

An assessment for eastern Bering Sea snow crab

Cody Szuwalski

September 13, 2021

Contents

A. Summary of Major Changes

B. Comments, responses and assessment summary

SSC and CPT comments + author responses	
CIE review summary + author responses	
Assessment summary	

C. Introduction

Distribution	
Life history characteristics	
Natural Mortality	
Weight at length	
Maturity	
Mating ratio and reproductive success	
Growth	
Management history	
ADFG harvest strategy	
History of BMSY	
Fishery history	

D. Data

Catch data	
Survey biomass and size composition data	
Spatial distribution of survey abundance and catch	
Experimental study of survey selectivity	

E. Analytic approach

History of modeling approaches for the stock

Model description

Model selection and evaluation

Results

Fits to data

 Survey biomass data

 Growth data

 Catch data

 Size composition data

Estimated population processes and derived quantities

F. Calculation of the OFL

Methodology for OFL

Calculated OFLs and interpretation

G. Calculation of the ABC

Author recommendations

H. Data gaps and research priorities

I. Ecosystem Considerations

J. References

Appendix A: Status quo assessment model population dynamics

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

Retained catches increased from relatively low levels in the early 1980s (e.g. retained catch of 11.85 kt during 1982) to historical highs in 1990s (retained catch during 1991, 1992, and 1998 were 143.02, 104.68, and 88.09 kt, respectively). The stock was declared overfished in 1999 at which time retained catches dropped to levels similar to the early 1980s (e.g. retained catch during 2000 was 11.46 kt). Retained catches have slowly increased since 1999 as the stock rebuilt, and retained catch during 2020 was the highest in the last 6 years (20.41 kt).

Discard mortality is the next largest source of mortality after retained catch and approximately tracks the retained catch. The highest estimated discard mortality occurred during 1992 at 17.06 kt which was 16% of the retained catch during that year. The most recent estimated discard mortality was 5.8 kt which was 28% of the retained catch.

3. Stock Biomass:

Observed mature male biomass (MMB) at the time of the survey increased from an average of 161.68 kt in the early to mid-1980s to historical highs 1990s (observed MMB during 1990, 1991, and 1997 were 443.79, 466.61, and 326.75 kt, respectively). The stock was declared overfished in 1999 in response to the total mature biomass dropping below the 1999 minimum stock size threshold. MMB in that year decreased to 95.85 kt. Observed MMB slowly increased after 1999, and the stock was declared rebuilt in 2011 when estimated MMB at mating was above $B_{35\%}$. However, after 2011, the stock declined and the observed MMB at the time of survey dropped to an all-time low in 2016 of 63.21 kt. Recently, MMB was increasing as a large recruitment moved through the size classes, but that recruitment has since disappeared and the observed mature male biomass at the time of the 2021 survey was 62.25 kt, a new all-time low.

4. Recruitment

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

5. Management

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

Year	MSST	Biomass (MMB)	TAC	Retained catch	Total catch	OFL	ABC
2015/2016	75.8	91.6	18.4	18.4	21.4	83.1	62.3
2016/2017	69.7	96.1	9.7	9.7	11	23.7	21.3
2017/2018	71.4	99.6	8.6	8.6	10.5	28.4	22.7
2018/2019	63	123.1	12.5	12.5	15.4	29.7	23.8
2019/2020	56.8	167.3	15.4	15.4	20.8	54.9	43.9
2020/2021	76.7	26.7	20.4	20.4	26.2	95.4	71.55
2021/2022		50.6				7.5	5.6

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

Year	MSST	Biomass (MMB)	TAC	Retained catch	Total catch	OFL	ABC
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	157.74
2021/2022		111.55				16.53	12.35

6. Basis for the OFL

The OFL for 2021 from the chosen model (21.2) was 7.5 kt fishing at $F_{OFL} = 0.37$ (26% of the calculated $F_{35\%}$, 1.43). The calculated OFL was an -92% change from the 2020 OFL of 95.4 kt. The projected ratio of MMB at the time of mating in 2022 to $B_{35\%}$ is 0.33.

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

Year	Tier	BMSY	MMB	Status	FOFL	Years	M
2021/2022	3c	153.4	50.6	0.33	0.37	1982-2019	0.27, 0.28

7. Probability Density Function of the OFL

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

8. Basis for ABC

The ABC for the chosen model was 5.62 kt, calculated by subtracting a 25% buffer from the OFL as recommended by the SSC.

A. Summary of Major Changes

1. Management: None

2. Input data:

Data added to the assessment included: 2021 eastern Bering Sea survey biomass and size composition data, 2020 directed fishery retained and discard catch, size composition for retained and discard catch, and groundfish discard size composition and discard from 2020.

3. Assessment methodology:

Management quantities were derived from maximum likelihood estimates of model parameters in a size-based, integrated assessment method. Only status quo models are presented because time-varying natural mortality is not currently functional in GMACS for terminally molting life histories. Jittering was not performed because of the compressed time frame, unexpected survey results, and resulting modeling challenges. Retrospective analyses were performed for selected model configurations.

4. Assessment results

The updated estimate from the author-preferred model of MMB (February 15, 2021) was 26.74kt which placed the stock at 17% of $B_{35\%}$. Projected MMB on February 15, 2022 from this assessment's chosen model was 50.64 kt after fishing at the OFL, which will place the stock at 33% of $B_{35\%}$. Fits to all data sources were acceptable for the chosen model (see discussion below). If the author-preferred model is adopted, the stock will be declared overfished.

B. Comments, responses and assessment summary

SSC and CPT comments + author responses

“The SSC recommends that the authors experiment with models that either allow those time -invariant parameters to be free or adding more constraints on the time-variance in these models. The SSC would like to see at least one model alternative emerge in September that alleviates the strong retrospective bias.”

A ‘mortality event’ in 2018 and 2019 is presented in several models and appears to be the most parsimonious way to fit the recent survey data. Based on anecdotes from the 2021 survey, variation in catchability as a result of movement into the northern Bering Sea cannot explain the disappearance of the 2015 cohort (data may be available at the time of the plan team meeting). It is possible the crab moved west off of the shelf, but data are lacking to explore this hypothesis and historical slope surveys generally found very few snow crab.

“The SSC further recommends that if a variation of the status quo (20.1) model is preferred, it would be ideal to review a parallel version of the GMACS model.”

GMACS cannot currently model time-variation in natural mortality when terminally molting life history is assumed. Only the models in which mortality events occurred in 2018 and 2019 were able to fit the data acceptably. Consequently, no GMACS models are presented this year.

CIE review summary + author responses

A review of the assessment for eastern Bering Sea snow crab by the Center for Independent Experts (CIE) occurred in March 2021. Three reviewers were asked to evaluate the assumptions, fits, and performance of both the status quo and GMACS assessments for snow crab. They were also asked to comment on the use of the BSFRF selectivity experiments, retrospective patterns, and identify data gaps. The reviewers responses are summarized below, and complete reviews are available as appendices to the snow crab assessment online.

In general, all reviewers supported the transition to GMACS and viewed it as a superior platform compared to building bespoke models for each stock. (It should be noted that this was before the 2021 survey data were available). They emphasized the need to implement and test jittering functionality in GMACS. Retrospective patterns were a key concern of all reviewers and the patterns in snow crab were of a magnitude that caused one reviewer to raise concern about the appropriateness of using the assessment to determine stock status. Process based research aimed at understanding potentially time-varying population processes like natural mortality, growth, catchability, selectivity, or maturity were suggested to address the retrospective patterns. If this research is not feasible or does not yield useful results, index based approaches or correction factors should be evaluated for use in management.

All three reviewers emphasized revisiting the data weighting scheme for the snow crab assessment, in particular, computing effective sample sizes for all of the size composition data sources. They also recommended considering more flexible patterns of survey and fishery selectivity while re-weighting the size composition data.

Bitter crab syndrome was brought up as a concern after a presentation research showed high prevalence in the northern portion of the population in recent years. Further field studies were suggested and spatio-temporal modeling of the disease was recommended. Spatio-temporal modeling of reproductive dynamics was also recommended, in addition to management strategy evaluation of the assessment using spatially explicit operating models that allow for variation in population processes both over time and in space.

Each of these points have been or are in the process of being explored. Several GMACS implementations have been presented at crab plan team meetings and are being refined for eventual adoption. Matthieu Veron (a postdoc under Andre Punt and Cody Szuwalski) has just started work to document and improve GMACS to facilitate this transition. Several methods of addressing retrospective patterns for snow crab have been explored and presented to the CPT with mixed results. More flexible survey selectivity patterns

and data weighting options are explored in this document and initial explorations of the impact of bitter crab syndrome on snow crab population dynamics are underway. Two spatio-temporal modeling projects are also underway, with Maxime Olmos as the responsible postdoc under Andre Punt, Cody Szuwalski, and others. The first is a fully spatial stock assessment model using VAST; the second is a management strategy evaluation aimed at understanding the impacts of temporal and spatial variation in population processes on management performance.

Much effort is being expended to address the issues the concerned the CIE reviewers, but achieving satisfactory resolution of these issues will be an on-going process.

Assessment summary

Eight assessment models are presented here:

- 20.1 – Last year’s accepted model (status quo) fit to last year’s data
- 21.1 – Last year’s accepted model (status quo) fit to this year’s data
- 21.1a – 21.1 + empirical availability
- 21.1b – 21.1 + mortality events in 2018 and 2019
- 21.1c – 21.1a + McAllister-Ianelli re-weighting
- 21.2 – 21.1a + mortality events in 2018 and 2019 + tighter priors on M and maturity smoothness
- 21.3 – 21.1a + mortality events in 2018 and 2019 + empirical selectivity
- 21.3a – 21.3 + FMSY = natural mortality

Adding the newest data to the status quo model resulted in a model that did not converge (21.1; max gradient = 1.46). The gradients for estimated ‘availabilities’ associated with the BSFRF data and natural mortalities were large (in addition to estimated recruitment deviations). Models 21.1a and 21.1b were aimed at finding a model configuration with a maximum gradient < 0.01. Only the model that used ‘empirical’ availabilities achieved this (21.1a). Re-weighting the size composition data was strongly encouraged by the CPT and CIE review. Model 21.1c implemented McAllister-Ianelli re-weighting, but this resulted in large changes in management quantities and poor convergence of models. Francis re-weighting resulted in similar outcomes and these outcomes were shared across model scenarios (not shown).

Model 21.2 combined empirical availability and mortality events in 2018 and 2019. Using the same weights as 21.1a, the model did not converge (maximum gradient = 8.65). Priors on natural mortality were stiffened (standard deviations reduced from 0.054 to 0.014) and smoothness penalties on the probability of terminally molting were increased from 0.5 to 2. This resulted in a maximum gradient of 0.1 (higher than desired, but lower than without the changes). This model was the most similar to last year’s status quo model, but also fit the recent survey data by incorporating mortality events in 2018 and 2019.

Re-weighting the size composition data is recommended practice, but doing so resulted in much higher estimated probabilities of terminally molting than observed. One potential reason for this is the assumption that survey selectivity was logistic. Model 21.3 relaxed this assumption by estimating a non-parametric selectivity curve (i.e. a selectivity parameter for each size class). Model 21.3 used the averages of the observed selectivity in a size class over the 2009, 2010, 2016, 2017, and 2019 BSFRF selectivity experiments as priors. The averages and standard deviations were weighted by sample sizes.

Models 21.1a, 21.2, 21.3, and 21.3a were the only models with ‘relative’ convergence (max gradients for 21.2 was ~0.1, the others were « 0.1), and model 21.1a did not fit the final years of data well. Although the management outcomes of the converged models are not terribly different (i.e. the stock is overfished and the OFL is much lower than last year), the underlying reference points have very different management implications.

Model 21.3 and 21.3a produced estimates of population processes similar to the best available information, but Model 21.2 did not. Model 21.3 returned estimates of the probability of molting to maturity that were most similar to observed (Figure 1) and estimates of survey selectivity that were more similar to the

implied selectivity from the BSFRF data and the underbag experiments that predate the BSFRF experiments (Figure 2; Somerton and Goodman, 2010; Somerton and Otto, 1998). However, the F35% produced when these processes were matched by the assessment was equivalent to an exploitation rate of 99.99%—i.e. all industry preferred size males can be taken in a given year. This occurred because more males molt to maturity at a smaller size, which were then protected from the fishery by a relatively large size at selection.

Model 21.2 maintained the structure of the status quo model and resulting reference points as closely as possible given the new data. The F35% from model 21.2 was equivalent to a ~76% exploitation rate—still relatively high, but at least in line with historical rates. This occurs because the estimated probability of maturing at smaller size was much lower in model 21.2 than 21.3 (Figure 1). Model 21.3a was introduced as a potential option for addressing the issue of target exploitation rates of ~100% from 21.3.

Several unprecedented events in the snow crab population in the Bering Sea are described in this assessment. A mass mortality event appears to have occurred for snow crab for the first time since the survey began and the biomass of important size categories of crab are at historic lows (Figure 3). For example, the observed biomass of males greater than 101mm carapace width was 12,437 tons in 2021. The second lowest the biomass has ever been was 20,740 t in 2016. When the stock was declared overfished in 1999, the observed biomass was 52,042 tons. Females are also currently at historic lows (Figure 4).

Model 21.3 and 21.3a provided estimates of important population processes that were closest to the available observations. Long term, a model similar to model 21.3 should be the goal (with some viable methodology for size composition re-weighting). However, evaluation of potential knock-on effects of the large increases in F35% is likely prudent before adoption, particularly given record-low abundances. Selecting model 21.3a in which FMSY is assumed to equal natural mortality may be an over-correction given information available about the reproductive biology of snow crab. Watson (1972) observed a 61mm carapace male fertilize a 64 mm female in the lab, so it is possible that smaller mature males are reproductively active and important. However, in Canada, only crab >95 mm carapace width were reported as ‘functionally mature’ in situ (Conan and Comeau, 1986; Ennis et al. 1988). Studies similar to these could be synthesized to develop a currency of management that better reflect the importance of larger crab to reproduction relative to morphometrically mature males. A more thorough evaluation of the best way to inform selectivity with the BSFRF data and re-weight size composition would be useful given the variety of shapes of the resulting survey selectivity curves. In light of the uncertainties associated with adopting model 21.3 or 21.3a, the author-preferred model for 2021 is model 21.2.

C. Introduction

Distribution

Snow crab (*Chionoecetes opilio*) are distributed on the continental shelf of the Bering Sea, Chukchi Sea, and in the western Atlantic Ocean as far south as Maine. In the Bering Sea, snow crab are distributed widely over the shelf and are common at depths less than ~200 meters (Figure 5 & Figure 6 for 2021 distribution). Smaller crabs tend to occupy more inshore northern regions (Figure 7) and mature crabs occupy deeper areas to the south of the juveniles (Figure 8 & Figure 9; Zheng et al. 2001). The eastern Bering Sea population within U.S. waters is managed as a single stock; however, the distribution of the population may extend into Russian waters to an unknown degree.

Life history characteristics

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

Natural Mortality

Relatively few targeted studies exist to determine natural mortality for snow crab in the Bering Sea. In one of these studies, Nevissi, et al. (1995) used radiometric techniques to estimate shell age from last molt (Figure 10). The total sample size was 21 male crabs (a combination of Tanner and snow crab) from a collection of 105 male crabs from various hauls in the 1992 National Marine Fishery Service (NMFS) Bering Sea survey. Representative samples for the 5 shell condition categories were collected from the available crab. Shell condition 5 crab (SC5 = very, very old shell) had a maximum age of 6.85 years (s.d. 0.58, 95% CI approximately 5.69 to 8.01 years; carapace width of 110 mm). The average age of 6 crabs with SC4 (very old shell) and SC5, was 4.95 years (range: 2.70 to 6.85 years). Given the small sample size, this maximum age may not represent the 1.5% percentile of the population that is approximately equivalent to Hoenig's method (1983). Tag recovery evidence from eastern Canada revealed observed maximum ages in exploited populations of 17-19 years (Nevissi, et al. 1995, Sainte-Marie 2002). A maximum time at large of 11 years for tag returns of terminally molted mature male snow crab in the North Atlantic has been recorded since tagging started about 1993 (Fonseca, et al. 2008). Fonseca, et al. (2008) estimated a maximum age of 7.8 years post terminal molt using data on dactyl wear.

In recent years, the mean for the prior for natural mortality used in the eastern Bering Sea snow crab assessment was based on the assumption that longevity would be at least 20 years in a virgin population of snow crab, informed by the studies above. Under negative exponential depletion, the 99th percentile corresponding to age 20 of an unexploited population corresponds to a natural mortality rate of 0.23. Using Hoenig's (1983) method a natural mortality equal to 0.23 corresponds to a maximum age of 18 years.

In contrast to the implied natural mortalities from the methodology used above, Murphy et al. (2018) estimated time-varying natural mortality for eastern Bering Sea snow crab with a mean of 0.49 for females and 0.36 for males (based on the output of state-space models fit to NMFS survey data; Figure 11). Further, natural mortality estimates produced from empirical analyses by Then et al. (2015) and Hamel (2015) using similar assumed maximum ages as the methodology above produce natural mortalities larger than 0.23 (Table 4). 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 4: 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
Hoening (1983)	0.19	0.212	0.257
Hoening (2015)	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 12). 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.

Natural mortality is one of the major axes of uncertainty considered in the assessment scenarios presented in this assessment. The median value of the priors used in this assessment are set equal to values resulting from assuming a maximum age of 20 years and applying Hamel’s methodology. A standard error of 0.054 was used for initial priors and was estimated using the 95% CI of ± 1.7 years on maximum age estimates from dactyl wear and tag return analysis in Fonseca, et al. (2008). Models 21.1c and 21.2 decrease this standard error to stiffen the prior on natural mortality, which facilitated relative convergence.

Weight at length

Weight at length is calculated by a power function, the parameters for which were recalculated by the Shellfish Assessment Program in August 2016 and resulted in very small changes in weight at length for males, but rather large changes for females. New weight at length parameters were applied to all years of data, rather than just the most recent observations and were used starting in 2016 for calculation of the OFL. To provide context for the change, a juvenile female crab of carapace width 52.5 mm was previously estimated to weigh 65 g and is now 48 g; a mature female crab of carapace width 57.5 mm was estimated to previously weigh 102 g and is now 67.7 g; and a male of carapace width 92.5 mm was previously estimated to weigh 450 g and now weighs 451 g.

Maturity

Maturity of females collected during the NMFS summer survey was determined by the shape of the abdomen, by the presence of brooded eggs, or egg remnants. Maturity for males was determined by chela height measurements, which were available most years starting from the 1989 survey (Otto 1998). Mature male biomass referenced throughout this document refers to a morphometrically mature male (i.e. large-clawed). A maturity curve for males was estimated using the average fraction mature based on chela height data and applied to years of survey data to estimate mature survey numbers that do not have chela height data available. The separation of mature and immature males by chela height may not be adequately refined given the current measurement to the nearest millimeter. Chela height measured to the nearest tenth of a millimeter by Canadian researchers on North Atlantic snow crab showed a clear break in chela height at small and large widths and fewer mature animals at small widths than the Bering Sea data measured to the nearest millimeter. Measurements taken in 2004-2005 on Bering Sea snow crab chela to the nearest tenth of a millimeter show a similar break in chela height to the Canadian data (Rugolo et al. 2005). The probability of maturing (which is different from the fraction mature at length) is a freely estimated (but smoothed) function of length for both sexes within the assessment model.

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

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

Mating ratio and reproductive success

Bering Sea snow crabs are managed using mature male biomass (MMB) as a proxy for reproductive potential. MMB is used as the currency for management because the fishery only retains large male crabs, which are nearly 100% mature. Male snow crabs are sperm conservers, using less than 4% of their sperm at each mating and females also will mate with more than one male. The amount of stored sperm and clutch fullness varies with sex ratio (Sainte-Marie 2002). If mating with only one male is inadequate to fertilize a full clutch, then females will need to mate with more than one male, necessitating a sex ratio closer to 1:1 in the mature population, than if one male is assumed to be able to adequately fertilize multiple females. Although mature male biomass is currently the currency of management, female biomass may also be an important indicator of reproductive potential of the stock.

Clutch fullness is recorded for the females measured in the survey (Figure 13). 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 coincides with periods of high fishing mortality, but the even then the proportion of barren females was low (Figure 14). Biennial spawning is another confounding factor in determining the reproductive potential of snow crab. Laboratory analysis showed that female snow crab collected in waters colder than 1.5 degrees C from the Bering Sea spawn only every two years.

Further complicating the process of quantifying reproductive capacity, clutch fullness and fraction of unmated females may not account for the fraction of females that may have unfertilized eggs, since these cannot be detected by eye at the time of the survey. The fraction of barren females observed in the survey may not be an accurate measure of fertilization success because females may retain unfertilized eggs for months after extrusion. To examine this hypothesis, NMFS personnel sampled mature females from the Bering Sea in winter and held them in tanks until their eggs hatched in March of the same year (Rugolo et al. 2005). All females then extruded a new clutch of eggs in the absence of males. All eggs were retained until the crabs were euthanized near the end of August. Approximately 20% of the females had full clutches of unfertilized eggs. The unfertilized eggs could not be distinguished from fertilized eggs by visual inspection at the time they were euthanized. Indices of fertilized females based on the visual inspection method of assessing clutch fullness and percent unmated females may overestimate fertilized females.

Growth

Several studies are available to estimate the growth per molt of male and female snow crab in the Bering Sea (Table 6). These studies include:

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

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

Management history

ADFG harvest strategy

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

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

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

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

History of BMSY

Prior to adoption of Amendment 24, B_{MSY} was defined as the average total mature biomass (males and females) estimated from the survey for the years 1983 to 1997 (921.6 million lbs; NPFMC 1998) and MSST was defined as 50% of B_{MSY} . Currently, the biological reference point for biomass is calculated using a spawning biomass per recruit proxy, $B_{35\%}$ (Clark, 1993). $B_{35\%}$ is the biomass at which spawning biomass per recruit is 35% of unfished levels and has been shown to provide close to maximum sustainable yield for a range of stock productivities (Clark, 1993). Consequently, it is an often used target when a stock recruit relationship is unknown or unreliable. The range of years of recruitment used to calculate biomass reference points is from 1982 to the present assessment year, minus 1.

Fishery history

Snow crab were harvested in the Bering Sea by the Japanese from the 1960s until 1980 when the Magnuson Act prohibited foreign fishing. After the closure to foreign fleets, retained catches increased from relatively low levels in the early 1980s (e.g. retained catch of 11.85 kt during 1982) to historical highs in the early and mid-1990s (retained catches during 1991, 1992, and 1998 were 143.02, 104.68, and 88.09 kt, respectively; Table 7). The stock was declared overfished in 1999 at which time retained catches dropped to levels similar to the early 1980s (e.g. retained catch during 2000 was 11.46 kt). Retained catches have slowly increased since 1999 as the stock rebuilt. Retained catch in the most recent year was 20.41 kt.

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

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 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 15). Bycatch in fisheries other than the groundfish trawl fishery has historically been relatively low. Size frequency data and catch per pot have been collected by observers on snow crab fishery vessels since 1992. Observer coverage has been 10% on catcher vessels larger than 125 ft (since 2001), and 100% coverage on catcher processors (since 1992).

Several modifications to pot gear have been introduced to reduce bycatch mortality. In the 1978/79 season, escape panels were 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 2020 were used in this analysis (Table 7). Discard size composition data from 1992 to 2017 were estimated from observer data and then combined with retained catch size compositions to become the ‘total catch’ size composition data, which are fit in the assessment. In 2018, observer data collection changed and only total catch size composition data and retained size composition data are produced. This is a sensible step in data collection, but the current formulation of the snow crab model accepts discarded size composition data as an input. So, from 2018 onward the discarded size compositions were calculated by subtracting the retained size compositions from the total size compositions. This mismatch of input data types will be addressed in an upcoming data overhaul for the assessment.

The discard male catch was estimated for survey year 1982 to 1991 in the model using the estimated fishery selectivities based on the observer data for the period of survey year 1992 to 2020. 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 5 for a summary of catch data.

Table 5: Data included in the assessment. Dates indicate survey year.

Data component	Years
Retained male crab pot fishery size frequency by shell condition	1982 - 2020
Discarded Males and female crab pot fishery size frequency	1992 - 2020
Trawl fishery bycatch size frequencies by sex	1991 - 2020
Survey size frequencies by, maturity, sex and shell condition	1982 - 2021
Retained catch estimates	1982 - 2020
Discard catch estimates from crab pot fishery	1992 - 2020
Trawl bycatch estimates	1993 - 2020
Total survey abundance estimates and coefficients of variation	1982 - 2021
2009 study area biomass estimates, CVs, and size frequency for BSFRF and NMFS tows	2009
2010 study area biomass estimates, CVs, and size frequency for BSFRF and NMFS tows	2010

Survey biomass and size composition data

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

Mature biomass for males and females at the time of the survey were the primary indices of population size fit to here. In the status quo assessment, total survey numbers were input to the model via the .DAT file (e.g. Figure 16), after which MMB and FMB at the time of the survey were calculated based on the size composition data, which were delineated by shell condition, maturity state, and sex. Distinguishing between mature and immature crab for the size composition was accomplished by demarcating any female that had eggs reported in the survey as ‘mature’. Mature male size composition data were calculated by multiplying

the total numbers at length for new shell male crab by a vector of observed proportion of mature males at length. The observed proportions of mature males at length were calculated by chelae height and therefore refers only to ‘morphometrically’ mature males. All old shell crab of both sexes were assumed to be mature. New shell crab were demarcated as any crab with shell condition index ≤ 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 8).

The NMFS summer surveys were canceled in 2020 due to the coronavirus pandemic.

Spatial distribution of survey abundance and catch

Spatial gradients exist in the survey data by maturity and size for both sexes. For example, larger males have been more prevalent on the southwest portion of the shelf (Figure 8) while smaller males have been more prevalent on the northwest portion of the shelf (Figure 5). Females have exhibited a similar pattern (compare Figure 6 to Figure 9). In addition to changing spatially over the shelf and by size class, distributions of crab by size and maturity have also changed temporally. The centroids of abundance in the summer survey have moved over time (Figure 17 & Figure 18). Centroids of mature female abundance early in the history of the survey were farther south, but moved north during the 1990s. Since the late 1990s and early 2000s, the centroids moved south again, but not to the extent seen in the early 1980s. This phenomenon was mirrored in centroids of abundance for large males (Figure 18).

Centroids of the catch have generally been south of 58.5 N, even when ice cover did not restrict the fishery moving farther north. This is possibly due to proximity to port and practical constraints of meeting delivery schedules. In general, the majority of catch was taken west and north of the Pribilof Islands, but this rule has had exceptions. The highest CPUEs in 2020 were found farther north than usual.

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

Experimental study of survey selectivity

The Bering Sea Fisheries Research Foundation (BSFRF) has conducted supplementary surveys in the Bering Sea in which snow crab were caught during 2009, 2010, 2016, 2017, and 2018. The location and extent of these surveys varied over the years as the survey goals changed. In 2009, the survey consisted of 108 tows around 27 survey stations and the goal was to improve understanding snow crab densities and the selectivity of NMFS survey gear (Figure 19). In 2010, the survey area was larger and still focused on snow crab. The mature biomass and size composition data gleaned from each of these experiments (and their complimentary NMFS survey observations; Figure 20 & Figure 21) are incorporated into the model by fitting them as an extra survey that is linked to the NMFS survey through a shared selectivity (see appendix A for a description of the way in which the surveys are related in the assessment model). Abundances estimated by the industry surveys were generally higher than the NMFS estimates, which suggests that the catchability of the NMFS survey gear is less than 1.

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

for at least some of the size classes) can provide an empirical estimate of catchability/selectivity (Figure 22). Empirical estimates of catchability/selectivity vary by year and size class across the different BSFRF data sets (Figure 23). The number of snow crab used to develop estimates of numbers at length likely contribute to these differences among years (Figure 24), but other factors may also influence catchability/selectivity at size of the NMFS survey gear (e.g. Somerton et al. 2013 show substrate type can influence selectivity). The assessments presented either treat these data as an additional survey with selectivity nested within the NMFS survey or directly as priors on survey selectivity (see appendix A for details).

The status quo model estimates a vector that represents the ‘availability’ of crab to the BSFRF experiments (see appendix A for a discussion of how this is modeled). Availability in this case just means how much of the population was in the area surveyed in the BSFRF experiments. In some models presented here, an ‘empirical’ availability is specified, rather than estimated. Because we know the size composition of the total NMFS survey and the size composition of the NMFS survey stations associated with the BSFRF experiments, we can directly calculate the ‘empirical availability’ simply by dividing the size composition of the subset of stations within the BSFRF survey area by the size composition of all the NMFS summer survey stations.

E. Analytic approach

History of modeling approaches for the stock

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

Model description

The integrated size-structured model used by NMFS (and presented here) was developed following Fournier and Archibald’s (1982) methods, with many similarities to Methot (1990). The model was implemented using automatic differentiation software developed as a set of libraries under C++ (ADModel Builder). ADModel Builder can estimate a large number of parameters in a non-linear model using automatic differentiation software extended from Greiwank and Corliss (1991) and developed into C++ class libraries.

The snow crab population dynamics model tracked the number of crab of sex s , shell condition v , maturity state m , during year y at length l , $N_{s,v,m,y,l}$. A terminal molt was modeled in which crab move from an immature to a mature state, after which no further molting occurred. The mid-points of the size bins tracked in the model spanned from 27.5 to 132.5mm carapace width, with 5 mm size classes. For the base assessment (21.1), 433 parameters were estimated. Parameters estimated within the assessment included those associated with the population processes recruitment, natural mortality (historically subject to a fairly informative prior), fishing mortality, selectivity (fishery, survey, and BSFRF experiments), catchability, and maturity. Weight at length, discard mortality, bycatch mortality, and parameters associated with growth and proportion of recruitment allocated to size bin were estimated outside of the model or specified. See appendix A for a more complete description of the population dynamics. Only scenarios based on the status quo model are presented this year, but GMACS models will be presented when the necessary functionality is available.

A ‘jittering’ approach has been historically used to find the estimated parameter vector that produced the smallest negative log likelihood for the assessment model (Turnock, 2016). Jittering was not implemented here because of the compressed time scale for assessment. Retrospective analyses were performed in which the terminal year of data was removed sequentially from the model fitting for the author preferred model. Then

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

Two different methods for re-weighting the size composition data were attempted here: Francis (2011) and McAllister-Ianelli (1997). Each method iteratively calculates the sample sizes based on the fits to the observed data (see references for the respective methods and the snow crab .TPL on github repo for implementation). Size composition data often are the most numerous in assessment models and re-weighting these data sources is done in an attempt to balance their contribution to the objective function with other, less numerous data sources. The outcome of re-weighting is often a smaller emphasis placed on the size composition data in the objective function.

Model selection and evaluation

Models were evaluated based on their fit to the data, the credibility of the estimated population processes, the magnitude of retrospective patterns, and the strength of the influence of the assumptions of the model on the outcomes of the assessment.

