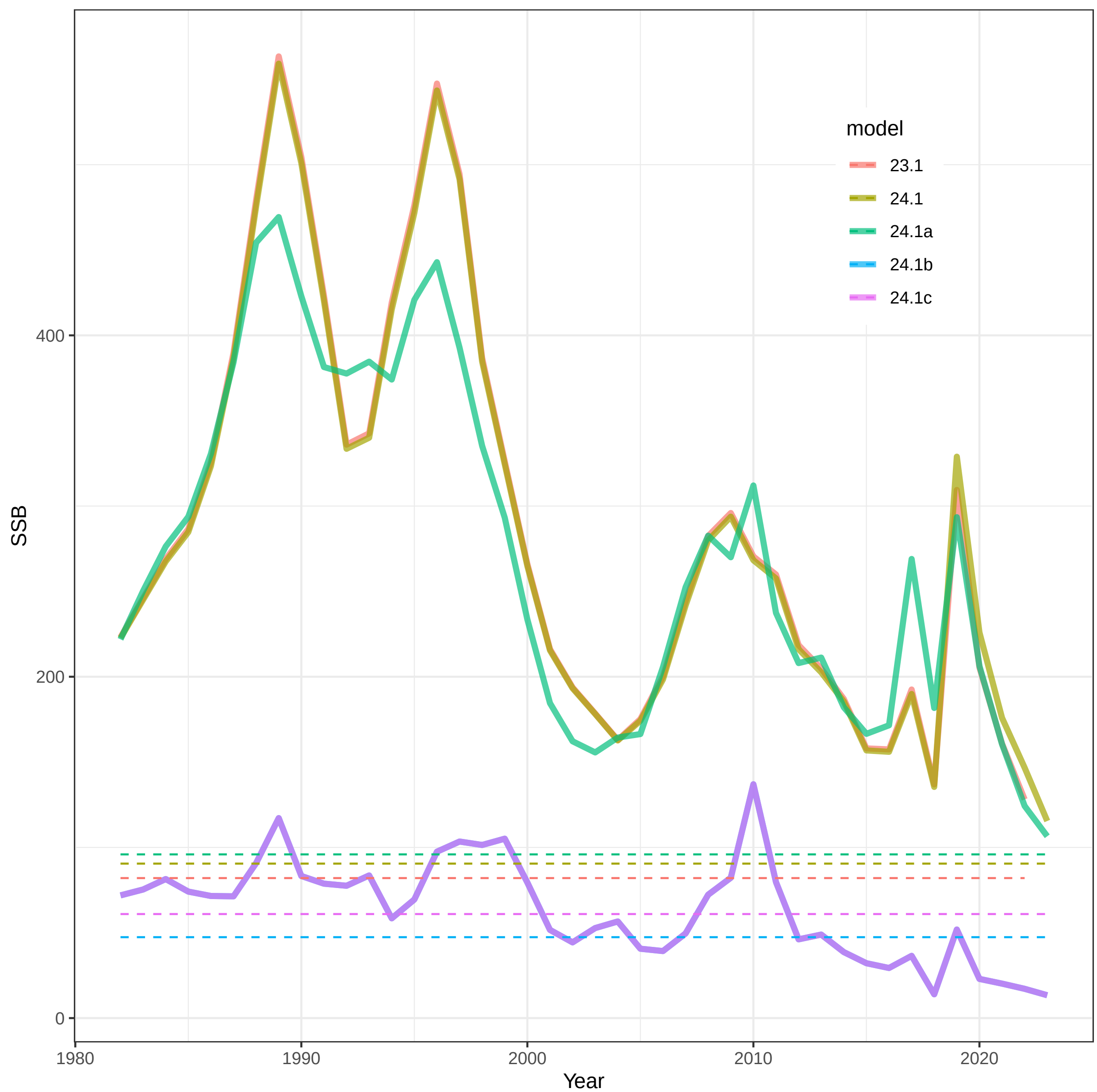

Figure 64: Model predicted mature biomass at mating time in 1,000 tonnes. Dashed horizontal lines are the MSST based on B35.

