The 2025 assessment for eastern Bering Sea snow crab

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Executive summary

1. *Stock*

Eastern Bering Sea snow crab, *Chionoecetes opilio.*

2. *Catches*

Retained catches increased from relatively low levels in the early 1980s (e.g. 11.85 kt during 1982) to historical highs in 1990s (retained catches during 1991, 1992, and 1998 were 143.02, 104.67, and 88.15 kt, respectively). The stock was declared overfished in 1999 at which time retained catches dropped to levels similar to the early 1980s (e.g. 11.46 kt). Retained catches slowly increased after 1999 before dropping again in 2016. Total allowable catches were reduced with the collapse of the population in 2021, the fishery was closed for the first time in 2022, and the closure continued through 2023. A small fishery occurred in 2024.

Discard mortality from the directed fishery is the next largest source of mortality after retained catch and approximately tracks the retained catch. The highest estimated discard mortality occurred during 1992 at 21.18 kt which was 20.24% of the retained catch during that year. Discard mortality in 2024 was 0.66 kt. Non-directed mortality continues to be very small at 0.09 kt in 2024.

3. *Stock Biomass*

Observed morphometrically mature male biomass (MMB) at the time of the survey increased from low levels in the early to mid-1980s to historical highs in the 1990s (observed MMB during 1990, 1991, and 1997 were 348.38, 219.72, and 194.36 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 91.33 kt. Observed MMB slowly increased after 1999, and the stock was declared rebuilt in 2011 when estimated MMB at mating was above $B_{35\%}$. However, recently the observed MMB has declined to historical lows and the stock was declared overfished again in 2021. MMB at the time of the survey was 113.01 kt in 2024.

4. *Recruitment*

Estimated recruitment shifted from a period of high recruitment to a period of low recruitment in the mid-1990s (corresponding with a late 1980s fertilization). A large year class recruited to the survey gear in the mid 2010s and was tracked until 2018 and 2019, but disappeared from the eastern Bering Sea shelf before reaching commercial size. After the recent collapse, what appears to be a relatively large recruitment occurred and last year's observed immature female biomass in the survey was the highest on record.

5. Management

Table 1: Historical status and catch specifications for snow crab (1,000t). MMB 2024/2025 and after is based on mature male biomass >=95mm carapace width.

Year	MSST	Biomass (MMB)	TAC	Retained catch	Total catch	OFL	ABC
2015/2016	75.8	91.6	18.4	18.4	21.4	83.1	62.3
2016/2017	69.7	96.1	9.7	9.7	11	23.7	21.3
2017/2018	71.4	99.6	8.6	8.6	10.5	28.4	22.7
2018/2019	63	123.1	12.5	12.5	15.4	29.7	23.8
2019/2020	56.8	167.3	15.4	15.4	20.8	54.9	43.9
2020/2021	76.7	26.7	20.4	20.4	26.2	95.4	71.6
2021/2022	91.6	41.3	2.5	2.5	3.6	7.5	5.6
2022/2023	78	92.4	0	0	0.06	10.3	7.7
2023/2024	95.9	155.91	0	0	0.11	15.44	7.72
2024/2025	46.75	19.0	2.1	2.1	2.81	19.6	6.86
2025/2026		31.1				3.26	2.6

Table 2: Historical status and catch specifications for snow crab (1,000t). MMB 2024/2025 and after is based on morphometrically mature male biomass.

Year	MSST	Biomass (MMB)	TAC	Retained catch	Total catch	OFL	ABC
2015/2016	75.8	91.6	18.4	18.4	21.4	83.1	62.3
2016/2017	69.7	96.1	9.7	9.7	11	23.7	21.3
2017/2018	71.4	99.6	8.6	8.6	10.5	28.4	22.7
2018/2019	63	123.1	12.5	12.5	15.4	29.7	23.8
2019/2020	56.8	167.3	15.4	15.4	20.8	54.9	43.9
2020/2021	76.7	26.7	20.4	20.4	26.2	95.4	71.6
2021/2022	91.6	41.3	2.5	2.5	3.6	7.5	5.6
2022/2023	78	92.4	0	0	0.06	10.3	7.7
2023/2024	95.9	155.91	0	0	0.11	15.44	7.72
2024/2025	90.05	137.5	2.1	2.1	2.81	19.6	6.86
2025/2026		160.8				44.29	35.4

Table 3: Historical status and catch specifications for snow crab (millions of lbs). MMB 2024/2025 and after is based on mature male biomass >=95mm carapace width.

Year	MSST	Biomass (MMB)	TAC	Retained catch	Total catch	OFL	ABC
2015/2016	167.11	201.94	40.57	40.57	47.18	183.2	137.35
2016/2017	153.66	211.86	21.38	21.38	24.25	52.25	46.96
2017/2018	157.41	219.58	18.96	18.96	23.15	62.61	50.04
2018/2019	138.89	271.39	27.56	27.56	33.95	65.48	52.47
2019/2020	125.22	368.83	33.95	33.95	45.86	121.03	96.78
2020/2021	169.09	58.86	44.97	44.97	57.76	210.32	157.85
2021/2022	201.94	91.05	5.51	5.51	7.94	16.53	12.35
2022/2023	171.96	203.71	0	0	0.13	22.71	16.98
2023/2024	211.42	343.72	0	0	0.24	34.04	17.02
2024/2025	103.07	41.89	4.63	4.63	6.19	43.21	15.12
2025/2026		68.56				7.19	5.73

Table 4: Historical status and catch specifications for snow crab (millions of lbs). MMB 2024/2025 and after is based on morphometrically mature male biomass.

Year	MSST	Biomass (MMB)	TAC	Retained catch	Total catch	OFL	ABC
2015/2016	167.11	201.94	40.57	40.57	47.18	183.2	137.35
2016/2017	153.66	211.86	21.38	21.38	24.25	52.25	46.96
2017/2018	157.41	219.58	18.96	18.96	23.15	62.61	50.04
2018/2019	138.89	271.39	27.56	27.56	33.95	65.48	52.47
2019/2020	125.22	368.83	33.95	33.95	45.86	121.03	96.78
2020/2021	169.09	58.86	44.97	44.97	57.76	210.32	157.85
2021/2022	201.94	91.05	5.51	5.51	7.94	16.53	12.35
2022/2023	171.96	203.71	0	0	0.13	22.71	16.98
2023/2024	211.42	343.72	0	0	0.24	34.04	17.02
2024/2025	198.53	303.14	4.63	4.63	6.19	43.21	15.12
2025/2026		354.5				97.64	78.04

6. Basis for the OFL

The author-preferred OFL for 2025 is 3.26 kt fishing at $F_{OFL} = 0.18$. This OFL is based on the tier 3 model output using >=95mm carapace width mature male biomass as the currency of management.

Table 5: Metrics used in designation of status and OFL (1,000 t). Status represents the status of the population after the completed fishing year and is used for overfished declarations. 'Years' indicates the year range used in the calculation of the proxy for BMSY. 'M' is the natural mortality for mature male crab. MMB here refers to mature biomass >=95mm carapace width. (continued below)

Year	Tier	BMSY	MMB	Status	Proj_MMB	Proj_Status	FOFL
2025/26	3b	93.5	30.21	0.32	31.05	0.35	0.18

Years	M
1982-2024	0.28

Management quantities were also calculated using morphometrically mature biomass as currency.

Table 7: Metrics used in designation of status and OFL (1,000 t). Status represents the status of the population after the completed fishing year and is used for overfished declarations. 'Years' indicates the year range used in the calculation of the proxy for BMSY. 'M' is the natural mortality for mature male crab. MMB here refers to morphometrically mature biomass. (continued below)

Year	Tier	BMSY	MMB	Status	Proj_MMB	Proj_Status	FOFL
2025/26	3b	180.1	159	0.88	160.8	0.89	34.37

Years	M
1982-2024	0.28

7. Basis for ABC

The author-preferred ABC is 2.6 kt, calculated by subtracting a 20% better from the OFL. This buffer accounts for scientific uncertainty not directly considered in the assessment like retrospective patterns and model misspecification. A buffer of 20% has been historically applied to crab stocks with data availability and model complexity sufficient for inclusion in Tier 3.

A. Summary of Major Changes

1. Management:

The eastern Bering Sea snow crab population was declared overfished in October 2021 and the directed fishery was closed by the State of Alaska for the 2022 and 2023 season. A small fishery occurred in 2024.

2. Input data:

Both catch data and survey data underwent significant updates this cycle due to improved workflows that allow for yearly provision of historical data. Until this year, a new year of data was appended to the data file and historical data were not changed. Specifics of changes in data streams are discussed below. In addition to data revisions, the most recent year of catch and survey data were added to the assessment.

3. Assessment methodology:

Management quantities were derived from maximum likelihood estimates of model parameters in a size-based, integrated assessment method using GMACS. Retrospective analyses and jittering analyses were performed. An application of tier 3 methodologies are used with assessment output from both a model with morphometrically mature male biomass and male biomass >=95mm carapace width to calculate management quantities.

4. Assessment results

The author-preferred OFL for 2025 is 3.26 kt fishing at $F_{OFL} = 0.18$. This OFL is based on the tier 3 model output using >=95mm carapace width as the currency of management.

B. Comments, responses and assessment summary

SSC and CPT comments + author responses from June 2025

SSC comments in italics Author response

The maximin analysis should be completed assuming a Ricker stock-recruitment relationship, but including the same compensation ratios as the original Clark (1991) analysis.

The Ricker curves (Figure 1) used in Clark were implemented in the maximin analysis presented last cycle (and now published in Fisheries Research: Szuwalski and Punt (2025) "Spawning-biomass-per-recruit proxies for fisheries reference points under multiple axes of uncertainty"). Incorporating these into the analysis shifted the SPBR% from ~36% to ~34% (Figure 2).

As the figures presented on the updated 1991+ catch data appear to indicate substantial differences in male discards, the SSC requests that the September document more clearly describe changes in the discard estimation and accounting process.

A presentation from January 2025 from ADFG (available on the council website) noted that the largest changes occurred for total catch through implementing consistent data filtering, expansion using directed pot lifts, and adjustments to biological strata. This process now allows for the production of a data file with all years of available data for each assessment cycle, rather than single years at a time which were appended to an existing data file. An apparent shift upwards in discards of males from the directed fishery results primarily from a change in when discard mortality is applied (before input into the data file [before 2025] or within the assessment code itself [after 2025]).

Given the findings described in Mullowney and Baker (2021) from Canadian research indicating that the molt to maturity may occur at smaller sizes when lower densities of large males are present, it would be useful to determine if there is evidence for the same process occurring in EBS snow crab, and whether fishing mortality on the large males is consistently high enough to result in a strong effect. Further, it would be useful to evaluate whether clutch fullness may be related to size at maturity or the abundance of large-sized crab.

Given that natural mortality events seem to switch among years and sexes depending on the model or input data, it would be prudent to investigate whether it is possible to estimate a direct link between natural mortality and a bottom temperature covariate of appropriate spatial and temporal scale

A manuscript describing both of these relationships for Bering Sea snow crab was presented in May/June 2024 (Figure 3; "Density dependence can modulate climate change impacts on populations") and is currently in review for external publication. In that manuscript, warmer temperatures were associated with elevated mortality and higher densities of large males were associated with lower probabilities of terminally molting at size. The SSC responded to this presentation with the following text: "The SSC emphasizes that projections of climate change impacts, while useful, are highly uncertain and… caution should be used when presenting these results."

Clutch fullness does not appear to be related to the abundance of large-size crab based on analyses in "Spatial depletion rates in the eastern Bering Sea snow crab fishery" (also presented in May 2024 and now in review for external publication). It is unclear if there is any relationship between clutch fullness and recruitment, though preliminary analyses suggest clutch fullness is not an important covariate for predicting recruitment strength.

These analyses come with the caveat that the Kodiak lab is revising their methods for analyzing the maturity data for snow crab.

To explore development of an ABC control rule, the SSC requests that a yield per recruit analysis be developed for snow crab.

Time did not allow for this exercise.

C. Assessment scenarios

Model summaries

Two assessment variants were considered this year:

- 24.1: accepted model from last year
- 25.3: Model structure and assumptions same as 24.1, but updated GMACS version and data

The SSC had also suggested a model run with growth estimated externally if convergence was an issue, but modifications made to the existing model produced satisfactory fits to the growth data within a model that produced a Hessian, so this was not done.

The key assumptions of these models include:

- the probability of terminally molting at size varies over time and size and is specified based on observations from the survey data
- survey selectivity is estimated by era (1982-88; 1989-present) and sex as a non-parametric curve subject to priors based on the BSFRF survey efficiency experiment data
- growth is a linear function of pre-molt carapace width with a specified variability around post-molt size
- all immature crab molt
- natural mortality is estimated by sex and maturity state with additional mortality events estimated in 2018 and 2019 and subject to a prior based on an assumed longevity of 20 years
- total and retained fishery selectivity are estimated logistic curves
- all non-directed bycatch (e.g. snow crab caught in the Tanner crab fishery or crab caught in the non-pelagic trawl fisheries) is lumped into a single 'fishery' for which a single selectivity is estimated
- recruitment is estimated separately for females and males and is allocated in the first 3 size bins

The largest changes to the assessment this year arise from revision of the data. Historically new data were updated in the assessment by appending the newest year of data to the existing data file. Revisions to the data pipeline at ADFG facilitated the provision of all of the catch data extending to 1991. In this process, analysts at ADFG also revised historical catch estimates, which resulted in some changes to the input catches for the assessment. A presentation from January 2025 from ADFG (available on the council website) noted that the largest changes occurred for total catch through implementing consistent data filtering, expansion using directed pot lifts, and adjustments to biological strata. This allowed revision of data entry mistakes in historical data.

Concurrently, the Kodiak lab has modified their data pipeline to provide the survey data in an R package called 'crabpack'. While transitioning to using crabpack for data pulls, a discrepancy with the calculated mature male biomass used in the assessment was found. This discrepancy was a result of the 2022 non-GMACS, status quo model using a time-invariant probability of terminal molt to calculate MMB and appending new measures of MMB to the existing data file. A time-varying probability of terminally molting was implemented in the model in 2022, but the historical data in the data file for MMB was not updated. When the MMB was recalculated with a time-varying probability of terminal molt, primarily the high historical values were affected (e.g. 1990 and 1991). These had been difficult for the model to fit in past assessments, but the revised data were fit better by the models presented here.

The strides made in data preparation made by the packages developed by ADFG and SAG in Kodiak will facilitate a more transparent and expedient processing of data for use in crab assessment. The work flow for preparation of data for the snow crab assessment will now calculate data inputs for all years available each time data are updated using the files and packages provided by ADFG and SAP, which will avoid issues with updating the data files a year at a time.

Last year the author-recommended OFL was based on a Tier 4 model using 95mm carapace width male biomass as the currency of management. A tier 4 rule was preferred because the model estimates of industry preferred males was much smaller than the survey estimate. The currency of 95mm carapace width crab was chosen because using morphometrically mature male biomass results in reference points that allow for the complete removal of large males. This is a non-nonsensical management action when the industry preferred crab are at historical lows and steadily trending downward in spite of conservative management from the State. The basic rationale provided for focusing management on the large males is two pronged: 1) if there are no large crab, there will be no fishery, and 2) uncertainties around the biology (particularly probability of terminally molting and the contribution of small males to reproduction) present risks too large to continue recommending OFLs that allow for the complete removal of large males. Using large males as the currency is more inline with the State of Alaska HCR, the federal HCRs for king crab that specify a size cutoff for maturity, and HCRs used by other nations that manage snow crab.

This year, the industry preferred males increased slightly, but the last 9 years are still the lowest biomass of industry preferred males on record (2025 is #7 and 8% of the maximum observed; see tech memo, Zacher et al., 2025). The rationale for using 95 mm carapace width crab has not changed since 2024, so it is still the author recommended currency of management. The assessment model has convergence problems again, but nothing that has prevented using the model for advice in the past. The model also produces estimates of industry preferred biomass more similar to the survey estimates than last year.

D. Introduction

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

Distribution

Snow crab (*Chionoecetes opilio*) are distributed on the continental shelf of the Bering Sea, Chukchi Sea, and in the western Atlantic Ocean as far south as Maine. In the Bering Sea, snow crab are distributed widely over the shelf and are common at depths less than ~200 meters (see tech memo; Zacher et al., 2025). Smaller crab tend to occupy more inshore northern regions and mature crab occupy deeper areas to the south of the juveniles (see Zacher et al., 2025; Zheng et al. 2001). The eastern Bering Sea population within U.S. waters is managed as a single stock; however, the distribution of the population may extend into Russian waters to an unknown degree.

Natural Mortality

Relatively few targeted studies exist to determine natural mortality for snow crab in the Bering Sea. Nevissi, et al. (1995) used radiometric techniques to estimate shell age from last molt (Figure 4). The total sample size was 21 male crab (a combination of Tanner and snow crab) from a collection of 105 male crab from various hauls in the 1992 National Marine Fishery Service (NMFS) Bering Sea survey. Representative samples for the 5 shell condition categories were collected from the available crab. Shell condition 5 crab (SC5 = very, very old shell) had a maximum age of 6.85 years (s.d. 0.58, 95% CI approximately 5.69 to 8.01 years; carapace width of 110 mm). The average age of 6 crab with SC4 (very old shell) and SC5, was 4.95 years (range: 2.70 to 6.85 years). Given the small sample size, this maximum age may not represent the 1.5% percentile of the population that is approximately equivalent to Hoenig's method (1983). Tag recovery evidence from eastern Canada revealed observed maximum ages in exploited populations of 17-19 years (Nevissi, et al. 1995, Sainte-Marie 2002). A maximum time at large of 11 years for tag returns of terminally molted mature male snow crab in the North Atlantic has been recorded since tagging started about 1993 (Fonseca, et al. 2008). Fonseca, et al. (2008) estimated a maximum age of 7.8 years post terminal molt using data on dactal wear.

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

In contrast to the implied natural mortalities from the methodology used above, Murphy et al. (2018) estimated time-varying natural mortality for eastern Bering Sea snow crab with a mean of 0.49 for females and 0.36 for males based on the output of state-space models fit to NMFS survey data. Further, natural mortality estimates produced from empirical analyses by Then et al. (2015) and Hamel (2015) using similar assumed maximum ages as the methodology above produced natural mortalities larger than 0.23 (Table 9). 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 9: Empirical estimates of natural mortality for a range of methods over a range of assumed maximum ages (column header).

	23	20	17
Then	0.277	0.315	0.365
Hoenig (1983)	0.19	0.212	0.257
Hoenig (2013)	0.194	0.223	0.261
Hamel	0.235	0.271	0.318

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

The median value of the priors used in this assessment are set equal to values resulting from assuming a maximum age of 20 years and applying Hamel's methodology (0.271). A standard error of 0.0054 was used for initial priors and was estimated using the 95% CI of +-1.7 years on maximum age estimates from dactal wear and tag return analysis in Fonseca, et al. (2008). Mortality events in 2018 and 2019 are estimated as additional mortality parameters applied by sex and maturity state to allow the model to fit recent population trends.

Maturity

Maturity of females collected during the NMFS summer survey was determined by the shape of the abdomen, by the presence of brooded eggs, or egg remnants. Maturity for males was determined by chela height measurements, which were available most years starting from the 1989 survey (Otto 1998; Figure 6 & Figure 7). Mature male biomass referenced throughout this document refers to a morphometrically mature male (i.e. large-clawed). A maturity curve for males was estimated using the average fraction mature based on chela height data and applied to years of survey data to estimate mature survey numbers that do not have chela height data available (see Richar and Foy, 2022 for details).

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

Mature male snow crab that do not molt may be important in reproduction. Paul et al. (1995) found that old shell mature male Tanner crab out-competed new shell crab of the same size in breeding in a laboratory study. Recently molted males did not breed even with no competition and may not breed until after ~100 days from molting (Paul et al. 1995). Sainte-Marie et al. (2002) stated that only old shell males take part in mating for North Atlantic snow crab.

Mating ratio and reproductive success

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

Clutch fullness is recorded for the females measured in the survey (see ESP; Fedewa et al., 2025). However, quantifying the reproductive potential of the female population from survey data can be difficult. For example, full clutches of unfertilized eggs may be extruded and appear normal to visual examination, and may be retained for several weeks or months by snow crab. Resorption of eggs may occur if not all eggs are extruded resulting in less than a full clutch. Female snow crab at the time of the survey may have a full clutch of eggs that are unfertilized, resulting in overestimation of reproductive potential. Barren females may be a more obvious indication of low reproductive potential and increased in the early 1990s, decreased in the mid-1990s, then increased again in the late 1990s. The highest levels of barren females coincided with periods of high fishing mortality, but even then the proportion of barren females was low (see ESP; Fedewa et al., 2025). Biennial spawning is another confounding factor in determining the reproductive potential of snow crab. Laboratory analyses showed that female snow crab collected in waters colder than 1.5 degrees C from the Bering Sea spawn only every two years.

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

Growth

Several studies are available to estimate the growth per molt of male and female snow crab in the Bering Sea. 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.
8. BSFRF/NMFS holding study 2021; 177 crab.

In the “Transit study”, pre- and post-molt measurements of 14 male crab that molted soon after being captured were collected. The crab were measured when shells were still soft because all died after molting, so measurements may be underestimates of post-molt width (L. Rugolo, pers. com.). The holding studies include only data for crab held less than 30 days because growth of crab held until the next spring’s molting was much lower. Crab missing more than two limbs were excluded due to other studies showing lower growth. Crab from the seasonal study were excluded that were measured less than 3 days after molting due to difficulty in measuring soft crab accurately (L. Rugolo, pers. comm.). In general, growth of snow crab in the Bering Sea appears to be greater than growth of some North Atlantic snow crab stocks (Sainte-Marie 1995). Crab in their first few years of life may molt more than once per year, however, the smallest crab included in the model are approximately 4 years old and would be expected to molt annually.

Management history

ADFG harvest strategy

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

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

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

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 crab greater than 101 mm plus 25% of the old shell crab greater than 101 mm, the catch is capped at 58%.

History of BMSY

Prior to adoption of Amendment 24, B_{MSY} was defined as the average total mature biomass (males and females) estimated from the survey for the years 1983 to 1997 (921.6 million lbs; NPFMC 1998) and MSST was defined as 50% of B_{MSY}. Currently, the biological reference point for biomass is calculated using a spawning biomass per recruit proxy, $B_{35\%}$ (Clark, 1993). $B_{35\%}$ is the biomass at which spawning biomass per recruit is 35% of unfished levels and has been shown to provide close to maximum sustainable yield for a range of stock productivities (Clark, 1993). Consequently, it is an often used target when a stock recruit relationship is unknown or unreliable. The range of years of recruitment used to calculate biomass reference points is from 1982 to the present assessment year, minus 1. However, recent analyses suggest SPR-based reference points do not provide a meaningful constraint on the snow crab fishery when the probability of having undergone terminal molt is specified to reflect observations in the survey. This is because a large fraction of the population matures (and ceases growing) at a size smaller than is harvested by the fishery.

Fishery history

Snow crab were harvested in the Bering Sea by the Japanese from the 1960s until 1980 when the Magnuson Act prohibited foreign fishing. After the closure to foreign fleets, retained catches increased from relatively low levels in the early 1980s (e.g. 11.85 kt during 1982) to historical highs in 1990s (retained catches during 1991, 1992, and 1998 were 143.02, 104.67, and 88.15 kt, respectively). The stock was declared overfished in

1999 at which time retained catches dropped to levels similar to the early 1980s (e.g. 11.46 kt). Retained catches slowly increased after 1999 before dropping again in 2016. Total allowable catches were reduced with the collapse of the population in 2021, the fishery was closed for the first time in 2022, and the closure continued through 2023. A small fishery occurred in 2024.

Discard mortality from the directed fishery is the next largest source of mortality after retained catch and approximately tracks the retained catch. The highest estimated discard mortality occurred during 1992 at 21.18 kt which was 20.24% of the retained catch during that year. Discard mortality in 2022 was 0.66 kt. Non-directed mortality continues to be very small at 0.09 kt in 2024.

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. Discards reached 50-100% of the magnitude of retained catch in the lead up to the collapse after the 2018-2019 heatwave because of the large year class entering the population. Female discard catch has been very low compared to male discard catch and has not been a significant source of mortality. Discard mortality rates for the directed fishery are assumed to be 30%. Discard of snow crab in groundfish fisheries has been highest in the yellowfin sole trawl fishery, and decreases down through the flathead sole trawl fishery, Pacific cod bottom trawl fishery, rock sole trawl fishery, and the Pacific cod hook-and-line and pot fisheries, respectively (Figure 8). Bycatch in fisheries other than the groundfish trawl fishery has historically been relatively low. Discard mortality rates from non-directed fisheries are assumed to be 80%. Size frequency data and catch per pot have been collected by observers on snow crab fishery vessels since 1992. Observer coverage has been 10% on catcher vessels larger than 125 ft (since 2001), and 100% coverage on catcher processors (since 1992).

Several modifications to pot gear have been introduced to reduce bycatch mortality. In the 1978/79 season, escape panels were required on pots used in the snow crab fishery to prevent ghost fishing. Escape panels consist of an opening with one-half the perimeter of the tunnel eye laced with untreated cotton twine. The size of the cotton laced panel was increased in 1991 to at least 18 inches in length. No escape mechanisms for undersized crab were required until the 1997 season when at least one-third of one vertical surface of pots had to contain not less than 5 inches stretched mesh webbing or have no less than four circular rings of no less than 3 3/4 inches inside diameter. In the 2001 season the escapement provisions for undersized crab was increased to at least eight escape rings of no less than 4 inches placed within one mesh measurement from the bottom of the pot, with four escape rings on each side of the two sides of a four-sided pot, or one-half of one side of the pot must have a side panel composed of not less than 5 1/4 inch stretched mesh webbing.

E. 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 2024 were used in this analysis (Table 14). Time series of discarded catch from the directed fishery are fit, but size composition data are for total catch. The discard male catch was estimated for survey years 1982 to 1991 in the model using the estimated fishery selectivities based on the observer data for the period of survey year 1992 to 2024. 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 10 for a summary of catch data range.

Table 10: Data included in the assessment. Dates indicate survey year. The 2020 survey was cancelled due to the pandemic.

Data component	Years
Retained male crab pot fishery size frequency by shell condition	1982 - 2024
Discarded Males and female crab pot fishery size frequencey	1992 - 2024
Trawl fishery bycatch size frequencies by sex	1991 - 2024
Survey size frequencies by, maturity, sex and shell condition	1982 - 2019, 2021 - 2025
Retained catch estimates	1982 - 2024
Discard catch estimates from crab pot fishery	1992 - 2024
Trawl bycatch estimates	1993 - 2024
Total survey abundance estimates and coefficients of variation	1982 - 2019, 2021 - 2025
Survey selectivity priors (BSFRF)	2009, 2010, 2016-2018

Survey biomass and size composition data

Estimates of of the numbers of crab by sex and size from the annual eastern Bering Sea (EBS) bottom trawl survey conducted by NMFS (e.g. Figure 9 & Figure 10; see Lang et al., 2018 for materials and methods; see the most recent tech memo for detailed description) are used to calculate the primary indices of abundance used in this assessment. Additional survey stations were added in 1989, which could alter the interpretation of catchability coefficient for the survey. Consequently, survey selectivity has been historically modeled in two 'eras' in the assessment (1982-1988, 1989-present). All survey data in this assessment used measured net widths instead of the fixed 50 ft net width based on Chilton et al.'s (2009) survey estimates. Carapace width and shell conditions were measured and reported for snow crab caught in the survey.

Mature male size composition data were calculated by multiplying the total numbers at length for new shell male crab by a vector of observed proportion of mature males at length. All old shell crab of both sexes were assumed to be mature. New shell crab were demarcated as any crab with shell condition index <= 2. The biomass of new and old shell mature individuals was calculated by multiplying the vector of numbers at length by weight at length. These vectors were then summed by sex to provide the input for assessment (Table 15). Input sample sizes are specified as 200 for both sexes and maturity states for all years of survey size composition data given the very large number of sampled crab (see tech memo for numbers).

Spatial distribution of survey abundance and catch

Snow crab are distributed widely over the eastern Bering Sea shelf, but their density and the extent of their distribution has changed over time (see tech memo). 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 while smaller males have been more prevalent on the northern portion of the shelf. 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.

Fishing effort has generally been south of 58.5 N, even when ice cover did not restrict the fishery moving farther north (Figure 11 & Figure 12). This is possibly due to the proximity to port and practical constraints of meeting delivery schedules. Unstandardized CPUE (hereafter just 'CPUE') in the fishery has varied over time and an increase in average CPUE occurred after rationalization (Figure 13). The change in CPUE in a given spatial area within a season can reflect the impact of the fishery on the population in that area. Declines in CPUE can be seen by spatial area over time within a season (Figure 14).

The observed distribution of large males during the summer survey and the fishery catch have historically differed, and the origin of this difference is unknown. It is possible that crab move between the fishery and the survey, but it is also possible that fishers do not target all portions of the distribution of large male crab equally. The underlying explanation of this phenomenon could hold implications for relative exploitation rates spatially and it has been suggested that high exploitation rates in the southern portion of the snow crab range may have resulted in a northward shift in snow crab distribution (Orensanz, 2004). Snow crab larvae likely drift north and east after hatching in spring. Snow crab appear to move south and west as they grow (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 15). Abundances estimated by the industry surveys were generally higher than the NMFS estimates, which suggests that the catchability of the NMFS survey gear is less than 1.

In 2016, 2017, and 2018, snow crab were not the focus of the BSFRF surveys, but were still caught in the BSFRF gear. Comparing the ratio of the number of crab caught at length in the BSFRF gear (which is assumed to have a catchability/selectivity of 1 over all size classes) to the number of crab caught at length within the same area in the NMFS survey gear (which is assumed to have a catchability/selectivity <= to 1 for at least some of the size classes) can provide an empirical estimate of catchability/selectivity (Figure 16). Empirical estimates of catchability/selectivity vary by year and size class across the different BSFRF data sets (Figure 17 & Figure 18). The number of snow crab used to develop estimates of numbers at length likely contribute to these differences among years (Figure 19), 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). GAMs fit to the empirical estimates of selectivity are used are priors on estimated selectivity in the currently used assessment model. The standard errors from the GAMs are input as weighting factors for each prior of selectivity at size and sex derived from the BSFRF data.

F. Analytic approach

History of modeling approaches for the stock

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

Model description

The Generalized Model for Assessing Crustacean Stocks (GMACS) was adopted as the assessment platform for snow crab in 2022 after a demonstration that GMACS could effectively reproduce the dynamics of the status quo model and offered structural improvements. GMACS is an integrated, size-structured model developed using automatic differentiation software developed as a set of libraries under C++ (ADModel Builder). ADModel Builder can estimate a large number of parameters in a non-linear model using automatic differentiation software extended from Greiwank and Corliss (1991) and developed into C++ class libraries. GMACS version 2.20.22 was used for the author-preferred model.

The snow crab population dynamics model tracks the number of crab of sex s, maturity state m, during year y at width w, $\mathrm{N}_{s,m,y,w}$. A terminal molt was modeled in which crab move from an immature to a mature state, after which no further molting occurred. The mid-points of the size bins tracked in the model spanned from 27.5 to 132.5 mm carapace width, with 5 mm size classes. For the author-preferred model, 407 parameters were estimated. Parameters estimated within the assessment included those associated with the population processes recruitment, growth, natural mortality (subject to an informative prior and two years of additional 'mortality events' estimated in 2018 and 2019), fishing mortality, selectivity (fisheries and survey), and catchability. The yearly probability of undergoing terminal molt, weight at size, discard mortality, bycatch mortality, variance in growth increment, and parameters associated with proportion of recruitment allocated to size bin were estimated outside of the model or specified. See the GMACS repo linked at the end of this document to peruse the control files that specify the populations dynamics.

A 'jittering' approach has been historically used to explore the impact of different starting values on the assessment output (Turnock, 2016). Jittering was implemented for both models with 2025 data. Retrospective analyses were also performed here in which the terminal year of data was removed sequentially from the model fitting process. Then time series of estimated MMB were compared between the most recent model and successive 'peels' of the data to identify retrospective patterns. A retrospective pattern is a consistent directional change in assessment estimates of management quantities (e.g. MMB) in a given year when additional years of data are added to an assessment. Parameter values were jittered based on a normal distribution centered on one with a standard deviation of 0.1 that was then translated to the parameter space defined by the initial value and its bounds.

A single population dynamics model is presented here, with the differences among the model runs related to data inputs and assumptions about reference points or currency of management.

Model selection and evaluation

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

Results

Model convergence and comparison

Model 25.3 produced a small maximum gradient and produced a Hessian matrix. However, jittering produced two clouds of 'converged' models with OFLs that differed by 5,000 tonnes and negative log likelihoods that differed by ~0.2 units (Figure 20). Repeating the jittering for a model that uses large males as currency produced two clouds of OFLs with a difference of approximately 1,000 tonnes (Figure 21). The difference in OFLs from both of these jittering runs resulted from differences in the terminal estimates of MMB, which were driven by differences in estimated recruitment in the recent past (Figure 22). Bimodality in management quantities has been a reoccurring problem in the assessment for snow crab. Below, the results for '25.3 gmacs' (i.e. the model with morphometrically MMB used as currency) and '25.3 gmacs (>=95mm)' are derived from the model that had the lowest negative log likelihood from 100 jitters.

The model had difficulties fitting the terminal year of female biomass and potential fixes were explored (e.g. inputting a yearly varying probability of terminal molt), but none yielded markedly different results from model '25.3 gmacs', so were not included here. This issue will be explored more fully for the May 2026 meeting.

Model fits

Fits to the survey indices of mature biomass were similar among models, even with the revision of the data (Figure 24). Updating the version of GMACS resulted in a downward revision of the 2018 mature female biomass estimate.

In May 2025, convergence issues arose with the addition of new growth data. This was solved in this assessment by only including data points for sizes modeled within the assessment model and using smaller input CVs for the points over 35 mm pre-molt carapace width for females. This is a range in which there were fewer observations which were historically poorly fit because of the abundance of data at smaller sizes. No changes were made to the CVs for male growth increment data. Updating the growth data in this manner resulted in changes in estimated molt increments given pre-molt carapace width for both males and females (Figure 25).The estimated molt increments for males were smaller than historical estimates for smaller pre-molt carapace width until approximately 60mm carapace width, when the estimated molt increments began to be larger than historical estimates.

Fits to the non-directed fishery catches were good for both the original and revised data sets (Figure 26). However, in the directed fishery, fits deteriorated somewhat with the updated dataset. Although most of the retained catch data were still fit well, the model was unable to capture several years of discarded data that historically were well fit (e.g. 1991, 1994 and 2019).

Only small differences were observed among models in the fits to size composition data for retained catch in the directed fishery, with the most recently occuring fishery (2021) showing the largest differences (Figure 27). Fits to the total size composition data from the directed fishery were distinctly different once the growth data were updated in the models (Figure 28). No visually discernible differences among models existed for female discards from the directed fishery (Figure 29). Fits to the non-directed fishery had some of the largest misfits of all data sources (particularly for male data), but this is unsurprising given a single estimated selectivity curve and potential changes in fishery behavior over time (Figure 30 & Figure 31).

Fits to the survey size composition data were broadly similar between the two models in most years (Figure 32 - Figure 39). Both models had issues fitting the size composition data for mature males immediately after the collapse, which could suggest some unmodelled size-based mortality (Figure 34).

Estimated population processes

The estimated abundance of commercially preferred of male crab (arguably the most important output of the assessment) varied among models (Figure 40). The early years during which differences in survey selectivity occurred were particularly different. Both models agreed that the abundance in recent years have been the lowest in the time series. The estimates of the most recent era of survey selectivity were fairly similar across models for both sexes (Figure 41).

Estimated fisheries selectivities were similar for both models (Figure 42). Estimated fully-selected fishing mortality for the directed fishery was highly variable and relatively high for most of the fishery history (Figure 43). The total fishery selectivity curve is shifted far to the right, so only the largest crab are experiencing the fully-selected fishing mortality. The probability of undergoing terminal molt used to separate crab into immature and mature survey indices were input as data to the assessment (Figure 44).

Trends in recruitment were very similar across models, with some variability in scale and differences in timing between the sexes (Figure 45). Differences in estimated recruitment in the most recent years were also observed for males among models and this appears to have contributed to the differences in OFLs among jittering runs.

Base estimates of natural mortality were similar for mature animals of both sexes, except for immature females, which were much higher with the new growth data and weighting scheme (Figure 46). All models estimated mortality events that removed at least 80% of crab by sex and maturity state (except for mature females) at some point during the marine heatwave of 2018-19.

MMB and management quantities

Estimated MMB time series had similar trends but the scales differed by up to ~50% in some years (Figure 47). The scale of MMB when large males were used in the calculation was predictably much lower than when morphometrically mature males were used, but the trends were similar. It should be noted that these values are calculated after the fishery, so the declining trends in these estimates are much larger, particularly for the large males, if MMB is calculated before the fishery (see discussion below). Changes in these estimates over the last ten assessment can be seen in Figure 48.

