An assessment for eastern Bering Sea snow crab

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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 slashed with the collapse of the population in 2021 and the fishery was closed for the first time in 2022.

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.

3. Stock Biomass:

Observed 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 24.21 kt in 2023, the lowest value on record.

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. Recent estimated recruitments were the lowest on record.

5. Management

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

Year	MSST	Biomass (MMB)	TAC	Retained catch	Total catch	OFL	ABC
2015/2016	75.8	91.6	18.4	18.4	21.4	83.1	62.3
2016/2017	69.7	96.1	9.7	9.7	11	23.7	21.3
2017/2018	71.4	99.6	8.6	8.6	10.5	28.4	22.7
2018/2019	63	123.1	12.5	12.5	15.4	29.7	23.8
2019/2020	56.8	167.3	15.4	15.4	20.8	54.9	43.9
2020/2021	76.7	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	136.9	92.4	0.0	0.0	0.05	10.3	7.7
2023/2024		69.2				0.31	0.25

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

Year	MSST	Biomass (MMB)	TAC	Retained catch	Total catch	OFL	ABC
2015/2016	167.11	201.94	40.57	40.57	47.18	183.2	137.35
2016/2017	153.66	211.86	21.38	21.38	24.25	52.25	46.96
2017/2018	157.41	219.58	18.96	18.96	23.15	62.61	50.04
2018/2019	138.89	271.39	27.56	27.56	33.95	65.48	52.47
2019/2020	125.22	368.83	33.95	33.95	45.86	121.03	96.78
2020/2021	169.09	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	301.81	203.71	0	0	0.11	22.71	16.98
2023/2024		152.56				0.68	0.55

6. Basis for the OFL

The OFL for 2023 from the author-preferred model (23.3a) was 0.31 kt fishing at $F_{OFL} = 0.05$ (17% of the calculated F_{MSY} proxy, 0.29). The projected ratio of MMB at the time of mating in 2023 to the B_{MSY} proxy is 0.26 under no directed fishing and 0.25 fishing at the F_{OFL}. This OFL was calculated from the model-derived estimates of MMB, used the estimated natural mortality as a proxy for F_{MSY}, and the average MMB from 1982-2022 as the target biomass. This is a departure from previous assessments that have used SPR-based reference points. Rationale for this shift is included within.

Table 3: Metrics used in designation of status and OFL (1,000 t). Status represents the status of the population after the completed fishing year and is used for overfished declarations. Proj_Status represents the projected fishery status after the coming fishery removes the OFL and is used in the harvest control rule. 'Years' indicates the year range used in the calculation of the proxy for BMSY. 'M' is the natural mortality for mature male crab. (continued below)

Year	Tier	BMSY	MMB	Status	Proj_MMB	Proj_Status	FOFL
2023/2024	3b	273.8	92.4	0.34	69.18	0.25	0.05

Years	M
1982-2022	0.29

7. Basis for ABC

The ABC for the author-recommended model was 0.25 kt, calculated by subtracting a 20% buffer from the OFL.

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 season.

2. Input data:

Data added to the assessment included: 2023 eastern Bering Sea survey biomass and length composition data and non-directed discard length frequency and discard biomass from 2022.

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 both tier 3 and tier 4 methodologies for calculating the OFL using both assessment model output and observed survey data are included here. Assessment changes explored in this document include specifying the probability of having undergone terminal molt and parameterizing survey selectivity as a non-parametric curve (rather than logistic) informed by the inferred selectivity from the BSFRF data as priors.

4. Assessment results

The updated estimate from the author-preferred model of MMB on February 15, 2022 was 92.39 kt which placed the stock at 34% of the B_{MSY} proxy. Projected MMB on February 15, 2023 from this year's author preferred model is 69.18 kt after fishing at the OFL, which would place the stock at 25% of the B_{MSY} proxy.

B. Comments, responses and assessment summary

SSC and CPT comments + author responses

SSC comment: The SSC agrees with the CPT to bring forward the status quo model and a Tier 4 random effects model. The SSC recommends that some variant of the simpler model be brought forward at the assessment author's discretion but does not want to be prescriptive about the configuration of the model. Any model that is brought forward should show adequate convergence properties, and the incremental effect of each change from the status quo model should be evaluated.

Convergence issues with the simpler model were solved by adjusting the way the priors on selectivity were specified. An intermediate model in which the BSFRF data are still treated as an additional survey, but the probability of having undergone terminal molt is specified based on survey observations is presented. If survey selectivity and the probability of undergoing terminal molt are not concurrently updated to reflect the best available information on the biology of snow crab (i.e. changing survey selectivity to non-parametric and using the observed probability of having undergone terminal molt), large changes in the scale of the stock occur.

SSC comment: Ideally it would be preferable to directly incorporate an environmental covariate in the assessment to inform temporal changes in natural mortality, but it must be acknowledged that such covariates are seldom available. The SSC recommends that a conservative approach be used for incorporating time-varying M. For example, it may be reasonable to fit an initial model with time-varying M in all years, and use that model to identify a smaller set of years where there is a strong signal to model with time-varying M.

No additional models incorporating time-varying natural mortality are presented in this document, but will be included in upcoming January and May documents.

SSC comment: When the external estimation approach is taken, estimates of uncertainty should be included in the assessment in addition to the point estimates, so that the uncertainty in external estimation is propagated through to assessment results. The SSC supports exploration of models with pre-specified growth parameters, as well as using BSFRF survey data as a prior for survey selectivity/catchability

The growth parameters associated with the molt increment model are estimated in all models presented here, but the variance in molt increment is specified because of convergence issues. This is potentially an important point for future exploration given the larger number of large males estimated in the fishery than observed in some years.

SSC comment: Field biologists and crab life history experts should be consulted to understand the reliability of (the molt probability) data for stock assessment. Rather than adding the raw survey estimates to the model, an initial analysis in a GLM modeling framework, which treats years as random effects, should be considered. This approach could provide smoother estimates, accommodate differing sample sizes by year and length, and deal appropriately with years in which data are missing.

The data were smoothed using a GAM and the average over time was input for years in which data do not exist. This accomplishes roughly what would occur if a GLM were applied to the data without temporal autocorrelation. Temporal autocorrelation may change the estimates for years without data and this is a potential avenue for future exploration.

SSC comment: The SSC supports the CPT recommendation for a model that includes males and females, does not model groundfish bycatch, but estimates selectivity and recruitment by sex, and includes a penalty of how much recruitment can vary between the sexes. A more strategic approach to data weighting could also be considered, such that female data would receive less weight than male data in model fitting. The primary consideration should be that estimation of female parameters should not have a large effect on male parameter estimation.

The models presented include both females and males, but female selectivities are estimated separately. Recruitments are linked insofar as a single recruitment is estimated each year and an additional parameter is estimated in each year to divide that recruitment between the sexes. However, the penalty on this parameter forcing it towards a 50/50 sex ratio is small, so recruitment can vary nearly independently between the sexes. Data weighting is an on-going issue and will hopefully be addressed after a model structure is settled upon.

SSC comment: F35% fishing mortality rate no longer results in a meaningful conservation constraint on the fishery for snow crab. To evaluate a potential alternative to the status quo, the SSC recommends that OFL and ABC estimates be provided for a modified Tier 3 approach for each model carried forward. This approach has the following characteristics: the OFL is calculated by replacing F35% in the Tier 3 harvest control rule by the model estimate of natural mortality. Biomass reference levels and status determination would be calculated using MMB as usual for Tier 3. The SSC requests evaluation of this approach by the assessment author and the CPT.

A tier 3 and tier 4 treatment were presented as written in the crab specs. That is, the tier 3 uses $B_{35\%}$ and $F_{35\%}$ as reference points and tier 4 uses the estimated M and the average of MMB from 1982-2022 as reference points. An additional table is included that uses natural mortality as a proxy for F_{MSY} and $B_{35\%}$ as a proxy for B_{MSY}, but this was provided after the first draft of the SAFE was submitted to the CPT and is not discussed in the SAFE.

Assessment summary

Six assessment models are presented here:

- 22.1 – Last year's accepted model
- 23.1 – Last year's model fit to this year's data
- 23.2 – 23.1 + specifying the probability of having undergone terminal molt based on survey data
- 23.3 – 23.2 + specifying survey selectivity based on the BSFRF data
- 23.3a – 23.3 + estimating survey selectivity with the BSFRF data as priors
- 23.3b – 23.3a + loosening the prior on natural mortality

An overview of the model assumptions can be seen in Table 7. All models converged and produced reasonable jittering and retrospective analyses. Including the probability of having undergone terminal molt as data is recommended because these data reflect the best available science on the biology of snow crab. Incorporating the BSFRF data as priors seems like a more direct and interpretable way of using the BSFRF data to inform selectivity.

High estimated fishing mortality has been flagged as a concern in previous assessments. A more thorough exploration of the interplay between fishing mortality, selectivity, and size composition data in GMACS showed that, even when fully-selected fishing mortalities are very high, the realized exploitation rate of large males is not close to the 100% implied by the fishing mortality.

Given these observations, the author-preferred model is 23.3a. However, using this model coupled with the status quo tier 3 reference points and harvest control rule would apply a 96% exploitation rate to crab 102-105 mm carapace width under the F_{OFL}, even with the >101 mm carapace width male abundances at all time lows. Such a high exploitation rate associated with the OFL may require additional consideration in a management context.

Application of a tier 4 harvest control rule results in a much smaller F_{OFL} (0.05) and OFL (0.31 t), which seem more reasonable in the current circumstances. However, the forward looking implications of adopting a tier 4 harvest control rule that still uses morphometrically mature male biomass as the currency of management and a model that estimates such low fishery selectivity in the size bins where the majority of the exploitable biomass exists is unclear. Consequently, the author recommends tier 4 HCRs be used for the 2023 assessment and suggests considering a currency of management that better reflects the impact of the fishery on the exploited fraction of the population in the future. Guidance on analyses that would be satisfactory rationale for changing the currency of management would be useful.

Analysis was also included on CPUE dynamics to provide an alternate way of quantifying the impact of the fishery on the stock. It showed that the average decline in CPUE was 11 (sd = 11) crab per pot per week and declines were significantly related to the amount of catch removed from an area.

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 2023 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. The separation of mature and immature males by chela height may not be adequately refined given the current measurement to the nearest millimeter. Chela height measured to the nearest tenth of a millimeter by Canadian researchers on North Atlantic snow crab showed a clear break in chela height at small and large widths and fewer mature animals at small widths than the Bering Sea data measured to the nearest millimeter. Measurements taken in 2004-2005 on Bering Sea snow crab chela to the nearest tenth of a millimeter show a similar break in chela height to the Canadian data (Rugolo et al. 2005).

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 9). 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 10). 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 2022 were used in this analysis (Table 10). 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 2022. 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 - 2022
Discarded Males and female crab pot fishery size frequencey	1992 - 2022
Trawl fishery bycatch size frequencies by sex	1991 - 2022
Survey size frequencies by, maturity, sex and shell condition	1982 - 2019, 2021 - 2023
Retained catch estimates	1982 - 2022
Discard catch estimates from crab pot fishery	1992 - 2022
Trawl bycatch estimates	1993 - 2022
Total survey abundance estimates and coefficients of variation	1982 - 2019, 2021 - 2023
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) 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 11).

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. 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). In 2010, the survey area was larger and still focused on snow crab. The mature biomass and size composition data gleaned from each of these experiments (and their complimentary NMFS survey observations) are incorporated into the status quo model by fitting them as an extra survey that is linked to the NMFS survey through a shared selectivity (see GMACS documentation on the github repo to see how a survey can be 'embedded' within another and the repo holding the files for this years snow crab assessment for implementation; both linked at the end of this document). The status quo assessment model estimates a vector that represents the 'availability' of crab to the BSFRF experiments. Availability in this case means how much of the population was in the area surveyed in the BSFRF experiments. Abundances estimated by the industry surveys were generally higher than the NMFS estimates, which suggests that the catchability of the NMFS survey gear is less than 1.

In 2016, 2017, and 2018, snow crab were not the focus of the BSFRF surveys, yet were still caught in the BSFRF gear. Comparing the ratio of the number of crab caught at length in the BSFRF gear (which is assumed to have a catchability/selectivity of 1 over all size classes) to the number of crab caught at length within the same area in the NMFS survey gear (which is assumed to have a catchability/selectivity <= 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).

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), 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, $N_{s,m,y,l}$. 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), catchability, and maturity. 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 for a more complete description of the population dynamics.

A 'jittering' approach has been historically used to explore the impact of different starting values on the assessment output (Turnock, 2016). Jittering was implemented for 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.

Model explorations presented here include changing the way that the BSFRF data are treated in the model and modifying the way the probability of having undergone terminal molt is modeled. In the status quo assessment, the BSFRF data are fit as an additional survey and act on estimated survey selectivity through shared selectivity parameters between the full NMFS bottom trawl survey data set and the portion of the NMFS survey footprint that corresponds with the area that was surveyed by BSFRF. An alternate way to incorporate these data is to calculate the inferred selectivity from the BSFRF data and use these point estimates and associated variance as direct priors on selectivity at size in the assessment (see above for description). The observed probability of having undergone terminal molt by year is based on chela height measurements and is available for the years 1989-to present, excluding the years 1994, 2008, 2012, 2014, 2016, and 2020. The mean probability of having undergone terminal molt at size was used for years with no data.

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 minor bug fixes to the assessment code. Retrospective patterns were relatively small compared to historical patterns (Figure 30). Jittering analyses produce bimodal management quantities in the OFL for model 23.1 and for $B_{35\%}$ in model 23.3 (Figure 31). Below, the fits to the data and estimated population processes are described for all considered models that include the most recent data. Contribution of likelihood components to the objective function are in Table 12 and parameter estimates and standard deviations are in Table 13 & Table 14. The total objective functions of 23.1 and 23.2 are comparable to one another, but not to 23.3, 23.3a, or 23.3b because those models include the BSFRF data as a direct prior on survey selectivity rather than as an additional index of abundance.

Fits to data

Survey biomass data

Fits to the survey mature male biomass were similar for all models for the majority of years in the the time series (Figure 32 & Figure 33) with the same data. However, differences in the estimated survey MMB in the first survey era and the final year of data existed, with models 23.3, 23.3a, and 23.3b producing estimates that were higher than the observation. Even with this over-prediction, model 23.3b fit the MMB from the recent survey era (1989-present) best among the models (Table 12).

Growth data

Small differences existed in the estimates of the relationship between pre- and post-molt increment existed among the models (Figure 34). The resulting size-transition matrix for males from author-preferred model appears to be broadly consistent with studies on crab growth (e.g. Herbert et al., 2001; Figure 35).

Catch data

All models fit the catch data well, with few visually discernible differences among models (Figure 36). The largest differences in fit among models occurred during the early 1990s for male discards. Existing differences in fit were amplified in the objective function by the small CVs placed on the different sources of catch data, with model 23.1 and 23.3b fitting the data best (Table 12).

Size composition data

Most years of retained and total catch size composition data were visually well fit by all models (Figure 37 & Figure 38). In some years, the 23.3 model series estimated more crab in the largest size bin than models 23.1 and 23.2 for both retained and total catch size composition data (e.g. 1992, 2005, 2009). Model 23.1 fit the directed fishery size composition data best based on the contributions to the objective function (Table 12).

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).

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 42, Figure 43, Figure 44, Figure 45, Figure 46, Figure 47, Figure 48 & Figure 49). 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. Predicted mature male size compositions from models that estimated a single ogive for the probability of having undergone terminal molt (models 23.1 and 23.2) were frequently bimodal. In some years this bimodality was reflected in the data (e.g. 2012 or 2023), but in other years it was not (e.g. 2002, 2005, and 2021). Model 23.1 fit 4 out of 8 survey size composition data sources at least marginally better than the other models. Fits to size composition data for the BSFRF survey selectivity experiments were similar across models (Figure 50).

Estimated population processes and derived quantities

Estimated population processes and derived quantities varied among models. MMB estimates from 23.1 and the 23.3 model series produced similar trends in estimated MMB, except for in the early 1980s and the last five years (Figure 51). The 23.3 series estimated increases in the MMB during 2018 and 2019 that the status quo model did not track. This may be related to the higher probability of having undergone terminal molt at smaller sizes included in the 23.3 model series. Changing the way the probability of having undergone terminal molt was modeled, but not changing the way survey selectivity was modeled resulted in large increases in estimated MMB (model 23.2 in Figure 51).

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 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. Models 23.1 and 23.2 estimated much higher biomass of the commercially preferred males than was observed in the survey (Figure 52). However, the 23.3 model series estimates were much closer to the observed survey estimates.

Some of the differences in the estimated commercial biomass are related to estimates of survey selectivity. The scale and shape of the survey selectivity curves changed markedly among models, responding to changes in the way the BSFRF data were incorporated into the model (Figure 53). Focusing on the male selectivity in the most recent era, incorporating only the new data on the probability of having undergone terminal molt into model 23.2 resulted in much lower estimated catchability, which was reflected in the higher estimates of spawning biomass (Figure 51). Incorporating the BSFRF data as priors on survey selectivity parameters in the 23.3 series changed the shape of the selectivity curve (Figure 53). The increases in selectivity at larger carapace widths contributed to lower estimates of MMB compared to 23.2. Estimating survey selectivity with the BSFRF priors resulted in lower estimates of selectivity than inferred from the BSFRF data for individuals less than ~100 mm carapace width, but higher estimates of selectivity above that size until >125 mm carapace width. Over all, estimates of survey selectivity for males mostly stayed within the implied uncertainty of the CVs associated with the BSFRF priors for model 23.3a and 23.3b (Figure 54).

The estimates of availability and selectivity from the models in which the BSFRF data were treated as an additional survey varied among models (22.1, 23.1, and 23.2; Figure 55). Model 22.1 and 23.1 produced changes in the estimates of availablity in 2010 in spite of being structurally identical.

Retained fishery selectivity estimates for males were nearly identical for all models, but capture selectivity in the directed fishery varied among models (Figure 56). Selectivity associated with non-directed bycatch also varied among models ("Trawl_bycatch" in Figure 56). Estimated fully-selected fishing mortality in the directed and non-directed fleets were higher in the 23 model series than in 23.1 and 23.2 (Figure 57). High estimates of fully-selected fishing mortality in the directed fishery have been an issue of concern in previous stock assessments. Some of the models presented here still estimate seemingly unreasonably high fishing mortalities in some years (e.g. 1991 and 2020). However, the high fishing mortalities are only acting on the fully-selected portion of the stock, which, given the estimated selectivities, is comprised of only the largest crab. The proportion of exploitable male biomass that is in these largest sizes is quite low (Figure 58).

A realized exploitation rate can be calculated by dividing the retained catch by the exploitable biomass (i.e. crab >101mm carapace width; Figure 58, middle panel). Although the realized exploitation rate is high in 2020 and the early 1990s, it is no where near the estimated fully-selected fishing mortality rates. For example, in 2020 the estimated fully-selected fishing mortality rate translates to an exploitation rate of ~100%, but the realized exploitation rate was closer to 40%.

The estimated probability of having undergone terminal molt in models 23.1 and 23.2 were very different from the specified probabilities derived from the survey data (Figure 59). The specified probabilities are calculated as the proportion of new shell crab by size that are mature based on chela height. 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 SPR-based reference points, which will be discussed below.

Patterns and scale in recruitment by sex varied somewhat among models, particularly with respect to the size and timing of the recent large pseudocohort (Figure 60). Generally, the models estimated a period of high average recruitment during the 1980s. Following that, a period of low average recruitment persisted from the early 1990s to 2014. A large recruitment was estimated to enter the modeled fraction of the population around 2014-2016. Recruitment entering the model was distributed primarily in the first three size bins for all models (Figure 60).

Estimated natural mortality ranged from 0.27 to 0.55 for immature and mature crab (Figure 61). Estimated mortality events in 2018 and 2019 were most intense for immature females and males, but even the lower mortalities for mature females and immature males resulted in >80% of crab dying.

F. Calculation of the OFL

Methodology for OFL

Tier 3

The tier 3 OFL was calculated using proxies for biomass and fishing mortality reference points and a sloped control rule. Proxies for biomass and fishing mortality reference points were calculated using spawner-per-recruit methods (e.g. Clark, 1991). After fitting the assessment model to the data and estimating population parameters, the model was projected forward 100 years using the estimated parameters under no exploitation and constant recruitment to determine 'unfished' mature male biomass-per-recruit. Projections were repeated in which the bisection method was used to identify a fishing mortality that reduced the mature male biomass-per-recruit to 35% of the unfished level (i.e. $F_{35\%}$ and $B_{35\%}$). Calculations of $F_{35\%}$ were made under the assumption that bycatch fishing mortality was equal to the estimated average value over the last 8 years.

Calculated values of $F_{35\%}$ and $B_{35\%}$ were used in conjunction with a Tier 3 control rule to adjust the proportion of $F_{35\%}$ that is applied based on the status of the population relative to $B_{35\%}$ (Amendment 24, NMFS). To determine the F_{OFL}, the population is projected to the time of fishing for the upcoming fishery under no fishing. If the MMB at that time exceeds 25% of $B_{35\%}$, a fishery can occur and the F_{OFL} is calculated as:

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

Where MMB is the projected 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 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).

Calculated tier 3 OFLs ranged from 8.58 to 37.10 kt (Table 15). Differences in OFLs were a result of differences in estimated MMB, calculated $B_{35\%}$ (which ranged from 110.01 - 189.24 kt), $F_{35\%}$ (which ranged from 1.50 - 205.67 yr^{-1}), and F_{OFL} (which ranged from 0.30 - 37.49 yr^{-1}; Table 15).

Tier 4

Tier 4 OFLs were calculated within GMACS using the estimated natural mortality as the proxy for F_{MSY} and the average morphometrically mature male biomass from 1982-2022 as the target biomass. A tier 4 OFL was also calculated using raw survey estimates of commercially size males (>101 mm carapace width).

Calculated tier 4 OFLs within GMACS ranged from 0.03 to 0.31 kt (Table 16). Differences in OFLs were a result of differences in estimated MMB, calculated B_{MSY} proxy (which ranged from 232.32 - 519.67 kt), F_{MSY} proxy (which ranged from 0.28 - 0.55 yr^{-1}), and F_{OFL} (which ranged from 0.00 - 0.05 yr^{-1}; Table 16).

The tier 4 OFL calculated from the survey data was 0 and the status was ~17% of the B_{MSY} proxy (Table 18).

G. Calculation of the ABC

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

Author recommendations

Two decisions need to be made to provide management advice for snow crab based on this assessment: 1) which model to choose and 2) which tier to use for the harvest control rule. All models converged and performed reasonably in jittering and retrospective analyses. The status quo model fit many of the data sources best, but it did not incorporate the best available science on the biology of snow crab. Given the importance of correctly modeling the biology, all models that include the data on terminal molt should be considered improvements over the status quo. Modeling selectivity as a non-parametric curve also is supported over logistic selectivity, given two separate data sources that suggest survey selectivity is not logistic (BSFRF and Somerton and Otto, 1998; Figure 28). Consequently, the 23.3 series have the most desirable characteristics of the models presented.

Estimating non-parametric selectivity (rather than specifying it) allows uncertainty in the estimate to be propagated, so 23.3a or 23.3b is preferable over 23.3. A potential downside of estimating the selectivity is that its weighting relative to other data sets is poorly understood and survey selectivity is an influential parameter in determining the OFL. The prior on natural mortality is quite tight, but it is highly confounded with other parameters (e.g. selectivity and catchability) which can make estimation difficult. Loosening the prior results in a much larger estimated natural mortality, which is in conflict with the assumption that snow crab have a maximum age of approximately 20 years. Given the influence on management quantities that changing M can have, loosening the prior should likely only be done after more extensive exploration of its impacts. Based on all of these considerations, the author-preferred model is 23.3a.

The second question for consideration is which tier to use in specifying the quantities in the harvest control rule. Tier 3 uses spawner-per-recruit proxies for fishing mortality and biomass targets; tier 4 uses natural mortality and an average mature male biomass over time for fishing mortality and biomass targets. Tier 3 rules produce fishing mortality reference points that allow for ~100% exploitation rates on commercially-preferred males in model 23.3a. This occurs because the updated information on the probability of having undergone terminal molt allows crab to mature (and stop growing) before reaching the size harvested in the fishery. This results in a large fraction of the mature biomass being protected from harvest, which then requires high exploitation rates on commercially-preferred males to reduce the MMB to 35% of unfished levels. The tier 4 rule applied within GMACS results in much lower fishing mortalities applied to the stock. The tier 4 rule applied to the survey data resulted in an even lower status than in GMACS and a closure of the fishery.

Based on these considerations, a tier 4 approach within GMACS is the author-preferred method for specifying the harvest control rule. The stock is at unprecedented lows and this warrants caution in management. Following the status quo tier 3 approach does not seem defensible given the current status of the stock. There is little practical difference between adopting the tier 4 rule within GMACS or within a survey-based rule, and retaining the model based assessment incorporates as much of the available information as possible into the analysis.

H. Data gaps and research priorities

Although the author-preferred HCR is based on tier 4, there are some inconsistencies within its specification for snow crab. Although natural mortality is often reported to be similar to F_{MSY}, the shape of estimated fishing selectivity for snow crab results in a non-uniform application of the target fishing mortality to the exploitable biomass. This results in a smaller fishing mortality applied to the exploitable biomass than natural mortality. The use of morphometrically mature male biomass as the currency of management further obfuscates the impact of a chosen target fishing mortality on the population as the fishing mortality is modified based on crab that are not subject to fishing mortality. The interchangability of a 70 mm carapace width male and a 120 mm carapace male in reproductive dynamics is a key, but difficult to corroborate assumption.

A potential approach that could address these inconsistencies is modifying the currency of management to reflect the exploitable biomass more closely and then choosing some fraction of unfished levels as a biomass target. This could provide a more interpretable analog to the status quo management given the issues translating the fully-selected fishing mortality to impacts to the stock as a result of the shape of fishery selectivity and morphometric maturity used as a currency of management. This would require more thorough testing and deliberation on what an appropriate fraction of unfished biomass levels should be to serve as a target, particularly under the potential for changing productivity of the stock.

Data weighting continues to be a topic that is acknowledged as important to modeling outcomes, but secondary to finding an appropriate model 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) should be undertaken.

Considerable effort has been expended since the May CPT meeting exploring male only models that are not presented here. These models may be useful in understanding the impacts of modeling both sexes in the same model and will be explored further in future documents.

I. Ecosystem considerations

Key questions related to ecosystem change include more thoroughly understanding the mortality event in 2018 and 2019, anticipating the potential for impacts of warming on mortality, recruitment, and other population processes, and understanding the potential for shifts in distribution and their impacts on the population and fishery. Several on-going projects are being conducted to inform these questions and results will be shared as they become available.

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

Input and output for the models described here can be found at https://github.com/szuwalski/snow_2023_9.

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

J. References

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Table 7: Key differences in presented models. (continued below)

Process	23.1	23.2	23.3	23.3a	23.3b
Sex	Both	Both	Both	Both	Both
Maturity	Single estimated ogive	Input	Input	Input	Input
BSFRF	Survey	Survey	Prior	Prior	Prior
Survey	Estimated logistic by sex and era	Estimated logistic by sex and era	Specified non-parametric	Estimated non-parametric	Estimated non-parametric
Growth	Linear estimated	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	By sex and maturity + 2018/19 + looser prior
Fishery	Logistic	Logistic	Logistic	Logistic	Logistic

Table 9: 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 10: 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	0	0	0	0.05

Table 11: 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

Table 12: 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	23.1	23.2	23.3	23.3a	23.3b
catch	Retained	-7.08	-4.15	5.03	2.92	-7.27
catch	Discard (male)	140.7	130.44	79.02	88.95	69.18
catch	Discard (female)	-69.66	-69.66	-69.66	-69.66	-69.66
catch	Trawl	-52.03	-52.03	-52.02	-52.02	-52.02
cpue	NMFS survey (era 1; females)	43.44	54.65	71.7	53.59	36.06
cpue	NMFS survey (era 2, females)	-28.82	-13.3	-8.25	-2.38	-16.41
cpue	NMFS survey (era 1, males)	32.15	35.28	49.98	46.62	43.13
cpue	NMFS survey (era 2, males)	21.33	-0.98	28.32	31.23	-5.25
growth_inc	1	1020.3	1061.75	1049.82	1038.86	1033.27
growth_inc	2	0	0	0	0	0
rec_dev	1	0.78	0.78	0.78	0.78	0.78
rec_dev	2	0	0	0	0	0
rec_dev	3	93.91	79.3	96.65	80.87	78.4
size_comp	Retained males	-3702.08	-3608.48	-3632.29	-3641.29	-3665.38
size_comp	Survey mature females (1982-1988)	-688.42	-685.48	-650.21	-678.99	-681.7
size_comp	Survey mature females (1989-present)	-3168.88	-3056.79	-2981.02	-3198.41	-3196.99
size_comp	Survey mature males (1982-1988)	-595.71	-581.17	-576.56	-582.62	-585.6
size_comp	Survey mature males (1989-present)	-2828.43	-2694.15	-2725.15	-2800.92	-2829.29
size_comp	Total males	-2708.96	-2630.54	-2629.61	-2638.41	-2662.37
size_comp	Discard females	-2283.93	-2275.2	-2272.08	-2270.88	-2275.2
size_comp	Non-directed bycatch (females)	-2539.63	-2481.05	-2486.45	-2460.89	-2436.49
size_comp	Non-directed bycatch (male)	-2435.53	-2426.65	-2349.29	-2358.69	-2369.79
size_comp	Survey immature females (1982-1988)	-624.89	-624.2	-588.64	-613.95	-628.55
size_comp	Survey immature females (1989-present)	-2966.22	-2999.83	-2840.13	-3045.46	-3034.88
size_comp	Survey immature males (1982-1988)	-577.99	-569.18	-521.78	-541.84	-544.7
size_comp	Survey immature males (1989-present)	-2828.2	-2815.83	-2711.59	-2791.83	-2807.43
Total	Total	-23714.45	-25638.68	-24378.36	-25155.73	-25297.88

Table 13: Parameter estimates and standard deviations. See .CTL files for names on github repo. A fix to display the names of the parameters is on the to do list.

Parameter	23.1	SD	23.2	SD
theta[1]	0.29	0	0.29	0
theta[2]	0.28	0	0.28	0
theta[5]	18.95	375.26	6.93	407.52
theta[13]	10.54	0.7	11.76	0.69
theta[14]	10.56	0.56	11.78	0.55
theta[15]	10.64	0.44	11.87	0.44
theta[16]	11.1	0.4	12.32	0.41
theta[17]	11.76	0.37	12.93	0.38
theta[18]	12.32	0.31	13.39	0.32
theta[19]	12.69	0.27	13.68	0.28
theta[20]	12.69	0.25	13.62	0.27
theta[21]	12.52	0.25	13.3	0.28
theta[22]	12.52	0.24	13.21	0.28
theta[23]	12.54	0.24	13.24	0.27
theta[24]	12.37	0.24	13.08	0.27
theta[25]	12.24	0.25	13	0.26
theta[26]	12.18	0.25	13.19	0.25
theta[27]	12.26	0.24	13.48	0.24
theta[28]	12.24	0.2	13.1	0.22
theta[29]	11.96	0.21	12.54	0.23
theta[30]	11.45	0.24	11.92	0.27
theta[31]	10.6	0.28	11	0.31
theta[32]	9.57	0.33	9.89	0.36
theta[33]	8.62	0.36	8.85	0.38
theta[34]	8.07	0.41	8.27	0.43
theta[35]	11.88	0.46	12.57	0.45
theta[36]	12.03	0.31	12.66	0.29
theta[37]	12.77	0.29	13.33	0.28
theta[38]	13.32	0.23	13.72	0.25
theta[39]	12.72	0.21	13.27	0.21
theta[40]	12.79	0.2	13.38	0.21
theta[41]	12.69	0.2	13.33	0.21
theta[42]	12.43	0.22	13.08	0.23
theta[43]	12.24	0.24	12.88	0.24
theta[44]	12.04	0.24	12.7	0.26
theta[45]	11.65	0.28	12.22	0.31
theta[46]	11.32	0.31	11.64	0.35
theta[47]	11.14	0.32	11.23	0.4
theta[48]	10.62	0.34	10.64	0.45
theta[49]	9.67	0.39	9.66	0.46
theta[50]	8.71	0.42	8.68	0.46
theta[51]	7.9	0.44	7.89	0.47
theta[52]	7.29	0.47	7.31	0.5
theta[53]	6.86	0.51	6.89	0.54
theta[54]	6.56	0.56	6.61	0.59
theta[55]	6.37	0.62	6.44	0.65
theta[56]	6.28	0.7	6.35	0.73
theta[57]	13.55	0.79	12.8	0.78

Parameter	23.1	SD	23.2	SD
theta[58]	13.54	0.64	12.8	0.64
theta[59]	13.55	0.48	12.82	0.48
theta[60]	13.76	0.36	13.06	0.37
theta[61]	14.53	0.29	13.83	0.34
theta[62]	14.69	0.27	14.13	0.33
theta[63]	13.79	0.26	13.4	0.34
theta[64]	12.58	0.28	12.24	0.35
theta[65]	11.42	0.33	11.1	0.39
theta[66]	10.19	0.37	9.88	0.42
theta[67]	9.44	0.41	9.12	0.46
theta[68]	9	0.46	8.62	0.5
theta[69]	8.76	0.52	8.32	0.56
theta[70]	8.57	0.56	8.08	0.61
theta[71]	8.38	0.59	7.86	0.64
theta[72]	8.2	0.6	7.65	0.65
theta[73]	8.05	0.62	7.47	0.66
theta[74]	7.94	0.64	7.32	0.67
theta[75]	7.86	0.68	7.2	0.69
theta[76]	7.8	0.72	7.1	0.71
theta[77]	7.76	0.78	7.04	0.76
theta[78]	7.73	0.86	7	0.83
theta[79]	7.44	1.25	6.79	1.18
theta[80]	7.4	1.14	6.77	1.1
theta[81]	7.35	1.03	6.64	1.05
theta[82]	7.45	0.99	6.55	0.96
theta[83]	7.55	0.99	6.64	0.95
theta[84]	7.68	1.01	6.9	1
theta[85]	6.47	1.03	5.79	1.02
theta[86]	5.15	1.05	4.52	1.04
theta[87]	4.11	1.07	3.5	1.06
theta[88]	3.35	1.08	2.75	1.07
theta[89]	2.86	1.1	2.27	1.09
theta[90]	2.54	1.13	1.95	1.12
theta[91]	2.31	1.15	1.71	1.14
theta[92]	2.12	1.17	1.53	1.16
theta[93]	1.98	1.2	1.39	1.19
theta[94]	1.87	1.22	1.28	1.21
theta[95]	1.78	1.25	1.19	1.24
theta[96]	1.71	1.27	1.12	1.26
theta[97]	1.65	1.3	1.06	1.29
theta[98]	1.61	1.34	1.02	1.33
theta[99]	1.59	1.38	1	1.37
theta[100]	1.58	1.43	0.99	1.42
Grwth[1]	2.23	0.08	2.35	0.08
Grwth[2]	-0.22	0	-0.21	0
Grwth[4]	-0.18	0.11	0.48	0.1
Grwth[5]	-0.3	0	-0.27	0
Grwth[10]	0.04	0	NA	NA
Grwth[11]	0.06	0.01	NA	NA
Grwth[12]	0.1	0.01	NA	NA
Grwth[13]	0.14	0.01	NA	NA
Grwth[14]	0.2	0.01	NA	NA

Parameter	23.1	SD	23.2	SD
Grwth[15]	0.22	0.01	NA	NA
Grwth[16]	0.24	0.01	NA	NA
Grwth[17]	0.28	0.02	NA	NA
Grwth[18]	0.28	0.02	NA	NA
Grwth[19]	0.25	0.02	NA	NA
Grwth[20]	0.26	0.02	NA	NA
Grwth[21]	0.42	0.02	NA	NA
Grwth[22]	0.82	0.02	NA	NA
Grwth[30]	0.05	0.04	NA	NA
Grwth[31]	0.06	0.02	NA	NA
Grwth[32]	0.43	0.04	NA	NA
Grwth[33]	0.77	0.02	NA	NA
Grwth[34]	0.92	0.01	NA	NA
Grwth[35]	0.96	0	NA	NA
log_slx_pars[1]	4.63	0.01	4.66	0
log_slx_pars[2]	1.59	0.03	1.46	0.03
log_slx_pars[3]	4.26	0.01	4.24	0.01
log_slx_pars[4]	0.98	0.03	1.04	0.03
log_slx_pars[5]	4.54	0.01	4.7	0.01
log_slx_pars[6]	2.19	0.02	2.38	0.02
log_slx_pars[7]	3.76	0.05	3.81	0.06
log_slx_pars[8]	2.05	0.14	2.06	0.15
log_slx_pars[9]	3.94	0.02	3.91	0.02
log_slx_pars[10]	1.27	0.05	1.22	0.06
log_slx_pars[11]	3.72	0.02	3.69	0.01
log_slx_pars[12]	1.64	0.07	1.38	0.06
log_slx_pars[13]	3.86	0.01	3.78	0.01
log_slx_pars[14]	1.27	0.03	1.2	0.03
log_slx_pars[15]	-3.94	0.94	-4.39	0.96
log_slx_pars[16]	-3.94	0.85	-4.39	0.87
log_slx_pars[17]	-3.94	0.75	-4.39	0.77
log_slx_pars[18]	-3.93	0.63	-4.39	0.66
log_slx_pars[19]	-3.91	0.52	-4.38	0.53
log_slx_pars[20]	-3.76	0.44	-4.25	0.46
log_slx_pars[21]	-3.42	0.41	-3.95	0.42
log_slx_pars[22]	-2.95	0.39	-3.55	0.39
log_slx_pars[23]	-2.52	0.36	-3.22	0.36
log_slx_pars[24]	-2.08	0.35	-2.8	0.34
log_slx_pars[25]	-1.89	0.33	-2.55	0.33
log_slx_pars[26]	-1.7	0.32	-2.34	0.32
log_slx_pars[27]	-1.27	0.32	-1.93	0.31
log_slx_pars[28]	-0.91	0.32	-1.46	0.31
log_slx_pars[29]	-1.01	0.31	-1.22	0.3
log_slx_pars[30]	-1.46	0.3	-1.22	0.3
log_slx_pars[31]	-1.7	0.31	-1.25	0.31
log_slx_pars[32]	-1.81	0.32	-1.29	0.33
log_slx_pars[33]	-1.77	0.33	-1.26	0.34
log_slx_pars[34]	-1.58	0.37	-1.17	0.38
log_slx_pars[35]	-1.48	0.45	-1.23	0.41
log_slx_pars[36]	-1.4	0.6	-1.32	0.46
log_slx_pars[37]	-3.36	1.19	-2.72	1.17
log_slx_pars[38]	-3.36	1.12	-2.72	1.1

Parameter	23.1	SD	23.2	SD
log_slx_pars[39]	-3.42	1.01	-2.77	1
log_slx_pars[40]	-3.65	0.88	-3.1	0.88
log_slx_pars[41]	-3.77	0.85	-3.41	0.85
log_slx_pars[42]	-2.84	0.84	-2.64	0.84
log_slx_pars[43]	-2.31	0.84	-2.16	0.84
log_slx_pars[44]	-2.07	0.84	-2.26	0.84
log_slx_pars[45]	-2.11	0.86	-2.53	0.85
log_slx_pars[46]	-2.29	0.88	-2.93	0.87
log_slx_pars[47]	-2.34	0.94	-3.07	0.91
log_slx_pars[48]	-2.34	1.02	-3.07	1
log_slx_pars[49]	-2.33	1.1	-3.07	1.08
log_slx_pars[50]	-2.33	1.17	-3.07	1.15
log_slx_pars[51]	-2.33	1.24	-3.07	1.22
log_slx_pars[52]	-2.33	1.31	-3.07	1.29
log_slx_pars[53]	-2.33	1.37	-3.07	1.35
log_slx_pars[54]	-2.33	1.43	-3.07	1.41
log_slx_pars[55]	-2.33	1.49	-3.07	1.47
log_slx_pars[56]	-2.33	1.54	-3.07	1.52
log_slx_pars[57]	-2.33	1.59	-3.07	1.58
log_slx_pars[58]	-2.33	1.65	-3.07	1.63
log_slx_pars[62]	-0.35	0.25	-0.27	0.25
log_slx_pars[63]	-0.66	0.22	-0.58	0.22
log_slx_pars[64]	-0.34	0.19	-0.29	0.19
log_slx_pars[69]	-0.4	0.22	-0.66	0.21
log_slx_pars[70]	-0.49	0.26	-0.81	0.26
log_slx_pars[71]	-0.56	0.27	-0.89	0.29
log_slx_pars[72]	-0.68	0.27	-0.97	0.29
log_slx_pars[73]	-0.6	0.3	-0.9	0.31
log_slx_pars[74]	-0.58	0.31	-0.83	0.32
log_slx_pars[75]	-0.63	0.29	-0.78	0.33
log_slx_pars[76]	-0.75	0.25	-0.77	0.34
log_slx_pars[77]	-0.83	0.25	-0.81	0.35
log_slx_pars[78]	-0.8	0.26	-0.86	0.39
log_slx_pars[79]	-0.74	0.28	-0.92	0.45
log_slx_pars[80]	-0.67	0.35	-0.98	0.53
log_slx_pars[81]	-0.6	0.48	-1.02	0.61
log_slx_pars[82]	-0.58	0.63	-1.05	0.7
log_slx_pars[83]	-0.38	0.54	0	0
log_slx_pars[84]	-1	0.32	-0.39	0.23
log_slx_pars[85]	-1.29	0.29	-0.23	0.27
log_slx_pars[86]	-0.68	0.28	-0.12	0.16
log_slx_pars[87]	-0.39	0.16	0	0
log_slx_pars[88]	-0.56	0.16	0	0
log_slx_pars[89]	-0.62	0.18	0	0
log_slx_pars[90]	-0.79	0.23	-0.31	0.23
log_slx_pars[91]	-0.73	0.35	-0.43	0.33
log_slx_pars[92]	-0.75	0.48	-0.58	0.41
log_slx_pars[93]	-0.75	0.62	-0.61	0.54
log_slx_pars[94]	-0.74	0.75	-0.61	0.67
log_slx_pars[95]	-0.74	0.85	-0.61	0.79
log_slx_pars[96]	-0.74	0.94	-0.61	0.89
log_slx_pars[97]	-0.74	1.03	-0.61	0.98

Parameter	23.1	SD	23.2	SD
log_slx_pars[98]	-0.74	1.11	-0.61	1.06
log_slx_pars[99]	-0.74	1.18	-0.61	1.14
log_slx_pars[100]	-0.74	1.25	-0.61	1.21
log_slx_pars[101]	-0.74	1.31	-0.61	1.27
log_slx_pars[102]	-0.74	1.38	-0.61	1.34
log_slx_pars[103]	-0.74	1.43	-0.61	1.4
log_slx_pars[104]	-0.74	1.49	-0.61	1.46
log_slx_pars[107]	4.58	0	4.58	0
log_slx_pars[108]	0.31	0.21	0.49	0.14
log_fbar[1]	-1.06	0.08	-0.97	0.1
log_fbar[2]	-6.6	0.09	-6.29	0.11
log_fdev[1]	NA	NA	NA	NA
log_fdev[2]	NA	NA	NA	NA
log_foff[1]	-5.83	0.16	-6.47	0.14
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]	1.77	0.14	1.98	0.1
m_dev_est[2]	2.4	0.09	0.92	0.18
m_dev_est[4]	0.62	0.39	0	0
m_dev_est[5]	2.23	0.08	2.26	0.08
m_dev_est[7]	0.8	0.4	0.91	0.33
m_dev_est[8]	1.88	0.17	1.63	0.2
m_dev_est[10]	2.5	0.22	2.48	0.23
m_dev_est[11]	2.51	0.71	2.19	0.88
m_mat_mult[1]	0	0.05	-0.07	0.04
m_mat_mult[2]	0.06	0.05	0.28	0.05
survey_q[1]	0.34	0.08	0.52	0.15
survey_q[2]	0.39	0.04	0.46	0.04
survey_q[3]	0.22	0.03	0.11	0.02
survey_q[4]	0.49	0.03	0.27	0.01
sd_log_recruits	NA	NA	NA	NA
ParsOut	NA	NA	NA	NA
sd_log_ssb	NA	NA	NA	NA
sd_last_ssb	38.36	2.71	63.24	4.44
log_slx_pars[61]	NA	NA	0	0

Table 14: Parameter estimates and standard deviations from considered models.