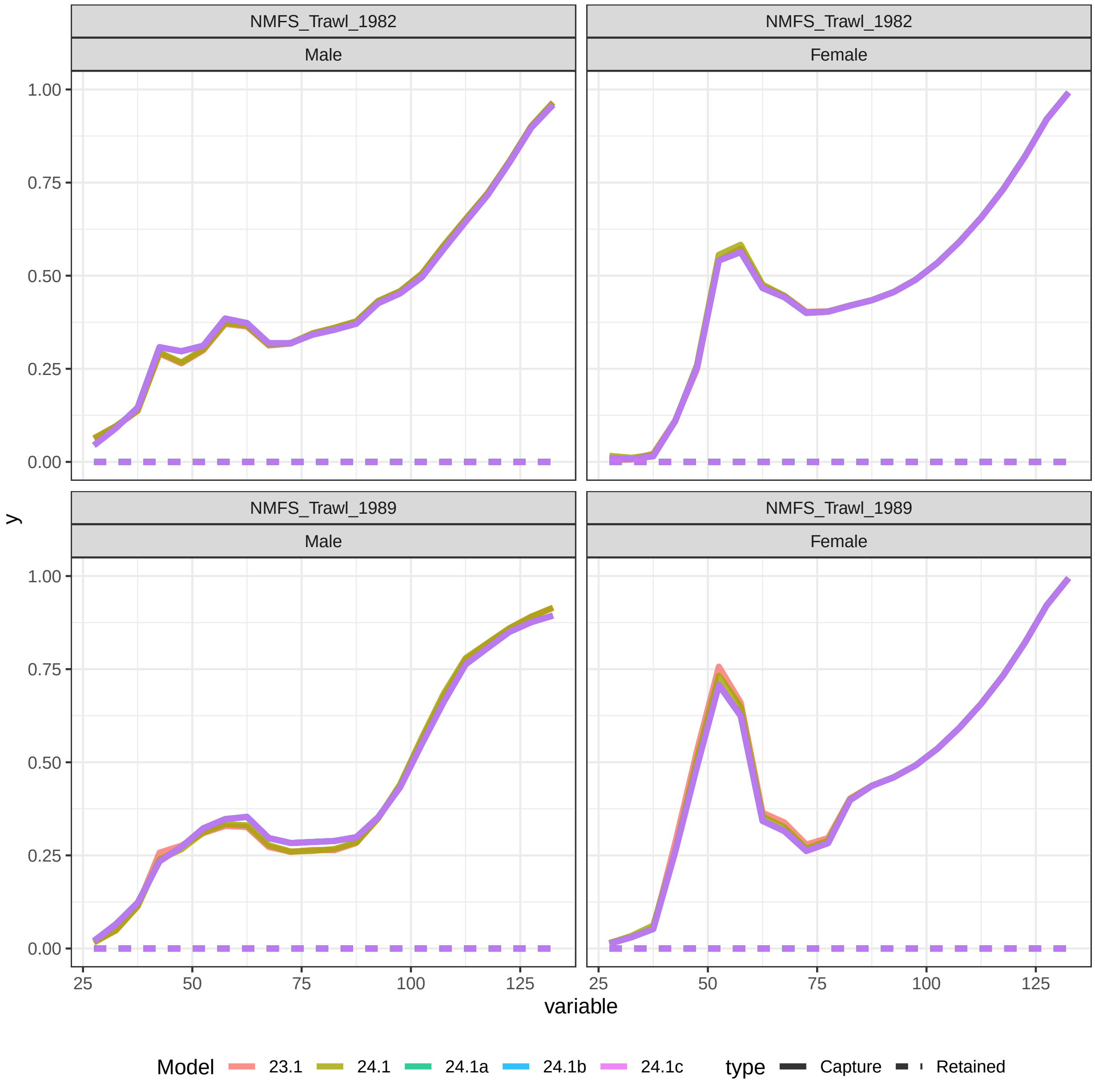

Figure 65: Estimated selectivities by NMFS survey, sex, and time period.

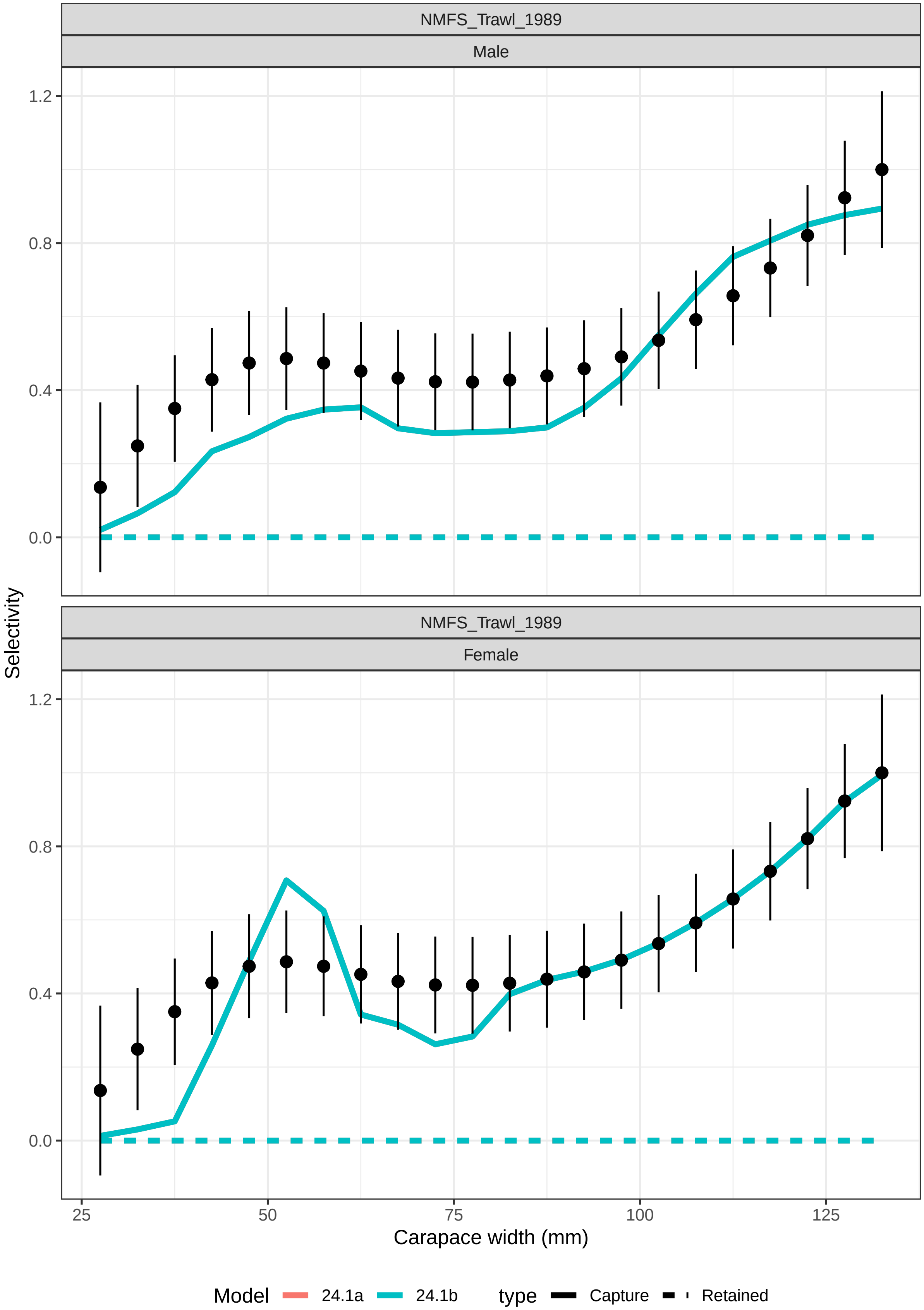

Figure 66: Estimated survey selectivity (lines) with normal priors derived from BSFRF selectivity experiment data. Points are the mean of the prior at a given size; intervals are 95th quantiles based on input CVs.