Results

Models 21.1, 21.1b, and 21.1c did not converge. Model 21.2 returned a maximum gradient of ~ 0.1 ; models 21.1a, 21.3, and 21.3a had maximum gradients of ~ 0.007 . All models for which retrospective analyses were performed displayed retrospective patterns with a Mohn’s rho larger than the commonly used rule of thumb of 0.3 (Hurtado et al., 2015; Figure 25). Retrospective patterns suggest that a process is varying over time that is not allowed to vary within the model (e.g. catchability) or the data are incomplete (e.g. not all catch is reported).

Below, the fits to the data and estimated population processes for all considered models are described. A comparison of the total likelihoods is not proper across models because 1) different weightings were applied to data sources and priors and 2) some models treat the data sources differently (e.g. BSFRF and empirical selectivity). However, the likelihoods of some data sources can be compared (Table 9).

Fits to data

Survey biomass data

Fits to the survey mature male biomass were fairly similar for all models for the majority of years in the the time series (Figure 26 & Figure 27). The largest differences in fits occur in the final four years of data, resulting from the estimated ‘mortality events’ in 2018 and 2019 in some models. Models without mortality events do not fit the survey data in 2017-2019 (e.g. 21.1, 21.1a, 21.1c). Models 21.1b, 21.2, 21.3, and 21.3a all pass through the confidence intervals for years 2017-2019. Models with mortality events fit the data better as seen through the likelihood component (“Survey mature biomass”; Table 9).

Growth data

All models presented fixed the growth parameters based on a linear regression between pre- and post-molt carapace width estimated outside of the assessment (Figure 28).

Catch data

Retained catch data were fit by all models well, with no visually discernible differences among models and differences in the likelihoods among models were insignificant (Figure 29 & Table 9). Female discard data were fit adequately given the specified uncertainty, though some differences in fits existed during 2016-2020 (Figure 29), but differences in the value of the likelihood component among models was less than 1. Male discard data during the period for which data exist (early 1990s to the present) were well fit by every model with little visually discernible difference (Figure 29). Fits to the trawl data were adequate for all models given the uncertainty in the data (Figure 29).

Size composition data

Retained catch size composition data were visually well fit by all models (Figure 30); total catch size composition data were similarly well fit (Figure 31). The most obvious difference among models occurred in the years in which some models implemented mortality events and others did not (2018 and 2019). More variability was seen among the fits to the bycatch size composition data, but the general shapes of the predicted size compositions were largely similar within years (Figure 32).

Fits to size composition data for the BSFRF survey selectivity experiments produced some notable runs of positive and negative residuals for the males in particular (Figure 33). The number of males was generally underestimated by the industry survey in 2009 and overestimated by the NMFS survey, while the opposite pattern was seen for females. Fits to the 2010 survey size composition data were better than the 2009 fits.

Size composition data for the NMFS survey were generally well fit and fits were visually similar for most models (Figure 34, Figure 35, Figure 36 & Figure 37). Models in which survey selectivity was non-parametric (21.3 and 21.3a) and models in which size composition data were re-weighted (21.1c) produced somewhat poorer fits to the data. Fits to the 2021 survey size composition for 2021 were poor for both males and females. For males, a likely reason this occurred is the large difference in the probability of terminally molting observed in 2021 compared to other years (Figure 1). For females, the lack of fit may be related to differences in mortality by size class not captured by the model. The distribution of residuals for male and female survey composition data for the chosen model varied by sex. Size composition data for females tended to be overestimated for larger size classes (Figure 38), whereas a pattern for males was less clear (Figure 39).

Both Francis and McAllister-Ianelli re-weighting produced smaller weights for most size composition data components (only M-I shown; Figure 40). However, very few of the models ran during the iterative process of either re-weighting process converged. Francis weighting methods essentially removed all weight from the size composition data across sources after several iterations. This appeared to be related to issues with convergence within the iteration process. With smaller weights on the size composition data, the model could stray into territories where the data are not fit well and then have a hard time returning to sensible parameter estimates. In contrast to the Francis weights, the McAllister-Ianelli weights converged to relatively stable values, in spite of the lack of convergence of the models. Models could be coaxed away from non-convergence by altering the priors on other processes like natural mortality and maturity (see model 21.2). This exercise underscores the sensitivity of the status quo snow crab assessment to data weights.

Estimated population processes and derived quantities

Estimated population processes and derived quantities varied among models. Projected MMB for the 2021 crab year ranged from 47.11 to 190.65 kt (Figure 41). For the author preferred model (21.2), estimated fishing mortality in the recent past has been above $F_{35\%}$ in the past two years (Figure 42). Estimated MMB has been less than $B_{35\%}$ since 2011, and estimates from author-preferred model suggest that the population is currently beneath the minimum stock size threshold of one half $B_{35\%}$ (Figure 42).

Estimates of selectivity and catchability varied among models (Figure 43). Estimated catchability in both eras was lower for males than for females. In era 1 (1982-1988), selectivity curves all had similar shapes, but

the catchability coefficients ranges from ~ 0.2 to ~ 0.9 between males and females. In era 2 (1989-present), catchability ranged from 0.7 - 0.83 for males; for females, it was 1 for all models that assumed a logistic selectivity.

Re-weighting the size composition data had a large impact on estimated survey selectivity. Size at 50% selection shifted from ~ 40 mm carapace width for males to ~ 85 mm carapace width. Re-weighting of the size composition data resulted in the largest males having a probability of selection in the survey gear close to 1. This selectivity pattern is similar to what was estimated by Somerton and Otto (1998) based on the underbag experiments performed with the NMFS survey gear.

The shape of estimated survey selectivity ogive was decidedly non-logistic when using the empirically derived selectivity from the BSFRF experiments from 2009, 2010, 2016, 2017, and 2018 (i.e. the extrapolated number of crab by size class in the experimental area estimated from the NMFS data divided by sum of the extrapolated number of crab by size class in the experiment area estimated from the NMFS data and the BSFRF data) as priors. Both 21.3 and 21.3a estimated a ‘hump’ in selectivity from ~ 40 -60 mm carapace width, after which selectivity increased until ~ 0.8 for the largest crab modeled. The BSFRF ‘availability’ curves varied from 2009 to 2010 and among models, with the availability of crab to the experimental survey generally increasing in 2010 (Figure 44; note that some of these models use ‘empirical’ availability).

Large differences among models existed in the estimated shape of the curve representing the probability of maturing (Figure 45). Model 21.1c estimated the highest probabilities of molting at small sizes; models 21.3 and 21.3a represented a middle ground; and the other models had estimates similar to the status quo model. Models 21.3 and 21.3a estimated the probability of terminally molting most similar to the observed data (Figure 1), but the average observed probability of terminal molt at carapace widths from 80-100 mm is still somewhat higher than estimates from model 21.3 and 21.3a. The observed probabilities are used to split the observed male numbers at length in the survey into immature and mature arrays, so one might expect an assessment model to faithfully return these probabilities. It is possible that model assumptions are influencing these estimates (e.g. growth or natural mortality).

Trends in estimated fishing mortality in the directed fishery were similar for all models, except for in the most recent years. Models that estimated mortality events in 2018 and 2019 estimated lower fishing mortalities in recent years than those that did not (Figure 46). Total and retained fishery selectivity was very similar for all models because of the weight put on the retained catch and its associated size composition data (Figure 46). Estimated size at 50% selection in the trawl fishery varied more than selectivity in the directed fishery, (Figure 46). Size at 50% selection for discarded females was similar for all models (Figure 46).

Patterns in recruitment by sex varied among models, particularly with respect to the size of the recent large pseudocohort (Figure 47). Generally, the models estimated a period of high recruitment in which 3 large male cohorts passed through the population during the 1980s and into the early 1990s. Following that, a period of low recruitment persisted from the early 1990s to 2013. Models in which mortality events were estimated also estimated large recruitment in the mid-2010s; those that did not estimate mortality events estimated much lower recruitments. Recruitment entering the model was placed primarily in the first three size bins (Figure 47).

Estimated natural mortality ranged from 0.23 to 0.33 for immature crab, 0.26 to 0.37 for mature female crab, and 0.26 to 0.30 for mature males (Figure 48).

F. Calculation of the OFL

Methodology for OFL

The OFL was calculated using proxies for biomass and fishing mortality reference points and a sloped control rule. Proxies for biomass and fishing mortality reference points were calculated using spawner-per-recruit methods (e.g. Clark, 1991). After fitting the assessment model to the data and estimating population parameters, the model was projected forward 100 years using the estimated parameters under no

exploitation 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.

Calculated values of $F_{35\%}$ and $B_{35\%}$ were used in conjunction with a Tier 3 control rule to adjust the proportion of $F_{35\%}$ that is applied based on the status of the population relative to $B_{35\%}$ (Amendment 24, NMFS).

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

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

Calculated OFLs and interpretation

OFLs calculated from maximum likelihood estimates of parameters in the suite of presented models ranged from 2.27 to 51.92kt (Table 10). Differences in OFLs were a result of differences in estimated MMB (see above), calculated $B_{35\%}$ (which ranged from 101.73 to 183.36kt; Table 10), $F_{35\%}$ (which ranged from 0.3 to 165.67 yr⁻¹; Table 10), and F_{OFL} (which ranged from 0.1 to 105.22 yr⁻¹; Table 10). Changes in the estimated probability of maturing strongly influenced the resulting reference points.

G. Calculation of the ABC

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

Author recommendations

Several unprecedented events in the snow crab population in the Bering Sea are described in this assessment. This is the first time a mass mortality event appears to have occurred for snow crab since the survey began and the biomass of important size categories of crab are at historic lows (Figure 3). For example, the observed biomass of males greater than 101mm carapace width was 12,437 tons in 2021. The second lowest the biomass has ever been was 20,740 t in 2016. When the stock was declared overfished in 1999, the observed biomass was 52,042 tons. Females are also currently at historic lows (Figure 4).

Model 21.3 and 21.3a provided estimates of important population processes that were closest to the available observations. Long term, a model similar to model 21.3 should be the goal (with some viable methodology for size composition re-weighting). However, evaluation of potential knock-on effects of the large increases in $F_{35\%}$ is likely prudent before adoption, particularly given record-low abundances. Selecting model 21.3a in which F_{MSY} is assumed to equal natural mortality may be an over-correction given information available about the reproductive biology of snow crab. Watson (1972) observed a 61mm carapace male fertilize a 64 mm female in the lab, so it is possible that smaller mature males are reproductively active and important. However, in Canada, only crab >95 mm carapace width were reported as ‘functionally mature’ in situ (Conan and Comeau, 1986; Ennis et al. 1988). Studies similar to these could be synthesized to develop a currency of

management that better reflect the importance of larger crab to reproduction relative to morphometrically mature males. A more thorough evaluation of the best way to inform selectivity with the BSFRF data and re-weight size composition would be useful given the variety of shapes of the resulting survey selectivity curves. In light of the uncertainties associated with adopting model 21.3 or 21.3a, the author-preferred model for 2021 is model 21.2.

H. Data gaps and research priorities

Moving to GMACS, understanding the relative benefits of incorporating data into the assessment vs. estimating parameters determining important population processes outside of the model, and reducing retrospective patterns through informed time-variation in population processes or process research are high priority tasks for the snow crab assessment. Evaluation of methods for incorporating the BSFRF data as priors on survey selectivity and methods for incorporating data on the probability of terminal molt more directly into the assessment also needs to occur. An enumeration of the ramifications of management with an F35% that can allow all males of industry-preferred size to be harvested needs to be performed, with particular attention paid to the appropriateness of the use of morphometrically mature males as the currency of management and the relative contribution to reproduction of males by size.

I. Ecosystem Considerations

The most important ecosystem consideration for snow crab in the EBS centers around what happened to the 2015 pseudocohort. It was observed for 4 years before being halved from the 2018 survey to the 2019 survey. In 2020, no survey occurred, and we grappled with two hypotheses for the decline in 2019—did the crab move or did the crab die? The 2021 survey data suggest that the crab died—they did not reappear in the EBS 2021 NMFS survey and preliminary information suggest they are not in the NBS either. It is possible the crab moved off of the shelf into deeper waters, but data to support or refute this are sparse. NMFS performs a EBS slope survey in some years, but there have generally been very few snow crab observed in these surveys and the area of the slope relative to the shelf is much smaller (Figure 49 & Figure 50). No slope survey was not performed in 2020 or 2021. If the trend of few crab on the slope was maintained and a mortality event(s) is the only remaining culprit for the declines seen in 2018 and 2019, what was the cause of mortality?

Predation is one possible driver of increased mortality. Pacific cod are one of the largest predators of snow crab in the Bering Sea. Crab found in cod stomach are primarily smaller than 60 mm carapace width, with that majority smaller than 40 mm carapace width (Figure 51). The crab that went missing from 2018 to 2019 were 50-70 mm carapace width. The crab missing from 2019 to 2021 were primarily from 65-85 mm carapace width, largely out of the range of predation risk by cod, which suggests cod were not the culprit. This notion is reinforced by the number and size composition of cod during those years (Figure 52 & Figure 53). Relatively few cod were present in the Bering Sea when these crab went missing and those that were present in larger numbers were small in body size.

Disease is another possible driver of increased mortality. Bitter crab syndrome is an infectious disease known to affect snow crab in the Bering Sea and it is thought to be fatal. Spikes in the prevalence of bitter crab syndrome mirrored the rise and fall of the 2015 cohort (Figure 54). While the increases in BCS since 2015 are far from a clear, causal driver, the potential for an infectious disease to cause mortality should be closely considered, particularly during periods in which densities of crab were at their highest ever observed.

The investigation into the disappearance of the 2015 pseudocohort will be an on-going process. Regardless of the outcome, the disappearance underscores the importance of a yearly survey for snow crab in the Bering Sea.

J. References

- Chilton, E.A., C.E. Armisted and R.J. Foy. 2009. Report to industry on the 2009 Eastern Bering Sea crab survey. AFSC Processed Report 2009-XX.
- Clark, W.G. 1991. Groundfish exploitation rates based on life history parameters. *Can. J. fish. Aquat. Sci.* 48: 734-750.
- Conan, G.Y. and Comeau, M. 1986. Functional maturity and terminal molt of male snow crab. *Can J. Fish Aquat Sci.* 43(9):
- Dawe, E.G., D.M. Taylor, J.M. Hoenig, W.G. Warren, and G.P. Ennis. 1991. A critical look at the idea of terminal molt in male snow crab (*Chionoecetes opilio*). *Can. J. Fish. Aquat. Sci.* 48: 2266-2275.
- Ennis, G.P., Hooper, R.G. Taylor, D.M. 1988. functional maturity in smalle male snow crab. *Can J Fish Aquat Sci.* 45(12):
- Ernst, B, J.M.(Lobo) Orensanz and D.A. Armstrong. 2005. Spatial dynamics of female snow crab (*Chionoecetes opilio*) in the eastern Bering Sea. *Can. J. Fish. Aquat. Sci.* 62: 250-268.
- Fonseca, D. B., B. Sainte-Marie, and F. Hazel. 2008. Longevity and change in shell condition of adult male snow crab *Chionoecetes opilio* inferred from dactyl wear and mark-recapture data. *Transactions of the American Fisheries Society* 137:1029-1043.
- Fournier, D.A. and C.P. Archibald. 1982. A general theory for analyzing catch-at-age data. *Can.J.Fish.Aquat.Sci.* 39:1195-1207.
- Greiwan, A. and G.F. Corliss(eds). 1991. Automatic differentiation of algorithms: theory, implementation and application. Proceedings of the SIAM Workshop on the Automatic Differentiation of Algorithms, held Jan. 6-8, Breckenridge, CO. Soc. Indust. And Applied Mathematics, Philadelphia.
- Hamel, O. 2015. A method for calculating a meta-analytical prior for the natural mortality rate using multiple life history correlates. *ICES Journal of Marine Science.* 72: 62-69.
- Hoenig, J. 1983. Empirical use of longevity data to estimate mortality rates. *Fish. Bull.* 82: 898-903.
- Lang, C. A., J. I. Richar, and R. J. Foy. 2019. The 2018 eastern Bering Sea continental shelf and northern Bering Sea trawl surveys: Results for commercial crab species. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-386, 220 p.
- McAllister, M.K. and Ianelli, J.N. 1997. Bayesian stock assessment using catch-at-age data and the sampling importance resampling algorithm. *Can. J. Fish. Aquat. Sci.* 54(2): 284-300.
- Mcbride (1982). Tanner crab tag development and tagging experiments 1978-1982. In Proceedings of the International Symposium of the Genus *Chionoecetes*. Lowell Wakefield Fish. Symp. Ser., Alaska Sea Grant Rep. 82-10. University of Alaska, Fairbanks, Alaska. Pp. 383-403.
- Method, R. D. 1990. Synthesis model: An adaptable framework for analysis of diverse stock assessment data. *Int. N. Pac. Fish. Comm. Bull.* 50:259-277.
- Murphy, J.T. Rugolo, L.J., Turnock, B.J. 2018. Estimation of annual, time-varying natural mortality and survival for Eastern Bering Sea snow crab (*Chionoecetes opilio*) with state-space population models. *Fish Res* 205: 122-131.
- Murphy, J.T. Rugolo, L.J., Turnock, B.J. 2017. Integrating demographic and environmental variables to calculate an egg production index for the Eastern Bering Sea snow crab (*Chionoecetes opilio*). *Fisheries Research.* 193: 143-157.
- Murphy, J. T., A. B. Hollowed, J. J. Anderson. 2010. Snow crab spatial distributions: examination of density-dependent and independent processes. Pp. 49-79. In G. Kruse, G. Eckert, R. Foy, G. Kruse, R. Lipcius, B. St. Marie, D. Stram, D. Woodby (Eds.), *Biology and management of Exploited Crab Populations Under Climate Change*. Alaska Sea Grant Program Report AK-SG-10-01, University of Alaska Fairbanks, AK. Doi:10.4027/bmecppc.2010.19

- Myers, R.A. 1998. When do environment-recruitment correlations work? *Reviews in Fish Biology and Fisheries*. 8(3): 285-305.
- Nevissi, A.E., J.M. Orensanz, A.J.Paul, and D.A. Armstrong. 1995. Radiometric Estimation of shell age in Tanner Crab, *Chionoecetes opilio* and *C. bairdi*, from the eastern Bering Sea, and its use to interpret indices of shell age/condition. Presented at the International symposium on biology, management and economics of crabs from high latitude habitats October 11-13, 1995, Anchorage, Alaska.
- NPFMC (North Pacific Fishery Management Council). 2007. Environmental Assessment for Amendment 24. Overfishing definitions for Bering Sea and Aleutian Islands King and Tanner crab stocks. North Pacific Fishery Management Council, Anchorage, AK, USA..
- NPFMC (North Pacific Fishery Management Council). 2000. Bering Sea snow crab rebuilding plan. Amendment 14. Bering Sea Crab Plan Team, North Pacific Fishery Management Council, Anchorage, AK, USA..
- NPFMC 1998. Bering Sea and Aleutian Islands Crab FMP. Bering Sea Crab Plan Team, North Pacific Fishery Management Council, P. O. Box 103136, Anchorage, Ak 99510.
- Orensanz, J.M., J. Armstrong, D. Armstrong and R. Hilborn. 1998. Crustacean resources are vulnerable to serial depletion - the multifaceted decline of crab and shrimp fisheries in the Greater Gulf of Alaska. *Reviews in Fish Biology and Fisheries* 8:117-176.
- Otto, R.S. 1998. Assessment of the eastern Bering Sea snow crab, *Chionoecetes opilio*, stock under the terminal molting hypothesis. In *Proceedings of the North Pacific Symposium on Invertebrate Stock Assessment and Management*. Edited by G.S. Jamieson and A. Campbell. *Can. Spec. Publ. Fish. Aquat. Sci.* 125. pp. 109-124.
- Parada, C., Armstrong, D.A., Ernst, B., Hinckley, S., and Orensanz, J.M. 2010. Spatial dynamics of snow crab (*Chionoecetes opilio*) in the eastern Bering Sea—Putting together the pieces of the puzzle. *Bulletin of Marine Science*. 86(2): 413-437.
- Paul, A.J., J.M. Paul and W.E. Donaldson. 1995. Shell condition and breeding success in Tanner crabs. *Journal of Crustacean Biology* 15: 476-480.
- Restrepo, V.R., G.G. Thompson, P.M. Mace, W.L. Gabriel, L.L. Low, A.D. MacCall, R.D. Methot, J E. Powers, B.L. Taylor, P.R. Wade, and J.F. Witzig. 1998. Technical guidance on the use of precautionary approaches to implementing National Standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act. NOAA Technical Memorandum NMFS-F/SPO-31.
- Rugolo, L.J., D. Pengilly, R. MacIntosh and K. Gravel. 2005. Reproductive dynamics and life-history of snow crab (*Chionoecetes opilio*) in the eastern Bering Sea. Final Completion Report to the NOAA, Award NA17FW1274, Bering Sea Snow Crab Fishery Restoration Research.
- Rodionov, S. 2004. A sequential algorithm for testing climate regime shifts. *Geophysical Research Letters* 21: L09204.
- Sainte-Marie, B., Raymond, S., and Brethes, J. 1995. Growth and maturation of the male snow crab, *Chionoecetes opilio* (Brachyura: Majidae). *Can.J.Fish.Aquat.Sci.* 52:903-924.
- Sainte-Marie, B., J. Sevigny and M. Carpentier. 2002. Interannual variability of sperm reserves and fecundity of primiparous females of the snow crab (*Chionoecetes opilio*) in relation to sex ratio. *Can.J.Fish.Aquat.Sci.* 59:1932-1940.
- Somerton, D.A. and Otto, R.S. 1999. Net efficiency of a survey trawl for snow crab and Tanner crab. *Fish Bull* 97: 617-625.
- Somerton, D.A. Weinberg, K.L., Goodman, S.E. 2013. Catchability of snow crab by the eastern Bering Sea bottom trawl survey estimated using a catch comparison experiment. *Can.J.Fish.Aquat.Sci.* 70: 1699-1708.
- Szuwalski, C.S. and Punt, A.E. 2013. Regime shifts and recruitment dynamics of snow crab, *Chionoecetes opilio*, in the eastern Bering Sea. *Fisheries Oceanography*, 22: 345-354.

- Szuwalski, C.S. and Punt, A.E. 2012. Fisheries management for regime-based ecosystems: a management strategy evaluation for the snow crab fishery in the eastern Bering Sea. *ICES Journal of Marine Science*. 70: 955-967.
- Tamone, S.L., M. Adams and J.M. Dutton. 2005. Effect of eyestalk ablation on circulating ecdysteroids in hemolymph of snow crab *Chionoecetes opilio*: physiological evidence for a terminal molt. *Integr. Comp. Biol.*, 45(120), p.166-171.
- Then, A. Y., Hoenig, J. M., Hall, N. G., and Hewitt, D. A. 2015. Evaluating the predictive performance of empirical estimators of natural mortality rate using information on over 200 fish species. *ICES Journal of Marine Science*, 72: 82–92.
- Turnock, B.J. 2016. Snow crab assessment model scenarios and convergence testing. Alaska Fishery Science Center.
- watson, J. 1972. Mating behavior in the spider crab, *Chionoecetes opilio*. *J Fish Res Board Can* 29: 447-449.
- Zheng, J., S. Siddeek, D. Pengilly, and D. Woodby. 2002. Overview of recommended harvest strategy for snow crabs in the Eastern Bering Sea. Regional Information Report No. 5J02-03. Alaska Department of Fish and Game. Juneau, Alaska.
- Zheng, J., G.H. Kruse, and D.R. Ackley. 2001. Spatial distribution and recruitment patterns of snow crabs in the eastern Bering Sea. Spatial Processes and management of marine populations. Alaska sea grant college program. AK-SG-01-02, 2001.

Appendix A: Status quo assessment model population dynamics

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

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

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

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

The dynamics after the initial year were described by:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Survey selectivity was informed by experimental surveys during the years 2009 and 2010. A portion of the NMFS summer survey tows were accompanied by an industry vessel using nephrops trawls with an assumed selectivity of 1 for all size classes. To represent the proportion of the population covered by the experiment, a vector was freely estimated by sex, $S_{ind,s,l,y}$. For some model iterations, an ‘empirical’ availability was calculated. The total NMFS survey size composition of males and females in 2009 and 2010 are known and the fraction of the NMFS survey size composition of males and females in the BSFRF experimental area are also known. Consequently, the ‘empirical availability’ can simply be calculated as the ratio of the experimental size composition to the total size composition data.

After identifying the fraction of the crab at length covered by the experimental surveys (either by estimating and ogive or inputting the empirical availability), the length frequencies of the NMFS data collected simultaneously with the experimental trawls can be calculated by multiplying the numbers at length ‘available’ to the experimental trawls by the overall survey selectivity, $S_{surv,s,l,y}$. The predicted numbers at length for the NMFS and industry data from the selectivity experiment were calculated by multiplying the respective selectivities by the survey numbers at length.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

L_x was the likelihood associated with data component x , where λ_x represented an optional additional weighting factor for the likelihood, $N_{x,y}^{eff}$ was the effective sample sizes for the likelihood, $p_{x,y,l}^{obs}$ was the observed proportion in size bin l during year y for data component x , and $\hat{p}_{x,y,l}$ was the predicted proportion in size bin l during year y for data component x .

Log normal likelihoods were implemented in the form:

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

L_x was the contribution to the objective function of data component x , λ_x was any additional weighting applied to the component, $\hat{I}_{x,y}$ was the predicted value of quantity I from data component x during year y , $I_{x,y}$ was the observed value of quantity I from data component x during year y and $CV_{x,y}$ was the coefficient of variation for data component x during year y .

Normal likelihoods were implemented in the form:

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

L_x was the contribution to the objective function of data component x , λ_x was represents the weight applied to the data component (and can be translated to a standard deviation), $\hat{I}_{x,y}$ was the predicted value of quantity I from data component x during year y , $I_{x,y}$ was the observed value of quantity I from data component x during year y .

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

Table 6: Observed growth increment data by sex

Female premolt length (mm)	Female postmolt length (mm)	Male premolt length (mm)	Male postmolt length (mm)
20.7	27	57.63	68.6
25.2	32	20.6	28.9
28.7	37.1	25.6	31.4
28.2	36.22	25.9	31.1
25.9	32.7	20	26.3
26.9	34.4	25.2	32.8
26.4	31.8	21	27.8
29	36.7	20.3	26.4
23	31.2	21.9	28.4
21.6	27.7	20.7	27.7
24.2	30.9	20.1	28
20.8	27.3	19.8	26.5
20.3	26.2	26	32.2
22.2	29.7	62.3	81.8
21.4	28	56.5	70
19.3	25.2	57	70
26.9	34.5	58.7	72.5
25.7	32.5	60.8	78.4
19.8	26.9	59.3	75.1
27.4	35.1	64	84.7
20.4	26.4	60.3	75.1
25.5	34.6	20.7	29.2
34.9	44.8	24	32.3
18.6	25.2	16.1	23
28.2	35.8	19.2	26.6
22.8	29.6	21.23	26.41
26.5	33.9	22.2	28.1
25.5	32.9	23.48	28.27
24.2	31.4	29.9	39.9
24.4	30.7	30.3	40.3
22.3	29.4	30.7	40.5
20.8	27.3	44.2	58.7
22.8	30.2	44.7	57.3
26.2	32.6	64.7	82.7
29.4	36.7	67.6	86
20.2	24.9	67.9	85.3
27.5	34.8	74.5	93.9
20.4	26.7	79.9	97.8
25.4	31.7	89.8	110
28.1	34.5	89.9	112.1
28.7	36	89.9	112.3
29.5	38.4	93.8	117.6
30.9	38.4	20	26.3
26	33.1		
29.1	38.4		
19.37	24.24		
20.7	27.4		
21.25	28.73		
21.94	28.71		
23.09	29.26		

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

Table 7: Observed retained catches, discarded catch, and bycatch.
Discards and bycatch have assumed mortalities applied.

Survey year	Retained catch (kt)	Discarded females (kt)	Discarded males (kt)	Trawl bycatch (kt)
1982	11.85	0.02	1.37	0.37
1983	12.16	0.01	1.34	0.47
1984	29.94	0.01	2.99	0.5
1985	44.45	0.01	4.35	0.43
1986	46.22	0.02	4.61	0
1987	61.4	0.03	5.99	0
1988	67.79	0.04	6.31	0
1989	73.4	0.05	7.25	0.1
1990	149.1	0.05	16.5	0.71
1991	143	0.06	13.02	1.5
1992	104.7	0.12	17.06	2.28
1993	67.94	0.08	5.32	1.57
1994	34.13	0.06	4.03	2.67
1995	29.81	0.02	5.75	1.01
1996	54.22	0.07	7.44	0.66
1997	114.4	0.01	5.73	0.82
1998	88.09	0.01	4.67	0.54
1999	15.1	0	0.52	0.47
2000	11.46	0	0.62	0.41
2001	14.8	0	1.89	0.31
2002	12.84	0	1.47	0.17
2003	10.86	0	0.57	0.46
2004	11.29	0	0.51	0.63
2005	16.77	0	1.36	0.2
2006	16.49	0	1.78	0.42
2007	28.59	0.01	2.53	0.18
2008	26.56	0.01	2.06	0.18
2009	21.78	0.01	1.23	0.47
2010	24.61	0.01	0.62	0.14
2011	40.29	0.18	1.69	0.15
2012	30.05	0.03	2.32	0.22
2013	24.49	0.07	3.27	0.11
2014	30.82	0.17	3.52	0.13
2015	18.42	0.07	2.96	0.13
2016	9.67	0.02	1.31	0.06
2017	8.6	0.02	1.93	0.04
2018	12.51	0.02	2.86	0.23
2019	15.43	0.02	5.07	0.24
2020	20.41	0	5.8	0.07

Table 8: Observed mature male and female biomass (1000 t) at the time of the survey and coefficients of variation.