Parameter	23.3b	SD	23.3	SD	23.3	SD
theta[1]	0.29	0	0.29	0	0.55	0.02
theta[2]	0.27	0	0.27	0	0.48	0.03
theta[5]	5.27	172.79	6.23	1308.1	6.79	166.31
theta[13]	8.84	0.69	9.57	0.73	10.34	0.76
theta[14]	8.86	0.55	9.58	0.6	10.35	0.64
theta[15]	8.92	0.43	9.63	0.47	10.39	0.51
theta[16]	9.3	0.38	9.87	0.38	10.56	0.41
theta[17]	9.98	0.36	10.57	0.39	11.19	0.41
theta[18]	10.76	0.32	11.25	0.35	11.83	0.38
theta[19]	11.45	0.26	11.68	0.27	12.23	0.3
theta[20]	11.69	0.22	11.86	0.25	12.38	0.27
theta[21]	11.61	0.22	11.9	0.25	12.39	0.27
theta[22]	11.65	0.22	11.93	0.25	12.37	0.26
theta[23]	11.73	0.21	11.92	0.24	12.29	0.25
theta[24]	11.56	0.21	11.71	0.24	12.02	0.25
theta[25]	11.38	0.21	11.49	0.24	11.74	0.26
theta[26]	11.3	0.2	11.33	0.22	11.46	0.24
theta[27]	11.34	0.18	11.37	0.21	11.41	0.23
theta[28]	11.12	0.15	11.16	0.16	11.31	0.18
theta[29]	10.43	0.15	10.46	0.17	10.59	0.18
theta[30]	9.55	0.19	9.57	0.2	9.71	0.21
theta[31]	8.53	0.25	8.56	0.26	8.72	0.26
theta[32]	7.54	0.31	7.56	0.31	7.76	0.32
theta[33]	6.74	0.34	6.77	0.34	7	0.35
theta[34]	6.31	0.4	6.34	0.4	6.58	0.41
theta[35]	13.74	0.51	14.04	0.41	14.86	0.43
theta[36]	13.45	0.29	13.75	0.21	14.58	0.22
theta[37]	13.02	0.23	13.3	0.24	14.13	0.23
theta[38]	13.11	0.2	13.34	0.2	14.15	0.19
theta[39]	12.39	0.19	12.67	0.19	13.41	0.19
theta[40]	12.46	0.21	12.71	0.2	13.38	0.2
theta[41]	12.3	0.2	12.49	0.19	13.1	0.18
theta[42]	11.92	0.24	12.13	0.22	12.71	0.22
theta[43]	11.62	0.25	11.81	0.25	12.36	0.24
theta[44]	11.18	0.24	11.37	0.24	11.87	0.23
theta[45]	10.51	0.28	10.69	0.28	11.16	0.28
theta[46]	10.1	0.3	10.26	0.3	10.71	0.29
theta[47]	9.97	0.27	10.09	0.27	10.52	0.25
theta[48]	9.31	0.28	9.44	0.28	9.8	0.27
theta[49]	8.16	0.33	8.29	0.33	8.63	0.33
theta[50]	7.13	0.37	7.25	0.37	7.6	0.37
theta[51]	6.35	0.42	6.46	0.42	6.82	0.42
theta[52]	5.79	0.46	5.89	0.46	6.24	0.46
theta[53]	5.38	0.51	5.47	0.51	5.81	0.51
theta[54]	5.08	0.56	5.17	0.55	5.49	0.55
theta[55]	4.88	0.61	4.96	0.61	5.27	0.6
theta[56]	4.77	0.69	4.85	0.69	5.15	0.67
theta[57]	9.63	0.56	11.23	0.57	12.55	0.68
theta[58]	9.69	0.41	11.41	0.5	12.61	0.58
theta[59]	9.99	0.3	11.71	0.42	12.7	0.46

Parameter	23.3b	SD	23.3	SD	23.3	SD
theta[60]	11.03	0.24	12.19	0.29	12.86	0.29
theta[61]	12.78	0.15	13.24	0.2	13.75	0.21
theta[62]	13.77	0.11	13.57	0.15	13.93	0.16
theta[63]	13.32	0.12	13.12	0.15	13.37	0.15
theta[64]	12.35	0.16	12.29	0.19	12.56	0.2
theta[65]	11.29	0.25	11.24	0.25	11.56	0.26
theta[66]	10.11	0.3	10.09	0.31	10.46	0.31
theta[67]	9.3	0.36	9.28	0.37	9.72	0.37
theta[68]	8.76	0.43	8.71	0.42	9.22	0.43
theta[69]	8.41	0.5	8.38	0.5	8.87	0.49
theta[70]	8.11	0.56	8.1	0.55	8.59	0.53
theta[71]	7.83	0.59	7.83	0.58	8.35	0.57
theta[72]	7.54	0.6	7.55	0.59	8.14	0.6
theta[73]	7.29	0.6	7.3	0.59	7.97	0.62
theta[74]	7.07	0.61	7.09	0.59	7.82	0.65
theta[75]	6.89	0.61	6.91	0.6	7.7	0.67
theta[76]	6.74	0.63	6.77	0.61	7.6	0.7
theta[77]	6.64	0.66	6.66	0.64	7.53	0.74
theta[78]	6.58	0.73	6.61	0.71	7.5	0.82
theta[79]	-16.35	1.44	-13.47	3757.8	-14.18	2.58
theta[80]	-16.4	1.39	-13.45	3757.8	-14.26	2.54
theta[81]	-16.66	1.33	-13.6	3757.8	-14.42	2.49
theta[82]	-16.11	1.32	-13.59	3757.8	-14.56	2.45
theta[83]	-15.14	1.32	-13.25	3757.8	-14.37	2.44
theta[84]	-14.17	1.31	-12.87	3757.8	-14.19	2.44
theta[85]	-14.99	1.31	-13.73	3757.8	-15.17	2.44
theta[86]	-16.12	1.33	-14.8	3757.8	-16.23	2.45
theta[87]	-17.08	1.34	-15.72	3757.8	-17.13	2.45
theta[88]	-17.8	1.34	-16.41	3757.8	-17.82	2.46
theta[89]	-18.3	1.35	-16.9	3757.8	-18.3	2.46
theta[90]	-18.64	1.36	-17.24	3757.8	-18.64	2.47
theta[91]	-18.91	1.36	-17.51	3757.8	-18.91	2.47
theta[92]	-19.13	1.35	-17.74	3757.8	-19.13	2.46
theta[93]	-19.32	1.34	-17.93	3757.8	-19.32	2.45
theta[94]	-19.48	1.32	-18.09	3757.8	-19.48	2.44
theta[95]	-19.62	1.28	-18.23	3757.8	-19.62	2.43
theta[96]	-19.74	1.24	-18.35	3757.8	-19.74	2.4
theta[97]	-19.84	1.19	-18.45	3757.8	-19.84	2.38
theta[98]	-19.92	1.13	-18.53	3757.8	-19.92	2.35
theta[99]	-19.97	1.05	-18.58	3757.8	-19.97	2.31
theta[100]	-20	0.95	-18.61	3757.8	-20	2.27
Grwth[1]	2.19	0.08	2.26	0.08	2.19	0.08
Grwth[2]	-0.22	0	-0.22	0	-0.22	0
Grwth[4]	0.45	0.1	0.24	0.11	0.2	0.11
Grwth[5]	-0.27	0	-0.28	0	-0.28	0
log__slx__pars[1]	4.68	0.01	4.68	0	4.67	0
log__slx__pars[2]	1.46	0.03	1.45	0.03	1.4	0.03
log__slx__pars[3]	4.23	0.01	4.23	0.01	4.24	0
log__slx__pars[4]	1.05	0.03	1.05	0.03	1.01	0.03
log__slx__pars[5]	4.8	0.02	4.79	0.02	4.73	0.01
log__slx__pars[6]	2.44	0.02	2.41	0.02	2.28	0.02
log__slx__pars[95]	4.58	0	4.58	0	4.58	0

Parameter	23.3b	SD	23.3	SD	23.3	SD
log_slx_pars[96]	0.55	0.11	0.55	0.11	0.61	0.1
log_fbar[1]	0.17	0.07	0.09	0.07	0.15	0.06
log_fbar[2]	-5.08	0.09	-5.15	0.09	-5.15	0.08
log_fdev[1]	NA	NA	NA	NA	NA	NA
log_fdev[2]	NA	NA	NA	NA	NA	NA
log_foff[1]	-7.61	0.1	-7.41	0.1	-7.23	0.1
log_fdov[1]	NA	NA	NA	NA	NA	NA
rec_dev_est	NA	NA	NA	NA	NA	NA
logit_rec_prop_est	NA	NA	NA	NA	NA	NA
m_dev_est[1]	1.51	0.13	1.78	0.11	1.15	0.12
m_dev_est[2]	0.39	0.28	0.9	0.17	0	0
m_dev_est[4]	0	0	0	0	0	0
m_dev_est[5]	2.52	0.08	2.47	0.07	2.08	0.06
m_dev_est[7]	0.56	0.48	0.89	0.35	0.13	0.43
m_dev_est[8]	1.99	0.15	1.82	0.17	0.98	0.25
m_dev_est[10]	2.67	0.19	2.73	0.29	2.08	0.23
m_dev_est[11]	2.48	0.81	1.74	1.3	1.32	0.96
m_mat_mult[1]	-0.47	0.04	-0.21	0.04	-0.38	0.04
m_mat_mult[2]	-0.01	0.05	0.08	0.05	0.09	0.05
sd_log_recruits	NA	NA	NA	NA	NA	NA
ParsOut	NA	NA	NA	NA	NA	NA
sd_log_ssb	NA	NA	NA	NA	NA	NA
sd_last_ssb	50.04	3.14	55.01	3.5	29.05	2.14
log_slx_pars[7]	NA	NA	-2.73	0.24	-3.39	0.25
log_slx_pars[8]	NA	NA	-2.31	0.16	-2.94	0.19
log_slx_pars[9]	NA	NA	-1.95	0.15	-2.55	0.18
log_slx_pars[10]	NA	NA	-1.2	0.12	-1.67	0.16
log_slx_pars[11]	NA	NA	-1.3	0.12	-1.74	0.15
log_slx_pars[12]	NA	NA	-1.18	0.11	-1.55	0.13
log_slx_pars[13]	NA	NA	-0.97	0.1	-1.27	0.12
log_slx_pars[14]	NA	NA	-0.99	0.1	-1.24	0.12
log_slx_pars[15]	NA	NA	-1.14	0.11	-1.35	0.12
log_slx_pars[16]	NA	NA	-1.13	0.11	-1.28	0.12
log_slx_pars[17]	NA	NA	-1.05	0.11	-1.15	0.12
log_slx_pars[18]	NA	NA	-1.01	0.12	-1.08	0.12
log_slx_pars[19]	NA	NA	-0.97	0.12	-1	0.12
log_slx_pars[20]	NA	NA	-0.84	0.11	-0.84	0.11
log_slx_pars[21]	NA	NA	-0.78	0.11	-0.76	0.11
log_slx_pars[22]	NA	NA	-0.68	0.11	-0.68	0.11
log_slx_pars[23]	NA	NA	-0.54	0.1	-0.56	0.1
log_slx_pars[24]	NA	NA	-0.43	0.1	-0.44	0.1
log_slx_pars[25]	NA	NA	-0.33	0.09	-0.34	0.09
log_slx_pars[26]	NA	NA	-0.21	0.08	-0.22	0.08
log_slx_pars[27]	NA	NA	-0.1	0.08	-0.11	0.08
log_slx_pars[28]	NA	NA	-0.04	0.11	-0.04	0.11
log_slx_pars[29]	NA	NA	-3.14	0.31	-4.62	0.25
log_slx_pars[30]	NA	NA	-3.5	0.32	-4.97	0.22
log_slx_pars[31]	NA	NA	-3.39	0.23	-4.41	0.2
log_slx_pars[32]	NA	NA	-2.02	0.16	-2.45	0.15
log_slx_pars[33]	NA	NA	-1.24	0.13	-1.53	0.13
log_slx_pars[34]	NA	NA	-0.6	0.09	-0.66	0.1
log_slx_pars[35]	NA	NA	-0.58	0.09	-0.51	0.09

Parameter	23.3b	SD	23.3	SD	23.3	SD
log_slx_pars[36]	NA	NA	-0.76	0.11	-0.72	0.11
log_slx_pars[37]	NA	NA	-0.81	0.12	-0.8	0.12
log_slx_pars[38]	NA	NA	-0.91	0.14	-0.92	0.14
log_slx_pars[39]	NA	NA	-0.91	0.14	-0.91	0.15
log_slx_pars[40]	NA	NA	-0.87	0.14	-0.87	0.14
log_slx_pars[41]	NA	NA	-0.83	0.14	-0.84	0.14
log_slx_pars[42]	NA	NA	-0.78	0.13	-0.79	0.13
log_slx_pars[43]	NA	NA	-0.72	0.13	-0.72	0.13
log_slx_pars[44]	NA	NA	-0.63	0.12	-0.63	0.12
log_slx_pars[45]	NA	NA	-0.53	0.11	-0.53	0.11
log_slx_pars[46]	NA	NA	-0.42	0.1	-0.42	0.1
log_slx_pars[47]	NA	NA	-0.31	0.09	-0.31	0.09
log_slx_pars[48]	NA	NA	-0.2	0.08	-0.2	0.08
log_slx_pars[49]	NA	NA	-0.08	0.08	-0.08	0.08
log_slx_pars[50]	NA	NA	-0.01	0.11	-0.01	0.11
log_slx_pars[51]	NA	NA	-3.93	0.23	-4.31	0.17
log_slx_pars[52]	NA	NA	-2.92	0.11	-3.2	0.14
log_slx_pars[53]	NA	NA	-2.05	0.1	-2.37	0.11
log_slx_pars[54]	NA	NA	-1.26	0.08	-1.58	0.1
log_slx_pars[55]	NA	NA	-1.18	0.07	-1.39	0.08
log_slx_pars[56]	NA	NA	-1.08	0.06	-1.21	0.07
log_slx_pars[57]	NA	NA	-1.04	0.06	-1.1	0.06
log_slx_pars[58]	NA	NA	-1.05	0.06	-1.07	0.06
log_slx_pars[59]	NA	NA	-1.21	0.06	-1.19	0.06
log_slx_pars[60]	NA	NA	-1.26	0.06	-1.19	0.06
log_slx_pars[61]	NA	NA	-1.25	0.06	-1.15	0.06
log_slx_pars[62]	NA	NA	-1.24	0.06	-1.1	0.06
log_slx_pars[63]	NA	NA	-1.17	0.06	-1.03	0.06
log_slx_pars[64]	NA	NA	-0.99	0.06	-0.84	0.06
log_slx_pars[65]	NA	NA	-0.78	0.07	-0.67	0.06
log_slx_pars[66]	NA	NA	-0.55	0.07	-0.51	0.07
log_slx_pars[67]	NA	NA	-0.38	0.07	-0.38	0.07
log_slx_pars[68]	NA	NA	-0.26	0.07	-0.27	0.07
log_slx_pars[69]	NA	NA	-0.2	0.07	-0.22	0.07
log_slx_pars[70]	NA	NA	-0.16	0.07	-0.16	0.07
log_slx_pars[71]	NA	NA	-0.12	0.08	-0.13	0.08
log_slx_pars[72]	NA	NA	-0.09	0.11	-0.09	0.11
log_slx_pars[73]	NA	NA	-4.12	0.16	-4.67	0.21
log_slx_pars[74]	NA	NA	-3.42	0.09	-3.81	0.11
log_slx_pars[75]	NA	NA	-2.85	0.09	-3.08	0.09
log_slx_pars[76]	NA	NA	-1.22	0.07	-1.38	0.07
log_slx_pars[77]	NA	NA	-0.63	0.06	-0.76	0.06
log_slx_pars[78]	NA	NA	-0.27	0.05	-0.35	0.05
log_slx_pars[79]	NA	NA	-0.39	0.05	-0.41	0.06
log_slx_pars[80]	NA	NA	-0.99	0.07	-0.97	0.08
log_slx_pars[81]	NA	NA	-1.06	0.1	-1	0.1
log_slx_pars[82]	NA	NA	-1.25	0.12	-1.17	0.12
log_slx_pars[83]	NA	NA	-1.2	0.15	-1.12	0.14
log_slx_pars[84]	NA	NA	-0.91	0.15	-0.89	0.14
log_slx_pars[85]	NA	NA	-0.83	0.14	-0.83	0.14
log_slx_pars[86]	NA	NA	-0.78	0.13	-0.78	0.13
log_slx_pars[87]	NA	NA	-0.71	0.12	-0.71	0.12

Parameter	23.3b	SD	23.3	SD	23.3	SD
log_slx_pars[88]	NA	NA	-0.62	0.12	-0.62	0.12
log_slx_pars[89]	NA	NA	-0.52	0.11	-0.52	0.11
log_slx_pars[90]	NA	NA	-0.42	0.1	-0.42	0.1
log_slx_pars[91]	NA	NA	-0.31	0.09	-0.31	0.09
log_slx_pars[92]	NA	NA	-0.2	0.08	-0.2	0.08
log_slx_pars[93]	NA	NA	-0.08	0.08	-0.08	0.08
log_slx_pars[94]	NA	NA	-0.01	0.11	-0.01	0.11

Table 15: 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.

Model	MMB	B35	F35	FOFL	OFL	M	avg_rec	Status
22.1	41.21	183.15	1.50	0.32	10.32	0.28	164.02	0.23
23.1	56.41	189.24	1.60	0.30	8.58	0.29	169.90	0.30
23.2	135.43	132.46	71.89	30.14	37.10	0.29	222.75	1.02
23.3	81.96	130.98	33.47	10.49	12.12	0.29	91.92	0.63
23.3a	92.39	155.91	53.25	14.96	15.44	0.29	141.66	0.59
23.3b	68.15	110.01	205.67	37.49	11.56	0.55	351.66	0.62

Table 16: Management quantities derived from maximum likelihood estimates by model using Tier 4 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.

Model	MMB	BMSY	FMSY	FOFL	OFL	M	avg_rec	Status
23.1	56.41	267.41	0.29	0.00	0.10	0.29	169.90	0.21
23.2	135.43	519.67	0.29	0.00	0.05	0.29	222.75	0.26
23.3	81.96	236.84	0.29	0.05	0.29	0.29	91.92	0.35
23.3a	92.39	273.83	0.29	0.05	0.31	0.29	141.66	0.34
23.3b	68.15	232.32	0.55	0.00	0.03	0.55	351.66	0.29

Table 17: Management quantities derived from maximum likelihood estimates by model using natural mortality and B35. Reported natural mortality is for mature males, average recruitment is for males, and status and MMB were estimates for February 15 of the completed crab year.

Model	MMB	BMSY	FMSY	FOFL	OFL	M	avg_rec	Status
23.1	56.41	189.24	0.29	0.06	2.10	0.29	169.90	0.30
23.2	135.43	132.46	0.29	0.21	2.42	0.29	222.75	1.02
23.3	81.96	130.98	0.29	0.12	0.59	0.29	91.92	0.63
23.3a	92.39	155.91	0.29	0.11	0.63	0.29	141.66	0.59
23.3b	68.15	110.01	0.55	0.16	0.52	0.55	351.66	0.62

Table 18: Survey-based tier 4 status and OFL (1,000 t). ‘Males_com’ is the observed biomass of >101mm carapace width males. Status represents the status of the population after the completed fishing year and is used for overfished declarations. Proj_Status represents the projected fishery status after the coming fishery removes the OFL and is used in the harvest control rule. ‘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	3c	59.64	9.996	0.1676	0	0	1982-2022	0.27

Table 19: 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 author-preferred model. 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	90.34	122.8	30.91	55.91	168.8	290.2	51.75	95.61
1983	68.67	134	35.23	61.38	128.3	316.8	57.05	102.2
1984	52.49	159.6	51.92	86.59	98.07	365.1	80.85	139.6
1985	41.16	176.4	58.81	95.54	76.93	402.6	89.54	151.1
1986	51.19	189.6	54.11	88.3	94.72	446.9	82.74	140.2
1987	126.5	224.7	60.11	99.26	237.3	536.9	92.84	158.9
1988	198	274.6	75.44	124	377.9	654.4	116	197.6
1989	274.5	314.8	110.2	182.3	454.8	763.6	150.5	255.6
1990	248.4	345.5	145	238	422.1	780.5	196.9	331.9
1991	204.6	284.4	126.8	210.7	350.4	654.1	173.5	295.7
1992	164.2	244.3	112.6	174.4	281.6	545.2	147.8	235.8
1993	137.1	204.9	73.01	116.8	233.5	489.6	97.47	160.2
1994	125.8	207.7	48.27	78.32	211.8	549.2	65.26	108.9
1995	131.7	220.6	41.64	71.11	218.6	610.4	58.29	102
1996	145.3	286.2	88.33	148.9	241.8	720.8	122.1	210.9
1997	140.8	305.7	126.7	207.1	238.1	701.3	171.6	288.4
1998	121	250.3	113.6	181.6	207.2	557.5	151.7	249.2
1999	96.71	175.2	69.37	108.3	166.7	404.1	91.74	147.8
2000	79.47	141.9	53.1	81.92	135.8	331.2	69.78	111.2
2001	75.38	114.7	37.43	59.19	126.9	279.2	49.97	81.57
2002	73.35	100.5	31.27	52.37	123.9	247.4	43.23	74.37
2003	65.17	97.85	38.52	63.49	111.2	225.5	52.51	88.89
2004	58.49	93.6	42.53	67.97	99.07	207.8	56.74	93.23
2005	71.61	98.93	37.87	59.12	115.6	232.9	49.97	80.44
2006	111	103.7	30.78	49.96	180.4	261.1	41.73	69.77
2007	113.6	132.1	44.1	72.48	192.1	327.4	59.89	101
2008	98.43	150.9	55.83	91.56	168.7	369.1	75.88	127.9
2009	83.57	170.3	76.51	121.1	142.5	381.2	101.6	165.5
2010	93.91	160.9	77.55	121.9	153.6	352.2	102.5	165.9
2011	128.8	170.1	82.98	125.8	211.2	364.6	107.2	167.4
2012	129.5	124.2	42.29	67.95	219	301.4	56.85	94.13
2013	113.5	110.9	33.68	56.9	194	278.5	46.68	80.85
2014	98.1	110.6	39.13	65.03	167.2	265.1	53.57	91.34
2015	91.07	85.47	24.45	40.54	154.3	215.5	33.59	57.27
2016	88.37	77.73	17.19	28.61	147.8	205.6	23.72	40.59
2017	127.1	93.34	17.89	30.24	202.4	252.5	24.87	43.11
2018	251.5	160.6	26.52	44.31	394.1	444.3	36.52	62.61
2019	131.8	162.6	33.43	59.9	206.9	432.2	48.31	88.12
2020	24.69	76.12	11.66	21.33	38.87	209.5	17.25	32.06
2021	18.95	51.1	5.84	10.29	29.85	146.6	8.41	15.15
2022	15.48	41.39	7.02	11.33	24.21	114	9.5	15.79
2023	14.73	31.9	5.98	9.5	23.15	86.75	8	13.1

Table 20: 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	9.346
1984	10.58
1985	19.84
1986	24.53
1987	24.15
1988	20.88
1989	16.71
1990	14.09
1991	15.76
1992	18.03
1993	16.36
1994	15.29
1995	12.83
1996	10.26
1997	8.271
1998	7.68
1999	6.685
2000	6.159
2001	5.22
2002	6.237
2003	6.782
2004	11.49
2005	11.01
2006	9.161
2007	7.392
2008	8.72
2009	11.87
2010	9.899
2011	8.579
2012	7.062
2013	7.473
2014	7.018
2015	14.32
2016	23.31
2017	32.05
2018	24.74
2019	8.068
2020	1.894
2021	1.696
2022	1.412
2023	1.142

Table 21: Maximum likelihood estimates of mature male biomass at mating, male recruitment (billions), and fully-selected total fishing mortaltiy.

Survey year	Mature male biomass	Male recruits	Fishing mortality
1982	221.1	2.34	0.54
1983	242.2	3.31	0.48
1984	263.1	4.55	0.93
1985	278.9	4.32	1.34
1986	315.7	0.34	1.45
1987	376.5	2.02	1.75
1988	462.3	0.21	1.49
1989	543.6	1.29	1.22
1990	485.7	4.68	2.56
1991	406.8	5.16	2.92
1992	321.8	0.91	3.49
1993	327.5	0.23	1.97
1994	400	0.08	1.38
1995	454.8	0.1	1.44
1996	525.2	0.54	1.15
1997	474.6	1.41	1.46
1998	370.6	0.06	1.42
1999	312.7	0.25	0.27
2000	254.6	0.3	0.31
2001	206.4	1.99	0.76
2002	185.6	1.17	0.69
2003	171.6	2.17	0.39
2004	156.6	1.81	0.38
2005	168.2	0.21	0.81
2006	192.3	0.32	0.97
2007	234.9	1.89	1.25
2008	272.3	1.26	0.8
2009	286.1	0.27	0.43
2010	261.1	0.47	0.4
2011	250.2	0.26	0.83
2012	209.5	1.09	1.38
2013	196.3	1.01	1.57
2014	179.3	6.55	1.83
2015	151.7	4.78	1.75
2016	153.3	0.36	1.04
2017	190.1	0.05	1
2018	126.2	0.05	3.25
2019	245	0.01	1.36
2020	145.5	0.11	4.96
2021	114.8	0.08	0.79
2022	92.39	0.05	0

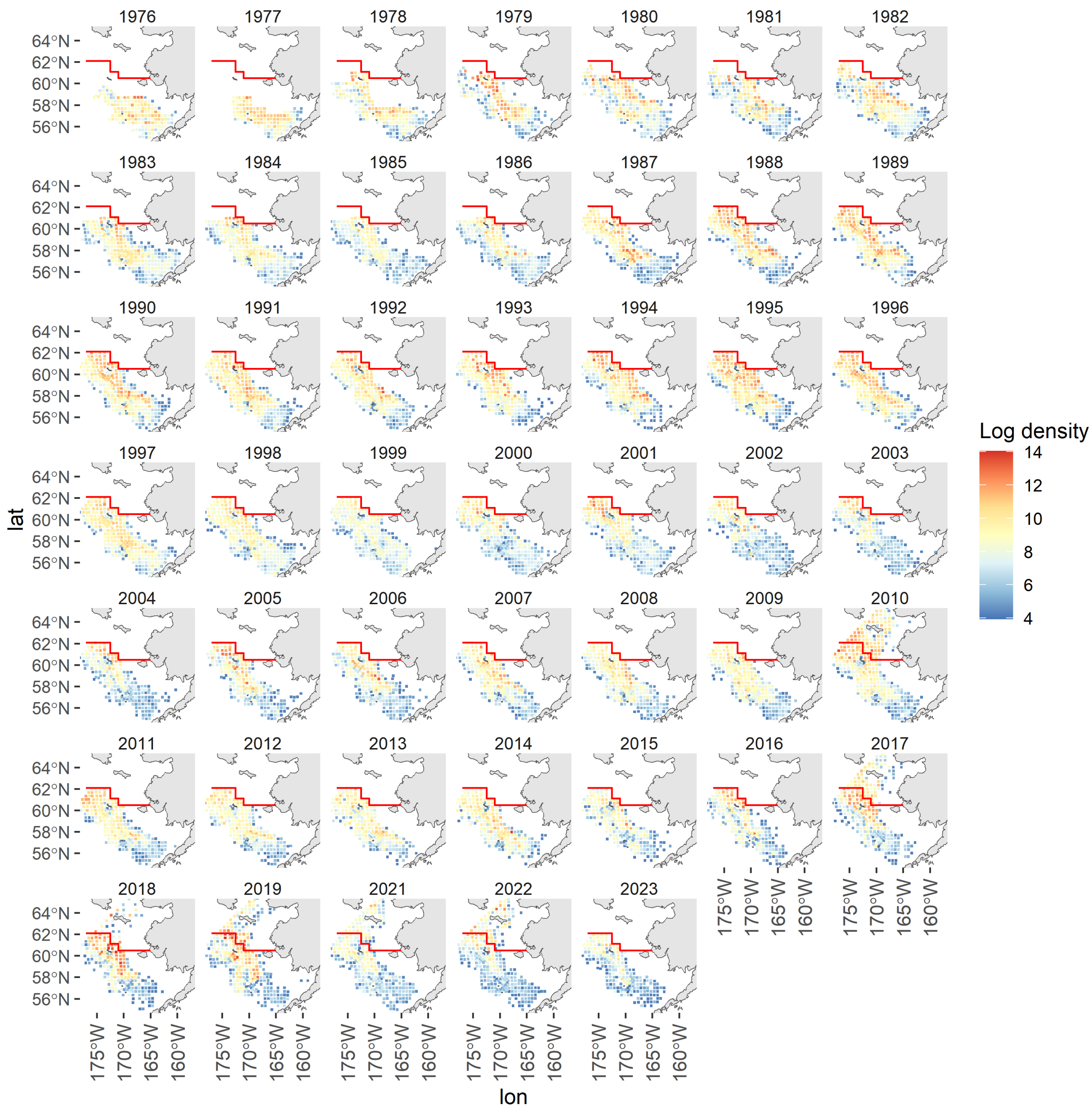


Figure 1: Observed relative density of all males over time during the NMFS summer survey. Each colored square in a facet represents a survey tow. Red line is the border between the EBS and NBS.

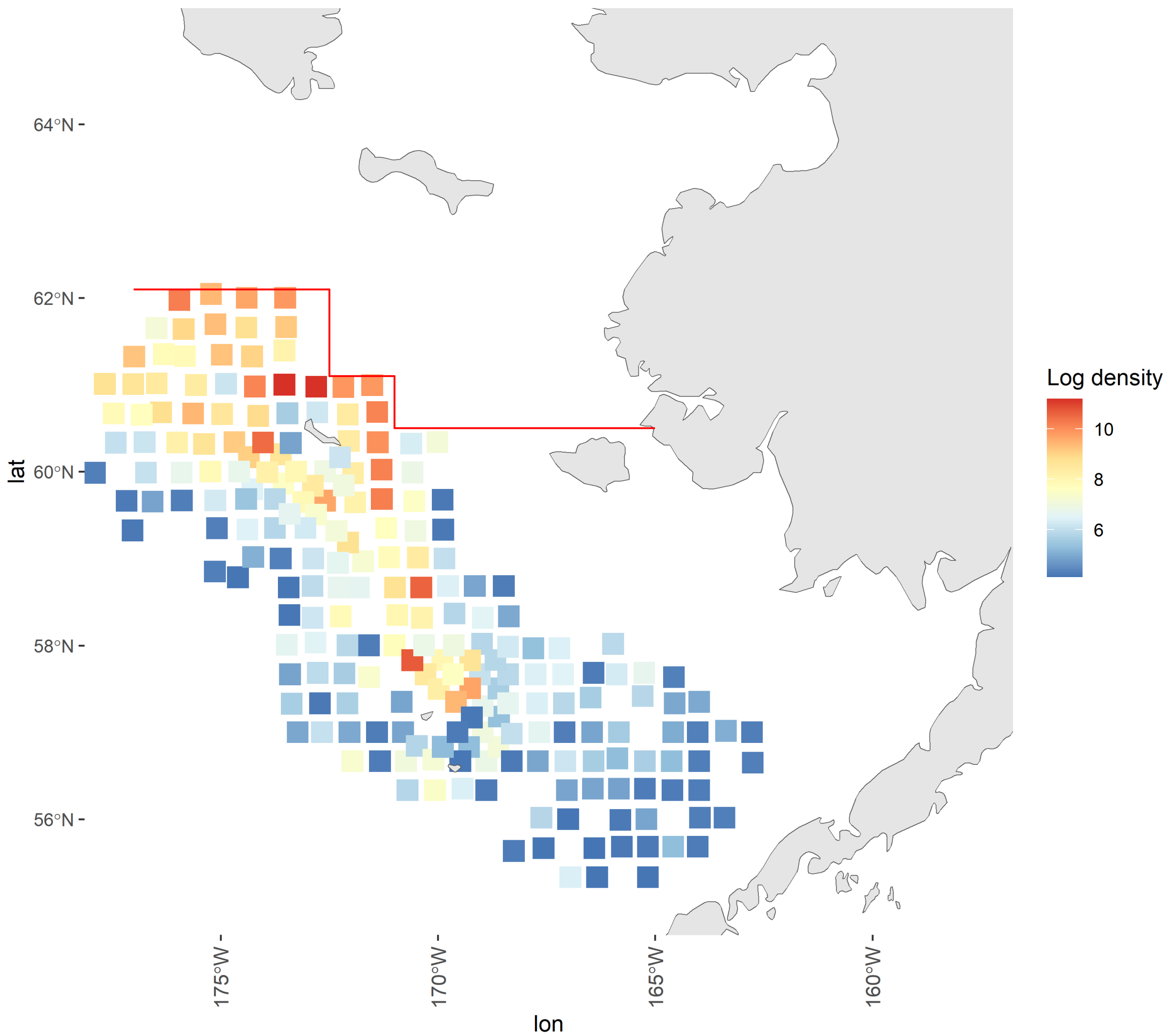


Figure 2: Observed relative density of all males at the time of the 2022 NMFS summer survey. Each colored square in a facet represents a survey tow. Red line is the border between the EBS and NBS.

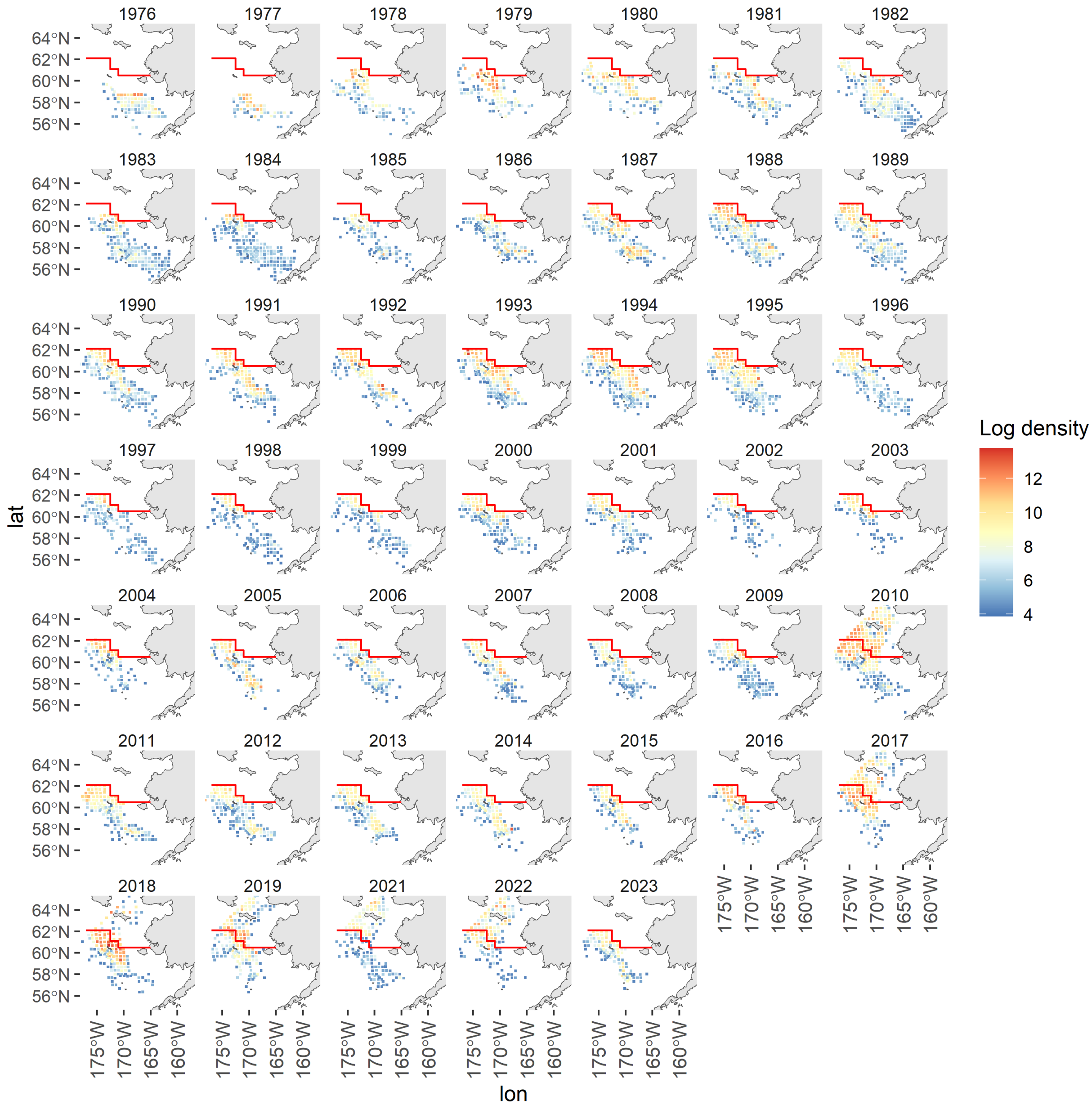


Figure 3: Observed relative density of 45-55 mm carapace width males over time during the NMFS summer survey. Each colored square in a facet represents a survey tow. Red line is the border between the EBS and NBS.

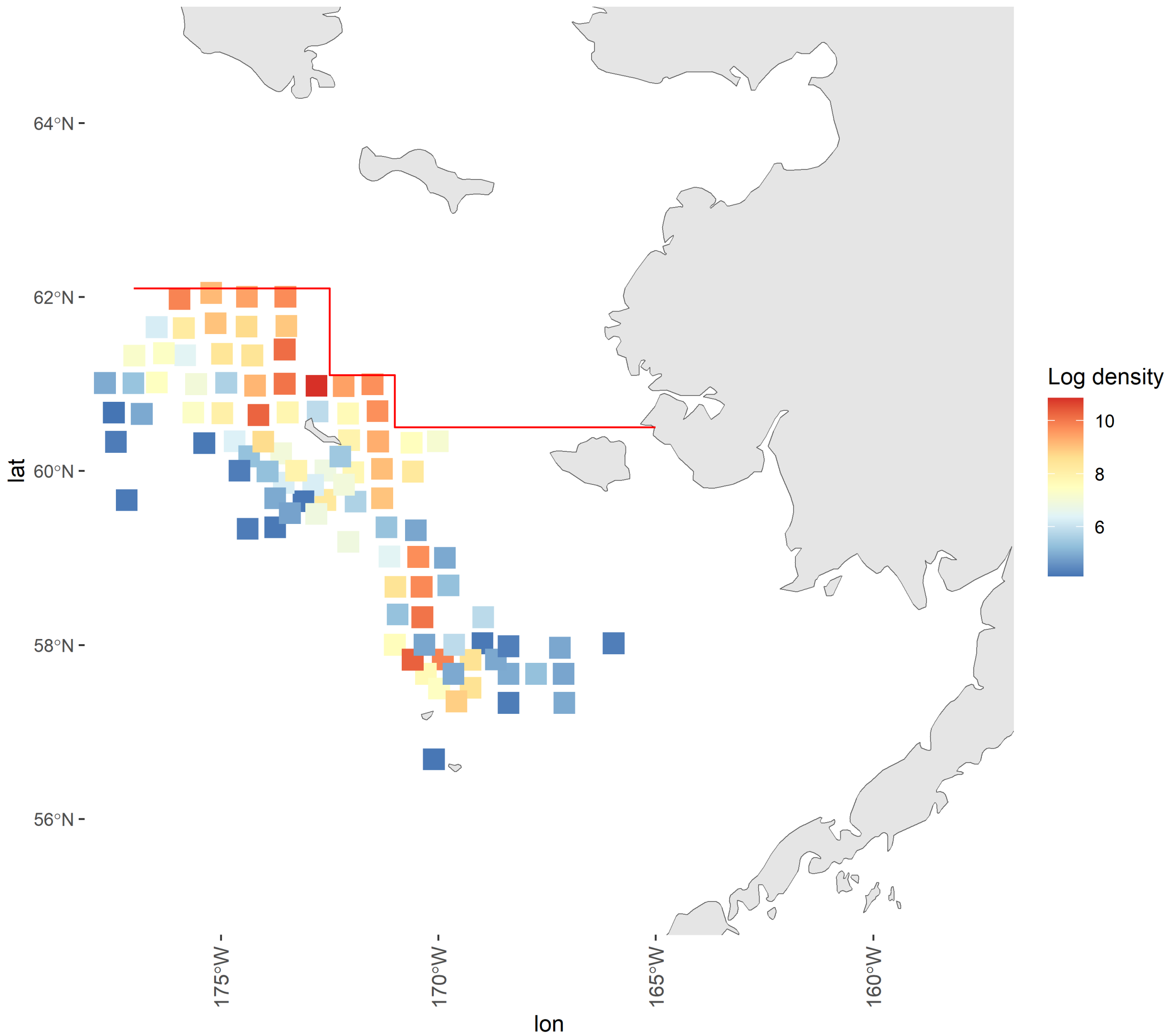


Figure 4: Observed relative density of males 45-55 mm carapace width at the time of the 2023 NMFS summer survey. Each colored square in a facet represents a survey tow. Red line is the border between the EBS and NBS.

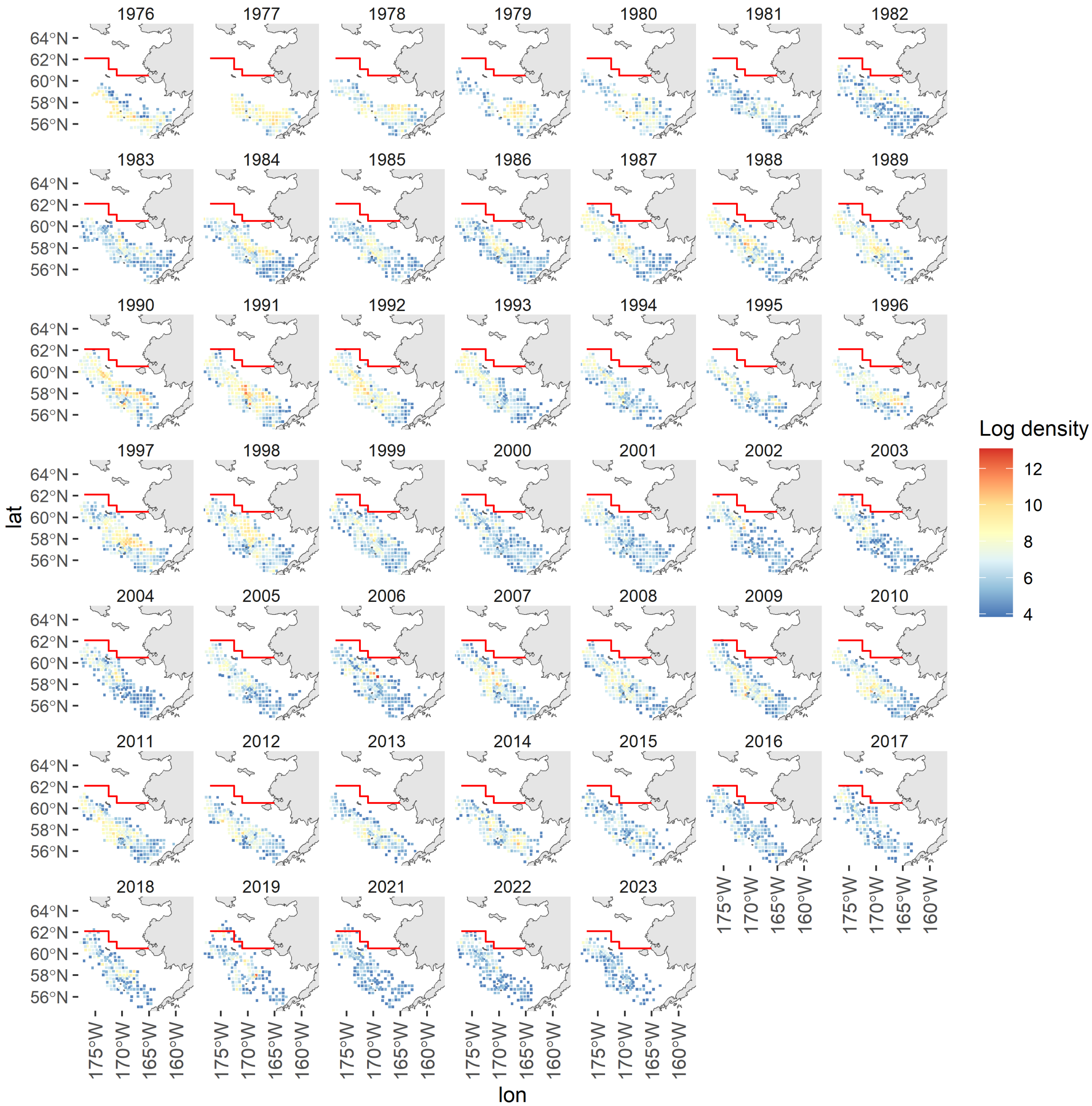


Figure 5: Observed relative density of >101 mm carapace width males over time during the NMFS summer survey. Each colored square in a facet represents a survey tow. Red line is the border between the EBS and NBS.