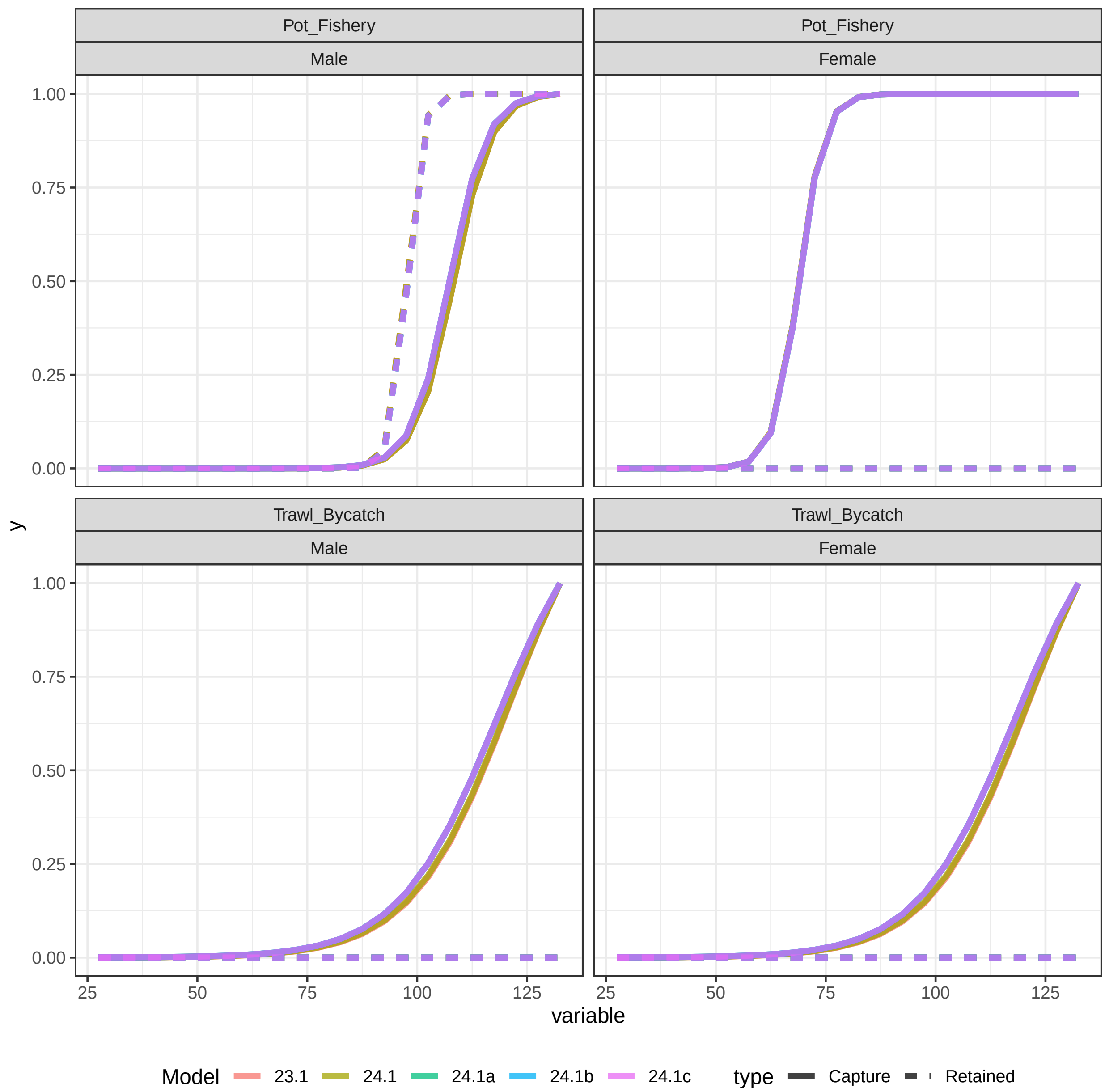

Figure 67: Estimated selectivities by fishing fleet and sex for capture and retained catches.