Differences in estimates and currencies of MMB resulted in large differences in the management targets and advice (Table 16; discussed below). All models that use morphometrically mature male biomass as the currency of management produced target fishing mortality rates that would allow for the removal of all of the largest male crab.

G. Calculation of the OFL

Methodology for OFL

Tier 3

Historically, the tier 3 OFL was calculated using proxies for biomass and fishing mortality reference points and a sloped control rule. Proxies for biomass and fishing mortality reference points were calculated using spawning-biomass-per-recruit methods (e.g. Clark, 1991). After fitting the assessment model to the data and estimating population parameters, the model was projected forward 100 years using the estimated parameters under no exploitation and constant recruitment to determine 'unfished' mature male biomass-per-recruit. Projections were repeated in which the bisection method was used to identify a fishing mortality that reduced the mature male biomass-per-recruit to 35% of the unfished level (i.e. $F_{35\%}$ and $B_{35\%}$). Calculations of $F_{35\%}$ were made under the assumption that bycatch fishing mortality was equal to the estimated average value over the last 10 years.

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

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

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

In addition to the status quo tier 3 control rule, a variation in which >=95mm carapace width mature male biomass was used as the currency of management is presented here.

Calculated tier 3 OFLs ranged from 3.26 to 44.29 kt (Table 16). Differences in OFLs were a result of differences in estimated MMB and the currency used for MMB.

Tier 4

Tier 4 HCRs were applied to rema-smoothed survey biomass estimates of three different size ranges: morphometrically mature males, large males (>=95mm), and preferred males (>101mm). The target biomass was set as the average of the time series from 1982-2024 and the target fishing mortality was set as 0.27, the median of the prior on natural mortality used in the integrated assessment. No kink exists in this harvest control rule. The resulting OFLs were 28.41 kt, 8.64 kt, and 6.11 kt for morphometric, large, and preferred males, respectively (Figure 49).

Calculation of the ABC

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

The buffers for the last five years used by the SSC were: 65% (2024), 50% (2023), (October 2022 SSC reports are not available online), 25% (2021), and 25% (2020).

Author recommendations

Recent changes to the population dynamics model used for snow crab aligned the GMACS model with the best available science on reproductive biology, particularly as seen through the probability of terminally molting. However, all of the large males can be removed from the population using that model and status quo reference points, which seems like an undesirable outcome when the population trend of large males is firmly negative. A range of different approaches to providing more rational management advice have been attempted in this assessment over the last several years.

A key change considered and repeatedly recommended is focusing management on the large males by shifting currency away from morphometrically mature biomass. If all other uncertainties are stripped away, we know one thing–the portion of the resource the fishery depends on for survival is on a downward spiral. If there are no large males, the fishery does not exist. If our goal is 'optimal yield', a downward spiral in the resource that supports the fishery is clearly counter to that goal. If we knew nothing else about snow crab except the time series of exploitable biomass, that should be enough information for managers to act.

It is difficult to make the case that status quo management (which is much more conservative than the federal HCR) is 'working' to provide sustainable levels of biomass of large males on which to fish. After the collapse in 1999 from periods of historical highs, the ratio of retained catch biomass to large male biomass (a rough proxy for exploitation rate) was greatly decreased (Figure 50) and the stock rebuilt, but to levels much lower than those observed in the 1990s (Figure 51). As fishing pressure was ramped up again, the stock began to decline again, this time to a much lower 'bottom' than in the 2000s, exacerbated by a marine heatwave in 2018 and 2019. The end result is a stock of commercially preferred males for which the 9 lowest observed survey biomasses occurred in the last 9 years.

However, we do know more about snow crab than just the time series of catch and survey biomass. In eastern Canadian stocks, they have reported changes in the size at terminal molt based on the density of large males in the population (Mullowney and Baker, 2021). This implies that to get large males, you must have large males in the population. In Alaska, there does appear to be a decrease in the probability of maturing at size for a male crab when densities of large males are higher (compare 2021 to 1991 in Figure 7, for example and refer to the appendix of the May 2024 snow crab assessment document in which the analysis behind Figure 3 is discussed). In addition to the potential for plasticity in size at maturity, there is also an unexplored potential for genetic changes if only small males are reproducing. So, even if the small mature males could sustain the population, it's not clear that the population produced would have the qualities needed to support the production of large biomasses of large males that the fishery captures.

As an example of how important the probability of terminally molting is to producing large males, we projected the stock forward ten years, once using the most recent probability of terminally molting (Figure 51) and once using the probability of terminally molting from 1991 (Figure 52; see Figure 7 for a comparison of ogives). In each scenario, two fishing strategies were considered: one in which no fishing occurred and one in which an OFL calculated based on large males was removed from the population each year. The trajectory of the stock under fishing at the OFL when the probability of terminally molting was set to that observed in 1991 was comparable to the unfished trajectory of the stock when the probability of terminally molting was set to the most recent value.

When these points are layered on top of the downward spiral of large male biomass, precaution seems more than appropriate if we hope to return to abundances of harvestable males similar to that in the past. In that context, the author-recommended OFL is 3.26 kt, based on the the tier 3 model and a currency of management set at 95 mm carapace width.

I. Data gaps and research priorities

Experimental evaluation of the prospect of density dependence in terminal molt processes would shed light on the importance of preserving large males in the population. The largest observation of immature females in the survey occurred during 2024 and would have spawned sometime in the last 5-6 years, which was a period of historically low large male biomass and may also have a link to density dependence or environment, both of which should be explored. Knowing how active small morphometrically mature males are in reproduction would provide a clearer path to management. Preliminary cam sled work may offer insights into this question.

Data weighting continues to be a topic that is acknowledged as important to modeling outcomes, but secondary to finding an appropriate model and harvest control rule configuration. A thorough examination of the data streams in the assessment including reconstructing historical time series before 1991 and reevaluating the data sets to which the assessment is fit (e.g. should immature crab or very large crab also be fit) may be useful and was at least partially undertaken this year. Data pipeline development will be an ongoing task as the packages used to prepare the data evolve. Probability of terminally molting for females, all available growth data, and pre-calculated morphometrically mature male biomass would be useful quantities to have in crabpack to ensure consistency among analyses.

J. Ecosystem considerations

See the ESP for snow crab specific indices of environmental variation that may be relevant to stock dynamics (Appendix A). See the risk table in Appendix B for factors that may influence choices of buffers. More broadly, scientific frameworks that quantify tradeoffs among fisheries would be useful in decision making and scientific communication.

K. Supplemental information

Input and output for the models described here can be found at https://github.com/szuwalski/snow_2025_9.

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

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Table 11: Likelihood components by category and model.

	24.1 Status quo	25.3 gmacs	25.3 gmacs (>=95mm)
Catch	-70.01	372.68	370.25
Index	107.50	142.06	142.67
Size	-28170.90	-28986.35	-28980.10
SRR	78.61	185.42	183.80
Tag	1040.70	7965.08	7965.12
Penalties:	1028.53	760.35	760.16
Priors:	224.19	386.98	383.97
Total:	-25761.38	-19173.78	-19174.14

Table 12: Individual likelihood components by model.

	24.1 Status quo	25.3 gmacs	25.3 gmacs (>=95mm)
Retained	-16.66	120.98	120.12
Discard (male)	69.72	377.21	375.64
Discard (female)	-69.66	-71.40	-71.40
Non-directed	-53.41	-54.11	-54.11
NMFS 1982-89 (m)	57.12	51.84	52.00
NMFS 1989-present(m)	-3.59	7.67	8.39
NMFS 1982-88 (f)	50.98	95.06	94.48
NMFS 1989-present (f)	2.99	-12.51	-12.19
Retained SC	-3634.65	-3645.22	-3645.34
Total SC	-2647.49	-2639.01	-2638.62
Discard SC (f)	-2270.66	-2528.85	-2528.77
Bycatch SC (f)	-2537.19	-2605.73	-2605.06
Bycatch SC (m)	-2418.24	-2542.95	-2542.23
NMFS 1982-89 (imm m)	-630.01	-635.48	-635.66
NMFS 1989-present(imm m)	-3135.12	-3167.86	-3169.62
NMFS 1982-88 (imm f)	-541.67	-581.38	-581.09
NMFS 1989-present (imm f)	-2915.90	-3002.56	-2997.62
NMFS 1982-89 (mat m)	-683.53	-684.25	-684.21
NMFS 1989-present(mat m)	-3312.09	-3401.56	-3400.98
NMFS 1982-88 (mat f)	-583.09	-575.55	-575.57
NMFS 1989-present (mat f)	-2861.27	-2975.96	-2975.32
Growth	1040.70	7965.08	7965.12

Table 13: Parameters estimated in the assessment. 'Theta' parameters are primarily the values for initial numbers at size. See control file for more in depth descriptions.

param	25.3 gmacs	25.3 gmacs (>=95mm)
G_pars_est[1]	0.98	0.99
G_pars_est[2]	-0.24	-0.24
G_pars_est[3]	0.25	0.25
G_pars_est[4]	-4.81	-4.81
G_pars_est[5]	-0.43	-0.43
G_pars_est[6]	0.25	0.25
log_add_cv[1]	-9.21	-9.21
log_add_cv[2]	-9.21	-9.21
log_add_cv[3]	-9.21	-9.21
log_add_cv[4]	-9.21	-9.21
log_fbar[1]	-0.21	-0.21
log_fbar[2]	-5.22	-5.22
log_fbar[3]	-4.00	-4.00
log_fbar[4]	-4.00	-4.00
log_fdev[1]	0.00	0.00
log_fdev[2]	0.00	0.00
log_fdev[3]	0.00	0.00
log_fdev[4]	0.00	0.00
log_fdov[1]	0.00	0.00
log_fdov[2]	0.00	0.00
log_fdov[3]	0.00	0.00
log_fdov[4]	0.00	0.00
log_foff[1]	-6.79	-6.80
log_foff[2]	0.00	0.00
log_foff[3]	0.00	0.00
log_foff[4]	0.00	0.00
log_vn[1]	0.00	0.00
log_vn[10]	0.00	0.00
log_vn[11]	0.00	0.00
log_vn[12]	0.00	0.00
log_vn[13]	0.00	0.00
log_vn[2]	0.00	0.00
log_vn[3]	0.00	0.00
log_vn[4]	0.00	0.00
log_vn[5]	0.00	0.00
log_vn[6]	0.00	0.00
log_vn[7]	0.00	0.00
log_vn[8]	0.00	0.00
log_vn[9]	0.00	0.00
logit_rec_prop_est:	0.00	0.00
M_pars_est[1]	0.28	0.28
M_pars_est[10]	-0.47	-0.72
M_pars_est[11]	0.91	0.90
M_pars_est[12]	0.00	0.00
M_pars_est[13]	1.00	1.00
M_pars_est[14]	1.67	1.63
M_pars_est[15]	1.10	1.82
M_pars_est[16]	0.00	0.00

param	25.3 gmacs	25.3 gmacs (>=95mm)
M__pars__est[2]	1.59	1.61
M__pars__est[3]	0.41	0.47
M__pars__est[4]	0.00	0.00
M__pars__est[5]	0.03	0.00
M__pars__est[6]	0.00	0.00
M__pars__est[7]	2.35	2.40
M__pars__est[8]	0.00	0.00
M__pars__est[9]	0.27	0.27
max gradient	0.00	0.01
number of parameters	407.00	407.00
objective function	-19173.78	-19174.14
par__devs[1]	0.00	0.00
rec__dev__est:	-0.08	-0.08
S__pars__est[1]	4.67	4.67
S__pars__est[10]	-1.32	-1.31
S__pars__est[11]	-1.02	-1.01
S__pars__est[12]	-1.00	-0.99
S__pars__est[13]	-1.13	-1.12
S__pars__est[14]	-1.10	-1.09
S__pars__est[15]	-1.03	-1.03
S__pars__est[16]	-1.00	-0.99
S__pars__est[17]	-0.98	-0.97
S__pars__est[18]	-0.87	-0.87
S__pars__est[19]	-0.86	-0.86
S__pars__est[2]	1.67	1.67
S__pars__est[20]	-0.99	-0.99
S__pars__est[21]	-0.85	-0.85
S__pars__est[22]	-0.74	-0.74
S__pars__est[23]	-0.51	-0.51
S__pars__est[24]	-0.33	-0.33
S__pars__est[25]	-0.24	-0.24
S__pars__est[26]	-0.32	-0.32
S__pars__est[27]	-4.33	-4.31
S__pars__est[28]	-3.48	-3.47
S__pars__est[29]	-2.75	-2.73
S__pars__est[3]	4.78	4.78
S__pars__est[30]	-1.93	-1.90
S__pars__est[31]	-1.72	-1.70
S__pars__est[32]	-1.49	-1.47
S__pars__est[33]	-1.25	-1.24
S__pars__est[34]	-1.17	-1.15
S__pars__est[35]	-1.23	-1.21
S__pars__est[36]	-1.24	-1.23
S__pars__est[37]	-1.21	-1.20
S__pars__est[38]	-1.16	-1.15
S__pars__est[39]	-1.13	-1.12
S__pars__est[4]	2.39	2.39
S__pars__est[40]	-0.98	-0.98
S__pars__est[41]	-0.78	-0.78
S__pars__est[42]	-0.46	-0.46
S__pars__est[43]	-0.32	-0.32
S__pars__est[44]	-0.20	-0.20

param	25.3 gmacs	25.3 gmacs (>=95mm)
S_pars_est[45]	-0.16	-0.16
S_pars_est[46]	-0.13	-0.13
S_pars_est[47]	-0.12	-0.12
S_pars_est[48]	-0.15	-0.15
S_pars_est[49]	4.21	4.22
S_pars_est[5]	-3.24	-3.21
S_pars_est[50]	0.99	0.99
S_pars_est[51]	-5.15	-5.14
S_pars_est[52]	-5.26	-5.25
S_pars_est[53]	-4.05	-4.04
S_pars_est[54]	-1.72	-1.72
S_pars_est[55]	-1.16	-1.16
S_pars_est[56]	-0.55	-0.54
S_pars_est[57]	-0.55	-0.55
S_pars_est[58]	-0.76	-0.76
S_pars_est[59]	-0.83	-0.83
S_pars_est[6]	-2.74	-2.71
S_pars_est[60]	-0.92	-0.92
S_pars_est[61]	-0.91	-0.91
S_pars_est[62]	-0.87	-0.87
S_pars_est[63]	-0.84	-0.84
S_pars_est[64]	-0.79	-0.79
S_pars_est[65]	-0.72	-0.72
S_pars_est[66]	-0.63	-0.63
S_pars_est[67]	-0.53	-0.53
S_pars_est[68]	-0.42	-0.42
S_pars_est[69]	-0.31	-0.31
S_pars_est[7]	-2.29	-2.26
S_pars_est[70]	-0.20	-0.20
S_pars_est[71]	-0.08	-0.08
S_pars_est[72]	0.00	0.00
S_pars_est[73]	-4.17	-4.17
S_pars_est[74]	-3.29	-3.31
S_pars_est[75]	-2.68	-2.67
S_pars_est[76]	-1.01	-1.00
S_pars_est[77]	-0.51	-0.51
S_pars_est[78]	-0.24	-0.24
S_pars_est[79]	-0.34	-0.34
S_pars_est[8]	-1.53	-1.51
S_pars_est[80]	-0.90	-0.91
S_pars_est[81]	-1.06	-1.06
S_pars_est[82]	-1.27	-1.27
S_pars_est[83]	-1.24	-1.24
S_pars_est[84]	-0.95	-0.95
S_pars_est[85]	-0.83	-0.83
S_pars_est[86]	-0.78	-0.78
S_pars_est[87]	-0.71	-0.71
S_pars_est[88]	-0.62	-0.62
S_pars_est[89]	-0.52	-0.52
S_pars_est[9]	-1.51	-1.48
S_pars_est[90]	-0.42	-0.42
S_pars_est[91]	-0.31	-0.31

param	25.3 gmacs	25.3 gmacs (>=95mm)
S_pars_est[92]	-0.20	-0.20
S_pars_est[93]	-0.08	-0.08
S_pars_est[94]	0.00	0.00
S_pars_est[95]	4.60	4.60
S_pars_est[96]	0.31	0.31
survey_q[1]	1.00	1.00
survey_q[2]	1.00	1.00
survey_q[3]	1.00	1.00
survey_q[4]	1.00	1.00
theta[1]	16.50	16.50
theta[10]	0.01	0.01
theta[11]	9.62	9.59
theta[12]	9.63	9.60
theta[13]	9.67	9.64
theta[14]	9.78	9.76
theta[15]	10.22	10.21
theta[16]	10.77	10.76
theta[17]	11.21	11.20
theta[18]	11.41	11.40
theta[19]	11.50	11.50
theta[2]	15.00	15.00
theta[20]	11.54	11.54
theta[21]	11.51	11.50
theta[22]	11.26	11.26
theta[23]	10.95	10.95
theta[24]	10.70	10.69
theta[25]	10.83	10.83
theta[26]	11.88	11.88
theta[27]	11.38	11.38
theta[28]	10.40	10.41
theta[29]	9.35	9.35
theta[3]	14.38	14.37
theta[30]	8.35	8.35
theta[31]	7.53	7.53
theta[32]	7.14	7.14
theta[33]	12.29	12.25
theta[34]	12.41	12.37
theta[35]	13.24	13.21
theta[36]	13.74	13.71
theta[37]	13.05	13.03
theta[38]	13.14	13.12
theta[39]	12.86	12.84
theta[4]	32.50	32.50
theta[40]	12.62	12.60
theta[41]	12.56	12.54
theta[42]	12.03	12.02
theta[43]	11.37	11.35
theta[44]	11.25	11.23
theta[45]	11.40	11.38
theta[46]	10.48	10.47
theta[47]	9.11	9.10
theta[48]	8.05	8.04

param	25.3 gmacs	25.3 gmacs (>=95mm)
theta[49]	7.28	7.28
theta[5]	1.00	1.00
theta[50]	6.75	6.74
theta[51]	6.36	6.36
theta[52]	6.08	6.07
theta[53]	5.87	5.87
theta[54]	5.77	5.76
theta[55]	12.16	12.15
theta[56]	12.18	12.17
theta[57]	12.23	12.22
theta[58]	12.37	12.36
theta[59]	13.53	13.52
theta[6]	0.00	0.00
theta[60]	13.59	13.59
theta[61]	12.99	12.99
theta[62]	12.15	12.15
theta[63]	11.03	11.03
theta[64]	9.97	9.97
theta[65]	9.25	9.25
theta[66]	8.83	8.83
theta[67]	8.63	8.63
theta[68]	8.58	8.58
theta[69]	8.48	8.48
theta[7]	0.00	0.00
theta[70]	8.28	8.28
theta[71]	8.02	8.03
theta[72]	7.77	7.77
theta[73]	7.53	7.53
theta[74]	7.30	7.31
theta[75]	7.14	7.15
theta[76]	7.05	7.06
theta[77]	-13.82	-13.82
theta[78]	-13.87	-13.87
theta[79]	-13.97	-13.97
theta[8]	-0.90	-0.90
theta[80]	-14.12	-14.13
theta[81]	-13.64	-13.64
theta[82]	-13.47	-13.47
theta[83]	-14.60	-14.60
theta[84]	-15.62	-15.61
theta[85]	-16.42	-16.42
theta[86]	-17.05	-17.05
theta[87]	-17.50	-17.50
theta[88]	-17.84	-17.84
theta[89]	-18.11	-18.11
theta[9]	0.75	0.75
theta[90]	-18.34	-18.34
theta[91]	-18.54	-18.54
theta[92]	-18.71	-18.71
theta[93]	-18.86	-18.86
theta[94]	-19.00	-19.00
theta[95]	-19.00	-19.00

param	25.3 gmacs	25.3 gmacs (>=95mm)
theta[96]	-19.00	-19.00
theta[97]	-19.00	-19.00
theta[98]	-19.00	-19.00

Table 14: Observed retained catches, discarded catch, and bycatch. Discards and bycatch do not have assumed mortalities applied. Units are 1,000 tonnes.

Year	Discard (females)	Discard (males)	Retained catch	Non-directed bycatch
1982	0.02	1.27	11.85	0.37
1983	0.01	1.24	12.16	0.47
1984	0.01	2.76	29.94	0.5
1985	0.01	4.01	44.45	0.43
1986	0.02	4.25	46.22	0
1987	0.03	5.52	61.4	0
1988	0.04	5.82	67.79	0
1989	0.05	6.68	73.33	0.1
1990	1.52	35.55	149.1	0.33
1991	0.2	9.03	143	4.45
1992	0.28	21.18	104.7	2.05
1993	0.12	22.27	67.94	1.13
1994	0.08	7.78	34.16	0.7
1995	0.02	14.73	29.8	1.04
1996	0.1	23.23	54.24	1.22
1997	0.1	7.1	110.4	0.73
1998	0.01	19.5	88.15	0.58
1999	0.01	4.13	15.1	0.24
2000	0	3.25	11.46	0.25
2001	0.02	3.98	14.8	0.18
2002	0	4.5	12.84	0.1
2003	0	2.4	10.86	0.14
2004	0	3.58	11.29	0.18
2005	0	0.62	16.77	0.19
2006	0	4.17	16.49	0.36
2007	0.02	5.77	28.59	0.31
2008	0.02	5.11	26.56	0.19
2009	0.01	4.28	21.78	0.39
2010	0.01	4.47	24.61	0.14
2011	0.19	3.73	40.29	0.14
2012	0.06	5.53	30.05	0.15
2013	0.12	10.61	24.49	0.16
2014	0.3	11.62	30.82	0.62
2015	0.12	10.9	18.42	1.58
2016	0.03	4.51	9.78	0.04
2017	0.03	5.88	8.6	0.1
2018	0.02	8.63	12.51	0.4
2019	0.02	15.61	15.43	0.21
2020	0	6.12	20.41	0.19
2021	0	1.68	2.52	0.13
2022	0	0	0	0.06
2023	0	0	0	0.11
2024	0	0.66	2.15	0.09

Table 15: 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 >=95mm (kt)	Males >101mm (kt)
1982	141.5	0.16	170.6	0.14	65.86	38.12
1983	82.18	0.2	146.9	0.13	68.05	38.92
1984	39.37	0.2	166.2	0.12	120	89.43
1985	5.89	0.22	69.76	0.11	55.69	45.01
1986	15.17	0.21	84.32	0.11	58.72	47.86
1987	119.5	0.19	181	0.11	107.5	78.76
1988	165.6	0.18	245.8	0.15	144.1	110.5
1989	256.7	0.32	245.4	0.11	143.2	98.36
1990	174.9	0.21	348.4	0.14	347.8	238.6
1991	199	0.24	381.7	0.15	348	286.3
1992	123.5	0.2	219.7	0.09	166.5	143.4
1993	127.1	0.17	175.3	0.1	98.86	80.03
1994	122.6	0.14	148.7	0.08	57.39	46.3
1995	165	0.14	193.1	0.13	61.76	41.01
1996	104.4	0.15	263.2	0.12	143.9	95.08
1997	101.4	0.2	284.1	0.1	232.4	178.3
1998	70.18	0.28	194.4	0.09	164.1	132.5
1999	29.85	0.24	91.33	0.09	67.35	53.96
2000	93.88	0.54	85.94	0.14	53.94	43.04
2001	74.84	0.3	114	0.12	56.45	42.78
2002	29.51	0.32	82.98	0.23	55.91	39.42
2003	38.76	0.41	63.1	0.12	44.42	32.83
2004	47.74	0.28	73.04	0.14	44.16	36.65
2005	62.6	0.22	117.2	0.11	50.07	41.24
2006	50.59	0.2	134.7	0.26	90.15	74.86
2007	54.45	0.32	147.1	0.15	99.88	77.64
2008	49.35	0.23	121.9	0.1	79.6	63.45
2009	50	0.23	120.9	0.13	103.2	81.36
2010	94.96	0.18	164.3	0.12	105.3	90.24
2011	169.1	0.19	154.3	0.11	111.7	96.8
2012	143.2	0.23	118	0.12	67.48	55.22
2013	125.7	0.21	99.3	0.12	58.39	45.42
2014	111.4	0.21	153.6	0.16	105.4	84.29
2015	81.63	0.18	81.16	0.12	46.41	37.26
2016	53.12	0.21	57.44	0.11	30.34	23.14
2017	105.9	0.22	87.01	0.13	29.74	22.3
2018	165.4	0.2	219.8	0.17	47.69	30.25
2019	109.2	0.2	161.3	0.17	55.28	32.08
2021	30.54	0.44	59.99	0.13	24.7	14.04
2022	21.43	0.34	36.5	0.15	20.67	14.65
2023	15.3	0.27	23.07	0.13	15.69	12.15
2024	41.9	0.23	61.6	0.12	23.49	18.13
2025	147.3	0.17	113	0.15	33.17	23.28

Table 16: Management quantities derived from maximum likelihood estimates by model using Tier 3 reference points. Reported natural mortality is for mature males, average recruitment is for males, and status and MMB were estimates for February 15 of the completed crab year.

	BMSY	Bcurr/BMSY	OFL(tot)	Fmsy	Fofl
24.1 Status quo	191.81	0.56	19.60	49.63	25.07
25.3 gmacs	180.06	0.88	44.29	39.52	34.37
25.3 gmacs (>=95mm)	93.52	0.32	3.26	0.73	0.18

Table 17: Maximum likelihood estimates of morphometrically mature male biomass (MMB), mature female biomass (FMB). Columns 2-3 are subject to survey selectivity; columns 4-5 are the population values.

Survey year	FMB	MMB	FMB_tot	MMB_tot
1982	71.34	111.9	156.1	278.4
1983	54.55	166.5	124.7	403.7
1984	42.38	212.9	112.6	497
1985	35.63	227.2	167.1	523
1986	40.83	221.9	341.9	519.7
1987	74.33	223	432.9	540.9
1988	123	242.6	478.7	595.6
1989	186.7	282.3	425.9	603.5
1990	180.1	292.4	381.2	609.4
1991	155.1	295.8	324.1	573
1992	132.5	264.7	287.7	529.1
1993	114.8	198.3	259.3	449.8
1994	103.1	153	247.3	394.1
1995	96.18	168.6	225.1	438.4
1996	90.36	207.4	196.4	491.8
1997	80.6	227.6	203.2	478.2
1998	75.6	205	168.9	412.9
1999	71.25	118.5	159.3	275.2
2000	62.7	96	143.2	223.7
2001	57.06	77.66	123.5	185.4
2002	50.66	66.54	106.7	163.6
2003	43.44	70.87	246.3	163.3
2004	66.78	86.81	235.5	187.9
2005	97.37	94.57	222.7	207.7
2006	93.53	102.5	193.2	241.4
2007	79.52	122.8	154.1	286.4
2008	64.77	136.4	128.9	309.6
2009	52.2	128.4	275.3	289
2010	75.76	180.9	264.9	357.7
2011	108.7	141.1	254.2	291.9
2012	105.7	108.3	227.1	249.6
2013	92.27	100.6	213.5	241.5
2014	82.87	90.96	180.2	216.2
2015	74.54	74.81	190	185.6
2016	70.04	64.29	244.8	177.7
2017	83.23	97.39	390.5	287.8
2018	124.9	167.2	352.1	495
2019	112.4	146.1	197.4	386.4
2020	0	0	105.8	249.1
2021	45.37	71.98	105.6	199.6
2022	40.49	58.36	108.4	160.6
2023	41.93	50.28	144.4	139.1
2024	50.08	57.05	159.5	166.2
2025	60.9	87.09	139.3	244.9

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

Survey year	Total numbers
1982	8.489
1983	11.18
1984	11.82
1985	17.53
1986	29.62
1987	26.53
1988	24.31
1989	17.71
1990	15.12
1991	15.42
1992	17.27
1993	14.31
1994	13.25
1995	10.79
1996	8.521
1997	9.26
1998	6.911
1999	6.76
2000	6.45
2001	5.1
2002	5.961
2003	17.08
2004	12.55
2005	11.15
2006	9.125
2007	7.119
2008	6.659
2009	18.65
2010	12.31
2011	9.499
2012	7.987
2013	9.031
2014	8.102
2015	18.92
2016	26.63
2017	31.67
2018	21.61
2019	12.31
2020	4.901
2021	6.545
2022	8.693
2023	15.69
2024	15.25
2025	12.64

Table 19: Maximum likelihood estimates of large mature male biomass at mating, male recruitment (billions), and fully-selected total fishing mortaltiy.

Survey year	Mature male biomass	Male recruits	Fishing mortality
1982	125.5	4.41	0.19
1983	164.9	2.38	0.13
1984	194.3	3.7	0.25
1985	188.5	4.51	0.36
1986	161.9	0.21	0.42
1987	130.4	1.97	0.64
1988	134.7	1.32	0.67
1989	145.6	0.71	0.7
1990	94.96	3.7	1.96
1991	117.6	4.35	1.2
1992	87.37	0.2	1.64
1993	62.73	0.74	1.85
1994	46.64	0.24	1.33
1995	50.82	0.31	1.36
1996	74.85	0.26	1.4
1997	89.93	0.9	1.28
1998	55.03	0.55	2.27
1999	58	0.84	0.53
2000	46.95	0.17	0.52
2001	31.25	1.89	0.95
2002	25.05	1.71	1.13
2003	34.89	1.78	0.55
2004	46.6	2.16	0.46
2005	50.38	0.62	0.38
2006	42.69	0.53	0.69
2007	46.93	0.83	0.98
2008	58.7	1.83	0.74
2009	61.44	0.28	0.54
2010	111.4	0.48	0.39
2011	67.92	0.41	0.79
2012	40.19	1.37	1.21
2013	34.98	1.57	1.5
2014	24.85	10.14	2.31
2015	18.93	7.26	2.19
2016	17.25	1.3	1.32
2017	23.41	1.58	1.01
2018	12.35	1.38	2.35
2019	44.24	0.9	1.1
2020	23.94	1.32	1.96
2021	27.08	2.69	0.29
2022	25.09	6.06	0
2023	21.17	2.25	0
2024	18.95	2.12	0.26

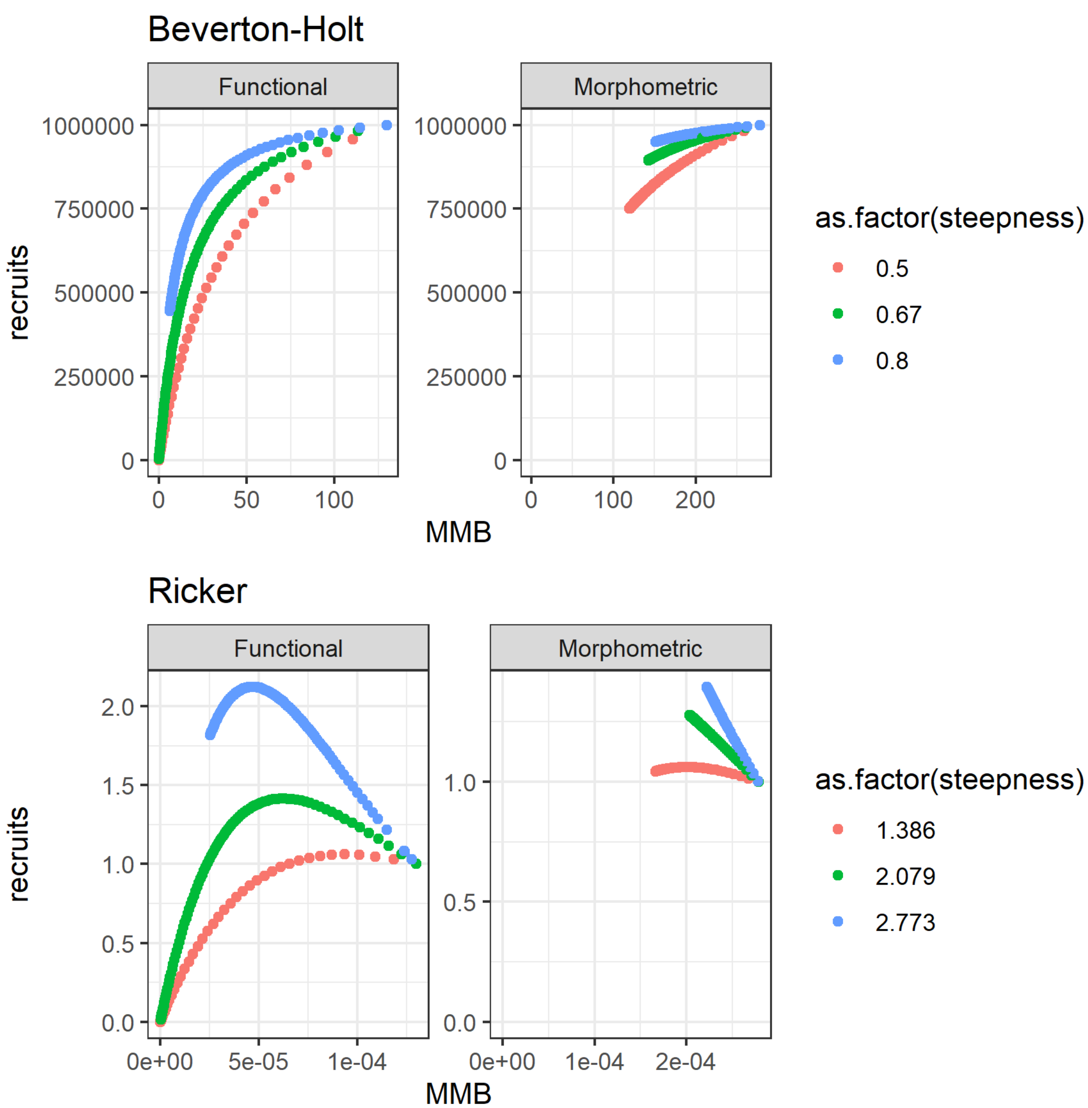


Figure 1: Ricker curves added to SBPR maximin analysis. Left column represents when 95mm carapace width crab are used as the management currency; right column is morphometrically mature. These are 'realized' curves over the range of fishing mortality used (0-5). Consequently, the curves 'realized' for the currency of morphometrically mature biomass are abbreviated because the spawning biomass cannot be depleted past a given point.

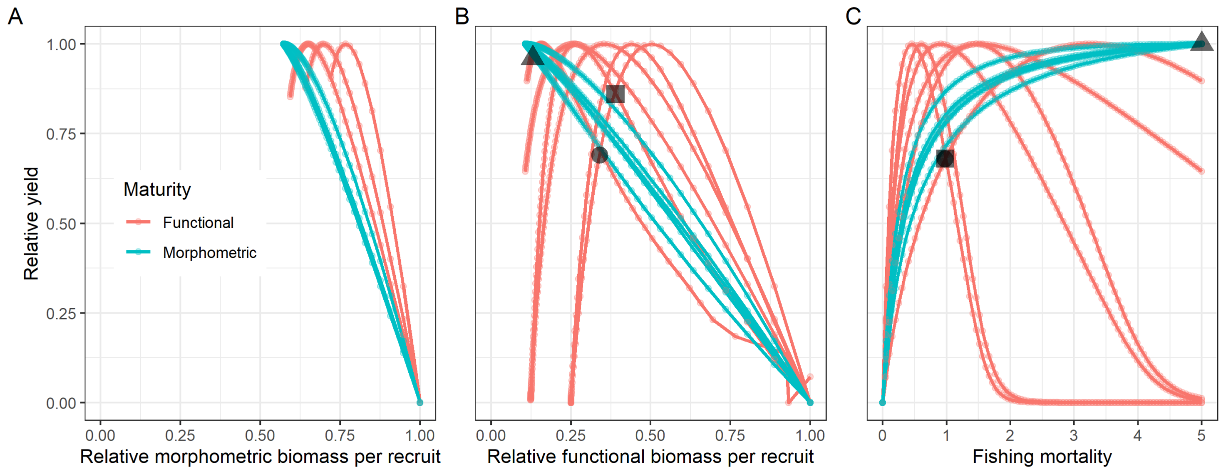


Figure 2: SBPR proxies from maximin analyses including Ricker curves. Relative equilibrium yield for scenarios in which recruitment is determined by morphometric biomass (blue) overlaid on scenarios in which recruitment is determined by functional biomass (red) for morphometric biomass-per-recruit (left), functional biomass-per-recruit (middle), and fishing mortality (right). Each line represents a different value for steepness. The triangles in panels B and C represent the maximin solution for the percentage of morphometric biomass-per-recruit over steepness space; the squares represent the maximin solution for the percentage of functional biomass-per-recruit. The circles represent the maximin solution over both uncertainty in steepness and the reproductively active portion of the biomass.