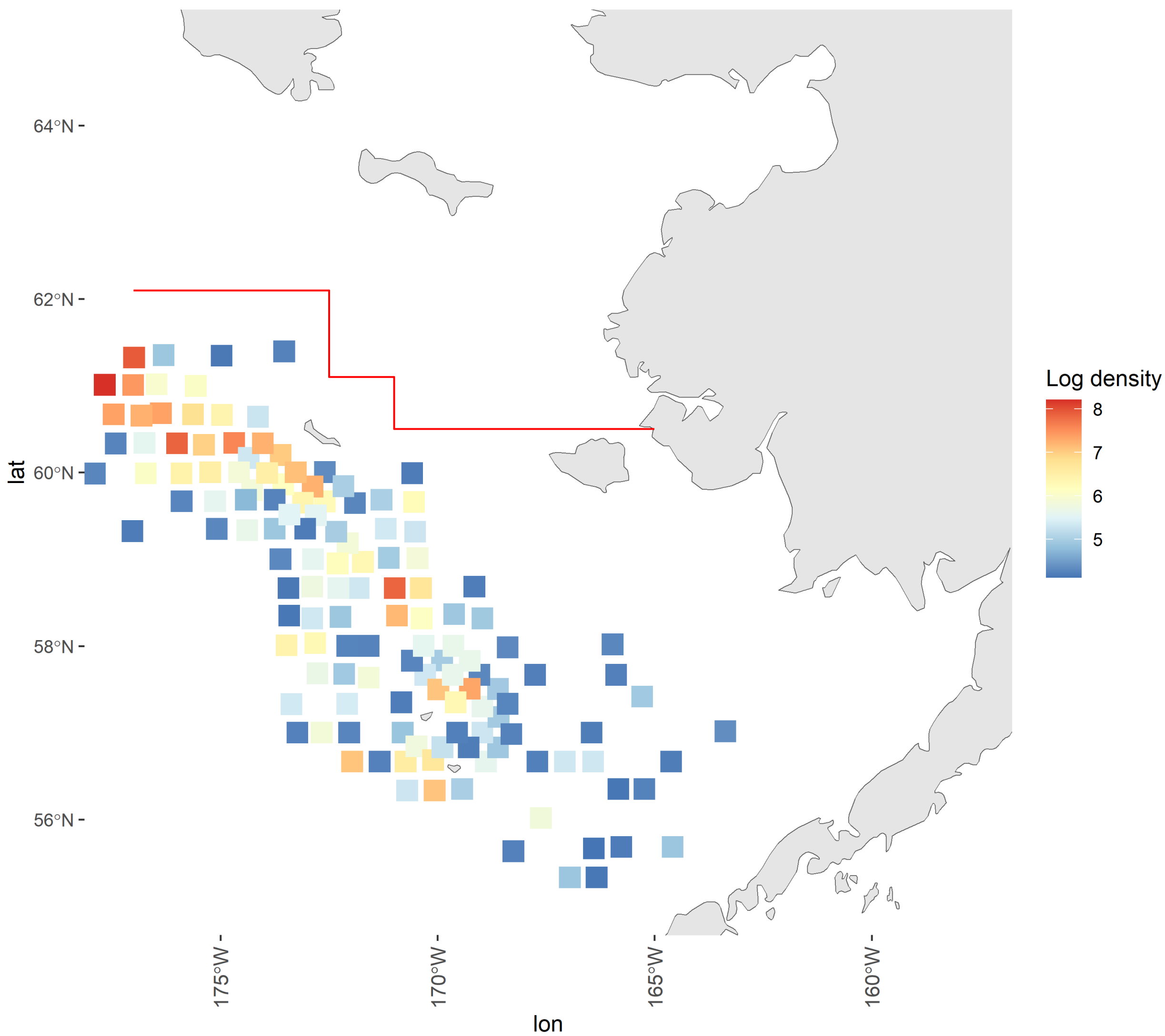


Figure 6: Observed relative density of males >101 mm carapace width at the time of the 2023 NMFS summer survey. Each colored square in a facet represents a survey tow. Red line is the border between the EBS and NBS.

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.

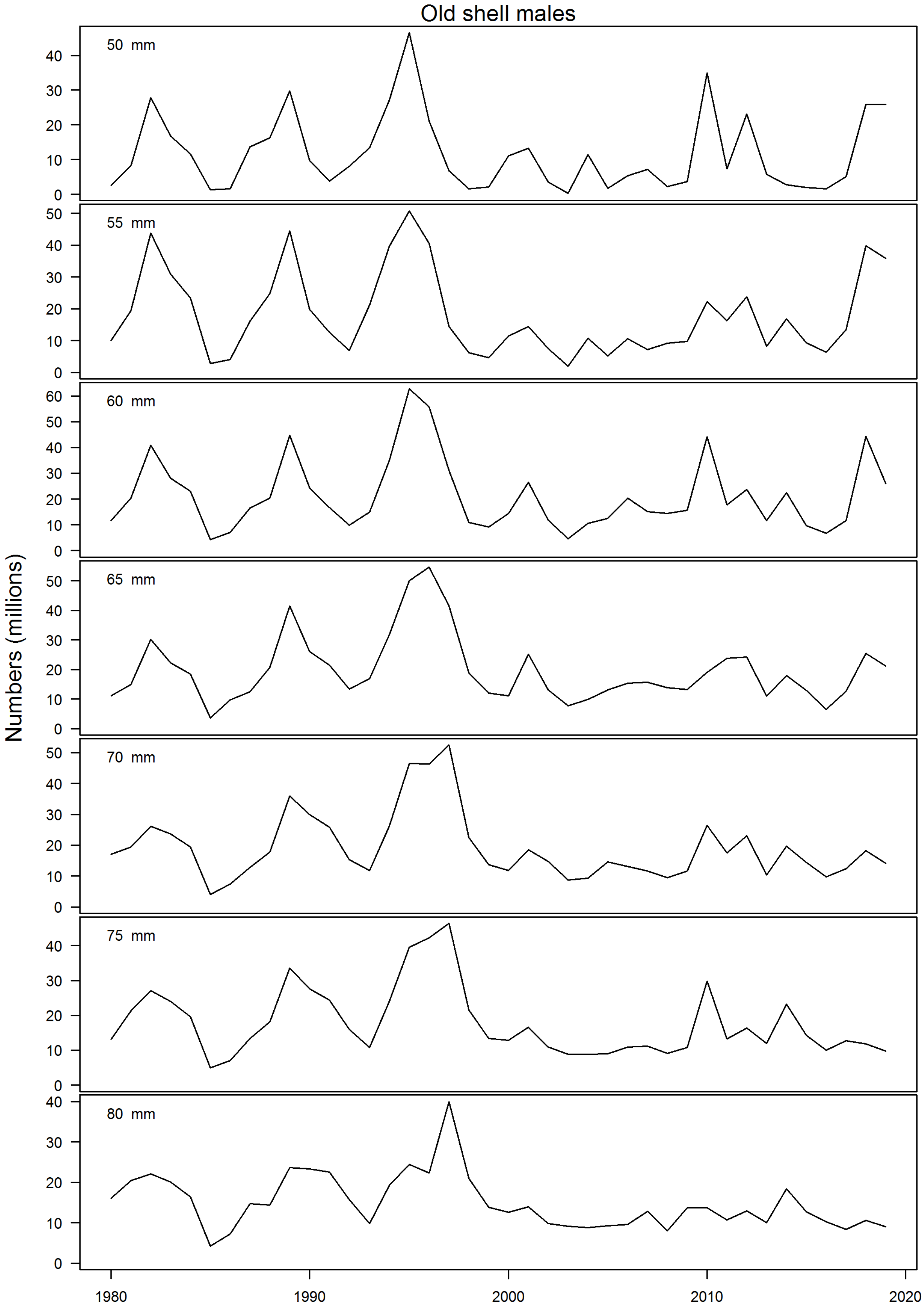


Figure 8: Observed numbers at length of old shell mature males by size class. The presented size bins are not vulnerable to the fishery, so all mortality is 'natural'. The decline in numbers in a size class after the recruitment collapse in the early 1990s demonstrates expected natural mortality for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

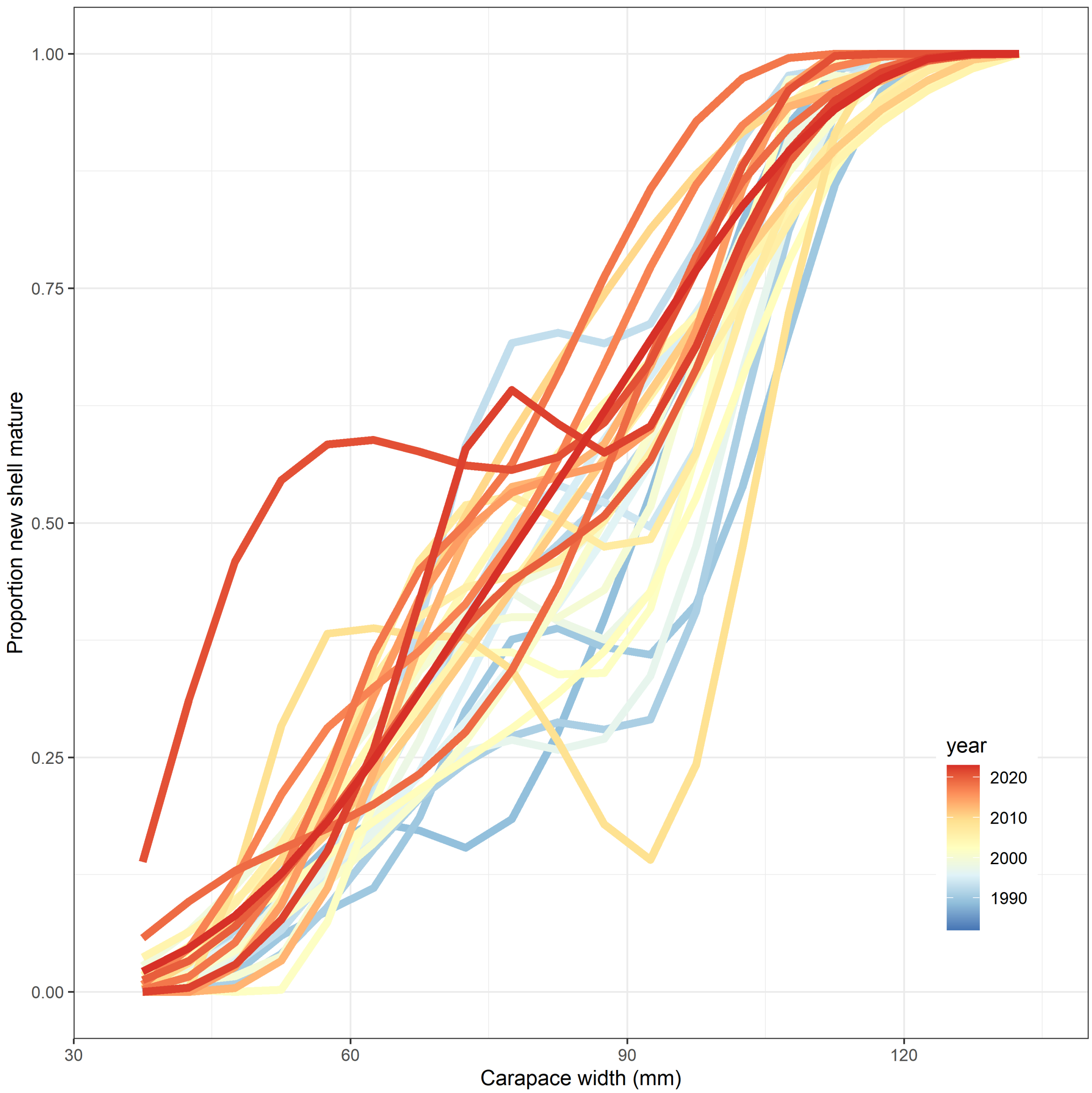


Figure 9: Observed probability of having undergone terminal molt at size for new shell male crab based on chelae height. Blue lines occurred farther back in history; red lines are most recent.

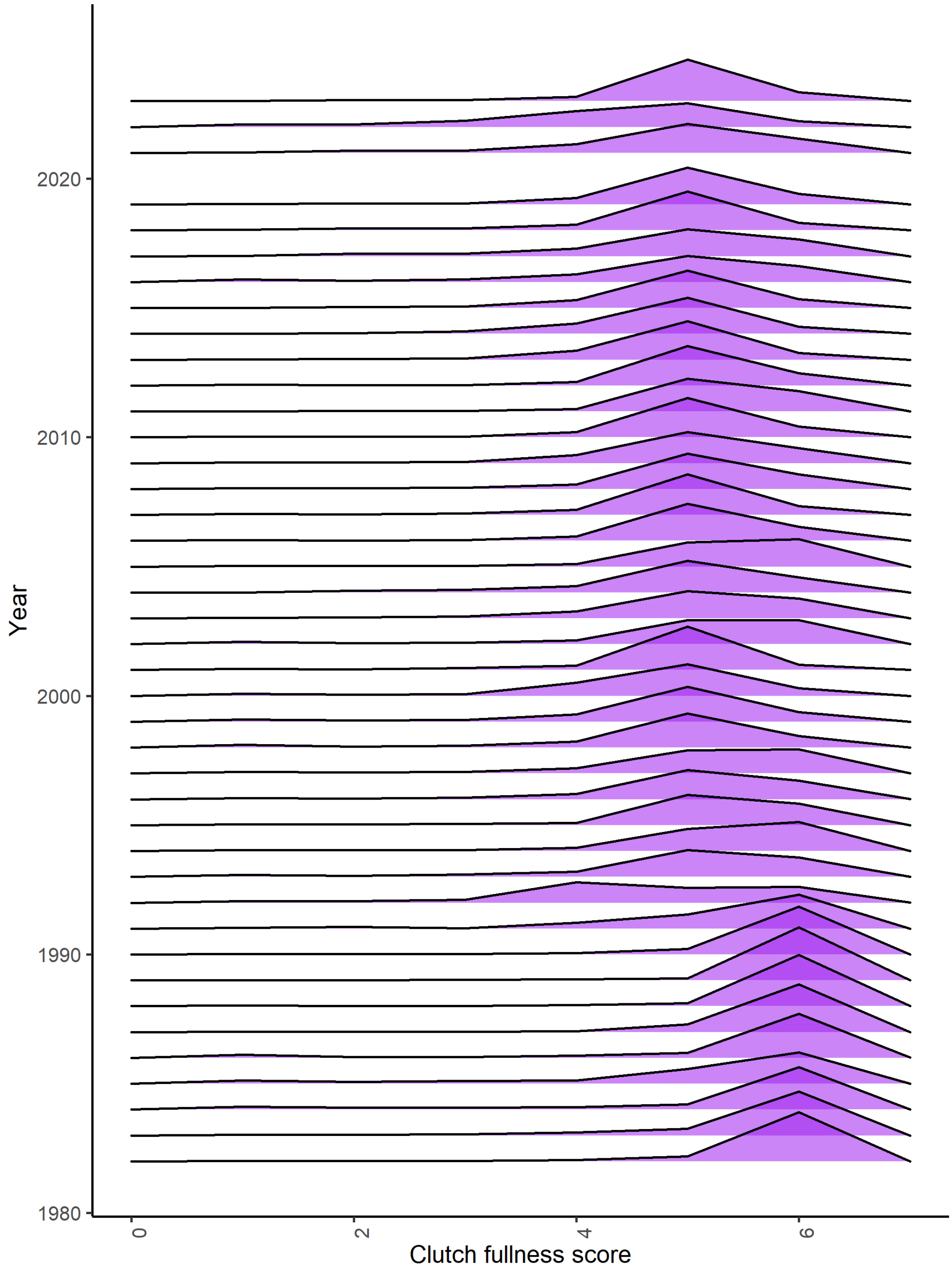


Figure 10: Clutch fullness scores from the 1982-2023 NMFS summer survey. Scores: 0 = immature, 1 = mature no eggs, 2 = trace to 0.125, 3 = 0.25, 4 = 0.5, 5 = 0.75, 6 = full of eggs; 7 = overflowing.

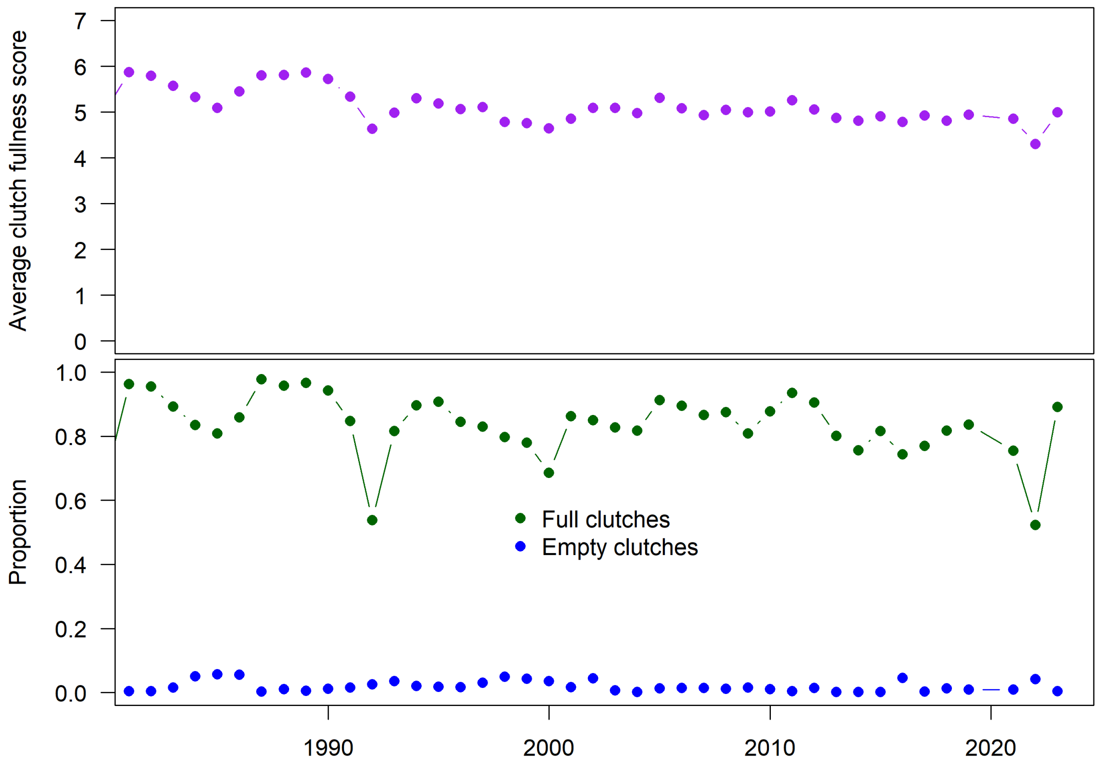


Figure 11: Time series of the average clutch fullness score (top) and the proportion of observed crab with full clutches (green) and empty clutches (blue) in the NMFS summer survey (bottom). Scores: 0 = immature, 1 = mature no eggs, 2 = trace to 0.125, 3 = 0.25, 4 = 0.5, 5 = 0.75, 6 = full of eggs; 7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

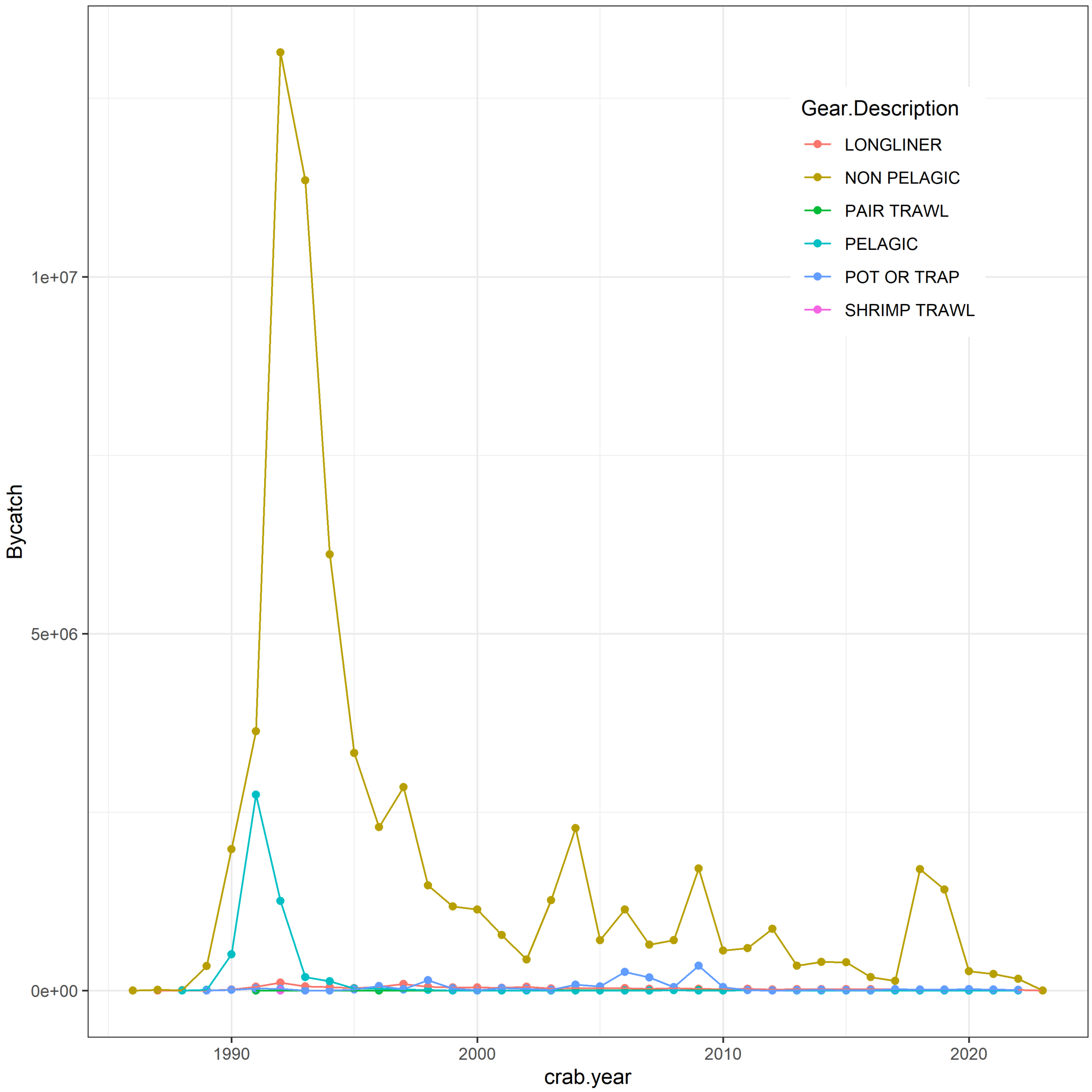


Figure 12: Time series of non-directed bycatch by gear in numbers of crab.

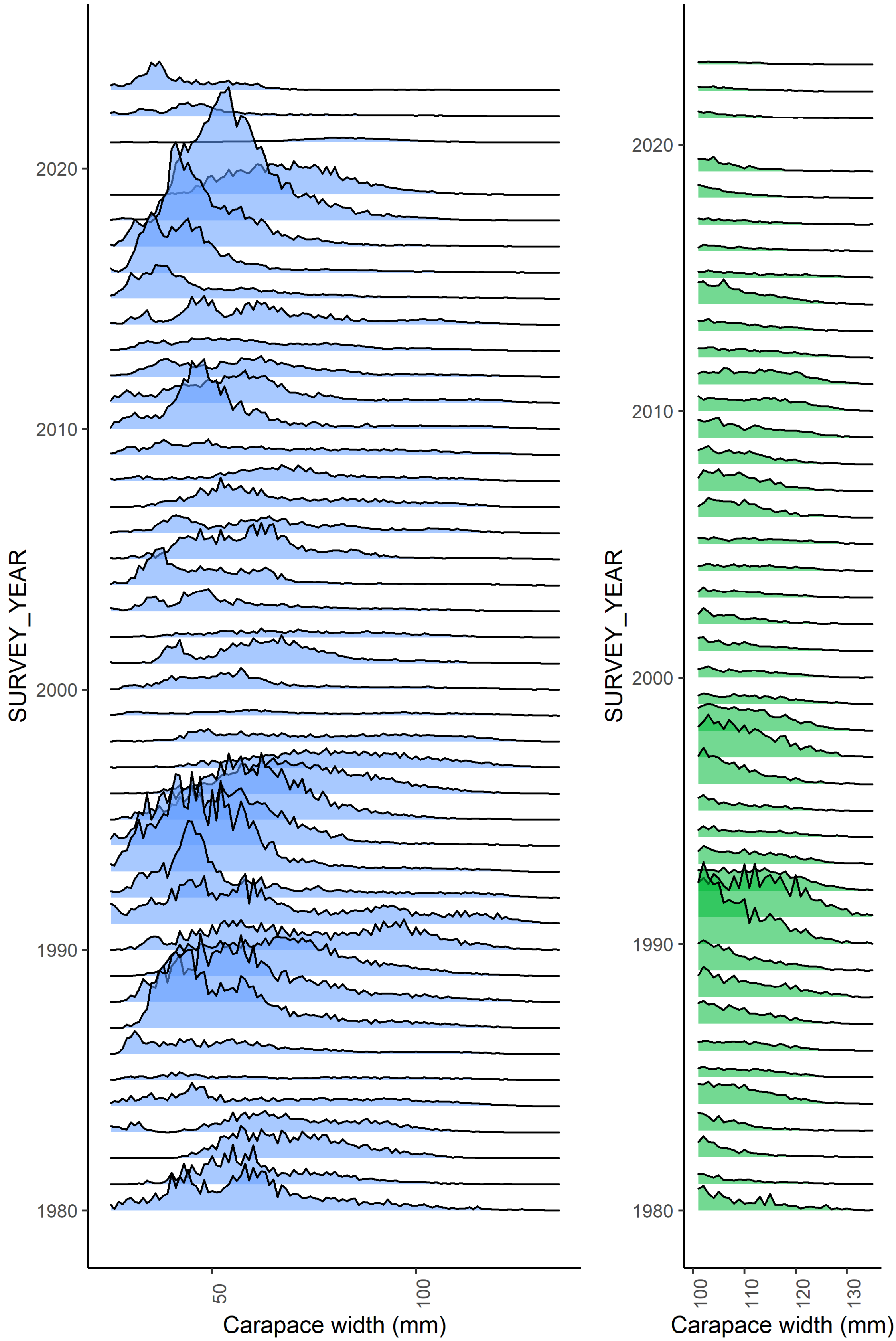


Figure 13: Raw total numbers at size of male crab observed in the survey. Blue are all numbers at size; green are males >101mm carapace width.

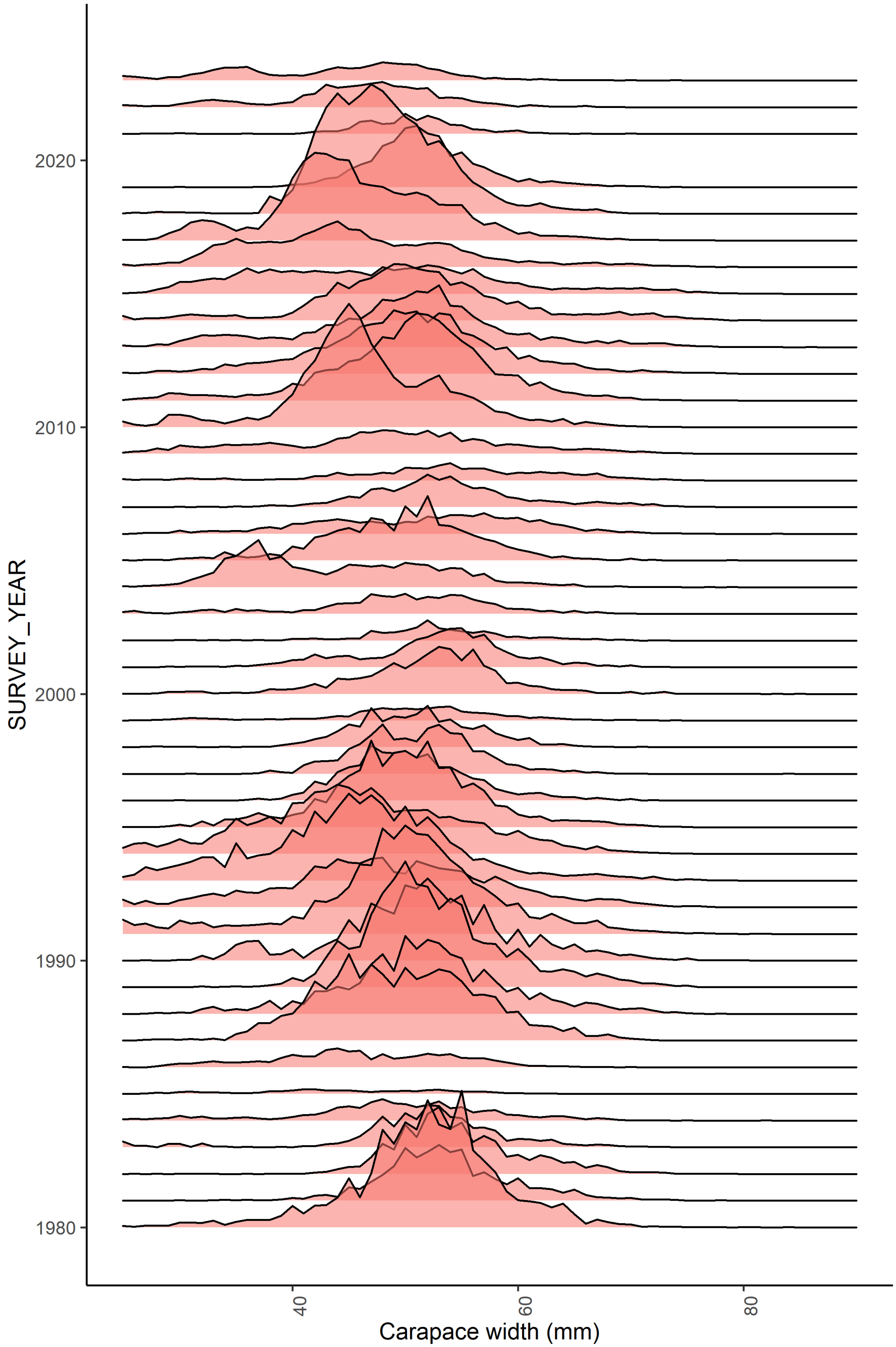


Figure 14: Raw total numbers at size of female crab observed in the survey.

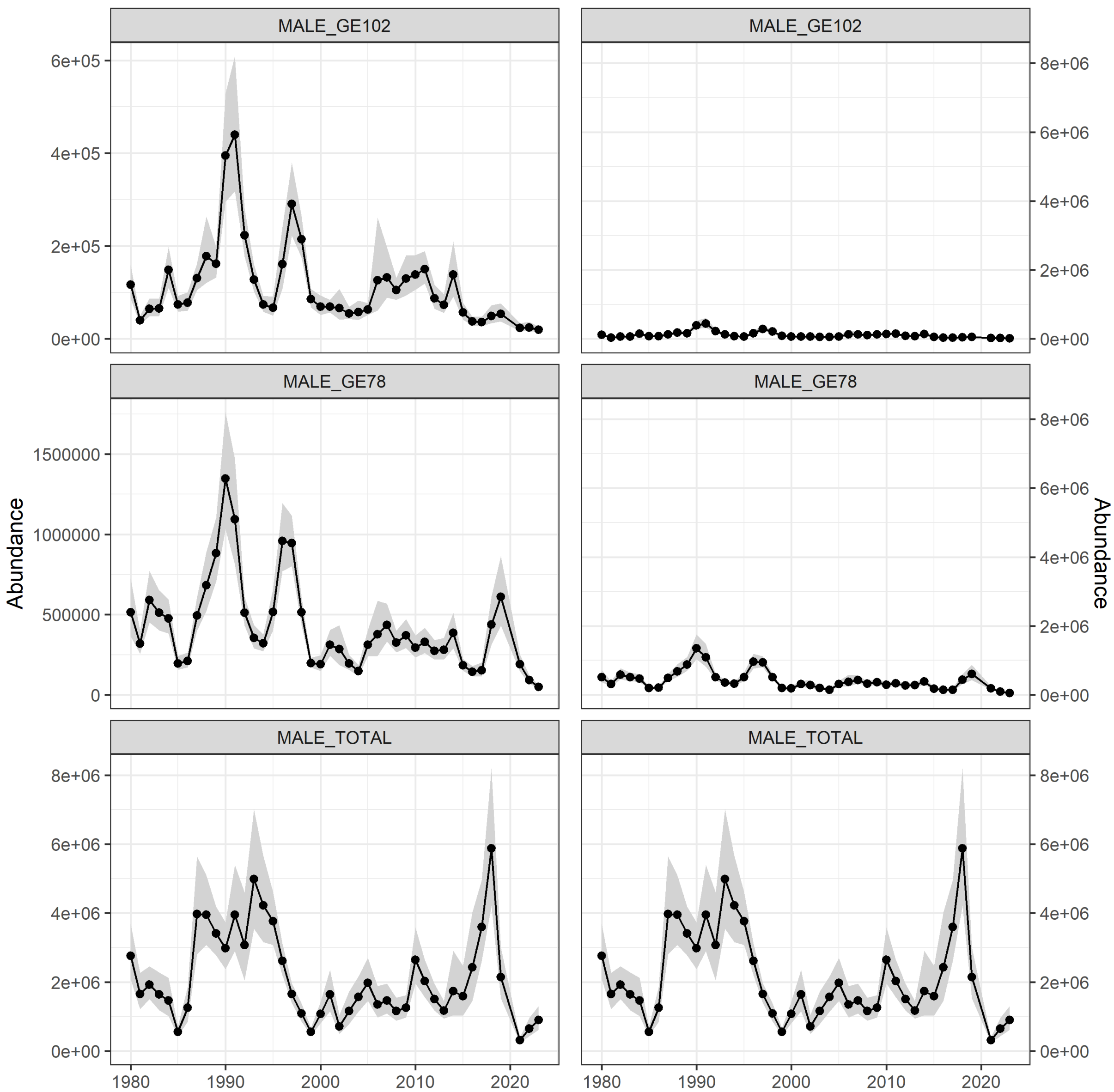


Figure 15: Abundance of males estimated from the NMFS summer survey over time for different size classes. GE102 means greater than or equal to 102 mm carapace width. Grey shading is 95th percent confidence interval. Left side allows for free y-axis; right side retains a common y-axis.

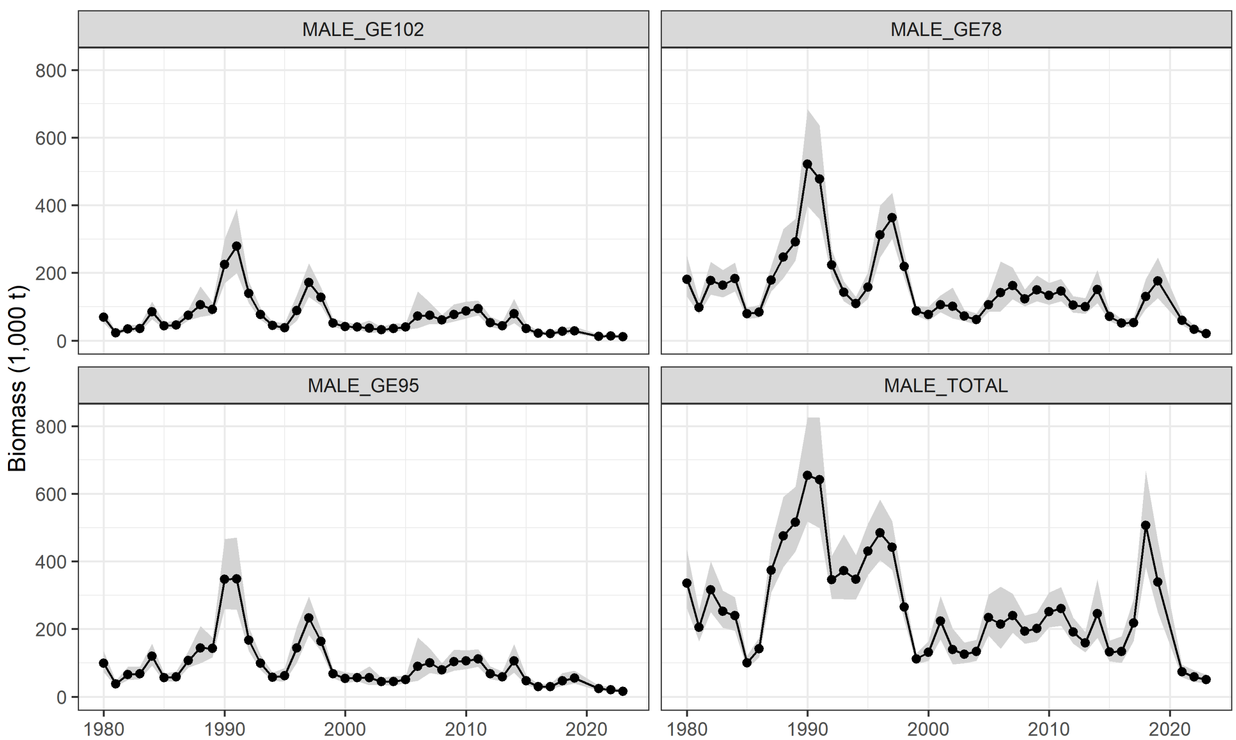


Figure 16: Biomass of males estimated from the NMFS summer survey over time for commercially relevant size classes. GE102 means greater than or equal to 102 mm carapace width. Grey shading is 95th percent confidence interval. Grey shading is 95th percent confidence interval.

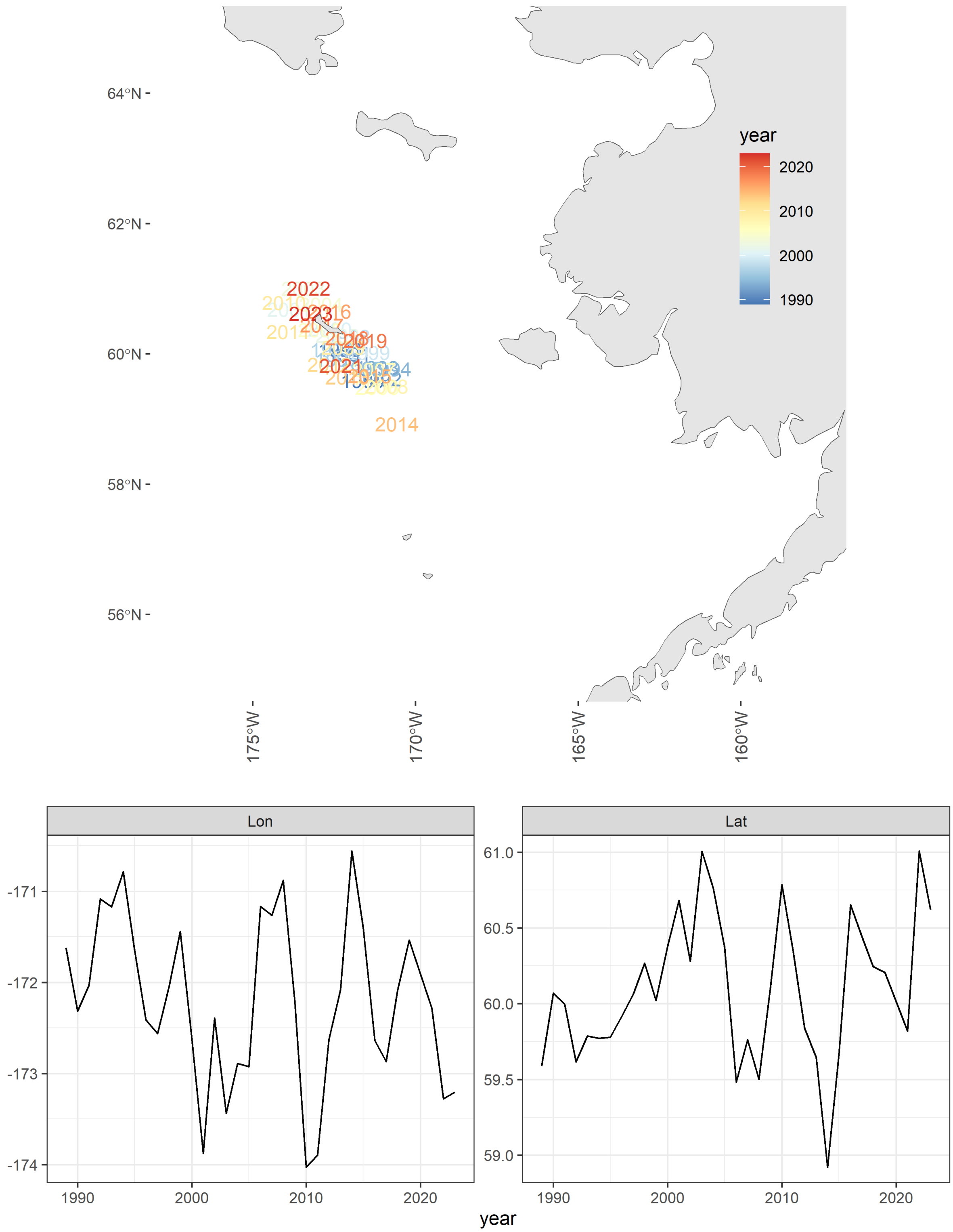


Figure 17: Centroids of abundance for males 45-85 mm carapace width. Map shows the centroid in space by year; blue colors are farther in the past. Bottom figures isolate the latidudinal and longitudinal components.

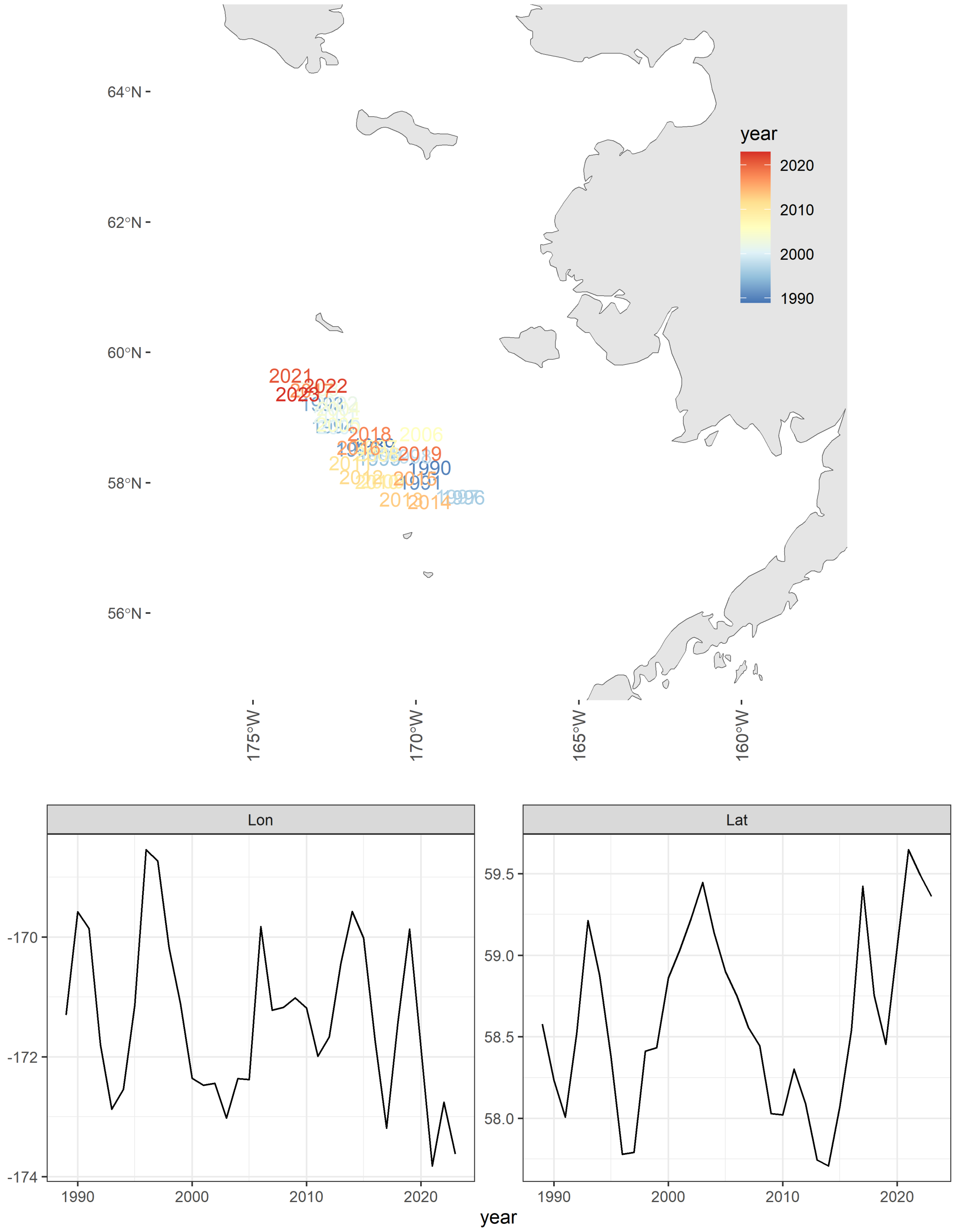


Figure 18: Centroids of abundance for males greater than 101 mm carapace width. Map shows the centroid in space by year; blue colors are farther in the past. Bottom figures isolate the latidudinal and longitudinal components.