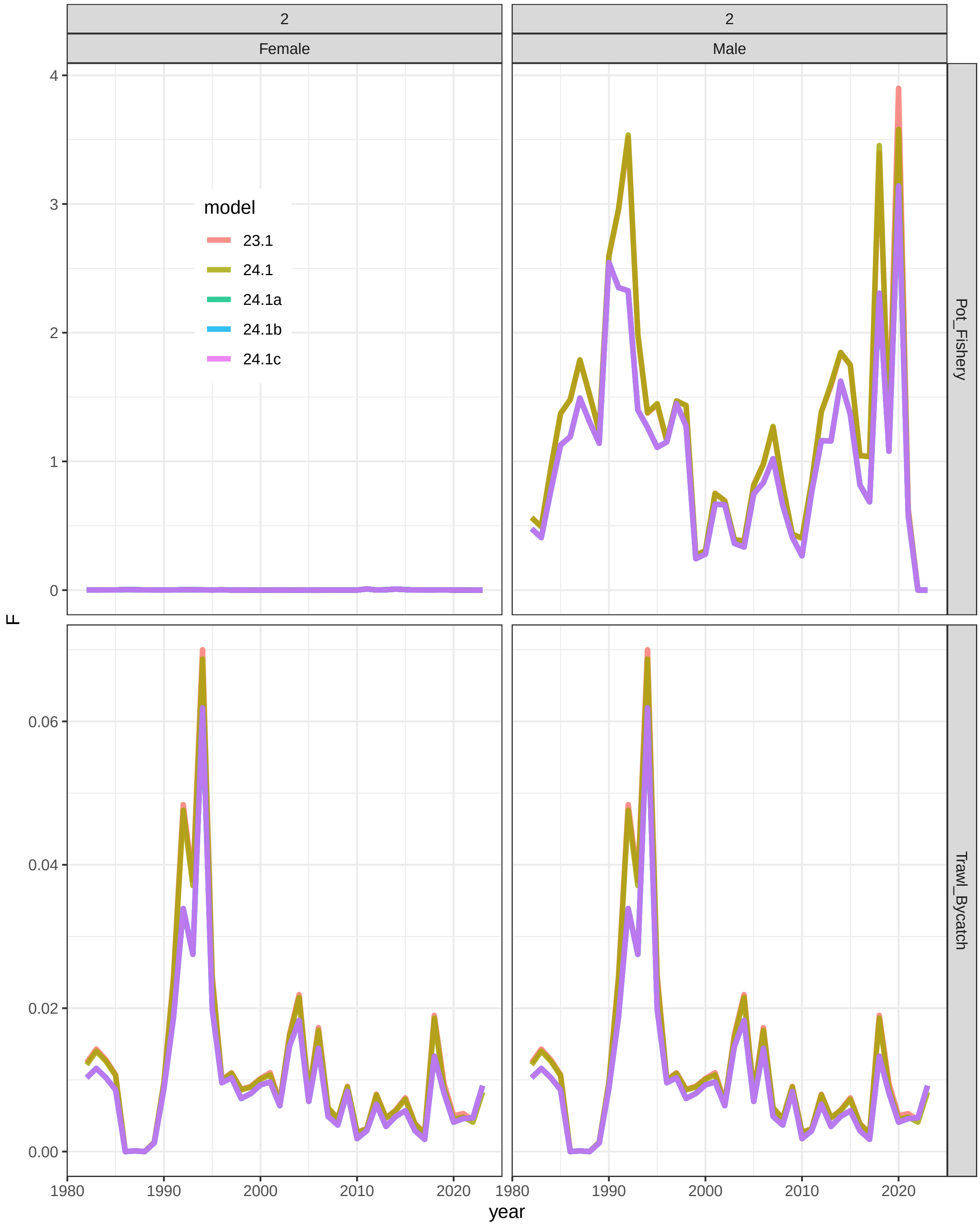

Figure 68: Estimated fishing mortalities for the directed and non-directed fisheries.

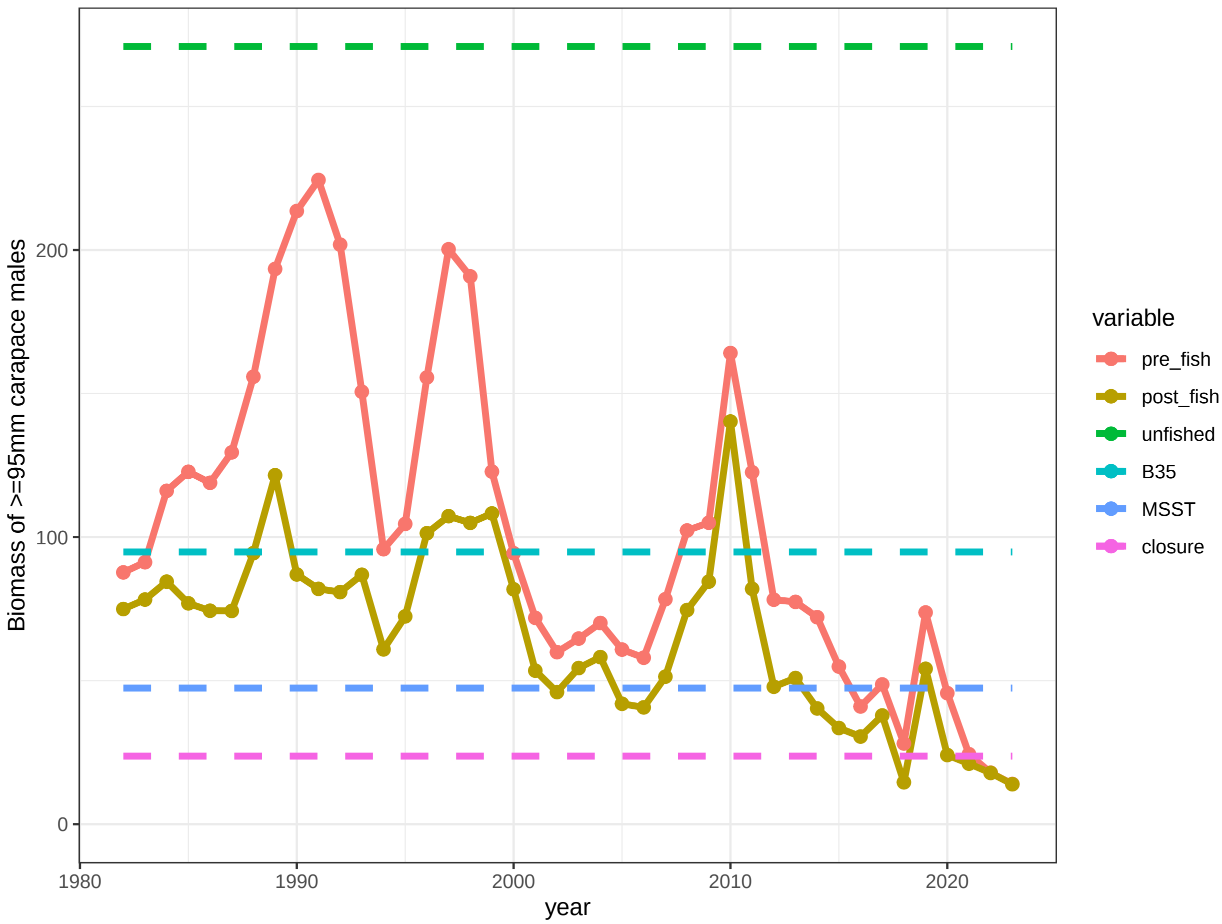

Figure 69: Model predicted biomass of >=95 mm carapace width males before and after the fishery with related reference points.