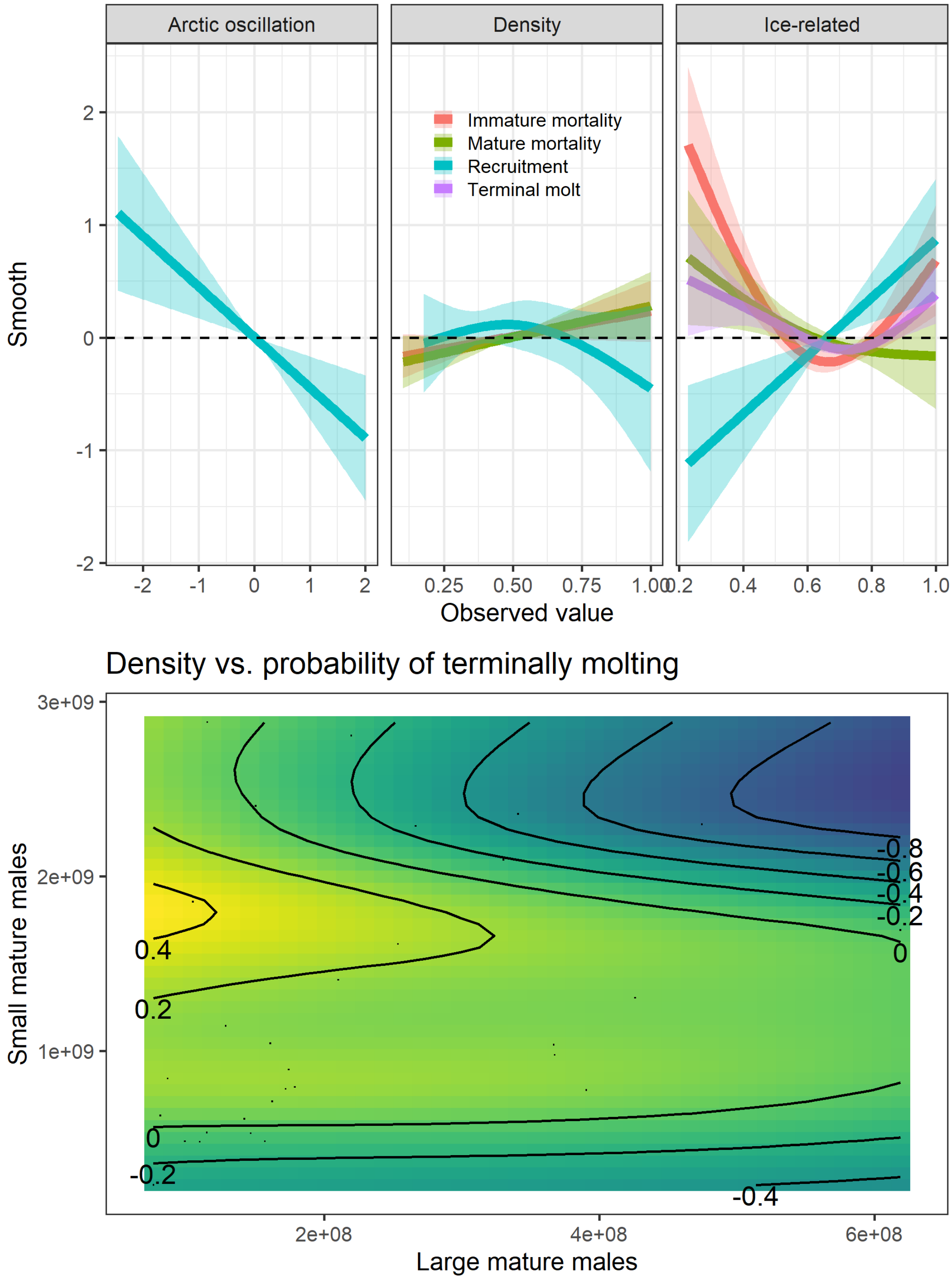


Figure 3: Environmental relationships to immature mortality, mature mortality, recruitment, and probability of terminally molting.

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

Figure 4: Radiometric estimates of shell age in male snow and tanner crab collected during the NMFS survey of 1992. Reproduced from Ernst et al. 2005's presentation of Nevissi et al. 1995.

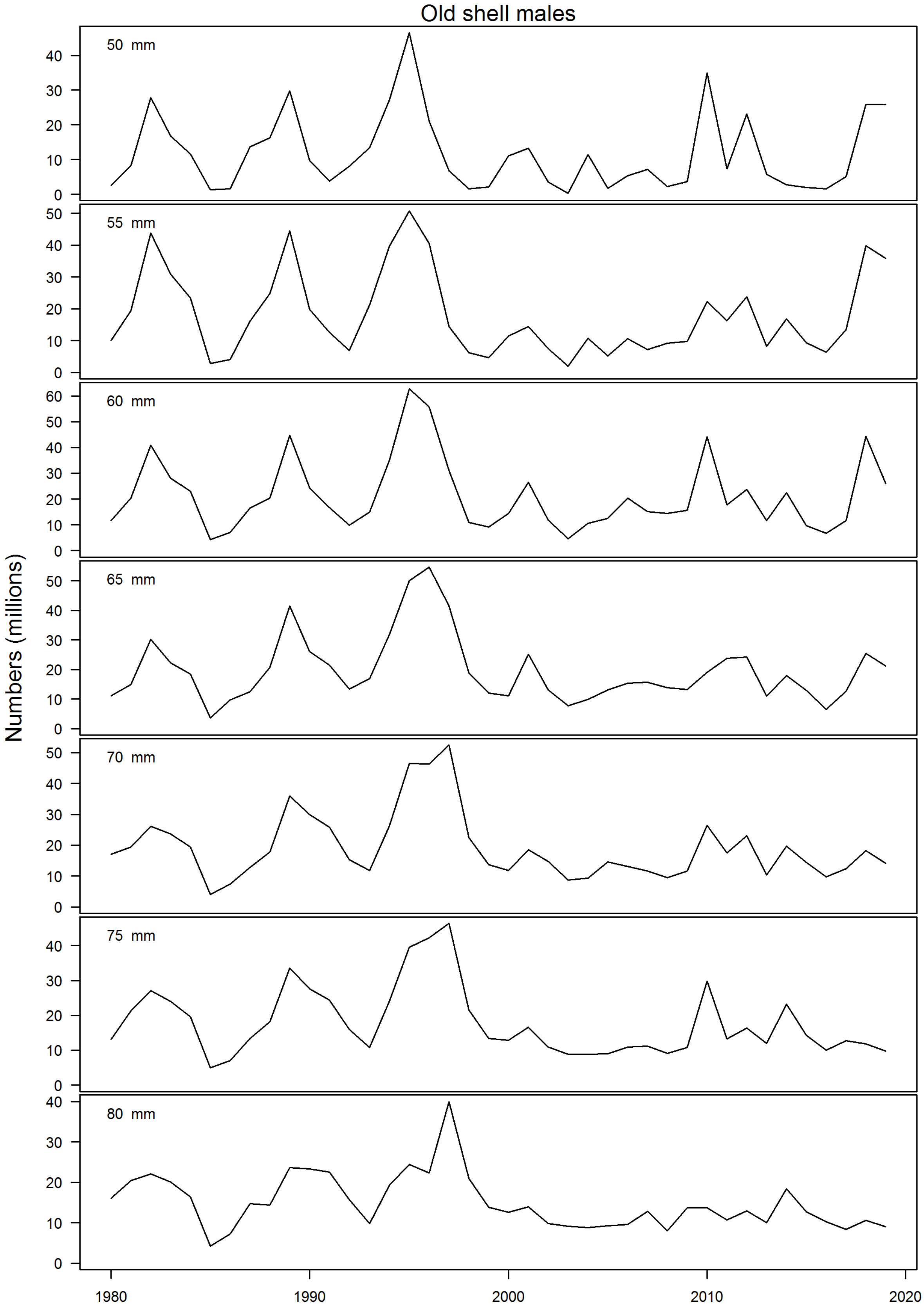


Figure 5: Observed numbers at length of old shell mature males by size class. The presented size bins are not vulnerable to the fishery, so all mortality is 'natural'. The decline in numbers in a size class after the recruitment collapse in the early 1990s demonstrates expected natural mortality for mature male individuals.

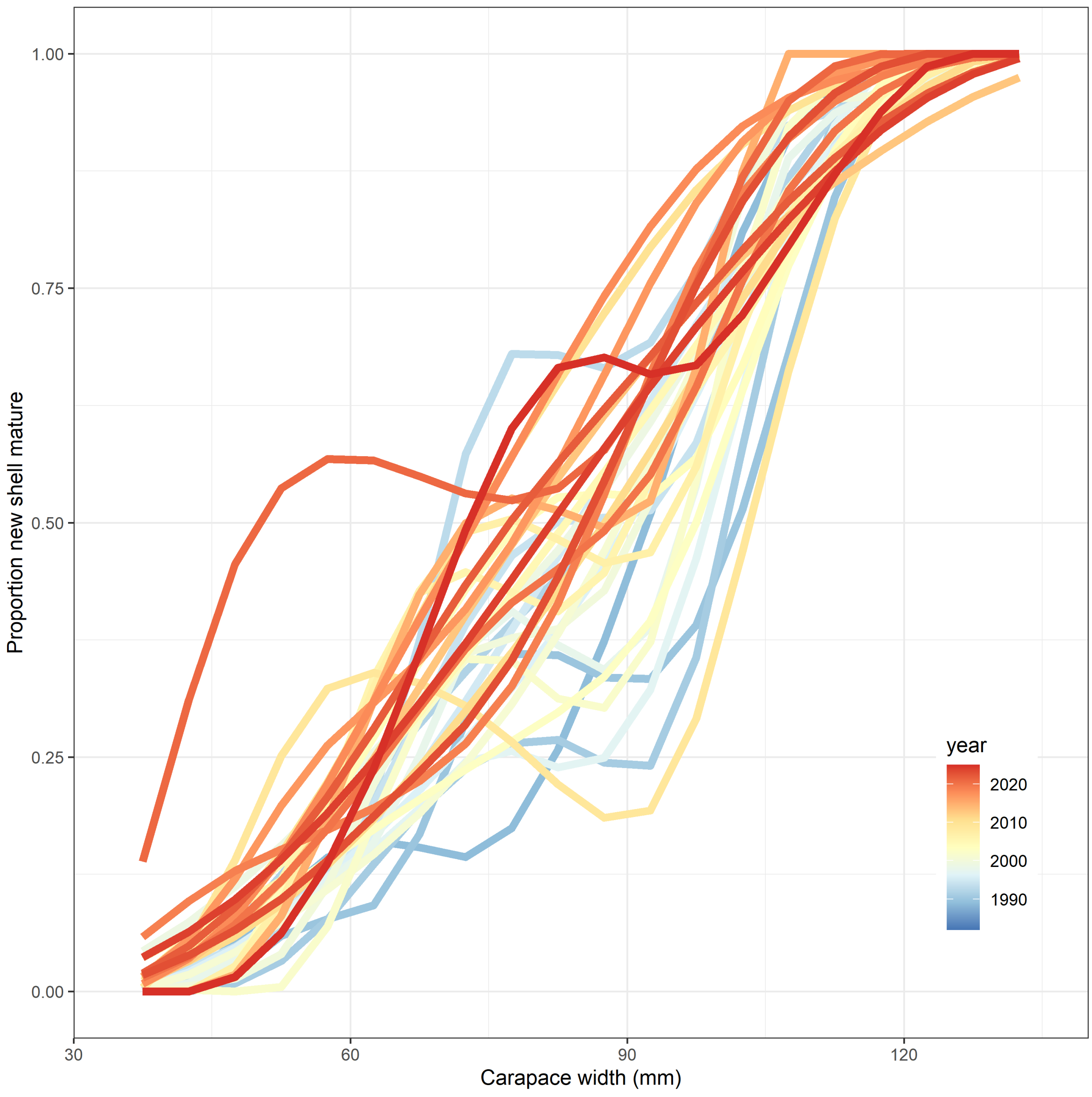


Figure 6: Observed probability of having undergone terminal molt at size for new shell male crab based on chelae height. Blue lines occurred farther back in history; red lines are most recent.

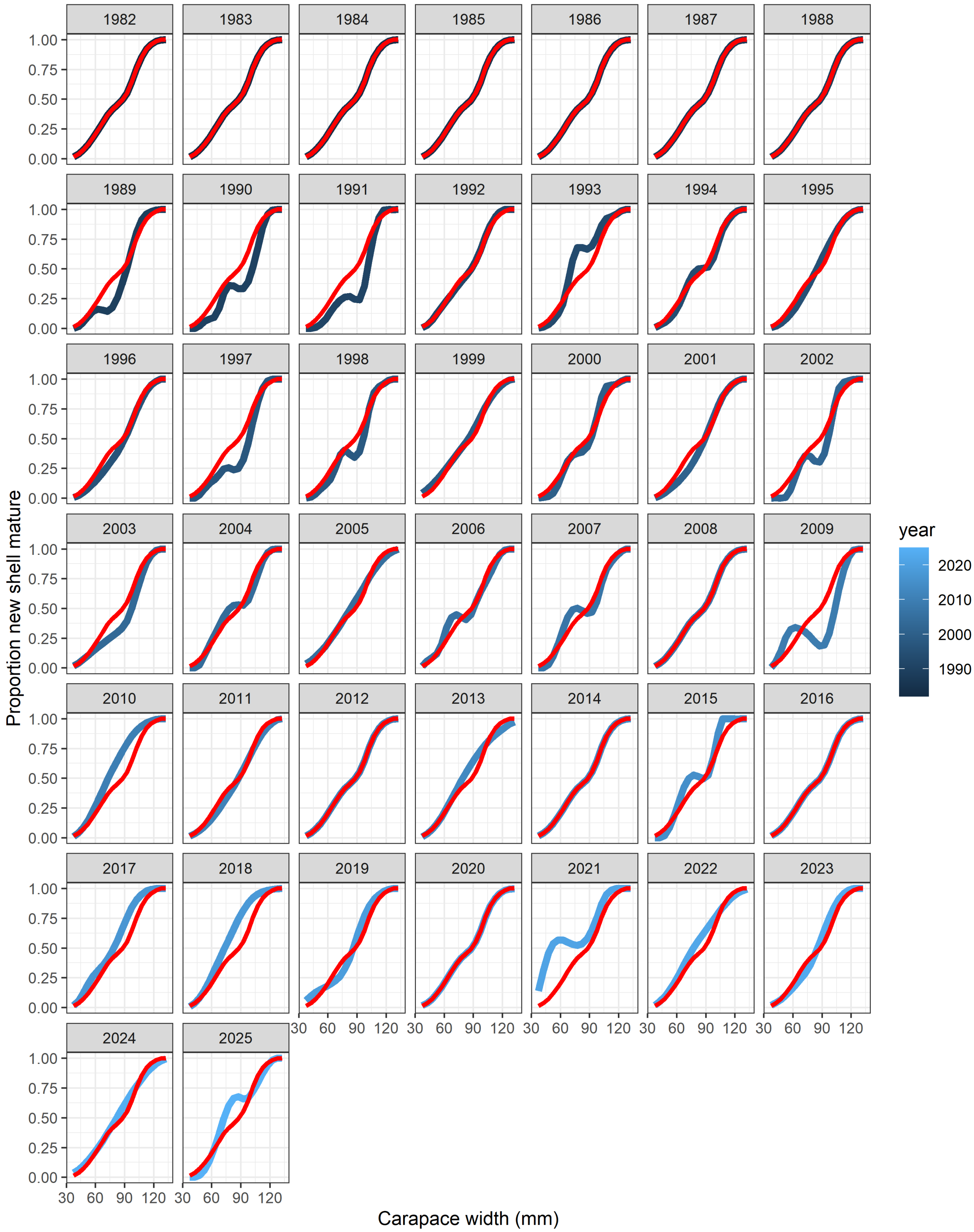


Figure 7: Observed probability of having undergone terminal molt at size for new shell male crab based on chelae height. Red line is median over all years data; blue lines are individual year's data.

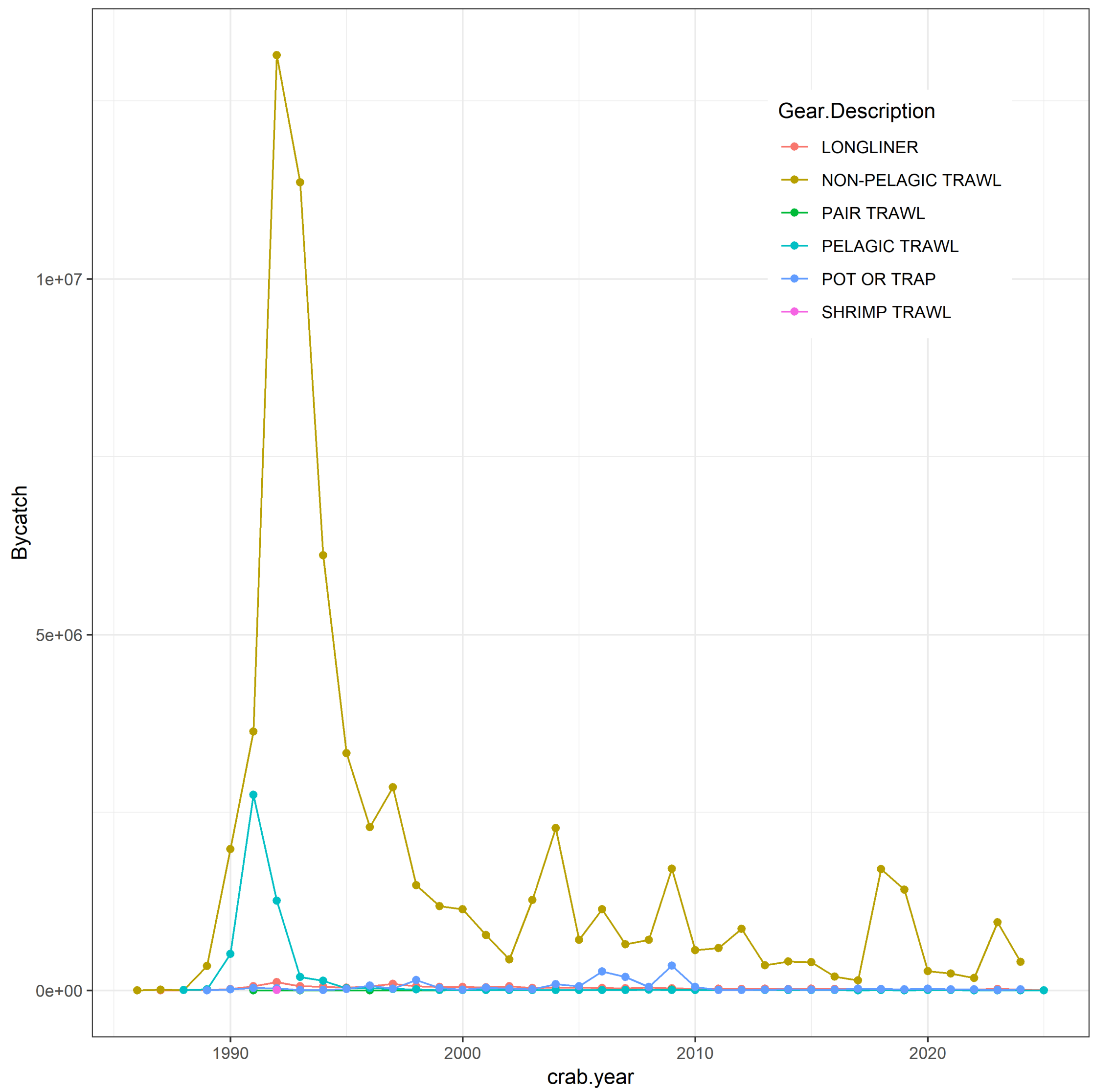


Figure 8: Time series of non-directed bycatch from the groundfish fisheries by gear in numbers of crab.

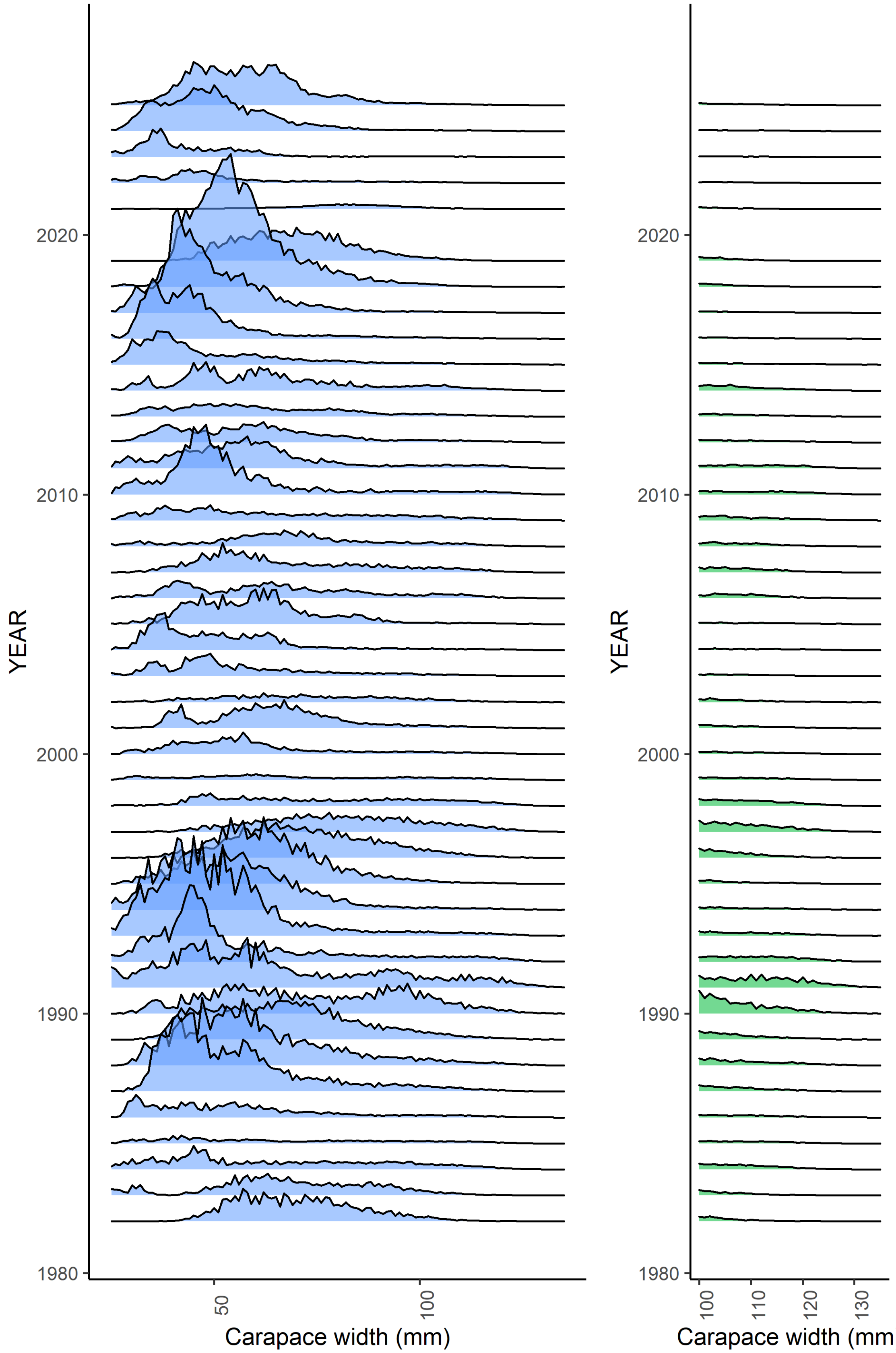


Figure 9: Raw total numbers at size of male crab observed in the survey. Blue are all numbers at size; green are males >101mm carapace width, the industry preferred size.

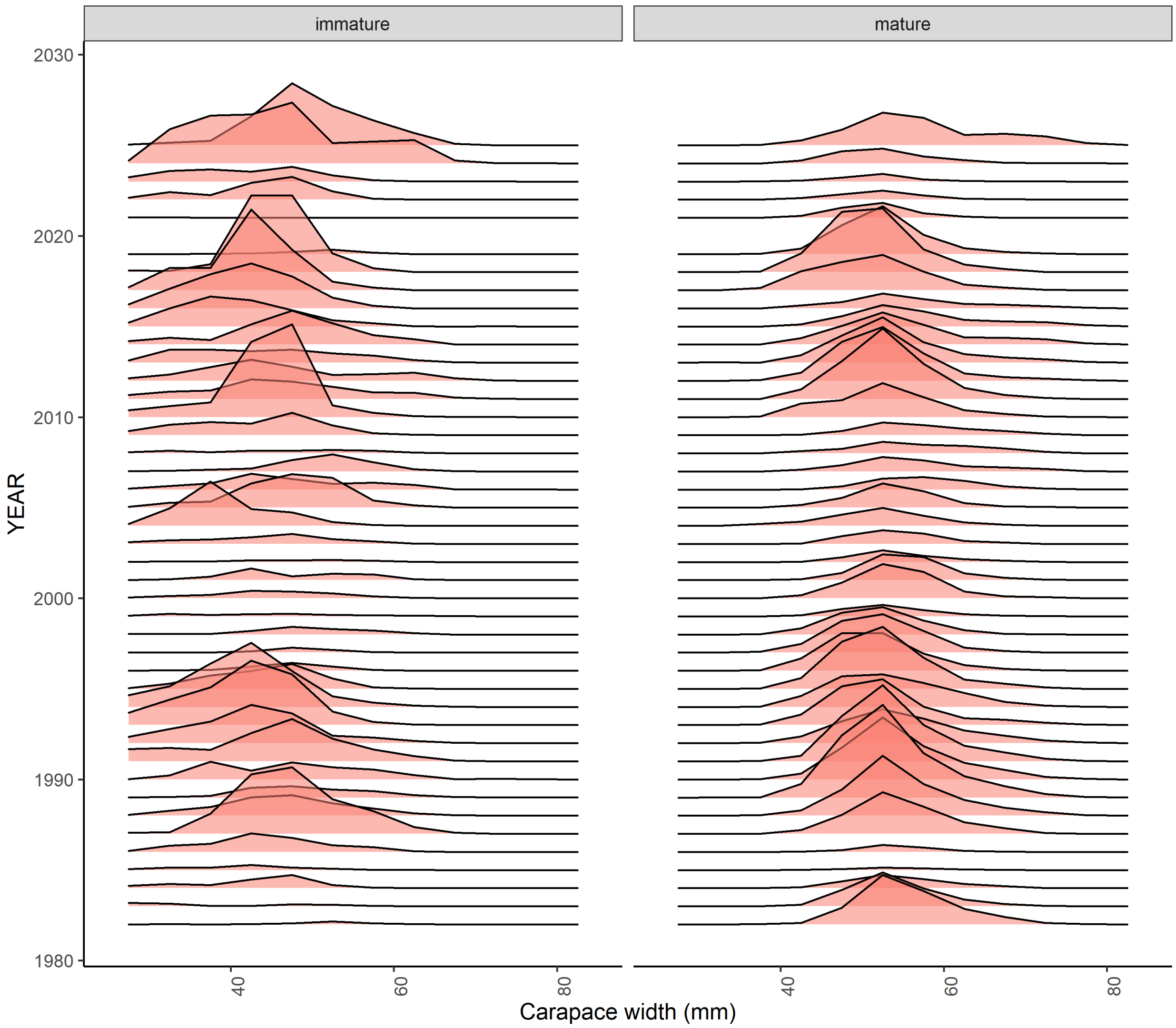


Figure 10: Raw total numbers at size of immature and mature female crab observed in the survey (binned at 5mm intervals).

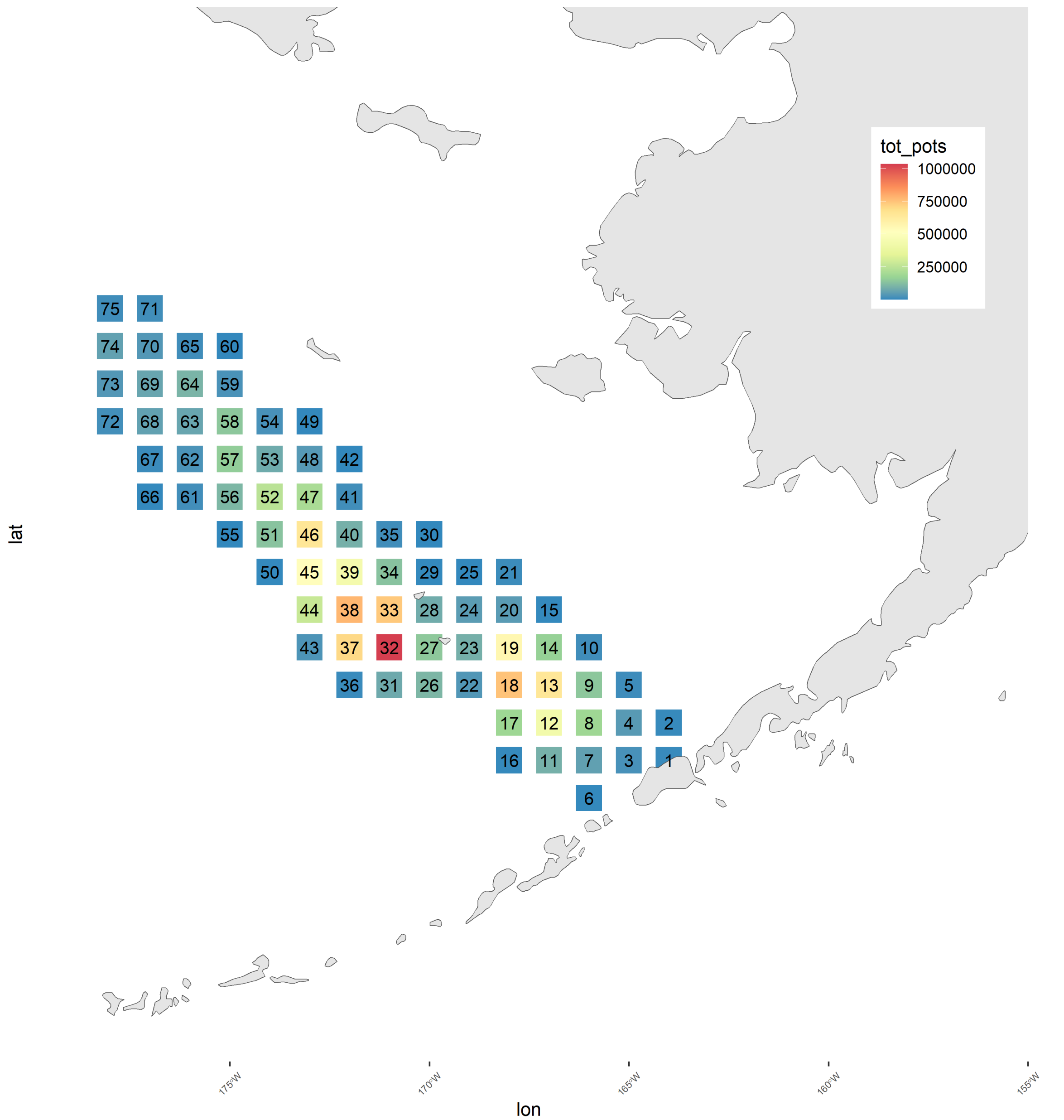


Figure 11: Distribution of effort in terms of potlifts in the directed fishery on the Bering Sea shelf summed from 1990-present. Squares are statistical areas defined by the state. Numbers are generated to give context to the following figures. Only data in areas that had three or more fishers and processors represented were used to make this figure. That accounts for 87% of the data points available.

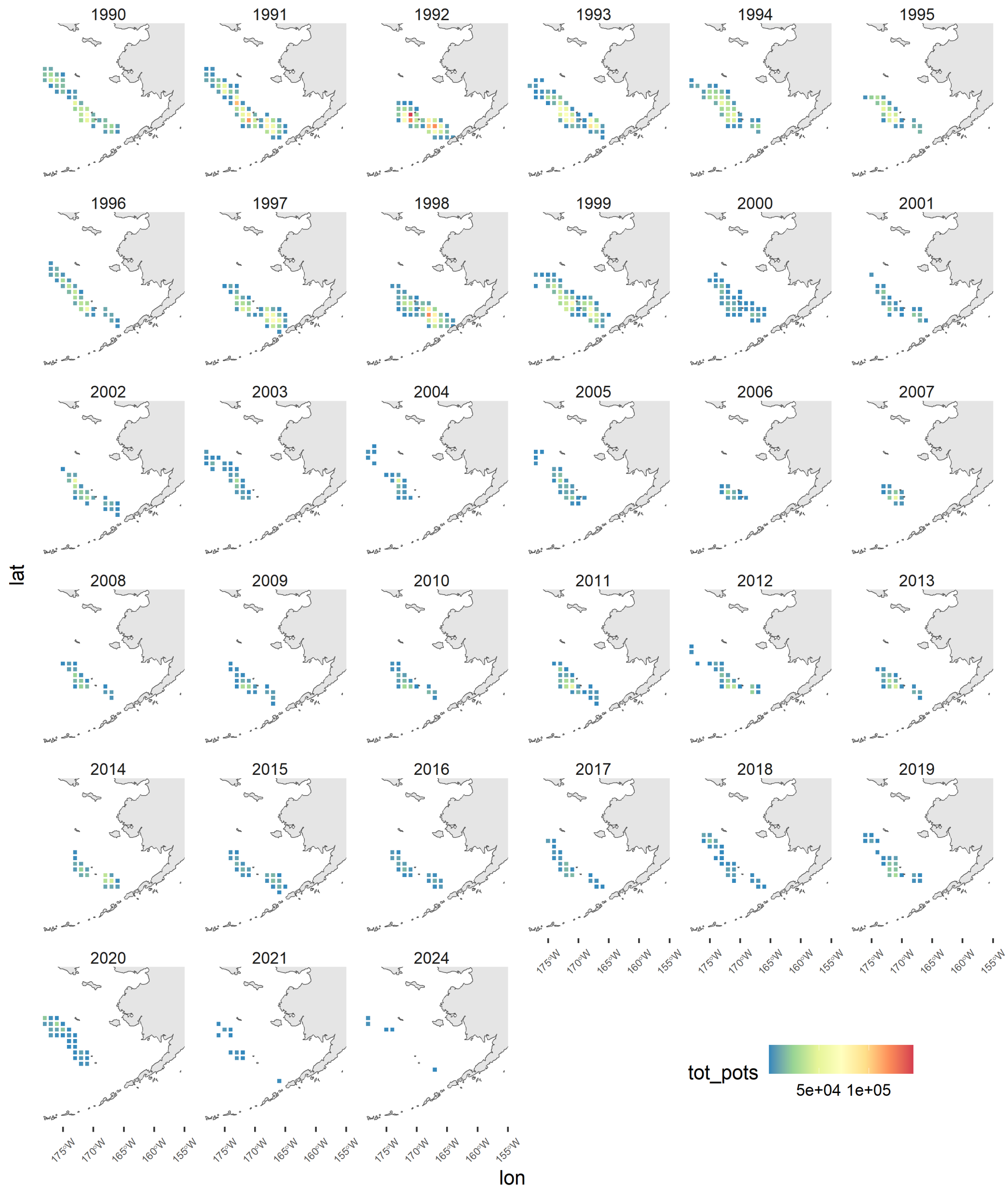


Figure 12: Yearly distribution of effort in terms of potlifts in the directed fishery on the Bering Sea shelf displayed from 1990-present.Only data in areas that had three or more fishers and processors represented were used to make this figure. That accounts for 87% of the data points available.

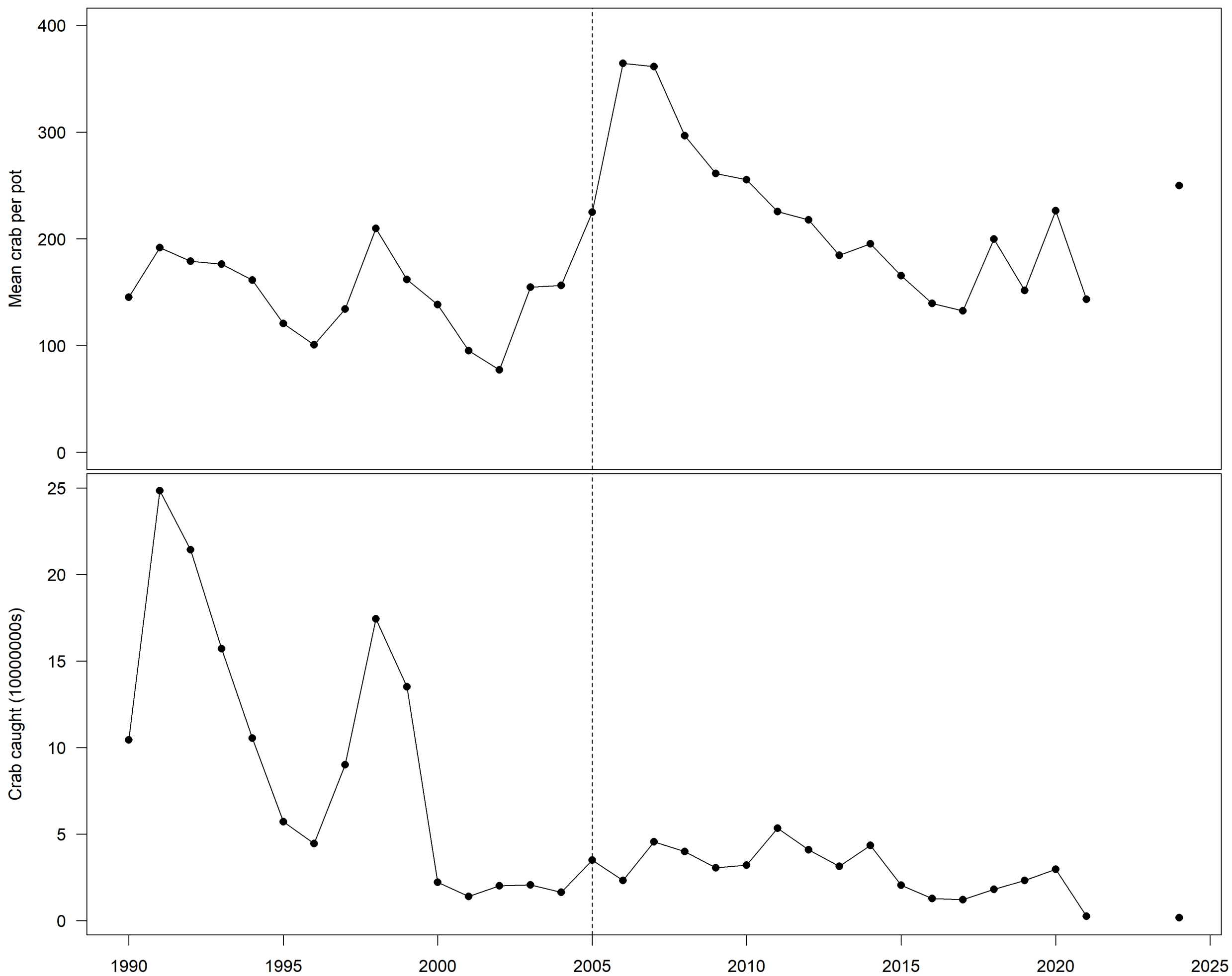


Figure 13: Yearly unstandardized catch per unit effort across from 1990-present with total number of crab captured (bottom).