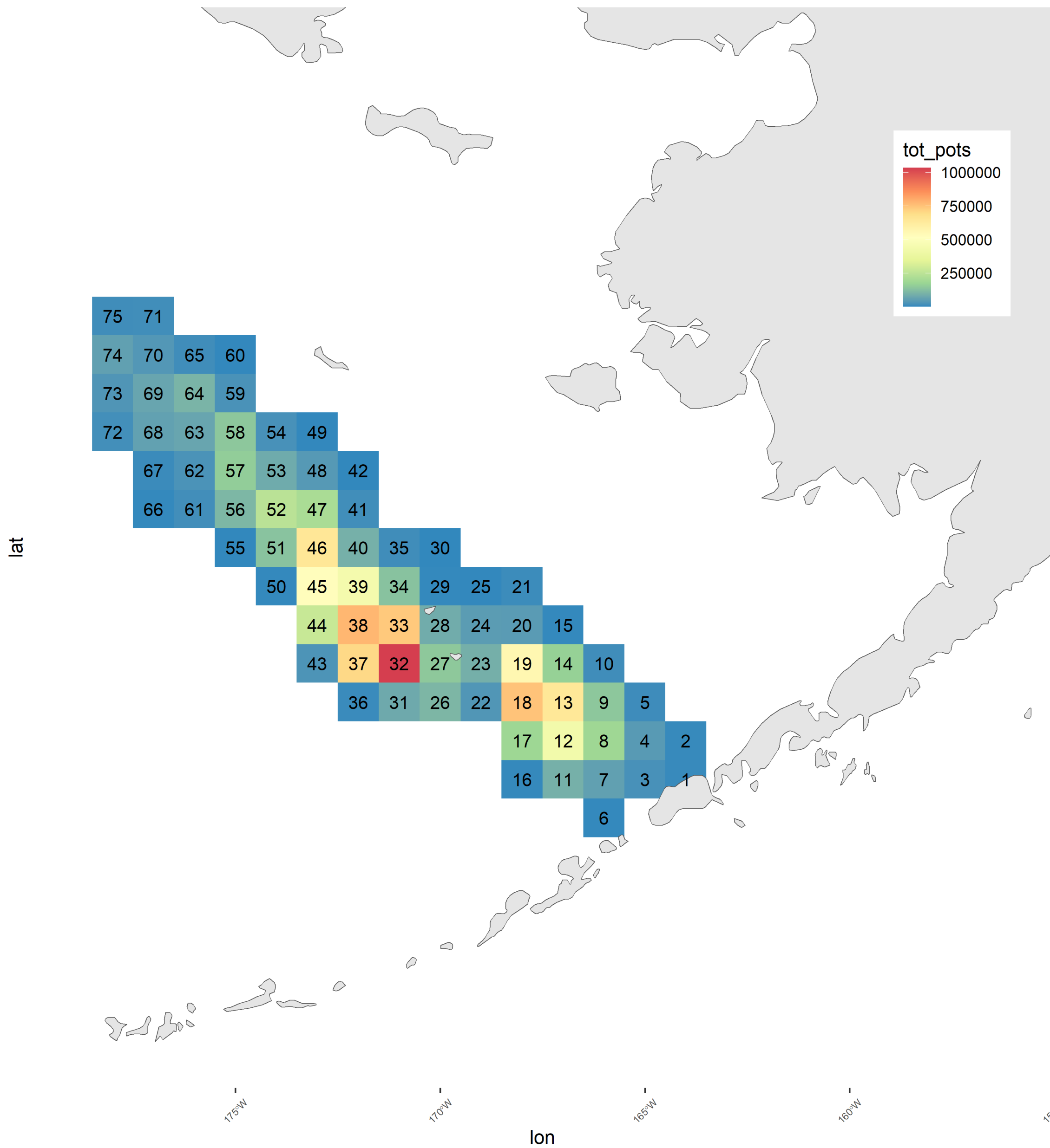


Figure 19: Distribution of effort in terms of potlifts in the directed fishery on the Bering Sea shelf summed from 1990-present. Squares are statistical areas defined by the state. Numbers are generated to give context to the following figures. Only data in areas that had three or more fishers and processors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

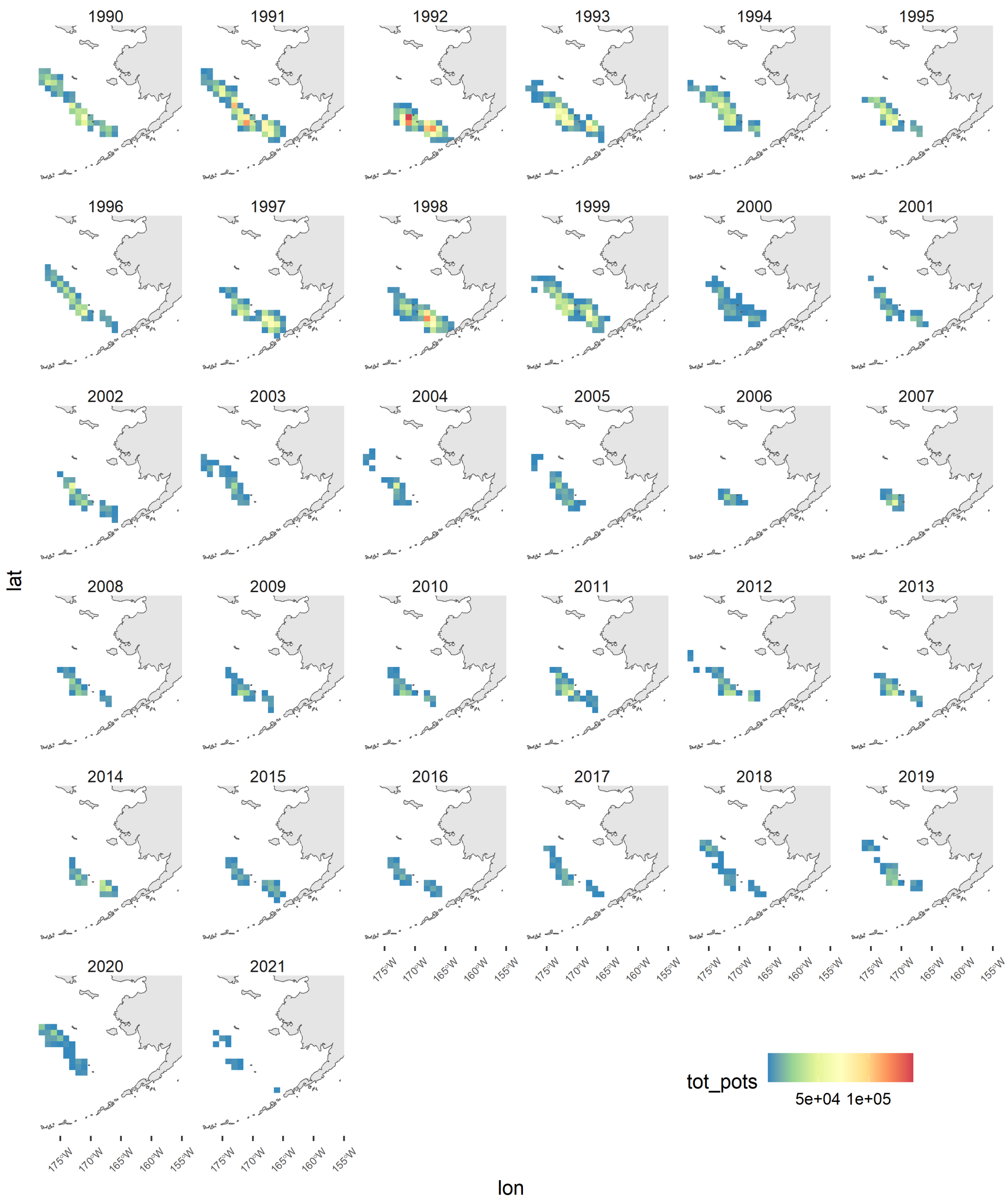


Figure 20: Yearly distribution of effort in terms of potlifts in the directed fishery on the Bering Sea shelf displayed from 1990-present.

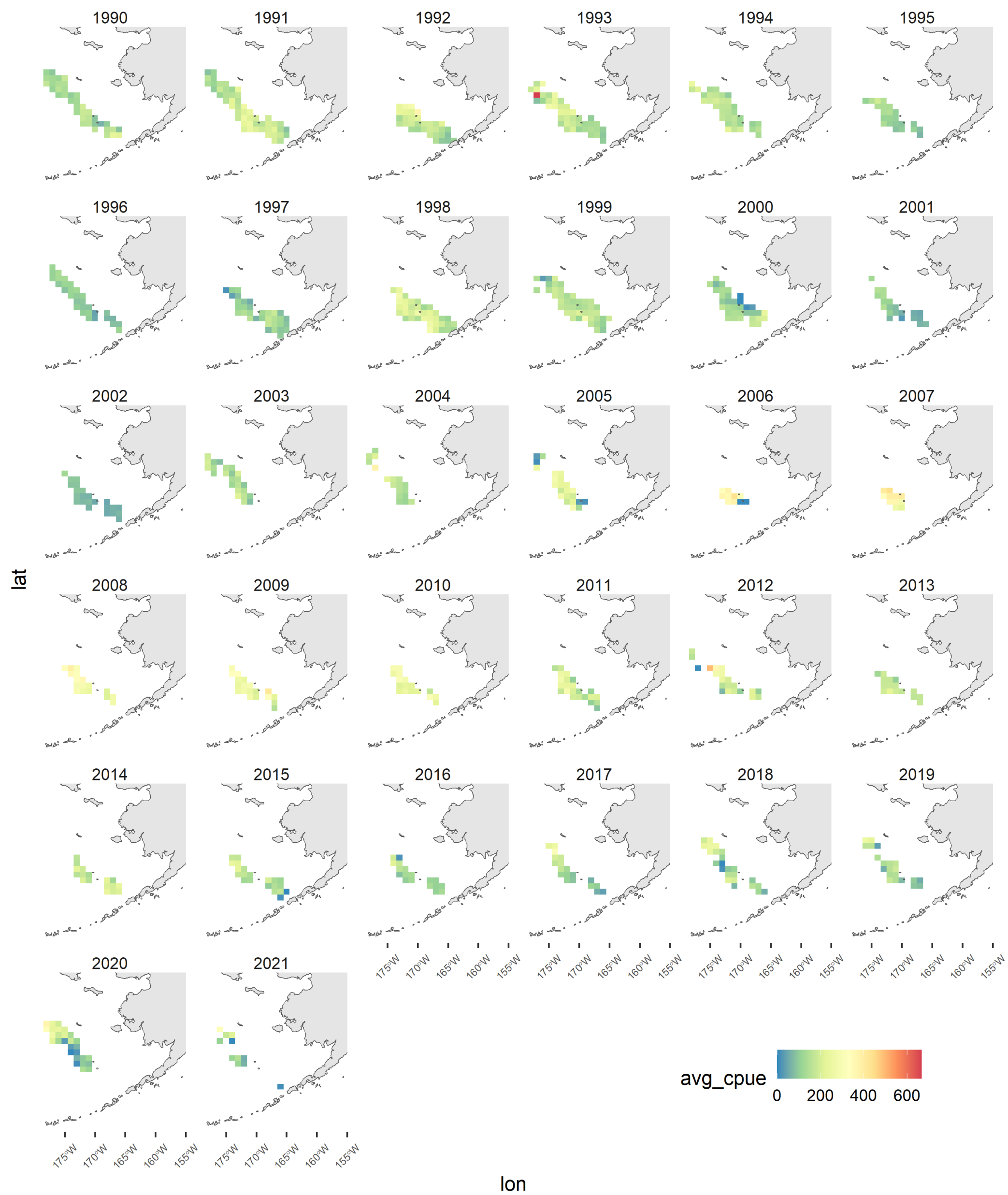


Figure 21: Yearly distribution of catch per unit effort across from 1990-present

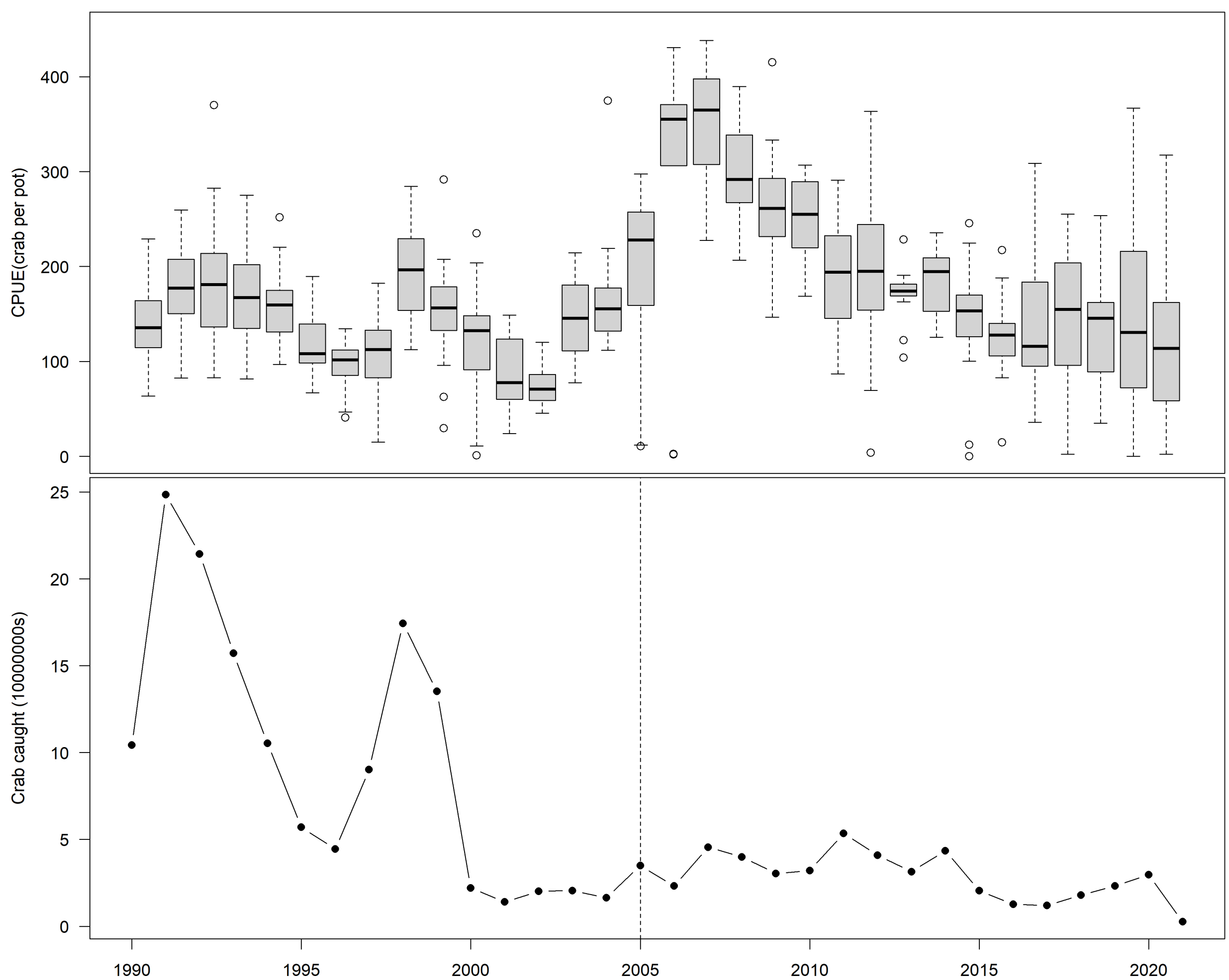


Figure 22: Catch per unit effort in the snow crab fleet (top) and total crab caught (bottom), courtesy of Ben Daly.

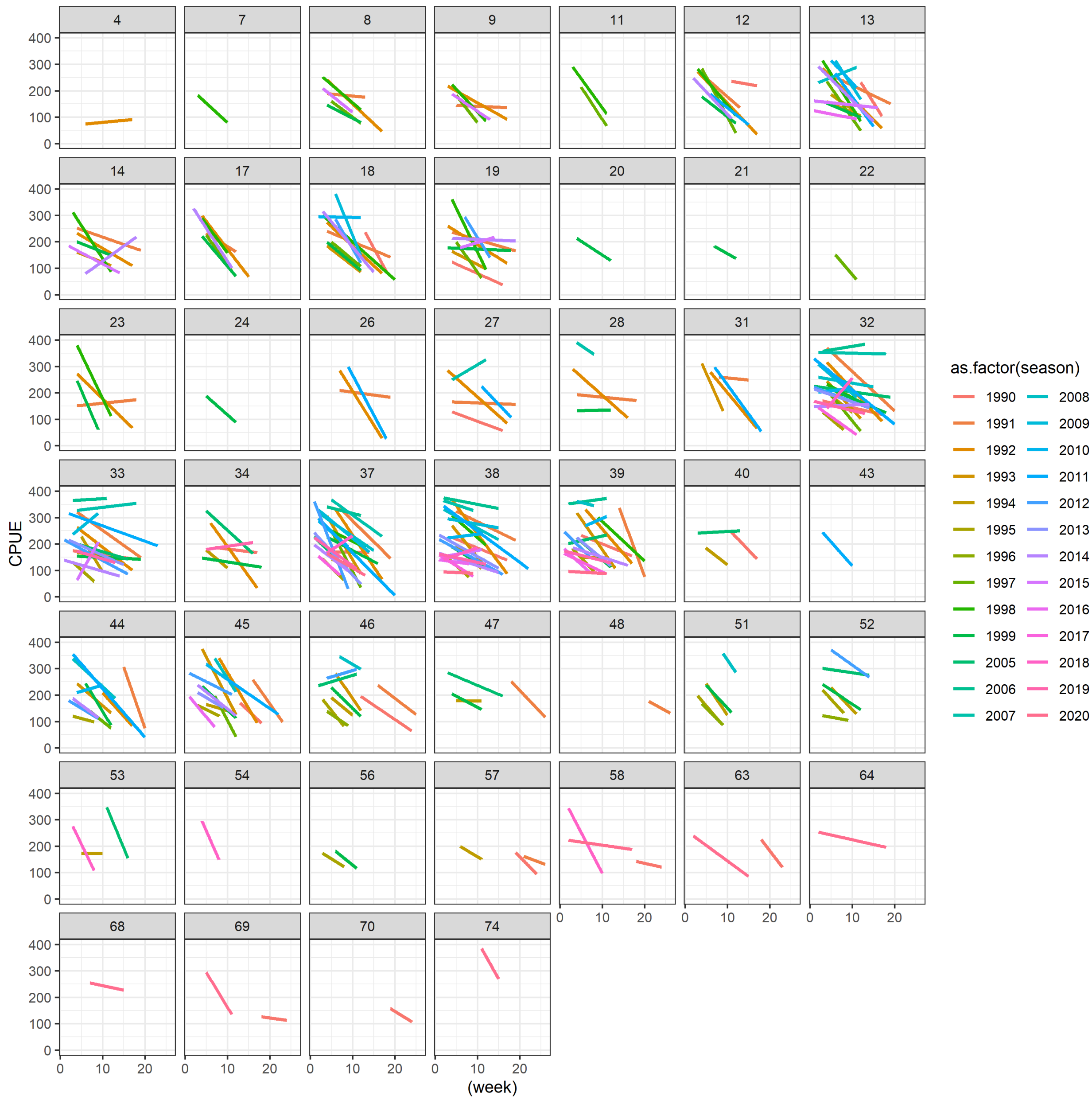


Figure 23: Trends in CPUE by statistical area. Each line is produced from a linear model fit through observed CPUE in a given area in a given year. Trends were only fit if the data represented in an area came included 3 or more fishers and processors and only if there were at least 5 weeks of CPUE data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

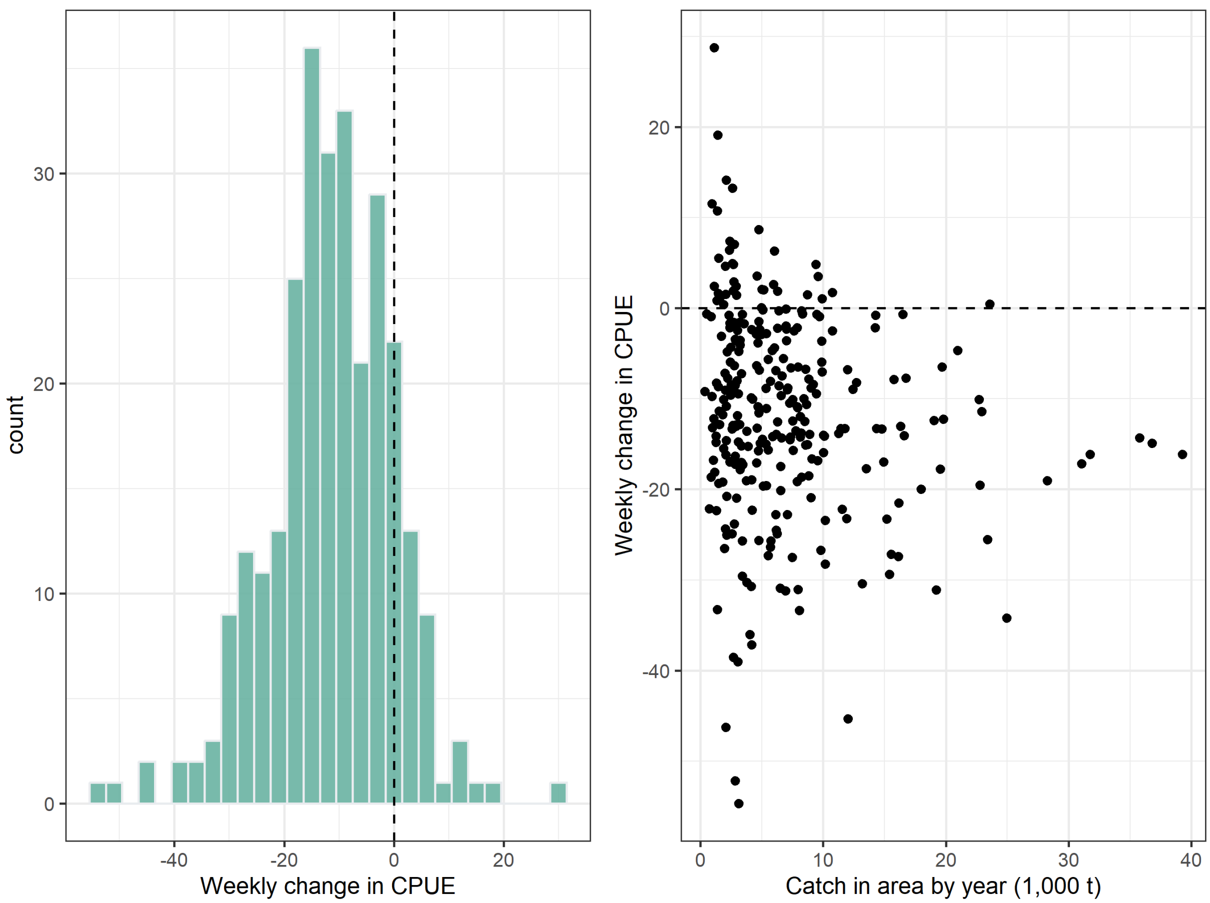


Figure 24: Distribution of the slopes of trends in inseason cpue by spatial area shown in previous figure. Slopes plotted against the catches removed in a given season and area.

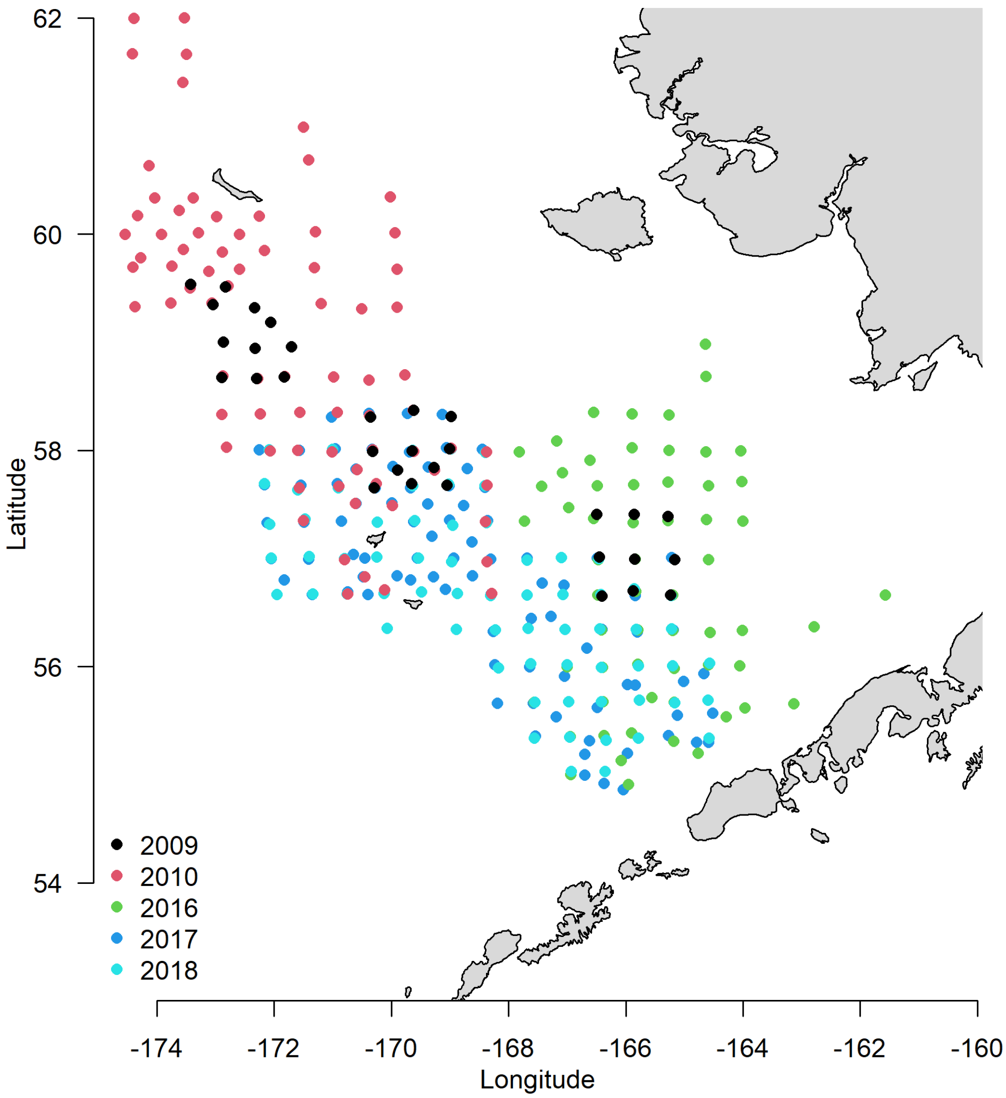


Figure 25: Location of BSFRF survey selectivity experiments that provided data used in this assessment over time.

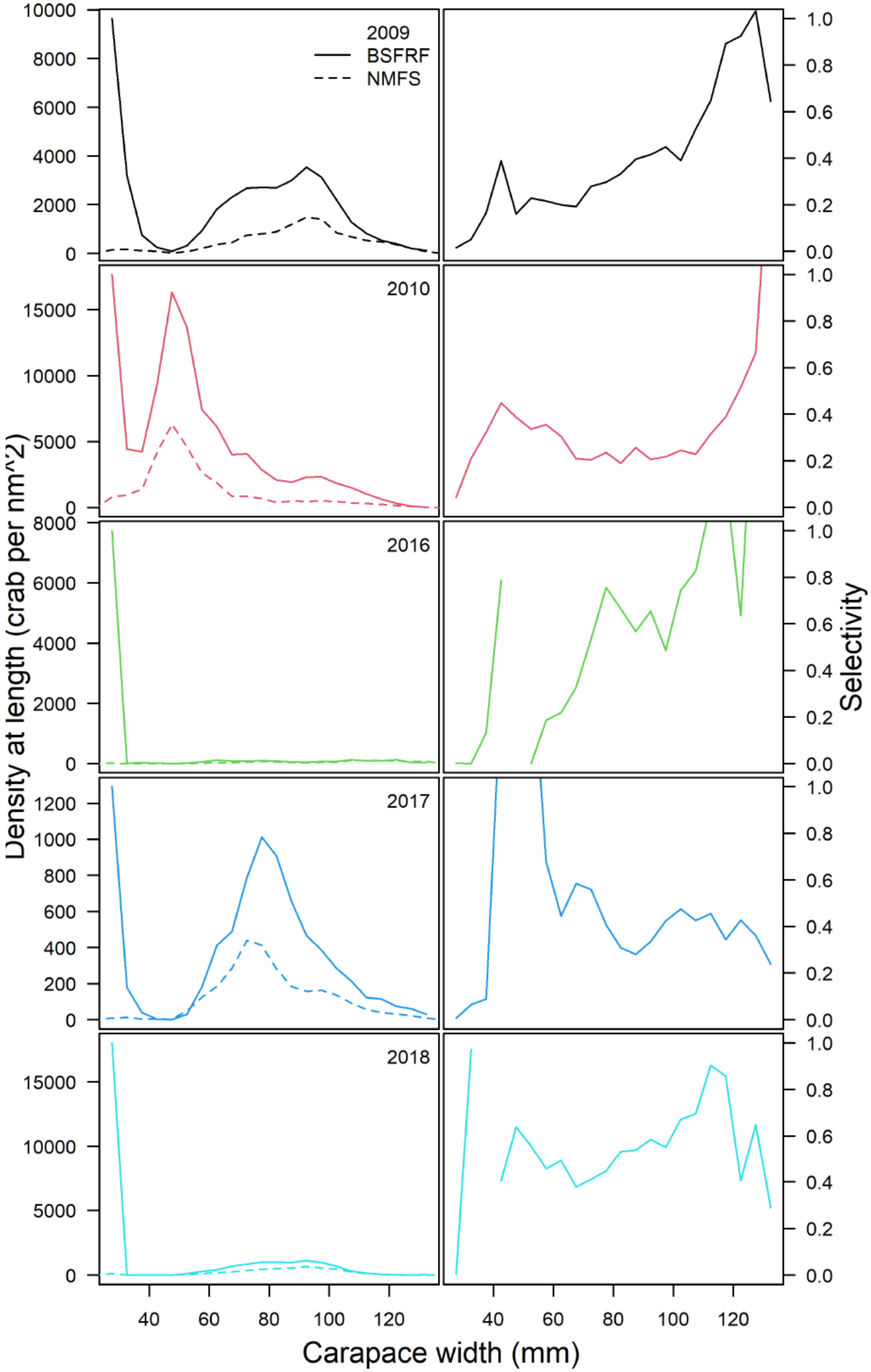


Figure 26: Observed numbers at length extrapolated from length composition data and estimates of total numbers within the survey selectivity experimental areas by year (left). Inferred selectivity (i.e. the ratio of crab at length in the NMFS gear to crab at length in the BSFRF gear.

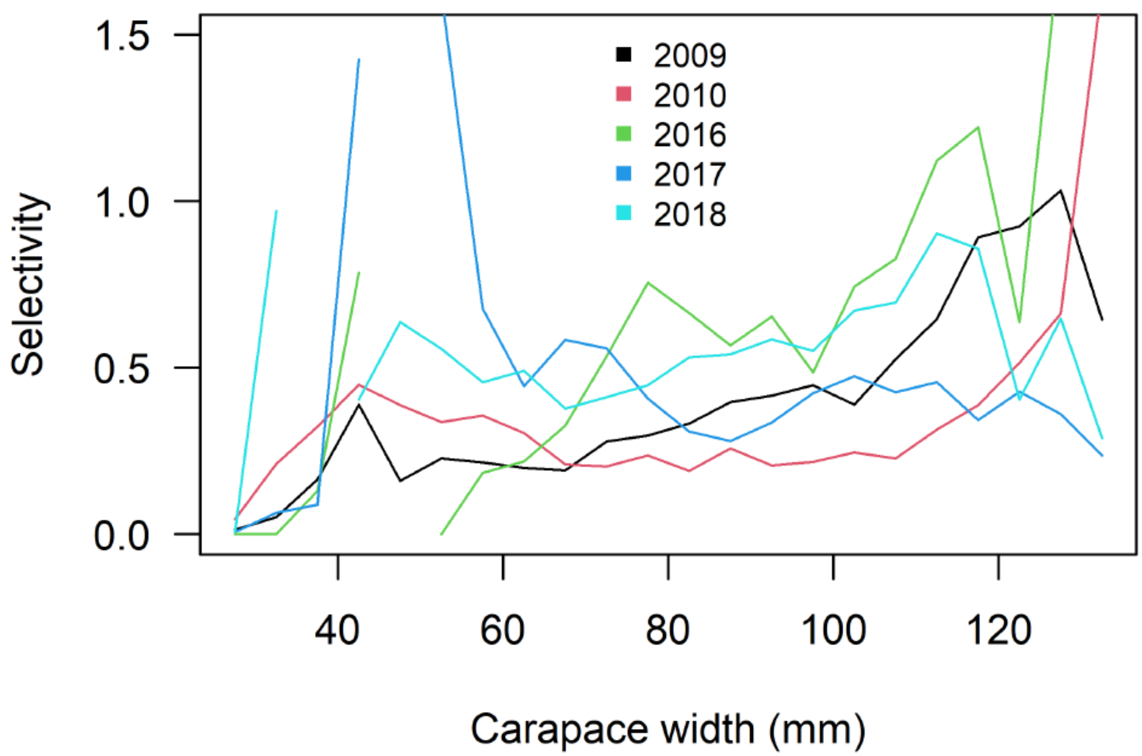


Figure 27: Inferred selectivity for all available years of BSFRF data.

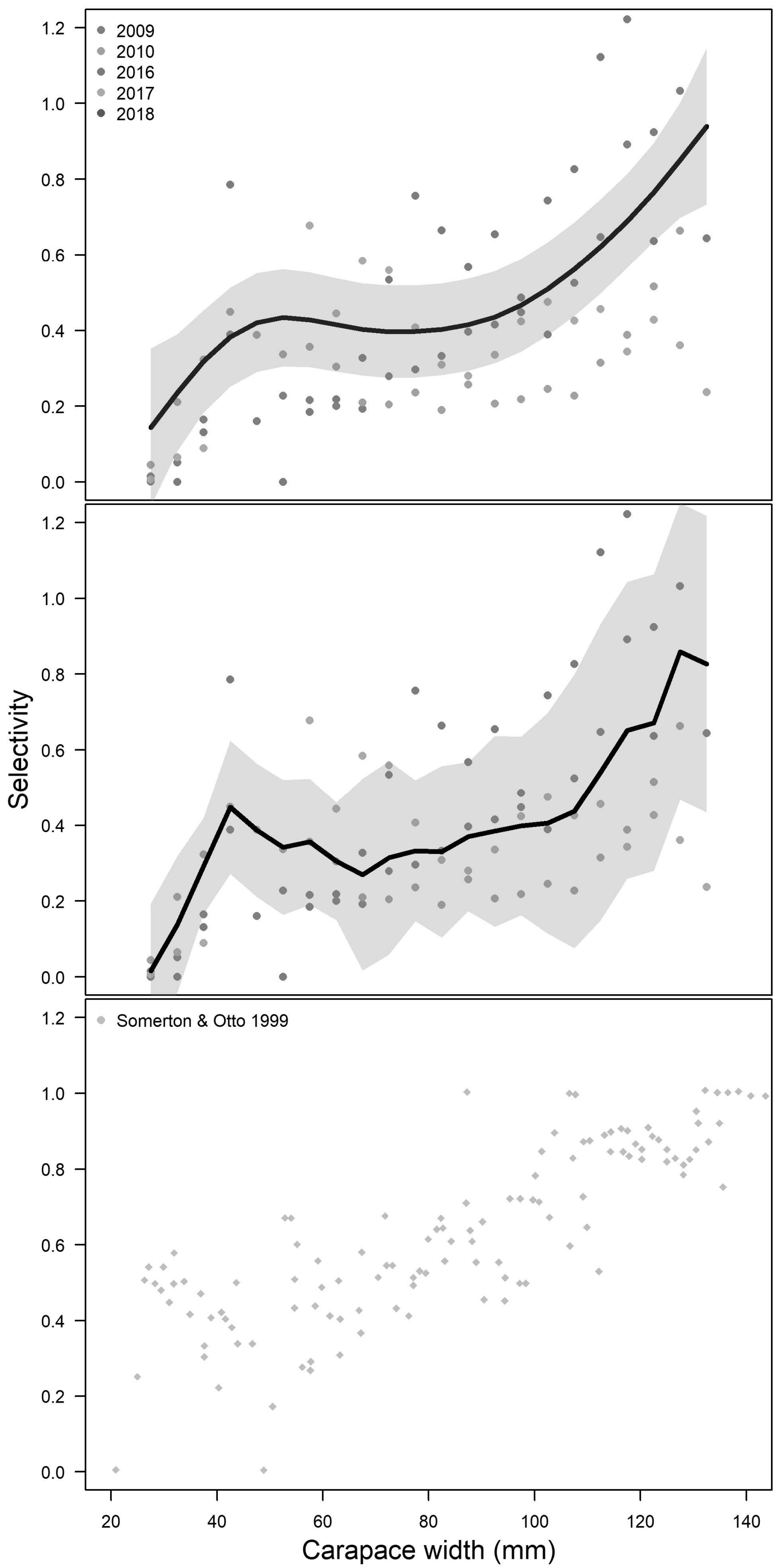


Figure 28: Inferred selectivity from BSFRF experiments with selectivity at size class estimated by generalized additive model (top). Inferred selectivity from BSFRF experiments with selectivity at size class estimated by sample size-weighted means and variances (middle). Somerton and Otto (1998) underbag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

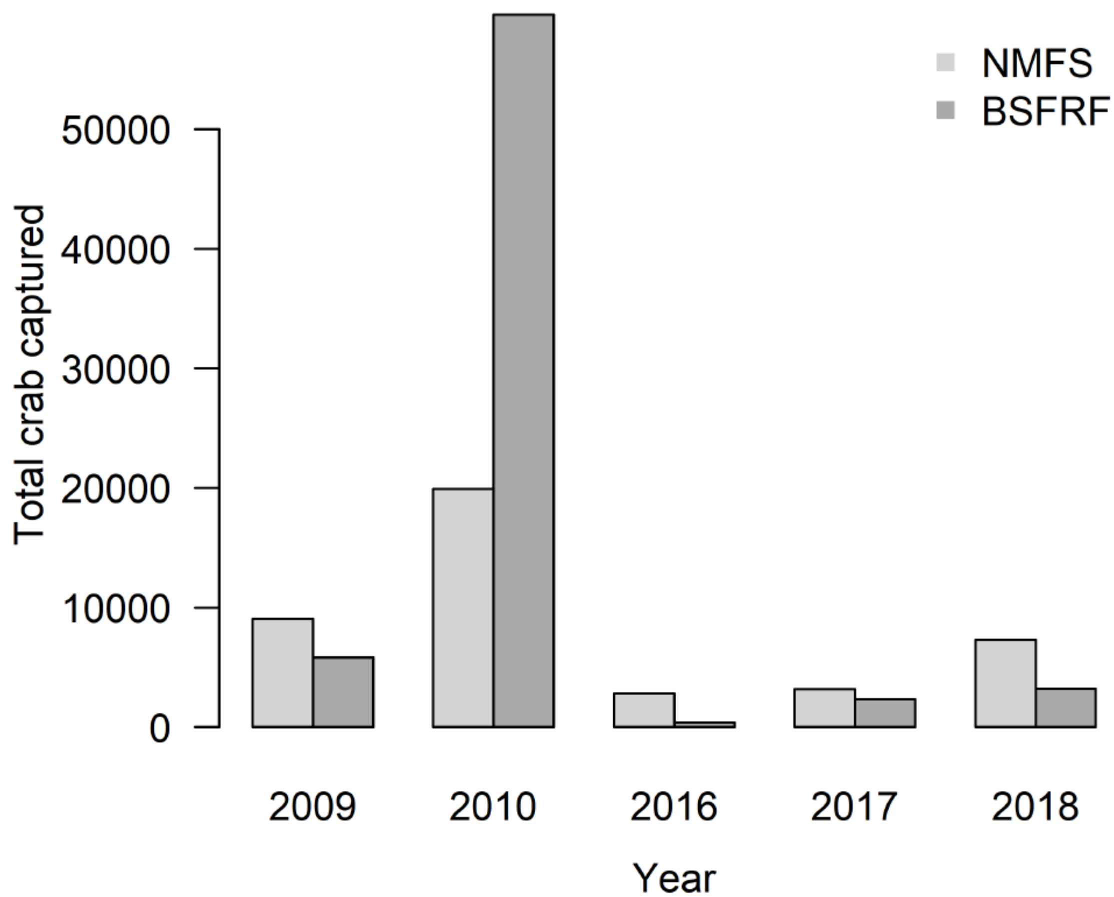


Figure 29: Number of crab collected in the BSFRF experimental areas by the NMFS survey and the BSFRF survey.

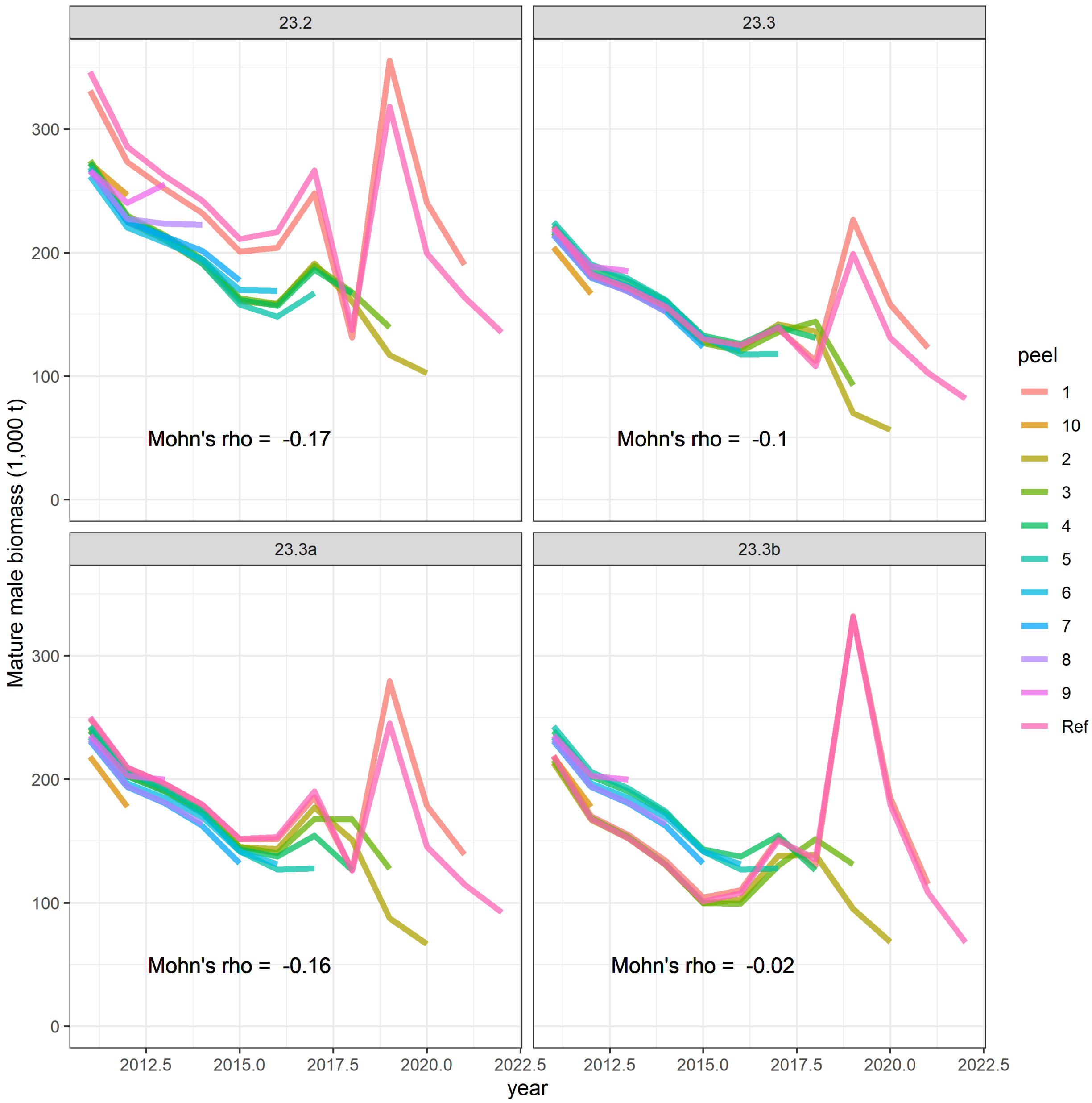


Figure 30: Retrospective patterns in estimated mature male biomass for selected models.