Survey year	Female mature biomass	Female CV	Mature male biomass	Male CV	Males >101mm (kt)	Males >101mm (million)
1982	144.4	0.15	176.8	0.14	33.34	60.91
1983	90.13	0.2	161.6	0.13	38.09	70.09
1984	42.32	0.19	177.7	0.12	88.73	151.8
1985	6.12	0.2	71.84	0.11	43.39	72.84
1986	15.74	0.18	89.81	0.11	46.7	77.91
1987	122.6	0.16	194.6	0.11	74.44	128.6
1988	169.9	0.17	259.4	0.15	104.7	173.1
1989	264.2	0.25	299.2	0.11	92.31	158.9
1990	182.9	0.19	443.8	0.14	224.7	386.4
1991	214.9	0.19	466.6	0.15	292.2	452.9
1992	131.4	0.18	235.5	0.09	143.9	227.3
1993	132.1	0.16	183.9	0.1	78.11	126.7
1994	126.2	0.15	171.3	0.08	44.78	72.57
1995	168.7	0.14	220.5	0.13	37.75	65.18
1996	107.3	0.14	288.4	0.12	87.57	155.2
1997	103.8	0.2	326.8	0.1	168.7	280.6
1998	72.73	0.25	206.4	0.09	126.7	209.7
1999	30.89	0.21	95.85	0.09	52.53	85.2
2000	96.46	0.52	96.39	0.14	41.88	69.83
2001	77.24	0.28	136.5	0.12	41.51	70.69
2002	30.22	0.28	93.17	0.23	36.56	64.16
2003	41.71	0.31	79.07	0.12	32.57	55.61
2004	50.16	0.26	79.57	0.14	35.99	57.42
2005	64.85	0.17	123.5	0.11	40.67	63.26
2006	51.93	0.17	139.3	0.26	71.13	120.9
2007	55.89	0.22	153.1	0.15	73.62	127.5
2008	57.15	0.19	142	0.1	66.56	113.6
2009	52.16	0.21	148.2	0.13	78.92	129.9
2010	98.01	0.17	162.8	0.12	88.35	138.3
2011	175.8	0.18	167.1	0.11	94.67	147.6
2012	149.4	0.2	122.2	0.12	53.17	85.35
2013	131.4	0.17	97.46	0.12	42.93	71.79
2014	119.7	0.19	163.5	0.16	81.39	138.8
2015	85.13	0.17	80.04	0.12	35.77	56.11
2016	55.39	0.21	63.21	0.11	21.96	36.51
2017	106.8	0.21	83.96	0.13	20.52	35.02
2018	165.9	0.18	198.4	0.17	26.75	48.08
2019	110.4	0.2	169.1	0.17	28.12	51.27
2021	31.66	0.43	62.25	0.13	12.43	23.17

Table 9: Contribution to the objective function by individual likelihood component by modeling scenario.

Likelihood component	20.1	21.1	21.1a	21.1b	21.1c	21.2	21.3	21.3a
Smoothness for recruitment	71.12	75.71	74.22	85.43	79.21	87.21	88.85	88.85
Constraint on initial numbers	2.83	2.87	2.91	2.89	4.22	2.96	2.91	2.91
Retained fishery	194.07	185.5	183.06	182.83	165.82	181.6	179.1	179.1
length comp								
Total fishery	560.36	585.04	583.92	583.3	860.04	583.59	581.81	581.81
length comp								
Female	127.32	142.24	143.12	140.86	20.9	141.66	140.46	140.46
length comp								
Survey	2298.23	2381.18	2397.71	2324.68	10793.8	2377.25	2283.5	2283.5
length comp								
Trawl length comp	169.34	181.36	178.02	175.37	77.07	176.62	184.99	184.99
2009 BSFRF	-45.58	-47.14	32.34	-47.65	5.7	23.97	31.26	31.26
length comp								
2009 NMFS	-36.62	-39.37	3.12	-39.86	-2.75	-1.35	0.12	0.12
length comp								
Prior on natural mortality	34.55	37.33	29.83	33.13	10.46	4.59	25.02	25.02
Prior and smoothness on maturity	45.6	42.21	41.58	41	32.05	42.57	36.72	36.72
Growth data (male)	0	0	0	0	0	0	0	0
Growth data (female)	0	0	0	0	0	0	0	0
2009 BSFRF	0.49	0.46	5.85	0.33	11.44	5.82	9.89	9.89
mature biomass								
2009 NMFS	0.34	0.45	11.35	0.33	10.53	10.67	10.51	10.51
mature biomass								
Fishery CPUE	0.4	0.43	0.4	0.28	0.55	0.25	0.27	0.27
Retained catch	6.02	4.87	5.11	3.67	4.28	3.69	4.07	4.07
Total catch	106.68	117.83	123.87	117.4	130.71	121.39	137.27	137.27
Trawl catch	11.64	9.6	8.85	8.13	12.66	7.45	7.2	7.2
Female discards	4	3.94	4.2	3.67	3.82	3.91	3.84	3.84
Survey mature biomass	215.85	251.03	268.23	180.59	233	211.36	203.96	203.96

Likelihood component	20.1	21.1	21.1a	21.1b	21.1c	21.2	21.3	21.3a
Penalties on F	23.97	29.57	29.08	26.45	32.68	26.36	26.48	26.48
2010 BSFRF mature biomass	5.53	10.23	33.06	10.56	9.78	35.2	9.63	9.63
2010 NMFS mature biomass	6.42	4.47	1.29	3.4	0.69	1.03	1.68	1.68
First year survey	273.98	273.42	273.58	273.5	255.97	275.51	277.62	277.62
length comp 2010 BSFRF	-24.2	-33.24	-22.12	-33.04	-5.83	-21.34	-19.64	-19.64
length comp 2010 NMFS	-30.65	-38.63	-25.18	-37.08	-1.68	-21.99	-28.11	-28.11
Smoothness of selectivity experiment	1.22	0	0	0	0	0	0	0
log_dev_50f	0	0	0	0	0	0	0	0
Smoothness of first year length comp	32.25	32.47	32.94	32.58	34.03	33.25	33.44	33.44

Table 10: Changes in management quantities for each scenario considered. Reported management quantities are derived from maximum likelihood estimates. Reported natural mortality is for mature males, average recruitment is for males, and status and MMB were estimates for February 2021.

Model	MMB	B35	F35	FOFL	OFL	M	avg_rec	Status
20.1	133.51	121.47	1.23	1.23	88.90	0.29	103.91	1.10
21.1	58.55	101.73	1.46	1.06	27.55	0.28	91.44	0.58
21.1a	69.93	106.87	1.79	1.40	35.70	0.29	92.51	0.65
21.1b	24.63	137.98	1.43	0.38	7.82	0.29	119.43	0.18
21.1c	171.58	183.36	165.67	105.22	51.92	0.27	158.00	0.94
21.2	26.74	153.42	1.43	0.37	7.50	0.27	106.14	0.17
21.3	41.82	173.36	4.76	1.15	17.03	0.30	146.83	0.24
21.3a	41.82	173.36	0.30	0.10	2.27	0.30	146.83	0.24

Table 11: Maximum likelihood estimates of predicted mature male (MMB), mature female (FMB), and males >101mm biomass (1000 t) and numbers (in millions) at the time of the survey from the author-preferred model. Columns 2-5 are subject to survey selectivity; columns 6-9 are the population values (i.e. the numbers at length are not modified by multiplying them by a selectivity curve—they are estimates of the underlying population).

Survey year	FMB	MMB	Male >101 biomass	Male >101 (millions)	FMB	MMB	Male >101 biomass	Male >101 (millions)
1982	60.16	124.6	35.38	65.8	75.31	251.7	56.58	105.2
1983	52.11	134.9	58.31	102.3	64.57	272.5	93.24	163.7
1984	41.77	139.3	74.29	125.6	51.8	281.8	118.8	200.9
1985	37.38	128.3	69.01	115.3	46.49	260.3	110.3	184.4
1986	43.35	113.9	40.18	67.61	54.19	232	80.93	136.2
1987	106.2	120.1	37.12	64.27	134.2	245.4	74.76	129.4
1988	184.8	205.5	45.21	77.95	187.7	285.4	91.05	157
1989	184.8	248	58.11	99.45	187.5	344.4	117	200.3
1990	161.4	300	79.42	134.9	163.7	415.7	160	271.7
1991	143.6	275.9	66.82	114.8	145.6	382.1	134.6	231.2
1992	134.2	229.5	53.89	93.27	136.1	317.8	108.5	187.8
1993	135.3	191.9	68.2	114.6	137.3	266.8	93.76	157.5
1994	143.4	159.6	39.65	64.91	145.5	222.8	54.51	89.24
1995	145	176.3	33.52	59.04	147.1	245.5	46.09	81.17
1996	130.3	252.1	88.47	154.2	132.1	349.1	121.6	212
1997	108.4	304.7	151.5	252.8	109.9	420.9	208.2	347.5
1998	88.88	228.4	108.4	177.8	90.09	315.6	149.1	244.4
1999	75.01	139.2	49.48	81.94	76.05	192.9	68.02	112.6
2000	67.78	111.5	36.66	60.65	68.75	154.7	50.41	83.38
2001	61.74	97.31	28.71	48.26	62.61	135	39.47	66.34
2002	55.02	96.3	30.19	51.81	55.79	133.5	41.51	71.23
2003	48.94	105.6	42.64	71.78	49.63	146.2	58.61	98.68
2004	49.75	110.2	49.36	81.31	50.5	152.8	67.86	111.8
2005	68.09	111.8	46.88	77.13	69.22	155.2	64.45	106
2006	81.7	124.6	48.09	80.88	82.95	172.9	66.11	111.2
2007	86.41	156.5	67.02	112.9	87.68	216.8	92.14	155.2
2008	84.22	180.4	84.5	141.3	85.43	249.6	116.2	194.3
2009	80.02	193.2	99.96	165.7	81.16	266.9	137.4	227.8
2010	83.54	187.2	104.9	171.6	84.79	258.4	144.2	235.9
2011	104.6	155.4	84.88	137.7	106.3	214.7	116.7	189.3
2012	109.2	112.5	50.09	82.91	110.7	155.6	68.86	114
2013	101.1	93.28	36.19	61.65	102.5	129.1	49.76	84.75
2014	94.65	84.76	34.42	58.22	96	117.3	47.32	80.04
2015	89.2	66.1	23.07	38.81	90.48	91.72	31.72	53.35
2016	95.66	59.5	16.85	28.48	97.12	82.93	23.16	39.15
2017	142.2	80.39	19.77	33.73	144.6	113.2	27.17	46.38
2018	227.4	144.9	33.91	58.07	231.2	203.9	46.62	79.84
2019	127.8	136.4	39.79	69.64	129.9	189.6	54.7	95.74
2020	50.21	40.95	15.94	28.05	51.06	56.61	21.91	38.57
2021	40.75	49.95	23.6	40.56	41.45	68.96	32.44	55.77

Table 12: Maximum likelihood estimates of predicted total numbers (billions), not subject to survey selectivity at the time of the survey. These are maximum likelihood estimates.

Survey year	Total numbers
1982	3.59
1983	4.397
1984	4.94
1985	6.115
1986	11.26
1987	11.03
1988	11.8
1989	9.267
1990	7.746
1991	6.451
1992	10.17
1993	9.661
1994	8.22
1995	6.524
1996	5.13
1997	4.076
1998	3.851
1999	3.717
2000	3.223
2001	2.835
2002	3.024
2003	3.977
2004	4.987
2005	5.64
2006	5.113
2007	4.335
2008	3.791
2009	4.269
2010	4.928
2011	4.148
2012	3.678
2013	3.555
2014	3.789
2015	5.085
2016	12.67
2017	18.91
2018	15.19
2019	6.735
2020	1.649
2021	1.42

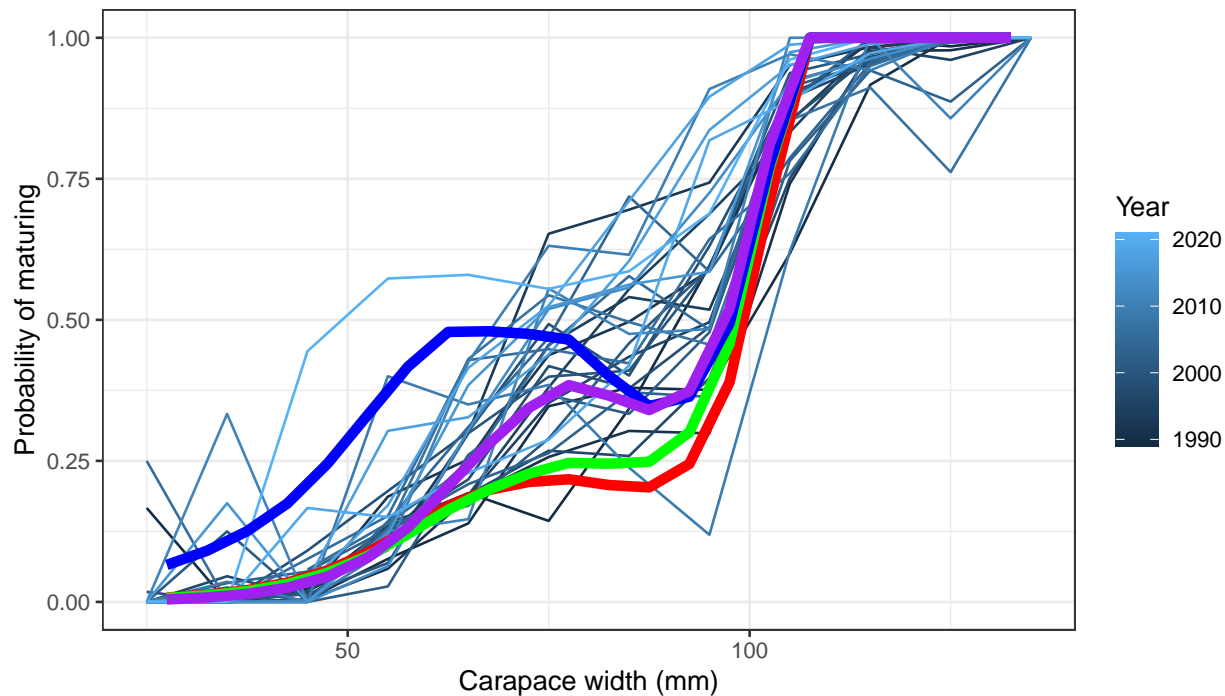


Figure 1: Comparison of estimated and empirically derived proportion maturing by size class. Blue lines are derived from observation of proportions of mature new shell males at a given size in a given year. Bold lines are assessment estimates. Blue = 21.1c; purple = 21.3; green = 21.2; red = 21.1.

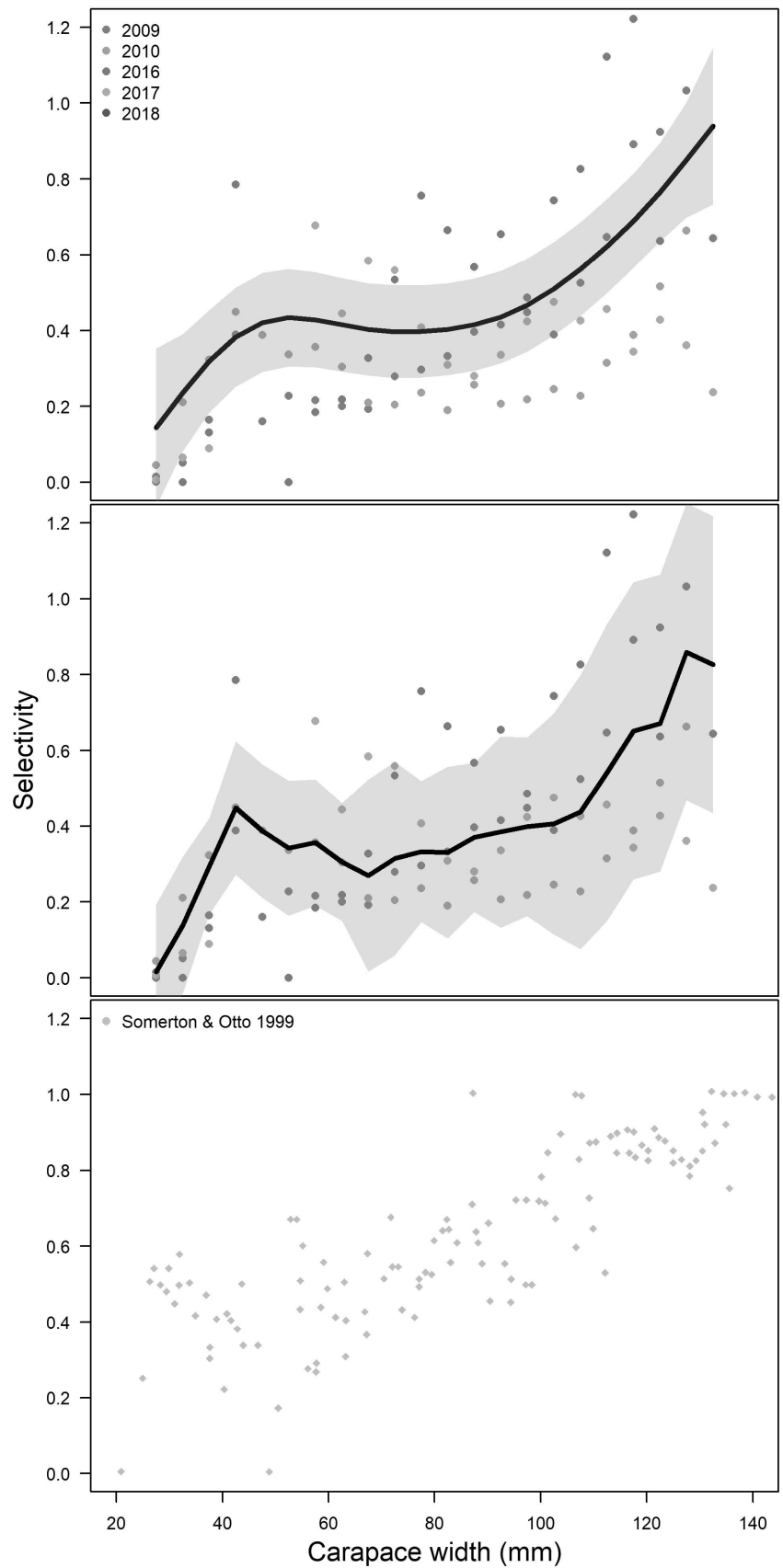


Figure 2: Implied selectivity from BSFRF experiments with selectivity at size class estimated by generalized additive model (top). Implied selectivity from BSFRF experiments with selectivity at size class estimated by sample size-weighted means and variances (middle). Somerton and Otto (1998) underbag experimental data.



Figure 3: Abundance of males estimated from the NMFS summer survey over time for different size classes. GE102 means greater than or equal to 102 mm carapace width.



Figure 4: Abundance of females estimated from the NMFS summer survey over time for different size classes. GE50 means greater than or equal to 50 mm carapace width.

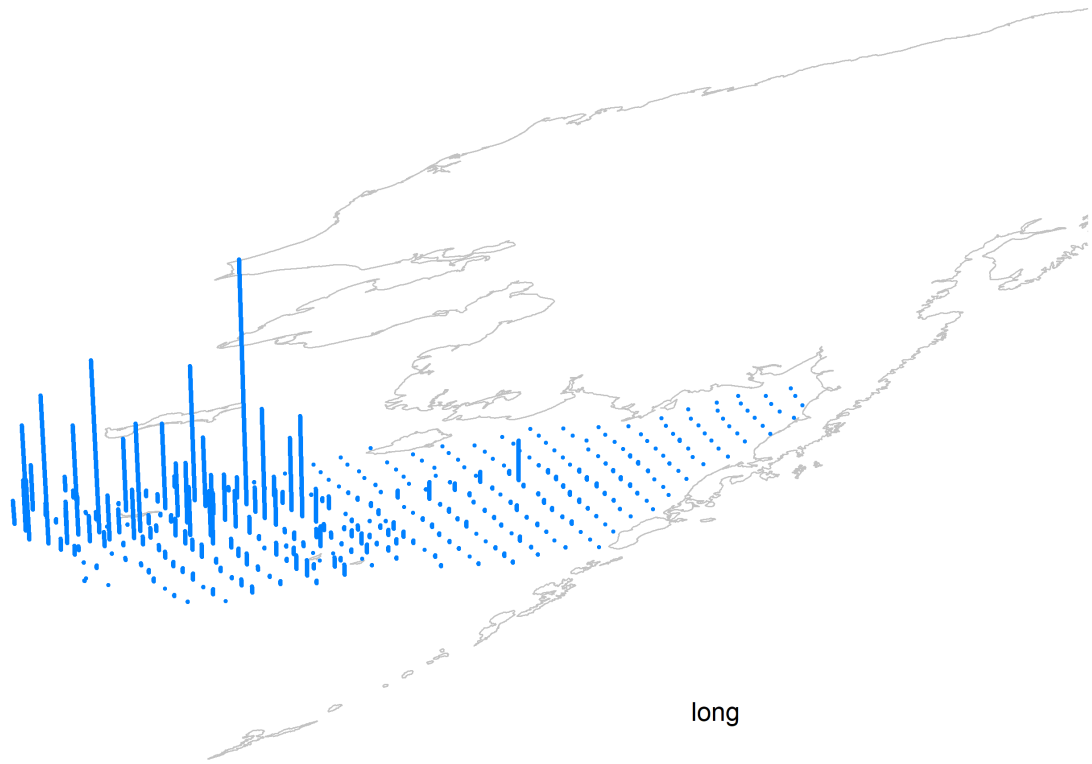


Figure 5: Observed relative density of all males at the time of the 2021 NMFS summer survey

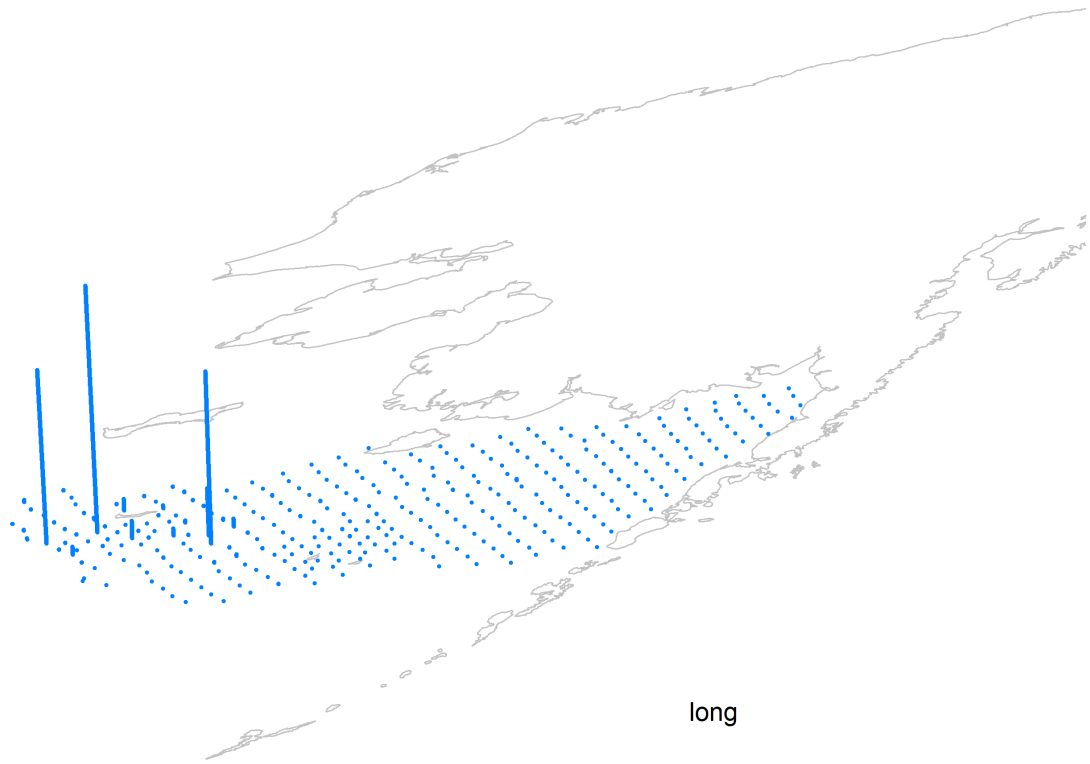


Figure 6: Observed relative density of all females at the time of the 2021 NMFS summer survey

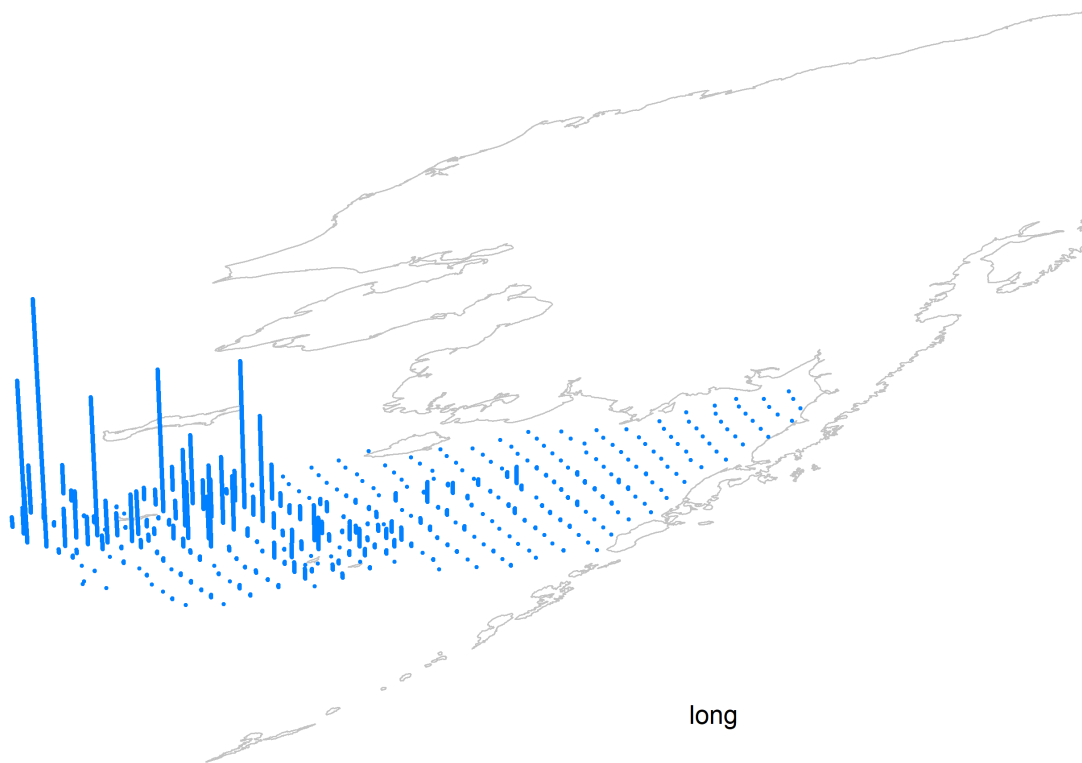


Figure 7: Observed relative density of males <70 mm carapace width at the time of the 2021 NMFS summer survey

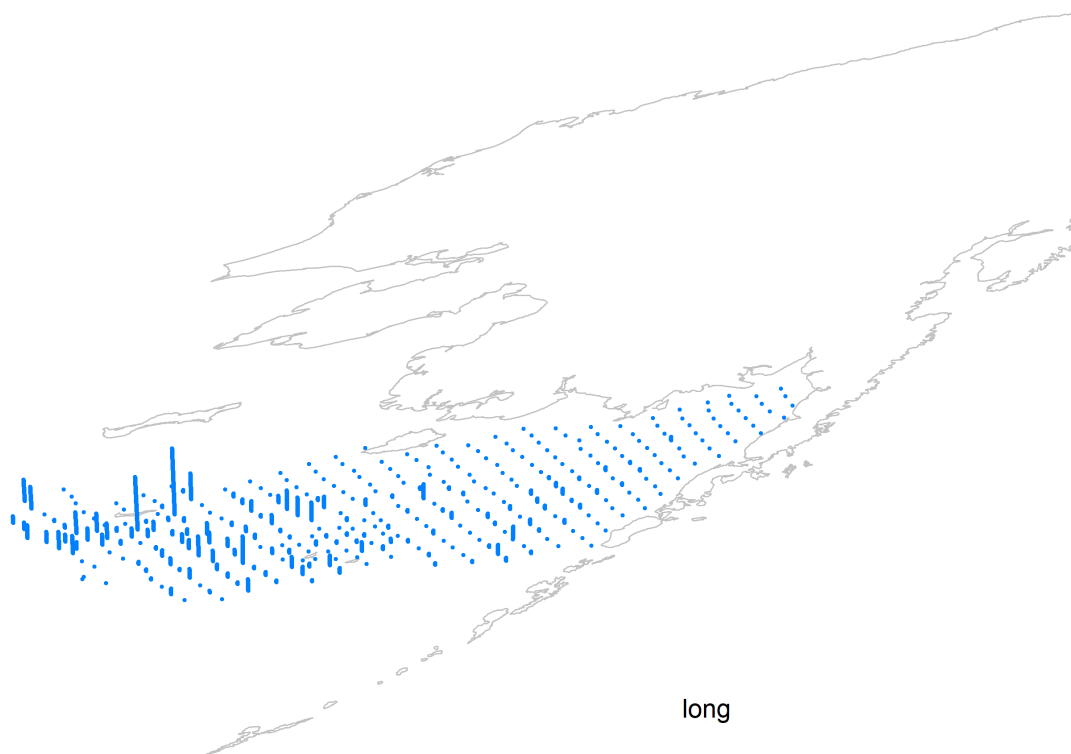


Figure 8: Observed relative density of males greater than 101 mm carapace width at the time of the 2021 NMFS summer survey

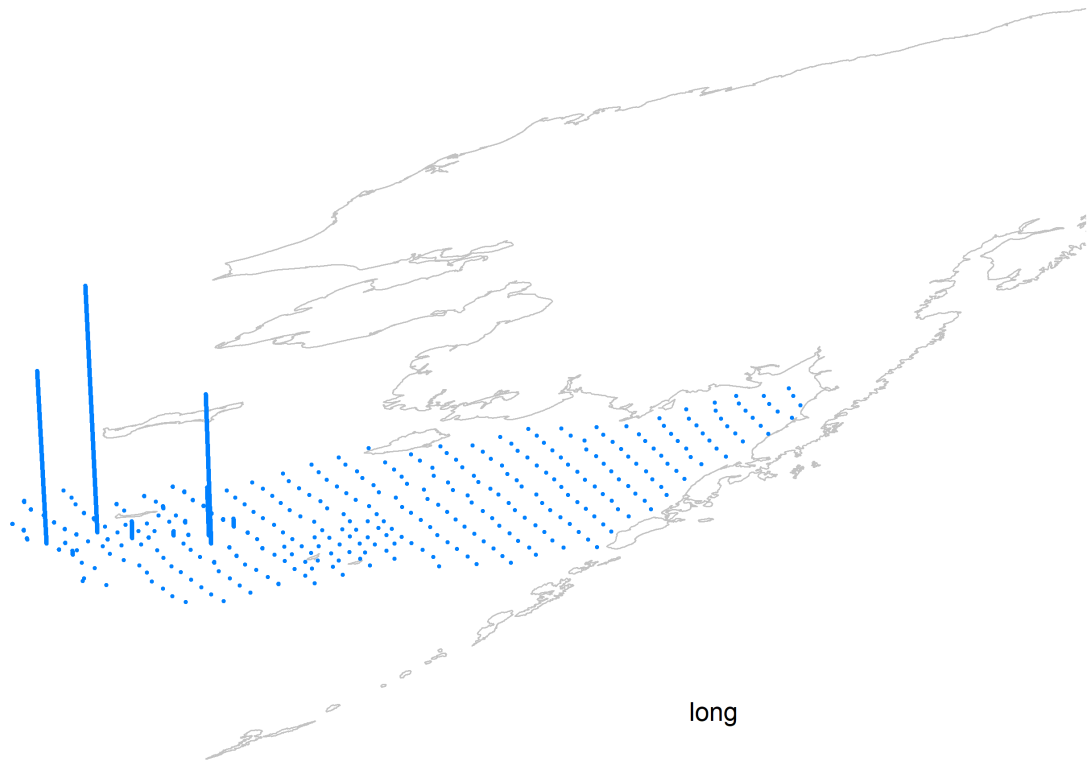


Figure 9: Observed relative density of mature females at the time of the 2021 NMFS summer survey

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

Figure 10: Radiometric estimates of shell age in male snow and tanner crabs collected during the NMFS survey of 1992. Reproduced from Ernst et al. 2005's presentation of Nevissi et al. 1995.