Figure 14: Trends in unstandardized CPUE by statistical area. Each line is produced from a linear model fit through observed CPUE in a given area in a given year. Trends were only fit if the data represented in an area came included 3 or more fishers and processors and only if there were at least 5 weeks of CPUE data in a given area, in a given season.

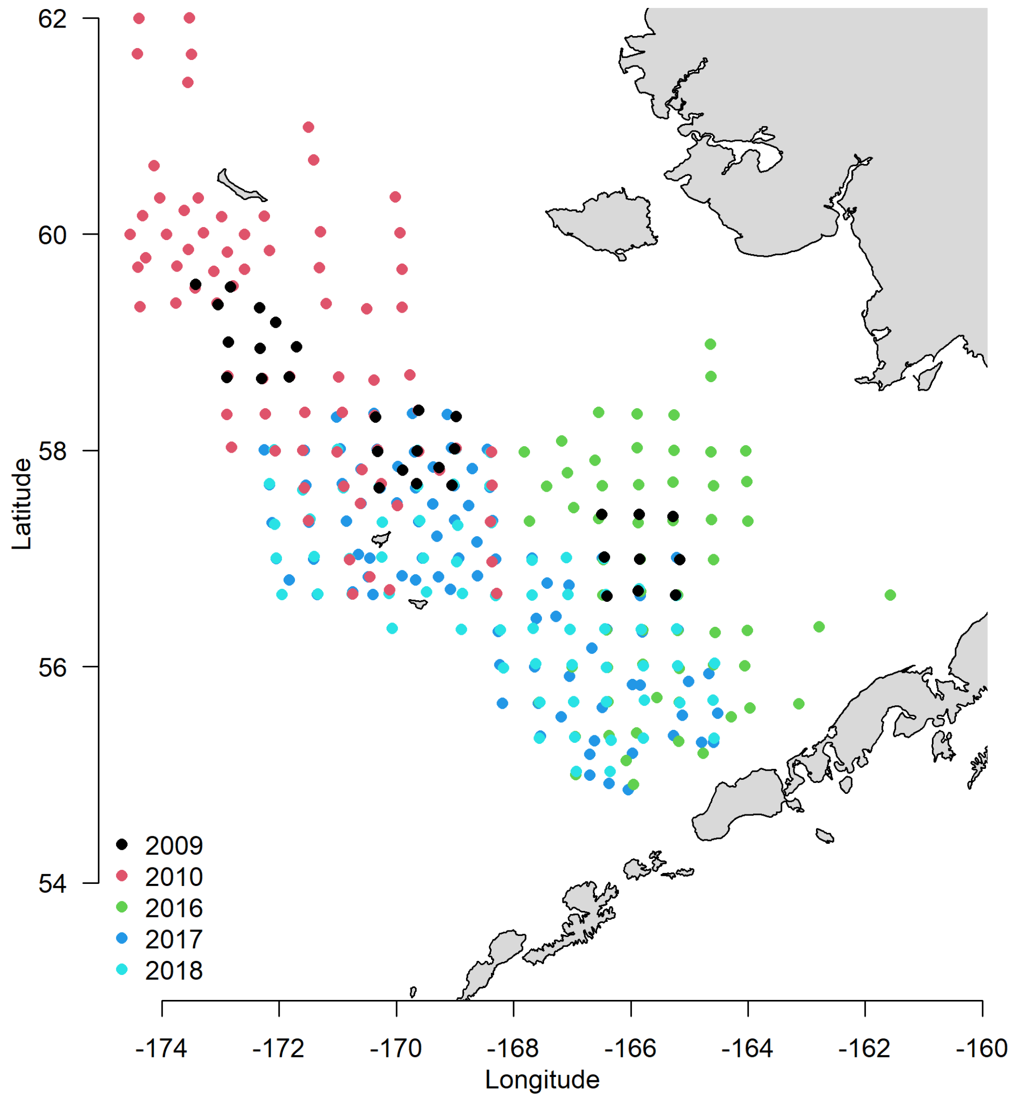


Figure 15: Location of BSFRF survey selectivity experiments that provided data used in this assessment over time.

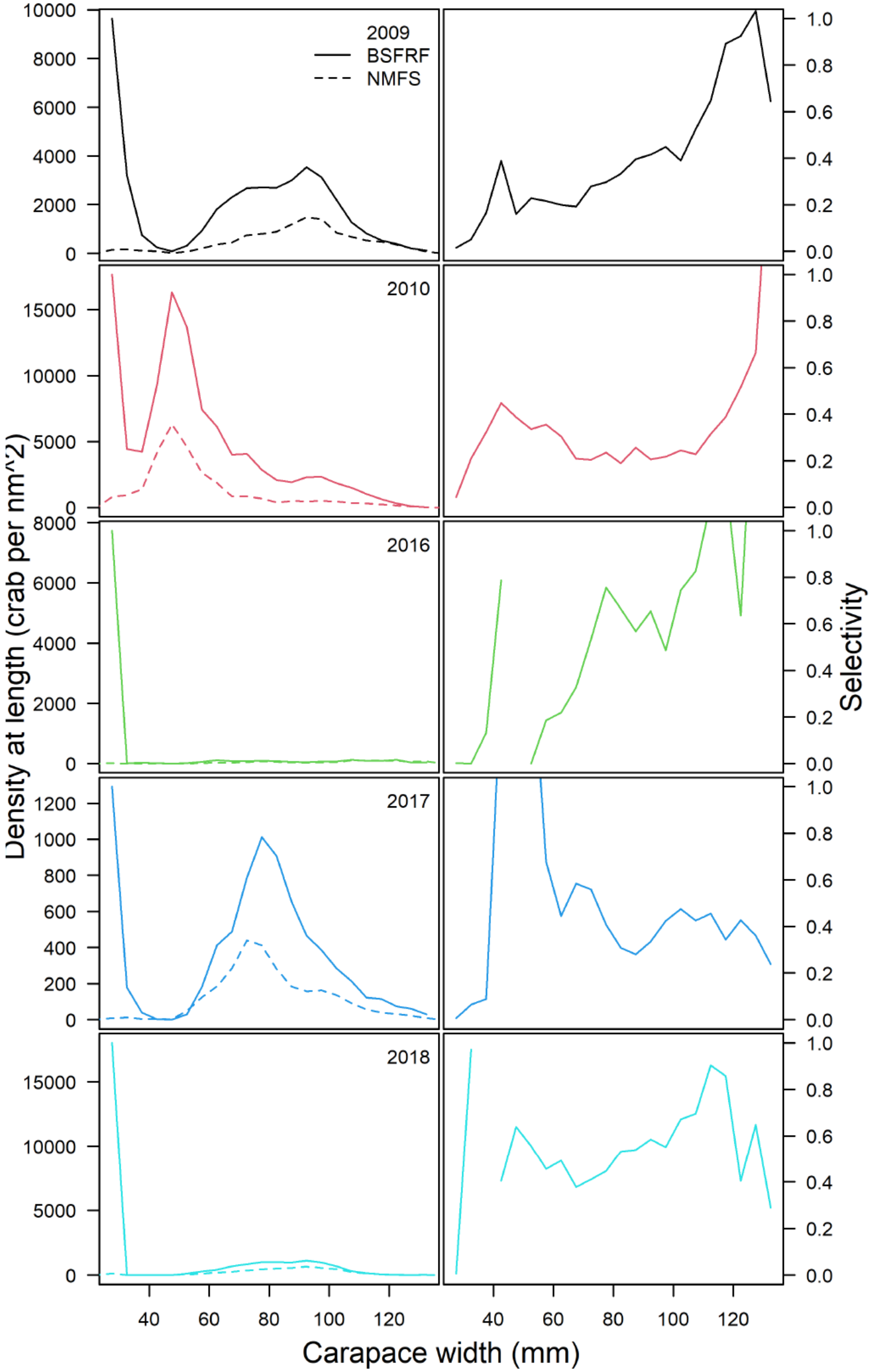


Figure 16: Observed numbers at length extrapolated from length composition data and estimates of total numbers within the survey selectivity experimental areas by year (left). Inferred selectivity (i.e. the ratio of crab at length in the NMFS gear to crab at length in the BSFRF gear) is on the right.

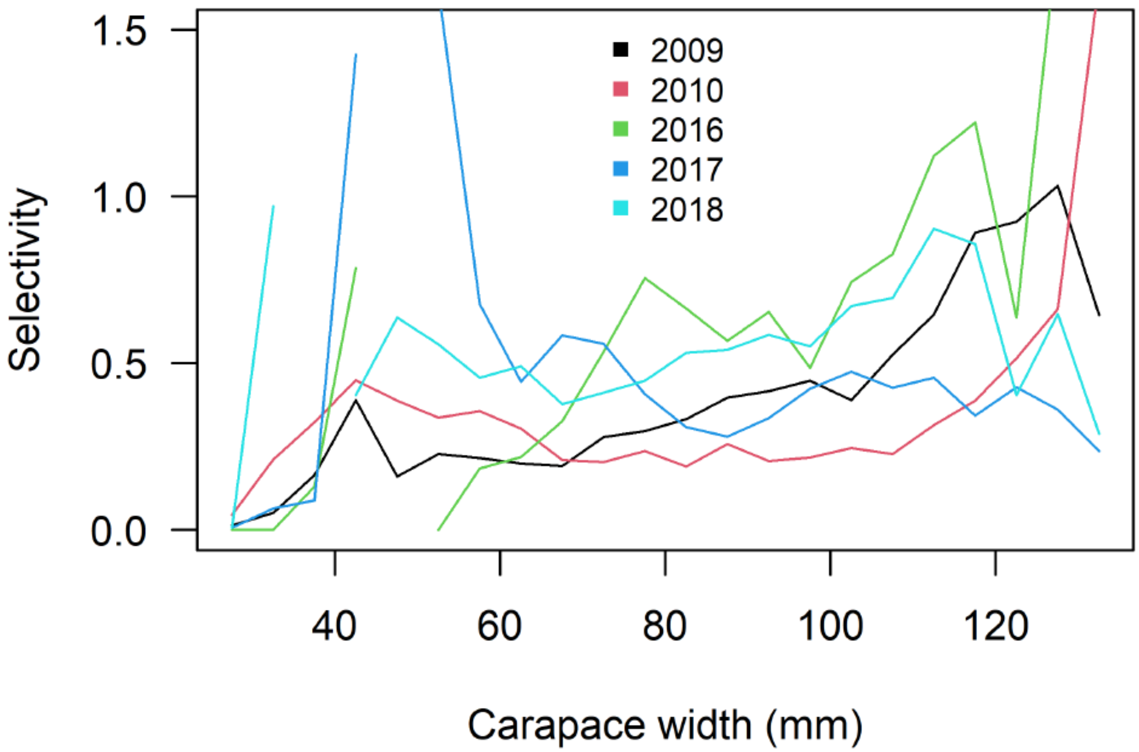


Figure 17: Inferred selectivity for all available years of BSFRF data.

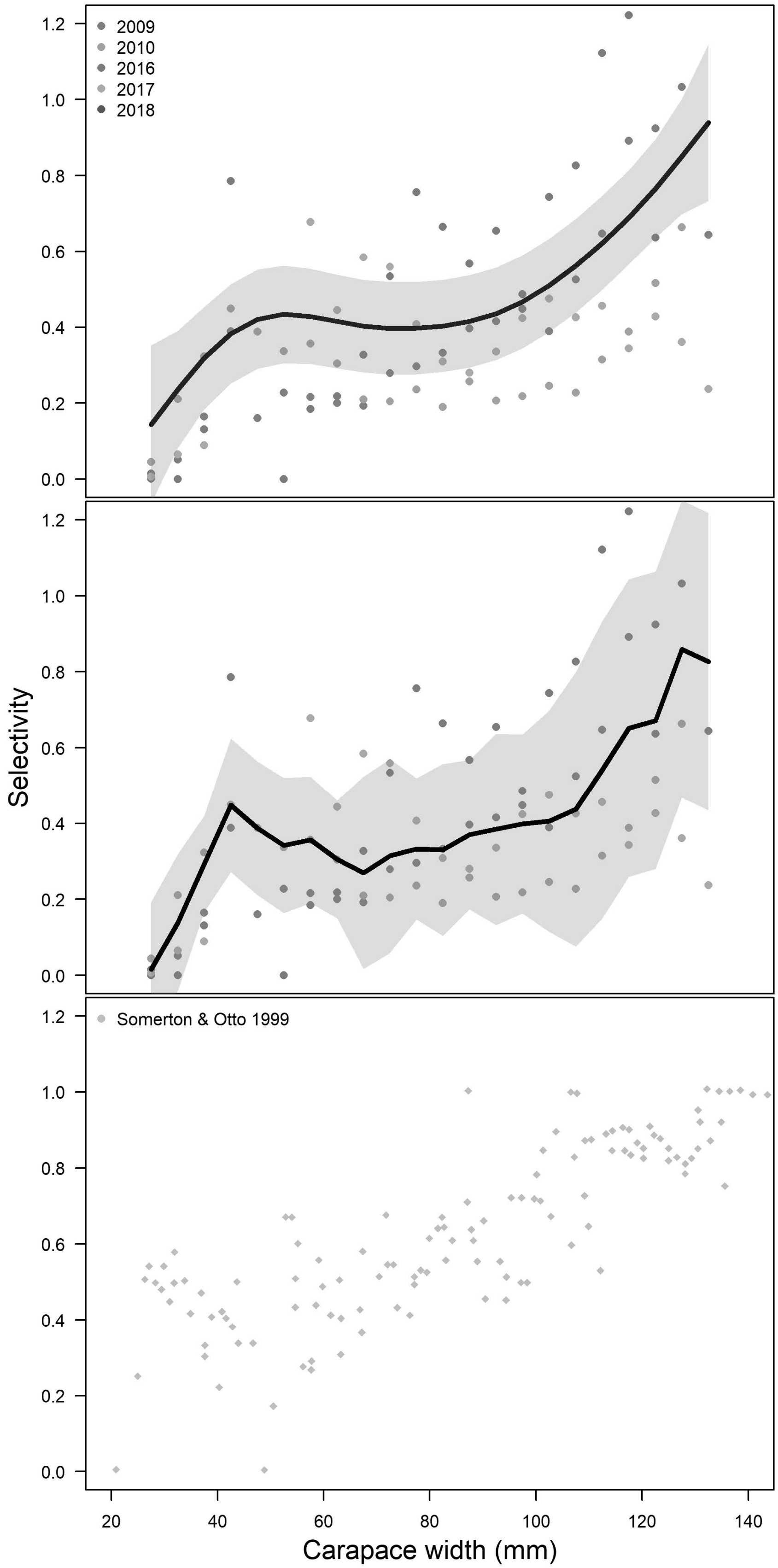


Figure 18: Inferred selectivity from BSFRF experiments with selectivity at size class estimated by generalized additive model (top). Inferred selectivity from BSFRF experiments with selectivity at size class estimated by sample size weighted means and variances (middle). Somerton and Otto (1998) underbag experimental data. Point estimates and associated CVs from the GAM were used as priors in model series 23.3.

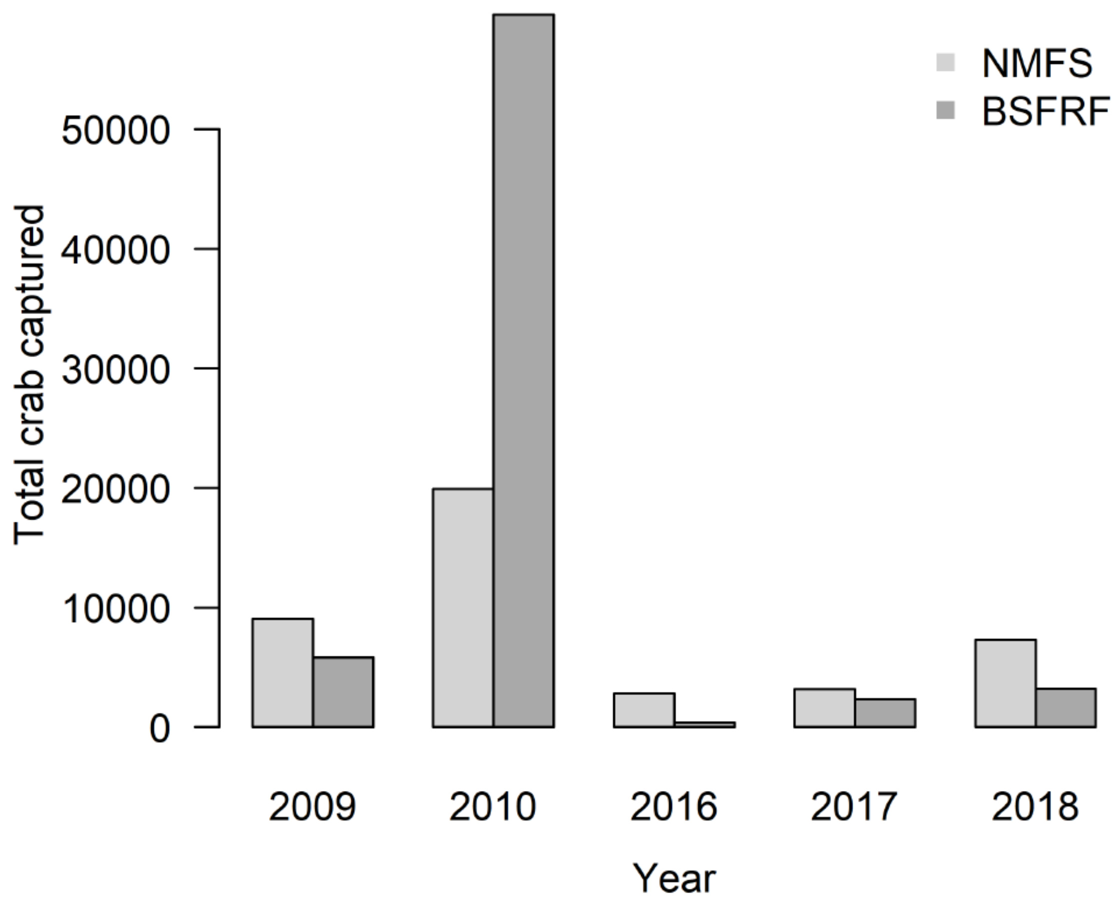


Figure 19: Number of crab collected in the BSFRF experimental areas by the NMFS survey and the BSFRF survey.

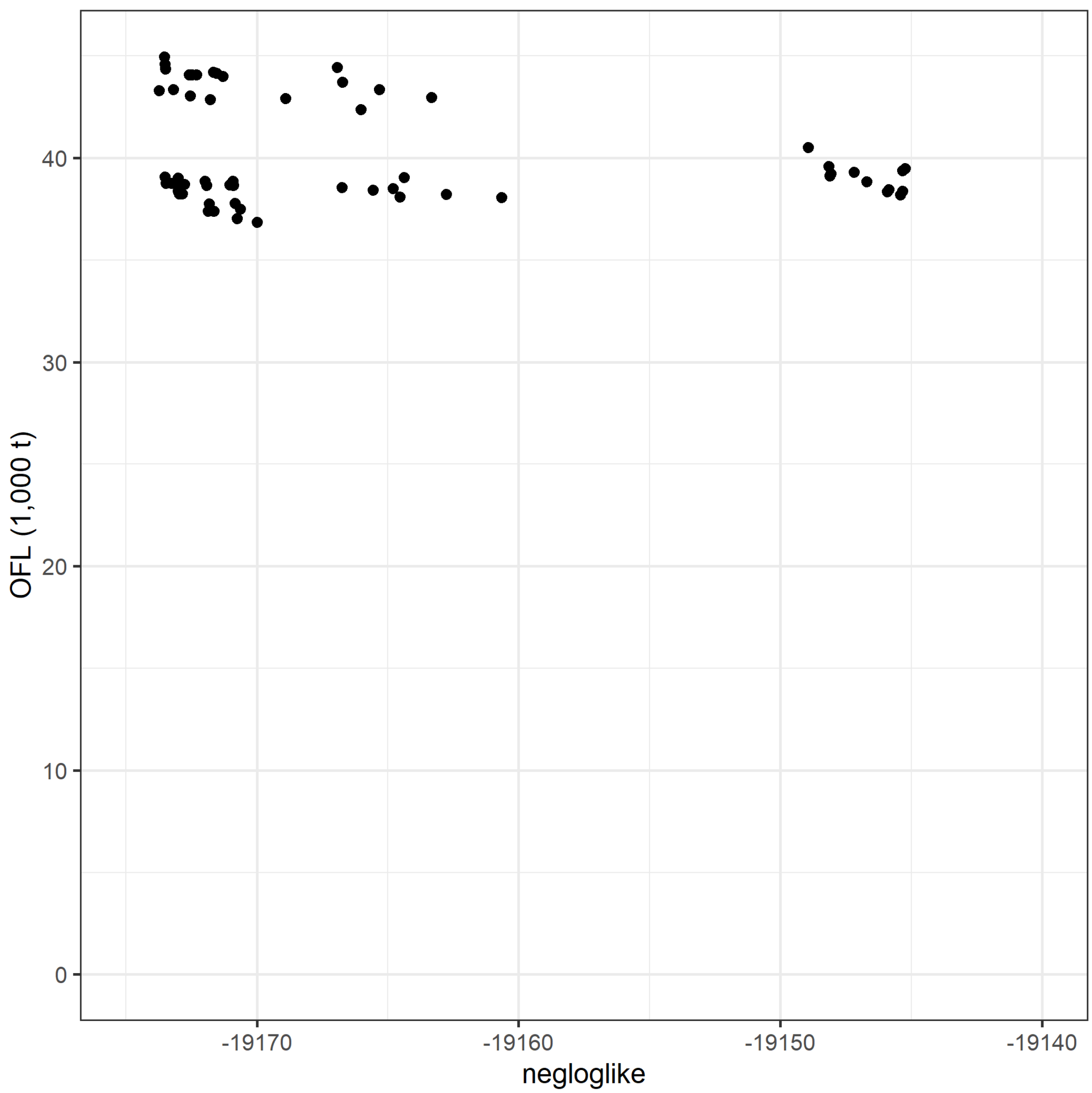


Figure 20: Directed OFLs resulting from 100 jitter runs for the model using morphometrically mature crab as currency.

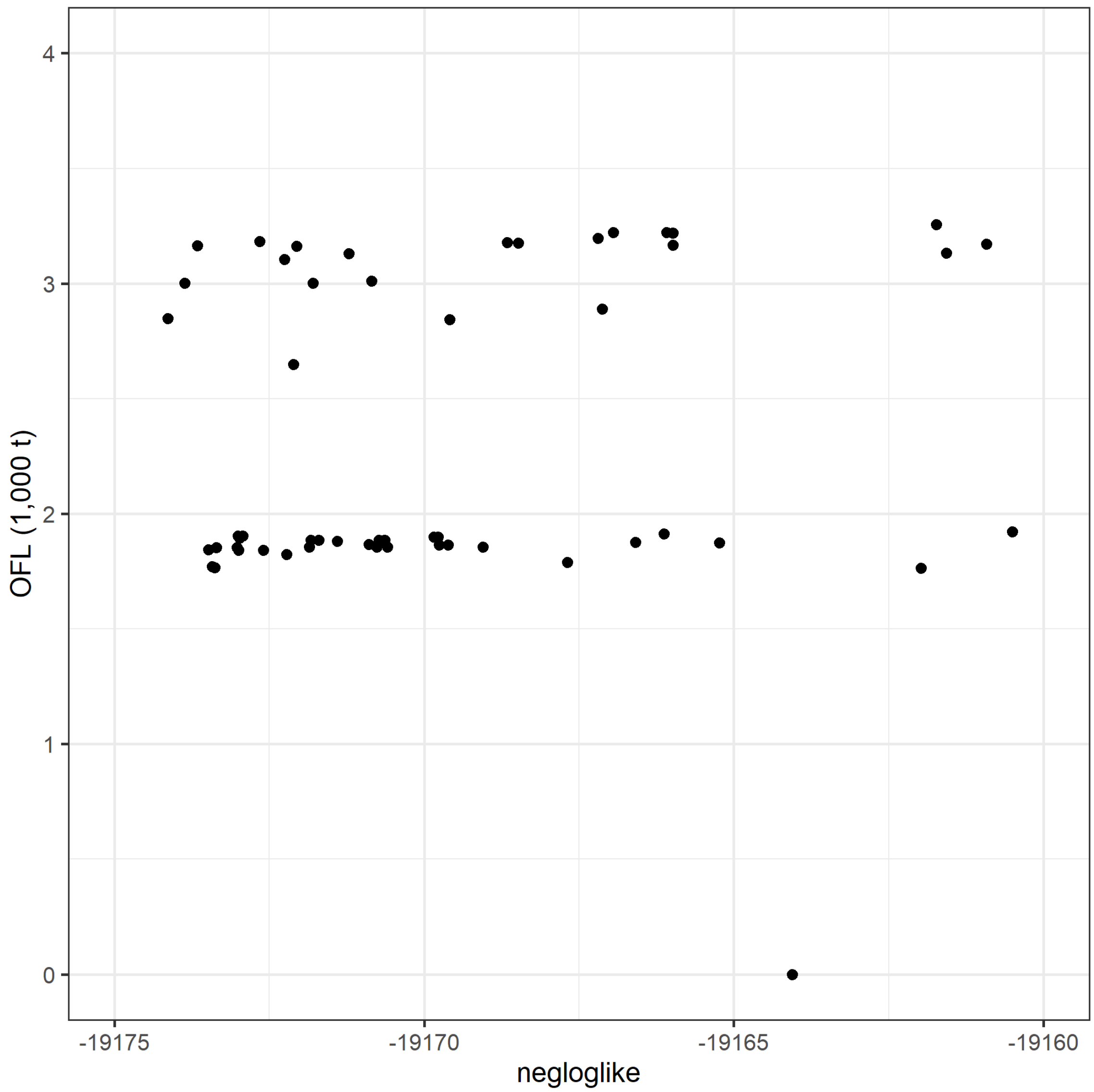


Figure 21: Directed OFLs resulting from 100 jitter runs for the model using 95mm crab as currency.

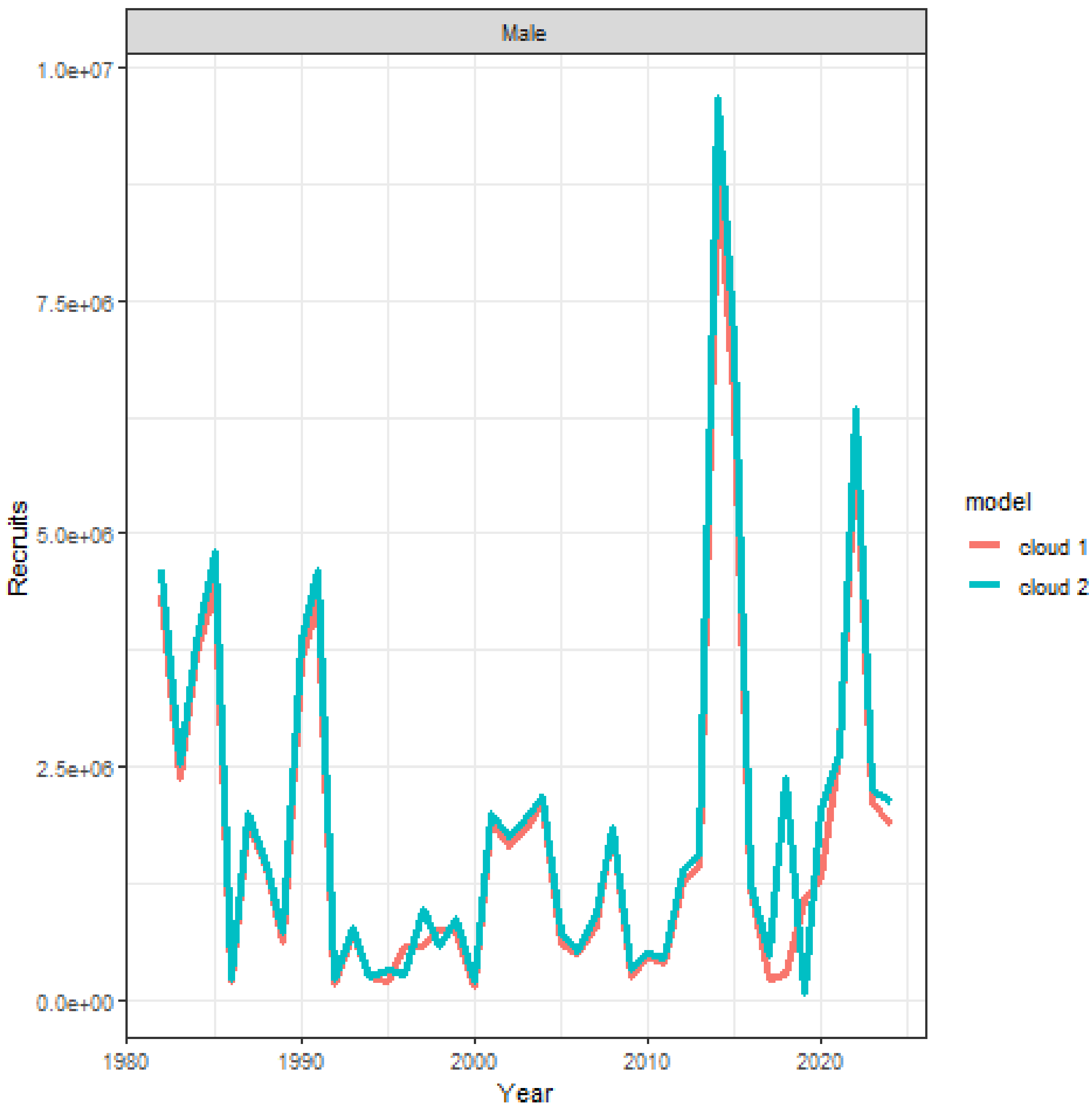


Figure 22: Estimated recruitment time series from two jitters runs from different 'clouds' of the previous plot.

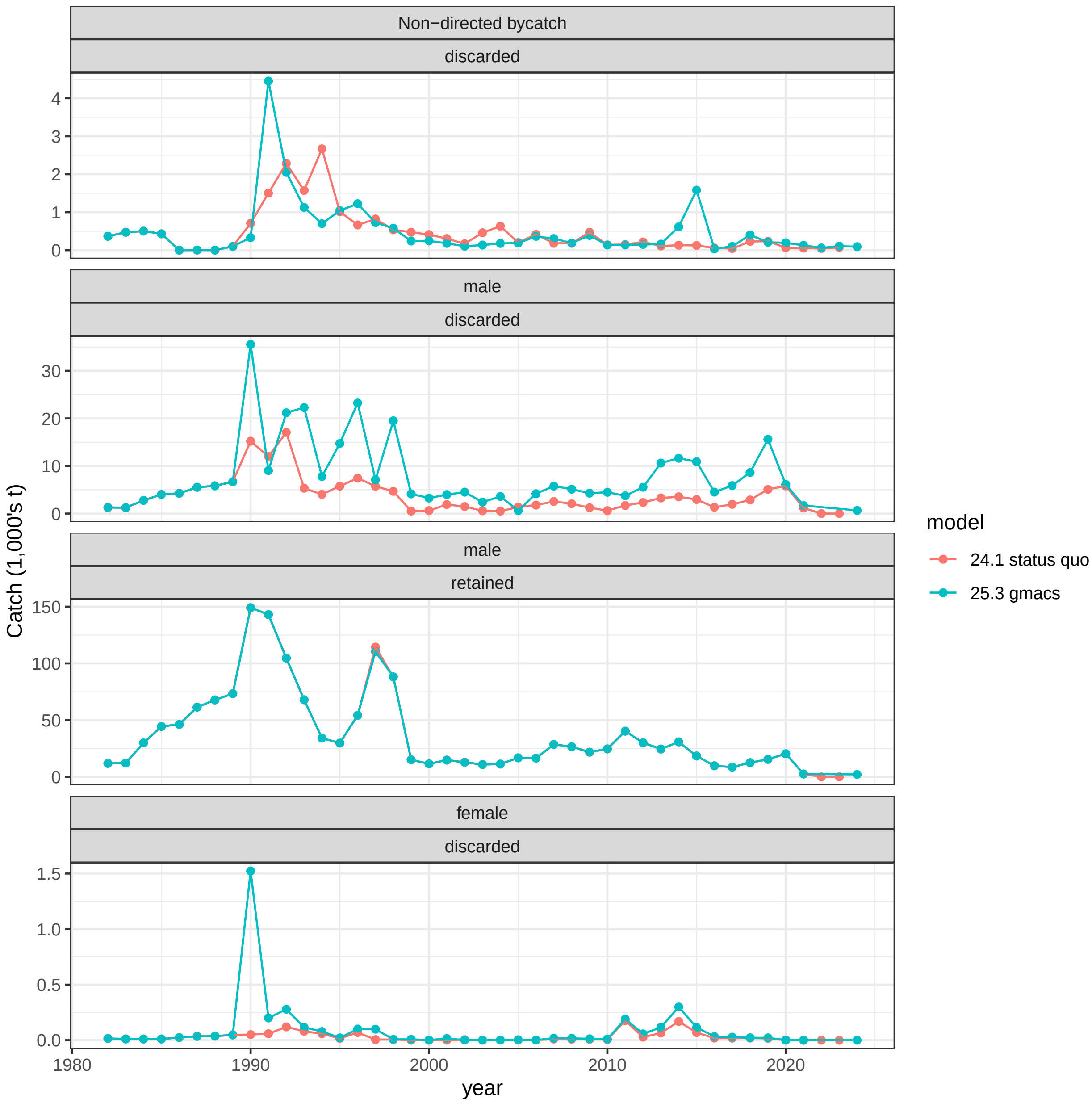


Figure 23: Updated catch time series. Shift upwards in discarded male crab is a result of applying discard mortality inside the assessment (25.3 gmacs) vs. outside (24.1 status quo). Interannual differences arise from changes in historical data.