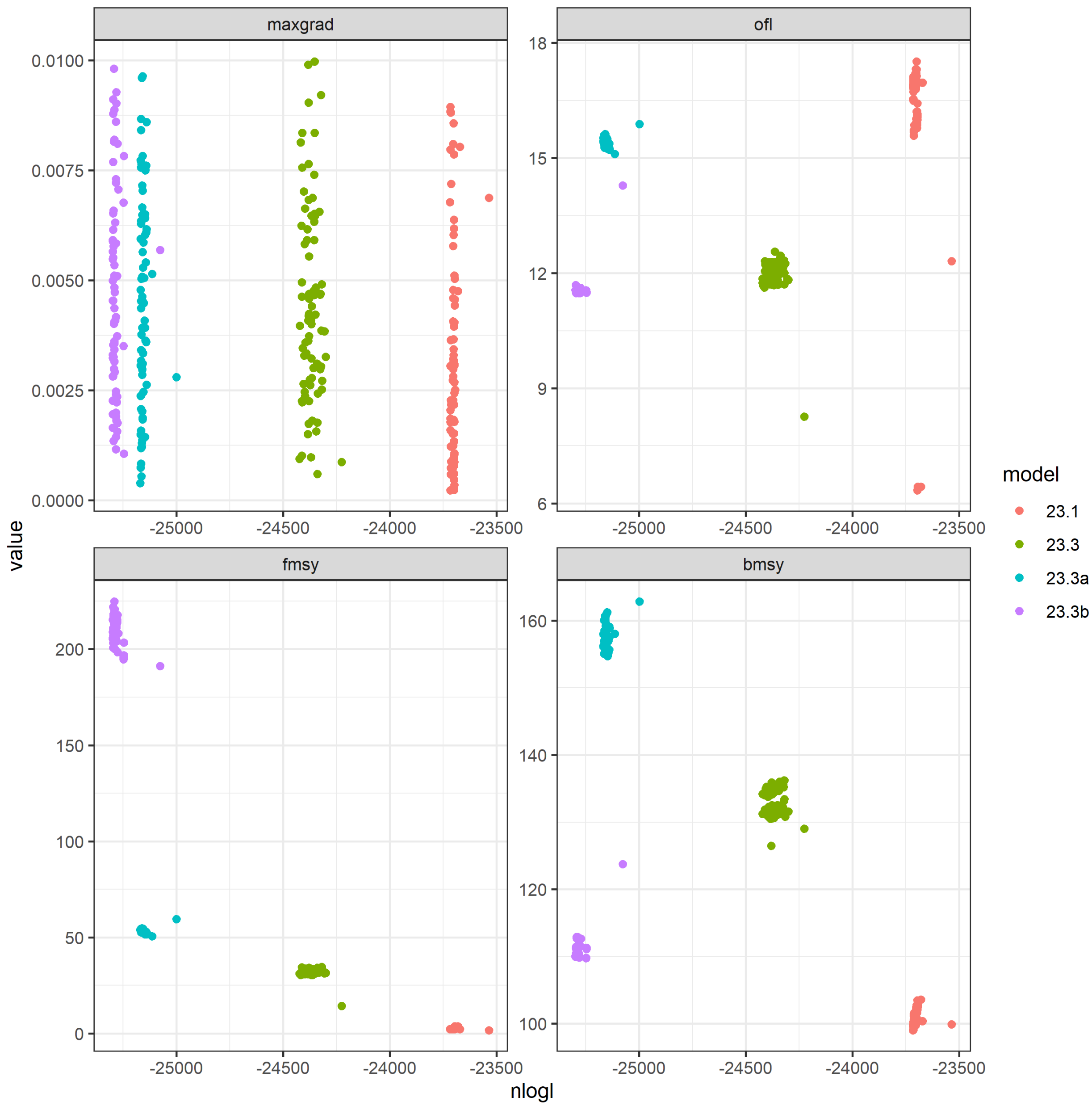


Figure 31: Output of 100 jittered model fittings for selected models. Top left is the maximum gradient component, top right is the overfishing level, bottom left is F35, and bottom right is B35. Each dot represent an instance of a jittered fitted model and are colored based on the OFL resulting from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

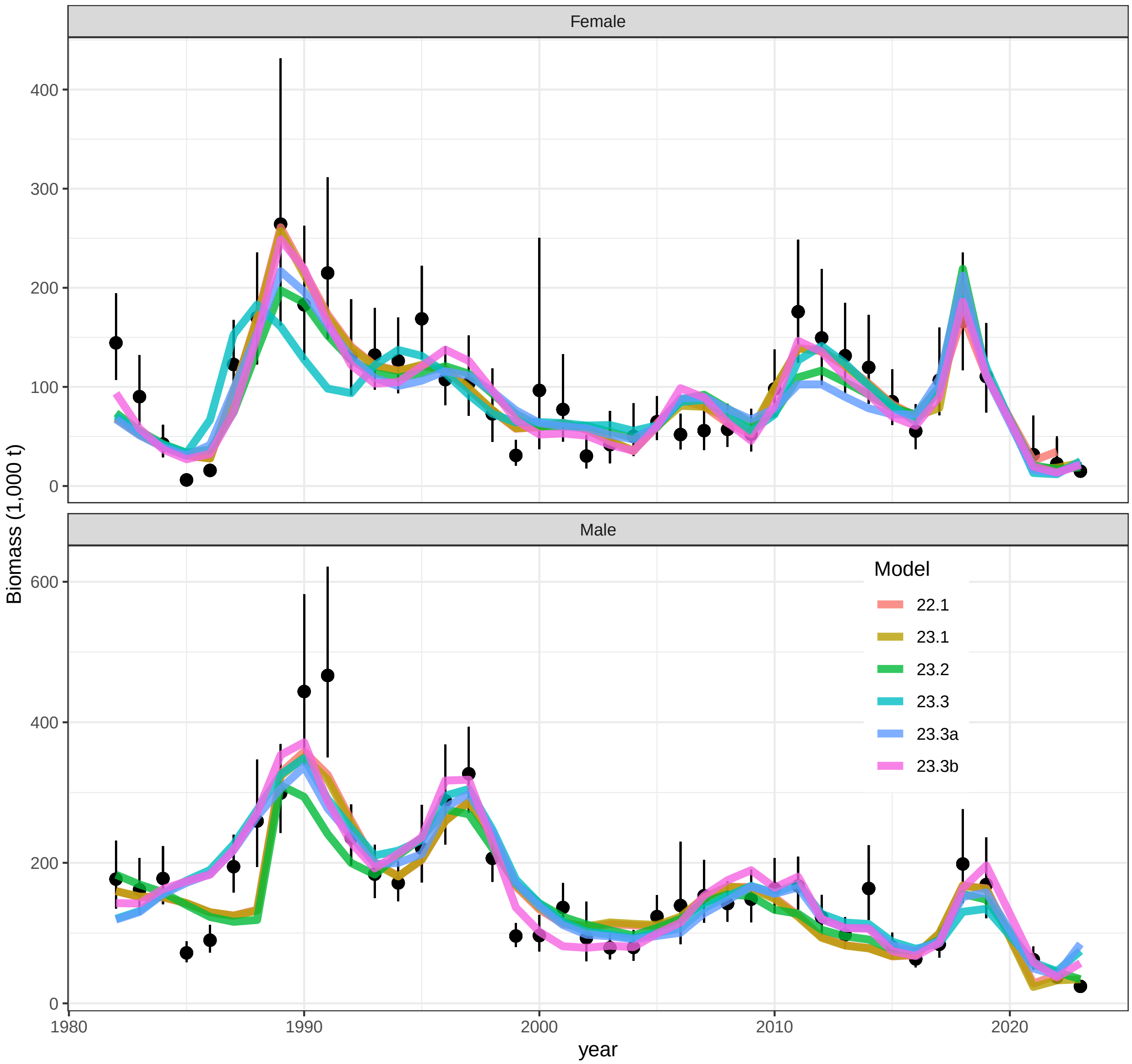


Figure 32: Model fits to the observed mature biomass at survey.

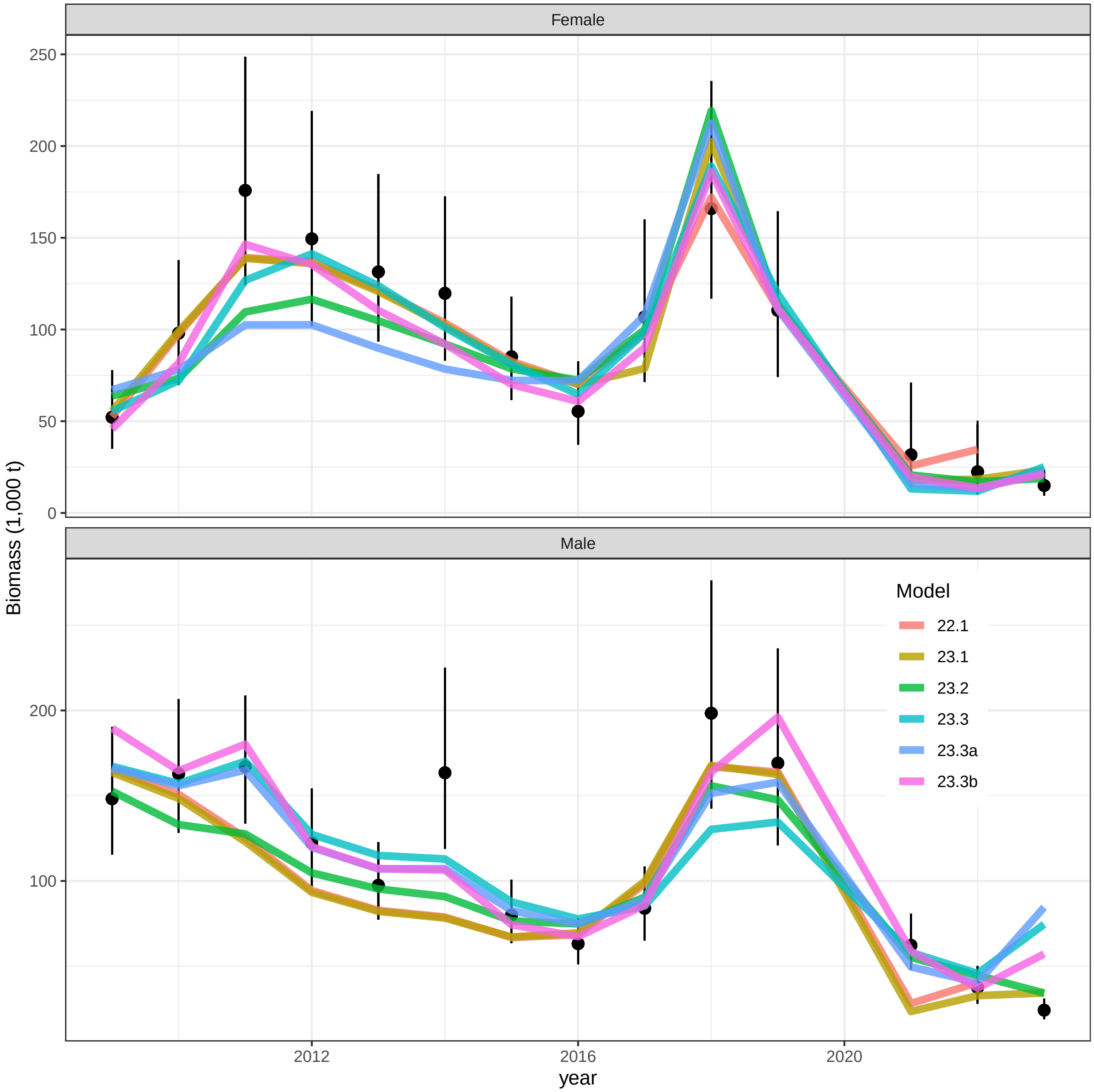


Figure 33: Model fits to the observed mature biomass at survey 2009-present

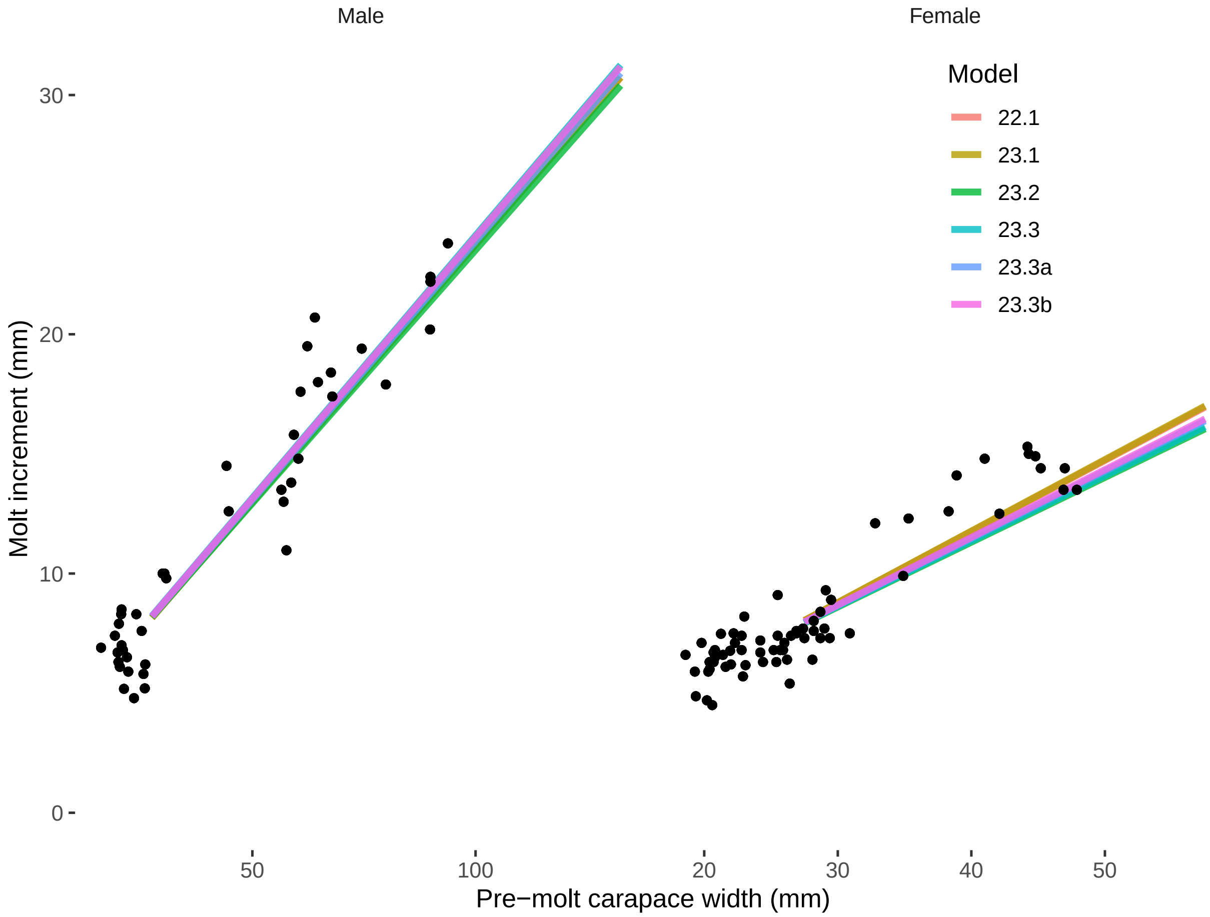


Figure 34: Model fits (colored lines) to the growth data (black dots).

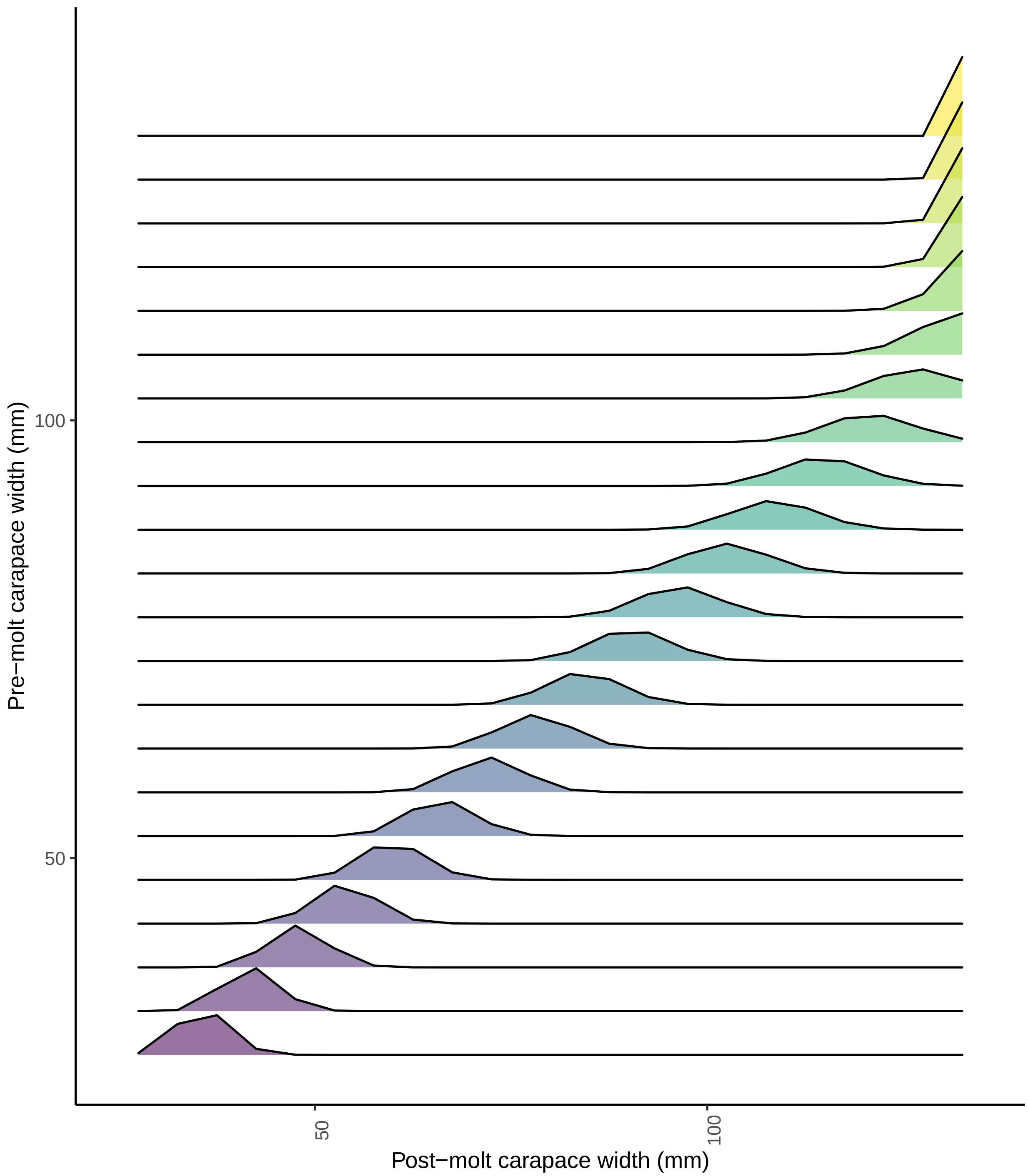


Figure 35: Size transition matrix from the author-preferred model.

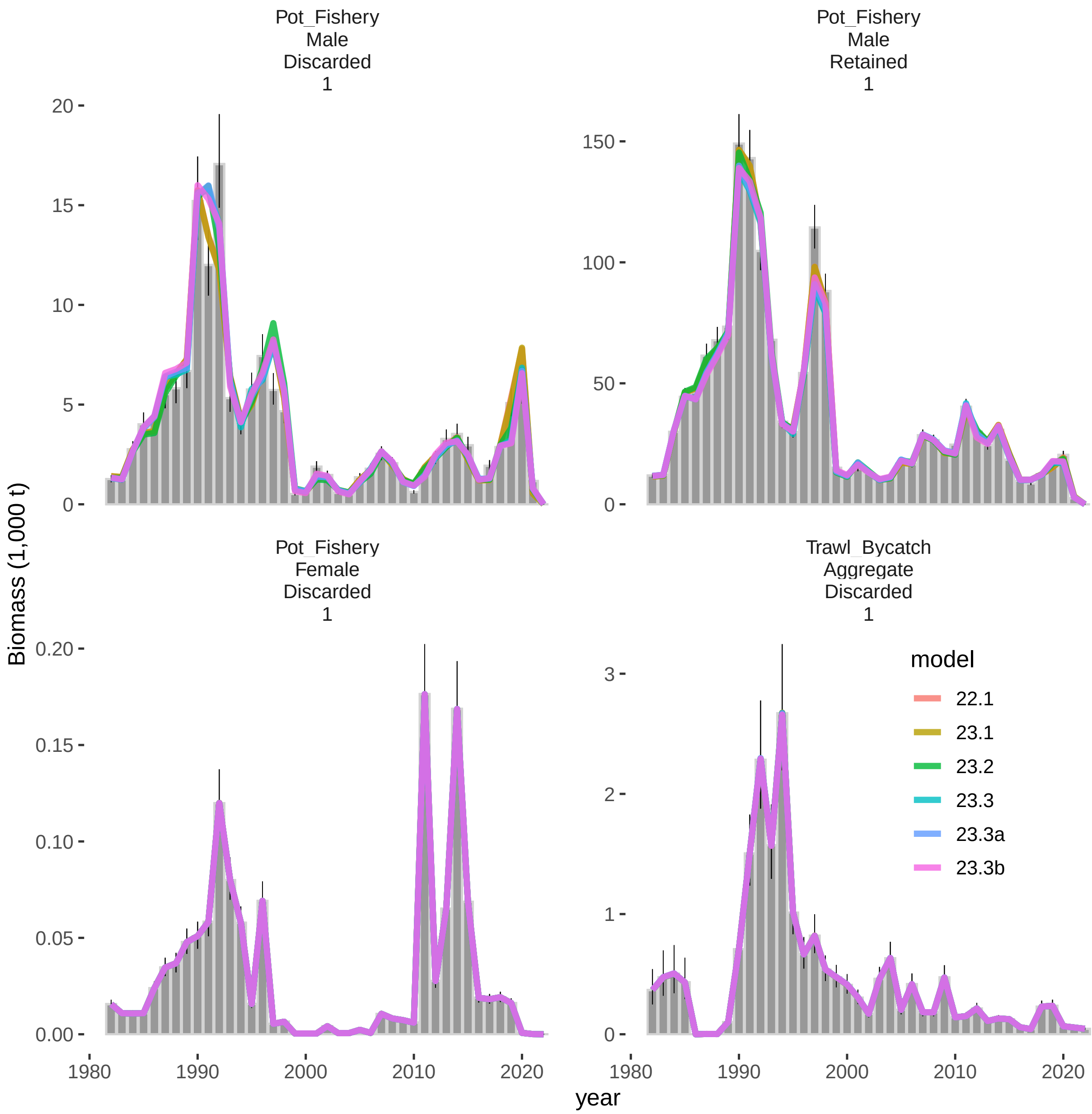


Figure 36: Model fits to catch data.

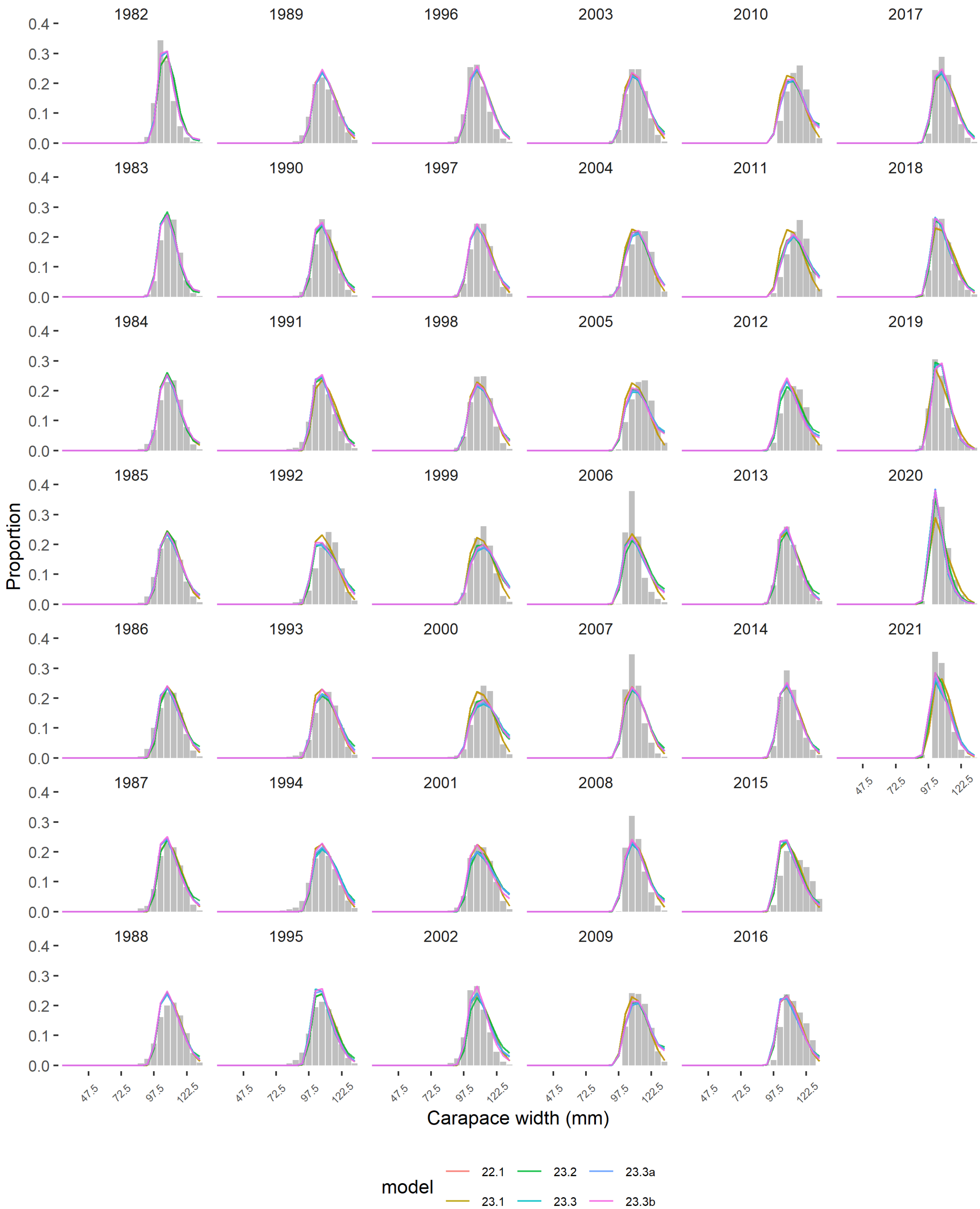


Figure 37: Model fits (lines) to the retained catch size composition data (grey bars).

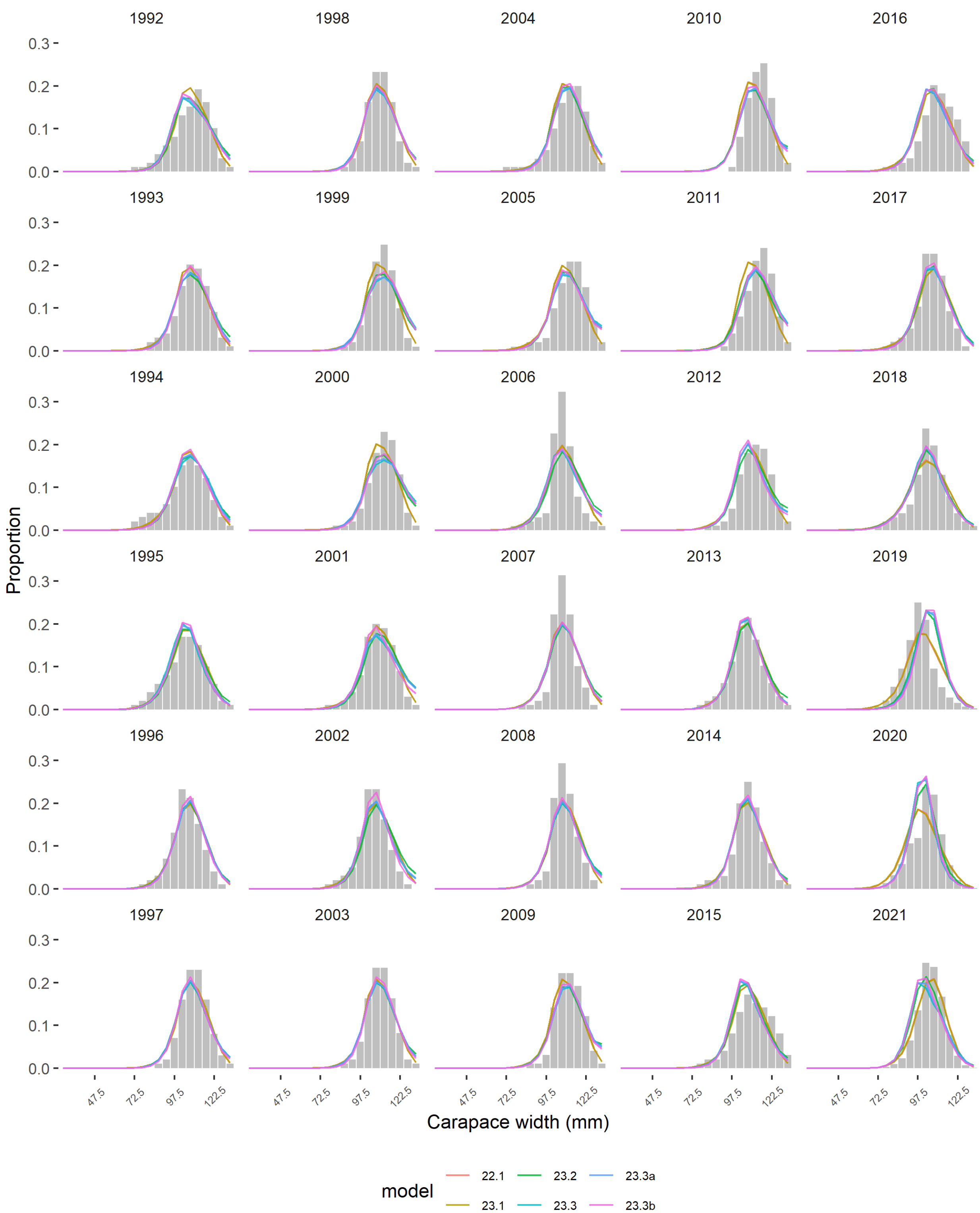


Figure 38: Model fits (lines) to the total catch size composition data (grey bars).

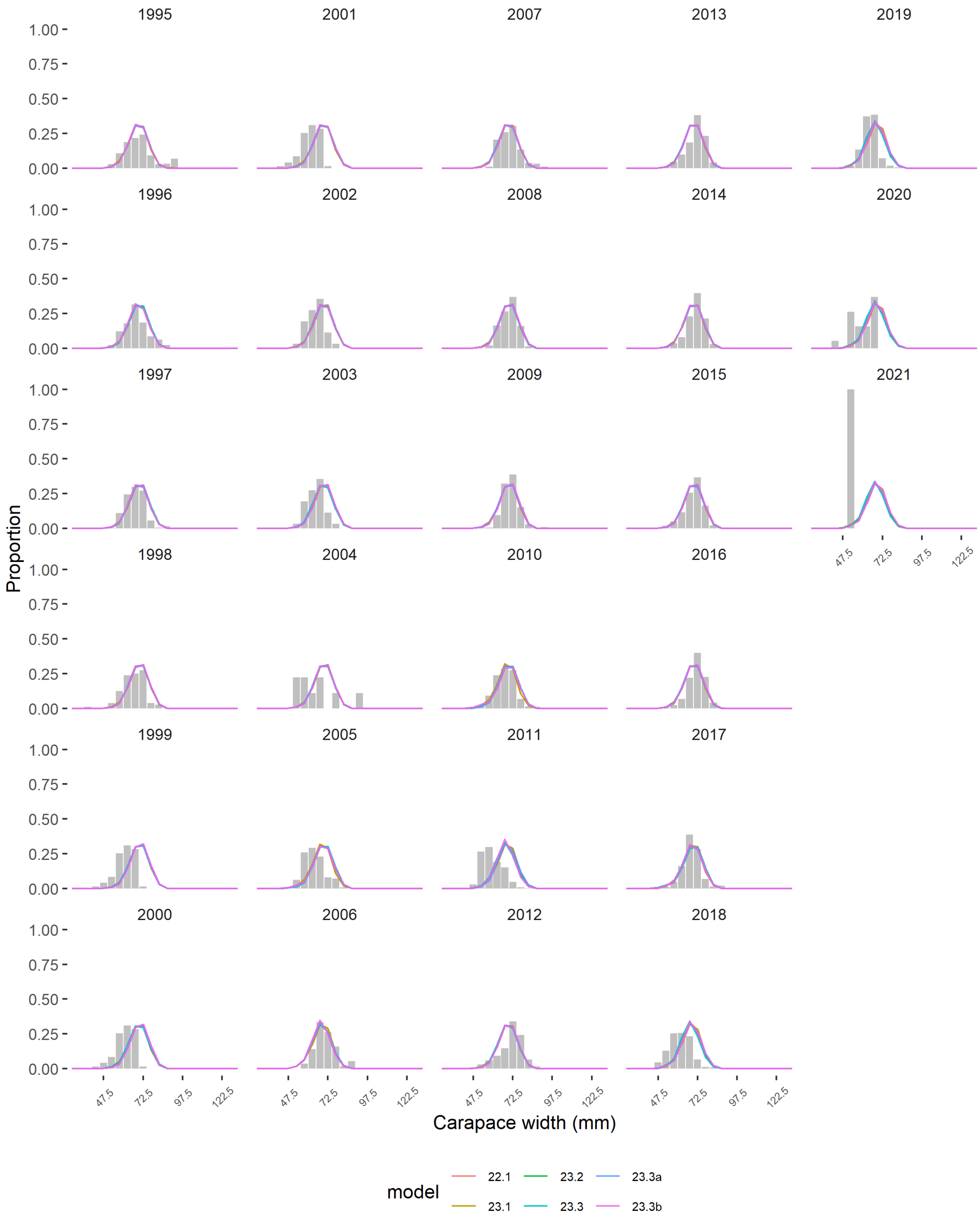


Figure 39: Model fits (lines) to the female discard size composition data (grey bars).

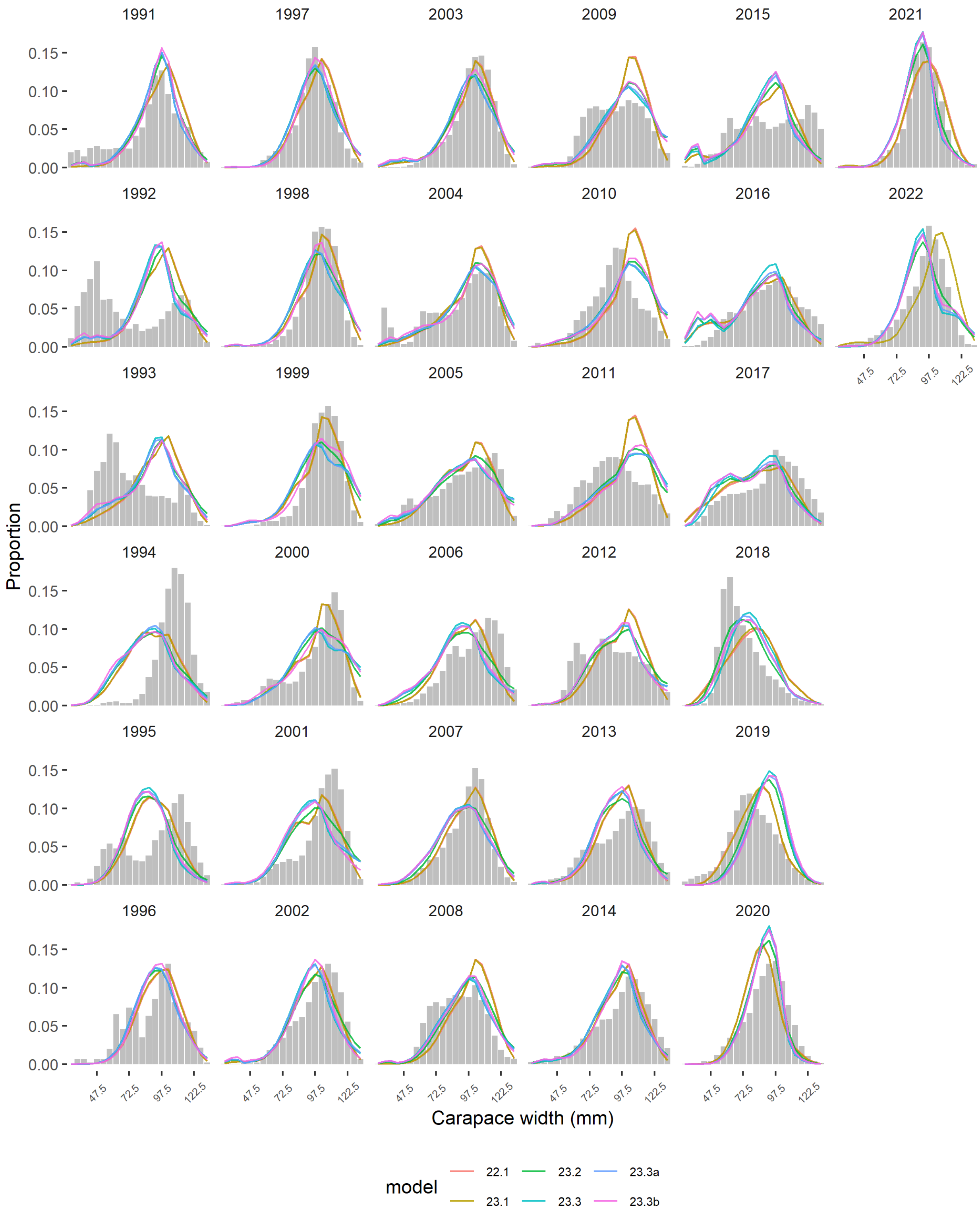


Figure 40: Model fits (lines) to the male non-directed fishery size composition data (grey bars).

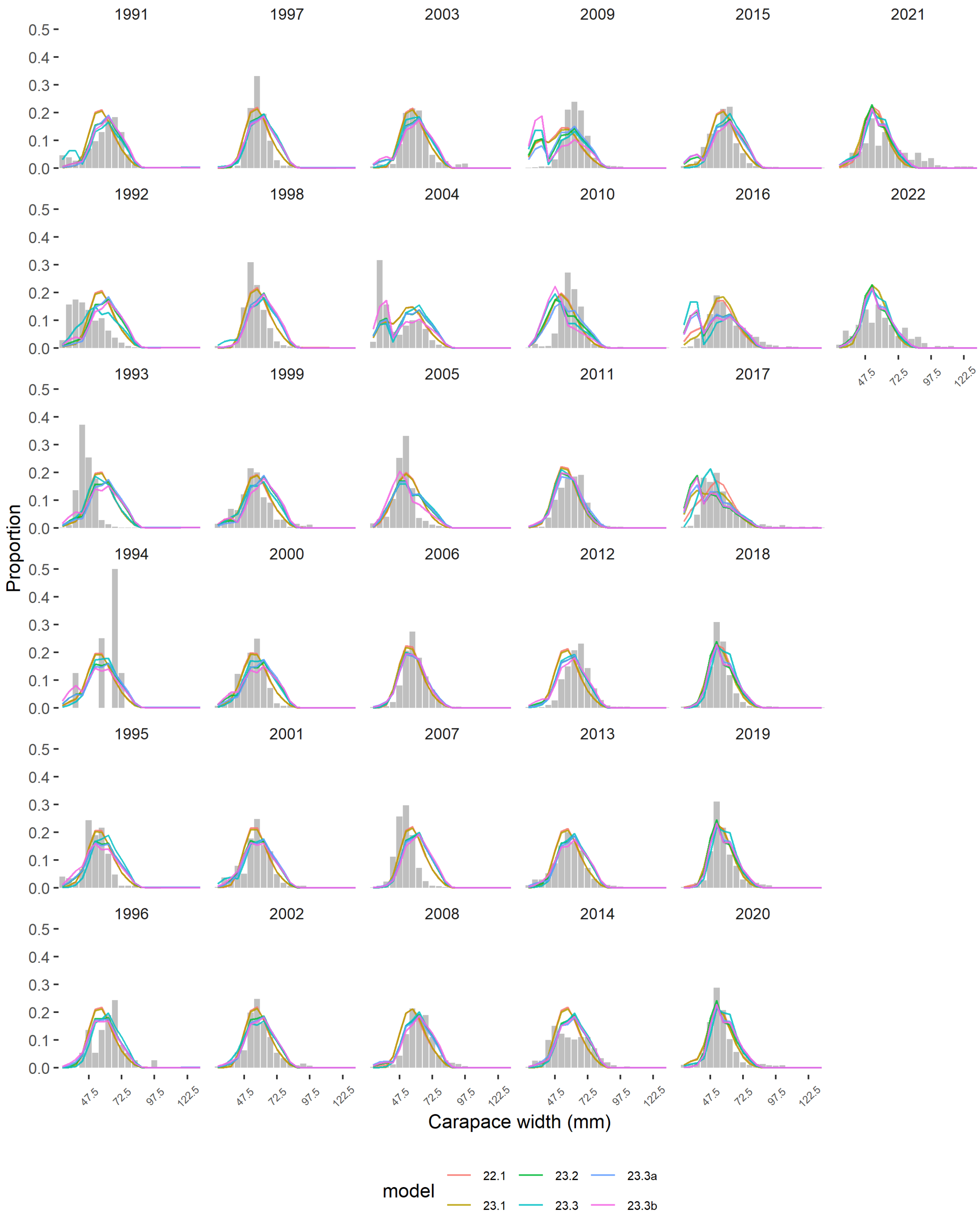


Figure 41: Model fits (lines) to the female non-directed size composition data (grey bars).

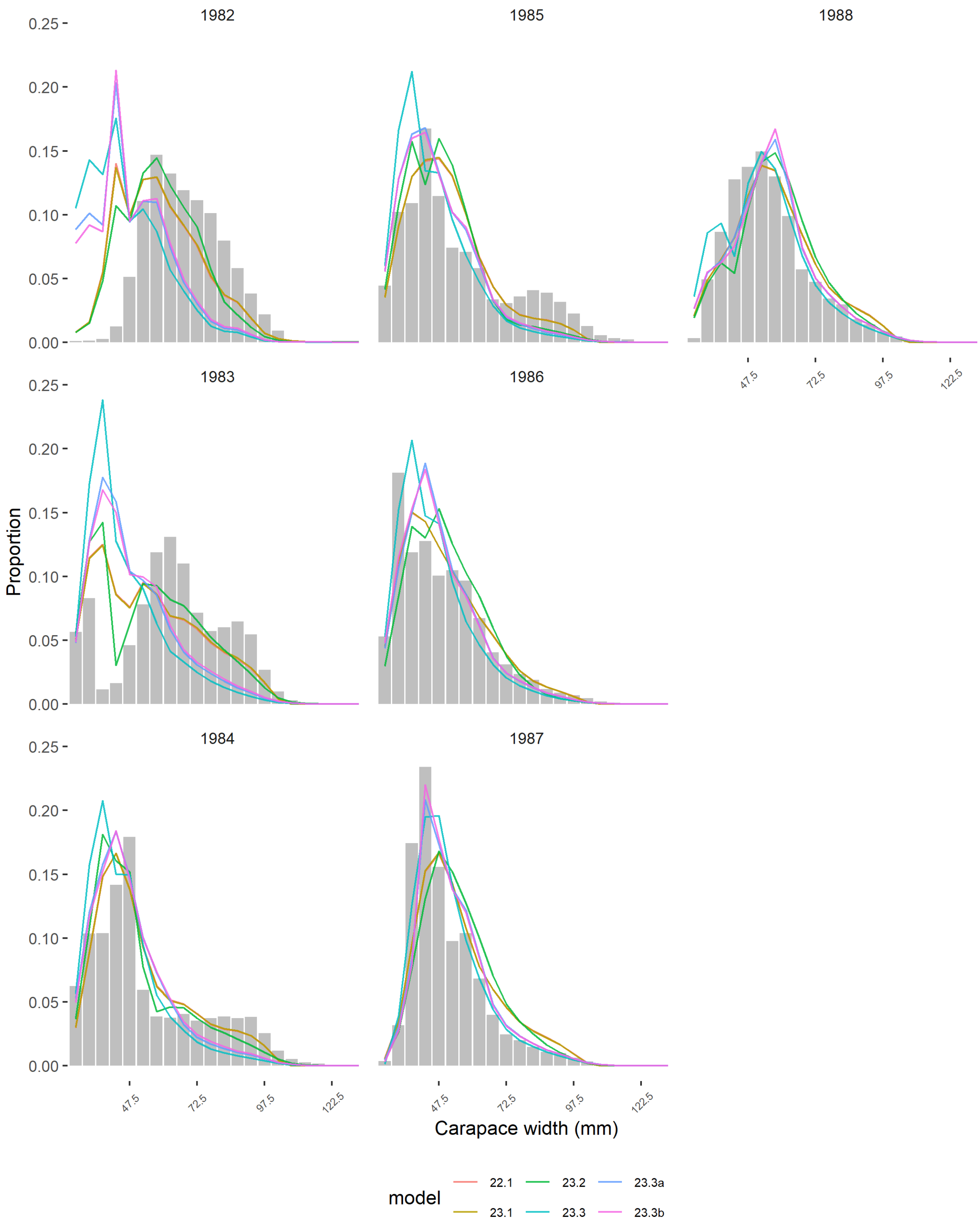


Figure 42: Model fits to immature male survey size composition data from 1982-1988.