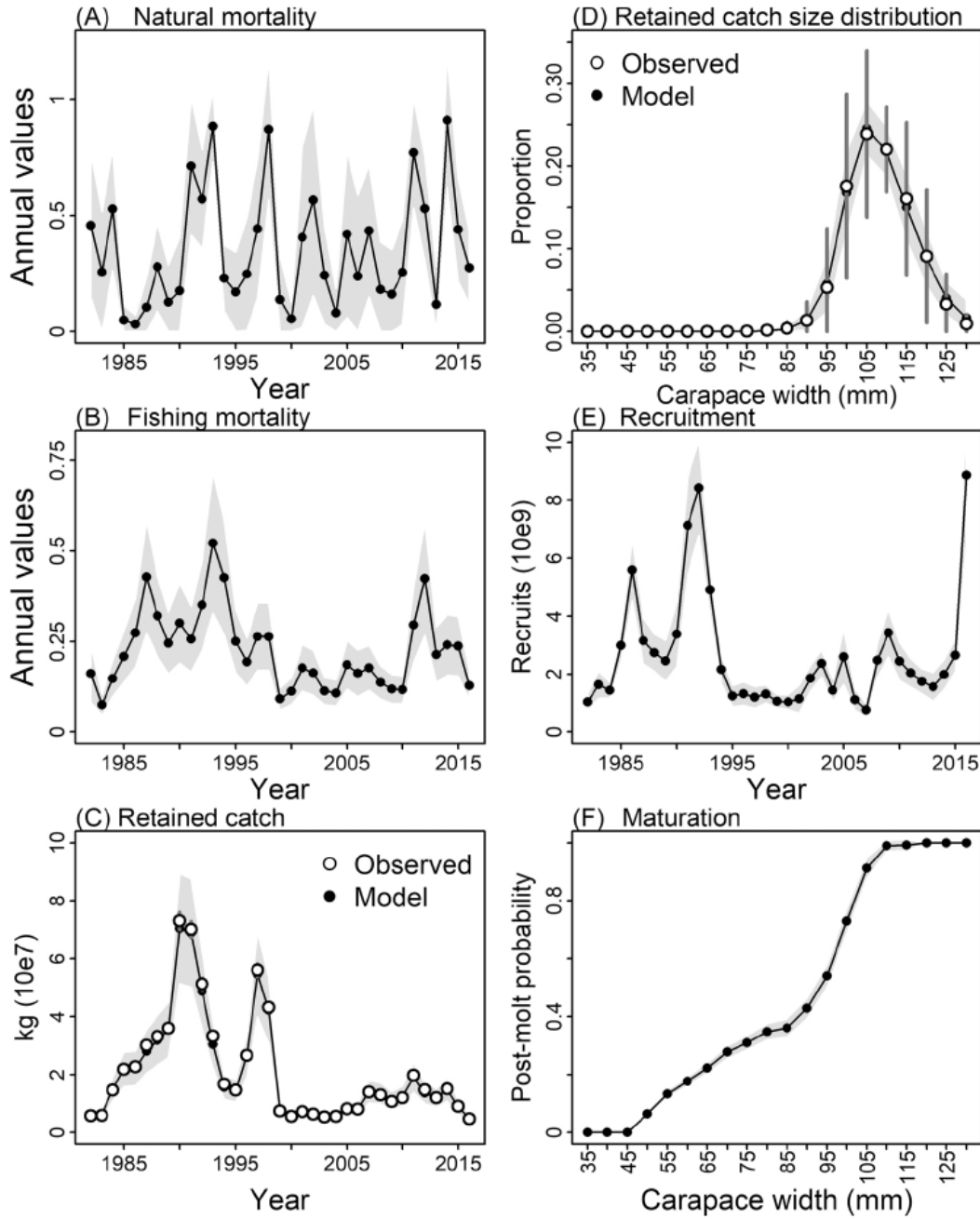


Figure 11: Estimated time-variation in natural mortality and other model output from Murphy et al. 2018.

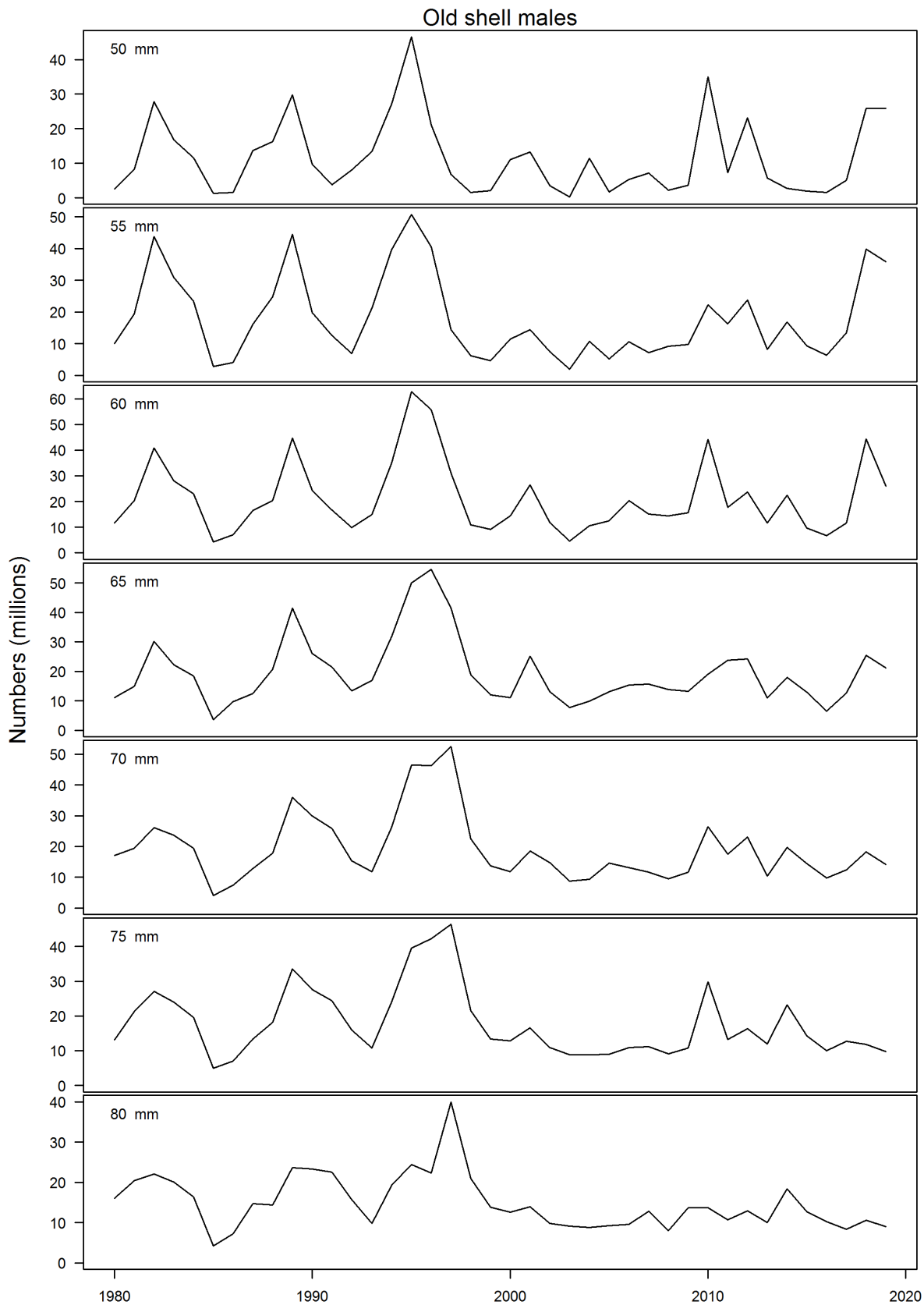


Figure 12: Observed numbers at length of old shell mature males by size class. The presented size bins are not vulnerable to the fishery, so all mortality is ‘natural’. The decline in numbers in a size class after the recruitment collapse in the early 1990s demonstrates expected natural mortality for mature male individuals.

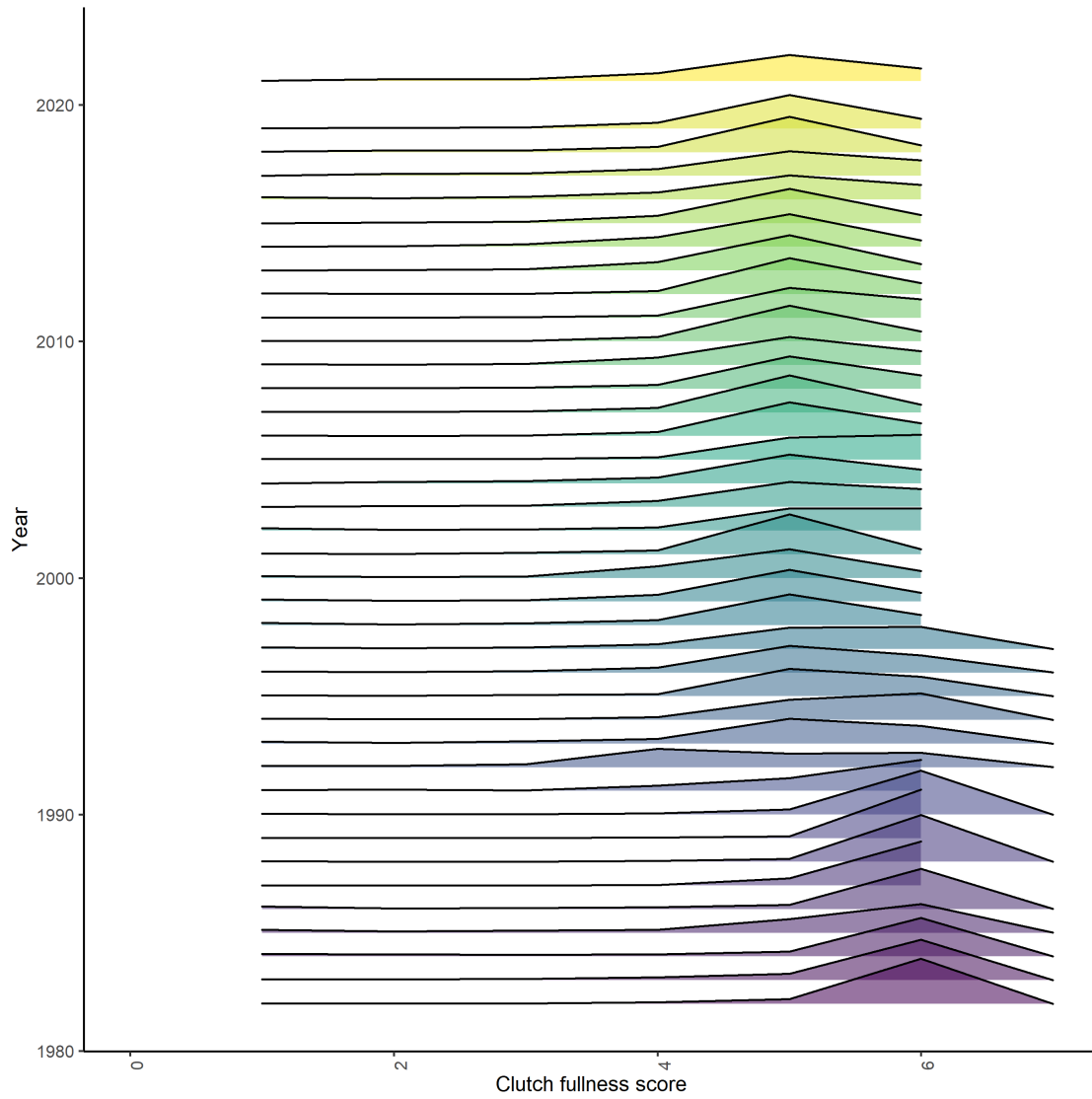


Figure 13: Clutch fullness scores from the 1982-2021 NMFS summer survey. Scores: 0 = immature, 1 = mature no eggs, 2 = trace to 0.125, 3 = 0.25, 4 = 0.5, 5 = 0.75, 6 = full of eggs; 7 = overflowing.

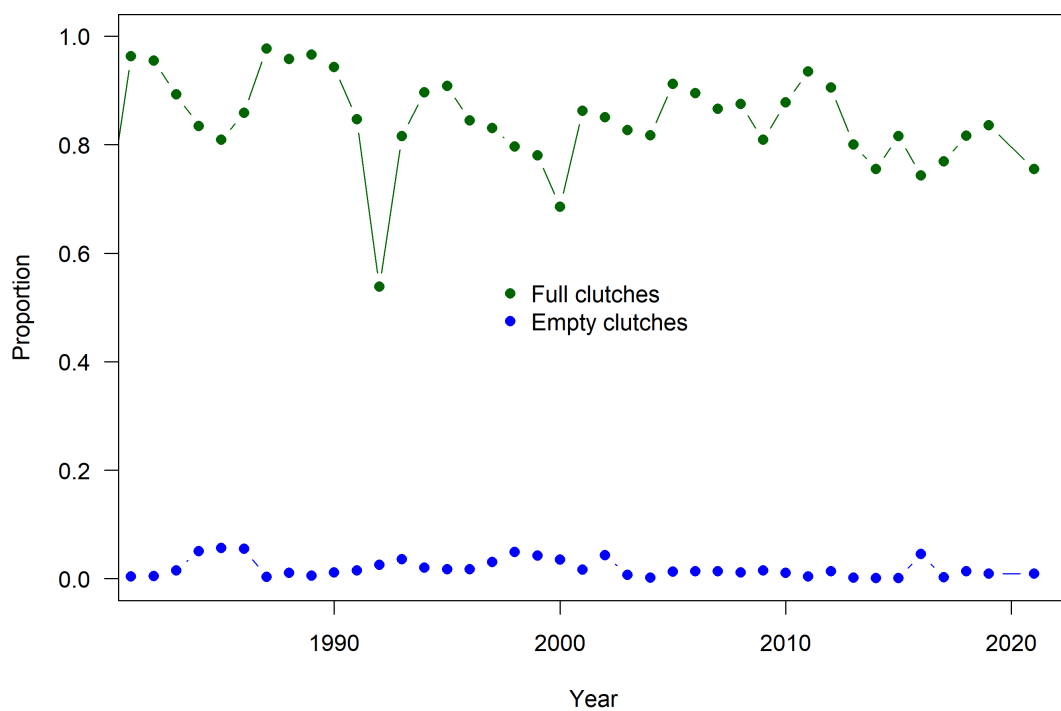


Figure 14: Time series of proportion of observed crab with full clutches (green) and empty clutches (blue) in the NMFS summer survey.

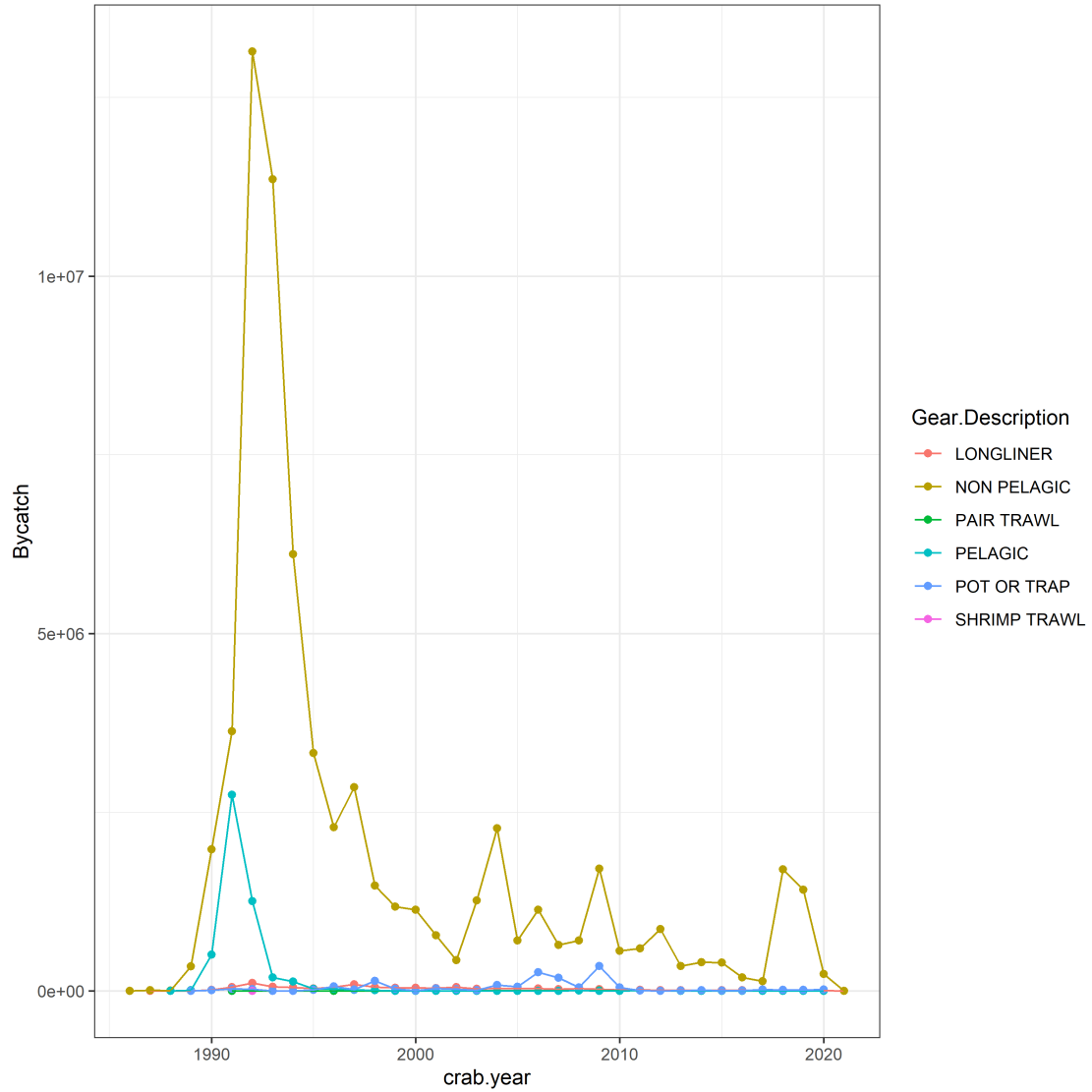


Figure 15: Time series of bycatch by gear in numbers of crab.

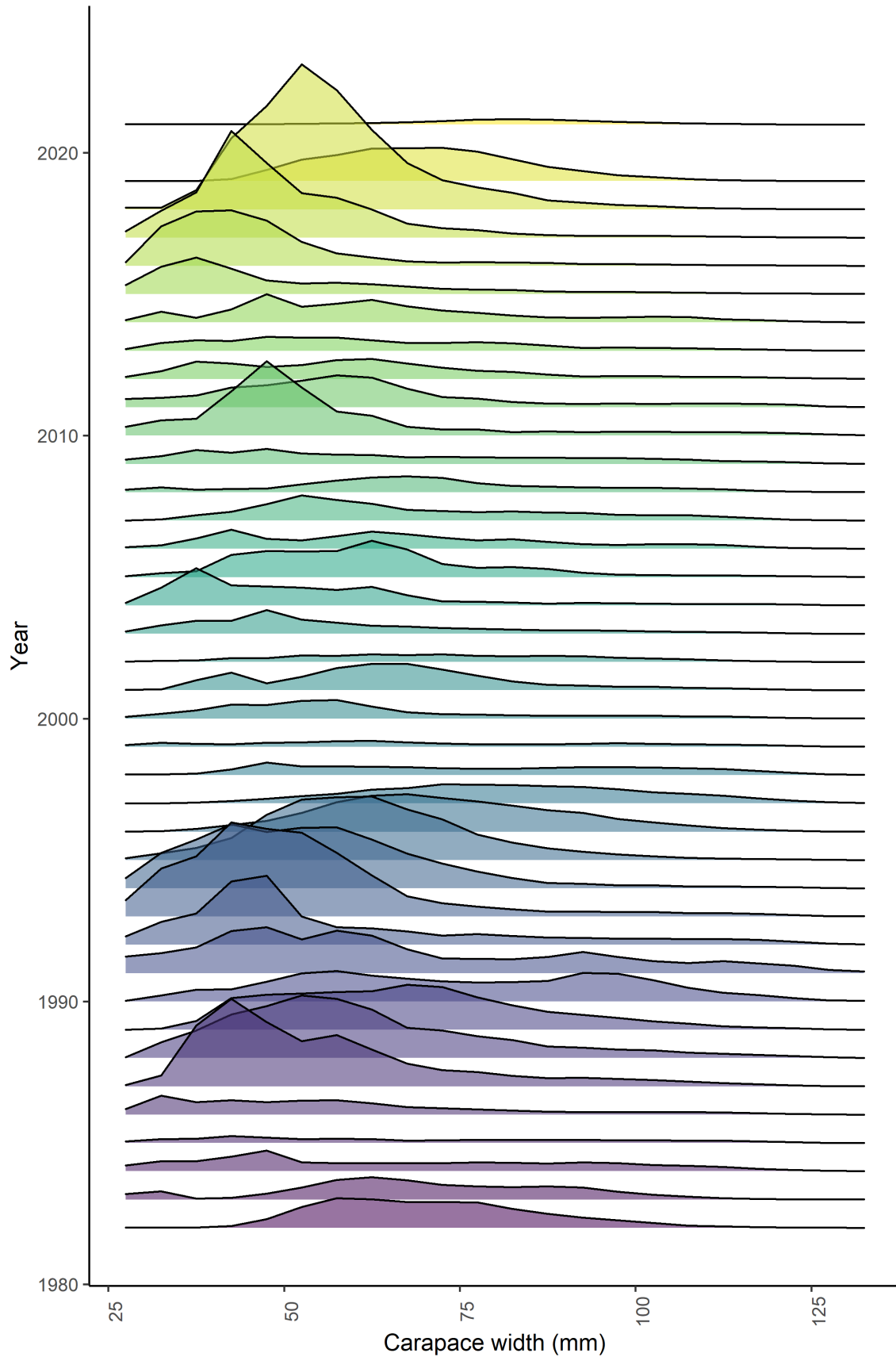


Figure 16: Raw total numbers at size of male crab observed in the survey.

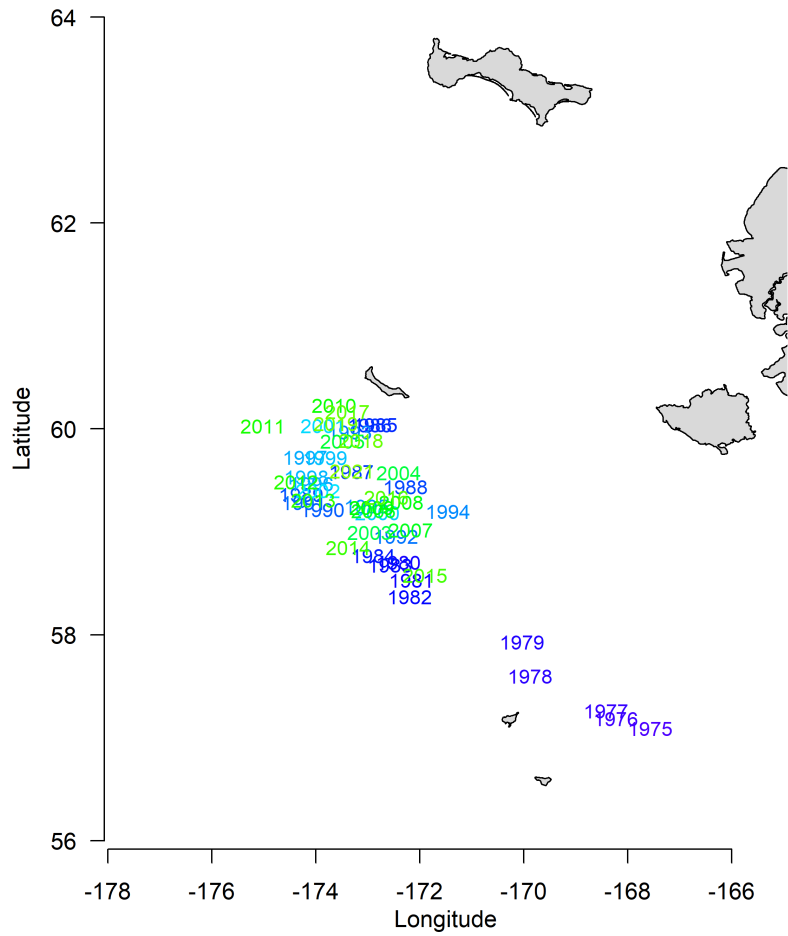


Figure 17: Centroids of abundance for mature females over time.

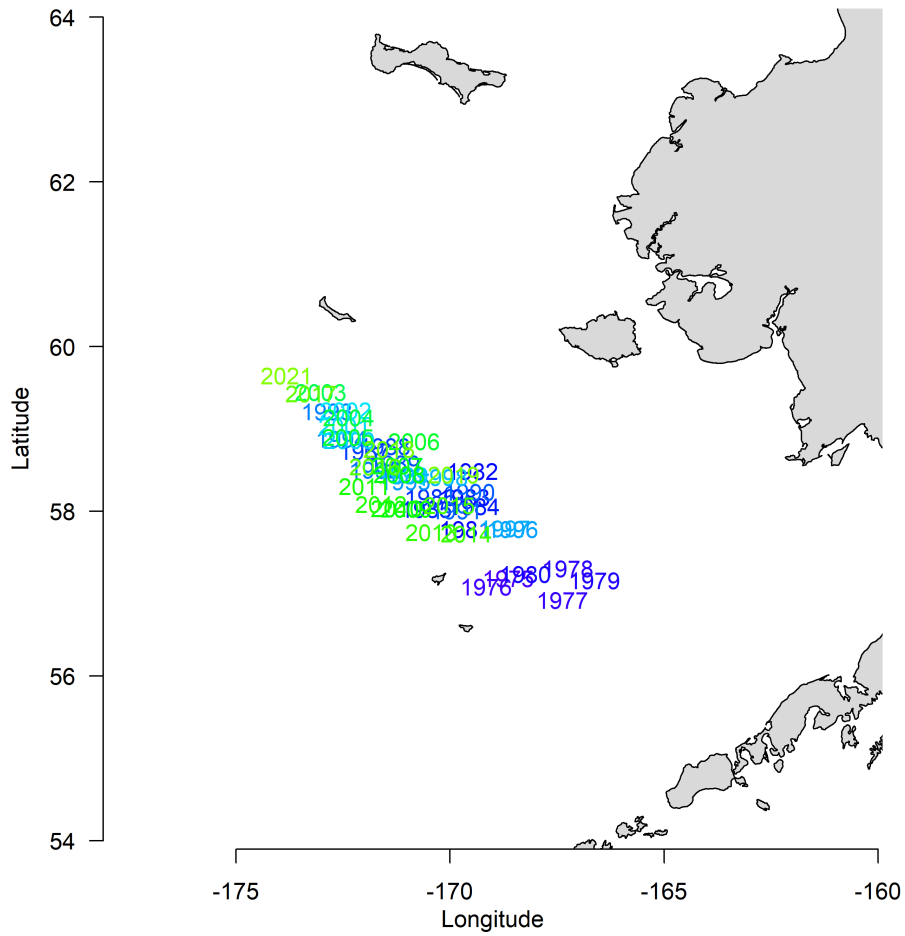


Figure 18: Centroids of abundance for males greater than 101 mm carapace width.

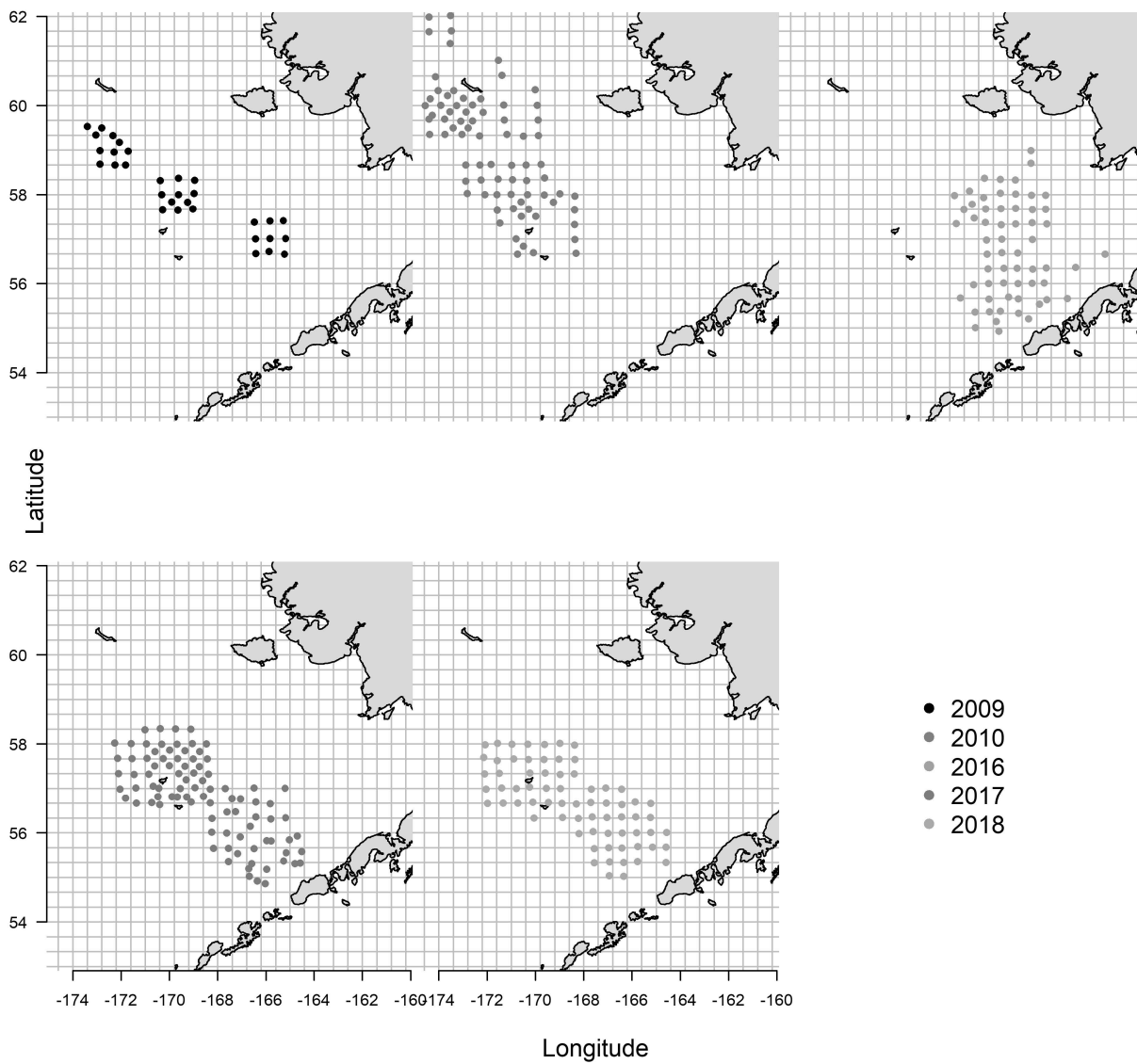


Figure 19: Location of BSFRF survey selectivity experiments.