Figure 70: Calculated exploitation rates on a selected size classes based on model predictions of numbers of crab before and after the season in which the fishery occurs. Exploitation rates are calculated as the difference between the post-fishery estimate of the total number of crab in a size group and the pre-fishery estimate, divided by the pre-fishery estimate.

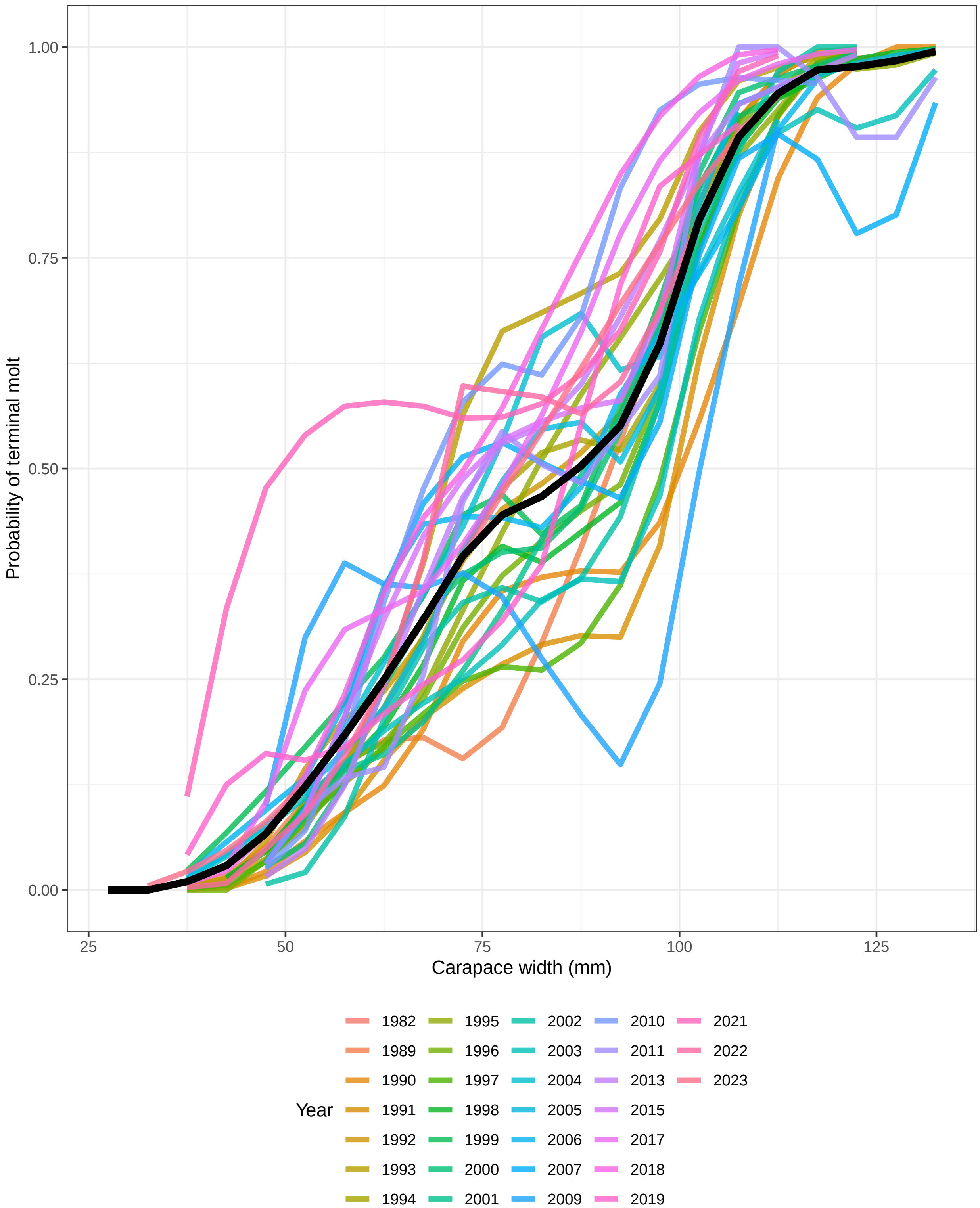

Figure 71: Estimated (black line) or specified (colored lines) probability(s) of maturing for male crab.