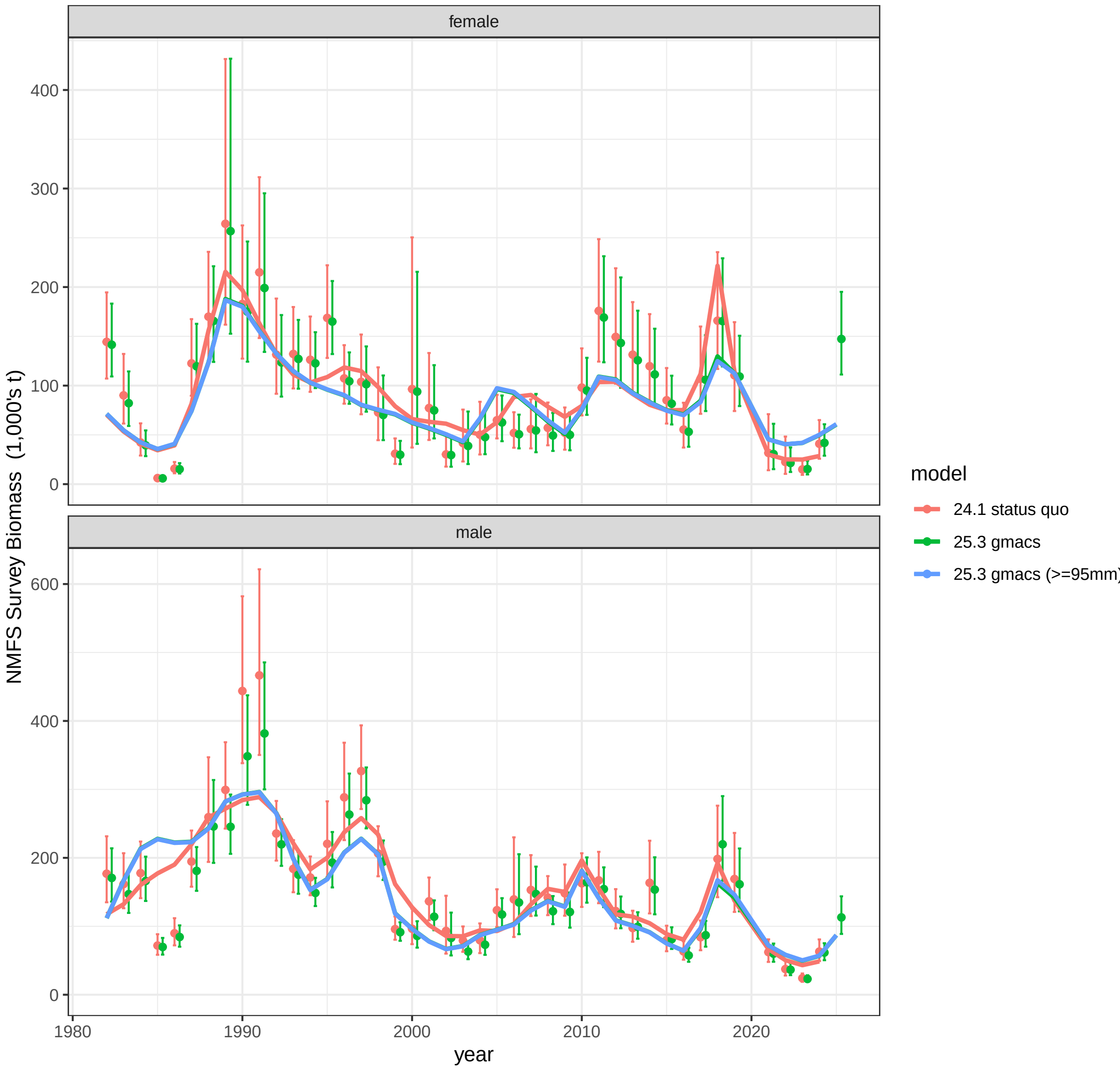


Figure 24: Model fits to the observed mature biomass at survey.

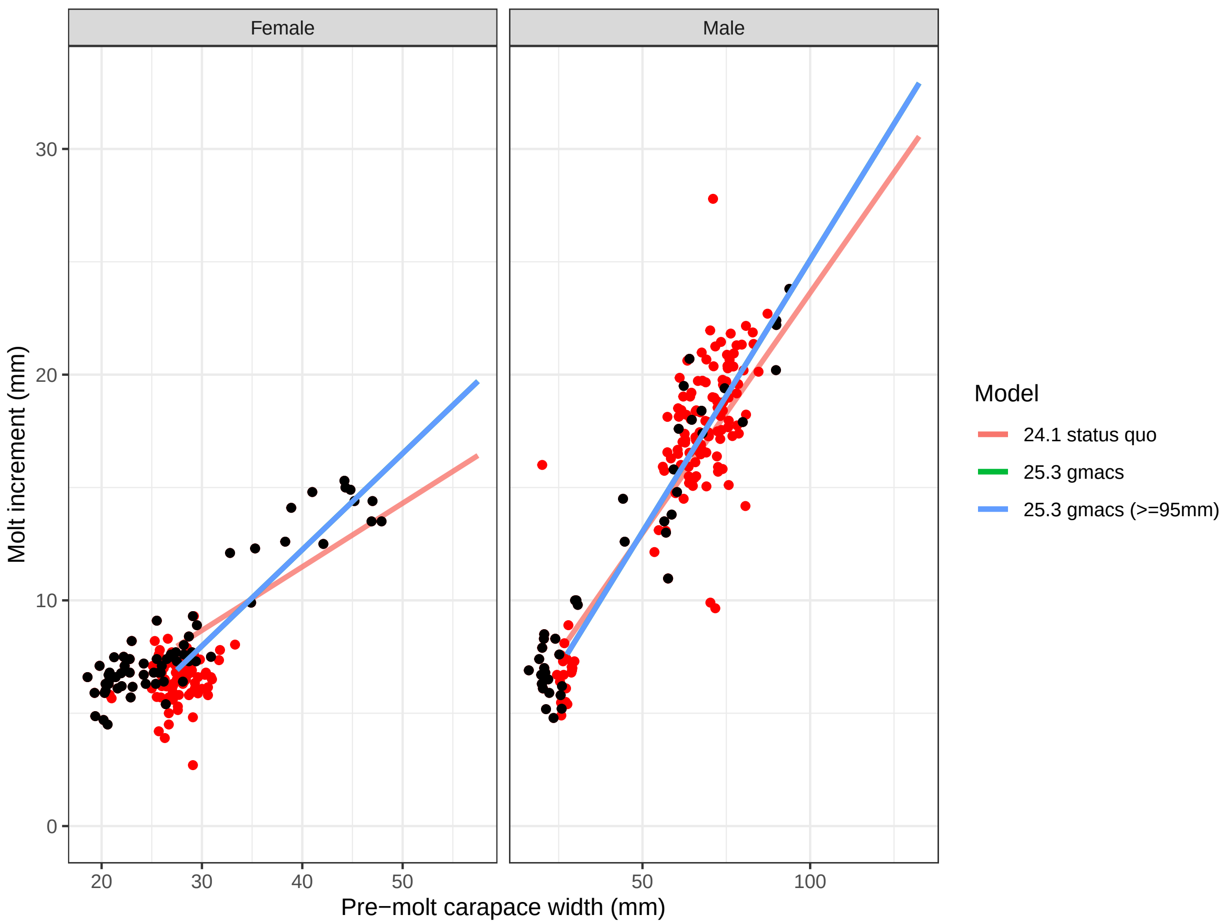


Figure 25: Model fits (colored lines) to the growth data (dots). Black dots are historical observations; red dots are new data for 2025.

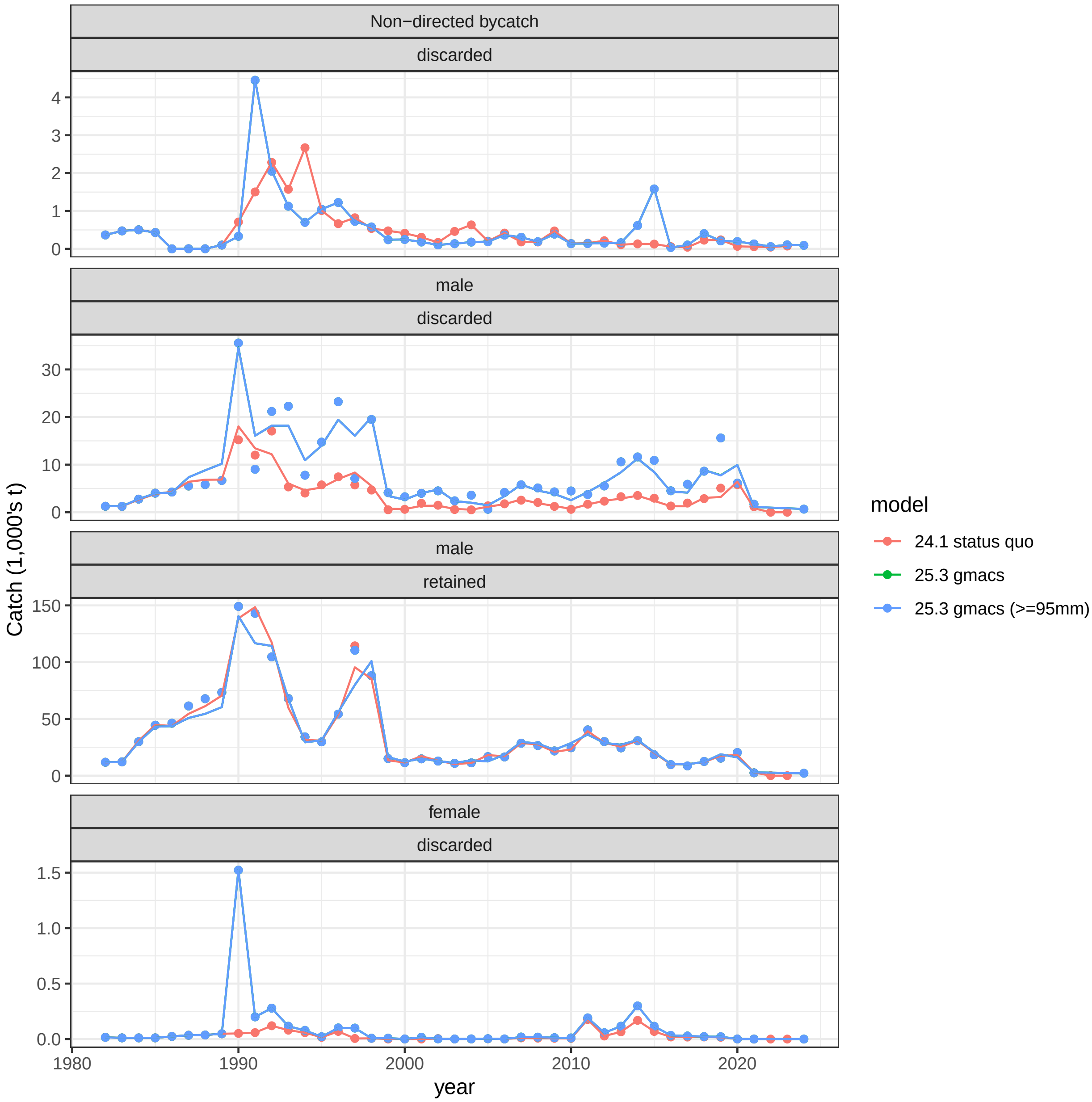


Figure 26: Model fits to catch data.

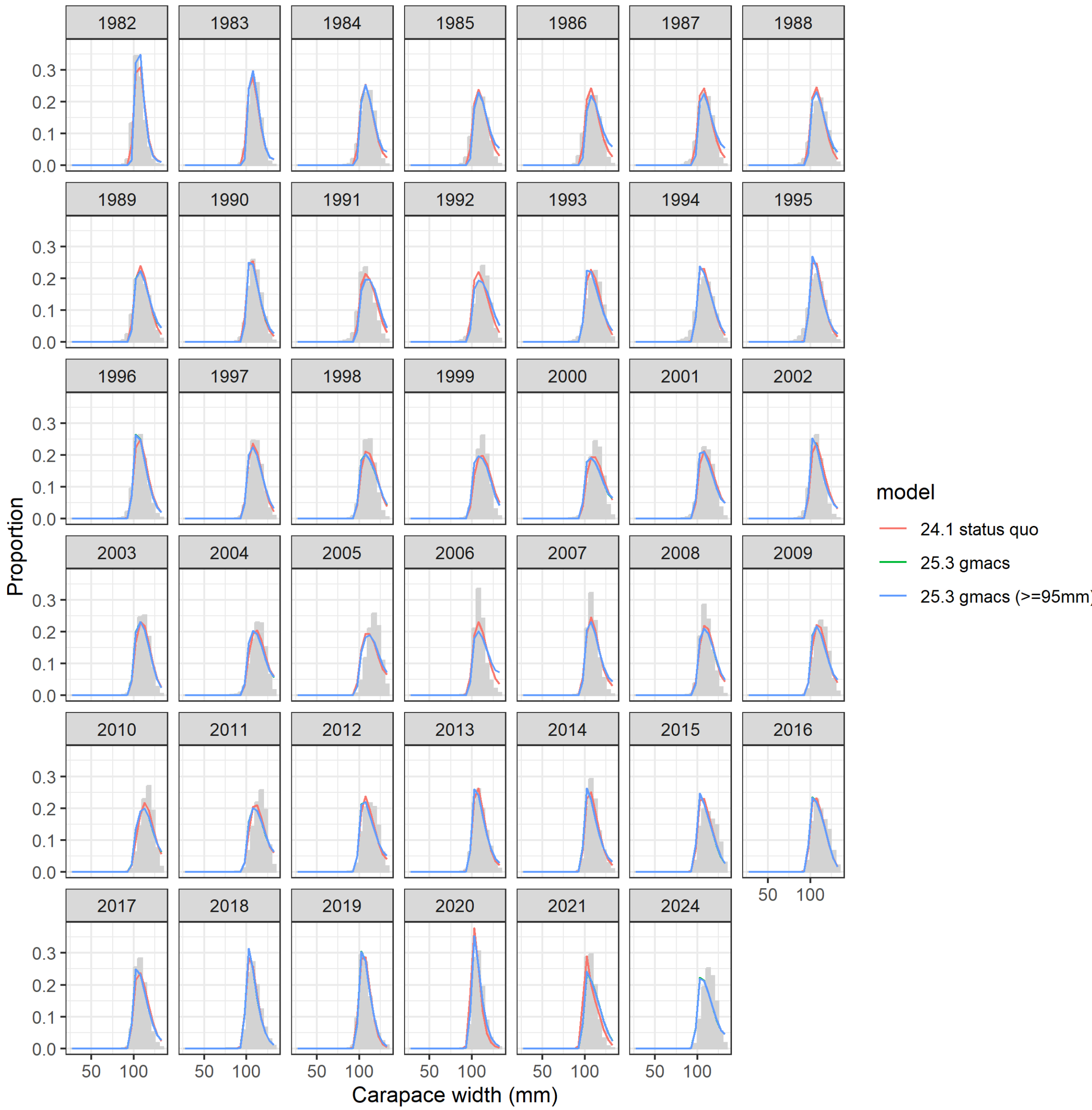


Figure 27: Model fits (lines) to the retained catch size composition data (grey bars).

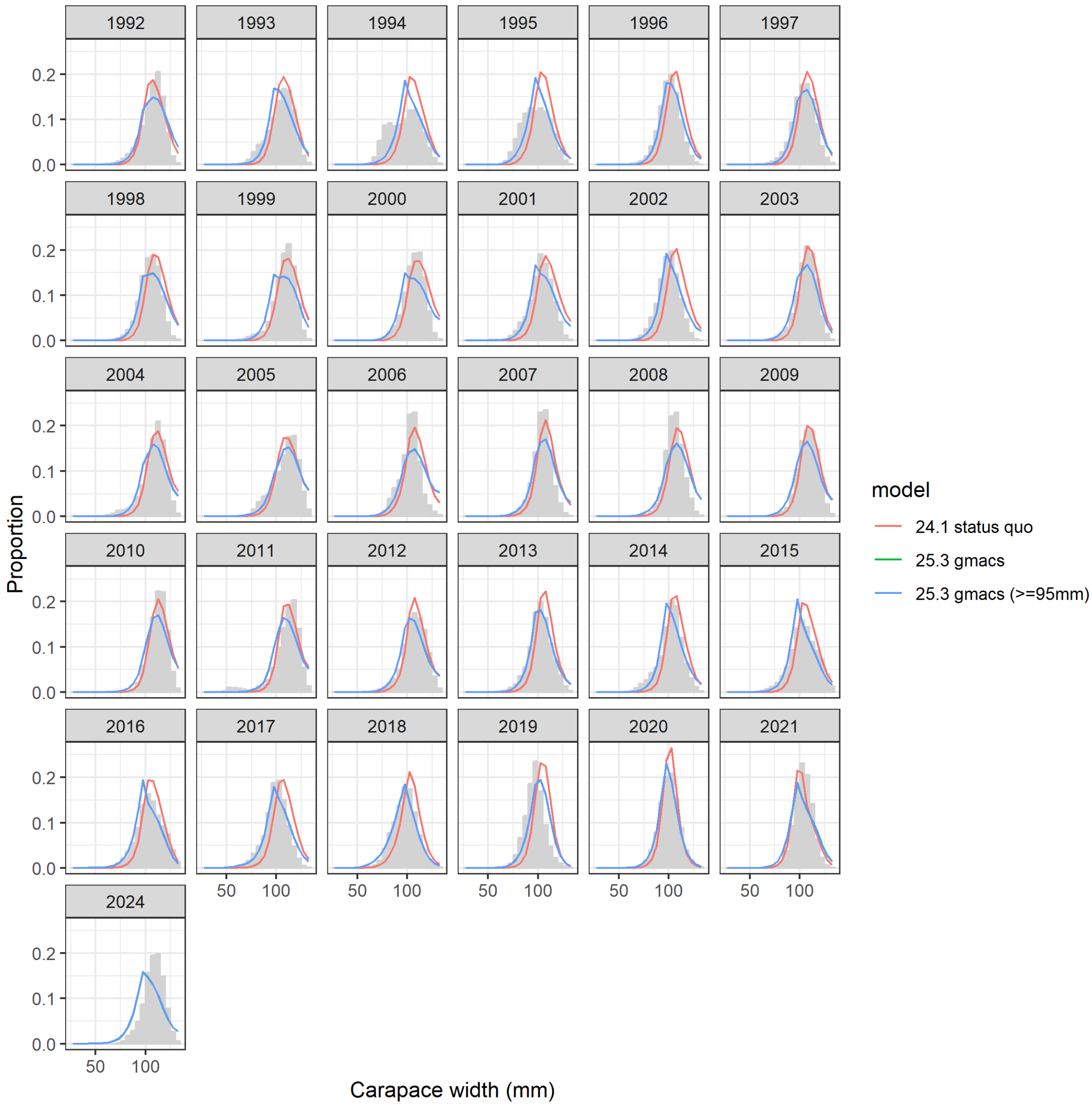


Figure 28: Model fits (lines) to the total catch size composition data (grey bars).

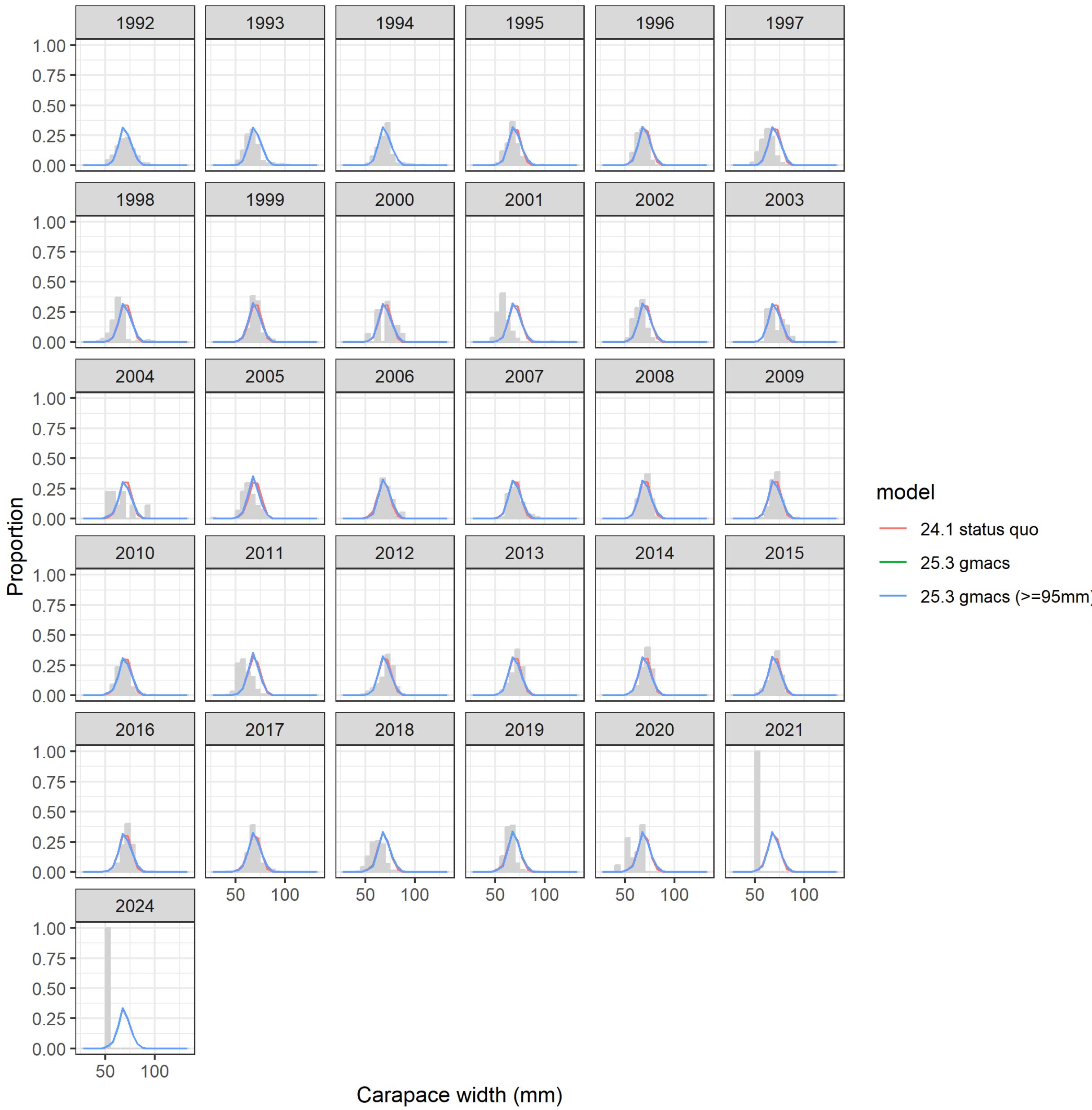


Figure 29: Model fits (lines) to the female discard size composition data (grey bars).

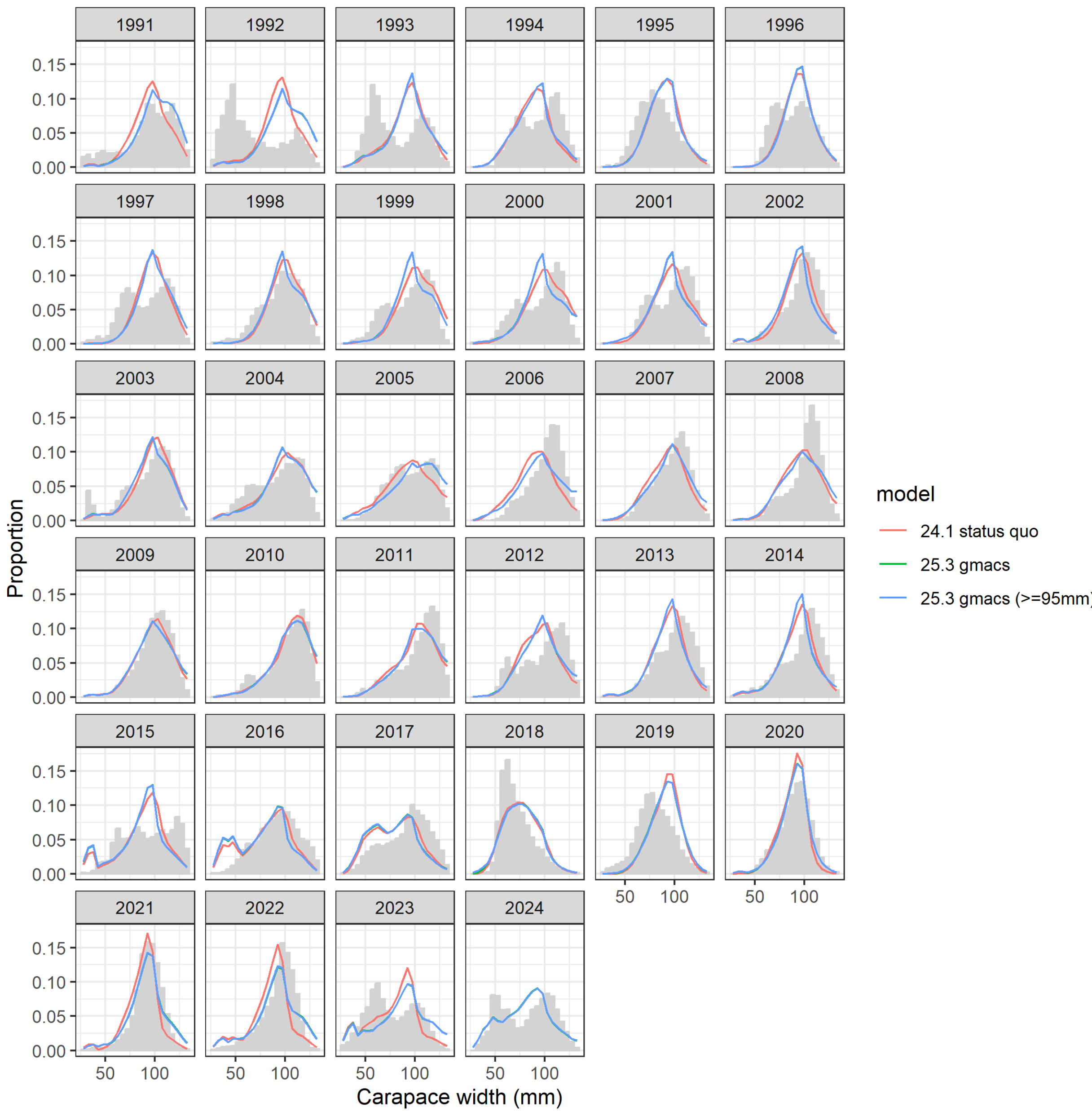


Figure 30: Model fits (lines) to the male non-directed fishery size composition data (grey bars).

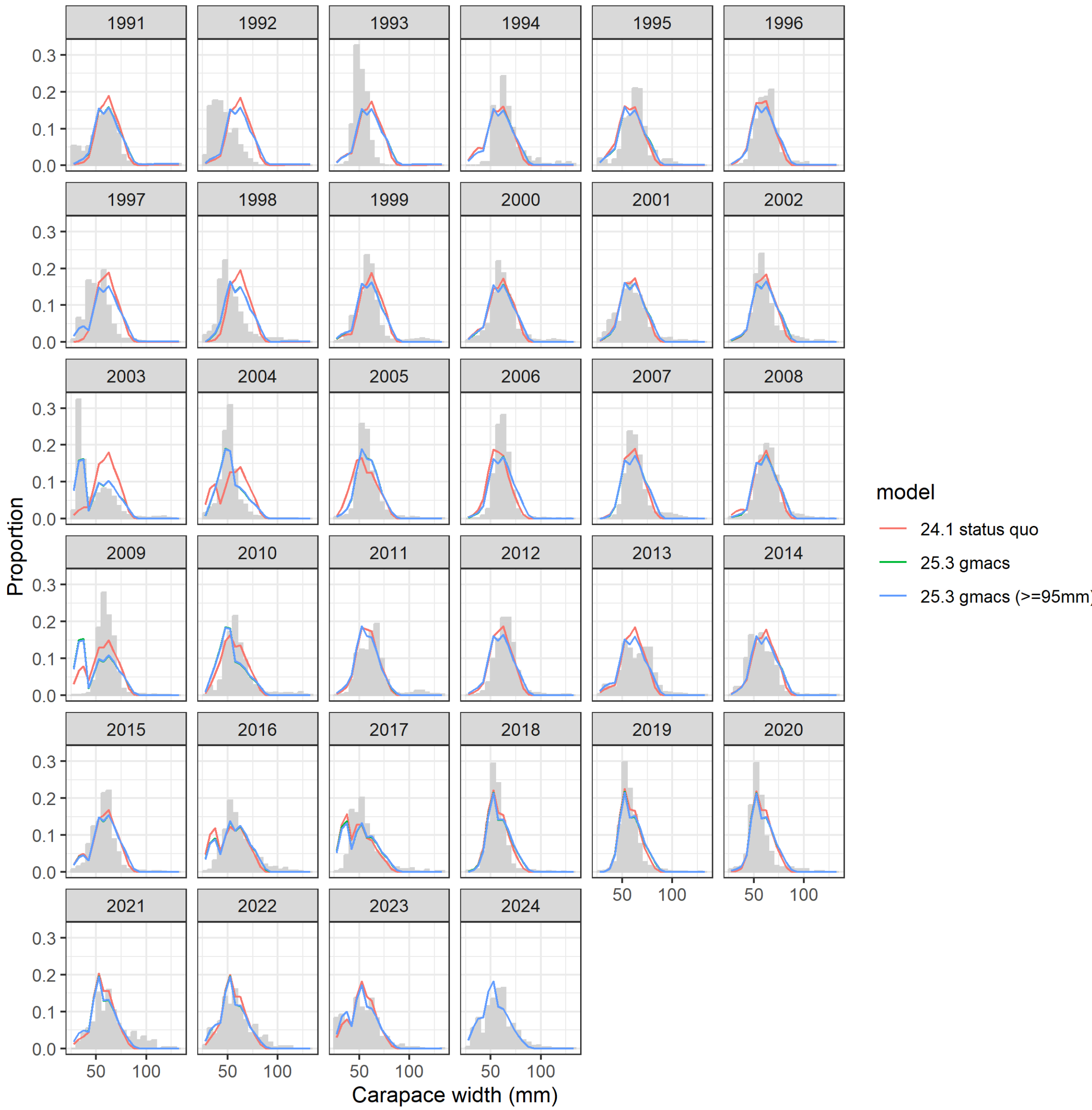


Figure 31: Model fits (lines) to the female non-directed size composition data (grey bars).

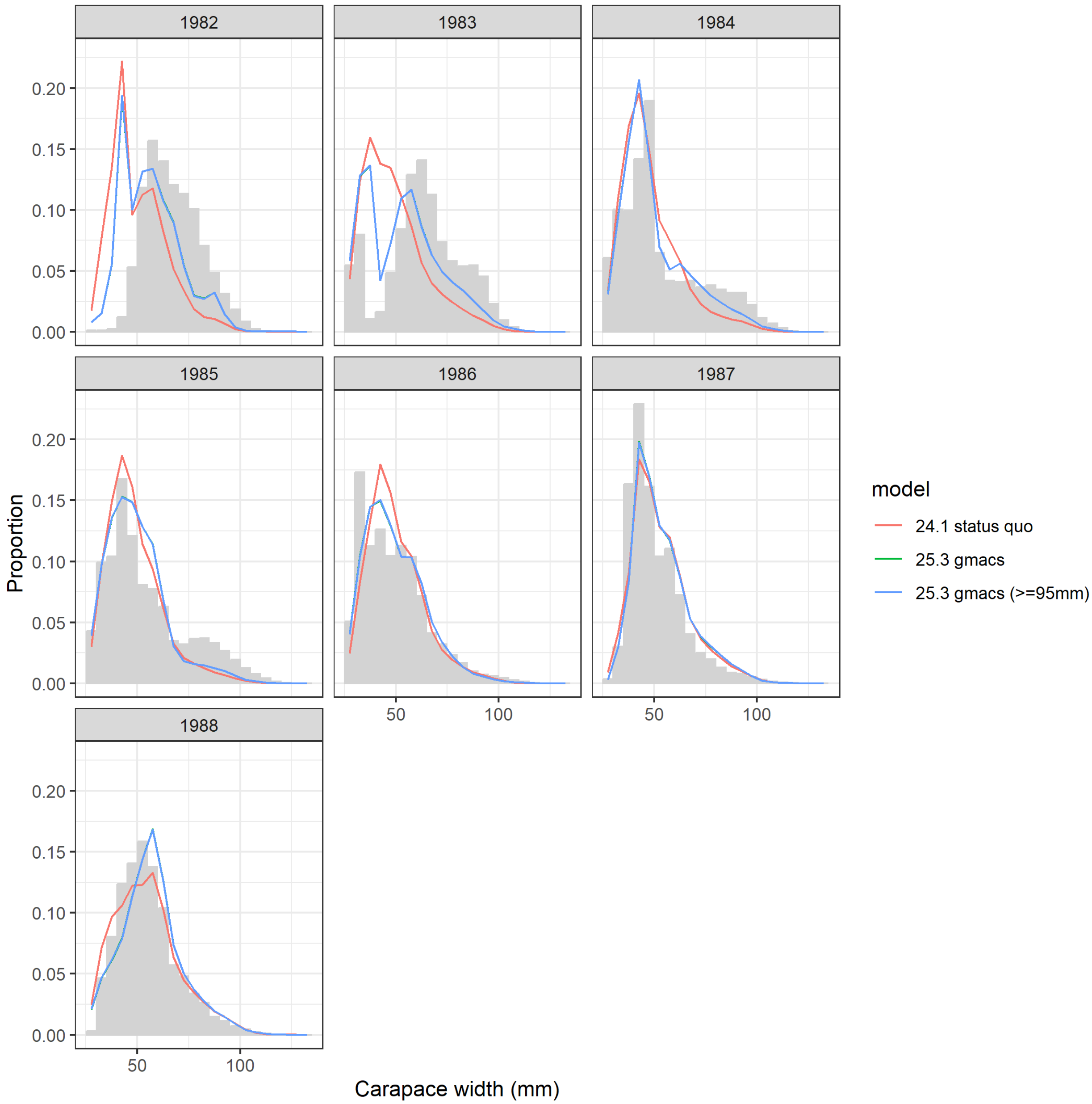


Figure 32: Model fits to immature male survey size composition data from 1982-1988.

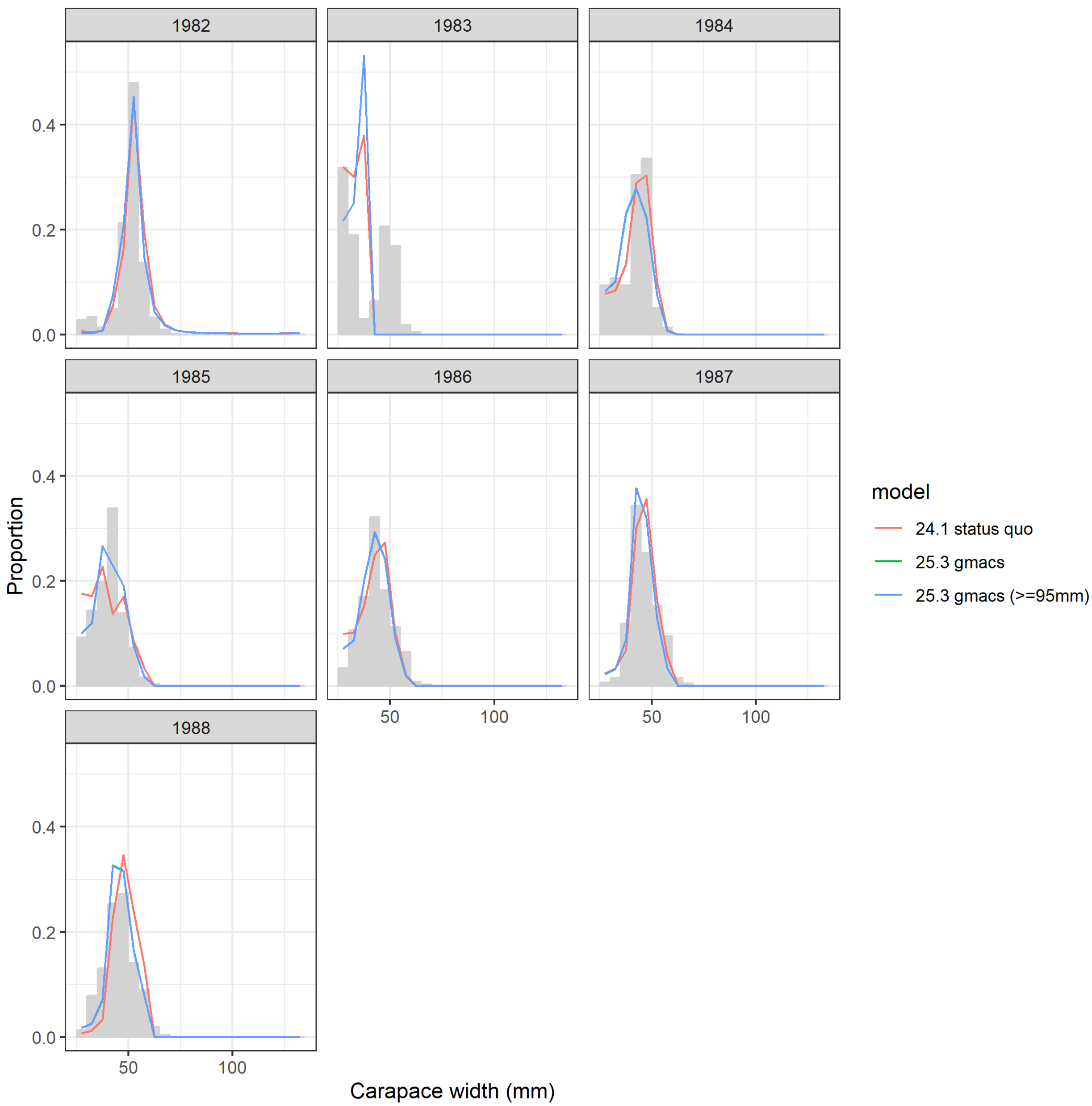


Figure 33: Model fits to immature female survey size composition data from 1982-1988.