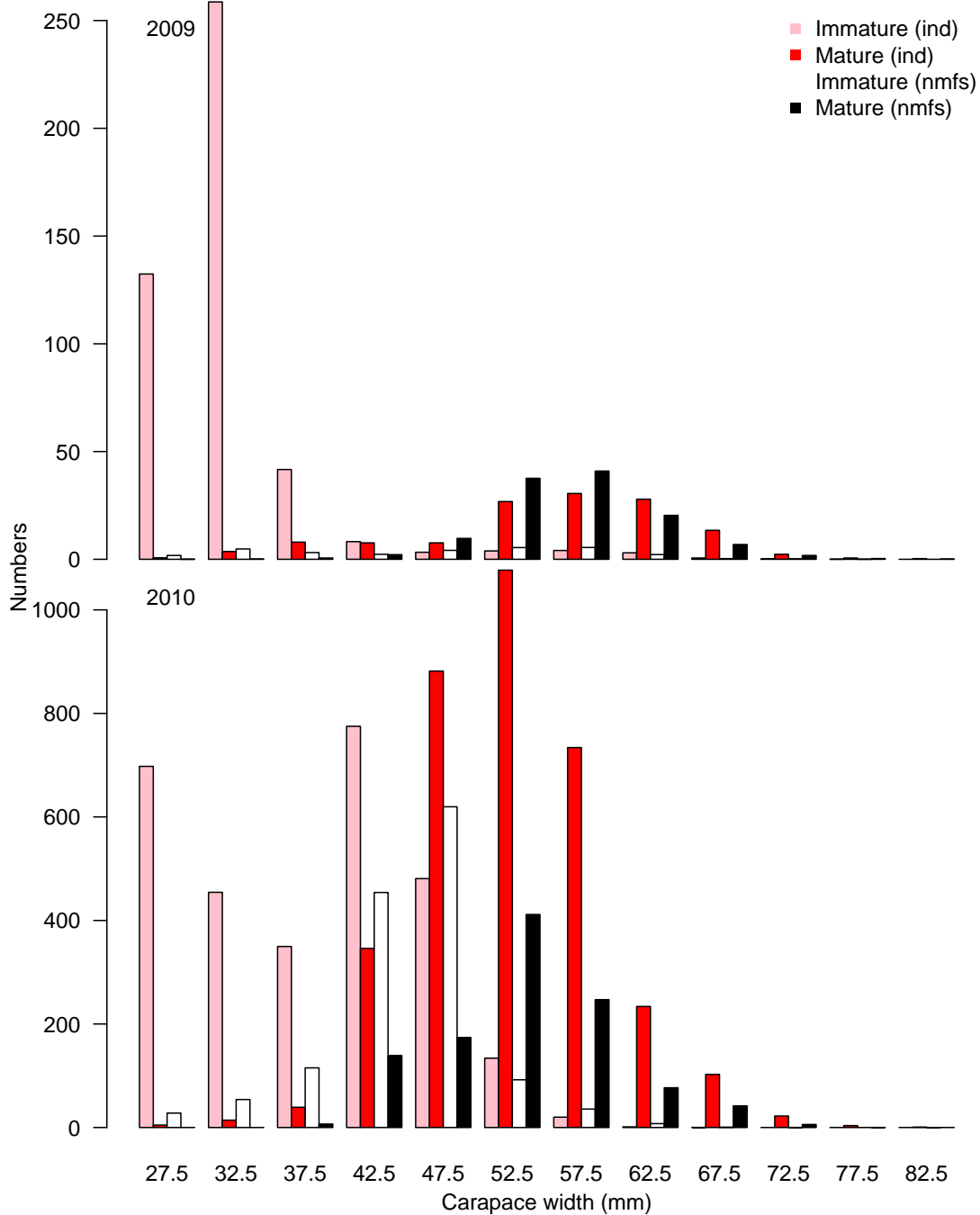


Figure 20: Raw female numbers from BSFRF survey selectivity experiments (2009 & 2010). Note a change in scale on the y-axis from 2009 to 2010

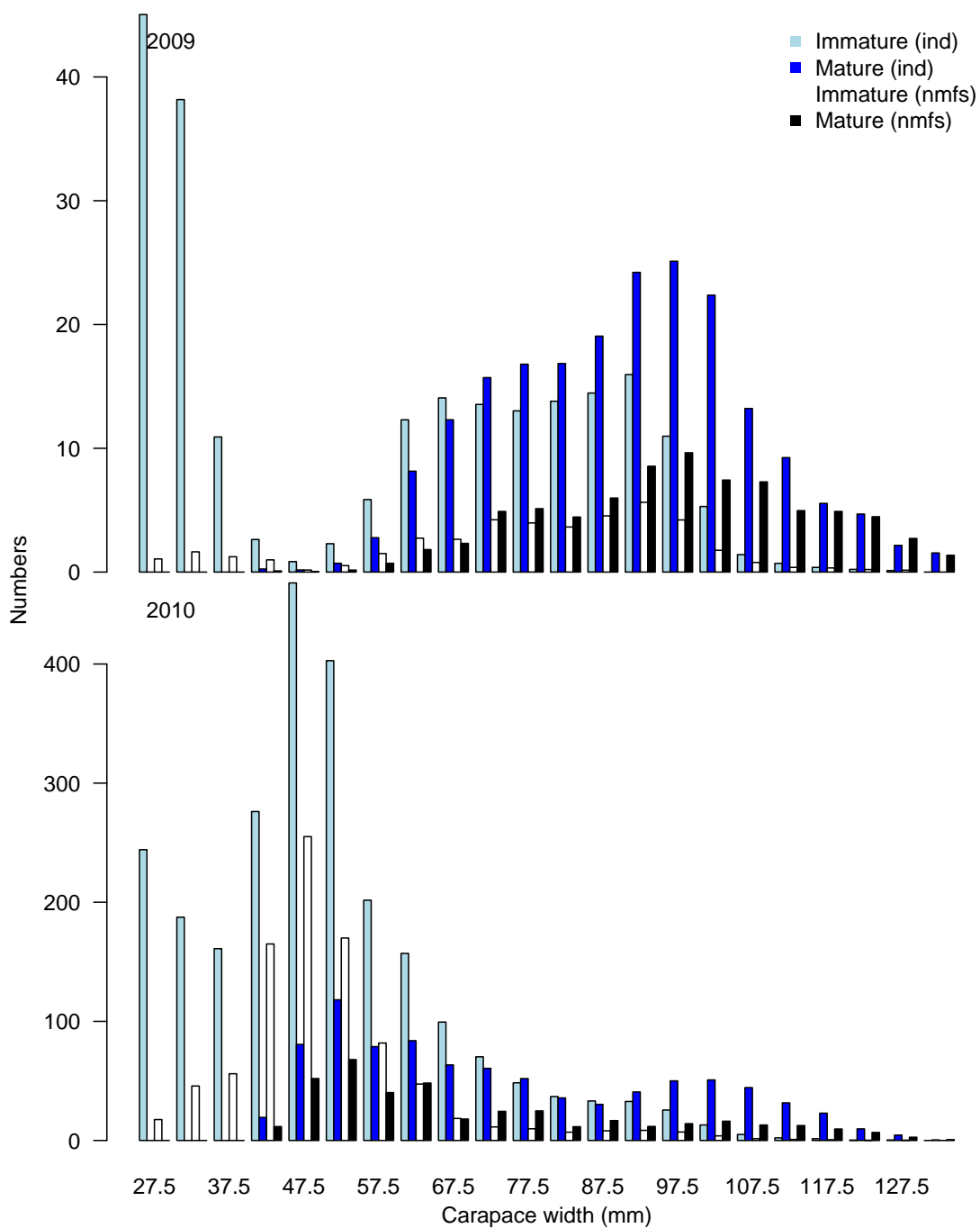


Figure 21: Raw male numbers from BSFRF survey selectivity experiments (2009 & 2010). Note a change in scale from 2009 to 2010 on the y-axis.

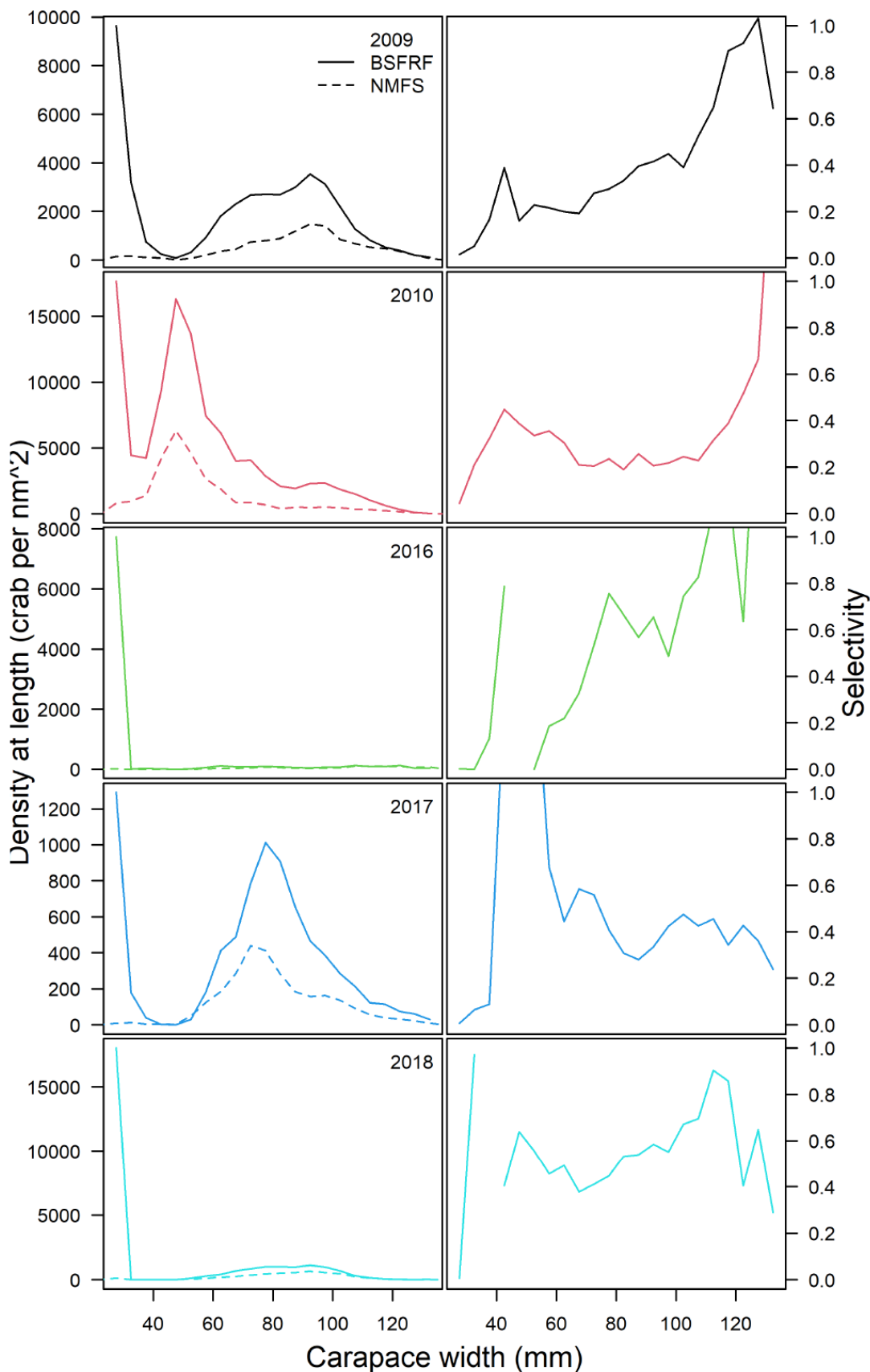


Figure 22: Observed numbers at length extrapolated from length composition data and estimates of total numbers within the survey selectivity experimental areas by year (left). Inferred selectivity (i.e. the ratio of crab at length in the NMFS gear to crab at length in the BSFRF gear).

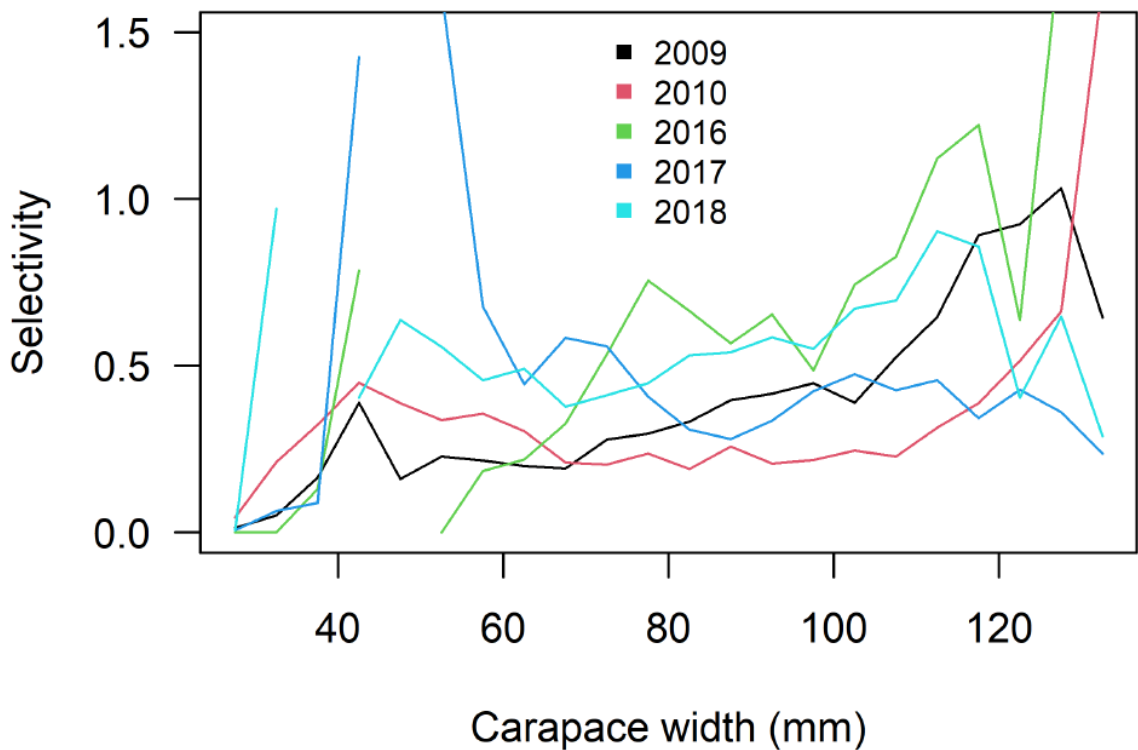


Figure 23: Inferred selectivity for all available years of BSFRF data.

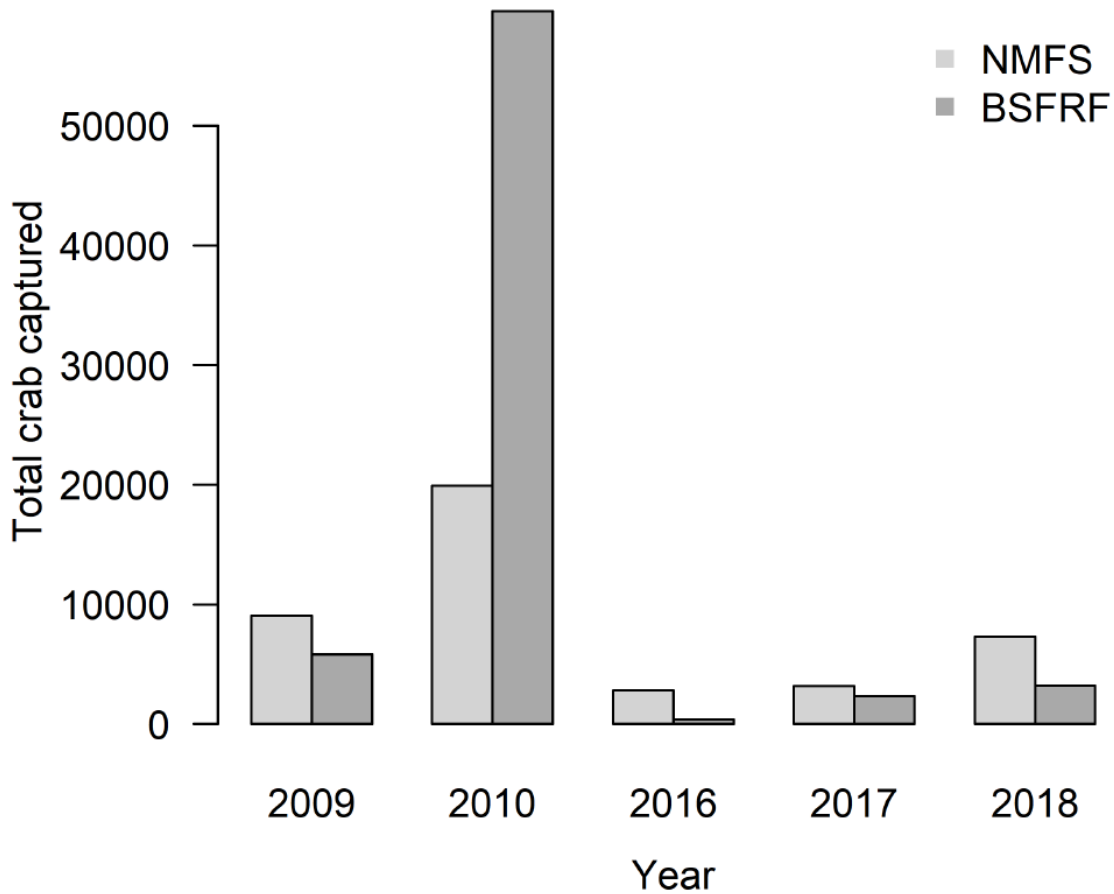


Figure 24: Number of crab from which estimates of biomass and length composition data were inferred within the survey selectivity experimental area.

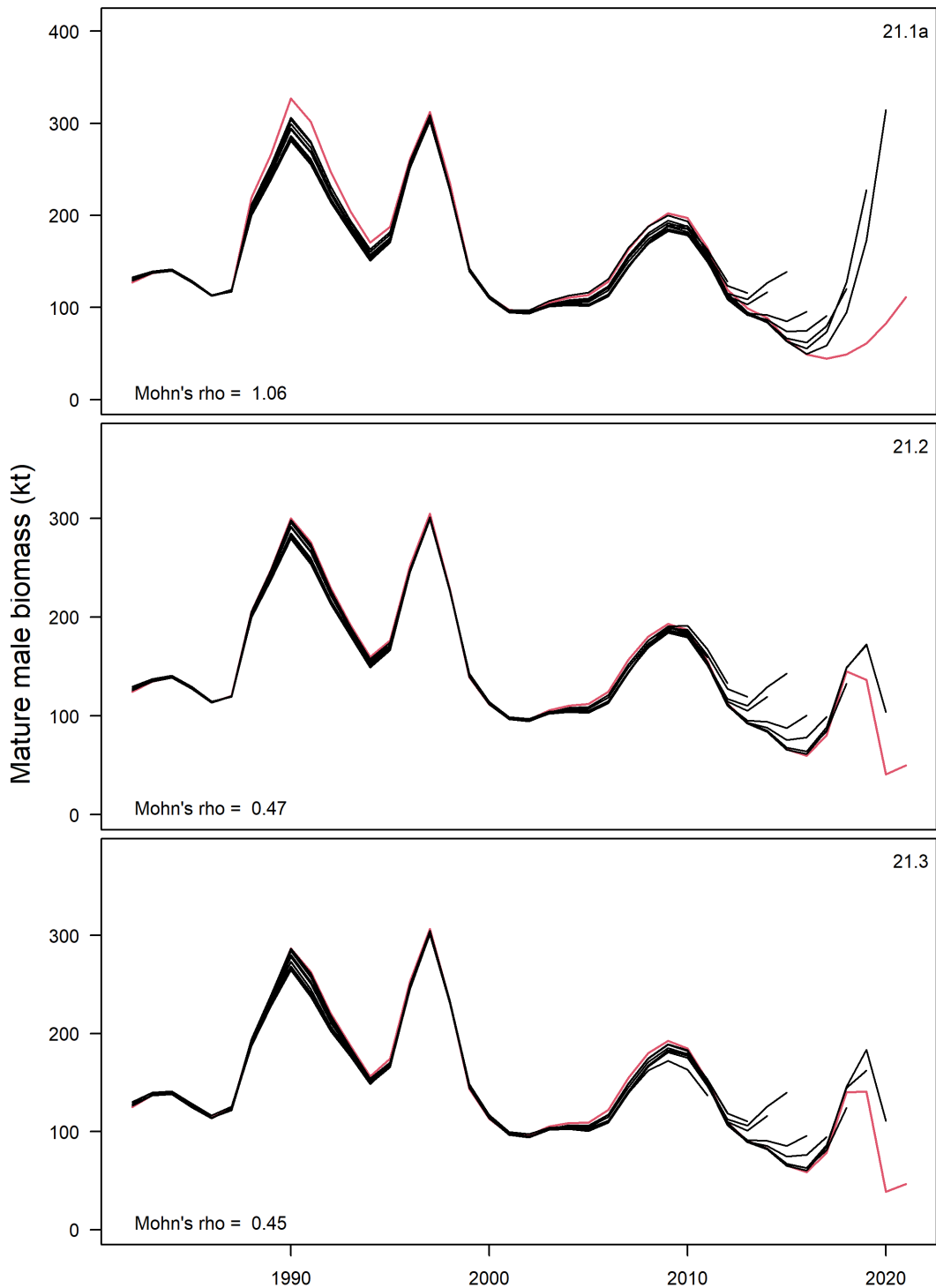


Figure 25: Retrospective patterns in estimated mature male biomass at the time of mating for models 21.1a, 21.2, 21.3, and 21.3a.