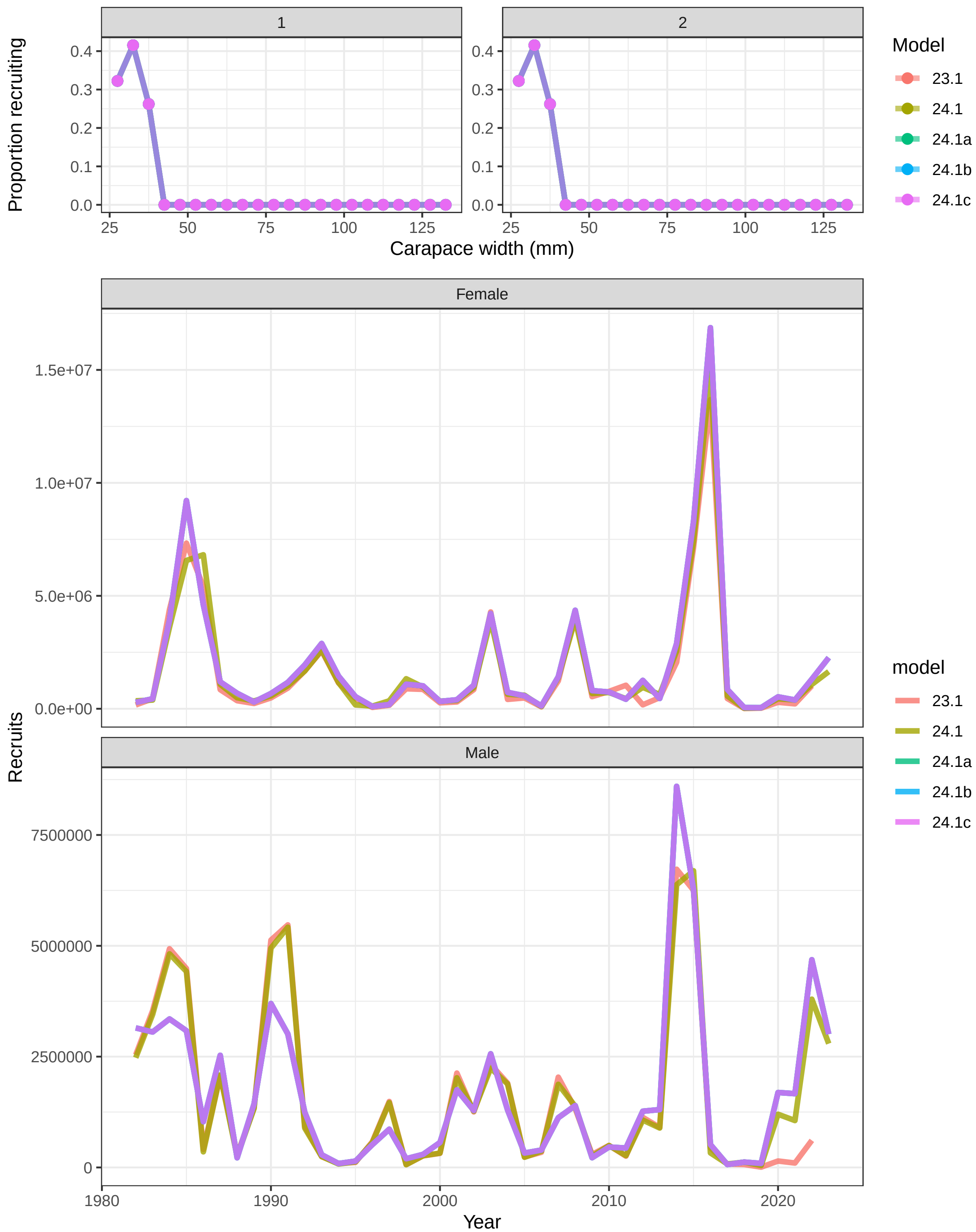

Figure 72: Estimated recruitment by sex (bottom) and proportions recruiting to length bin (top) by model.

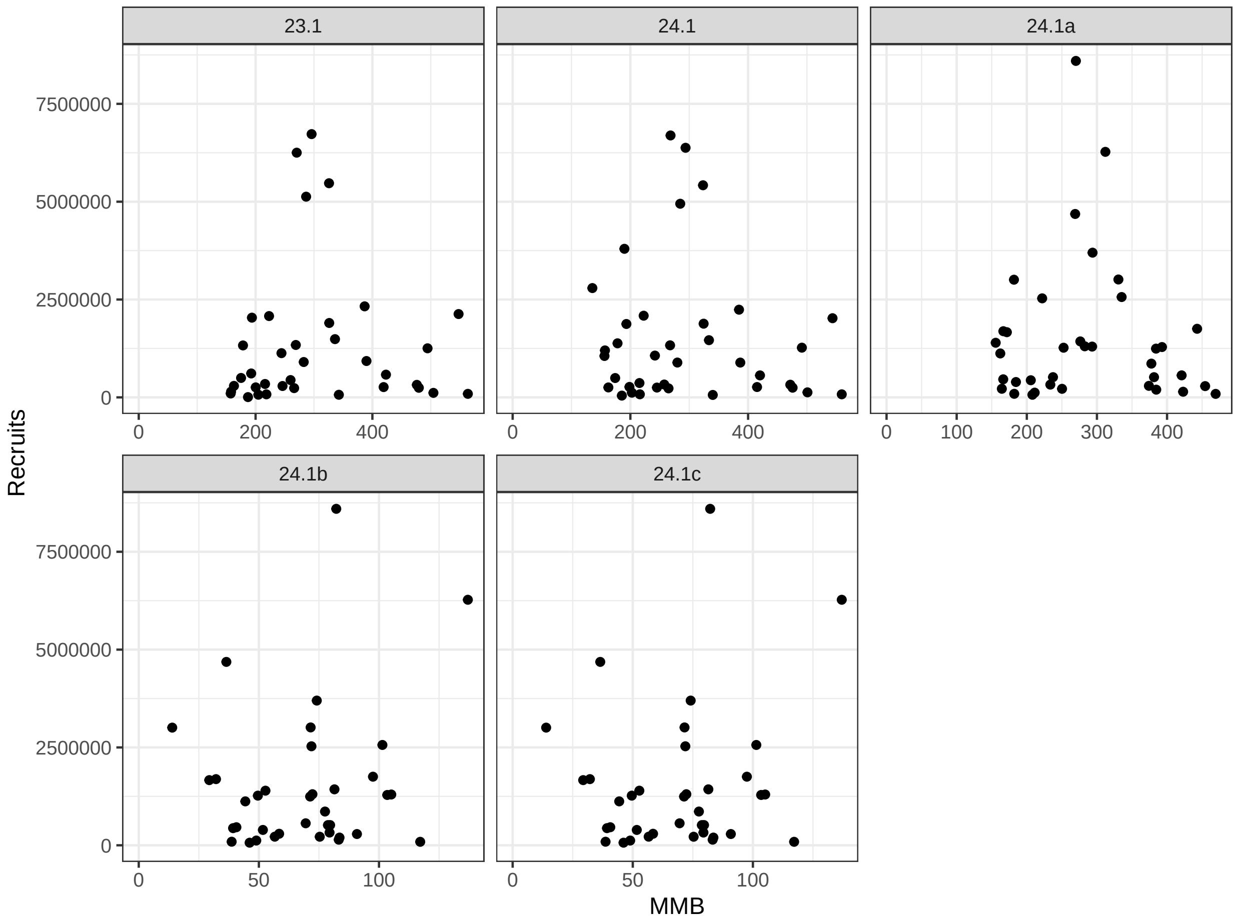

Figure 73: Estimated recruitment by sex (bottom) and proportions recruiting to length bin (top) by model.