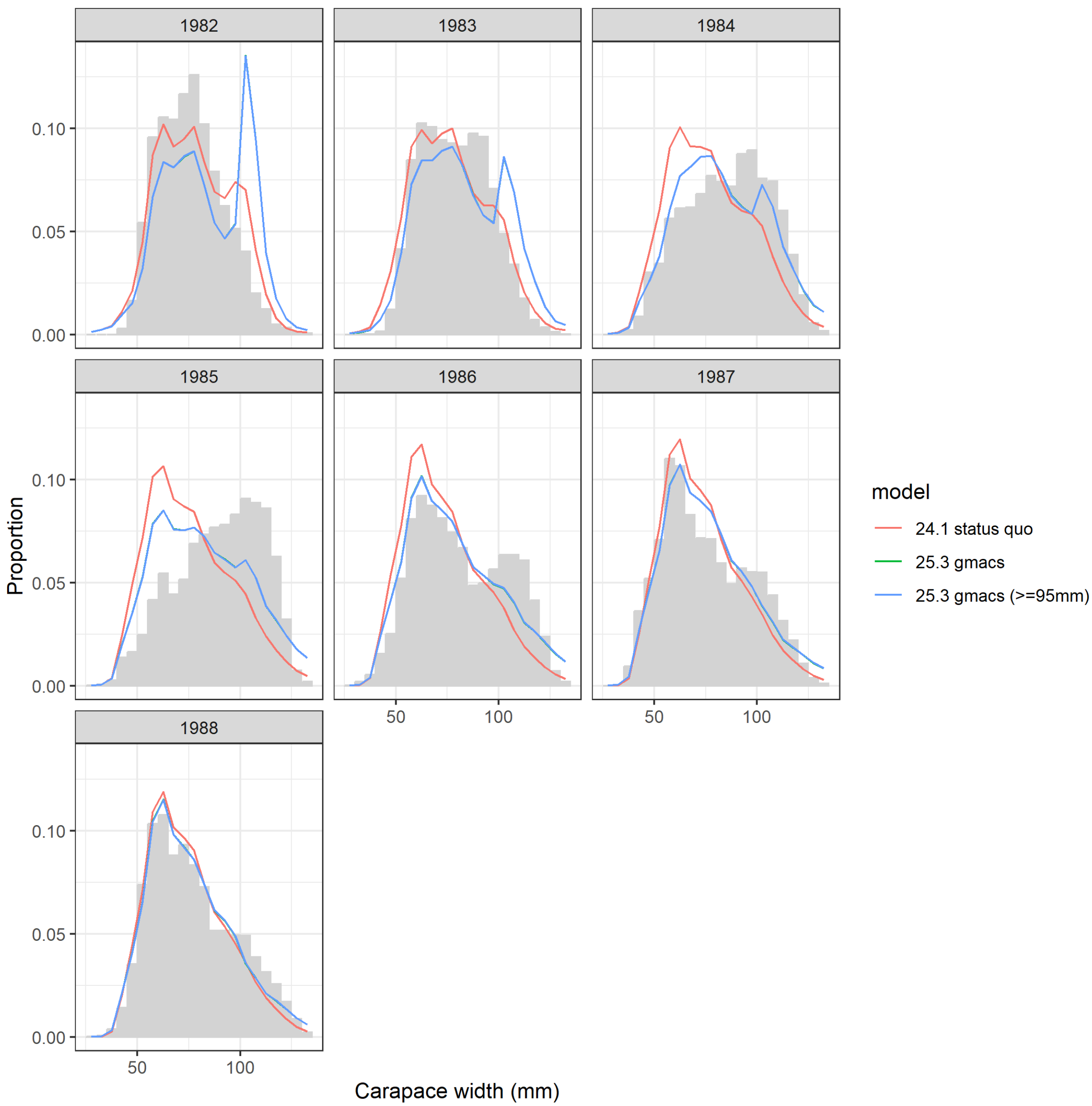


Figure 34: Model fits to mature male survey size composition data from 1982-1988.

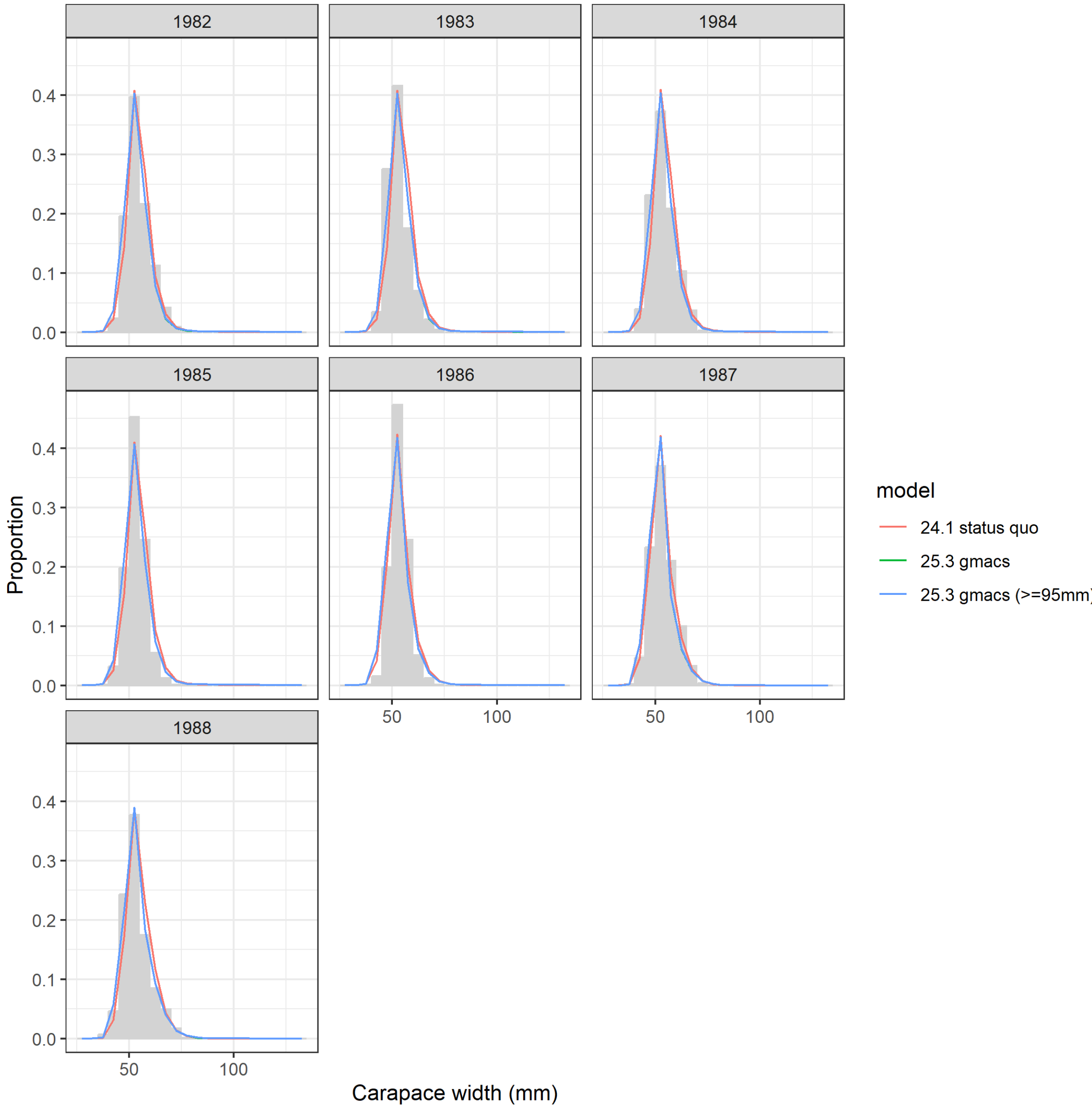


Figure 35: Model fits to mature female survey size composition data from 1982-1988.

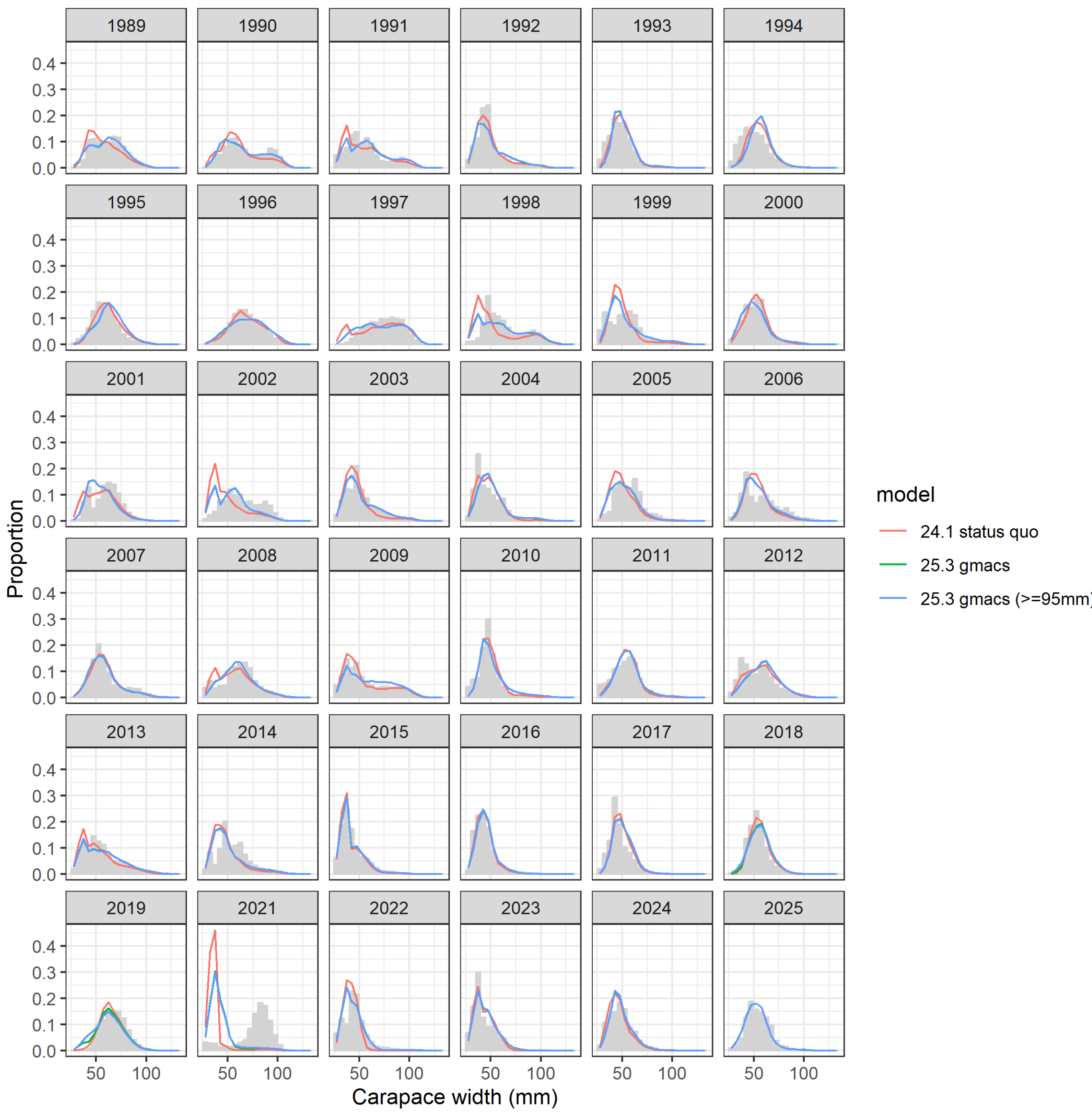


Figure 36: Model fits to immature male survey size composition data from 1989-present.

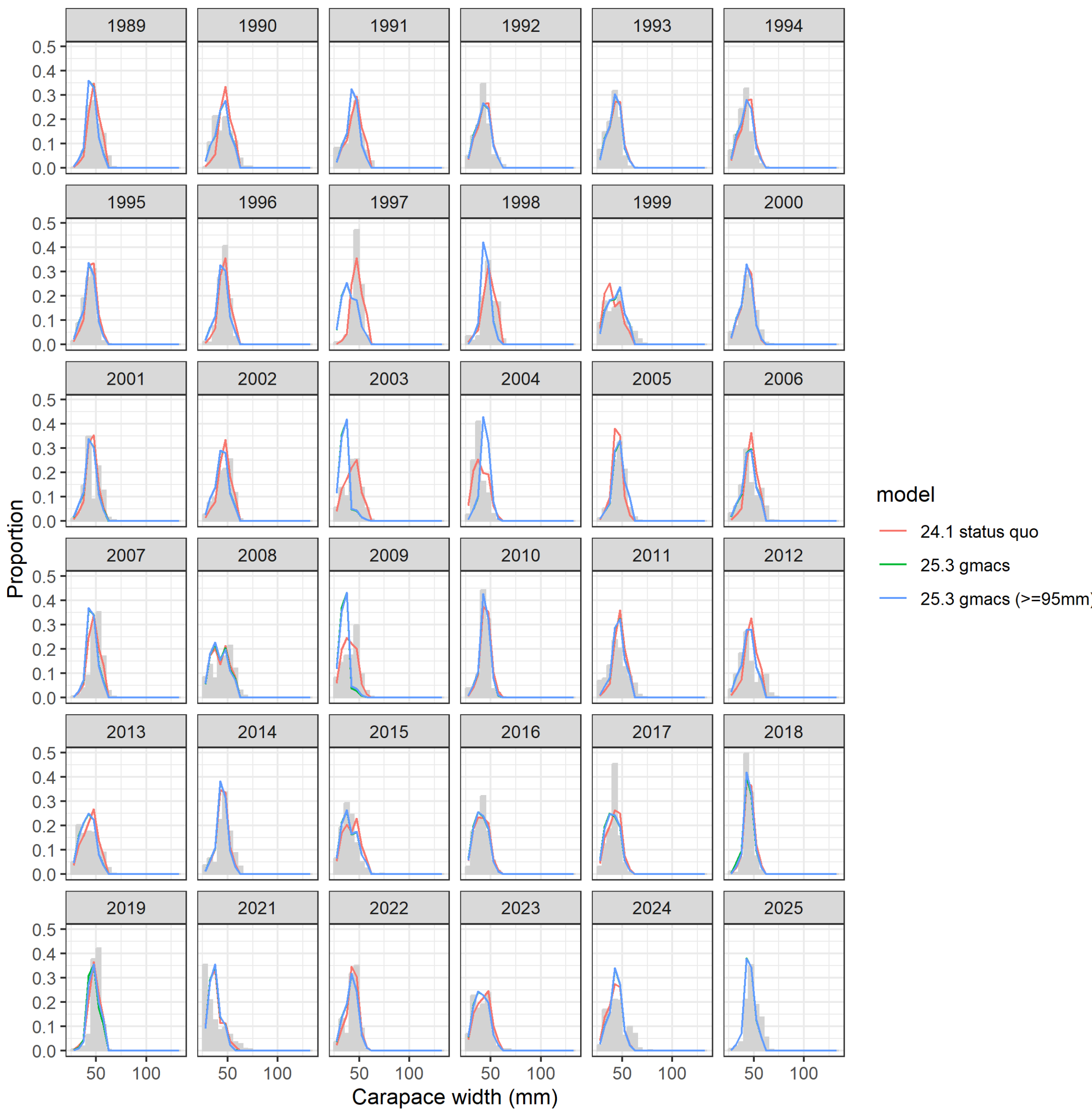


Figure 37: Model fits to immature female survey size composition data from 1989-present.

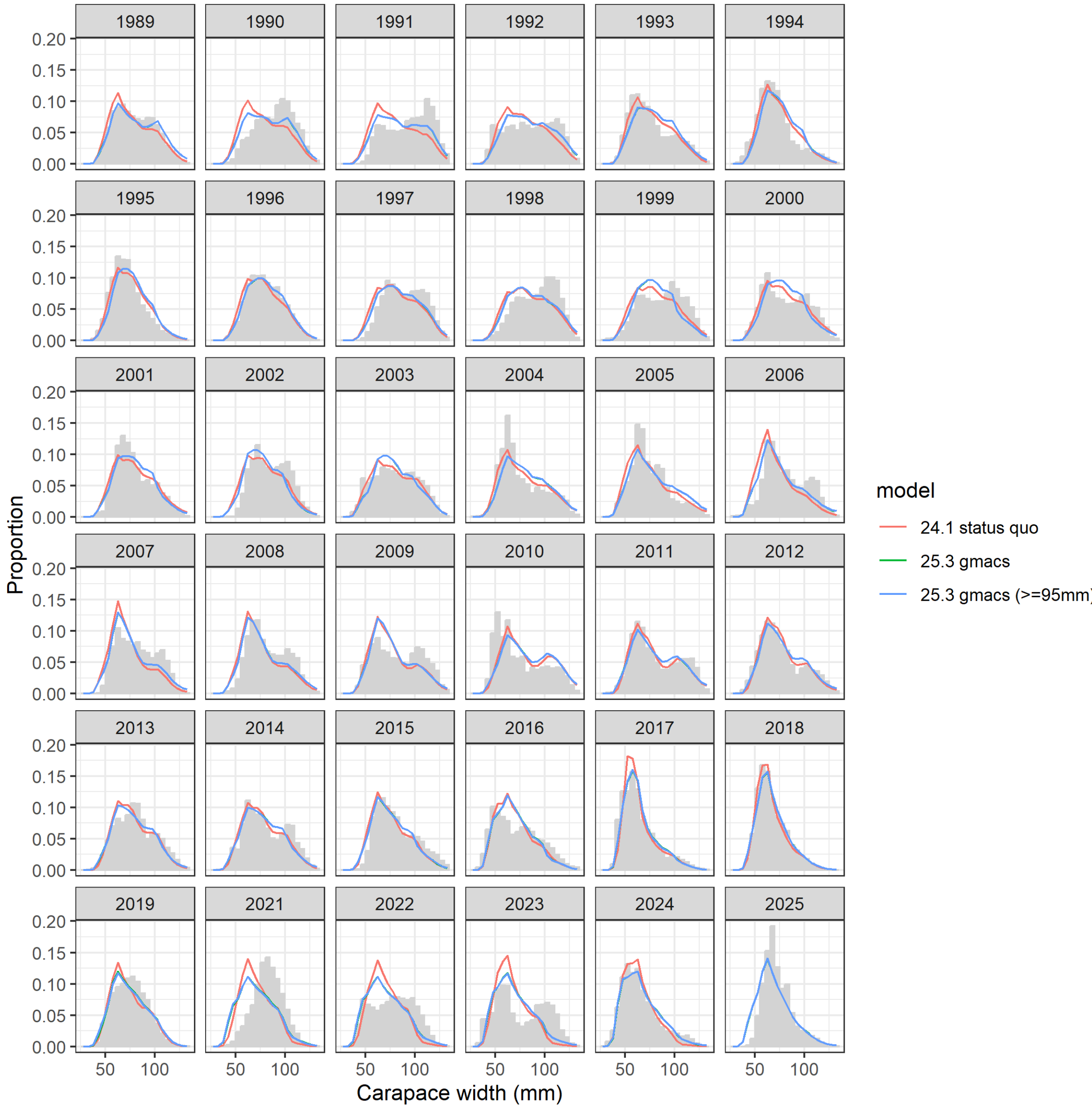


Figure 38: Model fits to mature male survey size composition data from 1989-present.

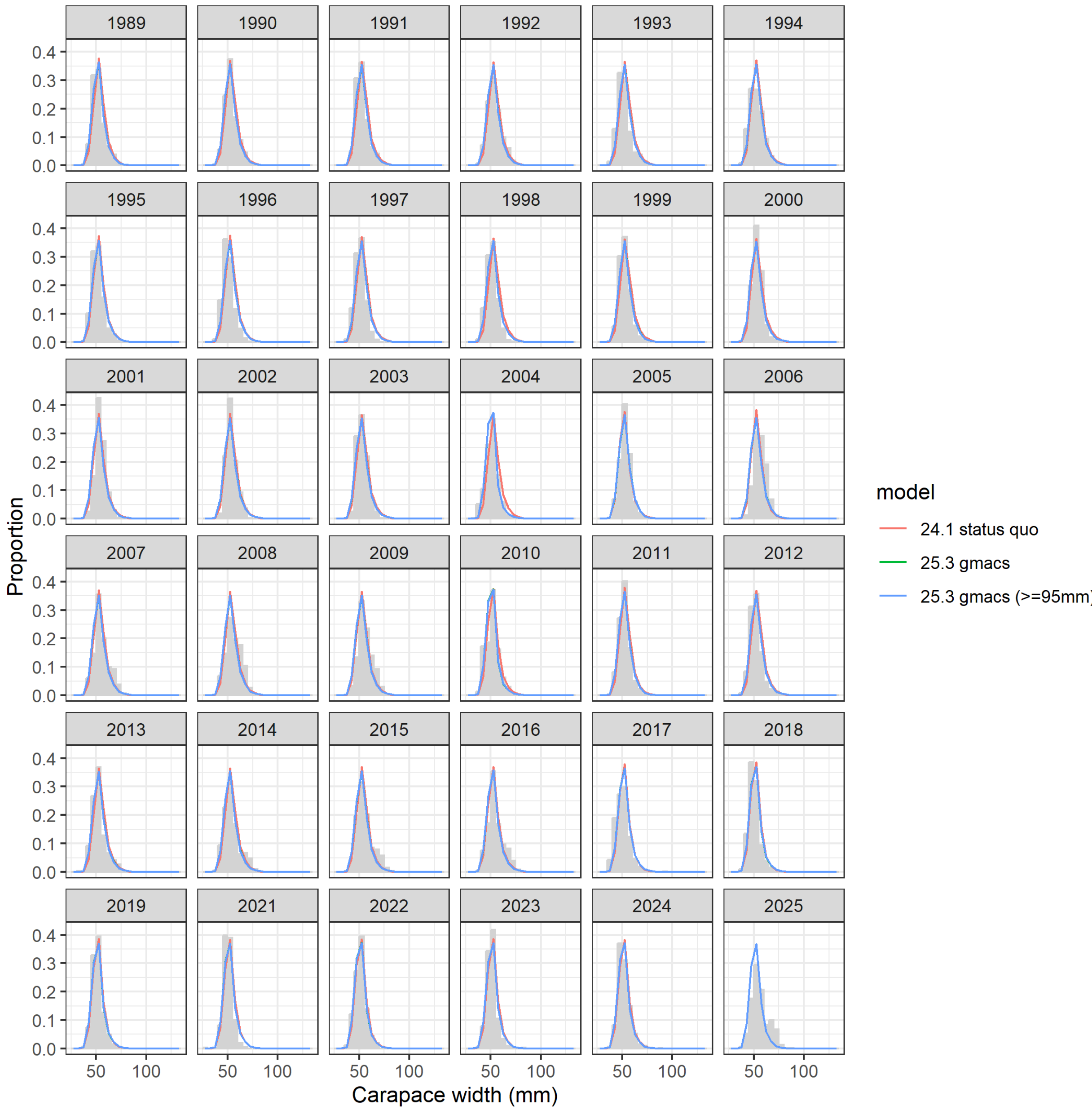


Figure 39: Model fits to mature female survey size composition data from 1989-present.

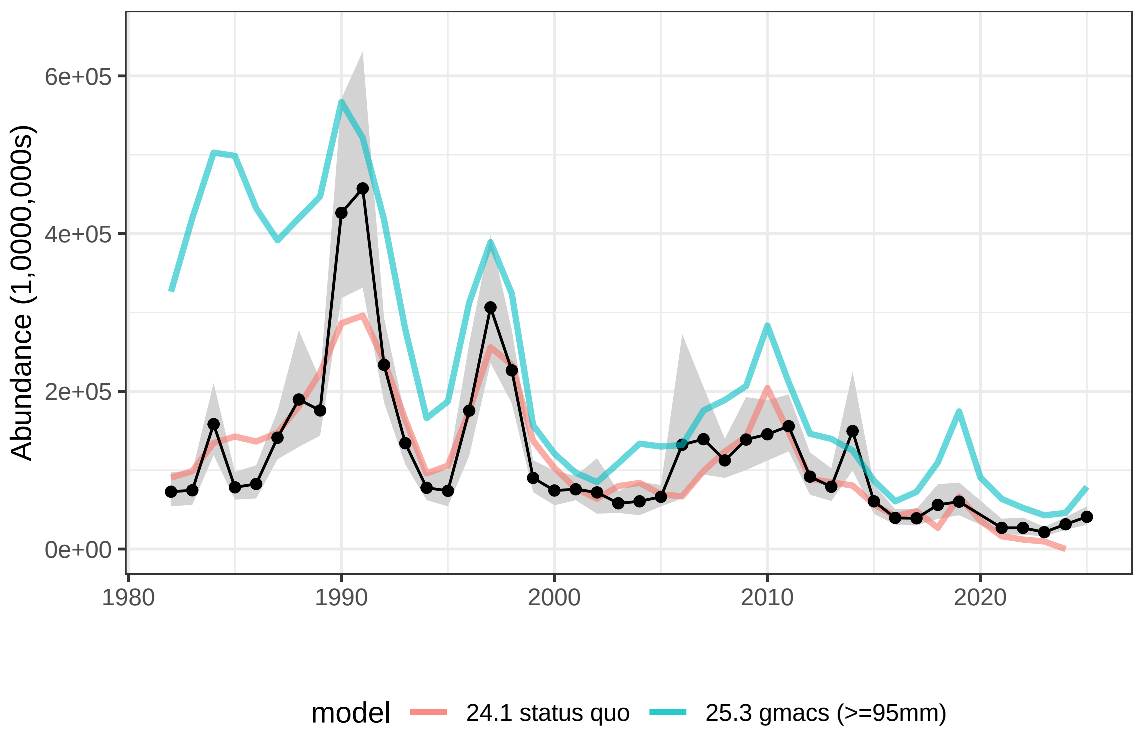


Figure 40: Estimated biomass of male crab >101mm carapace width from the survey (black line and dots with gray 95th CI) and from each model in the assessment (colored lines).

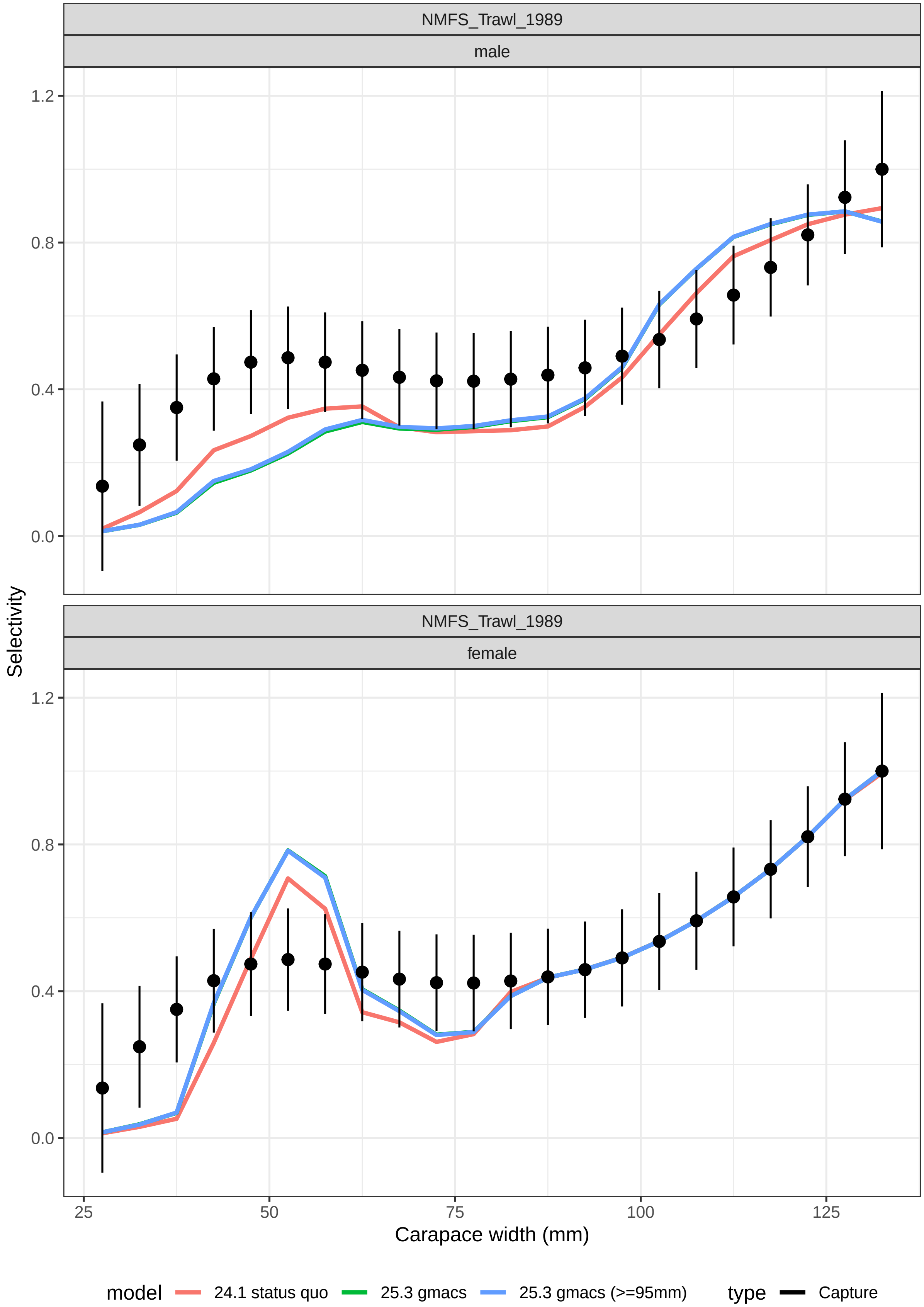


Figure 41: Estimated survey selectivity (lines) with normal priors derived from BSFRF selectivity experiment data. Points are the mean of the prior at a given size; intervals are 95th quantiles based on input CVs.

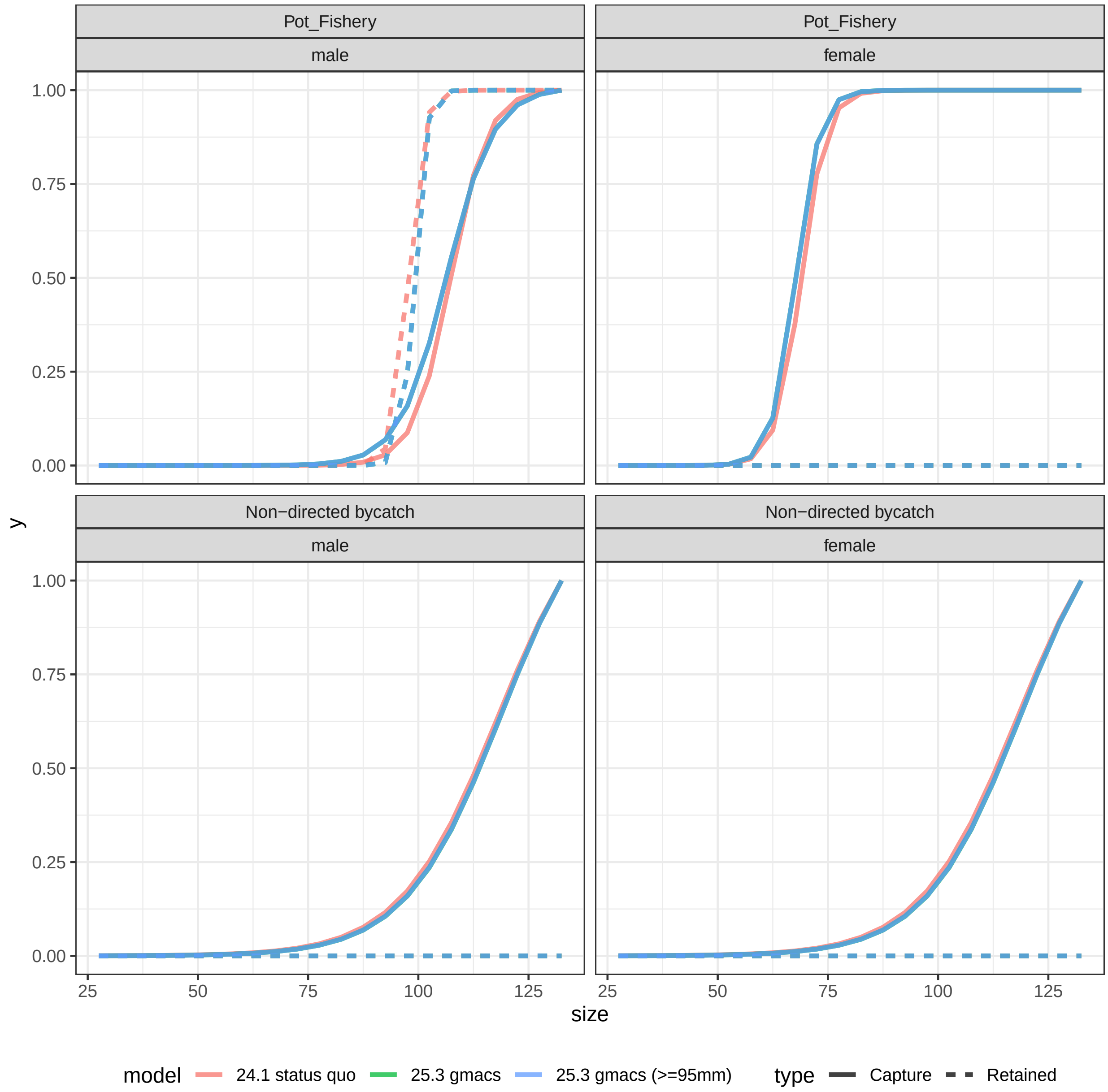


Figure 42: Estimated selectivities by fishing fleet and sex for capture and retained catches.

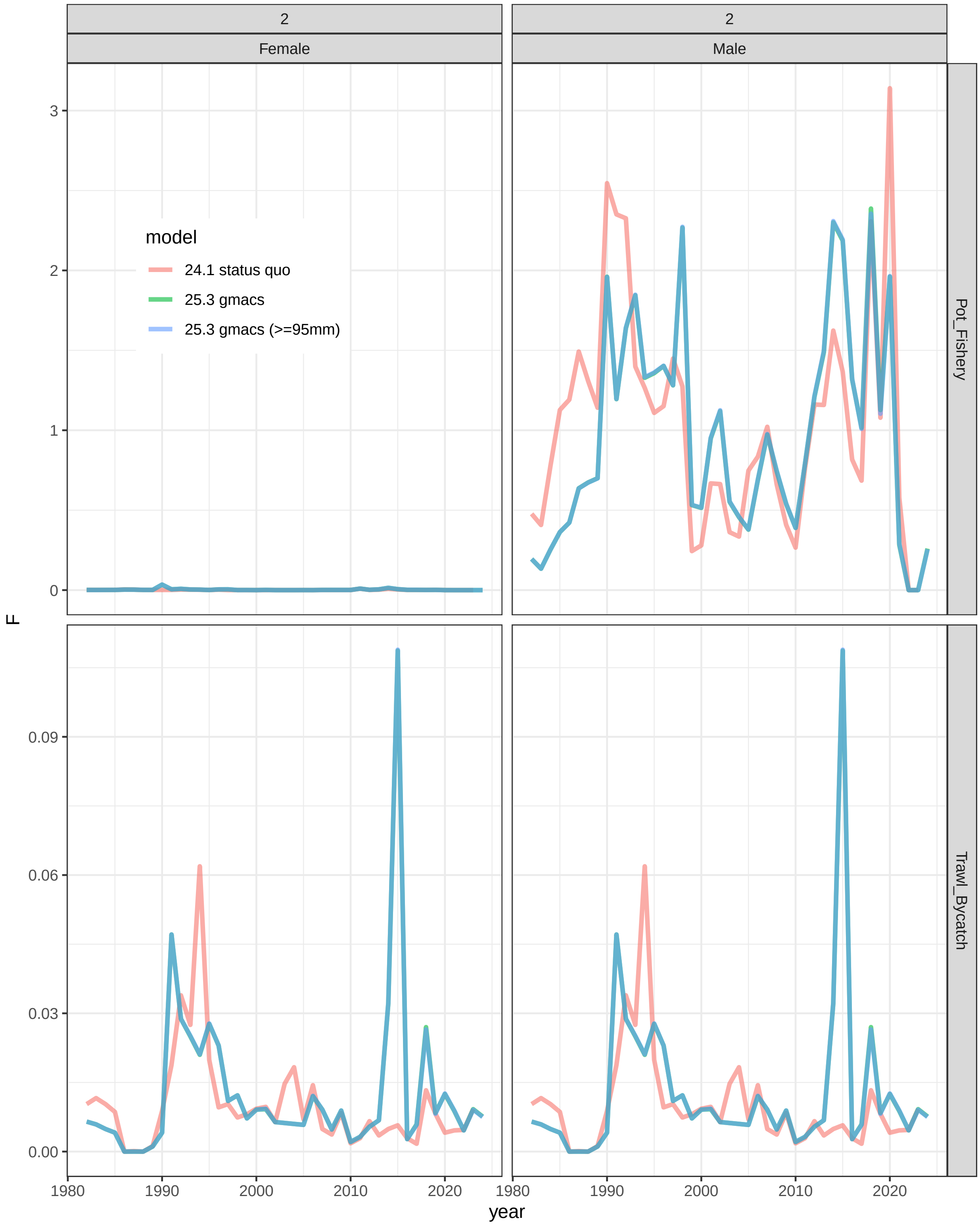


Figure 43: Estimated fishing mortalities for the directed and non-directed fisheries.