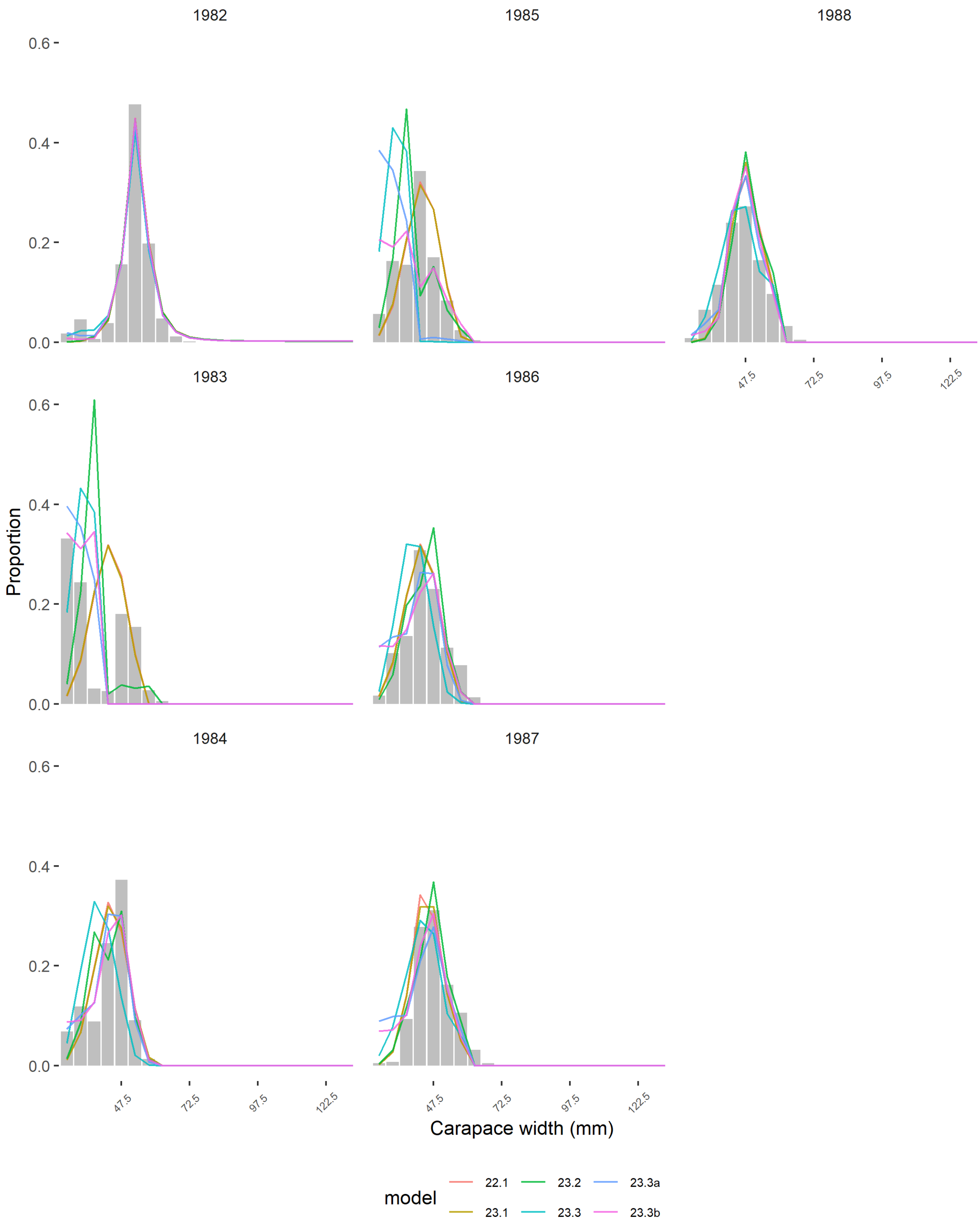


Figure 43: Model fits to immature female survey size composition data from 1982-1988.

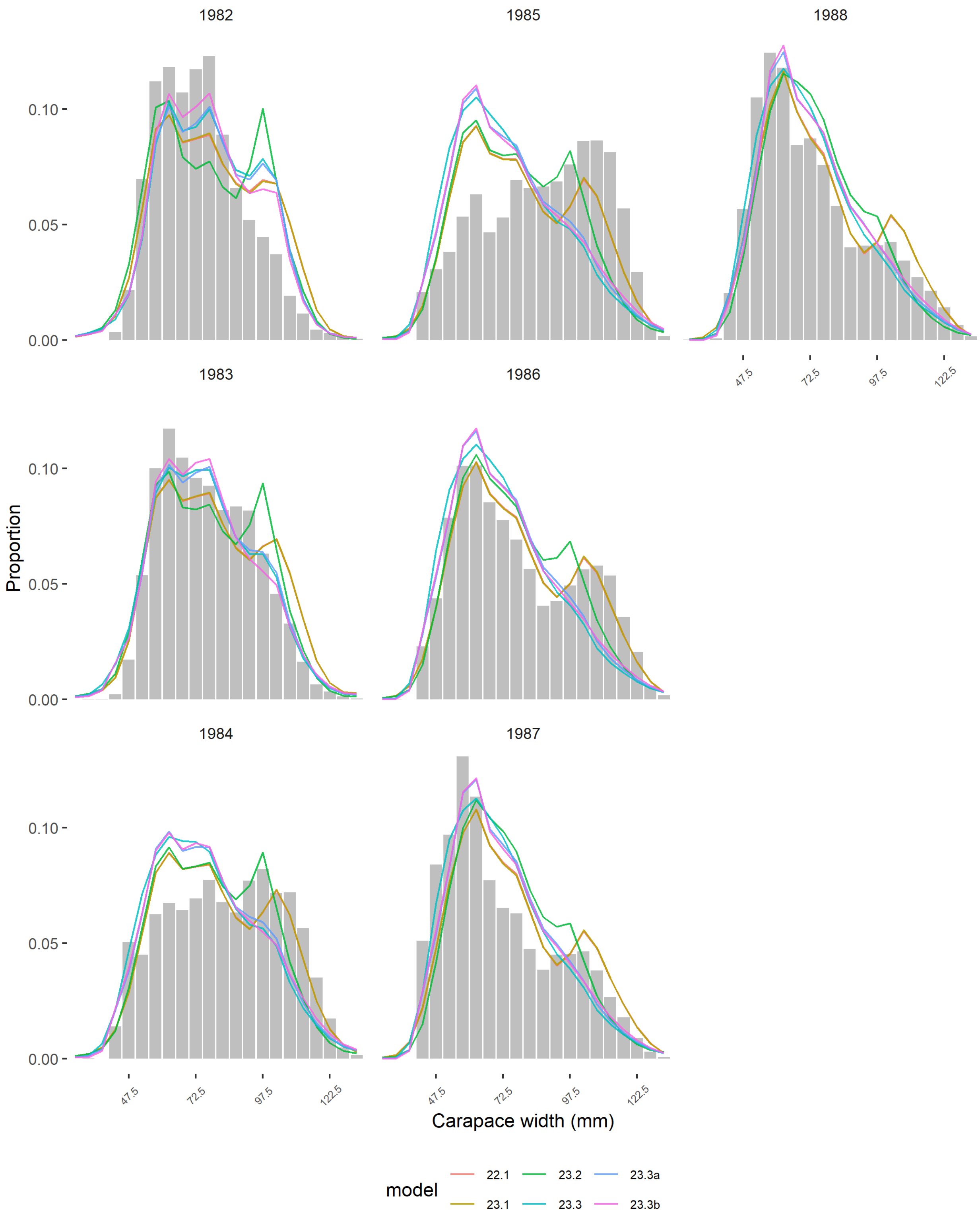


Figure 44: Model fits to mature male survey size composition data from 1982-1988.

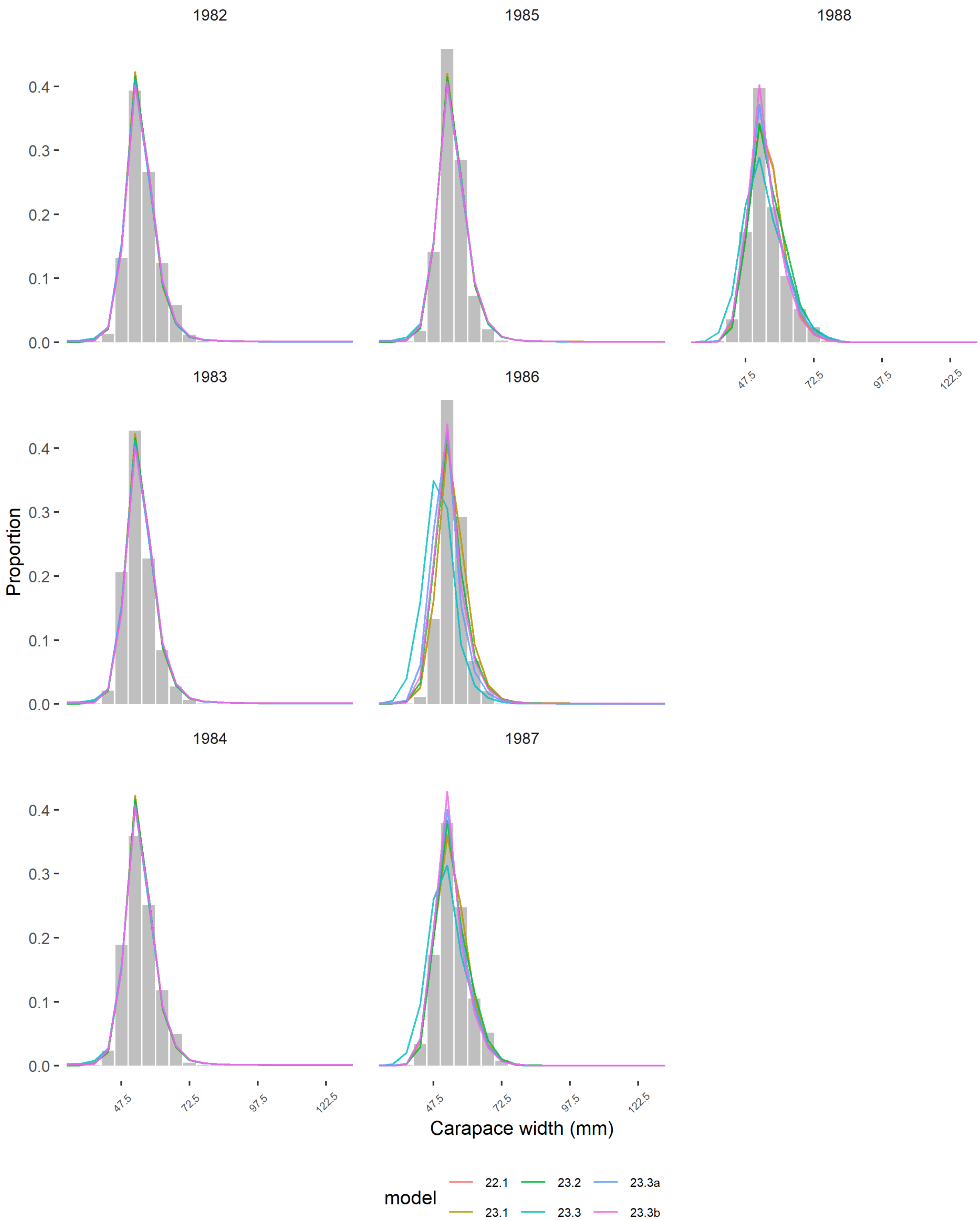


Figure 45: Model fits to mature female survey size composition data from 1982-1988.

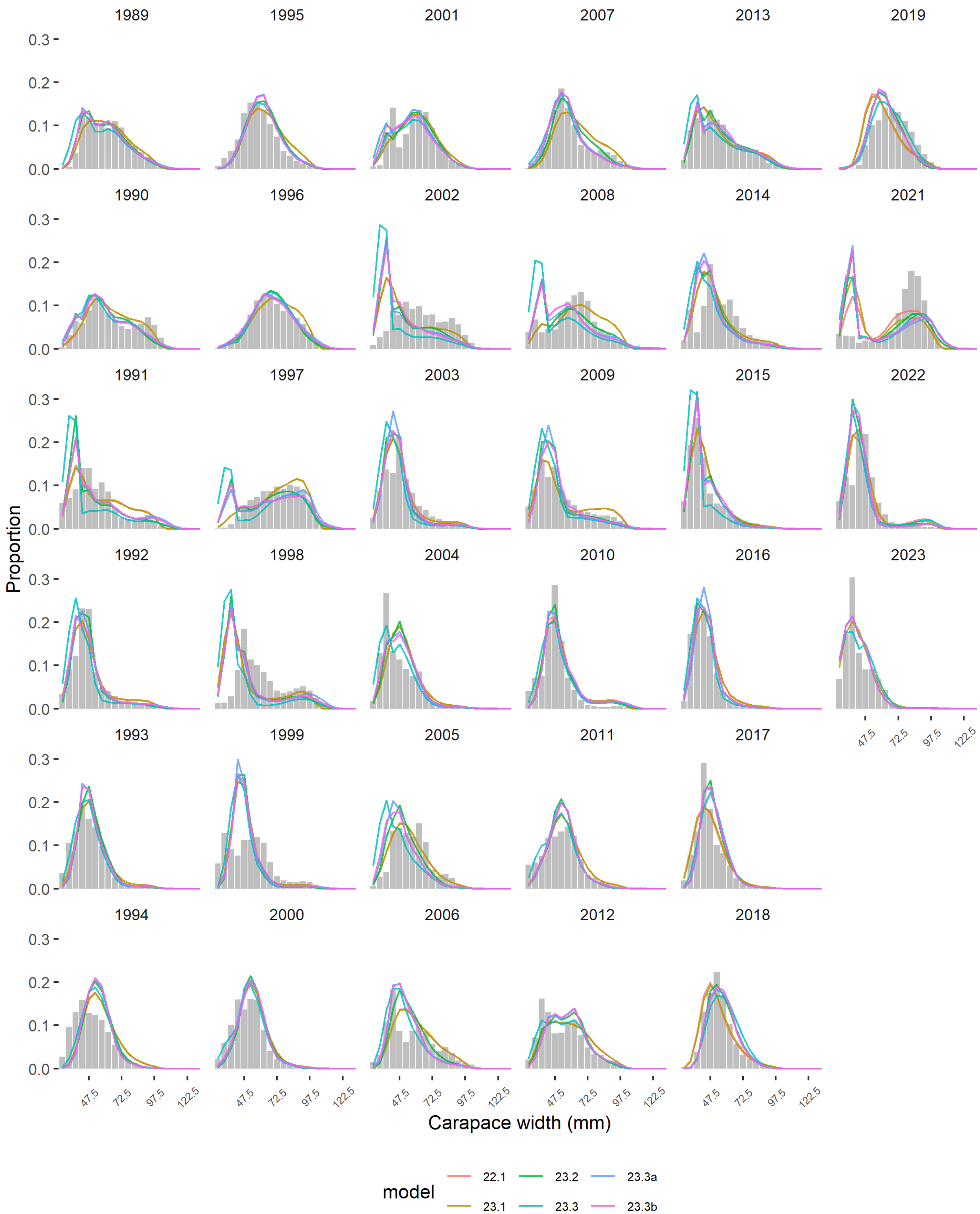


Figure 46: Model fits to immature male survey size composition data from 1989-present.

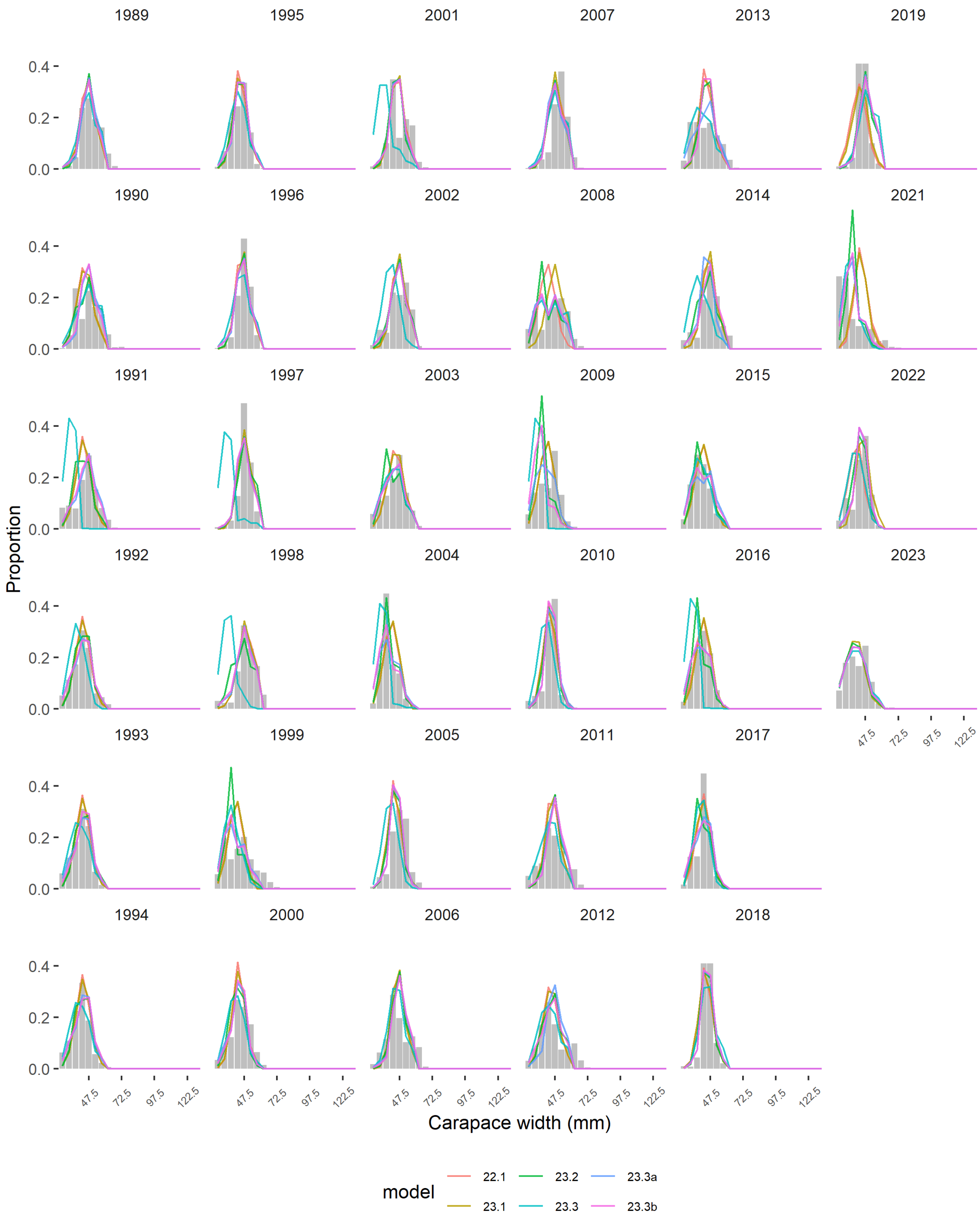


Figure 47: Model fits to immature female survey size composition data from 1989-present.

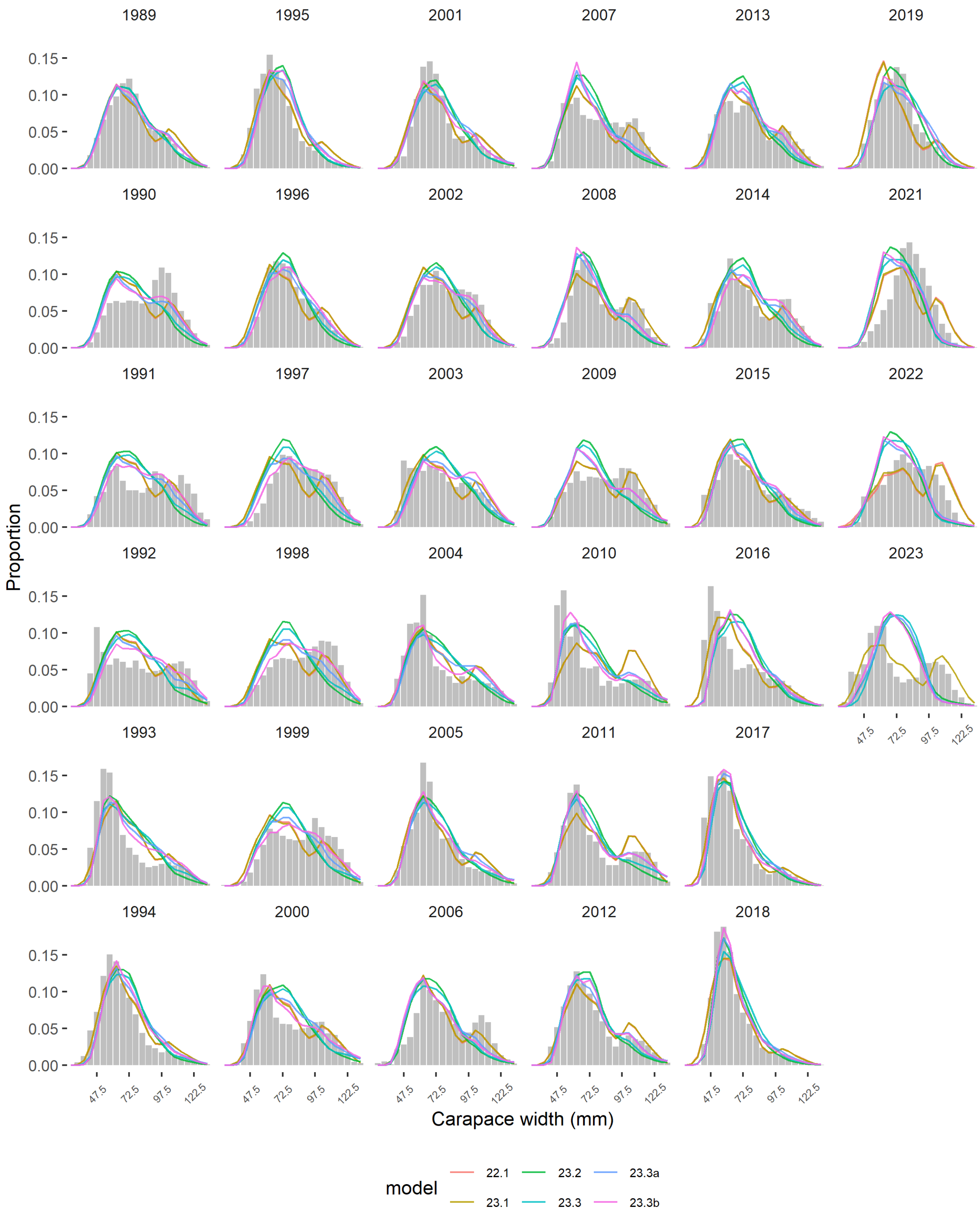


Figure 48: Model fits to mature male survey size composition data from 1989-present.

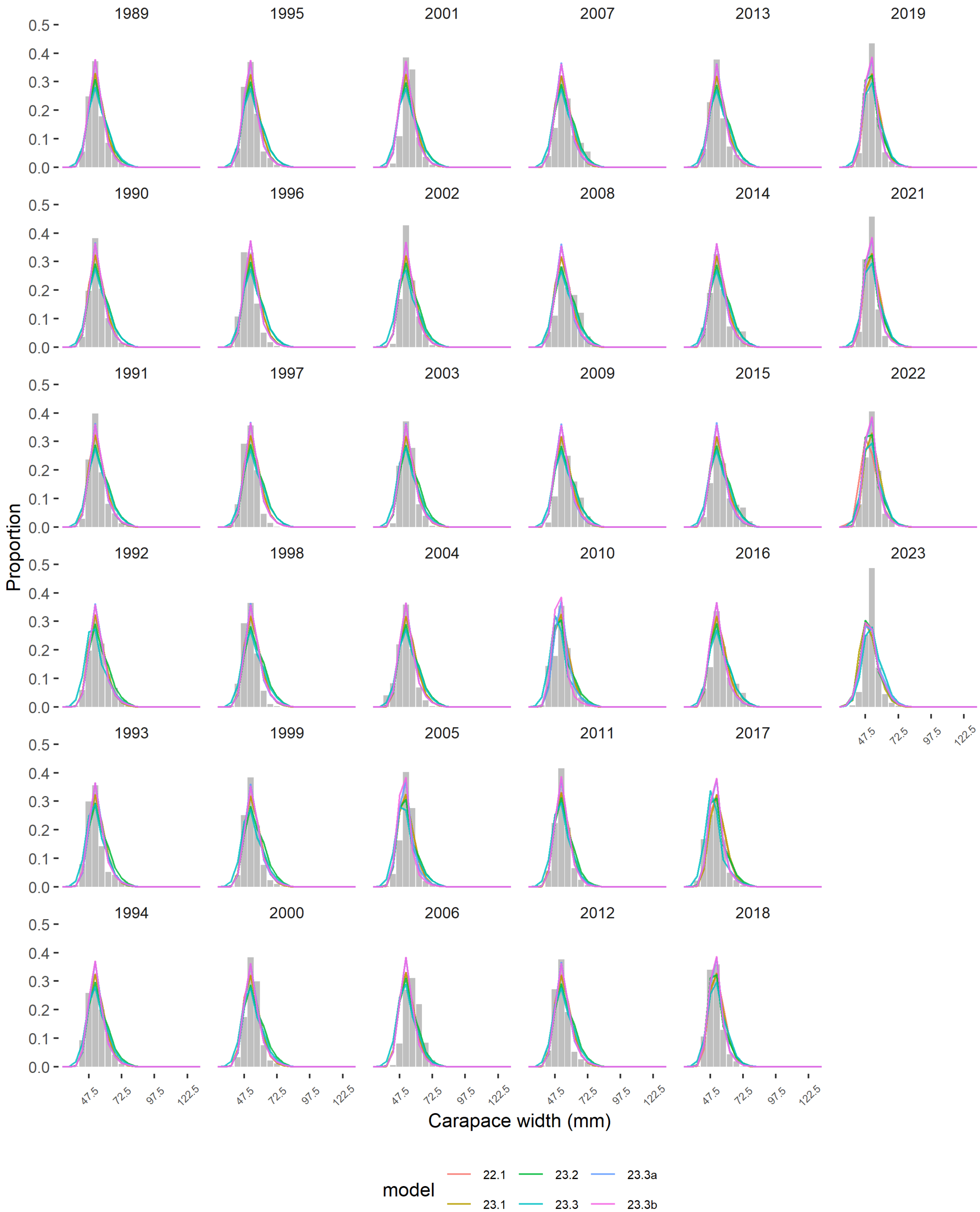


Figure 49: Model fits to mature female survey size composition data from 1989-present.

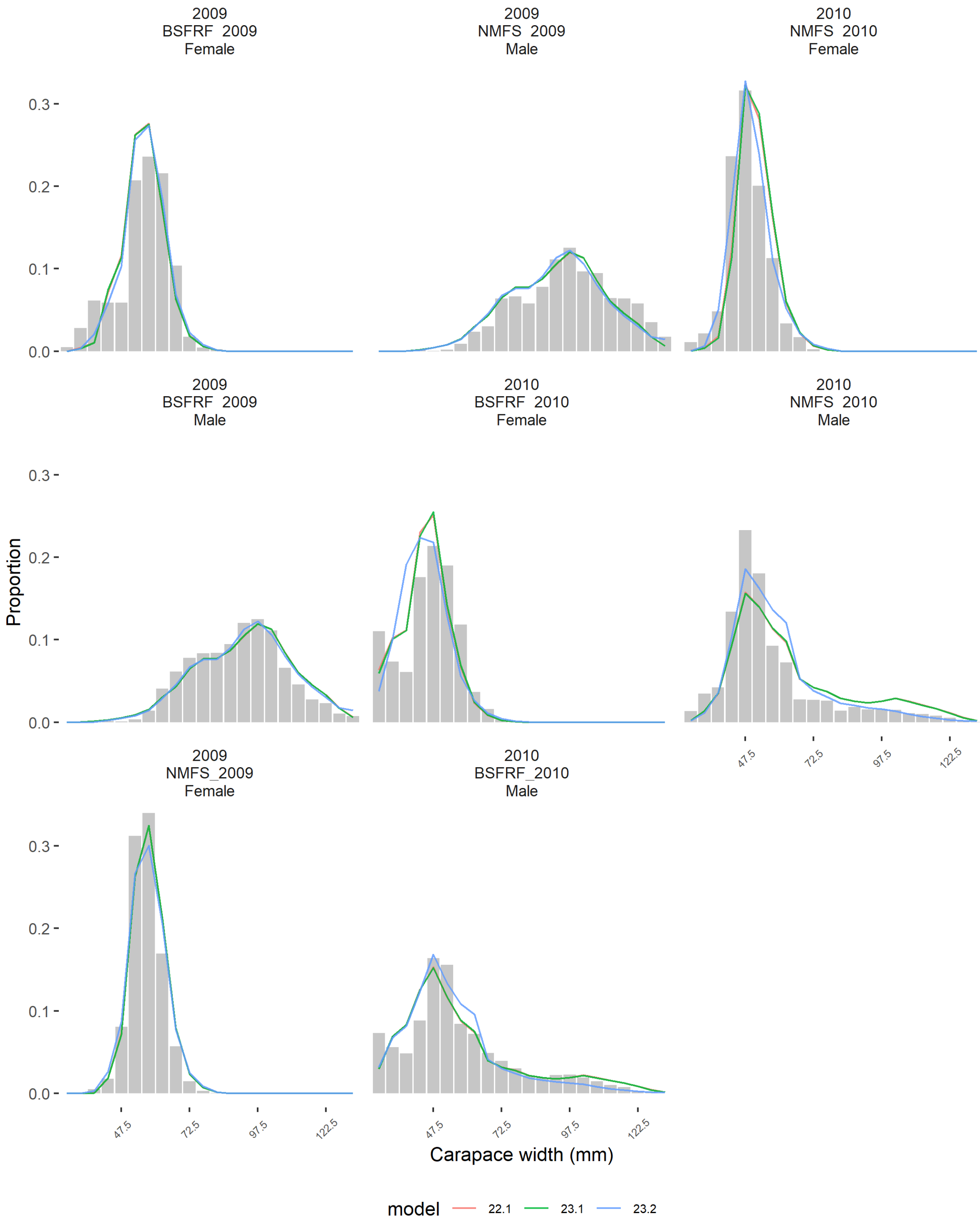


Figure 50: Model fits to BSFRF survey selectivity experiment size composition data. Figure labels indicate the year of the survey (top), the entity completing the survey (middle), and the sex of crab collected (bottom).

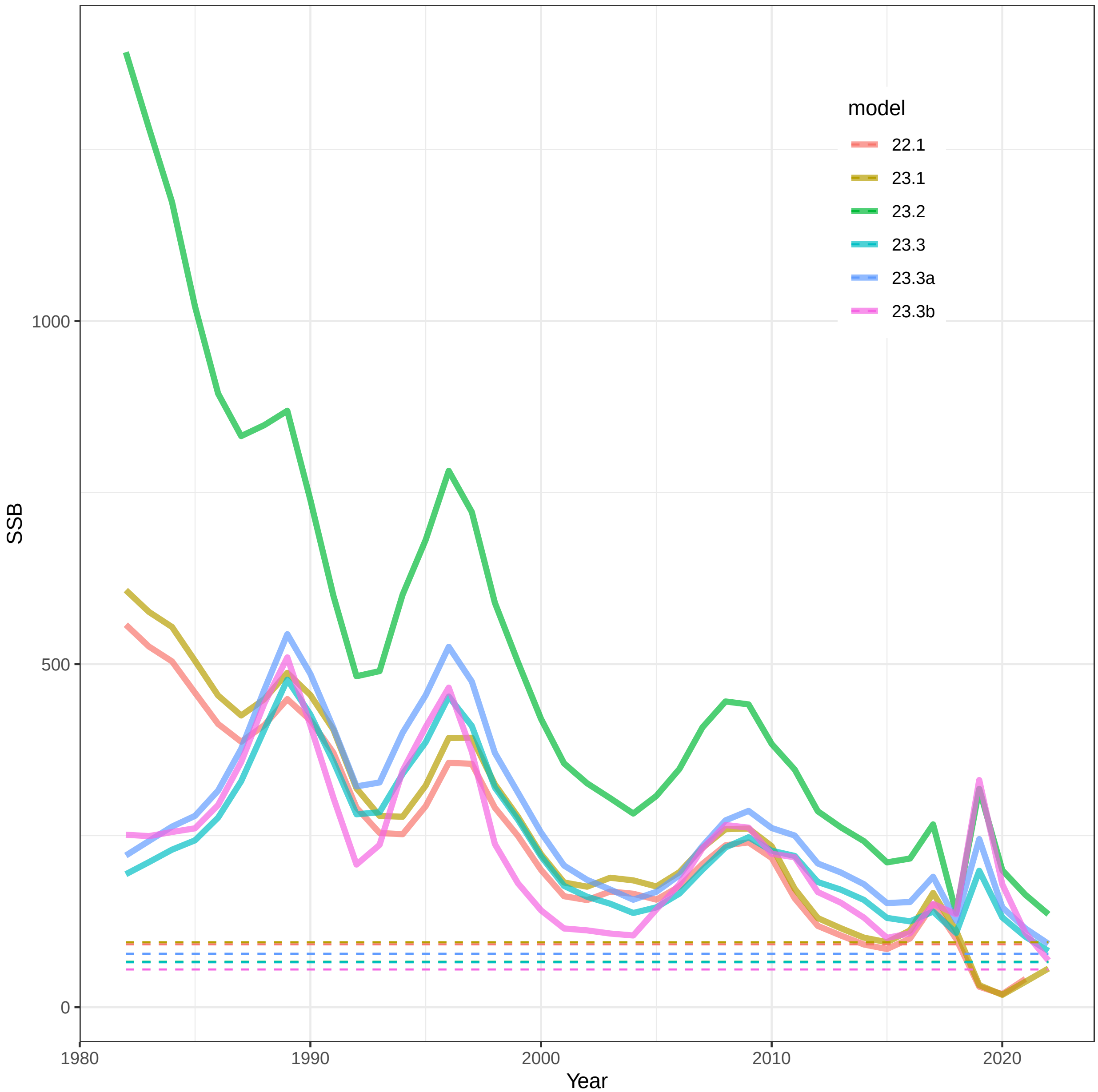


Figure 51: Model predicted mature biomass at mating time in 1,000 tonnes. Dashed horizontal lines are the MSST based on B35.

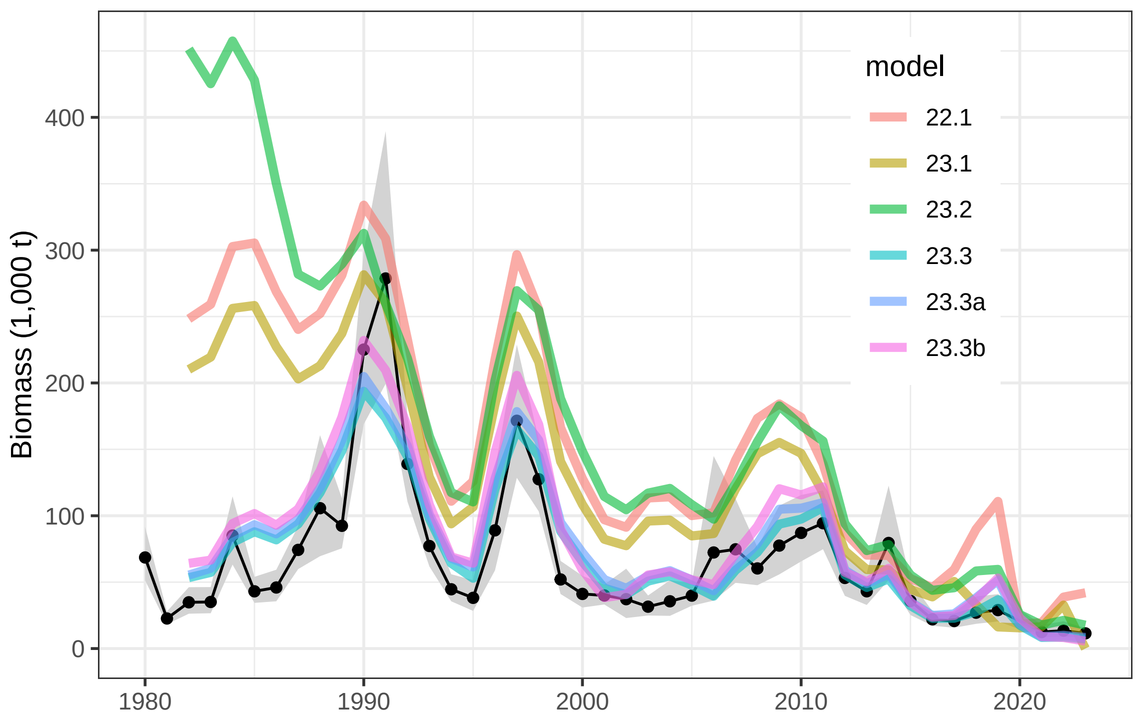


Figure 52: Estimated biomass of male crab >101mm carapace width from the survey (black line and dots with gray 95th CI) and from each model in the assessment (colored lines).

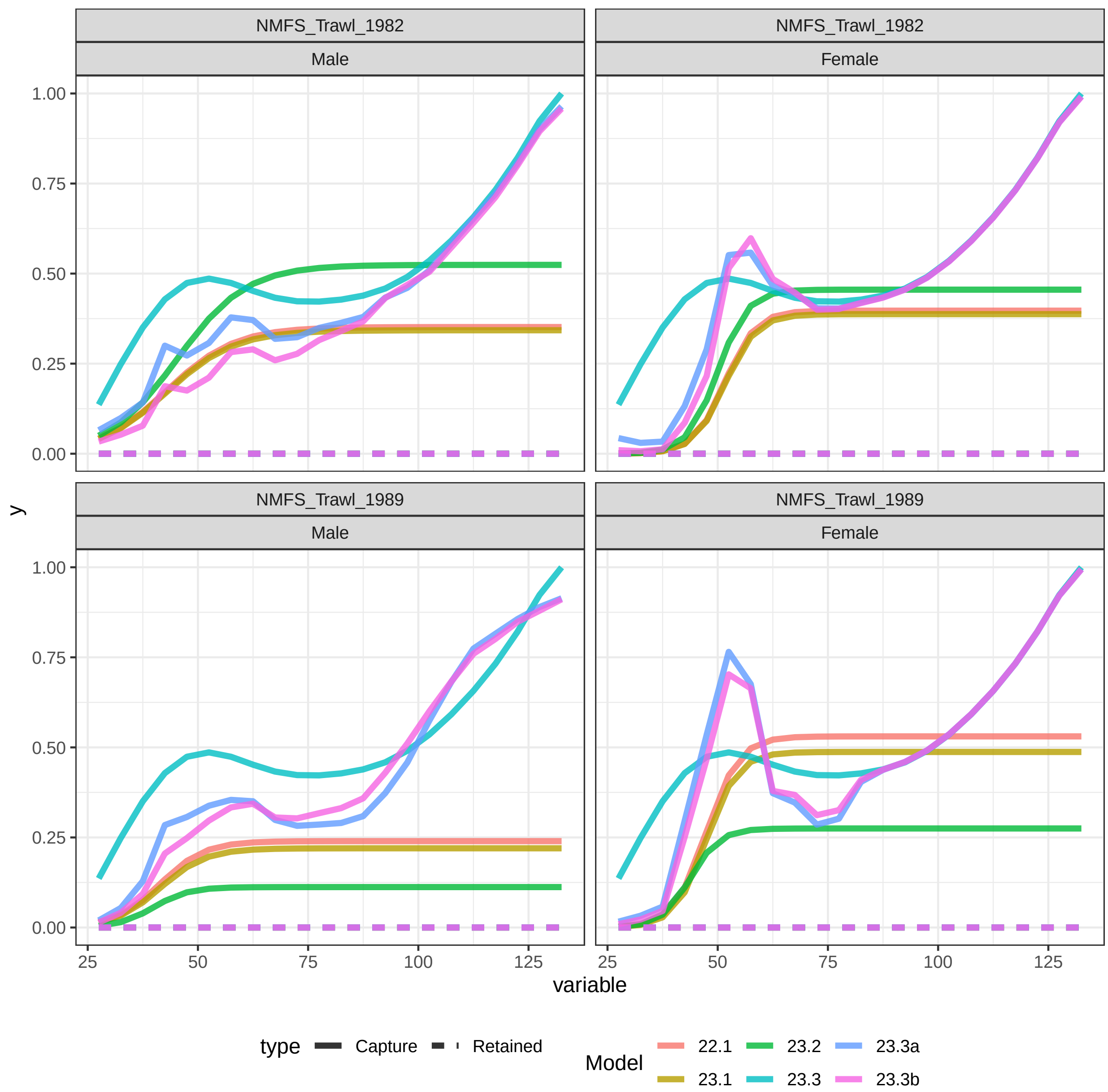


Figure 53: Estimated selectivities by NMFS survey, sex, and time period.

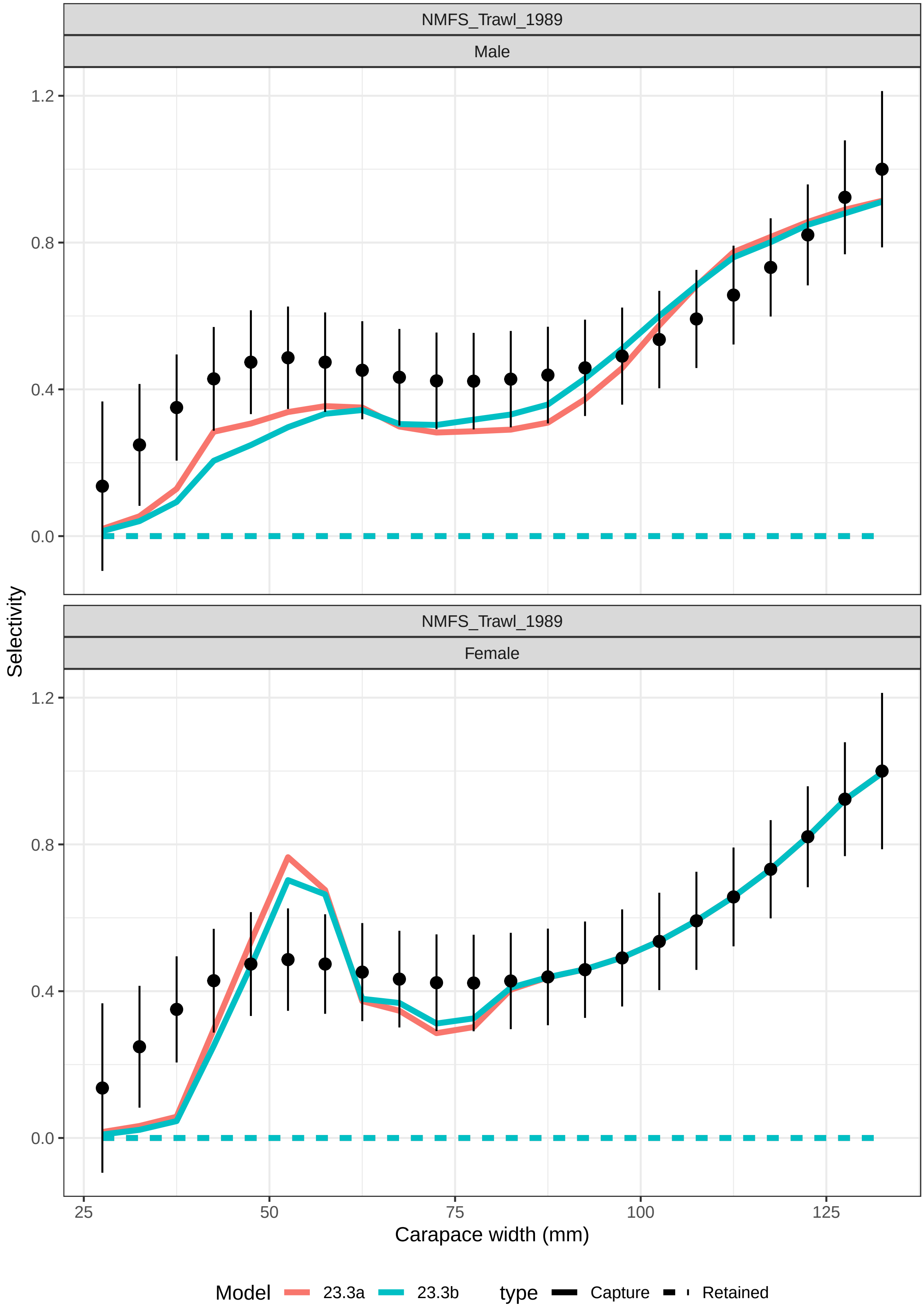


Figure 54: Estimated survey selectivity (lines) with normal priors derived from BSFRF selectivity experiment data. Points are the mean of the prior at a given size; intervals are 95th quantiles based on input CVs.