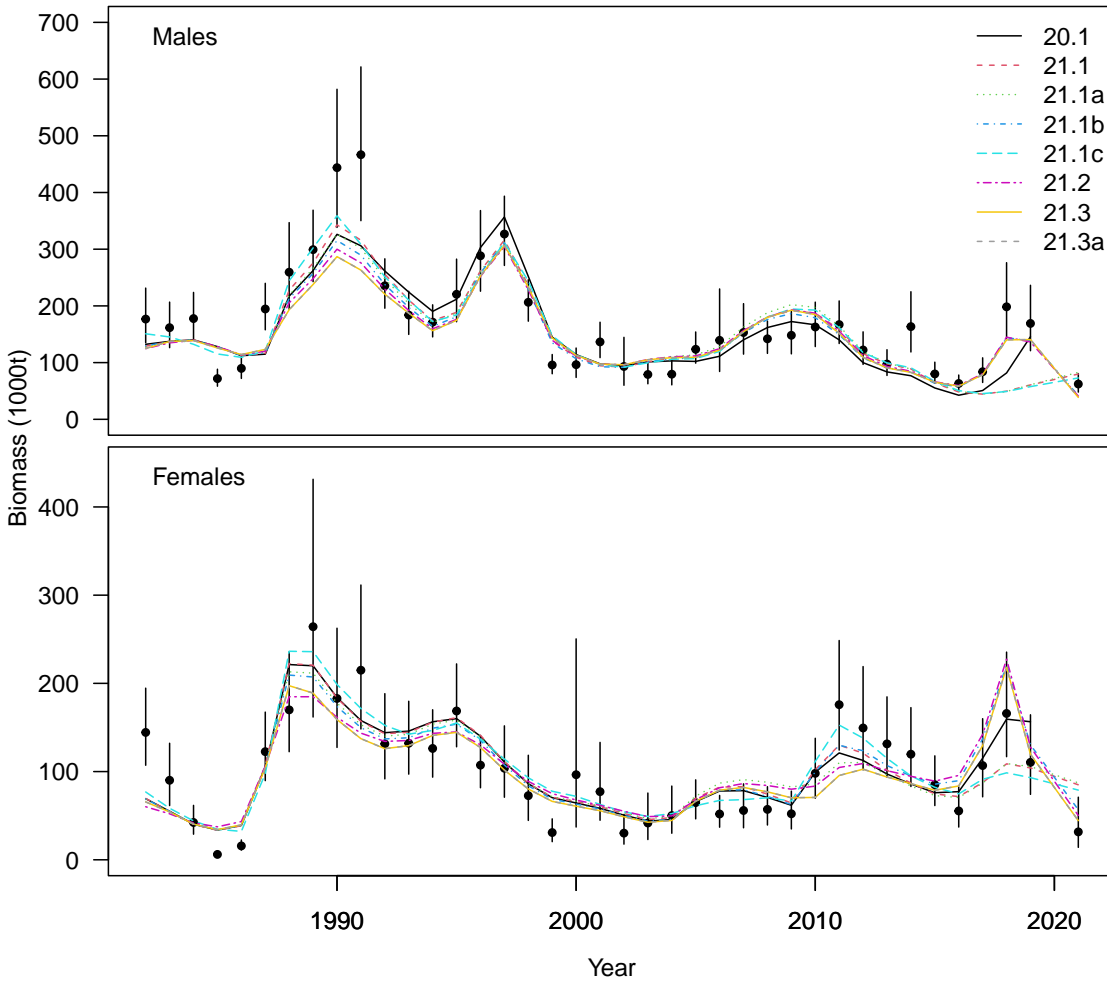


Figure 26: Model fits to the observed mature biomass at survey

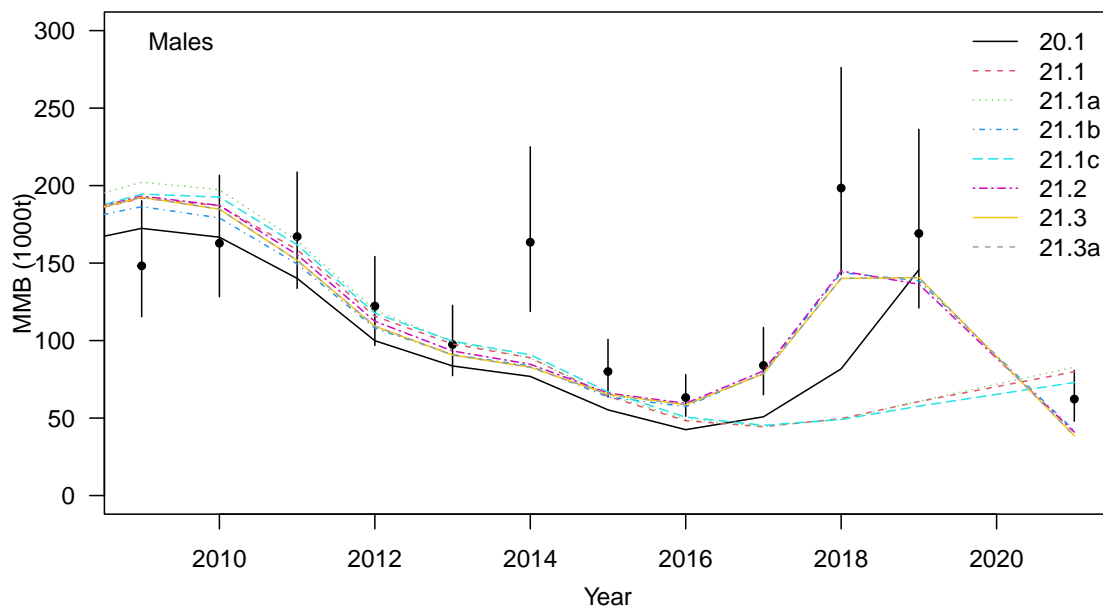


Figure 27: Model fits to the observed mature biomass at survey 2009-present

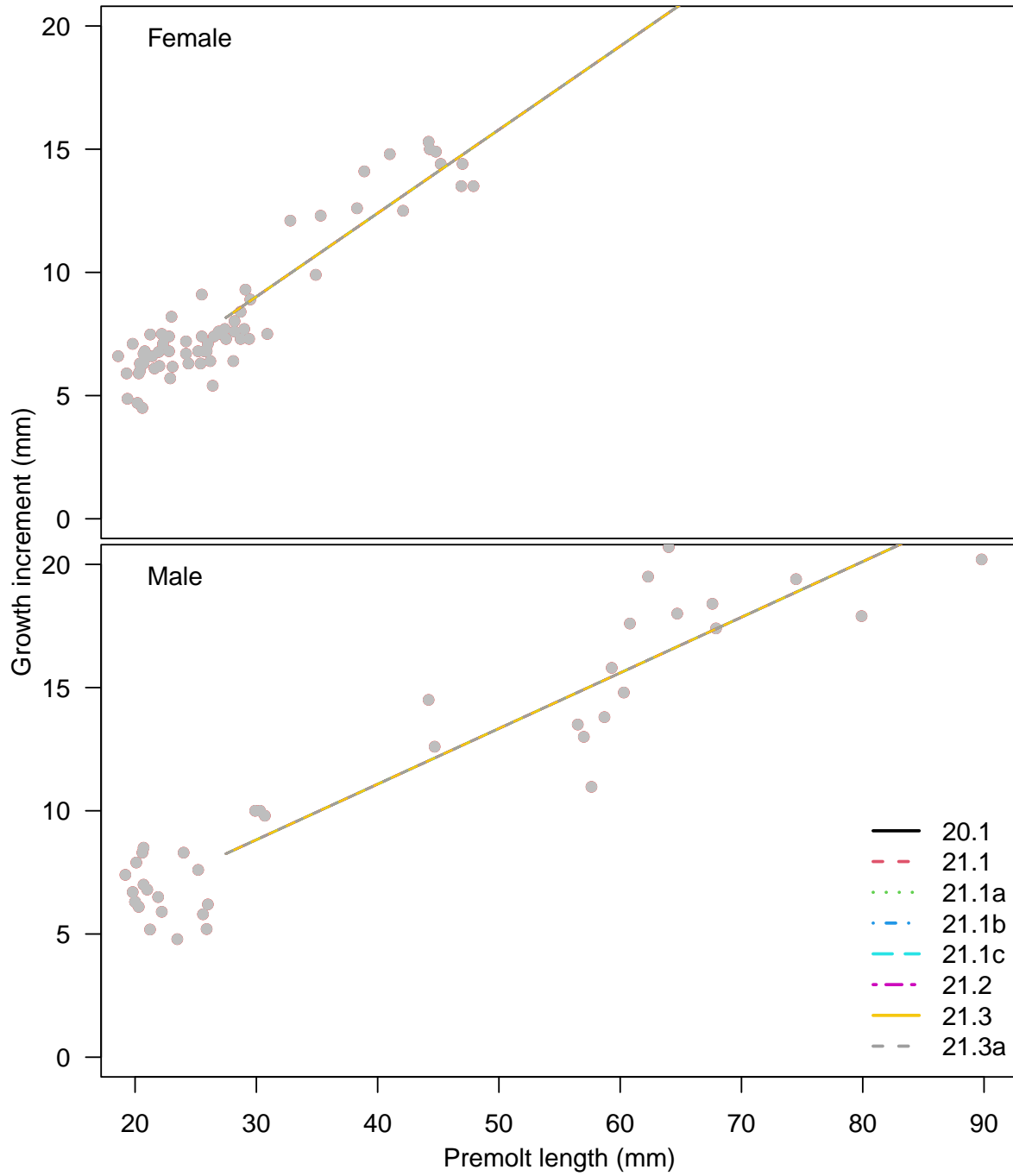


Figure 28: Model fits to the growth data

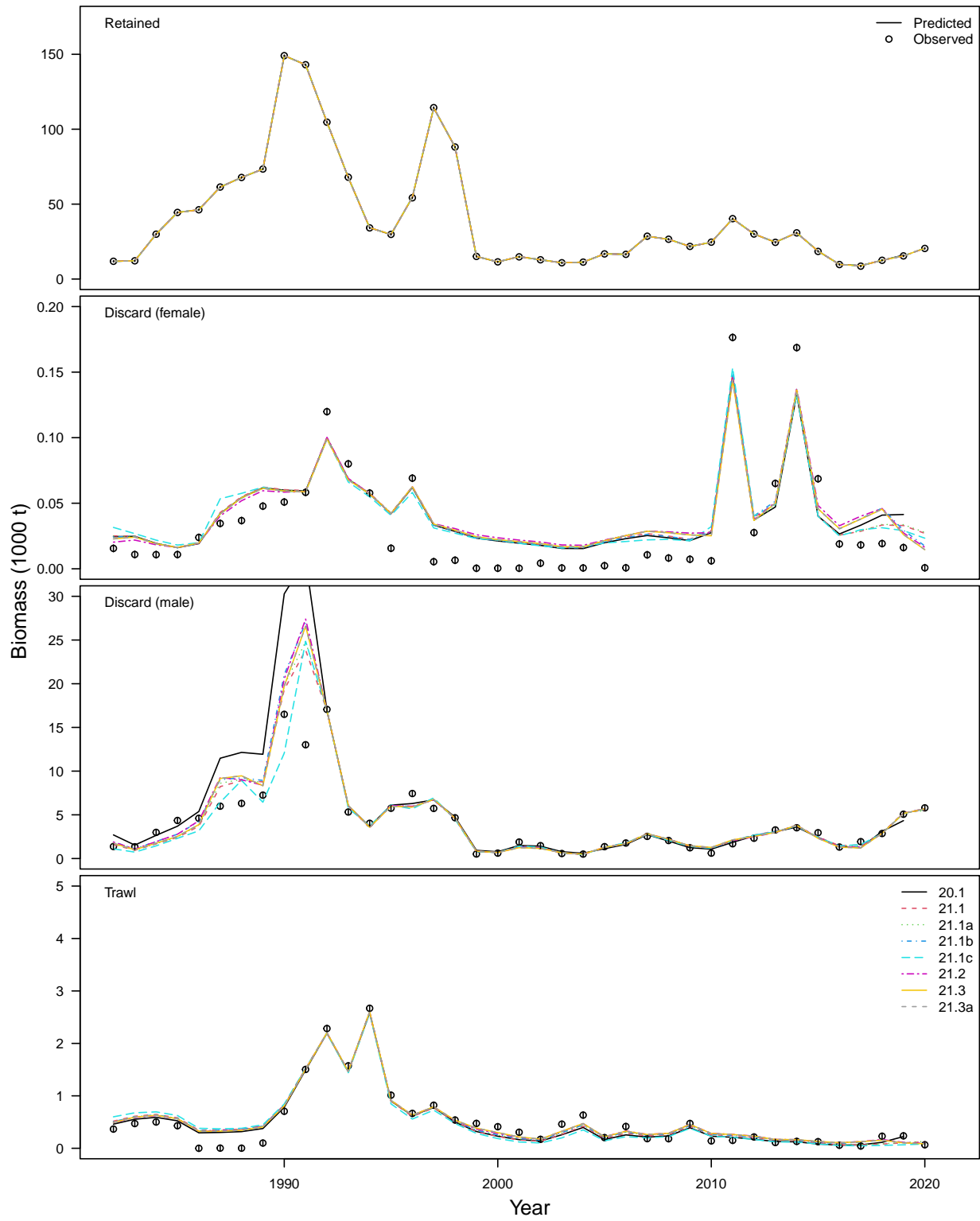


Figure 29: Model fits to catch data

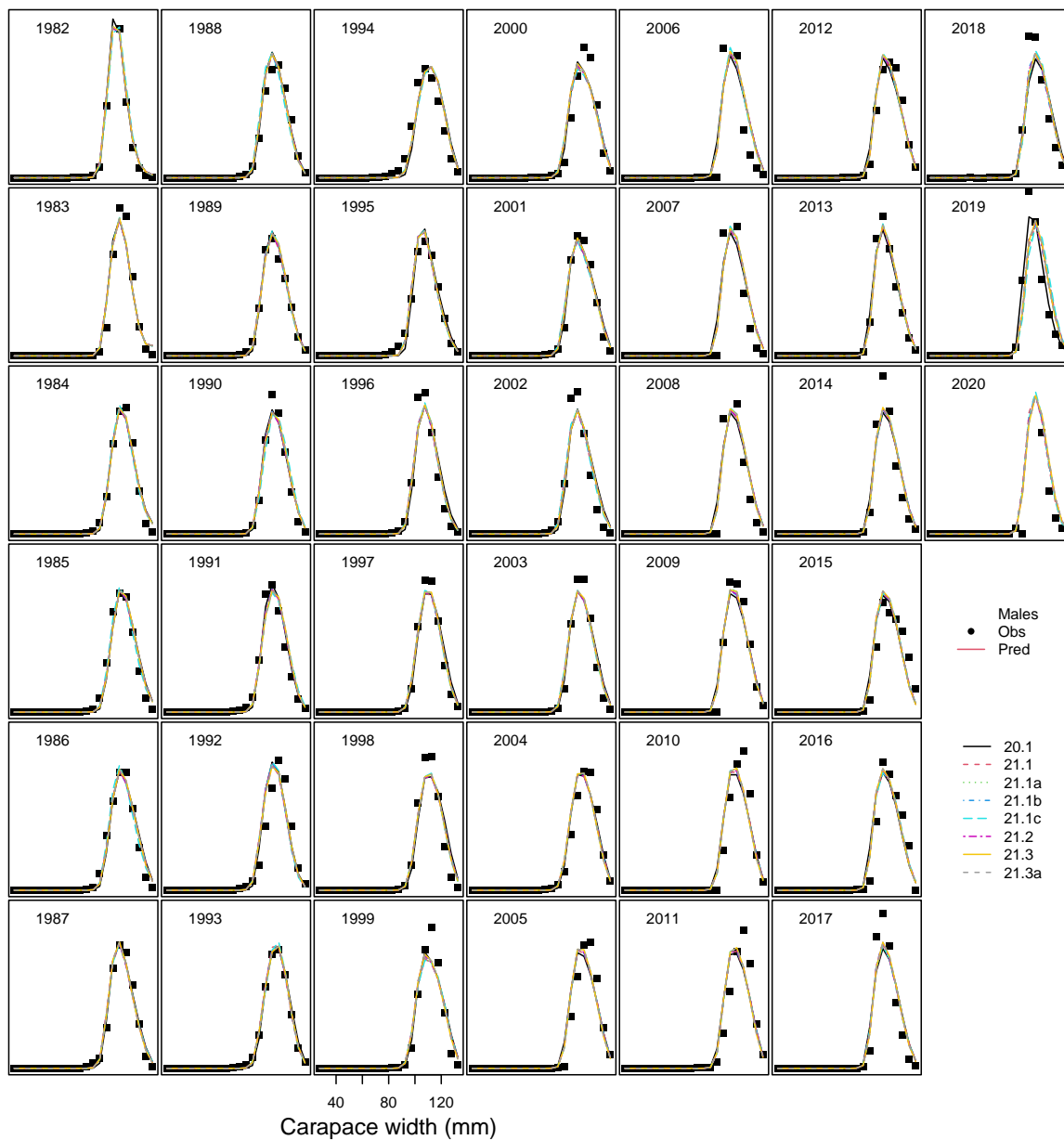


Figure 30: Model fits to retained catch size composition data

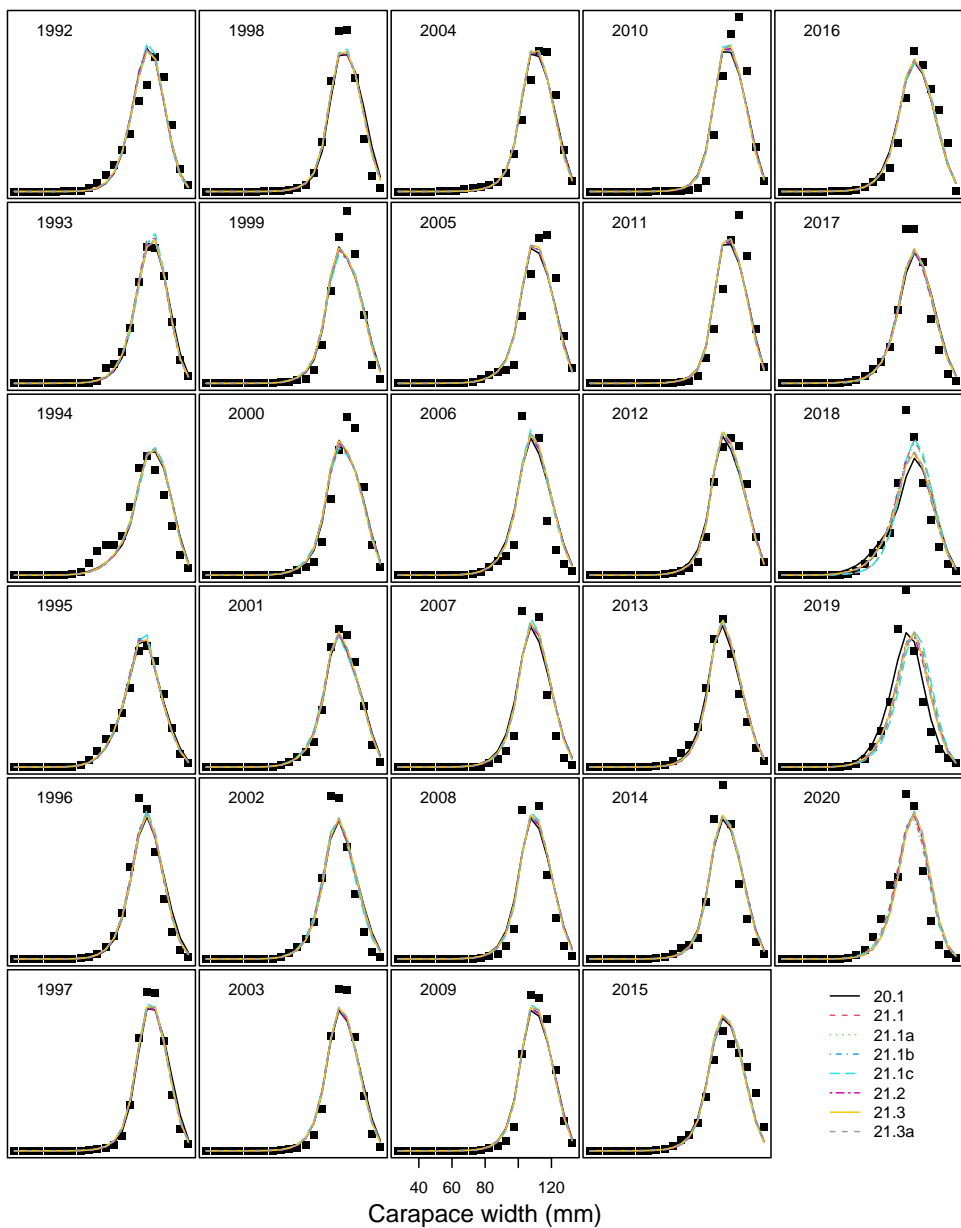


Figure 31: Model fits to total catch size composition data

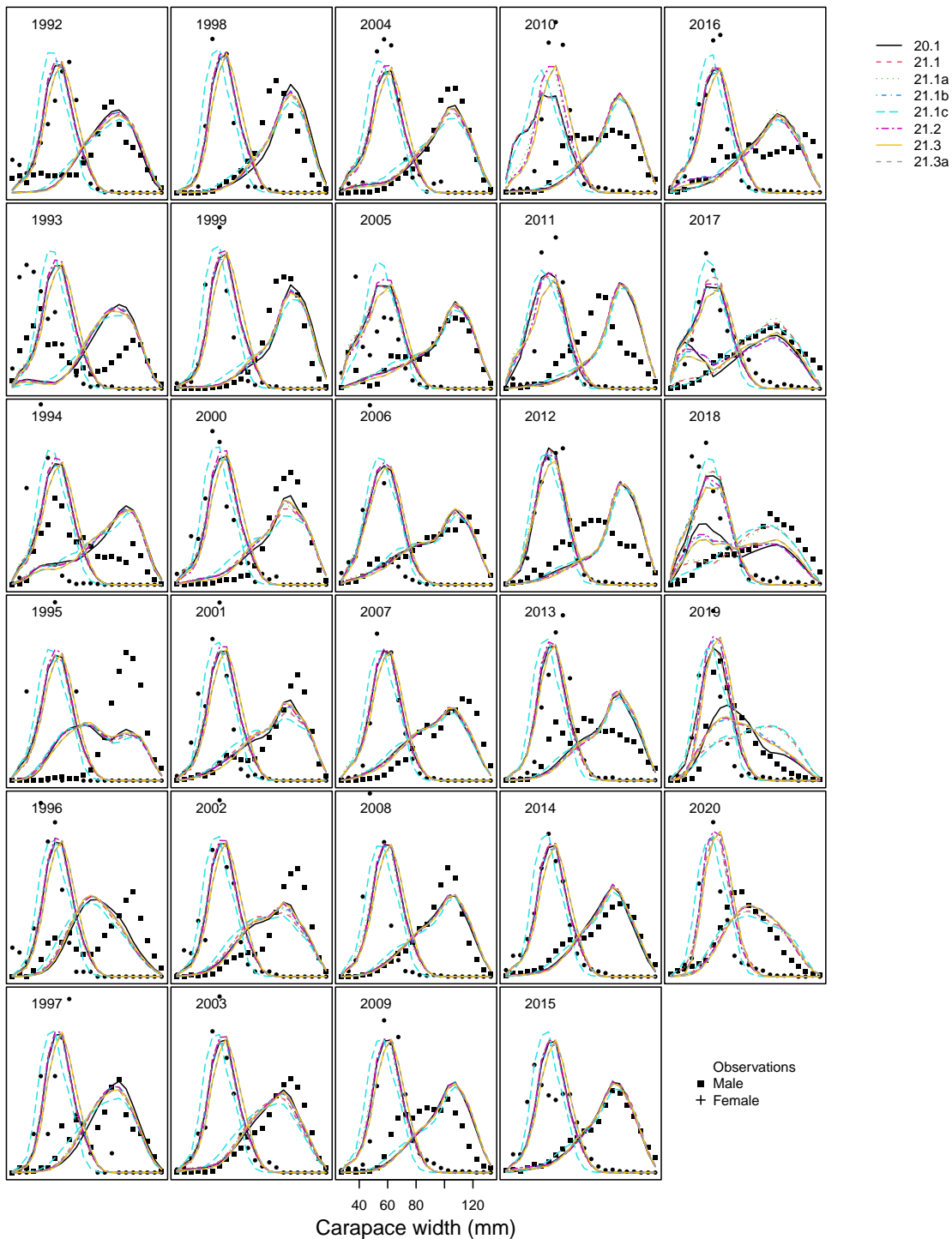


Figure 32: Model fits to trawl catch size composition data

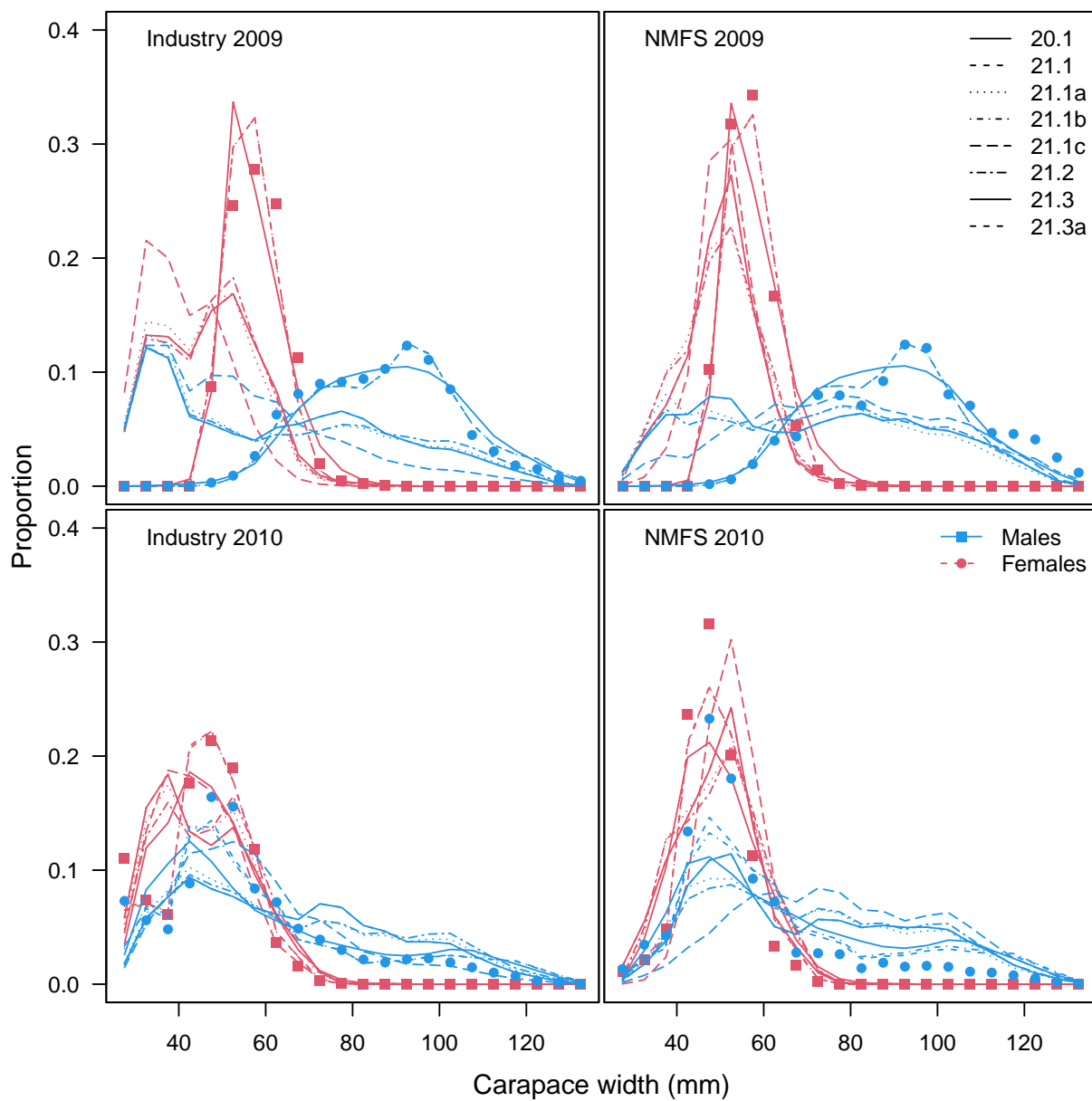


Figure 33: Model fits to size composition data from summer survey experiments (2009 & 2010)

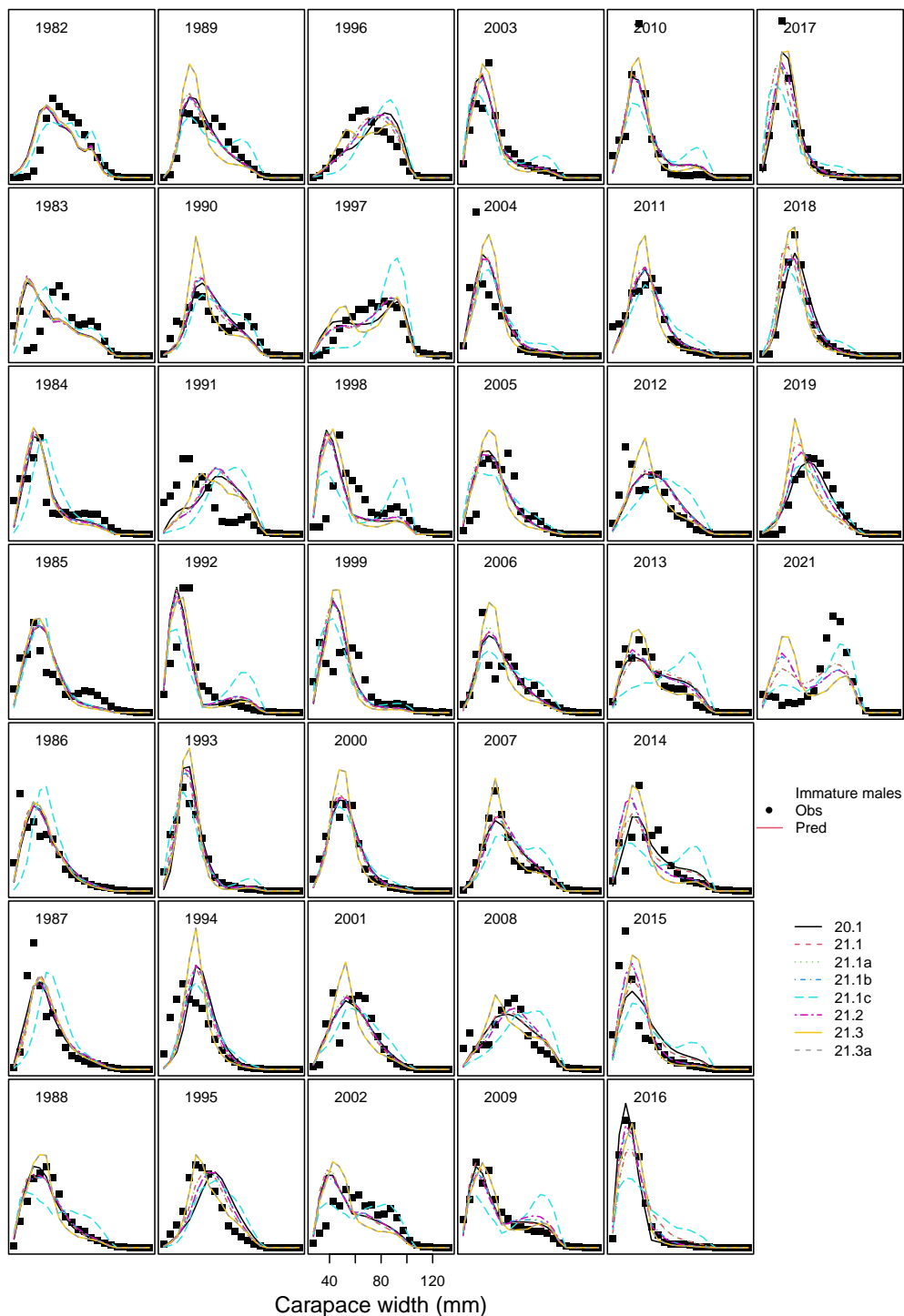


Figure 34: Model fits to immature male survey size composition data. Note that male and female survey selectivity proportions at length in a given year sum to 1. Consequently, the integral of predicted length compositions may appear to be different than the integral of the observed length composition data.

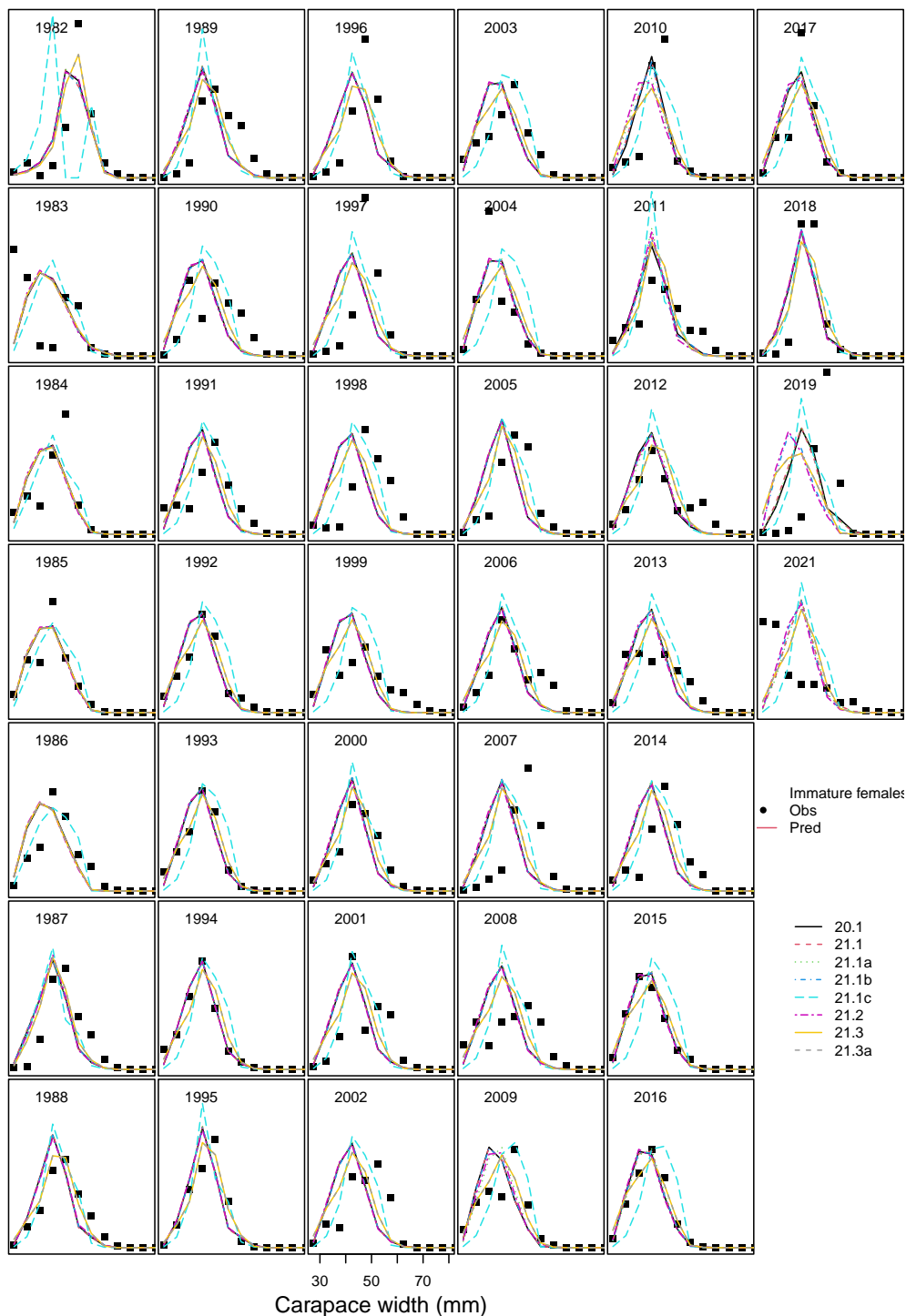


Figure 35: Model fits to immature female survey size composition data. Note that male and female survey selectivity proportions at length in a given year sum to 1. Consequently, the integral of predicted length compositions may appear to be different than the integral of the observed length composition data.

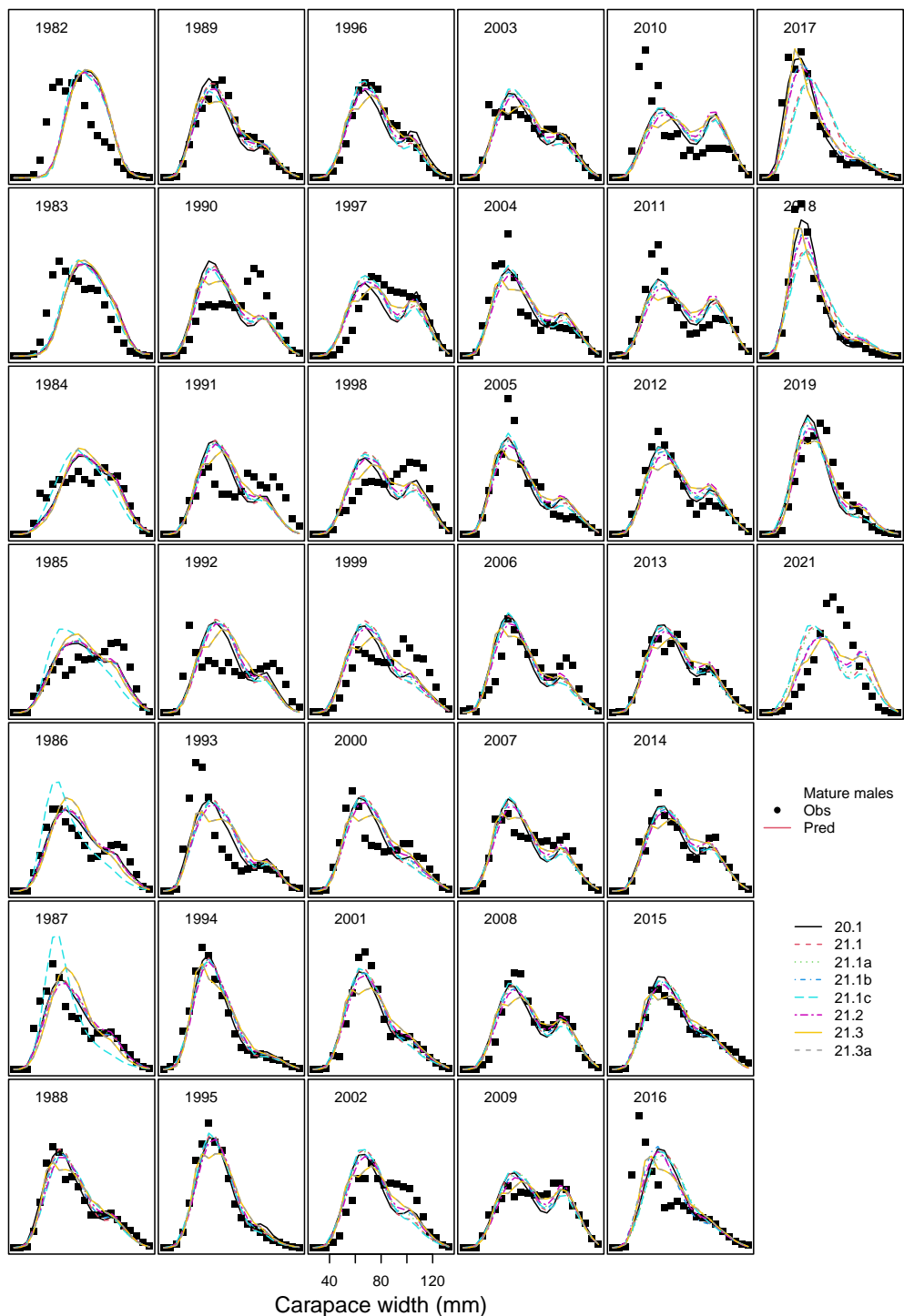


Figure 36: Model fits to mature male survey size composition data. Note that male and female survey selectivity proportions at length in a given year sum to 1. Consequently, the integral of predicted length compositions may appear to be different than the integral of the observed length composition data.