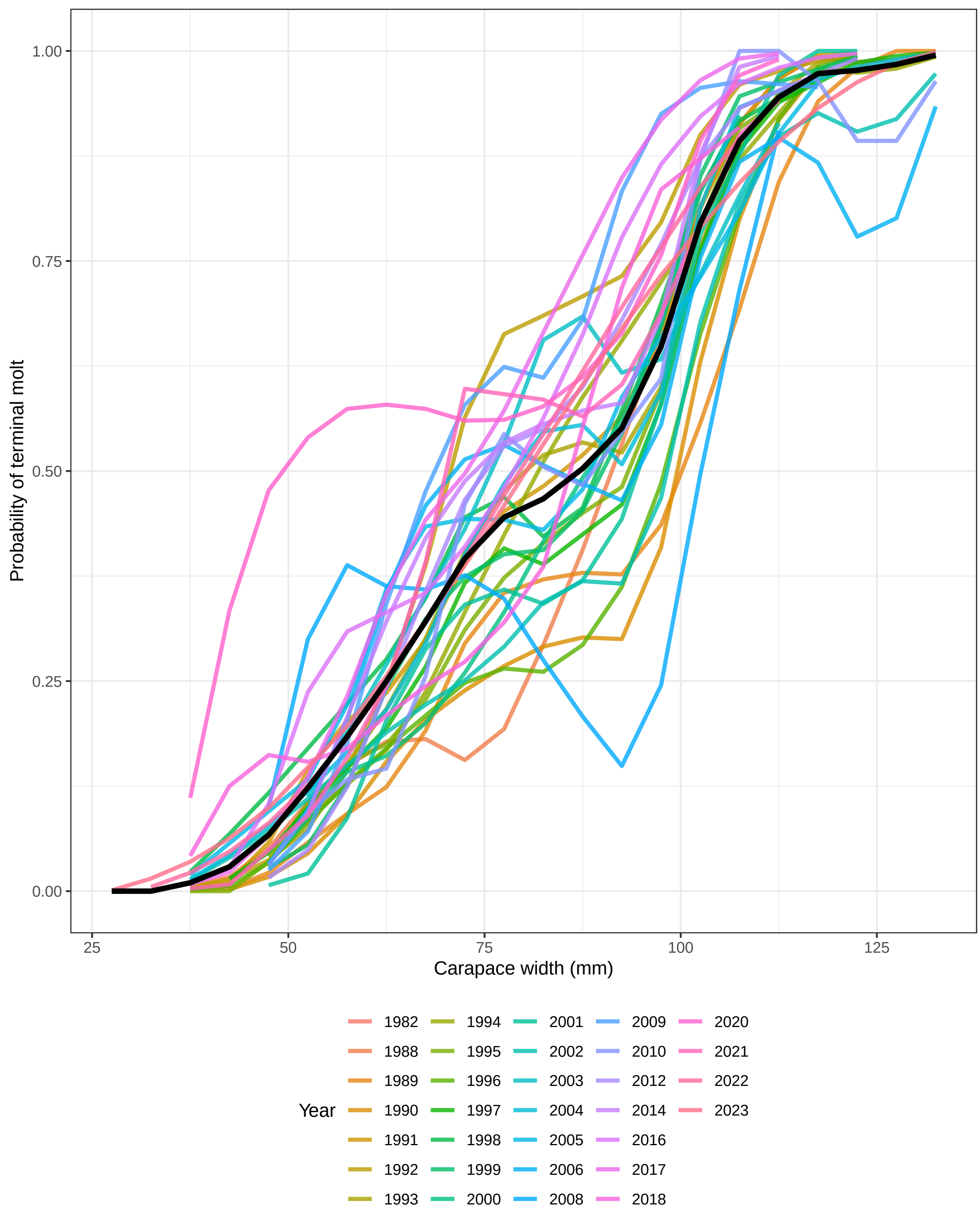


Figure 44: Estimated (black line) or specified (colored lines) probability(s) of maturing for male crab.

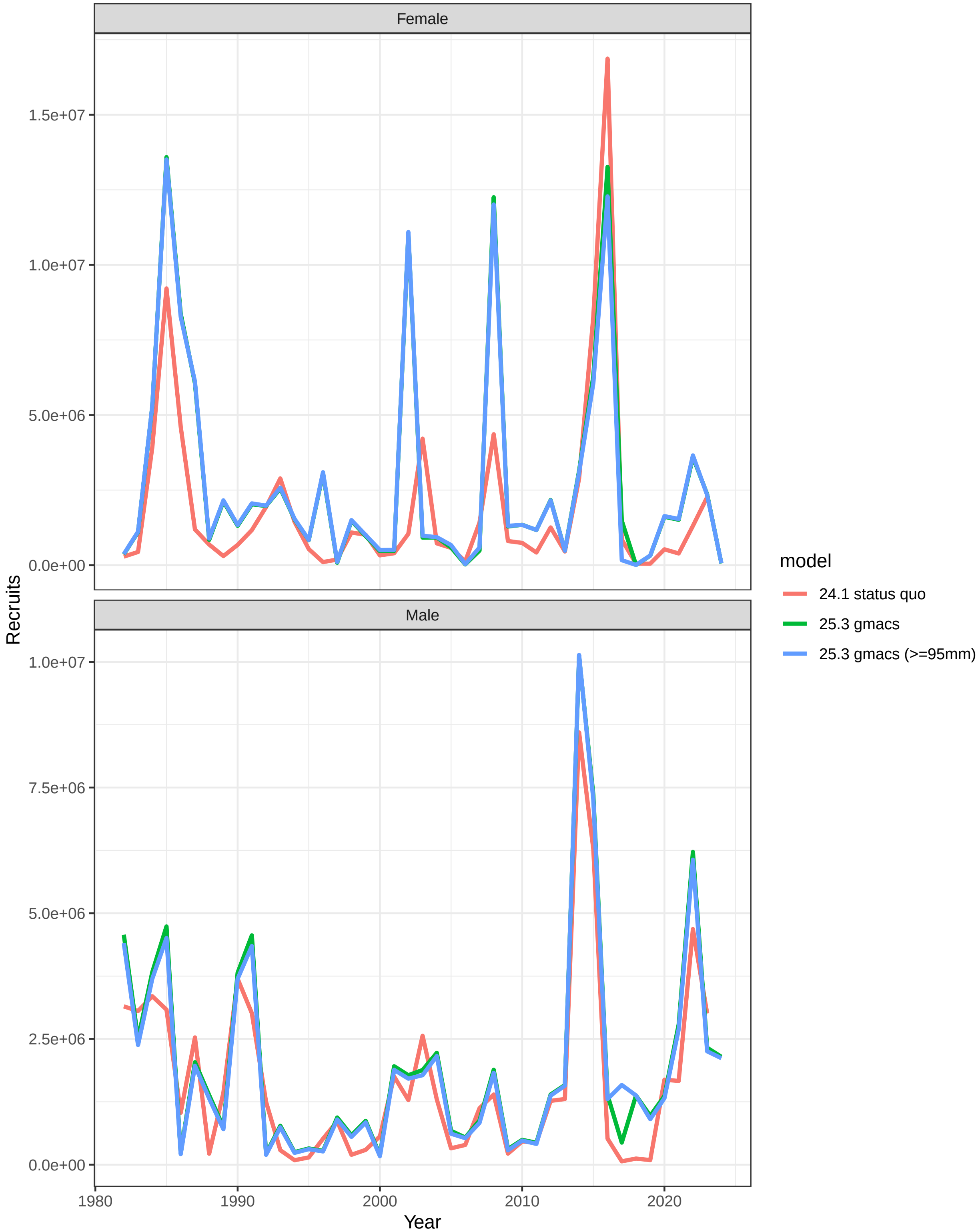


Figure 45: Estimated recruitment by sex (bottom) and proportions recruiting to length bin (top) by model.

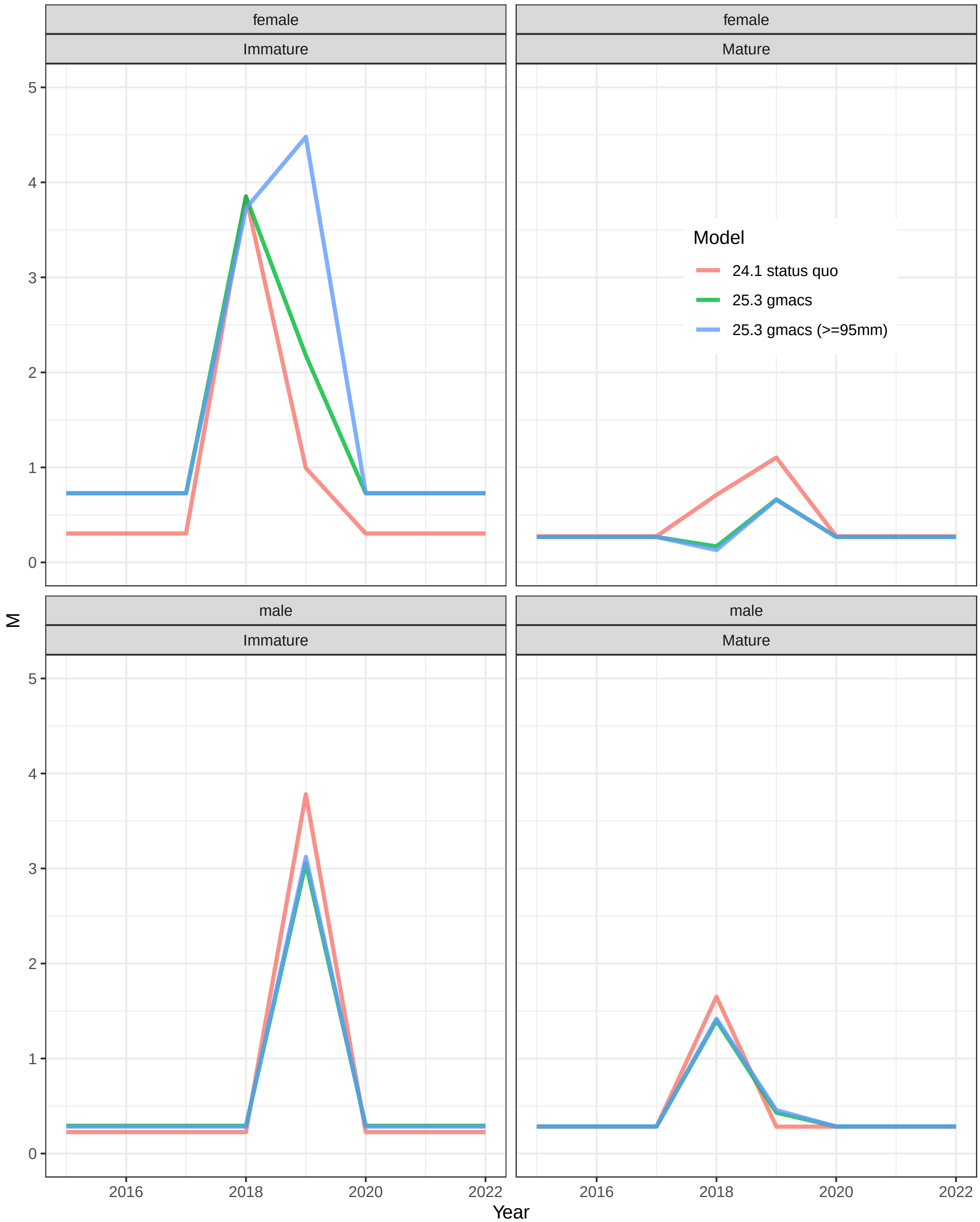


Figure 46: Estimated natural mortality by sex and maturity state. Natural mortality in all years previous to 2018 and after 2019 are equal to the estimated M in 2017.

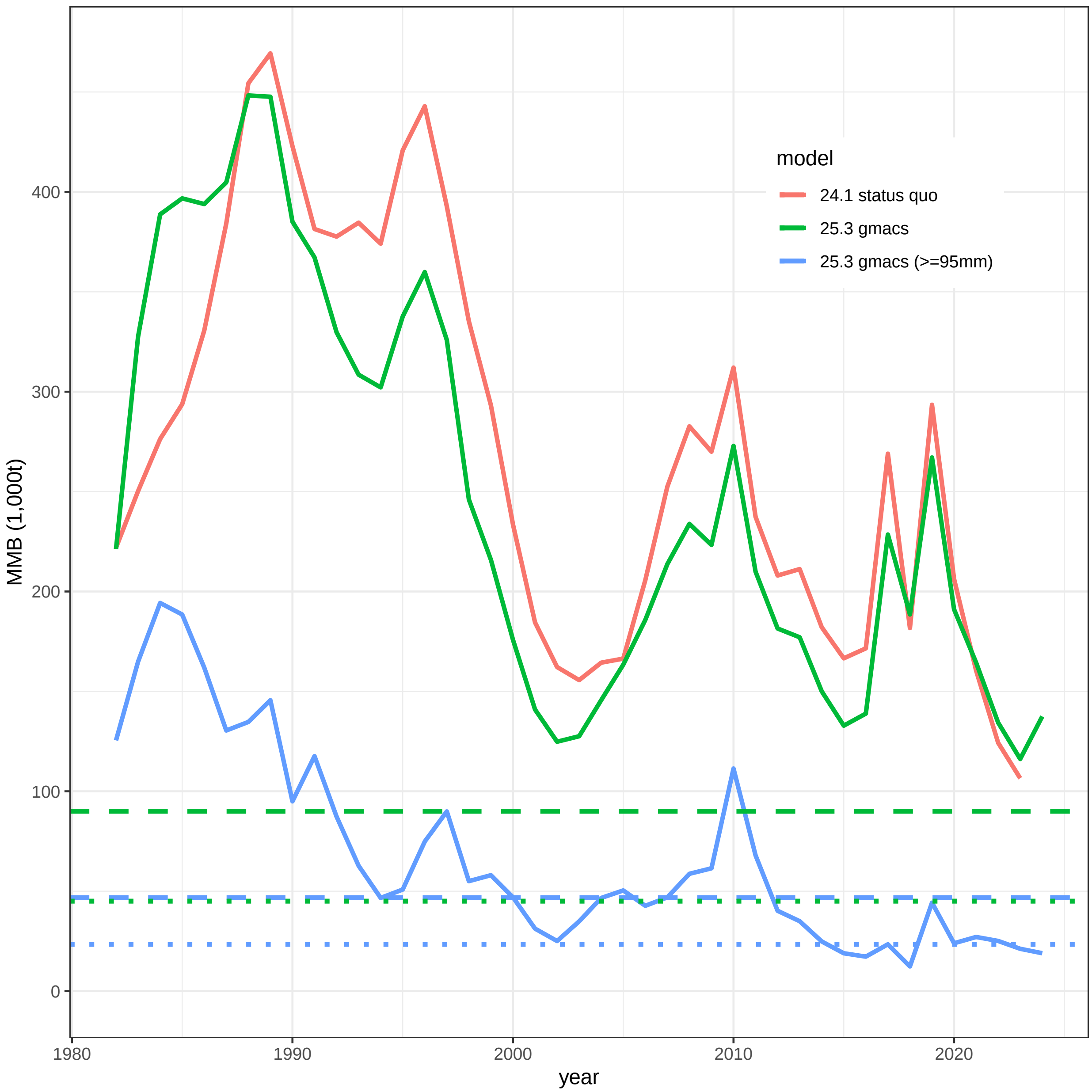


Figure 47: Model predicted mature male biomass at mating time in 1,000 tonnes. Dashed horizontal lines are half of the respective BMSY proxies based on B35% of a given management currency (i.e. MSST).

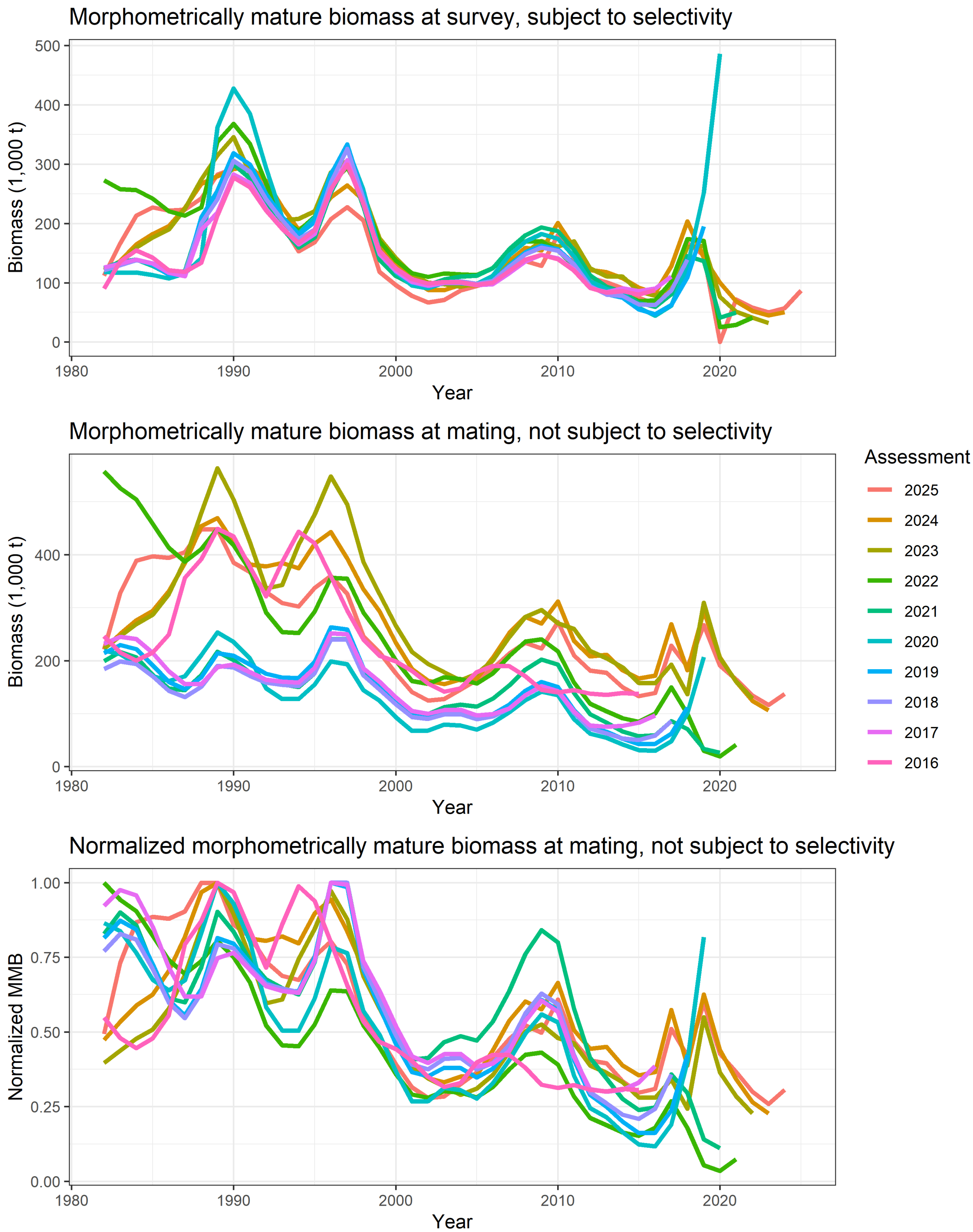


Figure 48: Estimates of morphometrically mature biomass from the last ten assessments for EBS snow crab. Top figure is estimated MMB at the time of the survey; essentially fits to the data. Middle figure is MMB at the time of mating and of the population (i.e. not subject to survey selectivity). Changes here reflect changes in the way survey selectivity and maturity have been modeled over time. Bottom figure normalizes the middle figure to compare trends more effectively.

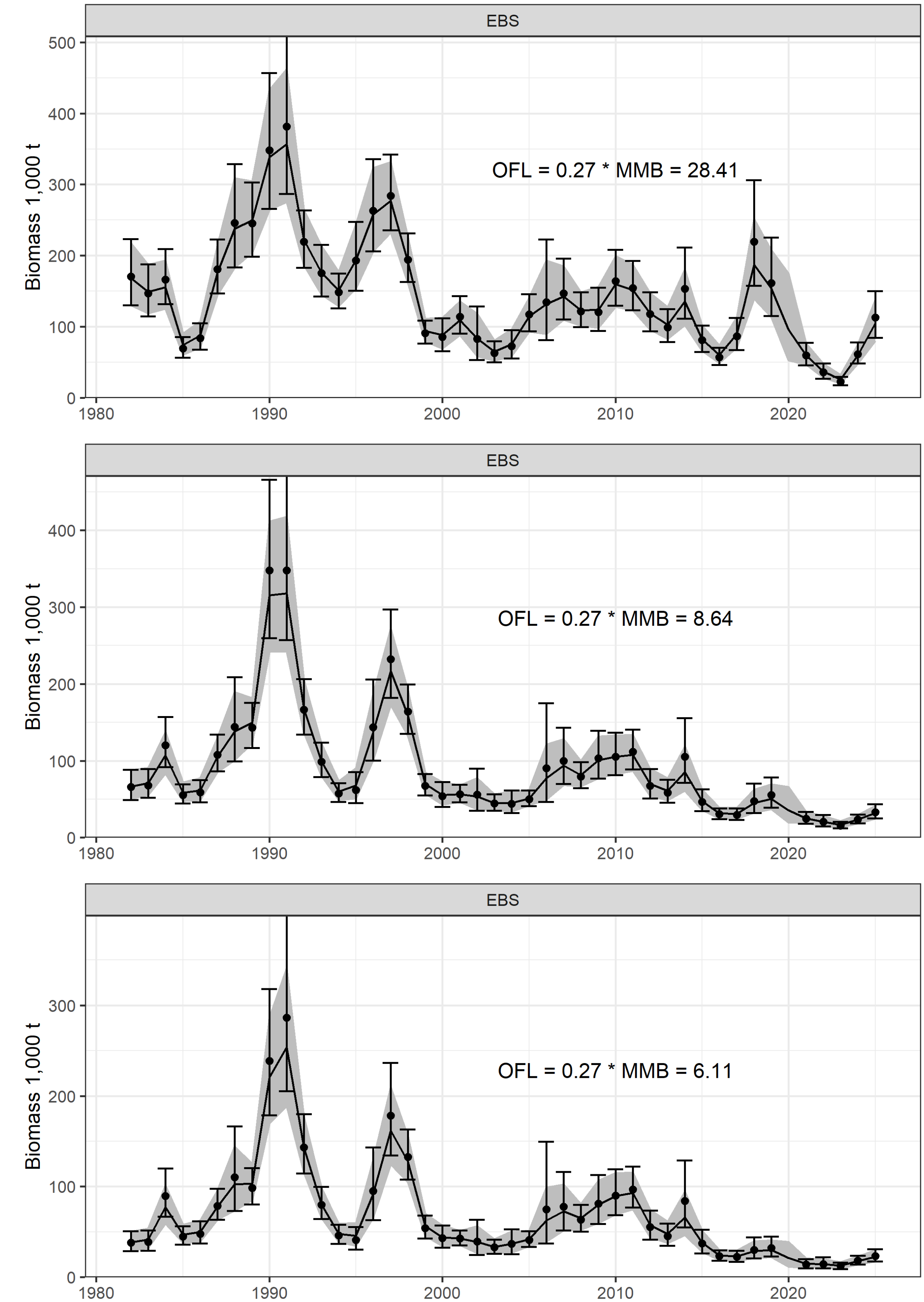


Figure 49: Rema-smoothed estimates (lines; grey bars are estimated uncertainty) for different classes of observed survey male biomass (from top–morphometric, large, preferred; dots with whiskers) with tier 4 HCR applied (text in each box).

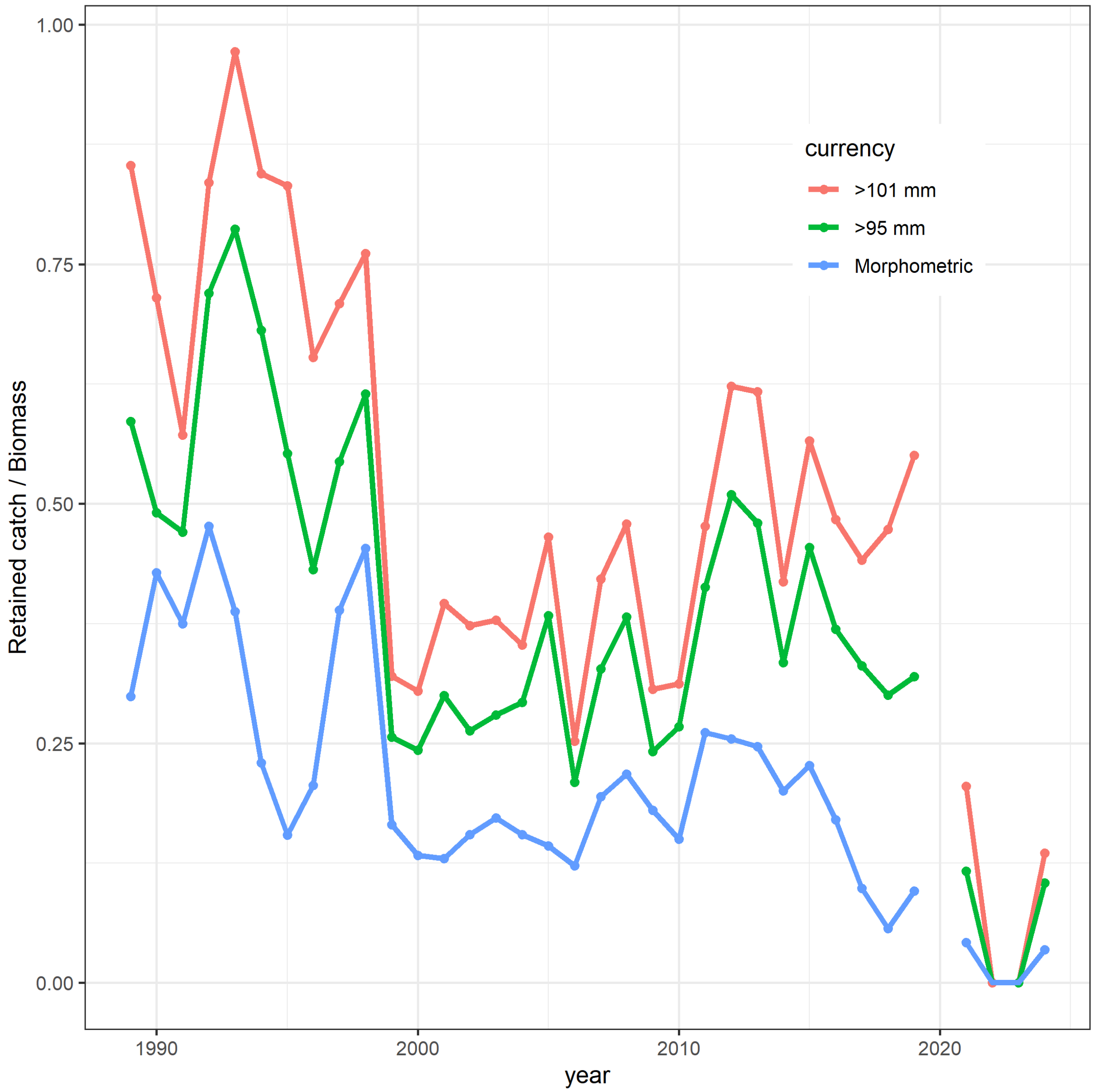


Figure 50: Retained catch biomass divided by the observed survey biomass of large males. These would be equivalent to exploitation rates if the survey biomass and retained catch were observed without error, survey selectivity for these sizes was equal to 1, and no natural mortality occurred between the survey and the fishery.

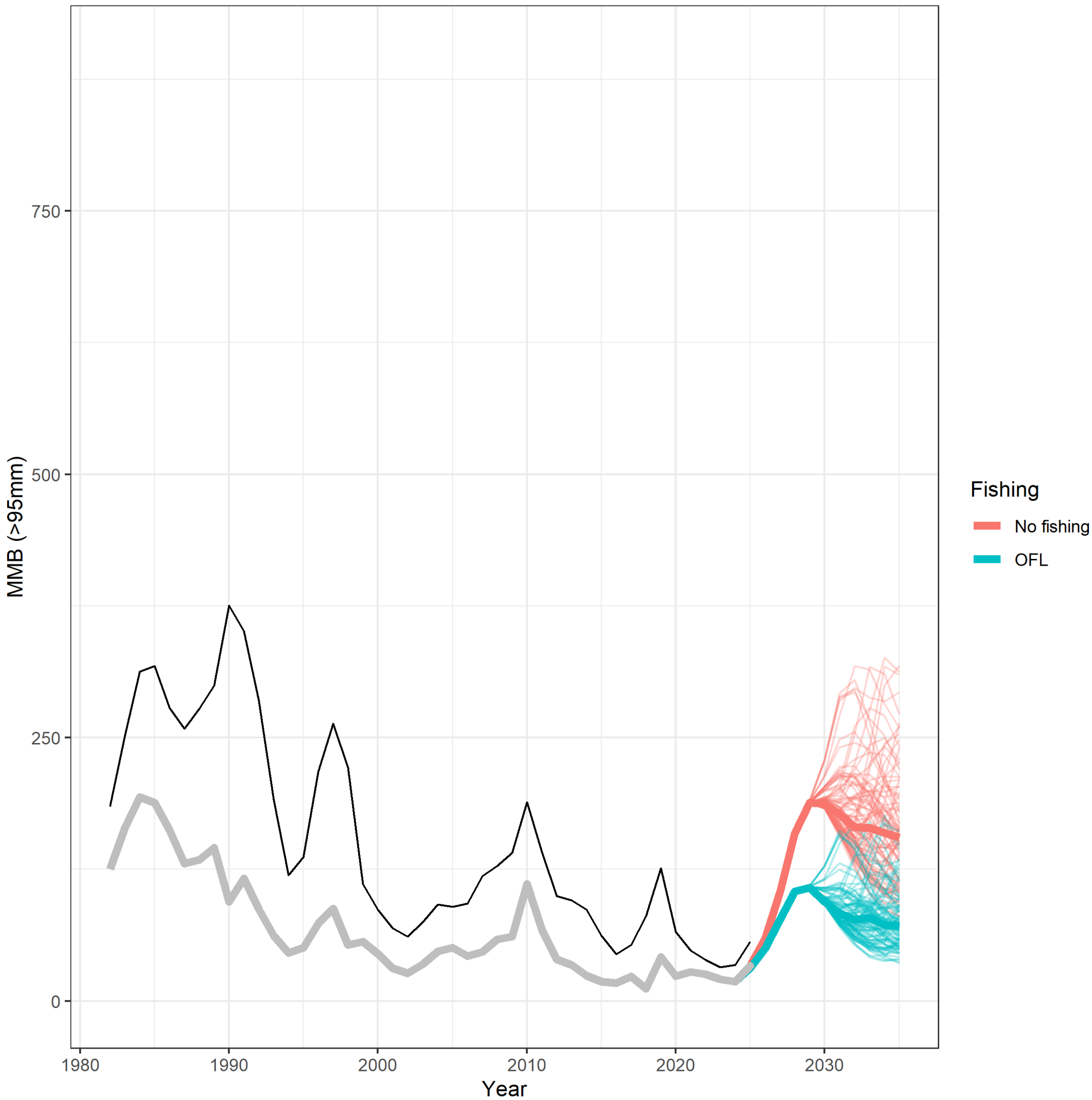


Figure 51: Model predicted large male biomass at survey (black line) and mating (grey line, which is after fishery removals). Blue and red lines are projections from the terminal year under the OFL and no fishing. These projections assume average probabilities of terminally molting and sample recruitment from 1982-2017.

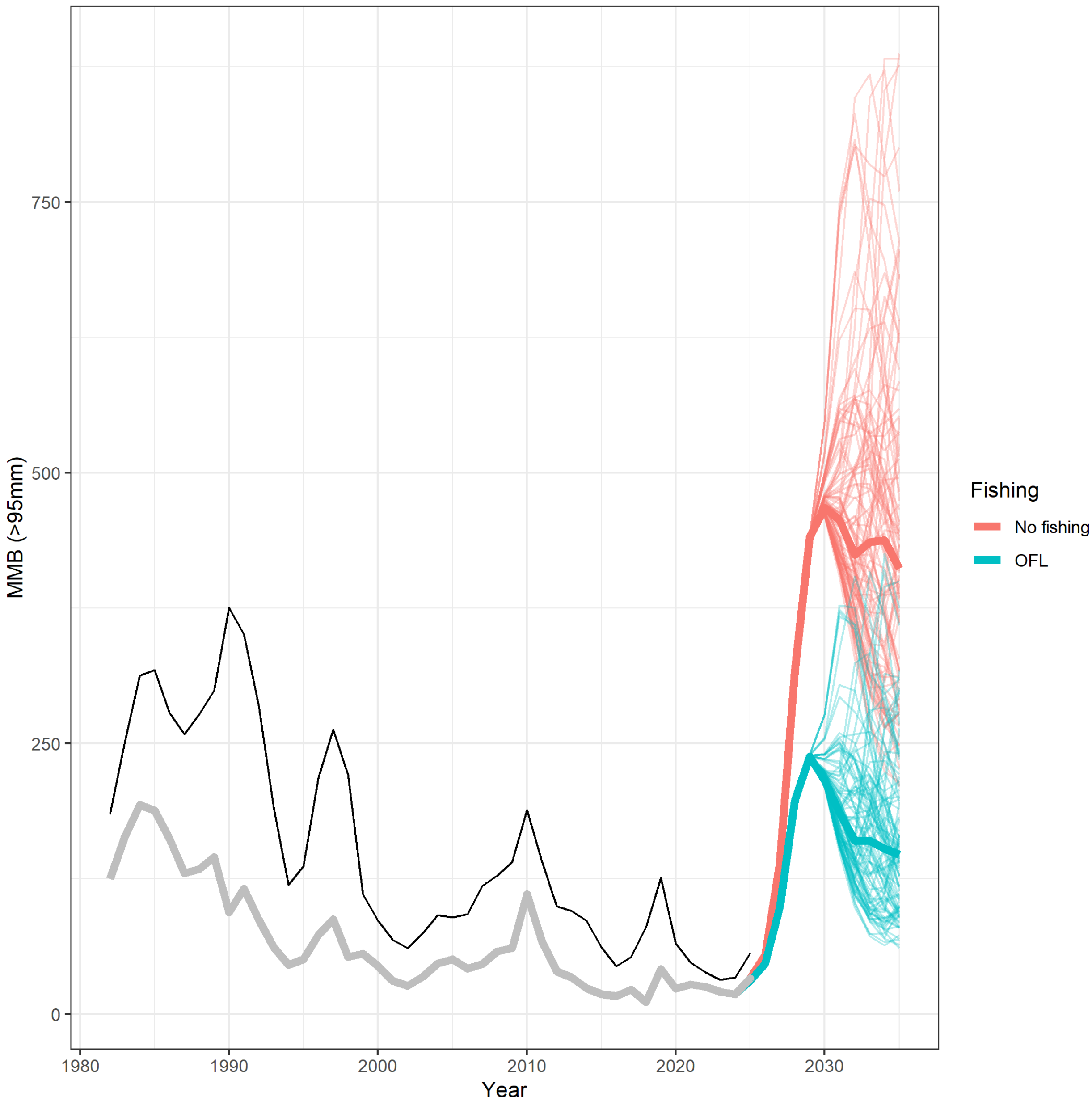
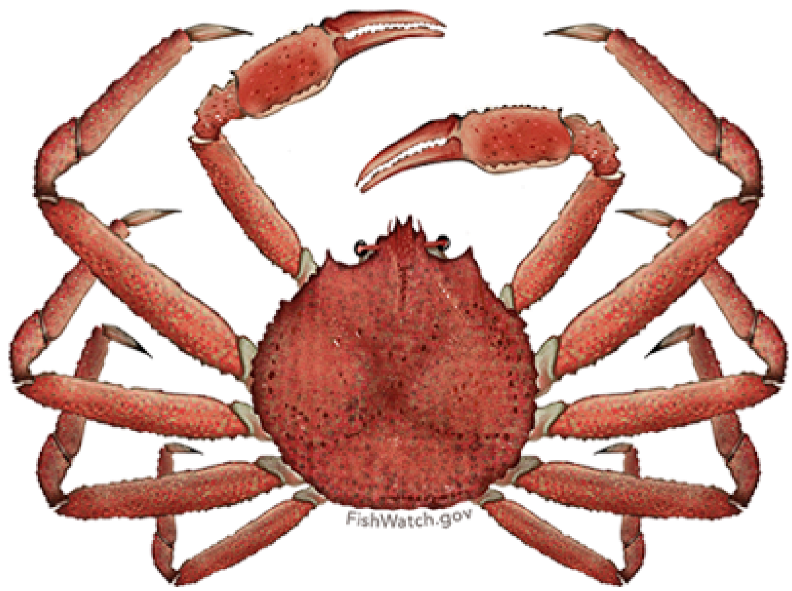


Figure 52: Model predicted large male biomass at survey (black line) and mating (grey line, which is after fishery removals). Blue and red lines are projections from the terminal year under the OFL and no fishing. These projections assume probabilities of terminally molting at size from 1991 and sample recruitment from 1982-2017.