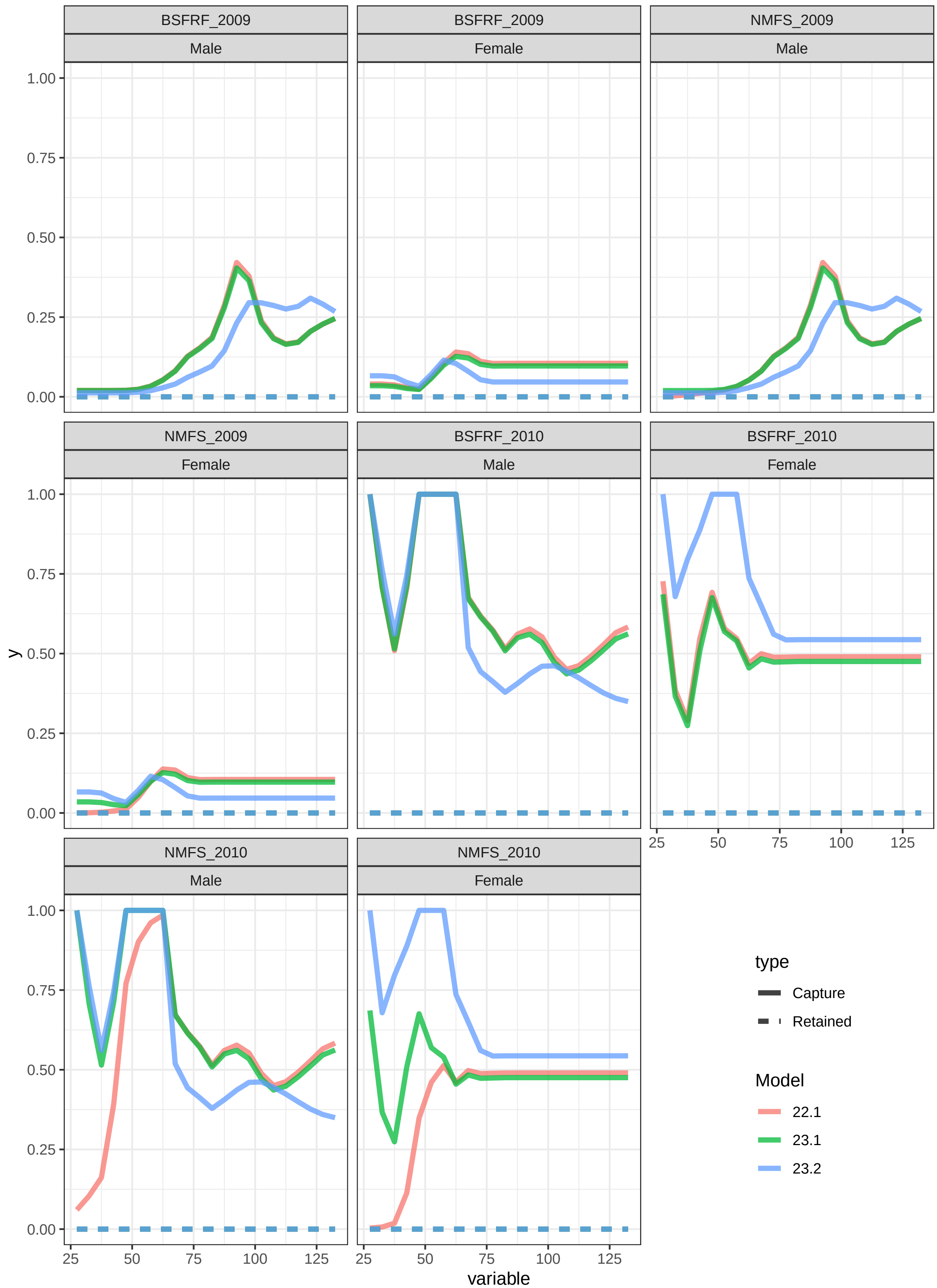


Figure 55: Estimated availability/selectivity for the BSFRF experimental data. Curves for BSFRF are availability*selectivity and curves for NMFS are only availability, which is then multiplied by the estimated selectivity in the previous figure to calculate size composition data.

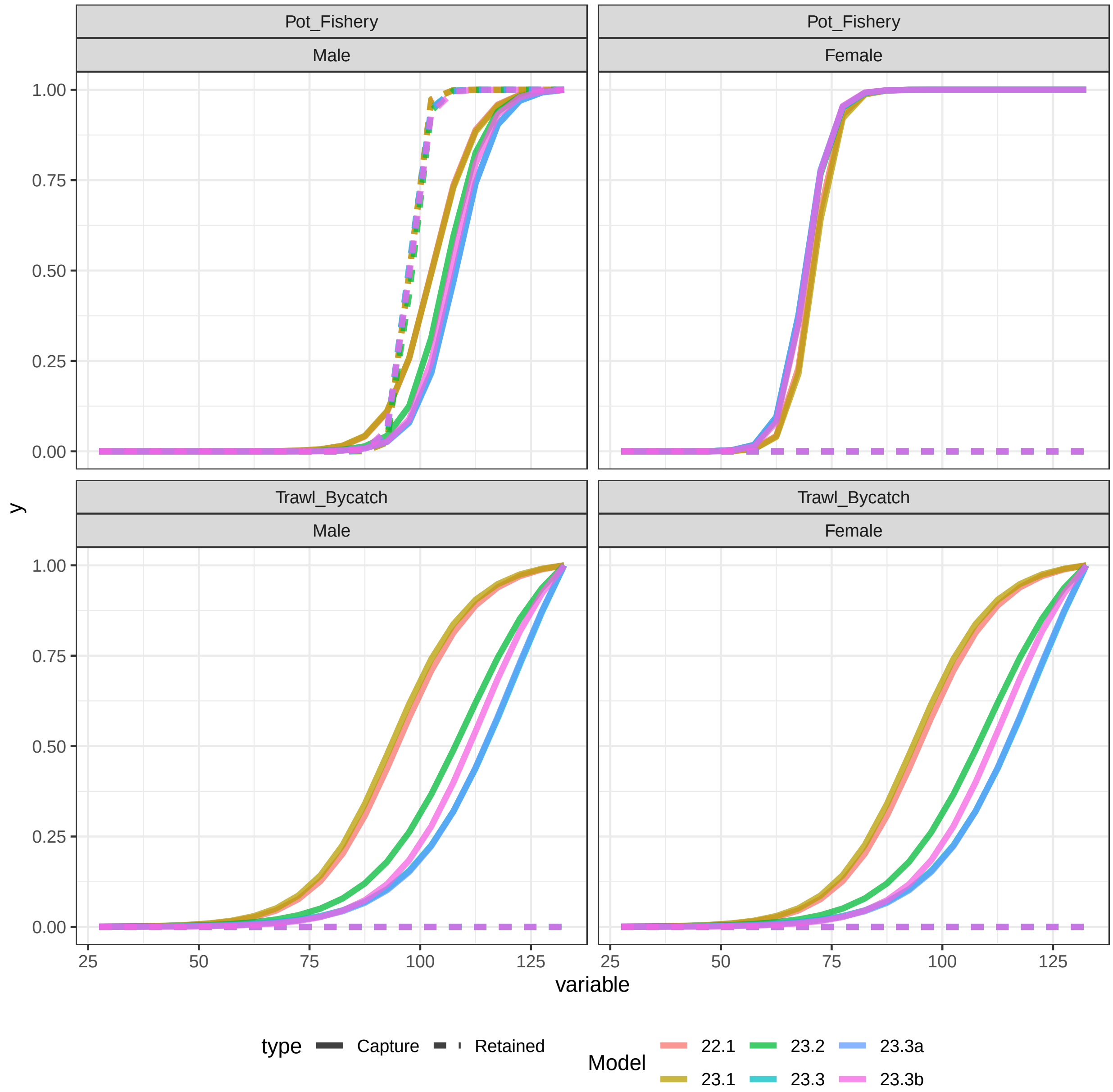


Figure 56: Estimated selectivities by fishing fleet and sex for capture and retained catches.

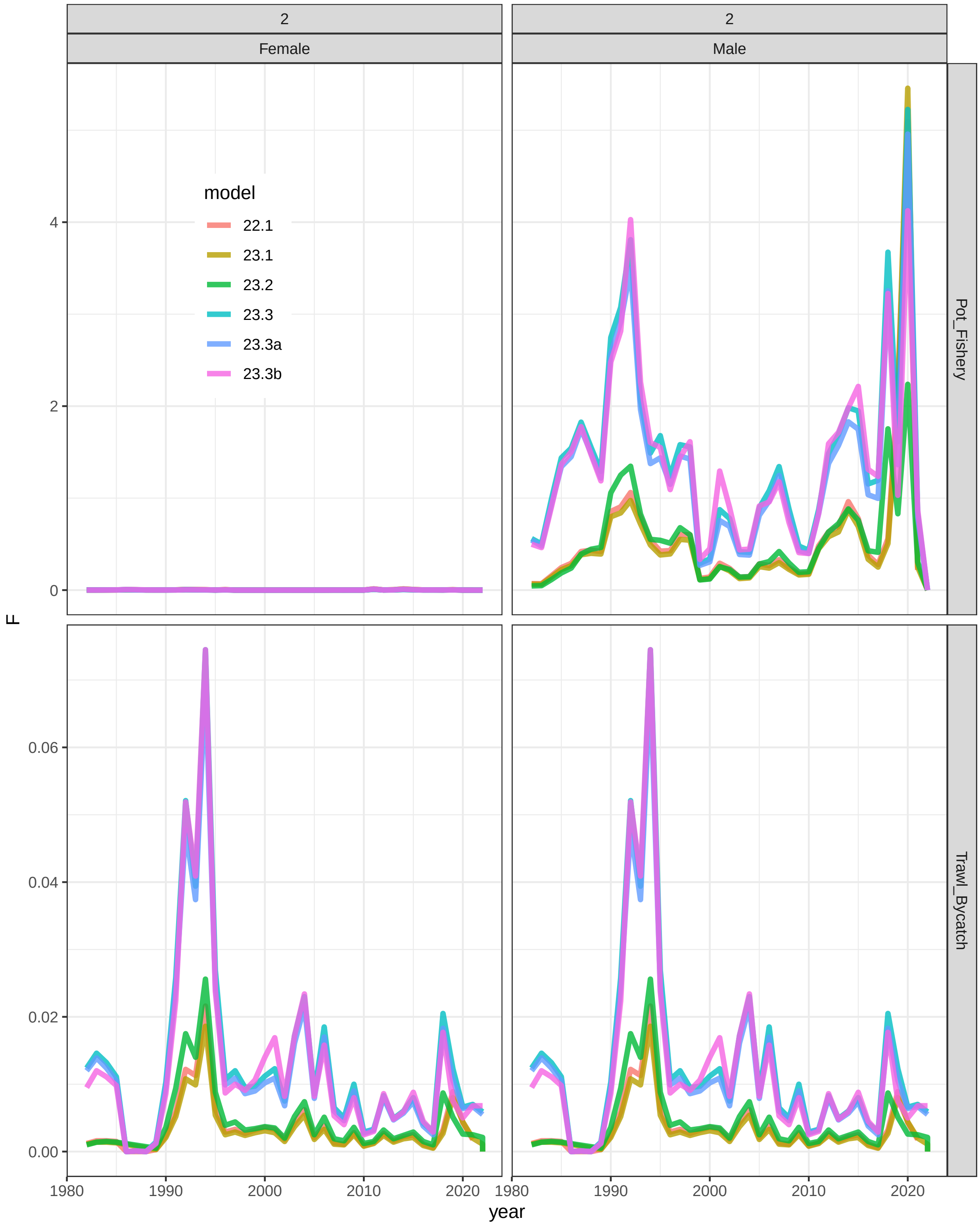


Figure 57: Estimated fishing mortalities for the directed and non-directed fisheries.

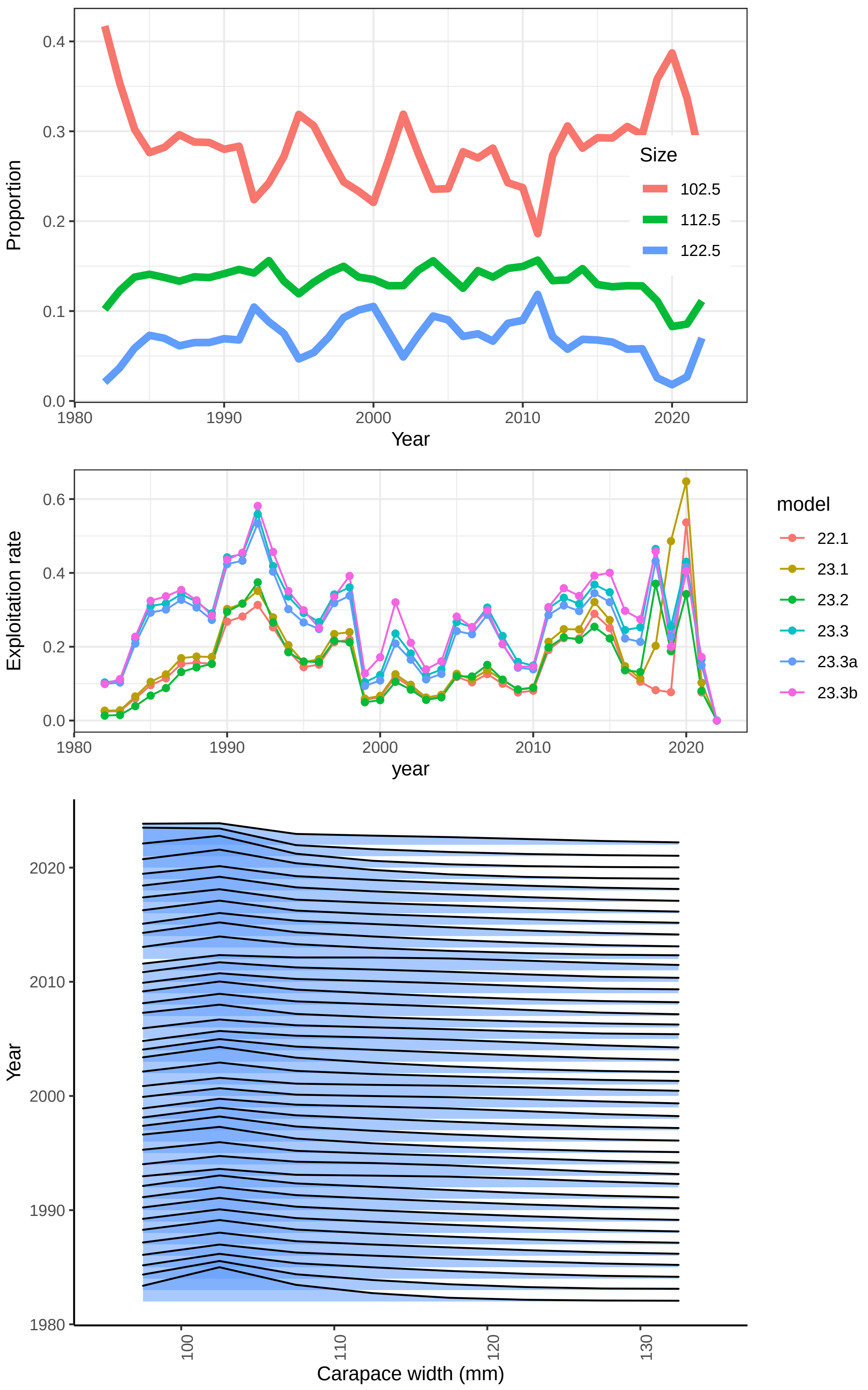


Figure 58: Proportion of biomass by size over time (bottom), realized exploitation rate by model (middle), and proportion of total biomass for select sizes over time (top).

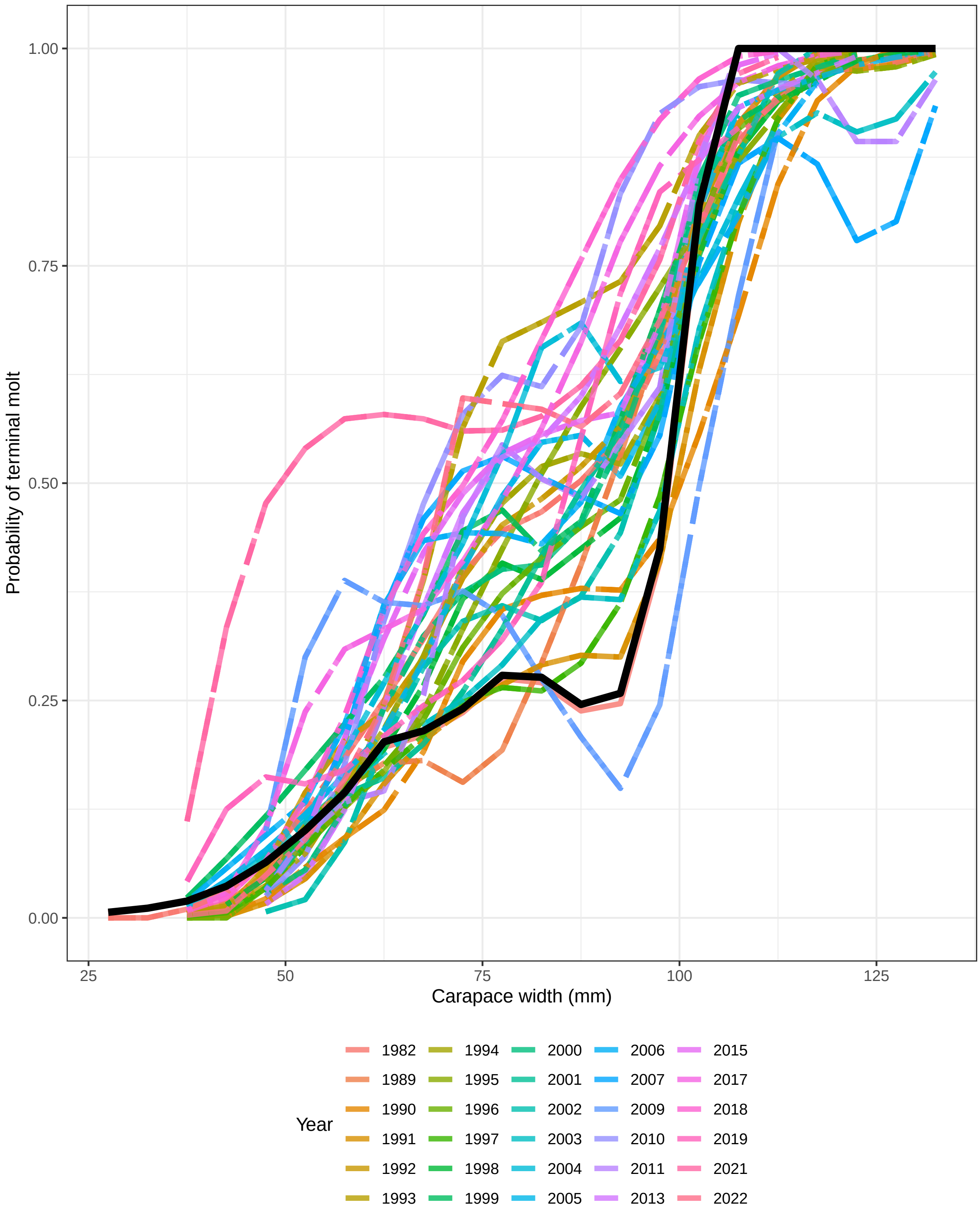


Figure 59: Estimated (black line) or specified (colored lines) probability(s) of maturing for male crab.

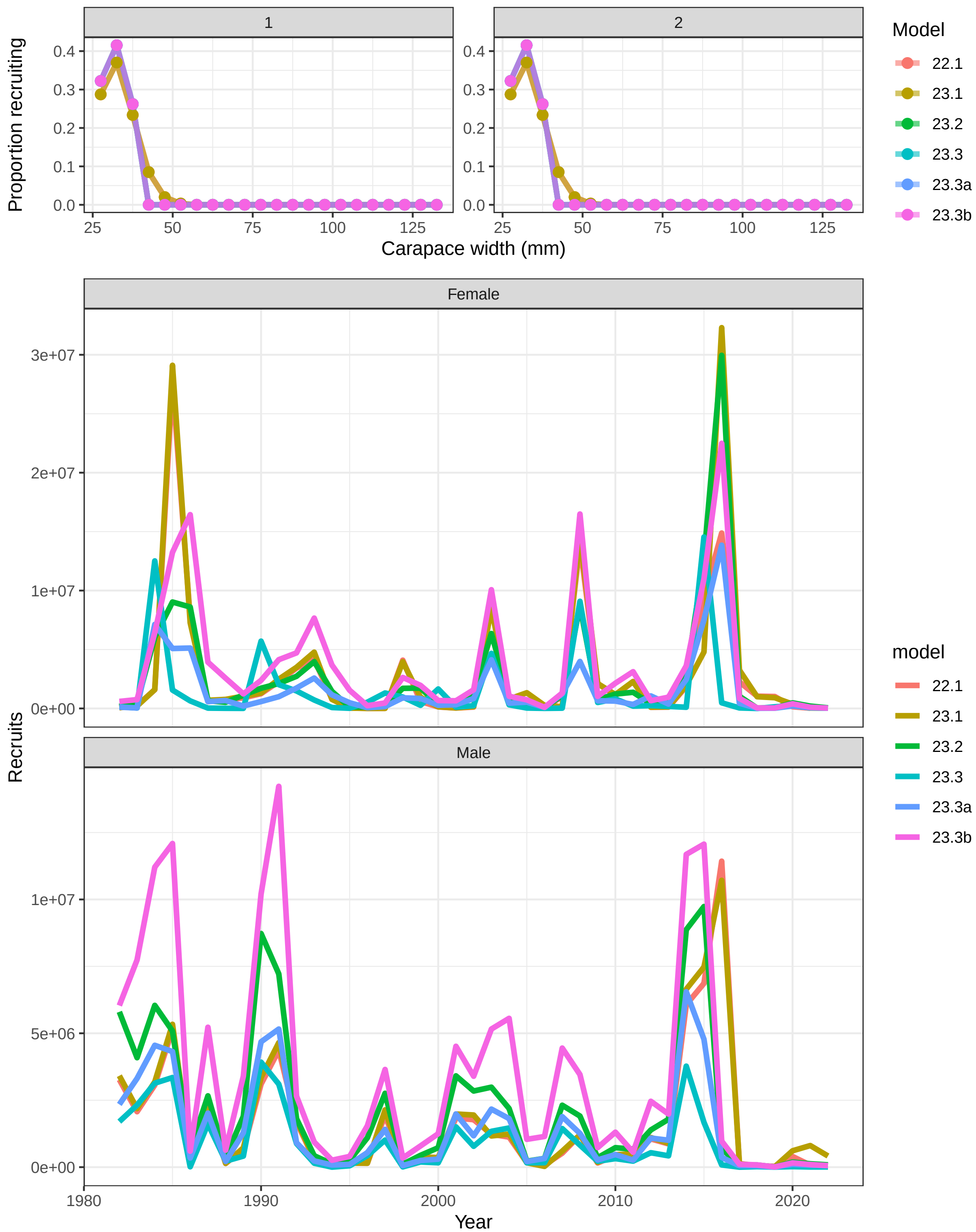


Figure 60: Estimated recruitment by sex (bottom) and proportions recruiting to length bin (top) by model.

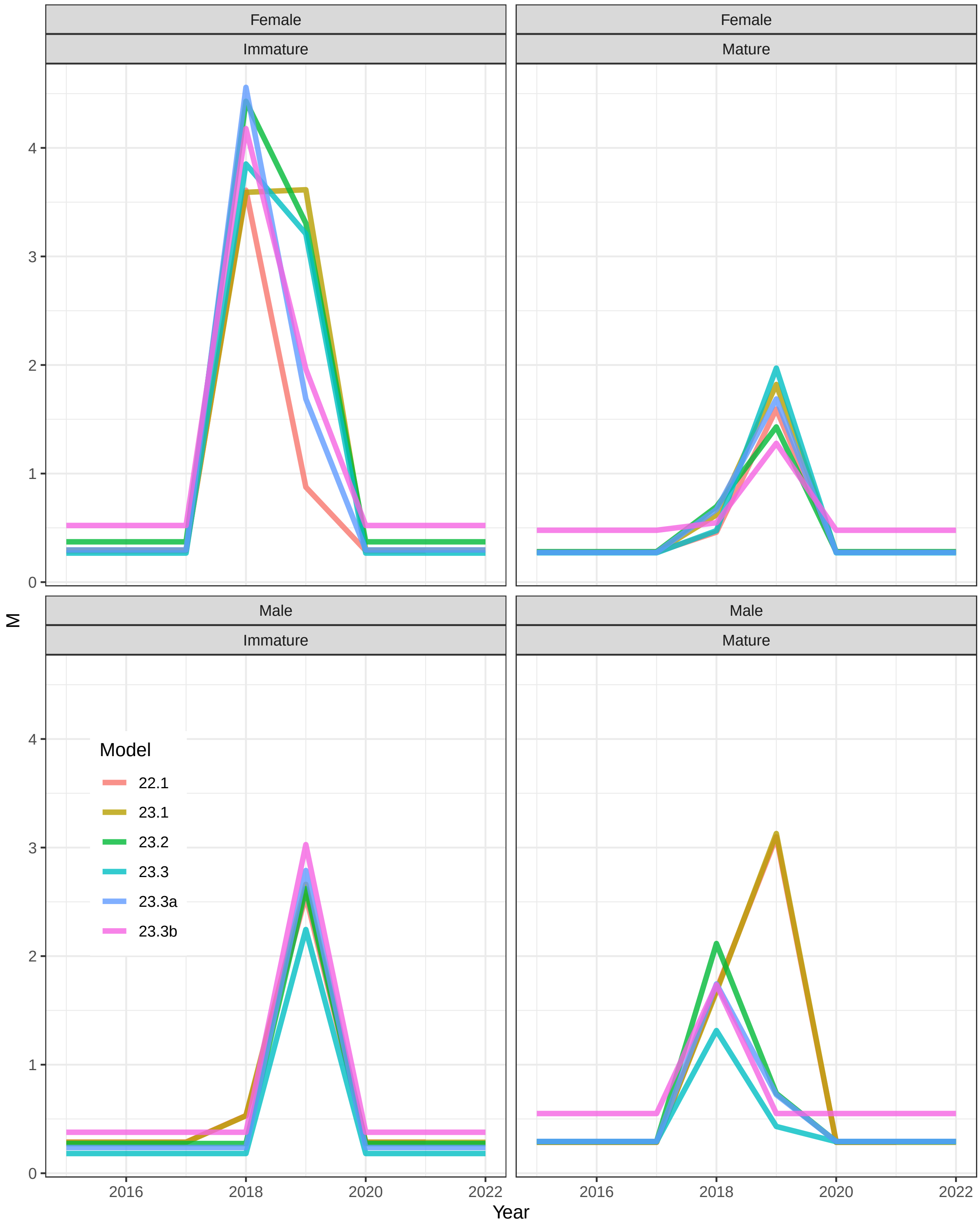


Figure 61: Estimated natural mortality by sex and maturity state. Natural mortality in all years previous to 2018 and after 2019 are equal to the estimated M in 2017.

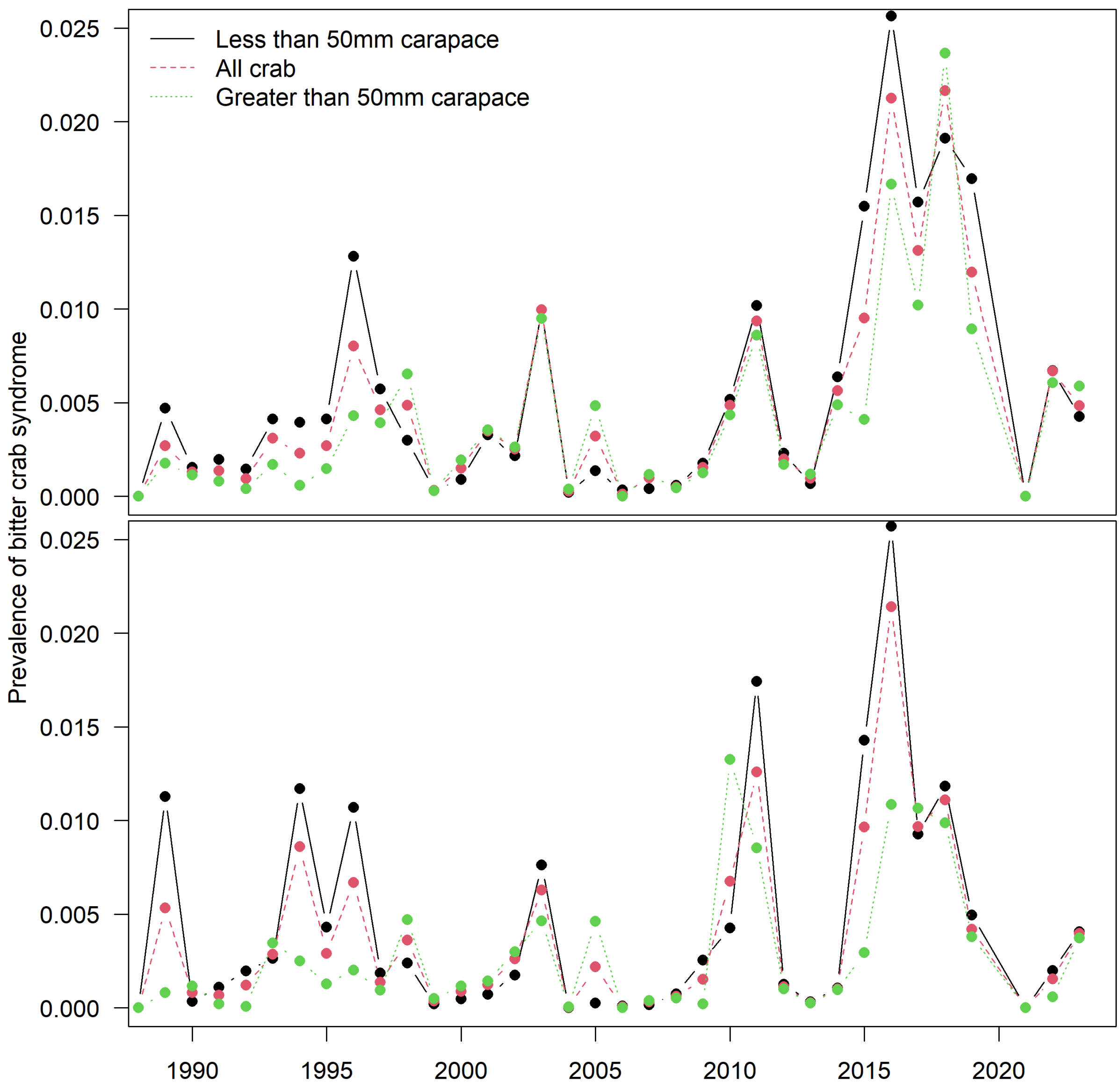
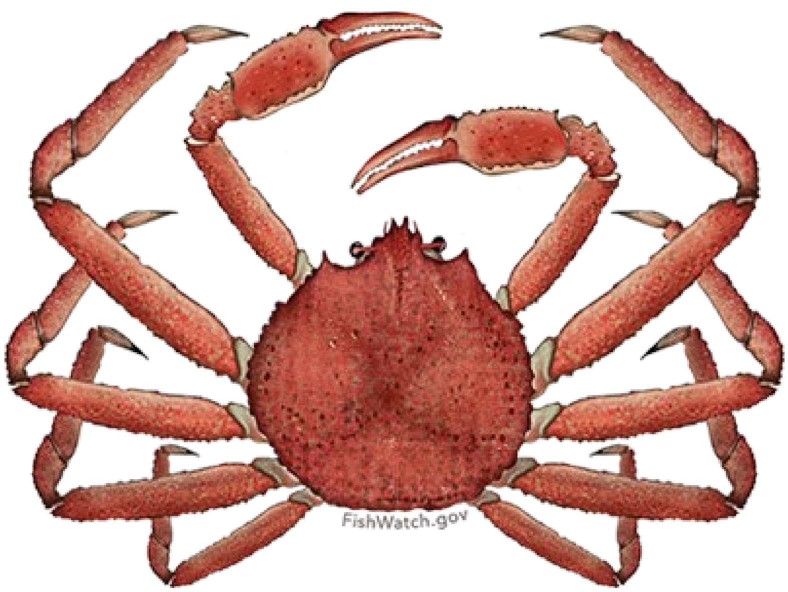


Figure 62: Prevalence of bitter crab syndrome over time. Top figure is the unweighted prevalence of visual evidence of BCS in crab observed in the survey. Bottom is the prevalence of BCS weighted by the sampling factor.

Appendix A. Ecosystem and Socioeconomic Profile of the Snow Crab Stock in the Eastern Bering Sea - Report Card

Erin Fedewa and Kalei Shotwell

September 2023



With Contributions from:

Kerim Aydin, Matt Callahan, Louise Copeman, Curry Cunningham, Ben Daly, Jean Lee, Jens Nielsen, and Jon Richar

Current Year Update

The ecosystem and socioeconomic profile or ESP is a standardized framework for compiling and evaluating relevant stock-specific ecosystem and socioeconomic indicators and communicating linkages and potential drivers of the stock within the stock assessment process (Shotwell et al., *Accepted*). The ESP process creates a traceable pathway from the initial development of indicators to management advice and serves as an on-ramp for developing ecosystem-linked stock assessments.

Please refer to the last full ESP document (Fedewa et al., 2022) which is available within the eastern Bering Sea (EBS) snow crab stock assessment and fishery evaluation or SAFE report for further information regarding the ecosystem and socioeconomic linkages for this stock.

Management Considerations

The following are the summary considerations from current updates to the ecosystem and socioeconomic indicators evaluated for snow crab:

- In 2023, summer bottom temperatures and the spatial extent of the cold pool remained near-average in the eastern Bering Sea following a 2018-2019 marine heat wave. The Arctic Oscillation was slightly positive this past winter.
- Juvenile snow crab occupied -0.3°C bottom waters on average, suggesting optimal cold-water habitat availability for predator refuge.
- Anomalously low levels of chlorophyll a in 2023 indicate a less pronounced spring bloom and poor feeding conditions for larval snow crab.
- Following a dramatic increase in the prevalence of bitter crab syndrome and Pacific cod predation in 2016 coinciding with a large snow crab recruitment event, disease prevalence remains near-average. Pacific cod consumption on snow crab has also remained near-average in 2021 and 2022.
- The center of mature male abundance remains more northerly than average, indicative of a large-scale distribution shift from historic mid-shelf habitats.
- Juvenile snow crab were in very poor body condition prior to the 2021 population collapse, although 2021-2023 condition estimates have returned to near-average.
- The Bering Sea snow crab fishery was closed to targeted fishing for the first time in history, representing severe economic hardships for industry alongside BBRKC fishery closures.
- Incidental catch of snow crab in EBS groundfish fisheries has remained near-average for the past 5-year period.

Modeling Considerations

The following are the summary results from the intermediate and advanced stage monitoring analyses for snow crab:

- The highest ranked predictor variables in the intermediate stage monitoring analysis were 1) juvenile snow crab temperature of occupancy and 2) Pacific cod consumption, although effect sizes were relatively small and marginal inclusion probabilities were < 0.5 for all predictors.
- The advanced stage monitoring analysis provides updates on developing research ecosystem linked models that are not yet included as a model alternative in the main stock assessment. We have not received updates on new research ecosystem linked models for snow crab at this time.

Assessment

Ecosystem and Socioeconomic Processes

We summarize important processes that may be helpful for identifying productivity bottlenecks and dominant pressures on the stock in conceptual models detailing 1) ecosystem processes by snow crab life history stage (Figure 1). Please refer to the last full ESP document (Fedewa et al., 2022) for more details.

Indicator Suite

The following list of indicators for snow crab is organized by categories: three for ecosystem indicators (physical, lower trophic, and upper trophic) and three for socioeconomic indicators (fishery performance, economic, and community). A title, short description and contact name for the indicator contributor are provided. We also include the anticipated sign of the proposed relationship between the indicator and the stock population dynamics where relevant. Please refer to the last full ESP document for detailed information regarding the ecosystem and socioeconomic indicator descriptions and proposed mechanistic linkages for this stock (Fedewa et al., 2022). Time series of the ecosystem and socioeconomic indicators are provided in Figure 2a and Figure 2b, respectively. Modifications to ecosystem indicators in 2023 include: 1) Chlorophyll-*a* concentrations derived from MODIS have now been replaced with a European Space Agency (ESA) GlobColour blended satellite product because the satellites that hold the MODIS instruments will soon be retired due to changes in their orbits, 2) due to the 2023 snow crab fishery closure, the industry-led Skipper Survey included in the last full ESP was not conducted, 3) winter sea ice extent data from the ERA5 reanalysis have been replaced with data from the NOAA National Snow and Ice Data Center, and 4) Pacific cod consumption estimates now include unidentified *Chionocetes* as well as identified *C. opilio* from stomach contents. These modifications will preclude direct comparison to indicator timeseries in previous ESP documents. In addition to indicator modifications, a new indicator, juvenile snow crab condition, has been added to the suite of upper trophic indicators.

Ecosystem Indicators:

Physical Indicators (Figure 2a.a-c)

- a.) Winter-spring **Arctic Oscillation** index from the NOAA National Climate Data Center (contact: E. Fedewa). Proposed sign of the relationship is negative and the time series is lagged five years for intermediate stage indicator analysis
- b.) The **areal extent of the summer cold pool** as EBS bottom trawl survey stations with bottom temperatures < 2°C (contact: E. Fedewa). Proposed sign of the relationship is positive and the time series is lagged four years for intermediate stage indicator analysis.
- c.) January-February average **winter sea ice extent** in the Bering Sea (contact: E. Fedewa). Proposed sign of the relationship is positive and the time series is lagged three years for intermediate stage indicator analysis.

Lower Trophic Indicators (Figure 2a.d-e)

- d.) April – June average **chlorophyll *a* concentration** on the north-middle shelf of the eastern Bering Sea, calculated with the ESA GlobColour blended satellite product (4km resolution, 8 day composite data; contact: M. Callahan and J. Nielsen). Proposed sign of the relationship is positive and the time series is lagged five years for intermediate stage indicator analysis.
- e.) Summer **benthic invertebrate density**, determined from EBS bottom trawl survey stations included in the 50th percentile of mean snow crab CPUE. Invertebrates include brittle stars, sea stars, sea cucumber, bivalves, non-commercial crab species, shrimp and polychaetes. (contact: E. Fedewa). Proposed sign of the relationship is positive and the time series is lagged one year for intermediate stage indicator analysis

Upper Trophic Indicators (Figure 2a.f-k)

a.) Mean juvenile snow crab **temperature of occupancy**; bottom temperature weighted by immature snow crab CPUE at each station of the EBS summer bottom trawl survey (contact: E. Fedewa). Proposed sign of the relationship is negative and the time series is lagged one year for intermediate stage indicator analysis.

b.) Prevalence of immature snow crab showing visual symptoms of **Bitter Crab Disease** during the summer EBS bottom trawl survey (contact: E. Fedewa). Proposed sign of the relationship is negative and the time series is lagged three years for intermediate stage indicator analysis.

c.) Mean carapace width of male snow crab at **50% probability of maturation**, as determined from maturity curves developed from EBS bottom trawl survey data (contact: J. Richar). Proposed sign of the relationship is positive.

d.) **Mature male snow crab area occupied**, calculated as the minimum area containing 95% of the cumulative mature male snow crab (>95mm) CPUE during the EBS summer bottom trawl survey (contact: E. Fedewa). Proposed sign of the relationship is positive.

e.) CPUE-weighted **average latitude** of the mature male snow crab stock (>95mm) during the EBS summer bottom trawl survey (contact: E. Fedewa). Proposed sign of the relationship is positive.

f.) The daily **summer consumption of snow crab** by Pacific cod in the EBS, estimated from Pacific cod diet compositions, EBS trawl survey CPUE, and temperature adjusted length-specific maximum consumption rates (contact: K. Aydin). Proposed sign of the relationship is negative and the time series is lagged three years for intermediate stage indicator analysis.

g.) Summer **snow crab juvenile condition**, as determined from water content in the hepatopancreas (% dry weight) sampled from snow crab on the EBS bottom trawl survey (contact: L. Copeman). Proposed sign of the relationship is positive and the time series is lagged one year for intermediate stage indicator analysis.

Socioeconomic Indicators: (all monetary values are inflation-adjusted to $2023 value)

Fishery Performance Indicators (Figure 2b. a-e)

a.) Annual **number of active vessels** in the snow crab fishery, representing the level of fishing effort assigned to the fishery (contact: J. Lee)

b.) Annual **catch-per-unit-effort** (CPUE), expressed as mean number of crabs per potlift, in the snow crab fishery, representing relative efficiency of fishing effort (contact: B. Daly)

c.) Annual **total potlifts** in the snow crab fishery, representing the level of fishing effort expended by the active fleet (contact: B. Daly)

d.) **Center of gravity**, expressed in latitude, as an index of spatial distribution for the snow crab fishery to monitor spatial shifts in fishery behavior (contact: B. Daly)

e.) Annual **incidental catch** of snow crab in EBS groundfish fisheries (contact: J. Lee)

Economic Indicators (Figure 2b. f-i)

f.) Percentage of the annual EBS snow crab **total allowable catch** (TAC) (GHL prior to 2005) that was harvested by active vessels, including deadloss discarded at landing (contact: B. Daly)

g.) Annual snow crab **ex-vessel value** of the snow crab fishery landings, representing gross economic returns to the harvest sector, as a principal driver of fishery behavior (contact: J. Lee)

h.) Annual snow crab **ex-vessel price per pound**, representing per-unit gross economic returns to the harvest sector, as a principal driver of fishery behavior (contact: J. Lee)

i.) Annual snow crab **ex-vessel revenue share**, expressed as vessel-average proportion of annual gross landings revenue earned from the EBS snow crab fishery (contact: J. Lee)

Indicator Monitoring Analysis

There are up to three stages (beginning, intermediate, and advanced) of statistical analyses for monitoring the indicator suite listed in the previous section. The beginning stage is a relatively simple evaluation by traffic light scoring. This evaluates the current year trends relative to the mean of the whole time series, and provides a historical perspective on the utility of the whole indicator suite. The intermediate stage uses importance methods related to a stock assessment variable of interest (e.g., recruitment, biomass, catchability). These regression techniques provide a simple predictive performance for the variable of interest and are run separate from the stock assessment model. They provide the direction, magnitude, uncertainty of the effect, and an estimate of inclusion probability. The advanced stage is used for testing a research ecosystem linked model and output can be compared with the current operational model to understand information on retrospective patterns, prediction performance, and comparisons of other model output.

Beginning Stage: Traffic Light Test

We use a simple scoring calculation for this beginning stage traffic light evaluation. Indicator status is evaluated based on being greater than (“high”), less than (“low”), or within (“neutral”) one standard deviation of the long-term mean. A sign based on the anticipated relationship between the ecosystem indicators and the stock (generally shown in Figure 1a and specifically by indicator in the Indicator Suite, Ecosystem Indicators section) is also assigned to the indicator where possible. If a high value of an indicator generates good conditions for the stock and is also greater than one standard deviation above the mean, then that value receives a ‘+1’ score. If a high value generates poor conditions for the stock and is greater than one standard deviation above the mean, then that value receives a ‘-1’ score. All values less than or equal to one standard deviation from the long-term mean are average and receive a ‘0’ score. The scores are summed by the three organizational categories within the ecosystem (physical, lower trophic, and upper trophic) or socioeconomic (fishery performance and economic performance) indicators and divided by the total number of indicators available in that category for a given year. The scores over time allow for comparison of the indicator performance and the history of stock productivity (Figure 3). We also provide five year indicator status tables with a color or text code for the relationship with the stock (Tables 1a,b) and evaluate each year’s status in the historical indicator time series graphic (Figures 2a,b) for each ecosystem and socioeconomic indicator. Socioeconomic indicators representing the target fishery are reported by calendar year through 2022, the last year that the fishery was open. Incidental catch is reported for the most recent full calendar year.

We evaluate the status and trends of the ecosystem and socioeconomic indicators to understand the pressures on the snow crab stock regarding recruitment, stock productivity, and stock health. We start with the physical indicators and proceed through the increasing trophic levels for the ecosystem indicators then evaluate the fishery performance and economic indicators as listed above. Here, we concentrate on updates since the last ESP report card. Overall, the physical and lower trophic indicators scored below average for 2023, while the upper trophic indicators were average (Figure 3). Compared to 2022 traffic light scores, recent year results are same for the physical and lower trophic indicators, and an increase for the upper trophic indicators. The fishery performance and economic indicators were not updated for 2023 due to the closure of the fishery.

Following the 2019-2020 highest Arctic Oscillation index in history (Zhang et al., 2021), the winter-spring Arctic Oscillation index returned to near-neutral in 2023. Poor snow crab recruitment has been associated with positive values of the Arctic Oscillation (Szuwalski et al., 2021), suggesting that large-scale weather and climate anomalies in 2019/2020 could have impacted stock productivity. Cold pool spatial extent and sea ice concentration in 2023 were average, indicating a return to near-normal conditions in the Bering Sea following anomalously warm temperatures and record low sea ice concentration in 2018-2019. Highly stenothermic juvenile snow crab appear to benefit from these cold bottom temperatures and increased sea ice extent (Dionne et al., 2003).