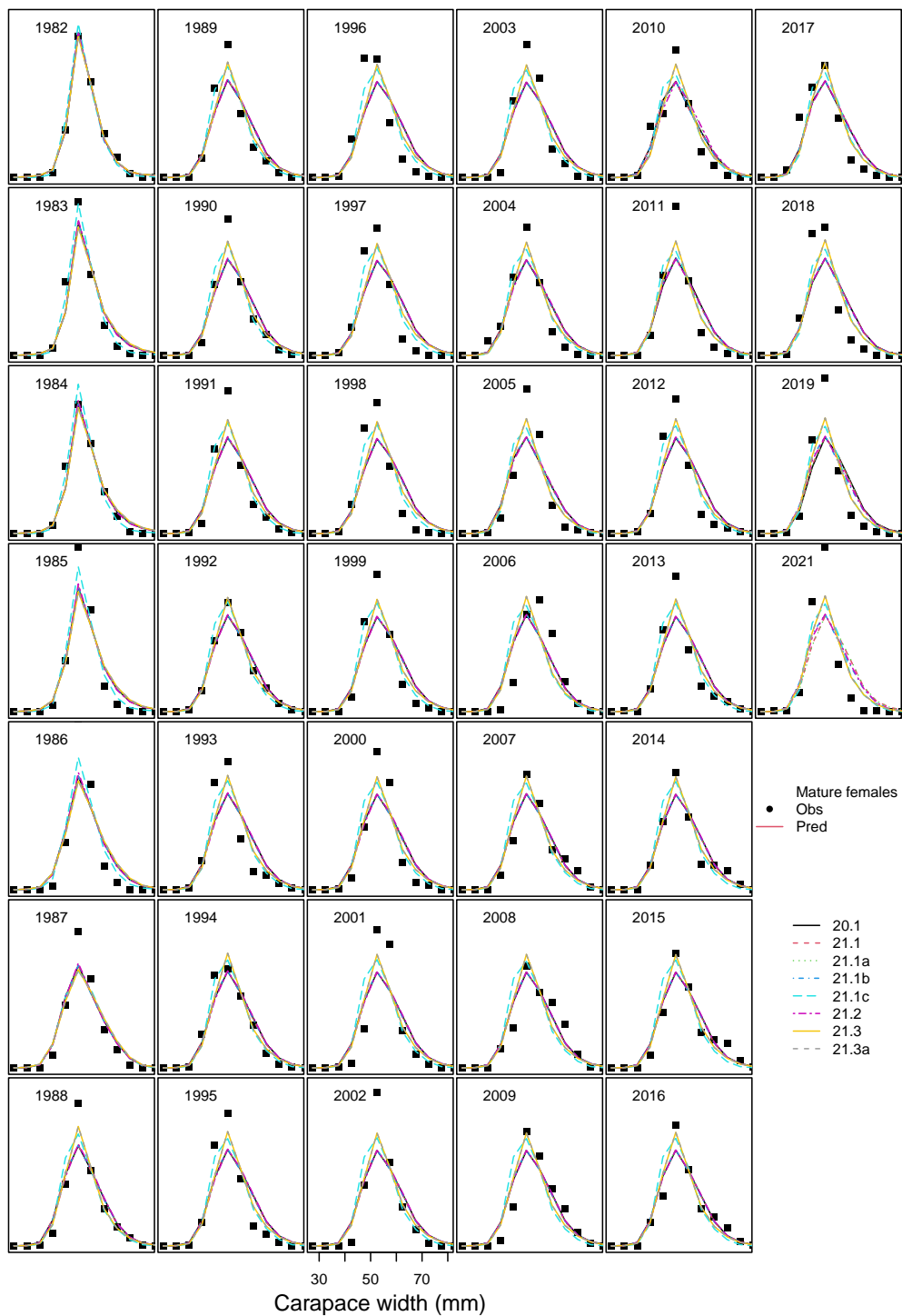


Figure 37: Model fits to mature female survey size composition data. Note that male and female survey selectivity proportions at length in a given year sum to 1. Consequently, the integral of predicted length compositions may appear to be different than the integral of the observed length composition data.

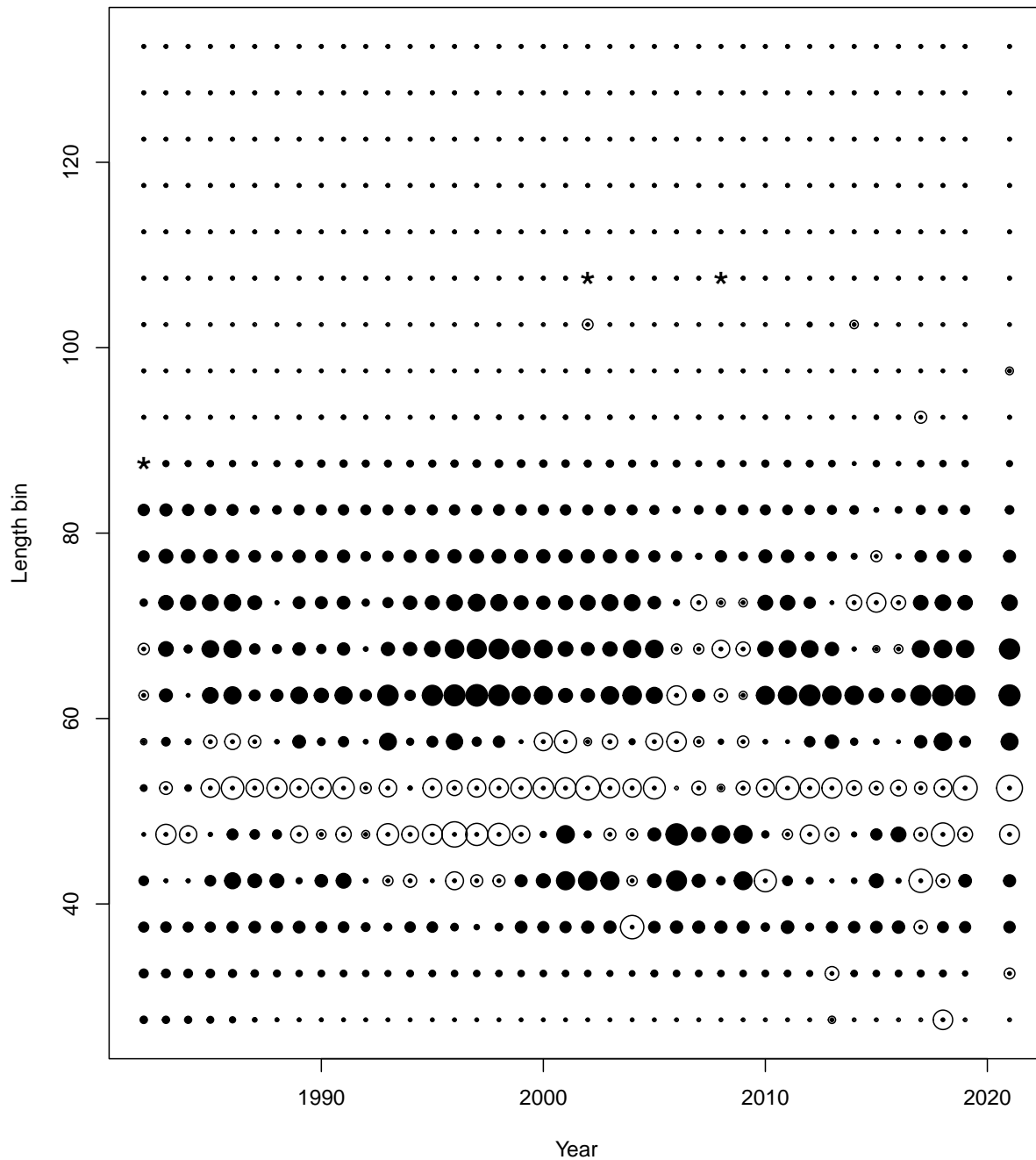


Figure 38: Residual bubble plot of the fits to the NMFS mature female for the author-preferred model. Open circles represent positive residuals; closed circles represent negative residuals.

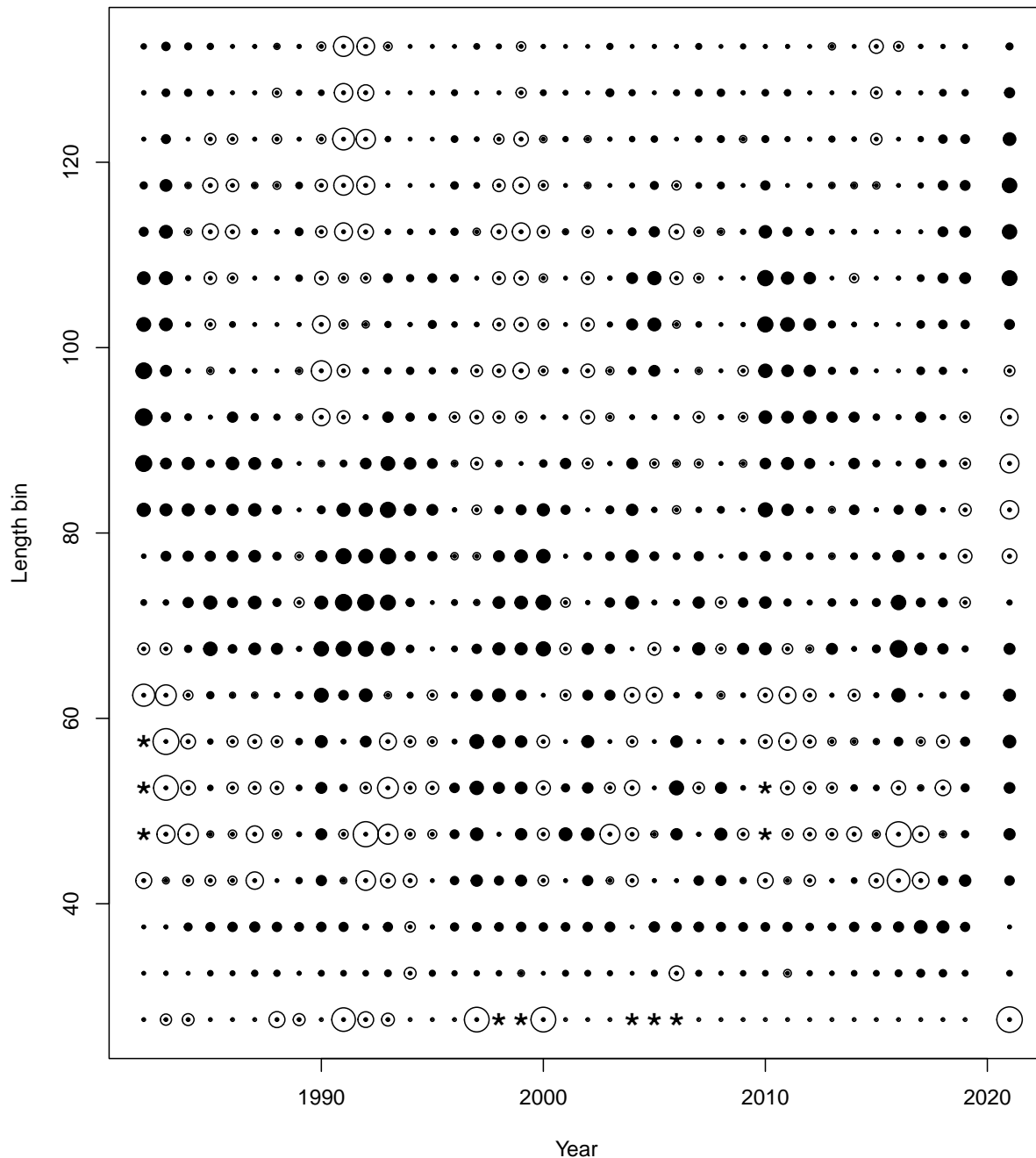


Figure 39: Residual bubble plot of the fits to the NMFS mature male for the author-preferred model. Open circles represent positive residuals; closed circles represent negative residuals.

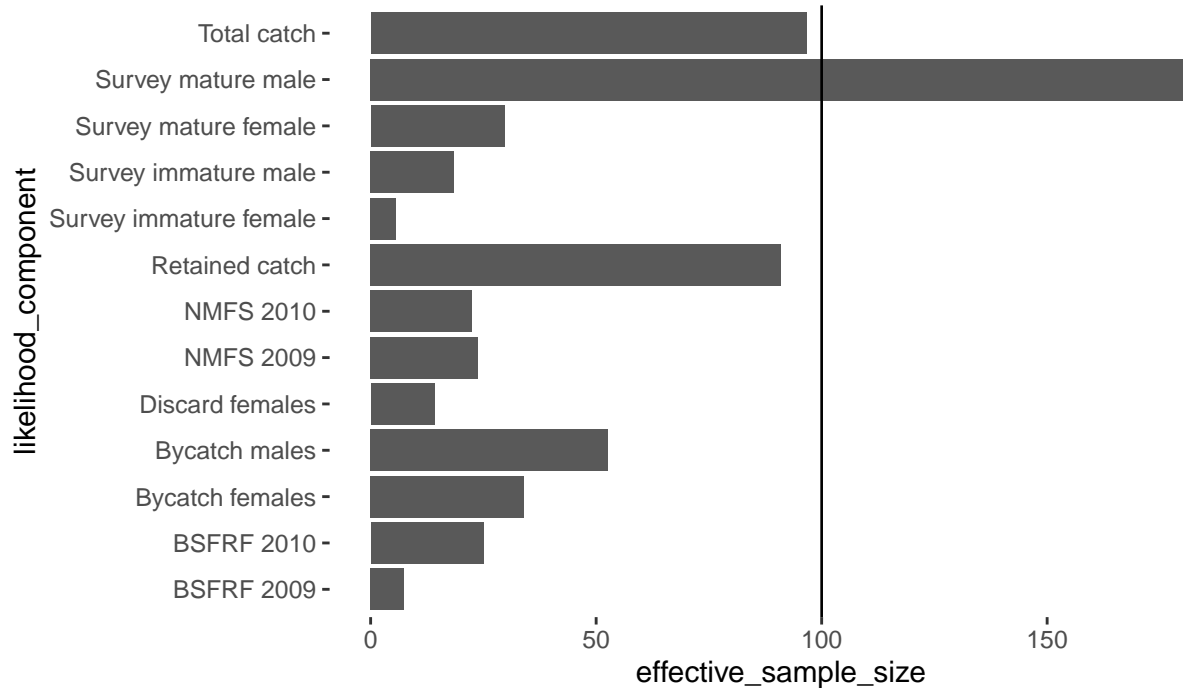


Figure 40: Effective sample sizes calculated by McAllister-Ianelli methods for model 21.1c.

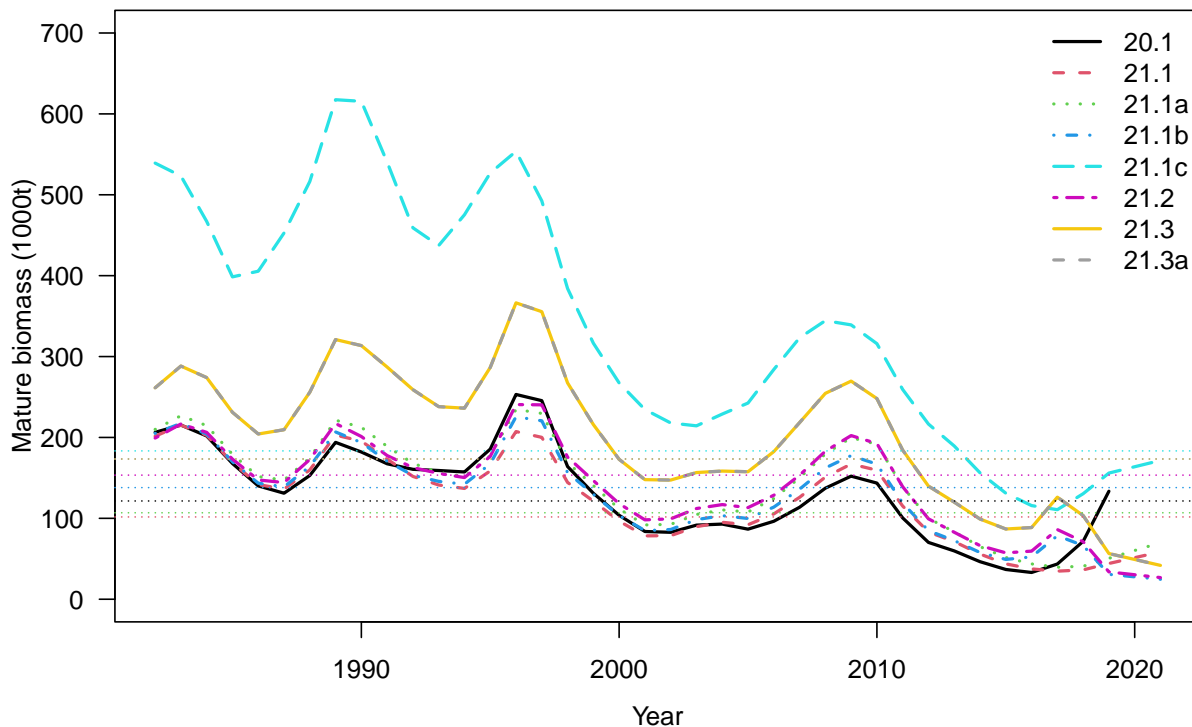


Figure 41: Model predicted mature biomass at mating time. Dotted horizontal lines are target biomasses.

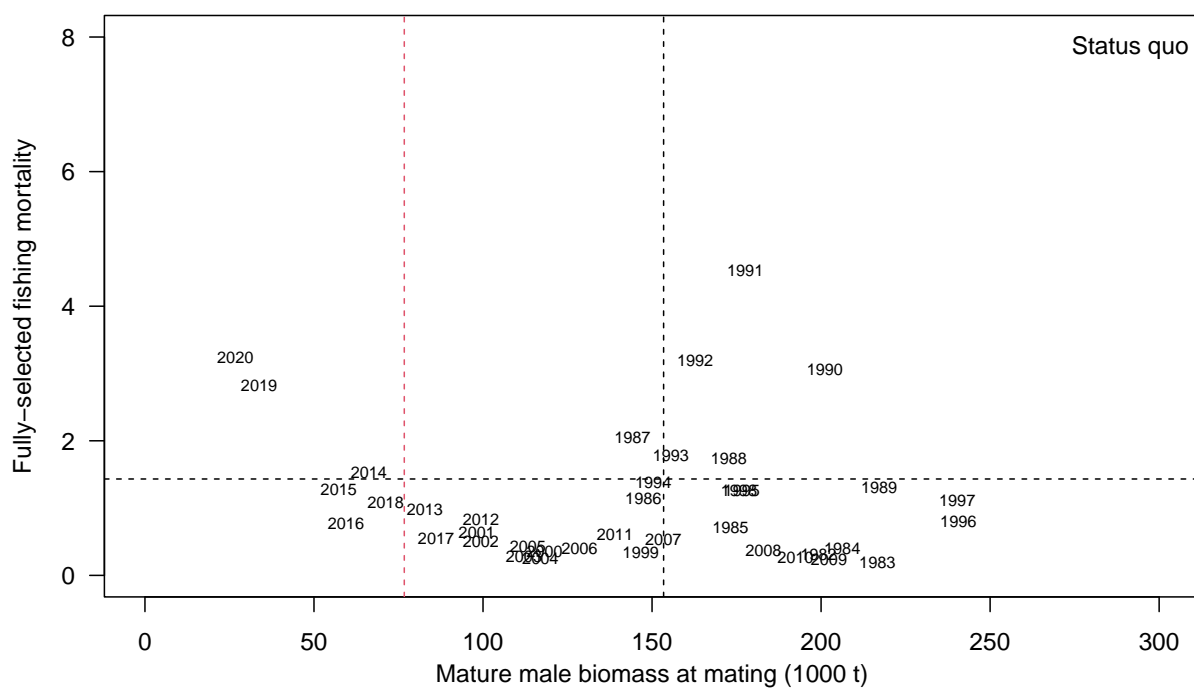


Figure 42: Kobe plot for the author-preferred model. Vertical dashed black line represents the MLE value for B35%; Vertical dashed red line represents the MSST, horizontal dashed black line represents F35%

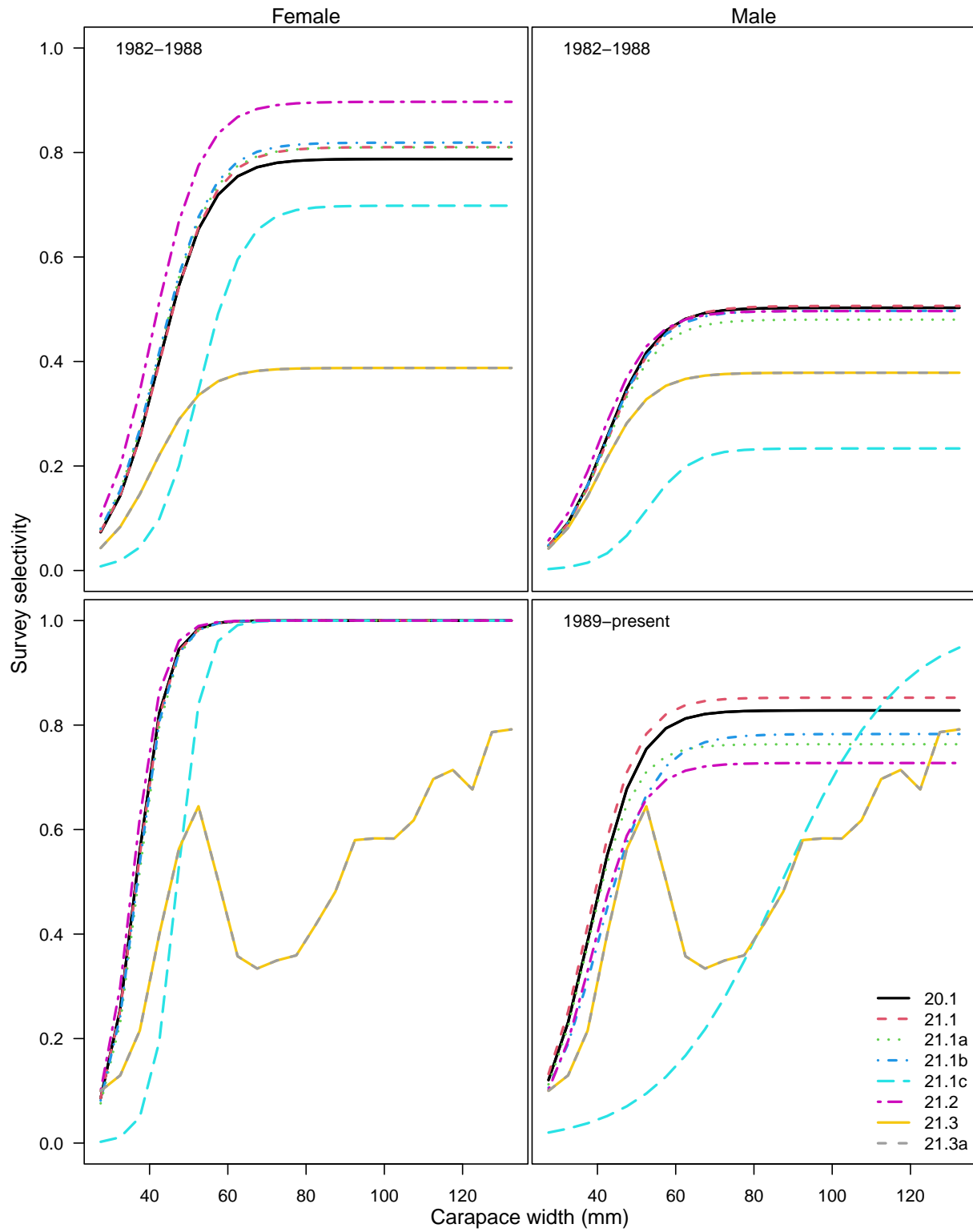


Figure 43: Estimated survey selectivity

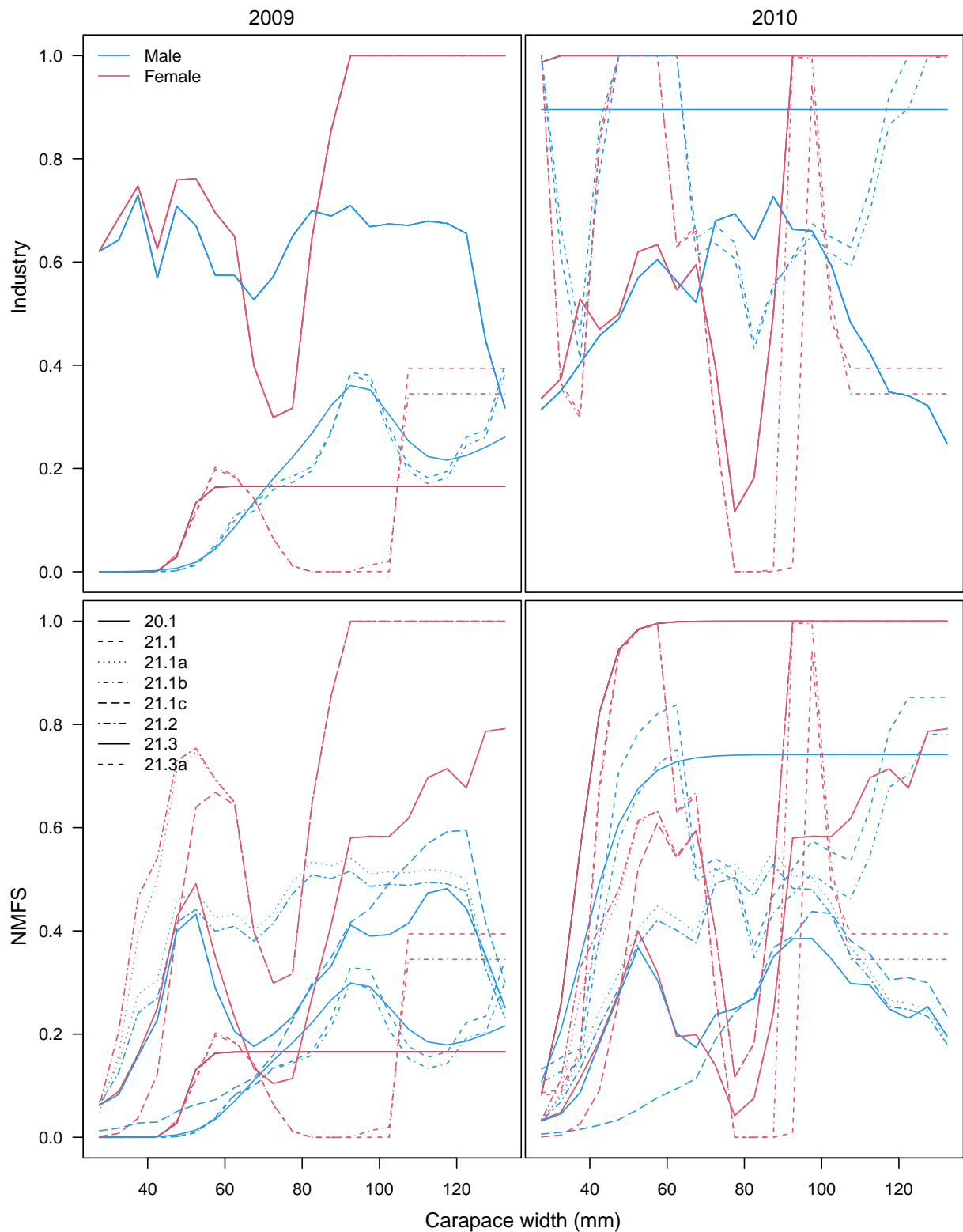


Figure 44: Estimated or specified availability (top row) and estimated experimental survey selectivity (availability * survey selectivity; bottom row).