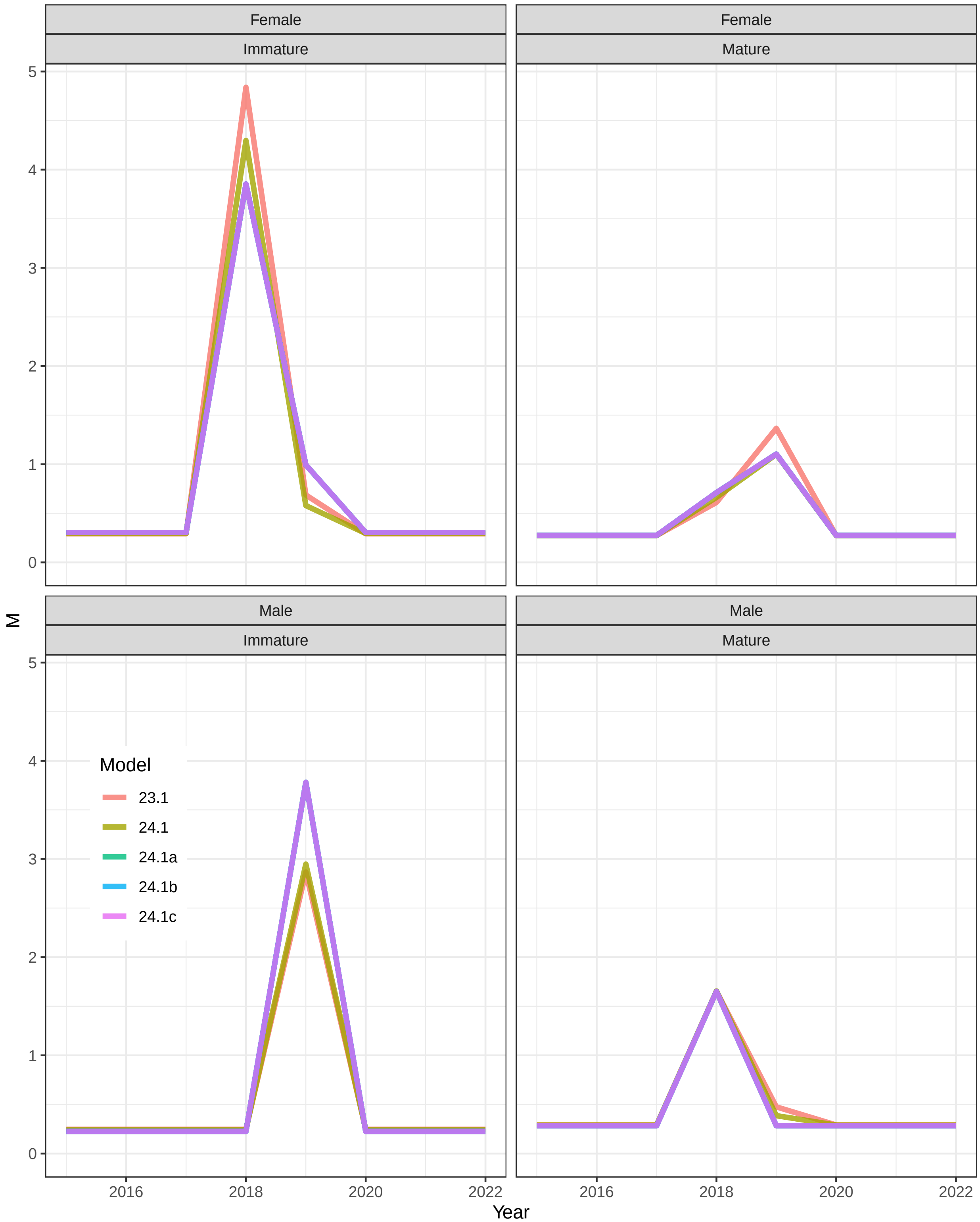

Figure 74: Estimated natural mortality by sex and maturity state. Natural mortality in all years previous to 2018 and after 2019 are equal to the estimated M in 2017.