Lower trophic level indicators include chlorophyll-*a* biomass and benthic invertebrate biomass, both of which represent potential prey resources for pelagic and benthic snow crab stages. Chlorophyll-a concentrations during the 2023 spring bloom were the lowest in the 26-year eastern Bering Sea time series. Sea ice extent in March indicates that while the bloom timing was near-average (J. Nielsen, personal communication), low chlorophyll-a concentrations and subsequently less diatoms in the water column may drive increased larval mortality due to less favorable feeding conditions (Incze et al., 1987). Benthic invertebrate density estimates are not yet available for 2023, but the time series has been trending upwards for the 5 years and increases in benthic invertebrate density in 2022 were attributed to above-average catches of non-commercial crab species, sea anemones and sea squirts.

Upper trophic level indicators include snow crab disease, predation, physiological condition and spatial distribution indicators. Bitter crab disease (BCD) prevalence remained below-average in 2023 following a record-high prevalence in 2016 that likely drove high mortality rates in juvenile snow crab. The 2016 peak in infection coincided with a large recruitment event of small (20-30mm) snow crab, which are more susceptible to BCD due to increased molt frequency (Messick and Shields, 2000). Below average disease prevalence following the 2021 snow crab population collapse is consistent with low stock density, although as the snow crab population continues to rebuild, an increased proportion of small snow crab in the system could lend to higher disease prevalence in the near future. Peaks in Pacific cod consumption of snow crab in 2016 also coincided with the large snow crab recruitment event, and this indicator has been trending downward since.

Following a dramatic reduction in male size at 50% probability of maturation in 2021, size at maturity increased by over 15mm in 2023 to remain slightly above the long-term average. While this indicator is indicative of population-level shifts in the average size at maturity, temporal trends may be driven by recruitment variability and cohort effects (Murphy 2021). Temperatures occupied by juvenile snow crab declined dramatically in 2022 from record-high temperatures in 2018-2021, and in summer 2023, juveniles occupied -0.3°C bottom waters on average. Occupied temperatures below 1°C indicate that cold-water habitat critical for evading groundfish predators was widely available for stenothermic juvenile snow crab. While mature male snow crab spatial extent was below-average in 2023, the male center of distribution has remained well above-average since 2021. High densities of large males northwest of St. Matthew Island and along the shelf edge in recent years may suggest temperature-driven distributional shifts (Orensanz et al., 2005).

The inclusion of a new upper trophic level indicator to quantify body condition of juvenile snow crab is both justified and timely due to concerns with high densities of snow crab and hypothesized starvation effects preceding the 2021 snow crab stock collapse (Szuwalski et al., *accepted*). Recent research has linked declines in body condition and lipid storage of early juvenile snow crab to warmer temperatures and reduced food quality in the Bering Sea (Copeman et al., 2021). Furthermore, previous laboratory studies have demonstrated that adequate energetic stores are prerequisites for molting, growth, and survival in snow crab early life history stages (e.g. Lovrich and Ouellet, 1994). A snow crab condition indicator was developed using hepatopancreas percentage dry weight (dry weight/wet weight ratio), and validated with fatty acid analyses (Copeman et al., *in prep*). The rapid incorporation of this indicator following the conclusion of the current year bottom trawl survey provides a metric for body condition of juvenile snow crab just prior to the energetically costly terminal molt, and annual data collections are planned for the foreseeable future. Despite the small sample size (n = 4 years), the new metric indicates that juvenile snow crab were in very poor condition in 2019 and indicator trends suggest poor survival to recruitment just prior to the stock collapse.

Fishery performance indicators are reported through the most recent calendar year (corresponding to the 2022-2023 crab season) and missing data are attributed to the 2023 directed snow crab fishery closure, with the exception of incidental catch in the (currently ongoing) EBS groundfish fisheries, reported through 2023. Due to a first-ever fishery closure, social and economic indicator information is extremely limited for 2023, and the ABSC Skipper Survey results reported in the last full ESP could not be conducted. However, we note that these missing data should emphasize the economic hardships being faced by the snow crab harvesters and processors during these closure periods in lieu of more meaningful community indicators that have not yet been developed. The following discussion notes trends in socioeconomic indicators in recent years leading up to the fishery closure.

The active snow crab fleet during 2022 declined to 42 vessels, the lowest level since 1977 at the beginning of the time series, and approximately 68% of the average number of vessels participating during the previous five years. Relative to the substantially reduced TAC (less than 13% of the previous year and less than 20% of the previous five-year average), less consolidation of fishing activity occurred than would be expected based on economic efficiency, and it is unclear if other factors driving this level of vessel participation will persist if TAC levels remain comparably low. CPUE in the fishery declined from 218 the previous year to 124 legal crab per potlift, and total potlifts declined from 172 thousand in 2021 to 37 thousand, with both indicators approaching the lower bound of one standard deviation below the long term (1991-current) average, respectively. The latitude of the center of gravity of fishing activity during 2022 shifted somewhat south compared to the previous year, but remained approximately two standard deviations greater than the long-term average. Incidental catch in EBS groundfish fisheries during 2021 declined for a fourth consecutive year to 77 thousand kg, approaching the lower bound of the long-term range of variation. TAC utilization reached 99% for the 2021-2022 snow crab fishery, however, fishing extended later than usual, with four vessels making landings later than May 15.

Economic performance indicators included in this ESP are reported through calendar year 2021, the most recent year for which data are available. With a TAC of 18.37 thousand metric tons, the highest since the 2014-2015 crab season, combined with historically high market values for snow crab driven by high consumer demand during the first two years of the covid-19 pandemic, estimated ex-vessel revenue in the snow crab fishery during 2021 exceeded $219 million, approaching the upper bound of one standard deviation above the long-term (1991-2021) average. Average ex-vessel price per pound reached a historical high in 2021, increasing by 25% from 2020, to $4.97 per pound, greater than two standard deviations higher than the historical average since 1991 (adjusted for inflation). As a result of the historically high ex-vessel value of the snow crab fishery during 2021, combined with the closure or reduced TAC levels in most crab and other fisheries targeted by the snow crab fleet, ex-vessel revenue share increased to an unprecedented 85% of total annual ex-vessel landings revenue, summed across all fisheries in which snow crab vessel landed catch during the 2021 calendar year. Although 2022 data is not yet available for economic performance indicators, news reports and other information indicate that market demand for crab and other premium seafood products contracted sharply in 2022, suggesting that economic returns for most or all of the fleet active during the 2021-2022 snow crab season were poor and many vessels likely operated at a loss.

Intermediate Stage: Importance Test

Bayesian adaptive sampling (BAS) was used to quantify the association between hypothesized ecosystem predictors and snow crab recruitment (survey abundance of immature male snow crab, 50 – 65mm), and to assess the strength of support for each hypothesis. In this stage, the full set of indicators is first winnowed to the predictors that have been identified as potential drivers of snow crab recruitment, and highly correlated covariates are removed. We further restrict potential covariates to those that can provide the longest model run and through the most recent estimate of recruitment. This results in a model run from 1993 through the 2021. We then provide the mean relationship between each predictor variable and snow crab recruitment over time (Figure 4a), with error bars describing the uncertainty (95% confidence intervals) in each estimated effect and the marginal inclusion probabilities for each predictor variable (Figure 4b). A higher probability indicates that the variable is a better candidate predictor of snow crab recruitment.

The highest ranked predictor variables based on this analysis were 1) juvenile snow crab temperature of occupancy, and 2) Pacific cod consumption. Inclusion probabilities < 0.5 indicate that the selected suite of indicators explained little variation in snow crab recruitment. Intermediate stage indicator importance tests in future ESP report cards will explore additional statistical techniques to address potential non-stationarity and missing observations.

Advanced Stage: Research Model Test

New research models are currently being explored to assess potential mechanisms for increased mortality (e.g. bitter crab syndrome, cod predation, cannibalism) in 2018-2019 (Szuwalski et al., *accepted*).

Data Gaps and Future Research Priorities

Future research should support the development of indicators that quantify snow crab physiological and biological responses to rapidly changing ecosystem conditions in the Bering Sea. Recent, dramatic population declines emphasize the importance of understanding proximate causes and mechanisms for mortality including predator-prey interactions, disease dynamics, shifts in benthic prey production, and responses to thermal stress. Proposed laboratory studies, for example, should focus on defining thermal limits across snow crab life history stages and quantifying temperature-dependent growth, respiration and consumption rates. Many previous studies are limited to mature snow crab and have been assessed only on the eastern Canadian snow crab stock (e.g. Foyle et al. 1989), potentially limiting the applicability of published results to the eastern Bering Sea snow crab stock.

Early life history data gaps also result in difficulties identifying potential recruitment bottlenecks and mechanistic linkages during larval and early benthic stages. Preliminary data collection on existing NOAA survey platforms has facilitated the enumeration of snow crab larvae (J. Weems, personal communication), and relating larval presence and CPUE data to environmental conditions will be critical for groundtruthing existing IBM modeling efforts and better understanding environmental drivers of larval supply and settlement success.

The limited scope and timeliness of socioeconomic indicators reported in the ESP provide limited information regarding the economic stresses on the harvest and processing sectors of the Bering Sea crab fisheries and associated communities resulting from the recent declines in the two principal Bering Sea crab fisheries. These stresses, if persistent, have the potential to induce substantial structural changes in crab harvest and processing industries, as well as management changes intended to mitigate adverse social and economic effects, ultimately inducing systematic operational changes in the behavior of snow crab fishing vessels. Developing community indicators to highlight these economic hardships during fishery closures is also of critical importance in light of multiple crab fishery closures. Research in spatial aspects of the EBS snow crab fishery with direct relation to the stock assessment may provide the basis for further development of relevant and informative socioeconomic indicators for use in the ESP. As well, improving the timeliness of socioeconomic indicators should be explored, including use of models for nowcast/forecast of time series, and or alternate or proxy measures that track key socioeconomic indicators.

As indicators are improved or updated, they may replace those in the current suite of indicators to allow for refinement of the BAS model and potential evaluation of performance and risk within the operational stock assessment model. Modifications to current indicators or additional indicators proposed for the 2024 snow crab ESP include: 1) developing a snow crab mature female clutch fullness indicator, as a measure of fecundity or reproductive potential, 2) refining the Pacific cod consumption indicator by standardizing consumption rates by the number of snow crab in the EBS/NBS, 3) including spring bloom type (i.e. ice-associated or open-water) and bloom timing indicators (contact J. Nielsen) as proxies for larval snow crab/spring bloom temporal overlap and pelagic energy exchange to the benthos, and 4) developing indicators that quantify overlap between crab and fishing gear during vulnerable life history periods, and metrics of vulnerable to these fishing gear interactions. The annual request for information (RFI) for the snow crab ESP will include these data gaps and research priorities along with a list of additional new indicators that could be developed for the next full ESP assessment.

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Tables

Table 1a. First stage ecosystem indicator analysis for snow crab, including indicator title and the indicator status of the last five available years. The indicator status is designated with text, (greater than = "high", less than = "low", or within 1 standard deviation = "neutral" of time series mean). Fill color of the cell is based on the sign of the anticipated relationship between the indicator and the stock (blue or italicized text = good conditions for the stock, red or bold text = poor conditions, white = average conditions). A gray fill and text = "NA" will appear if there were no data for that year.

Indicator category	Indicator	2019 Status	2020 Status	2021 Status	2022 Status	2023 Status
Physical	Winter Spring Arctic Oscillation Index Model	neutral	**high**	neutral	neutral	neutral
	Summer Cold Pool SEBS Survey	**low**	NA	**low**	neutral	neutral
	Winter Sea Ice Advance BS Satellite	**low**	neutral	neutral	neutral	neutral
Lower Trophic	AMJ Chlorophylla Biomass SEBS Satellite	neutral	neutral	neutral	neutral	**low**
	Summer Benthic Invertebrate Density SEBS Survey	neutral	NA	neutral	neutral	NA
Upper Trophic	Summer Snow Crab Juvenile Temperature Occupancy	**high**	NA	**high**	neutral	neutral
	Summer Snow Crab Juvenile Disease Prevalence	neutral	NA	neutral	neutral	neutral
	Annual Snow Crab Male Size Maturity Model	neutral	NA	**low**	neutral	neutral
	Summer Snow Crab Male Area Occupied SEBS Survey	**low**	NA	neutral	neutral	neutral
	Summer Snow Crab Male Center Distribution SEBS Survey	neutral	NA	*high*	*high*	*high*
	Summer Snow Crab Consumption Pacific cod Model	neutral	NA	neutral	neutral	NA
	Summer Snow Crab Juvenile Condition SEBS Survey	**low**	NA	neutral	neutral	neutral

Table 1b. First stage socioeconomic indicator analysis for snow crab, including indicator title and the indicator status of the last five available years. The indicator status is designated with text, (greater than = "high", less than = "low", or within 1 standard deviation = "neutral" of time series mean). A gray fill and text = "NA" will appear if there were no data for that year.

Indicator category	Indicator	2019 Status	2020 Status	2021 Status	2022 Status	2023 Status
Fishery Performance	Annual Snow Crab Active Vessels EBS Fishery	neutral	neutral	neutral	low	NA
	Annual Snow Crab CPUE Fishery	neutral	neutral	neutral	neutral	NA
	Annual Snow Crab Potlift Fishery	neutral	neutral	neutral	neutral	NA
	Annual Snow Crab Center Distribution EBS Fishery	high	neutral	high	high	NA
	Annual Snow Crab Incidental Catch EBS Fishery	neutral	neutral	neutral	neutral	neutral
Economic	Annual Snow Crab TAC Utilization EBS Fishery	neutral	neutral	neutral	neutral	NA
	Annual Snow Crab Exvessel Value EBS Fishery	neutral	neutral	neutral	low	NA
	Annual Snow Crab Exvessel Price EBS Fishery	high	high	high	high	NA
	Annual Snow Crab Exvessel Revenue Share EBS Fishery	neutral	high	high	neutral	NA

Figures

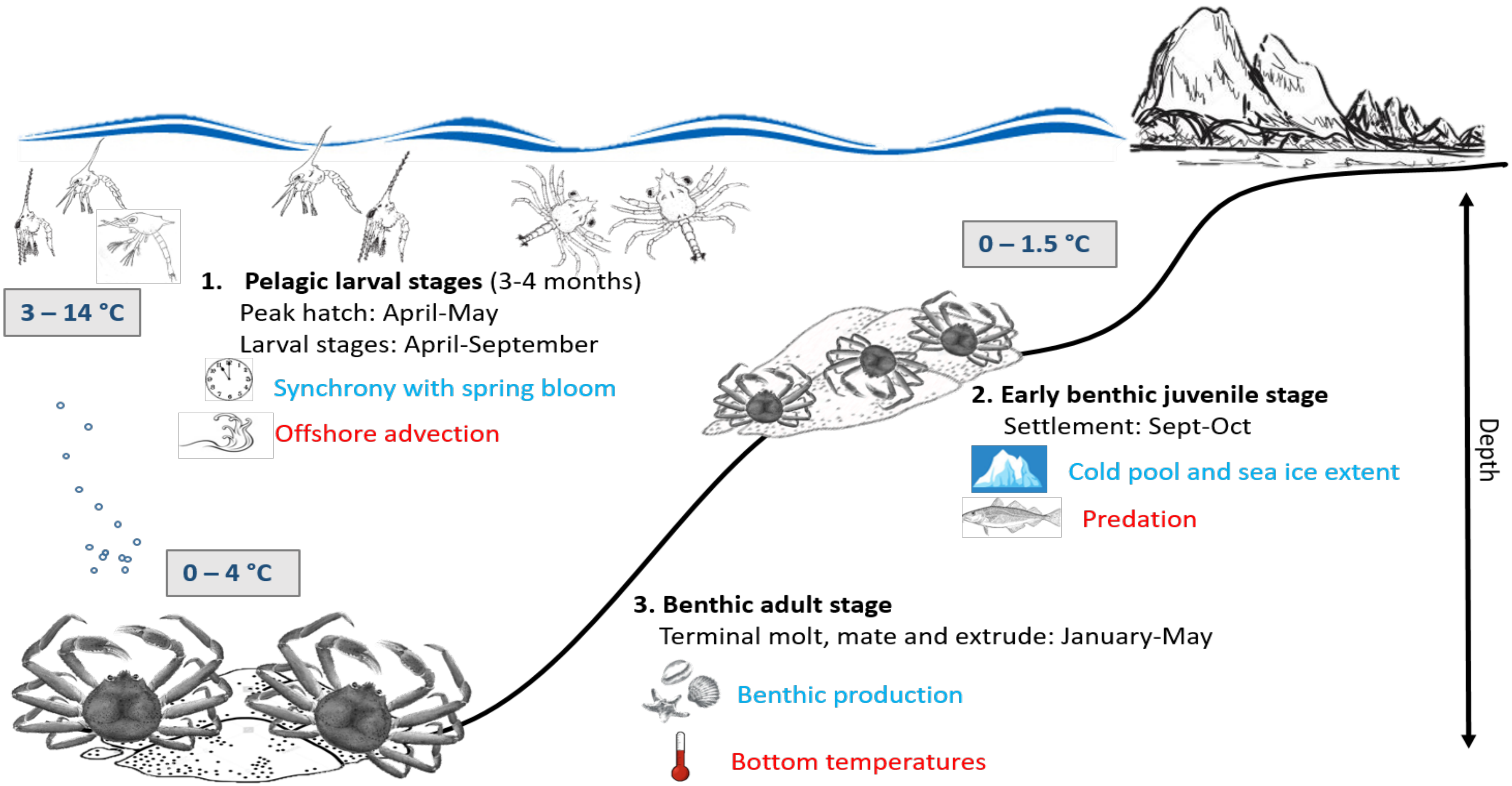

Figure 1: Life history conceptual model for snow crab summarizing ecological information and key ecosystem processes affecting survival by life history stage. Red text means increases in process negatively affect survival, while blue text means increases in process positively affect survival.

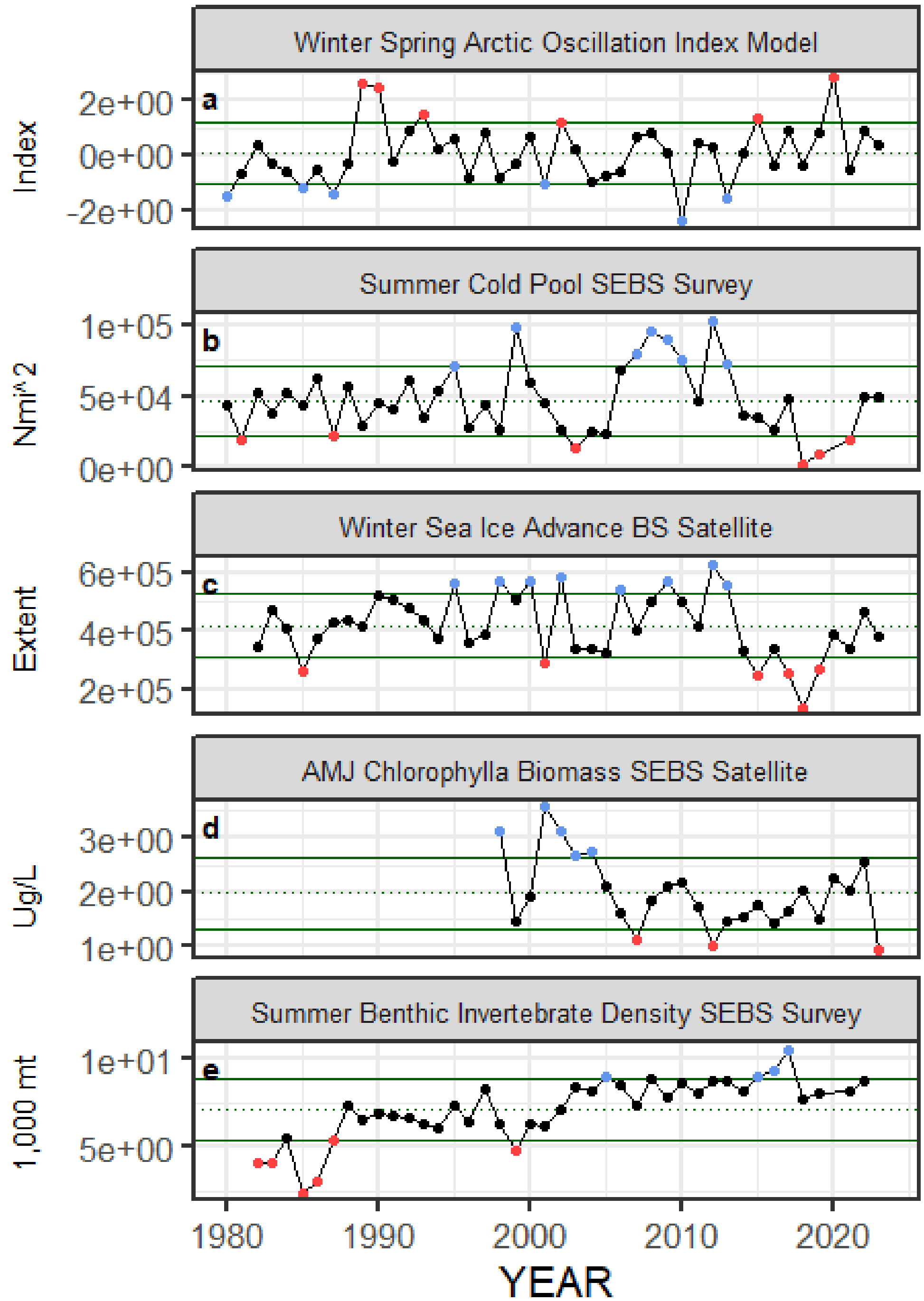

Figure 2a. Selected ecosystem indicators for snow crab with time series ranging from 1980 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. Dots in the time series are colored if above or below 1 standard deviation of the time series mean and the color represents the proposed relationship for stock, black circle for neutral.

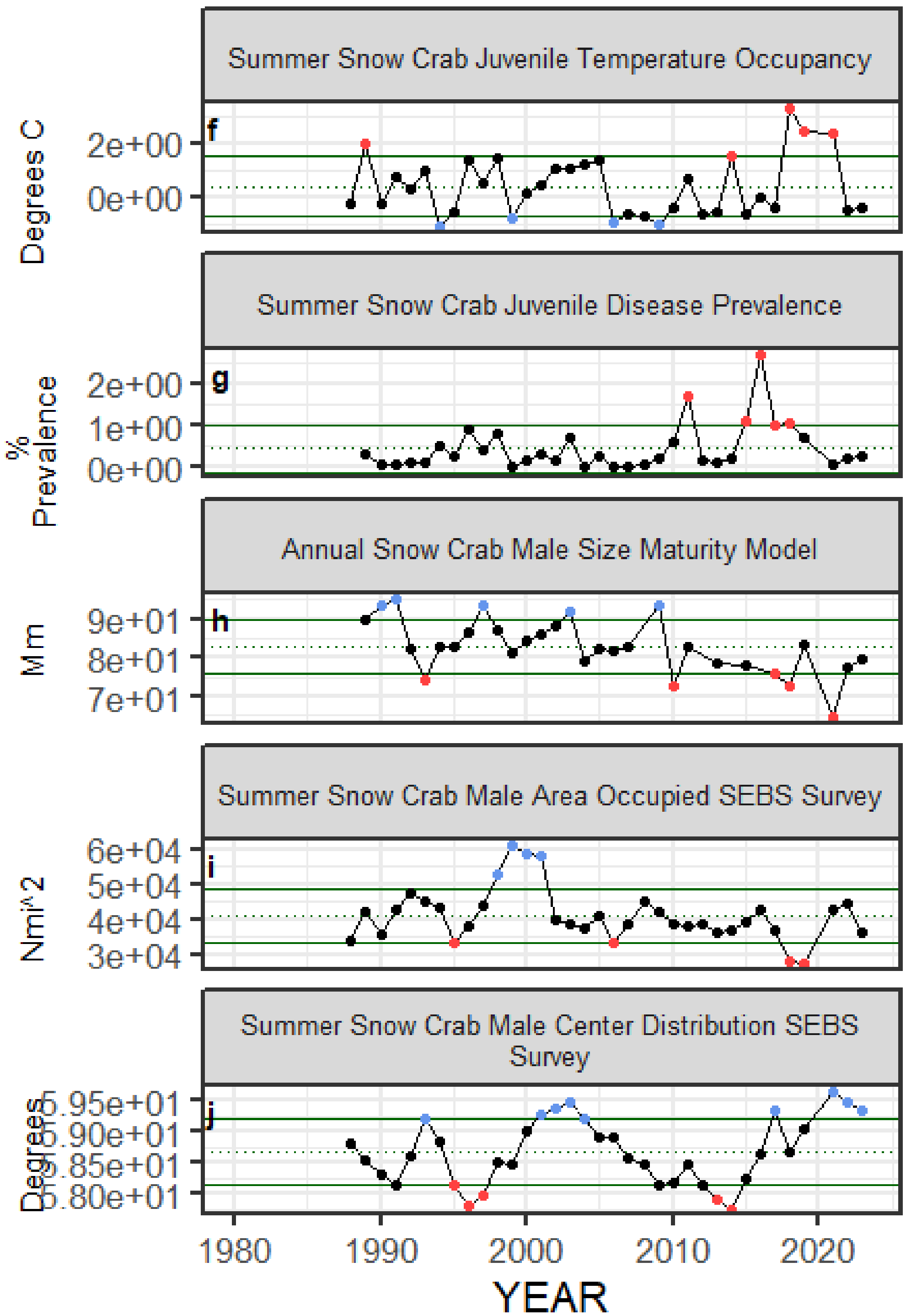

Figure 2a (cont.). Selected ecosystem indicators for snow crab with time series ranging from 1980 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. Dots in the time series are colored if above or below 1 standard deviation of the time series mean and the color represents the proposed relationship for stock, black circle for neutral.

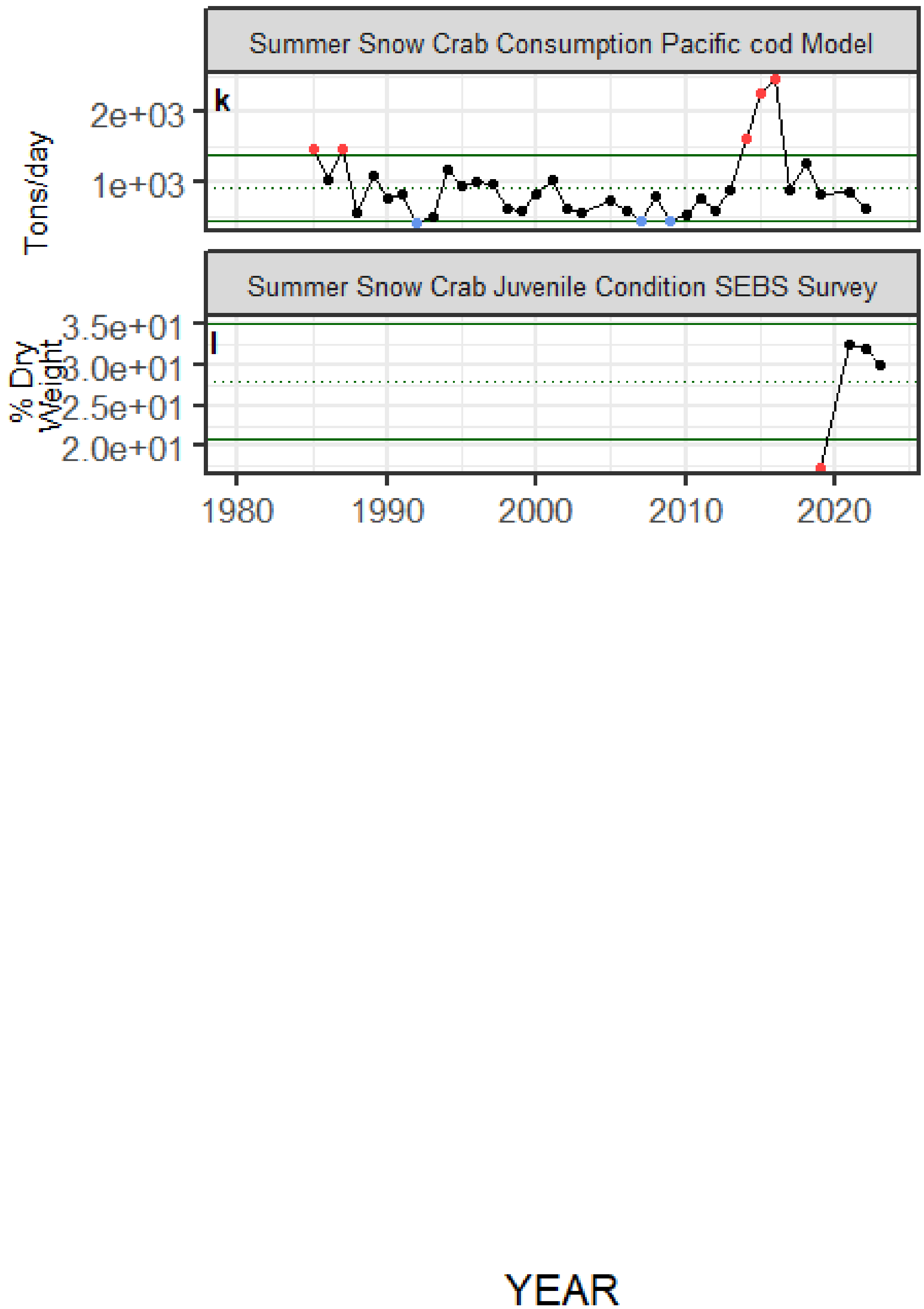

Figure 2a (cont.). Selected ecosystem indicators for snow crab with time series ranging from 1980 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. Dots in the time series are colored if above or below 1 standard deviation of the time series mean and the color represents the proposed relationship for stock, black circle for neutral.

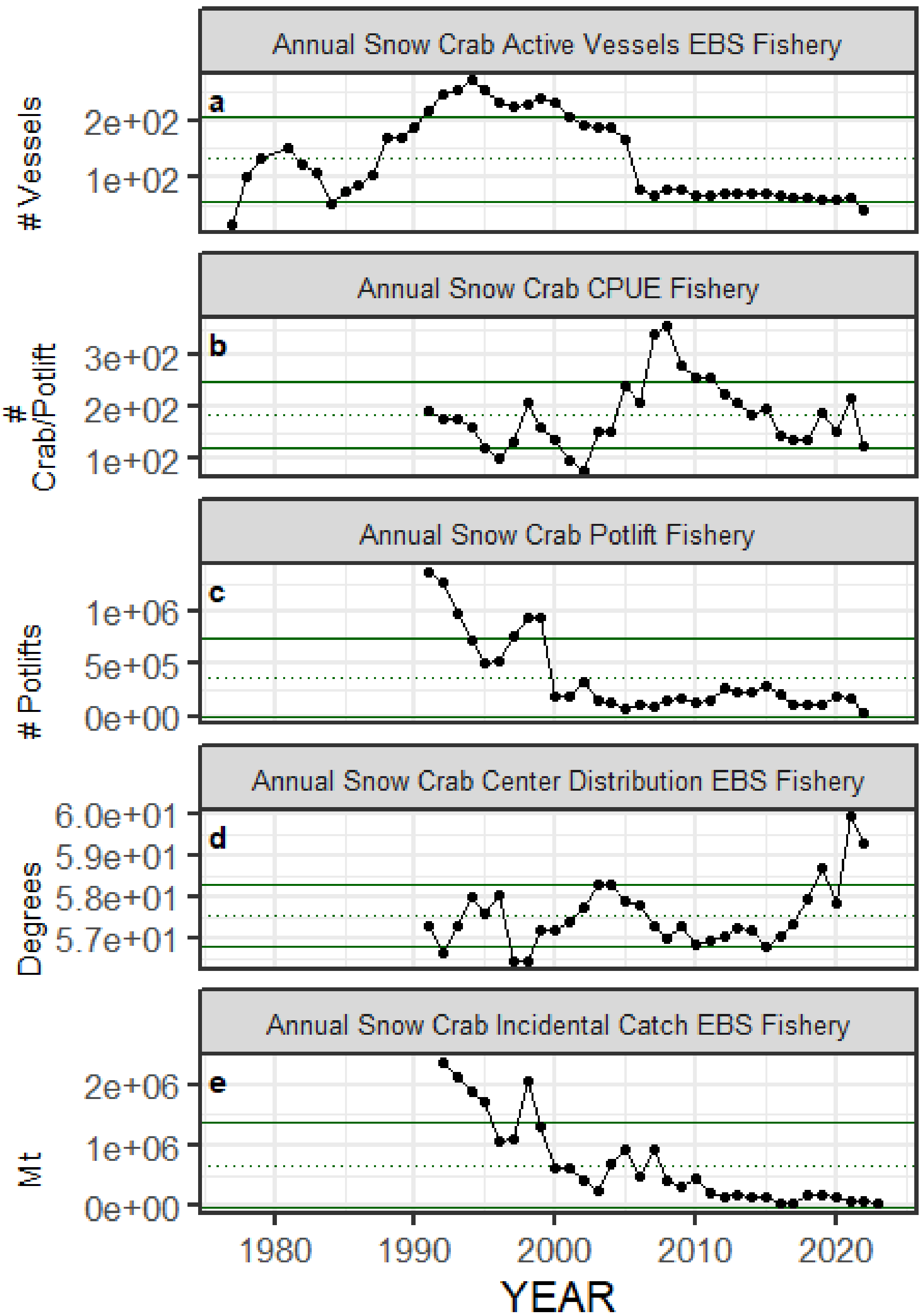

Figure 2b. Selected socioeconomic indicators for snow crab with time series ranging from 1966 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

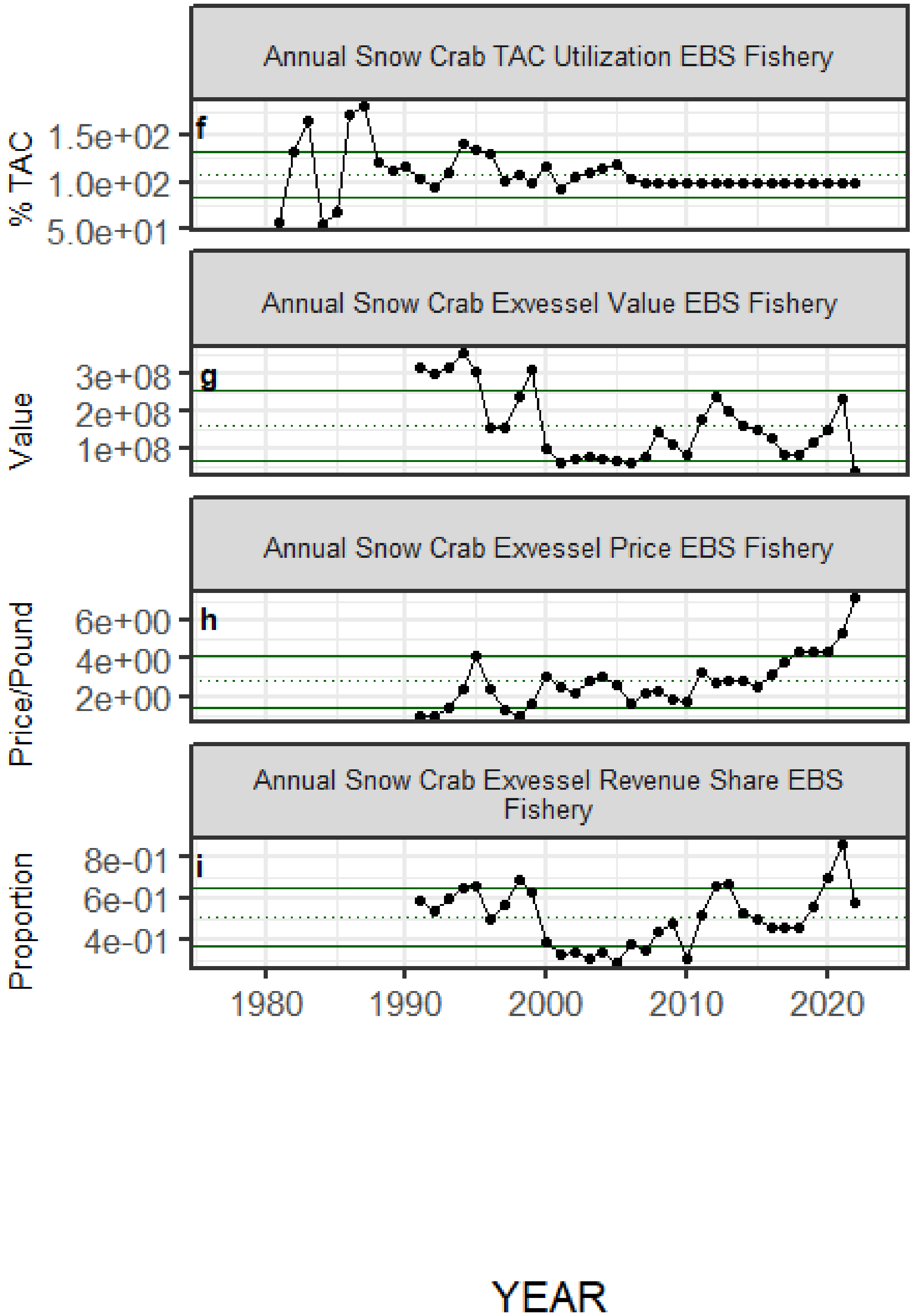

Figure 2b (cont.). Selected socioeconomic indicators for snow crab with time series ranging from 1966 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

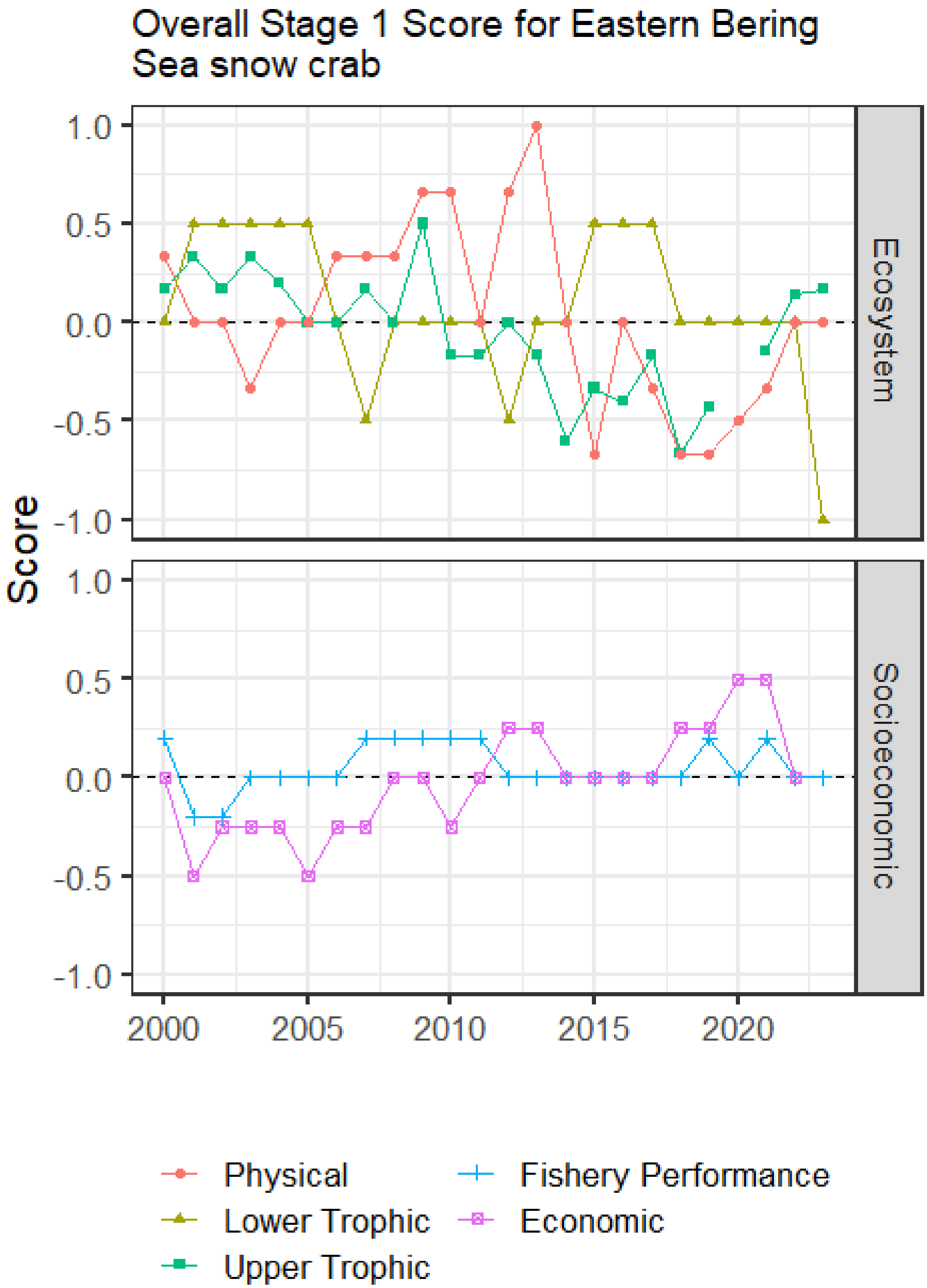

Figure 3: Simple summary traffic light score by category for ecosystem and socioeconomic indicators from 2000 to present.

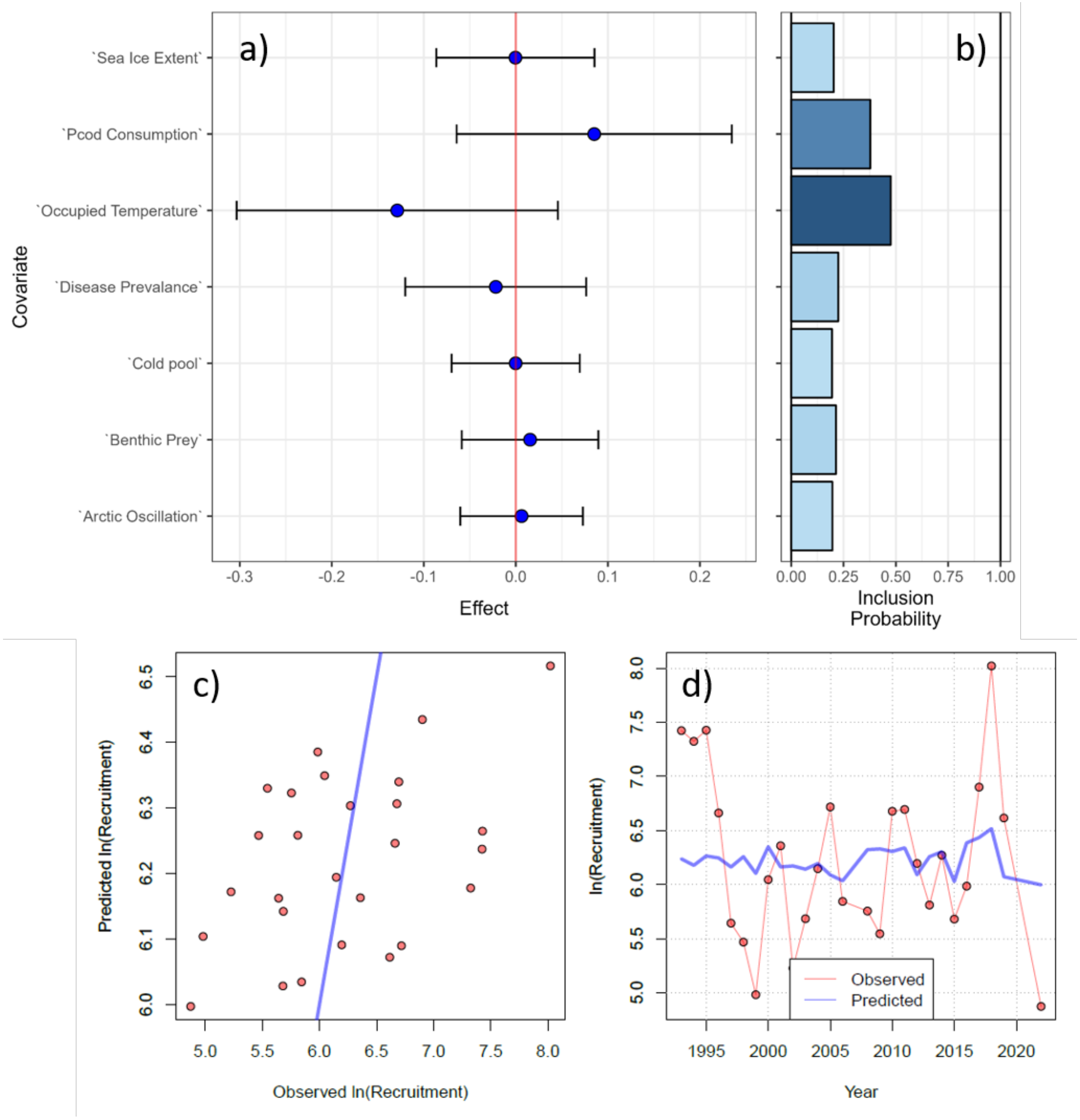

Figure 4. Bayesian adaptive sampling output showing the mean relationship and uncertainty (± 1 SD) with log-transformed EBS male snow crab recruitment (50-65mm male snow crab survey abundance): a) the estimated effect and b) marginal inclusion probabilities for each predictor variable of the subsetted covariate ecosystem indicator dataset. Output also includes model c) predicted fit (1:1 line) and d) average fit across the recruitment time series (1993 – 2021).