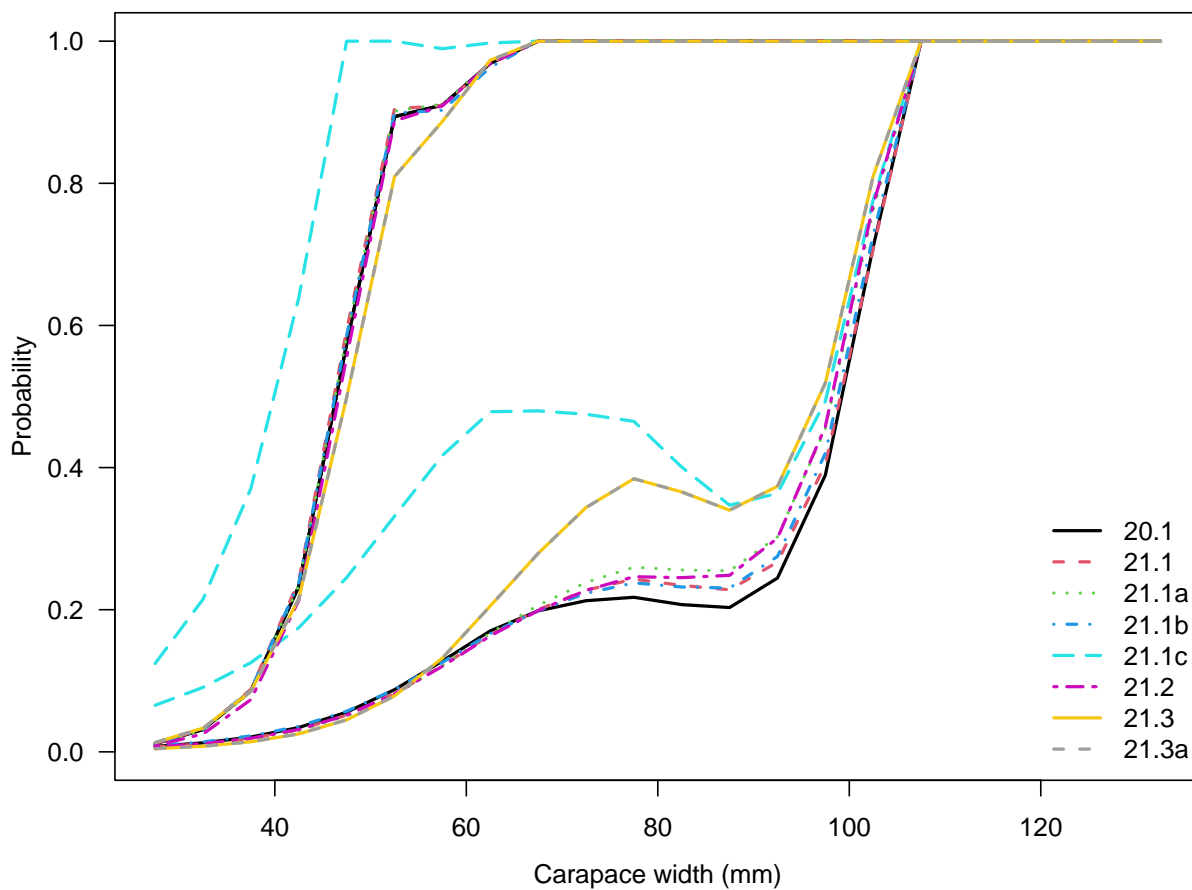


Figure 45: Estimated probability of maturing

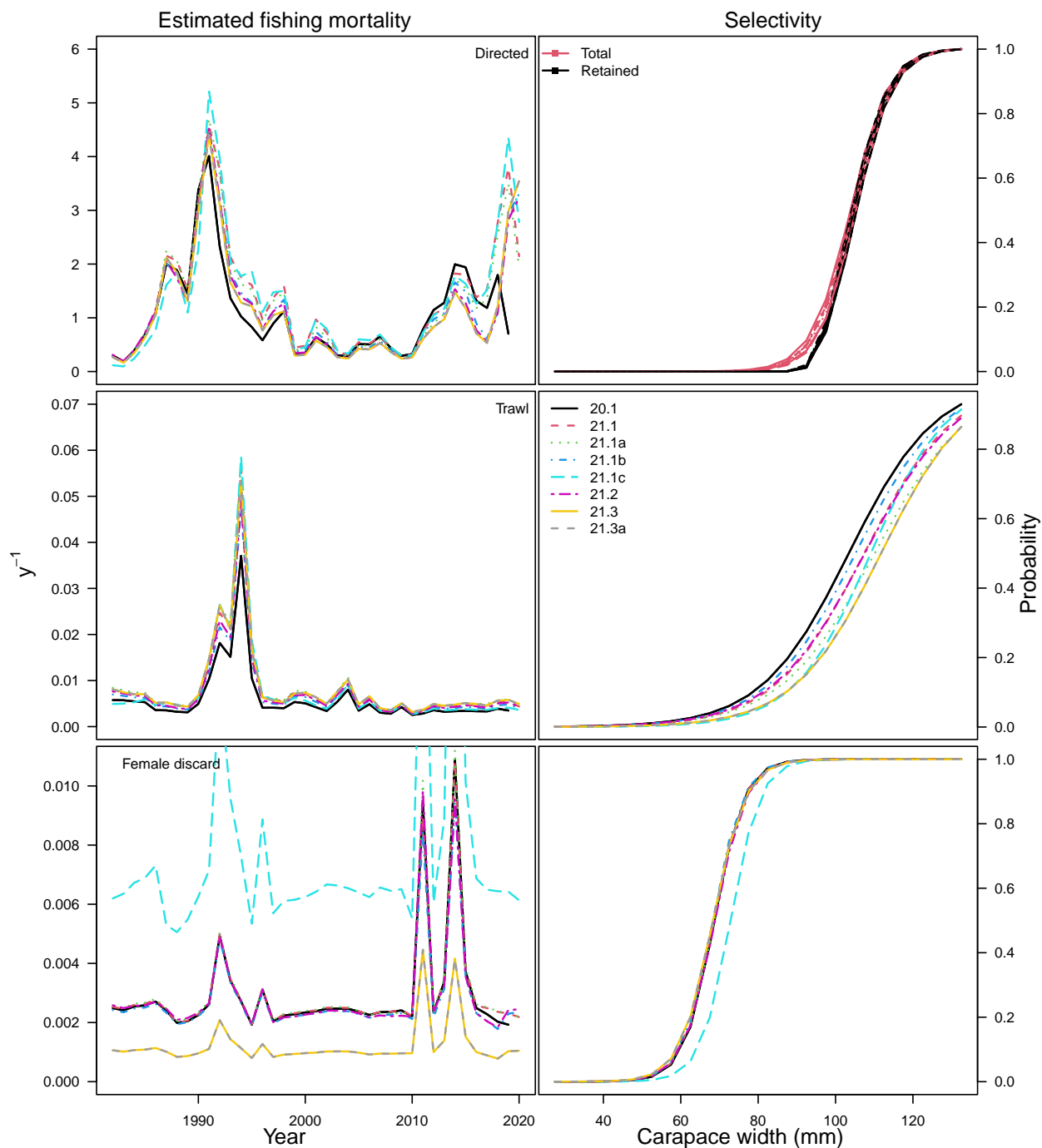


Figure 46: Model predicted fishing mortalities and selectivities for all sources of mortality

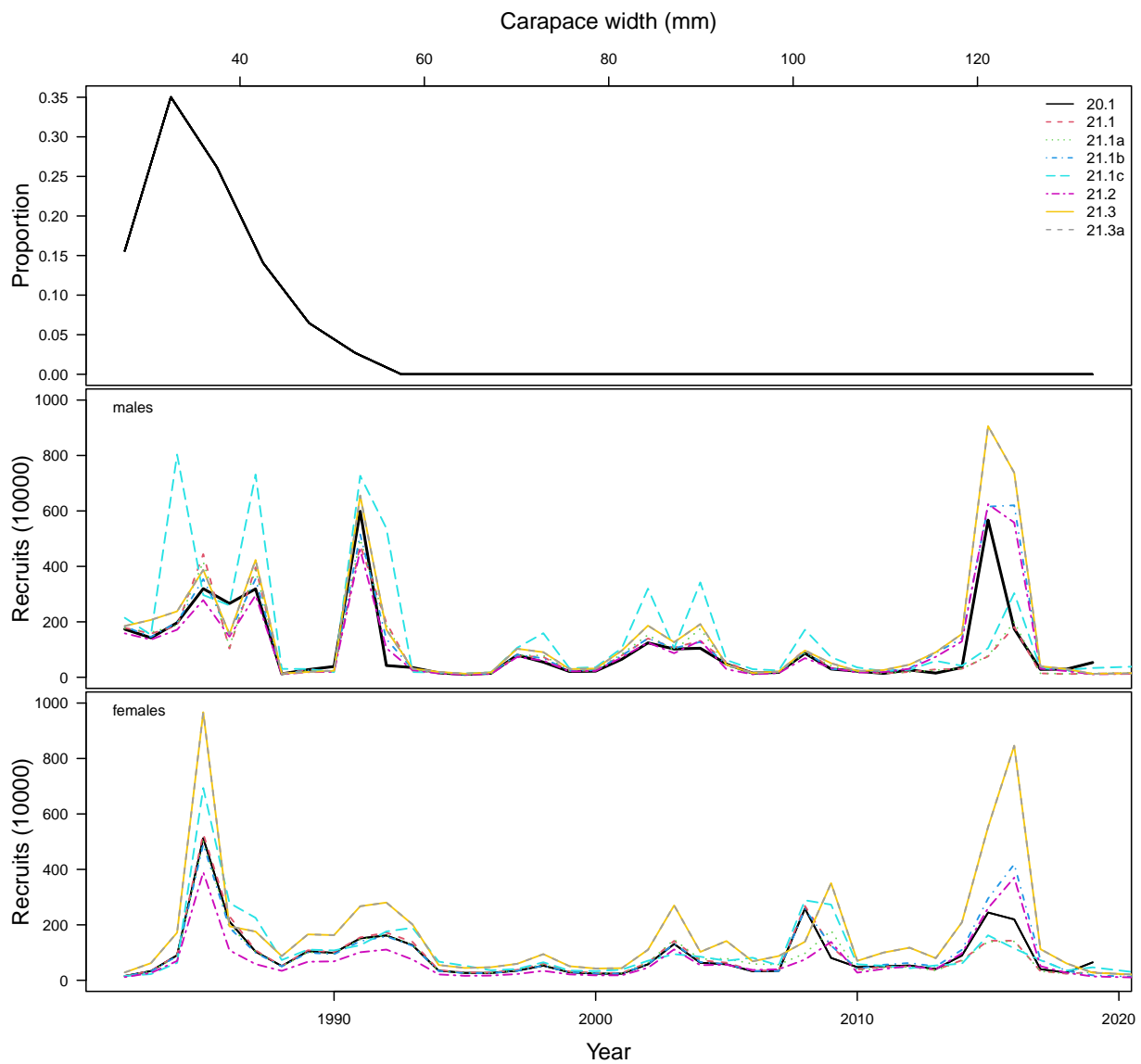


Figure 47: Estimated recruitment and proportions recruiting to length bin.

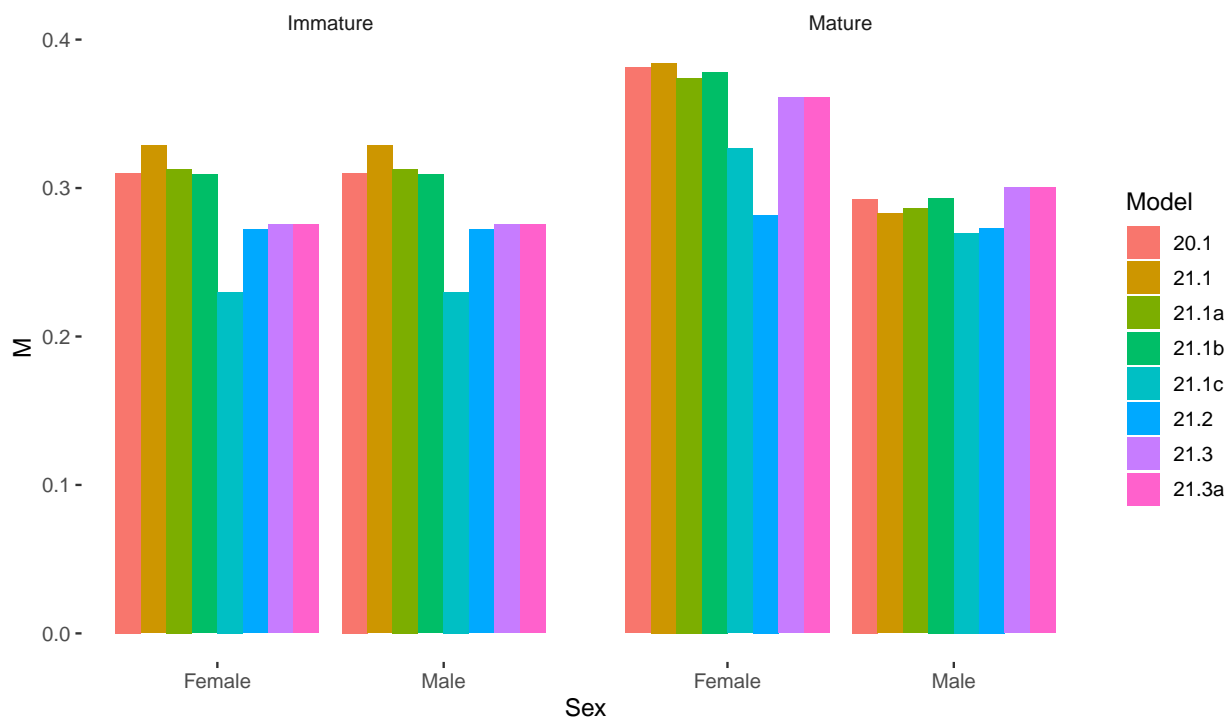


Figure 48: Estimated natural mortality by sex and maturity state.

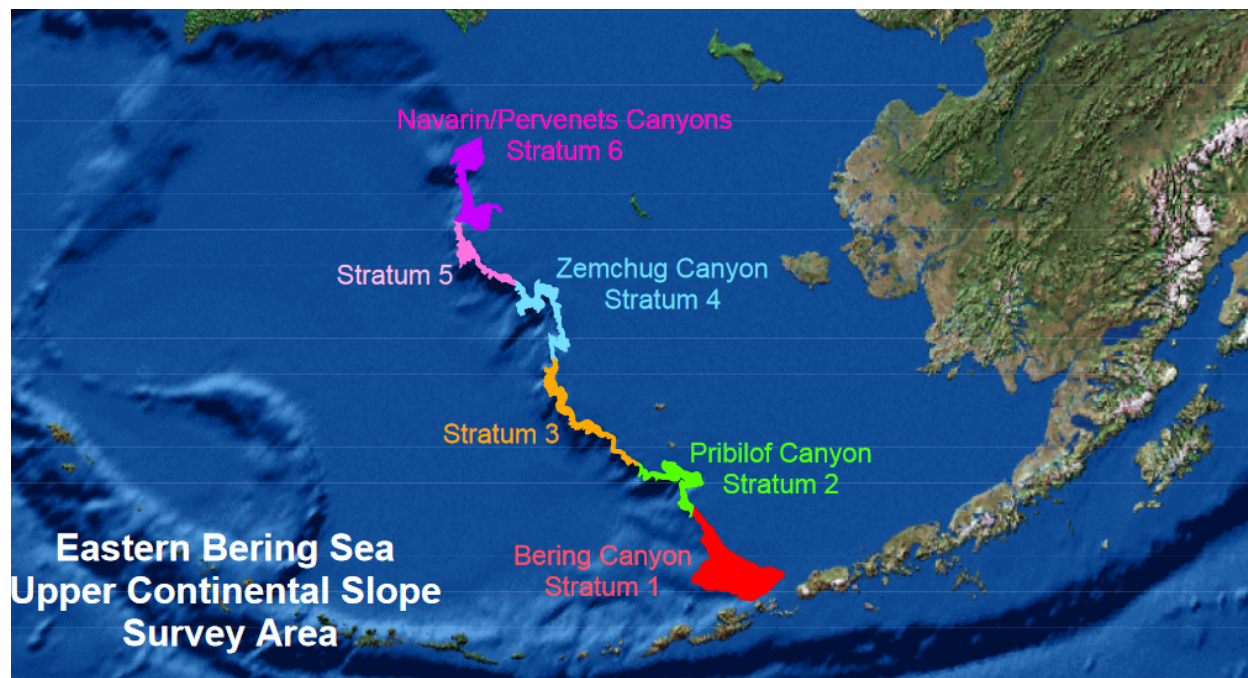


Figure 49: Location of the survey strata on the eastern Bering Sea slope.

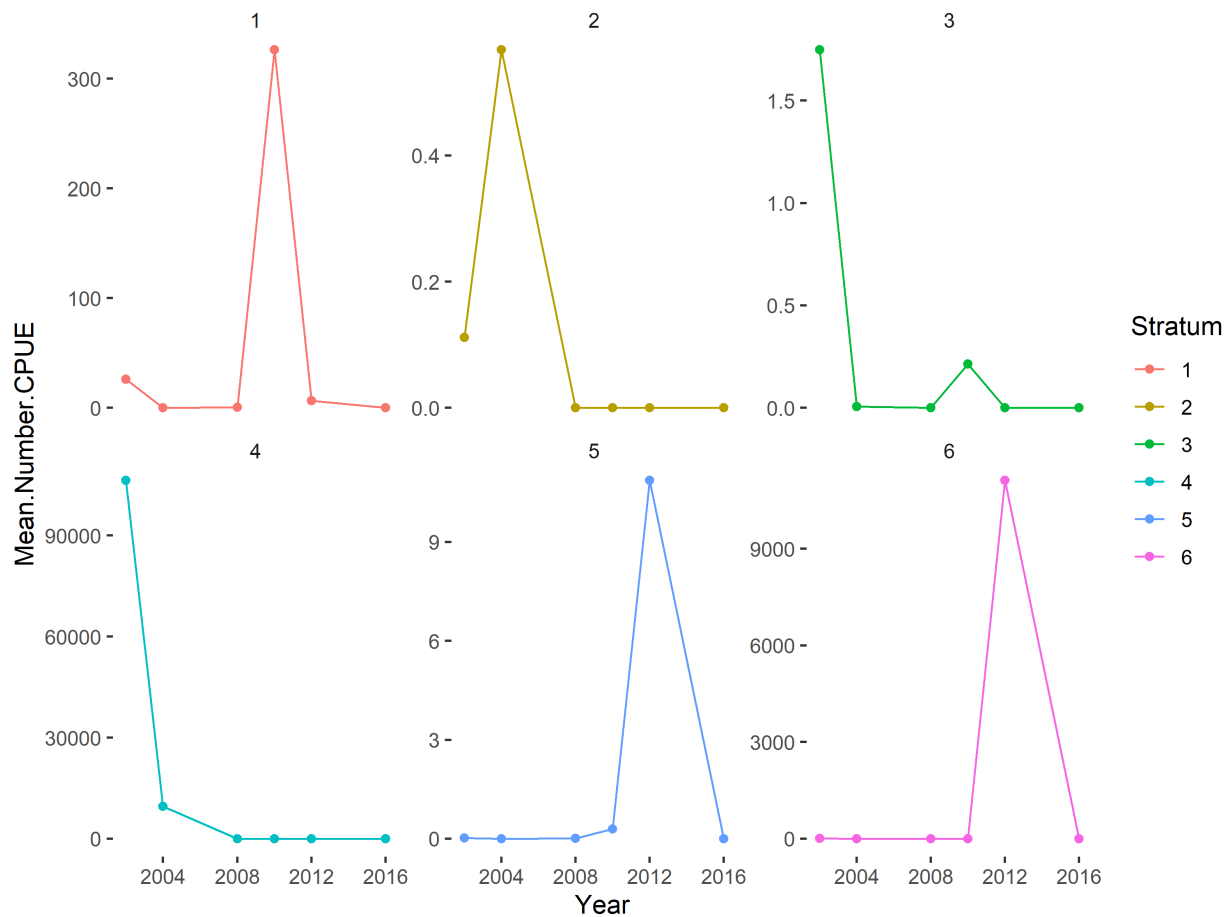


Figure 50: Mean catch per unit effort by strata over time in the EBS slope survey.

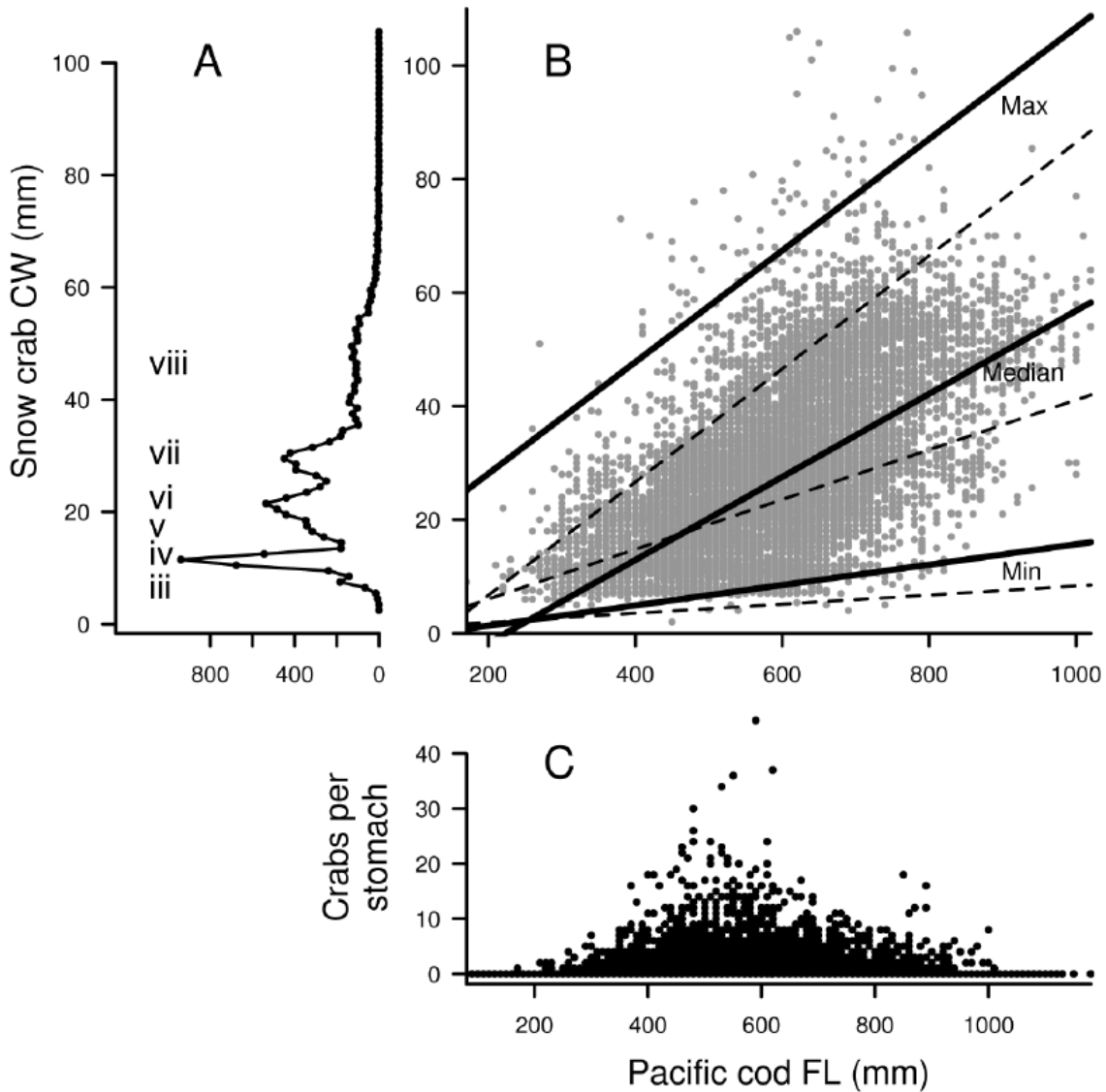


Figure 8. Number and size of snow crabs in cod stomach contents in relation to cod size. (A) Size-frequency distribution of crabs from stomach contents, indicating correspondence between modes and instars. (B) Relationship between cod size and crab size; solid lines indicate the estimated 1 (Min), 50 (Median), and 99 (Max) percentile quantile regressions; broken lines correspond to quantile regressions reported by Chabot et al. (2008, fig.2a using all data) for snow crabs ingested by Atlantic cod off eastern Canada. (C) Observations of number of crabs per stomach in relation to cod size.

Figure 51: Carapace width of crab eaten by a given size of crab reproduced from Burgos et al. 2013.

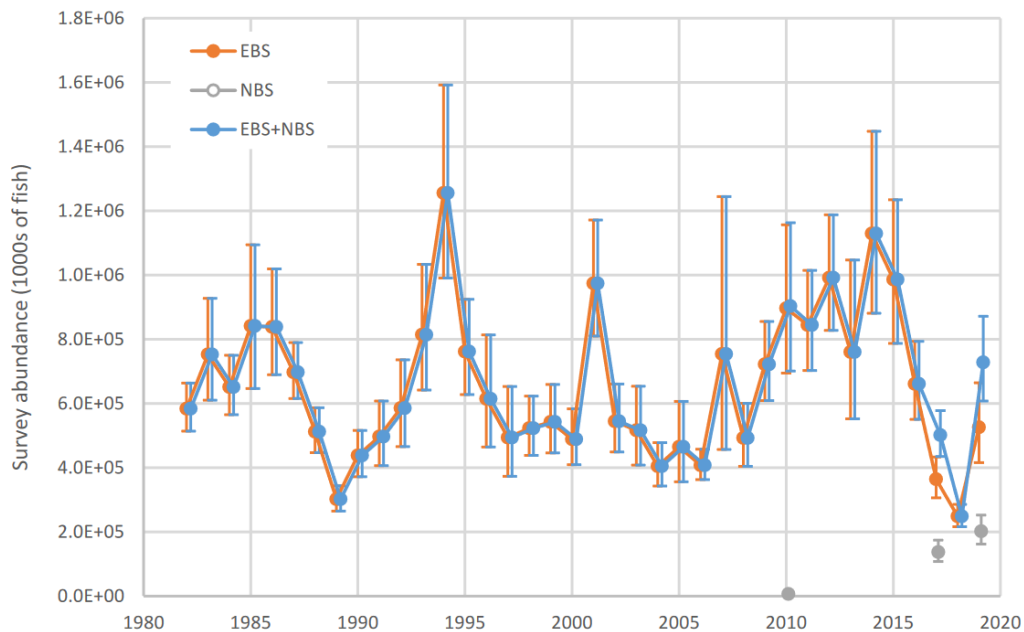


Figure 2.6. Trawl survey abundance time series (design-based).

Figure 52: Abundance of cod in the eastern Bering Sea summer survey from Thompson et al. 2020.

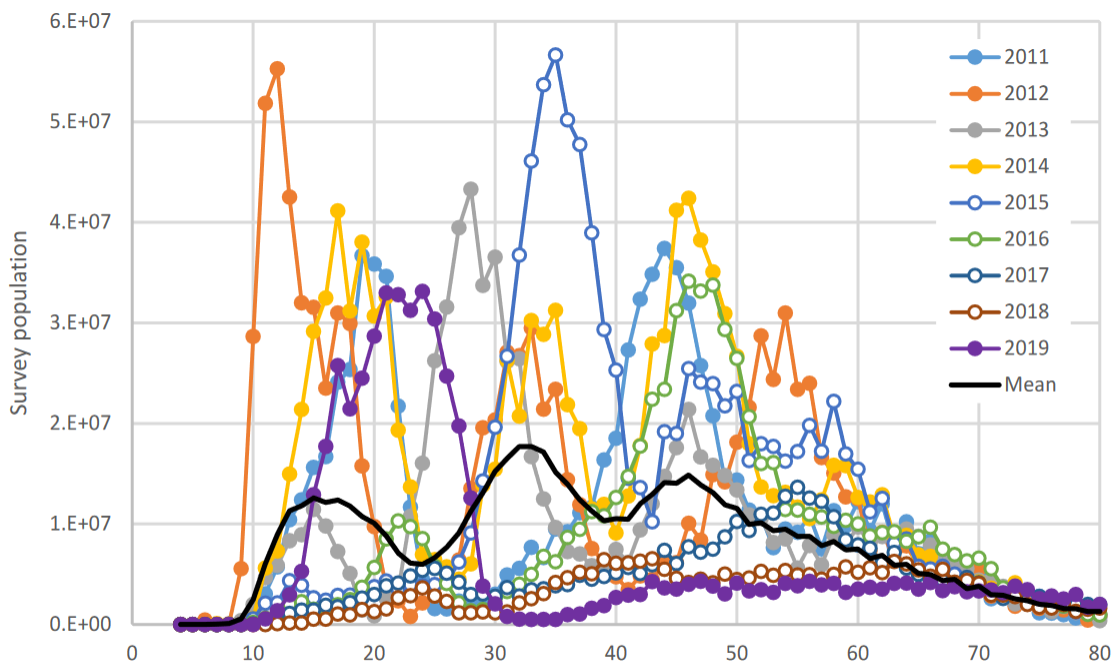


Figure 2.9a. Recent survey size compositions (EBS).

Figure 53: Size composition of cod in the eastern Bering Sea summer survey from Thompson et al. 2020.

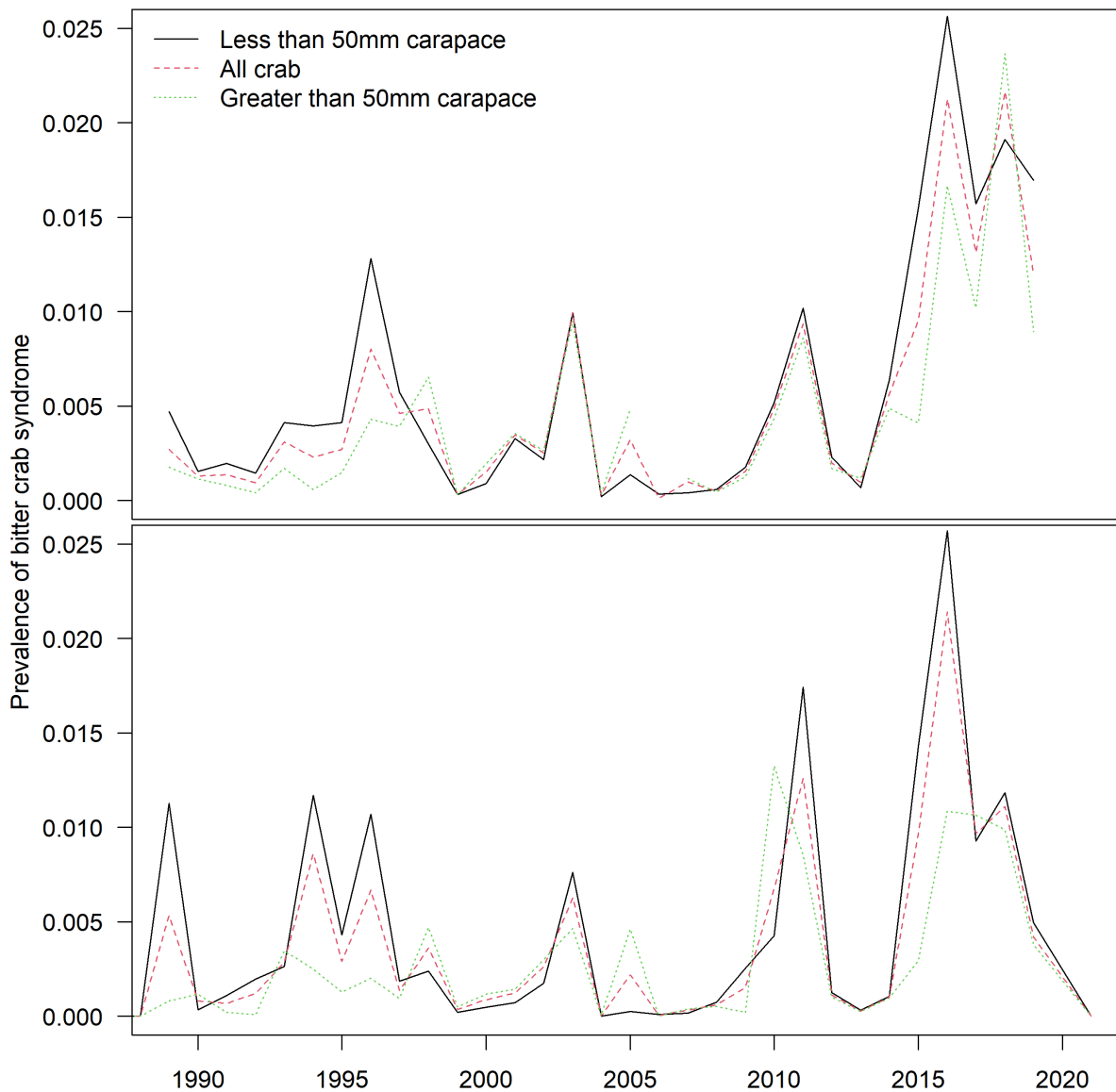


Figure 54: Prevalence of bitter crab syndrome over time. Top figure is the unweighted prevalence of visual evidence of BCS in crab observed in the survey. Bottom is the prevalence of BCS weighted by the sampling factor.