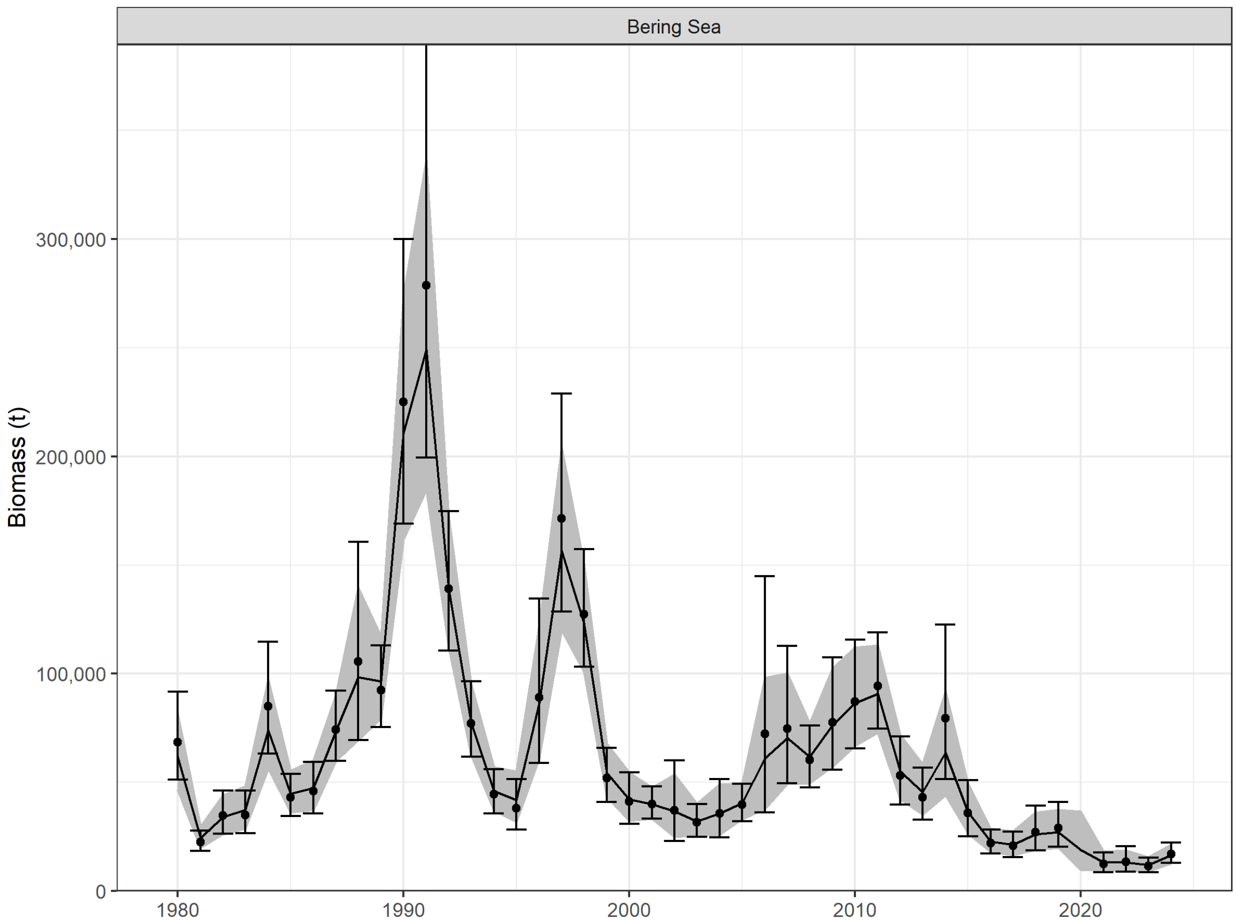

Figure 75: Survey biomass of >101mm carapace width male crab smoothed using REMA.

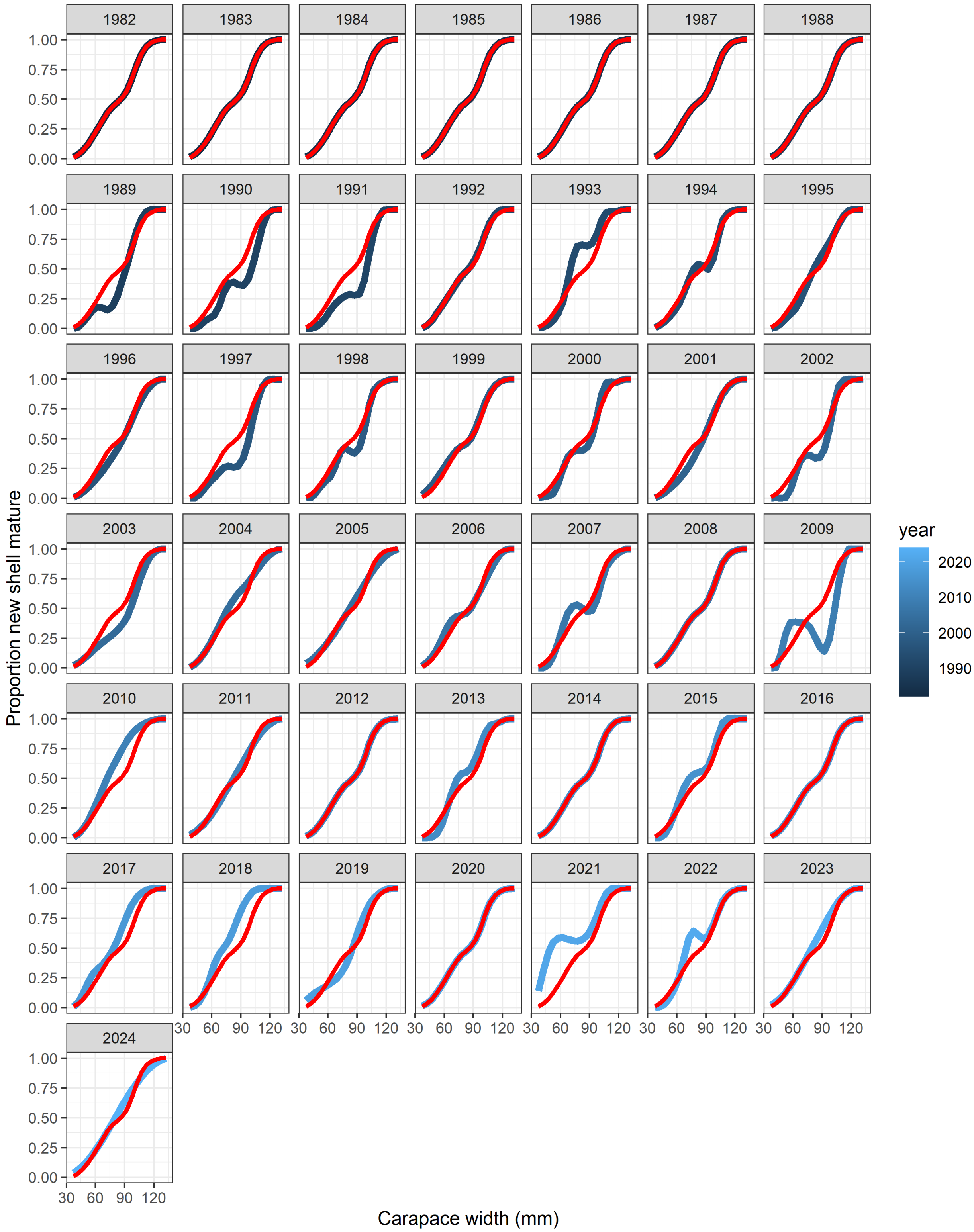

Figure 76: Observed probability of having undergone terminal molt over time (blue lines) with the median probability ove time overlaid (red). Data were not collected for years during which the red line overlays the blue line perfectly.