Appendix A. Ecosystem and Socioeconomic Profile of the eastern Bering Sea snow crab stock - Update

Erin Fedewa, Kalei Shotwell, and Brian Garber-Yonts (Editors)

September 2025



With Contributions from:

ESP Data: Kerim Aydin, Matt Callahan, Louise Copeman, Ben Daly, Jean Lee, and Jens Nielsen

This report may be cited as: Fedewa, E., Shotwell, K., and Garber-Yonts, B. 2025. Appendix A. Ecosystem and Socioeconomic Profile of the eastern Bering Sea snow crab stock - Update. *In*: Szuwalski 2025. An Assessment for eastern Bering Sea snow crab. North Pacific Fishery Management Council, Anchorage, AK. Available from https://www.npfmc.org/about-the-council/plan-teams/bsai-crab-planning-team/.

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Executive Summary

The Ecosystem and Socioeconomic Profile (ESP), is a standardized framework for compiling and evaluating relevant stock-specific ecosystem and socioeconomic indicators and communicating linkages and potential drivers of the stock within the stock assessment process (Shotwell et al., 2023). This update report provides supporting information for the eastern Bering Sea (EBS) snow crab ESP report card (Fedewa et al., 2025), and details the methodology and results from statistical analyses used to monitor current year status and trends of ecosystem and socioeconomic indicators. The EBS snow crab stock was evaluated at the intermediate indicator analysis stage using the Bayesian Adaptive Sampling (BAS) importance method. Highlights of the indicator assessment are summarized below as considerations that can be used for evaluating concerns in the main stock assessment or other management decisions.

Acceptable Biological Catch (ABC) Considerations:

The following are summary results from the indicator analysis that can inform ABC decisions:

Predictive Indicators:

- There were no ecosystem indicators that quantitatively predicted EBS snow crab recruitment

Contextual Indicators:

- Mean bottom water temperature in the EBS increased by 0.5°C and winter/spring sea ice extent declined by 18% from 2024 to 2025. Despite warm conditions, juvenile snow crab occupying temperatures < 1°C indicate that thermal thresholds were not likely exceeded in 2025 and cold-water habitat was available.
- Juvenile snow crab energetic condition fell below laboratory-derived starvation thresholds during the population collapse, although a rebound in energetic condition post-collapse (2021-2025) indicates conditions suitable for high survival and stock recovery.
- Bitter crab disease and Pacific cod predation indicators that represent proximate mechanisms for mortality have remained below average for the past five years.
- A contraction in the area occupied by mature males since 2022 has coincided with a steady decline in the spatial extent of the cold pool and a southward shift in the mature male snow crab center of abundance. A reduced spatial footprint was an apparent red flag during the recent snow crab population collapse, suggesting that the spatial extent of the stock should be closely monitored if it continues trending downward.
- The size at which 50% of the male snow crab population molted to maturity has been trending down for the past three decades, and decreased from 2024 to 2025. Mature female mean size at maturity increased substantially from 2024 to 2025, consistent with a cohort of large, immature females that were observed by the NOAA bottom trawl survey in 2024. These notable trends in growth and maturity alongside increased mature female abundance in 2025 contributed to a strongly female-skewed operational sex ratio, although < 1% of mature females with empty clutches suggests high reproductive potential despite depressed abundances of large male snow crab.

Fishery-Informed Indicators:

- Total effort in the fishery, as measured by number of active vessels (25) and total potlifts (15.7 thousand), was at a historical low during the 2024/25 fishery.

- CPUE of retained crab in the 2024/25 fishery increased to 219, well above the long term average, from a relatively extreme low of 124 during the last open season (2021/22), and the highest level since 2011/12.
- Crab vessel captain observations on fishing conditions in the 2024/25 fishery, as reported in the Alaska Bering Sea Crabbers Skipper Survey, are consistent with high fishery CPUE. The majority (67%) of captains reported a greater than 10% increase in abundance of industry-preferred males relative to the previous open season, with 38% of respondents reporting a 25% or greater increase. The most commonly reported change in fishing practice from 2021/22 was setting pots at greater depth (48% of respondents) and the principal driver of change in fishing practices (43% of responses) was proportion of undesirable (dirty, low meat fill, bitter crab, etc) crab, compared to 10% of respondents indicating low CPUE as the principal driver.
- The center of distribution of fishing activity in the 2024/25 fishery remained near the extreme northern bound of the historical range, at 59.67 degrees North latitude, marginally north of the center of distribution during the 2021/22 season, and only slightly south of the 59.92 degree historical extreme observed during the 2020/21 season.
- Incidental catch of EBS snow crab to date in 2025 groundfish fisheries is at a historical low of 27.4 thousand metric tons.

Total Allowable Catch (TAC) Considerations:

The following are the summary results from the indicator analysis that can inform TAC decisions:

- Predictive, contextual and fishery-informed ABC considerations above can also be used to inform TAC considerations within the purview of the State TAC setting process. Ecosystem indicators in the monitoring category may also be relevant to TAC considerations, but are not interpreted here.
- Economic and community indicators for the 2024/25 fishery are not yet available. The fishery was closed for the 2023/24 fishery.

Introduction/Background

An ESP was recommended for EBS snow crab in 2021 and the ESP full report was created in 2022 (Fedewa et al., 2022). The ESP full report is provided as an appendix to the operational stock assessment and fishery evaluation or SAFE report for the EBS snow crab stock and is reviewed and evaluated at the same time as the operational stock assessment. The elements of an ESP full report include a justification supporting the ESP recommendation, description of data streams used in the ESP, comprehensive literature review, synthesis of ecosystem and socioeconomic processes, description of the selected indicator suite, statistical analysis of the indicators according to the data availability of the stock, summary conclusions, and a final section detailing data gaps and research priorities.

In years following full reports, an ESP update report may be created in conjunction with the full or updated SAFE report schedule. The ESP update includes mainly static elements in a short background to recap the ESP full report, reference the conceptual model, provide descriptions of the selected indicators used in the indicator analysis, and update the statistical analysis with new data. Any necessary changes to the indicator suite such as newly available indicators, modifications due to data changes, or removals can also be catalogued. The intent of an ESP update report is to provide results of new data since the last ESP full report. It is not a full re-evaluation of the indicator selection or analysis choices. If a full re-evaluation is recommended, a subsequent ESP full report can be scheduled depending on regional prioritization.

A simplified report card infographic is also created in conjunction with the ESP full or update report to highlight the most important takeaways of the ESP. The ESP report card is a rapid communication presented with the SAFE report while the ESP full or update report contains supporting information for the report card and is appended to the SAFE report. For access to the ESP full report or subsequent update reports please visit the Alaska ESP webpage at https://akesp.psmfc.org.

Ecosystem and Socioeconomic Processes

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

Indicator Assessment

Selected indicators for EBS snow crab are organized into categories: three for ecosystem indicators (larval, juvenile, and adult) and three for socioeconomic indicators (fishery-informed, economic, and community). For detailed information regarding these ecosystem and socioeconomic indicators and the proposed mechanistic linkages for EBS snow crab, please refer to the previous ESP documents (Fedewa et al., 2022). Time series of these indicators are provided in Figure A.2a (ecosystem indicators) and Figure A.2b (socioeconomic indicators).

The following nomenclature was used to describe these indicators within the list:

- "Average": Used if the value in the time series is near the long-term mean (dotted green line in Figure A.2).
- "Above average" or "Below average": Used if the value is above or below the mean but was within 1 standard deviation of the mean (in between solid green lines in Figure A.2).
- "Neutral": Used in Table A.1 for any value within 1 standard deviation of the mean.
- "High" or "Low": Used in Table A.1 if the value was more than 1 standard deviation above or below the mean (above or below the solid green lines in Figure A.2).

The ESP full report evaluates the indicator suite as a whole when the ESP is first created (Fedewa et al., 2022). The ESP update report maintains all these indicators but may require some modifications each year to ensure delivery of the best scientific information available. Changes this year are documented below.

New indicators in the 2025 suite include:

- Female Snow Crab Size at Maturity

Modified indicators in the 2025 suite include:

- Winter/Spring Sea Ice Extent: Transitioned from NSIDC winter sea ice extent in the Bering Sea to a spatially resolved sea ice concentration product from the ERA5 reanalysis dataset.
- Female Snow Crab Reproductive Failure: This modified indicator replaces the Female Snow Crab Reproductive Potential indicator, and measures the proportion of mature females with empty clutches rather than the proportion with full clutches.
- Spatial Extent of Bottom Waters < 0°C: Previously reported as the Summer Cold Pool Spatial Extent, recent research suggests that < 0°C is a more meaningful thermal threshold for juvenile snow crab rather than constraining the area to < 2°C only, as typically defined (Fedewa et al., in revision). For this ESP, we refer to the spatial extent of bottom waters < 0°C as the "cold pool" for ease of understanding and consistency.
- Chlorophyll *a* Concentration: Transitioned from the ESA GlobColour blended satellite product to the ESA OC-CCI blended satellite product.
- Pacific Cod Consumption: Pacific cod consumption estimates previously classified all unidentified *Chionocetes* sp. prey items as *C. opilio*. New methods classify *Chionocetes* sp. as

either *C. opilio* or *C. bairdi* based on the proportion of each crab species in a given stratum at a given Pacific cod length bin.

Note: These modifications preclude direct comparison with previous ESP indicator time series.

Indicator Suite

Below we list 1) a short description of each indicator, including the data source and contributor, 2) the indicator lag assigned for ecosystem indicator analysis, as determined by the proposed mechanistic relationship between the stock and indicator (ecosystem indicators only), 3) factors driving indicator trends, and 4) potential implications of indicator trends for EBS snow crab.

Ecosystem Indicators:

Larval Indicators (Figure A.2a. a-b)

a. Arctic Oscillation Index: January - March Arctic Oscillation index from the NOAA National Climate Data Center. Proposed sign of the relationship is negative. Contact: Erin Fedewa.
    - Lag assigned for ecosystem indicator analysis: 7 years
    - Factors influencing trends: The Arctic Oscillation is a measure of the relative strength of low pressure over the Arctic and is defined by surface atmospheric weather patterns.
    - Implications: Poor snow crab recruitment has been associated with positive values of the Arctic Oscillation (Szuwalski et al., 2021).

b. Chlorophyll *a* Concentration: Mean April – June average chlorophyll *a* concentration on the north-middle shelf of the EBS (BSIERP regions 9 and 5), calculated with the ESA OC-CCI blended satellite product. Proposed sign of the relationship is positive. Contact: Matt Callahan and Jens Nielsen.
    - Lag assigned for ecosystem indicator analysis: 7 years
    - Factors influencing trends: Spring chlorophyll *a* concentration is directly influenced by the timing and magnitude of the spring bloom, and strongly impacts the amount of energy that is transferred through trophic pathways in the Bering Sea.
    - Implications: Low chlorophyll concentrations and subsequently less diatoms in the water column may drive increased larval mortality due to less favorable feeding conditions (Incze et al., 1987). A reduction in diatoms would also suggest less production reaching the seafloor, which may negatively impact juvenile snow crab lipid storage and energetic condition (Copeman et al., 2021).

Juvenile Indicators (Figure A.2a. c-h)

c. Spatial Extent of Bottom Waters < 0°C: The total area (nmi²) of all EBS bottom trawl survey stations with bottom temperatures < 0°C. Proposed sign of the relationship is positive. Contact: Erin Fedewa.
    - Lag assigned for ecosystem indicator analysis: 1 year
    - Factors influencing trends: The spatial extent of bottom waters less than 0°C is determined by winter sea ice extent and winds.
    - Implications: The EBS snow crab population collapse was attributed, in part, to the absence of bottom waters < 0°C during the 2018-2019 marine heatwave (Szuwalski et al., 2023; Litzow et al., 2024), suggesting that declines in cold-water habitat availability negatively impact snow crab recruitment and productivity.

d. Juvenile Snow Crab Temperature of Occupancy: Mean bottom temperature weighted by immature snow crab CPUE during the EBS summer bottom trawl survey, representing the realized thermal niche of juvenile snow crab. Proposed sign of the relationship is negative. Contact: Erin Fedewa.

- Lag assigned for ecosystem indicator analysis: 1 year
- Factors influencing trends: Temperatures occupied by juvenile snow crab are directly influenced by bottom temperatures in the Bering Sea and thermal preferences of stenothermic juveniles. Realized thermal niches are also influenced by species interactions.
- Implications: Occupied temperatures < 0°C are critical for supporting high snow crab density and elevated energetic reserves (Fedewa et al. in revision). Occupied temperatures > 2°C have been suggested as an upper temperature threshold for juvenile snow crab (Murphy 2020). Marine heatwaves and the resulting loss of climate refugia are expected to increase temperatures occupied by juvenile snow crab beyond thermal preferences.

e. Winter/Spring Sea Ice Extent: January-April average winter sea ice concentration in the Bering Sea from the ERA5 reanalysis dataset. Concentration values represent the percentage of the EBS covered by sea ice in winter/spring, with values below 15% considered ice-free. Proposed sign of the relationship is positive. Contact: Erin Fedewa.

- Lag assigned for ecosystem indicator analysis: 3 years
- Factors influencing trends: Winter sea ice in the Bering Sea is driven by atmospheric CO_2, ocean heat transport and winds.
- Implications: Low levels of sea ice have been associated with dampened productivity of snow crab (Mullowney et al., 2023).

f. Juvenile Snow Crab Disease Prevalence: Prevalence (%) of immature snow crab showing visual symptoms of Bitter Crab Disease (BCD) during the summer EBS bottom trawl survey, calculated as the abundance of visually positive immature crab divided by total immature abundance. Proposed sign of the relationship is negative. Contact: Erin Fedewa.

- Lag assigned for ecosystem indicator analysis: 3 years
- Factors influencing trends: Bitter crab disease tends to occur at stations with high population density of small, new shell crab, and 2 - 4°C bottom temperatures (Balstad et al., 2024). However, visual detection methods substantially underestimate disease prevalence, and infections detected with sensitive PCR assays at disease monitoring sites indicate that prevalence levels are much higher than reported here (Fedewa et al., 2025).
- Implications: Because bitter crab disease is assumed fatal and primarily affects small crab, increases in visual disease prevalence are expected to negatively impact survival and recruitment success. Disease monitoring is critical when large cohorts enter the population because an increased proportion of small snow crab in the system could lead to higher disease prevalence and mortality.

g. Juvenile Snow Crab Energetic Condition: Summer snow crab juvenile energetic condition is estimated from water content in the hepatopancreas (% dry weight) sampled from snow crab on the EBS bottom trawl survey. Proposed sign of the relationship is positive. Contacts: Erin Fedewa and Louise Copeman.

- Lag assigned for ecosystem indicator analysis: 1 year
- Factors influencing trends: Dramatic declines in energetic condition during the 2018-2019 snow crab population collapse were driven by warming during a marine heatwave and high snow crab population density (Fedewa et al., in revision). Declines in lipid storage in juvenile snow crab have also been linked to warmer temperatures and reduced food quality in the Bering Sea (Copeman et al., 2021).

- Implications: Increased energetic condition suggests favorable conditions for high survival and recruitment, whereas energetic condition that falls below a laboratory-derived threshold of 22.6% has been attributed to starvation-induced mortality (Copeman et al., in prep).

h. Pacific Cod Consumption: The daily summer consumption of snow crab (mt/day) by Pacific cod in the EBS, estimated from Pacific cod diet compositions, EBS trawl survey CPUE, and temperature adjusted length-specific maximum consumption rates. Pacific cod consumption estimates include unidentified *Chionocetes* sp. as well as identified *C. opilio* from stomach contents. Unidentified crab were extrapolated to *C. opilio* based on identified *C. bairdi* and *C. opilio* proportions by cod size and stratum. Proposed sign of the relationship is negative. Contact: Kerim Aydin.
    - Lag assigned for ecosystem indicator analysis: 4 years
    - Factors influencing trends: Consumption rates are driven by Pacific cod abundance, juvenile snow crab abundance, the spatial extent of the cold pool, and the spatial overlap between Pacific cod and snow crab (Reum et al. in revision).
    - Implications: High consumption rates indicate increased top-down predation pressure, and the potential for reduced recruitment of juvenile snow crab.

Adult Indicators (Figure A.2a. i-o)

i. Benthic Prey Density: Summer benthic invertebrate density (kg/km²), estimated from EBS bottom trawl survey stations included in the 50th percentile of mean snow crab CPUE. Invertebrates are subset to include species observed in snow crab diet studies, and include brittle stars, sea stars, sea cucumber, bivalves, non-commercial crab species, shrimp and polychaetes. Proposed sign of the relationship is positive. Contact: Erin Fedewa.
    - Lag assigned for ecosystem indicator analysis: 1 year
    - Factors influencing trends: Environmental factors such as bottom temperature, primary production and ice cover likely affect spatiotemporal variation in epibenthic invertebrates, but the dynamics remain poorly understood (Yeung and McConnaughey, 2006).
    - Implications: High benthic invertebrate density may suggest increased prey availability for juvenile and adult snow crab. However, the bottom trawl survey does not sample key prey items such as polychaetes and bivalves well, thus this indicator is a fairly coarse proxy for prey quantity.

j. Male Snow Crab Size at Maturity: Carapace width (mm) at 50% probability of having undergone terminal molt for male snow crab, as determined from maturity ogives developed from EBS bottom trawl survey data for newshell males only. Proposed sign of the relationship is positive. Contact: Erin Fedewa.
    - Not included in ecosystem indicator analysis
    - Factors influencing trends: Temporal shifts in size at terminal molt in male snow crab are likely driven by recruitment variability, density dependent growth, and ocean temperatures (Murphy 2021; Mullowney and Baker, 2021). Larger size at maturity has also been linked to higher abundances of large males, suggesting that increased competition for mates may delay the terminal molt to later instar stages.
    - Implications: Directional downward shifts in size at terminal molt lead to a higher abundance of small mature males that are protected from the fishery, resulting in higher exploitation rates on large, industry preferred males. In addition, the potential for sperm

limitation in populations depleted of large male snow crab may decrease reproductive potential of the stock (Baker et al., 2022).

k. Female Snow Crab Size at Maturity: Mean carapace width (mm) of newshell mature female snow crab, weighted by newshell mature female density. Proposed sign of the relationship is positive. Contact: Erin Fedewa.
    - Not included in ecosystem indicator analysis
    - Factors influencing trends: Temporal shifts in size at terminal molt in snow crab are likely driven by recruitment variability, density dependent growth, and ocean temperatures (Orensanz et al. 2007; Murphy 2021).
    - Implications: Because fecundity increases with female size, directional downward shifts in size at maturity could decrease reproductive potential.

l. Mature Male Snow Crab Area Occupied: The minimum area containing 95% of the cumulative mature male snow crab CPUE during the EBS summer bottom trawl survey. Proposed sign of the relationship is positive. Contact: Erin Fedewa.
    - Not included in ecosystem indicator analysis
    - Factors influencing trends: The spatial extent of snow crab in the EBS contracts in response to warmer bottom temperatures and a smaller cold pool extent (Fedewa et al., 2021). Spatial extent is also influenced by snow crab abundance due to density dependent range contraction (Murphy et al., 2010).
    - Implications: Declines in the spatial extent of mature male snow crab can result in density-dependent prey limitation and starvation-induced mortality, which are exacerbated in warm temperatures due to increased metabolic demand (Szuwalski et al., 2023). Dramatic declines in the spatial extent of mature males preceded the 2019-2021 population collapse, emphasizing the importance of this indicator as a potential red flag.

m. Mature Male Snow Crab Center of Abundance: CPUE-weighted average latitude of the mature male snow crab stock during the EBS summer bottom trawl survey. Proposed sign of the relationship is positive. Contact: Erin Fedewa.
    - Not included in ecosystem indicator analysis
    - Factors influencing trends: Historically, centroids of abundance have tracked bottom temperatures, and were further south with colder temperatures (Orensanz et al., 2005).
    - Implications: Centroids of abundance are expected to shift north under warming as snow crab track preferred cold-water habitat. This may have implications for availability to the snow crab fishery and NOAA bottom trawl survey.

n. Female Snow Crab Reproductive Failure: The proportion of hardshell mature female snow crab with no eggs, empty egg cases, or dead eggs. Hardshell crab are designated as code “2” to “5” from the EBS bottom trawl survey shell condition indices. Proposed sign of the relationship is negative. Contact: Erin Fedewa.
    - Lag assigned for ecosystem indicator analysis: 8 years
    - Factors influencing trends: Female reproductive failure is driven by the inability to find a mate, and/or utilize stored sperm reserves to fertilize egg clutches (Webb et al., 2016; Murphy et al., 2017). An increased frequency of clutch failure may indicate sperm limitation, or energetic limitations imposed on extrusion and fertilization. Barren clutches can also be attributed to senescence, suggesting that a mature female population composed of old-shell females (primarily shell condition 5) may drive year to year trends in the proportion of empty clutches.

- Implications: A low proportion of mature females with empty clutches indicates high reproductive potential, and suggests that the majority of females were able to find mates or utilize stored sperm during the mating season.

o. Snow Crab Operational Sex Ratio: The ratio of large male (> 95 mm CW) to mature female snow crab abundance in the EBS. The proposed sign of the relationship is positive under the assumption that the sex ratio will always be < 0.5 because only large males are used in the calculation. Contact: Erin Fedewa.
   - Not included in ecosystem indicator analysis
   - Factors influencing trends: The operational sex ratio is directly influenced by the relative abundances of large males and mature females. Non-synchronous shifts in abundance between the two sexes, or a male population dominated by small mature males are two mechanisms for a skewed operational sex ratio.
   - Implications: A female-biased operational sex ratio suggests the possibility for sperm limitation (Baker et al., 2022), however, a high proportion of full clutches in mature females indicates that female sperm reserves are likely sufficient for egg production.

Socioeconomic Indicators:

Fishery Informed Indicators (Figure A.2b. a-h)

a. Number of Active Vessels: Annual number of active vessels in the snow crab fishery to represent the level of fishing effort assigned to the fishery. Contacts: Jean Lee and Brian Garber-Yonts.
   - Factors influencing trends: BSAI crab fishing vessels are highly specialized for the fishery and have a limited portfolio of non-crab fishing targets. Variation in the size of the EBS snow crab fleet is driven by the TACs in the EBS snow crab, BBRKC and, increasingly, Tanner crab fisheries, with crab harvest quota leasing facilitating adjustment of the fleet to achieve efficient deployment of harvesting capacity.Anecdotal evidence suggests some vessels may temporarily operate at a loss in order to retain crew and access to quota lease contracts.
   - Implications: Variation in the size and composition of the active fleet may have implications for overall fleet behavior, including intervessel coordination and search efficiency.

b. Fishery CPUE: Annual catch-per-unit-effort (CPUE), expressed as mean number of crabs per potlift, in the snow crab fishery to represent relative efficiency of fishing effort. Contact: Ben Daly.
   - Factors influencing trends: Annual fishery CPUE can vary based on a suite of factors including total fishery potlifts, EBS snow crab abundance, pot gear soak time, pot gear configuration, bait. weather/tides/sea ice, and fleet dynamics.
   - Implications: Changes in CPUE can be used to interpret shifts in relative stock abundance and/or distribution, inform management decisions, and explain timing and distribution of fishing effort.

c. Fishery Total Potlifts: Annual total potlifts in the snow crab fishery to represent the level of fishing effort expended by the active fleet. Contact: Ben Daly.
   - Factors influencing trends: Annual fishery total potlifts can vary based on a suite of factors including number of active vessels, TAC size, CPUE, weather/tides, distance to fishing grounds, and fleet dynamics.
   - Implications: TBD

d. Centroid of Fishery: Center of gravity, expressed in latitude, as an index of spatial distribution for the snow crab fishery to monitor spatial shifts in fishery behavior. Contact: Ben Daly.
   - Factors influencing trends: TBD
   - Implications: TBD

e. Annual Incidental Catch: Annual incidental catch of snow crab in EBS groundfish fisheries. Contact: Brian Garber-Yonts and Jean Lee.
   - Factors influencing trends: TBD
   - Implications: TBD

f. Alaska Bering Sea Crabbers (ABSC) Skipper Survey Perceived Abundance: Responses from a single question in the ABSC Skipper Survey, disseminated to all skippers following the completion of the most recent fishery. Skippers were asked to rank perceived abundance of industry preferred male snow crab during the 2024/2025 fishery relative to the last snow crab season. Open-ended “other” response choice was not included. Contact: Cory Lescher.
   - Factors influencing trends: Perceived abundance can vary based on a suite of factors including fishing location, soak time and skipper skill and experience.
   - Implications: Changes in perceived abundance often help to explain skipper adaptation strategies, and can be used as a relative measure of stock status.

g. Alaska Bering Sea Crabbers (ABSC) Skipper Survey Changes in Fishing Practices: Responses from a single question in the ABSC Skipper Survey, disseminated to all skippers following the completion of the most recent fishery. Skippers were asked to select the most significant change they made in fishing practices during the 2024/2025 fishery relative to the last snow crab season. Open-ended “other” response choice was not included. Contact: Cory Lescher.
   - Factors influencing trends: Changes in fisher behavior can be driven by factors such as increased bycatch, low CPUE, shifts in stock abundance and/or distribution, operating cost, and experience and knowledge.
   - Implications: Changes in fishing practices can be used to interpret trends in fishery performance metrics and the health of the stock.

h. Alaska Bering Sea Crabbers (ABSC) Skipper Survey Principal Driver of Changes: Responses from a single question in the ABSC Skipper Survey, disseminated to all skippers following the completion of the most recent fishery. Skippers were asked to select their main reason for any change in fishing practices during the 2024/2025 fishery relative to the last snow crab season. Open-ended “other” response choice was not included. Contact: Cory Lescher.
   - Factors influencing trends: Motivation for changes in fisher behavior can be driven by bycatch and fishery regulations, TAC allocation and CPUE.
   - Implications: Understanding the motivation for changes in fishing practices can assist fishery managers in developing more effective management strategies.

Economic Indicators (Figure A.2b. i-k)

i. Ex-vessel Value: Annual snow crab ex-vessel value of the snow crab fishery landings represents gross economic returns to the harvest sector, as a principal driver of fishery behavior. Contact: Brian Garber-Yonts and Jean Lee.
   - Factors influencing trends: Data for the 2024/25 fishery is not yet available. The fishery was closed for the 2023/24 season.
   - Implications: TBD

j. Ex-vessel Price: Annual snow crab ex-vessel price per pound represents per-unit economic returns to the harvest sector, as a principal driver of fishery behavior. Contact: Brian Garber-Yonts and Jean Lee.
   - Factors influencing trends: Data for the 2024/25 fishery is not yet available. The fishery was closed for the 2023/24 season.
   - Implications: TBD

k. Ex-vessel Revenue Share: Annual snow crab ex-vessel revenue share, expressed as vessel-average proportion of annual gross landings revenue earned from the EBS snow crab fishery. Contact: Brian Garber-Yonts and Jean Lee.
   - Factors influencing trends: Data for the 2024/25 fishery is not yet available. The fishery was closed for the 2023/24 season.
   - Implications: TBD

Indicator Analysis

Ecosystem and socioeconomic indicators are monitored through distinct workflows, depending on the management decisions they are intended to inform (Figure A.3). Ecosystem indicators generally inform the acceptable biological catch (ABC) and can either be incorporated directly into the model through predictive or causal inference, or indirectly through contextual avenues such as risk tables (Dorn and Zador, 2020). Socioeconomic indicators related to the performance or behavior of the fishery can also impact the ABC both directly by informing time-varying fishery selectivity and indirectly through context in the risk table. Other socioeconomic indicators such as those related to the economics of the fishery or the communities that are supported by the fishery impact decisions further downstream of the stock assessment process and generally are used in decisions related to total allowable catch (TAC). Additionally, all indicators selected for monitoring in the ESP may inform TAC deliberations.

We evaluated the ecosystem indicators through a series of stages using statistical tests that increase in complexity depending on the data availability of the stock (Shotwell et al., 2023). The beginning stage is a relatively simple evaluation by traffic light scoring. This evaluates the indicator value from each year relative to the mean of the whole time series and includes the proposed sign of the overall relationship between the indicator and the stock health. The intermediate stage uses importance methods related to a stock assessment parameter of interest (e.g., recruitment, growth, catchability). These regression techniques estimate predictive performance for the parameter of interest and are run separate from the stock assessment model. They provide the direction, magnitude, uncertainty of the effect, and an estimate of inclusion probability. The advanced stage is used for providing visibility on current research ecosystem models and may be used for testing a research ecosystem linked stock assessment model where output can be compared with the current operational stock assessment model to understand information on retrospective patterns, prediction performance, and comparisons to model outputs.

The three stages can be considered as gates for how to monitor the indicator suite and are generally related to the data availability for the stock assessment. Data-limited stocks would only have enough information for the beginning stage and simple scoring analysis. Age- or length-structured assessment models with moderate to rich data availability would be able to move past the beginning stage or gate and evaluate the indicators using importance methods external to the assessment model. The most data rich stocks with an integrated ecosystem-linked modeling platform could move past the intermediate stage or gate to evaluate indicators using the advanced methodology (e.g., integrated age-structured stock assessment model with dynamic structural equation modeling or DSEM, Champagnat et al., *in review*).

We evaluated the socioeconomic indicators using only the beginning stage statistical tests and did not assign a proposed relationship between the indicator and the stock, as the role of socioeconomic indicators in the stock assessment process is currently being evaluated by the North Pacific Fishery Management Council (NPFMC or Council, December 2023, 2024 memorandum). Once recommendations are provided after the evaluation, we will update the analysis options for socioeconomic indicators. We also note, per Scientific and Statistical Committee (SSC) guidance, that the socioeconomic indicators can provide a combination of performance and context, and any overall scores by category should only include indicators that reflect performance. In this way, higher scores should reflect “good” conditions for the stock and would not be influenced by indicators that are included for context (e.g., composition of product form, or market share).

Ecosystem Indicator Analysis

The EBS snow crab stock is data-rich with an associated size-structured model (Generalized Model for Assessing Crustacean Stocks or GMACS); therefore the ecosystem indicators were evaluated using intermediate indicator analysis stage methods. Results from this intermediate stage analysis are used to categorize ecosystem indicators as a) predictive indicators that demonstrate a robust quantitative relationship with the population process of interest, b) contextual indicators that provide anticipatory information to inform a management concern or highlight a potential red flag related directly to the status or health of the stock, but lack predictive skill, or c) monitoring indicators that do not demonstrate quantitative links to population processes, nor provide information that is immediately relevant to the stock and/or fishery managers. The intent of this indicator categorization is to succinctly communicate potential red flags for the stock based on current-year indicator trends and stock-indicator relationships, while providing a mechanism to down-weight indicators that don’t quantitatively inform population processes. Monitoring indicators are reported in this document and will continue to be evaluated annually, but we limit our interpretation and synthesis to predictive and contextual indicators only in an effort to communicate only the most relevant ecosystem considerations for setting biological reference points for the current year.

Bayesian adaptive sampling (BAS) was used to quantify the strength and direction of association between ecosystem indicators and EBS snow crab recruitment. BAS explores model space, or the full range of candidate combinations of predictor variables, to estimate marginal inclusion probabilities for each predictor, model weights for each combination of predictors, and generate Bayesian model-averaged predictions for snow crab recruitment (Clyde et al., 2011). Snow crab recruitment was calculated using the EBS bottom trawl survey abundance of newshell male “pre-recruit” snow crab (≥ 65mm carapace width and ≤ 80mm carapace width) under the assumption that this size class represents Instar X (~ 6.7 - 7.7 years post-settlement), and individuals that are 1 -2 molts away from terminally molting and recruiting to the fishery (Sainte-Marie et al., 1995).

Prior to running BAS, the full suite of 15 ecosystem indicators was winnowed to the predictors that directly relate to recruitment. We eliminated the following indicators, as they are not hypothesized to drive snow crab recruitment and instead, provide contextual information about the stock or a relevant management concern: 1) operational sex ratio, 2) male size at maturity, 3) female size at maturity, 4) mature male area occupied, and 5) mature male center of abundance. We further restricted potential covariates to those that provided the longest model run, and through the most recent estimate of recruitment when possible. Given the short time series length for juvenile snow crab energetic condition (n = 6 years, 2019/2021-2025) relative to other ecosystem indicators, this indicator was dropped from the final BAS model. With lags applied, chlorophyll-*a* concentration (n = 21 years, 2005-2025) and female reproductive failure (n = 30 years, 1996-2025) limited the 1989 model run start date and were therefore also eliminated. The Pacific cod consumption time series included data up to 2024 only, as a current-year update is not yet available due to the lag time in stomach processing following the completion of the EBS bottom trawl survey.

Ecosystem indicator lags were assigned to the remaining indicator suite based on hypothesized mechanistic linkages between the proposed life history stage and the indicator, as well as targeted size ranges that the indicators are hypothesized to have the greatest impact on. Preliminary sensitivity analyses indicate that BAS results are fairly robust to +/- 1 year lags, although the inability to accurately age crab results in difficulties assigning lags with high confidence. Pre-recruit male snow crab were assumed to be 6 - 7 years old, therefore larval indicators were assigned a lag of six years. Juvenile snow crab disease prevalence, Pacific cod consumption and sea ice extent disproportionately impact small juvenile snow crab, and were therefore assigned representative lags of 3 - 4 years. Benthic invertebrate density, spatial extent of bottom waters < 0°C and juvenile snow crab temperature occupied were assigned a lag of one year, as prey resources and thermal conditions are likely to be an integrated effect that depends more on recent conditions to inform survival of pre-recruits.

Prior to running the model, we also eliminated highly correlated indicators ($r \geq 0.6$) with the understanding that high correlations among predictors may "dilute" inclusion probabilities and render them less useful as a posterior summary of variable importance. The spatial extent of bottom waters < 0°C time series was highly correlated with juvenile snow crab temperature occupied ($r = -0.78$), and Pacific cod consumption was highly correlated with disease prevalence ($r = 0.6$). We chose to drop the spatial extent of bottom waters < 0°C from the final model while retaining juvenile snow crab temperature occupied, given that temperatures occupied are a more direct measure for thermal conditions experienced by highly stenothermic juvenile snow crab. Likewise, we eliminated disease prevalence from the final suite of predictors with the knowledge that our measure of visual prevalence greatly underestimates true disease prevalence, and there is likely more confidence in a direct estimate of consumption. This resulted in a final suite of 5 predictors: juvenile snow crab temperature occupied, sea ice extent, Pacific cod consumption, benthic prey density and Arctic Oscillation (Figure A.4). Because missing data are dropped from BAS model runs, 18 years were dropped due to incomplete observations, and resulted in a model run from 1989 - 2025. NAs due to the cancellation of the 2020 EBS bottom trawl survey were especially problematic, and resulted in 2020, 2021 and 2024 being dropped from the analysis after lagging indicators.

The final model selected using BAS was the intercept-only model (Figure A.5), indicating that the ecosystem indicators tested had no predictive skill for estimating snow crab recruitment over the years evaluated. We provide the mean relationship between each predictor variable and the estimates of EBS snow crab recruitment over time (Figure A.6a) and the marginal inclusion probabilities for each predictor variable (Figure A.6b) to illustrate that credible intervals for all effect sizes overlapped zero, and marginal inclusion probabilities were < 0.5. Model predicted fit (Figure A.6c) and average predicted fit across the recruitment time series subset (1989 - 2025; Figure A.6d) were also very poor. Because the BAS analysis presented here identified no indicators that demonstrated predictive capacity, we categorized the full suite of ecosystem indicators as either contextual (juvenile snow crab temperature occupied, sea ice extent, disease prevalence, juvenile snow crab energetic condition, Pacific cod consumption, male snow crab size at maturity, male snow crab area occupied, male snow crab center of abundance, female snow crab reproductive failure and snow crab operational sex ratio) or monitoring (Arctic oscillation index, chlorophyll-a concentration, spatial extent of bottom waters < 0°C, benthic prey density and female snow crab size at maturity) based on the criteria listed above.

We also summarize recent indicator trends and provide management considerations by providing a five year status table of the indicators organized into predictive, contextual, or monitoring categories (Table A.1). Indicator status is evaluated based on being greater than ("high"), less than ("low"), or within (“neutral”) one standard deviation of the long term mean. Potential concerns for the health or status of the stock are identified using predictive relationships (predictive ecosystem indicators) or proposed mechanistic relationships (contextual ecosystem indicators) with the stock, and are communicated as a sign and associated color relative to the indicator value and directional indicator-stock relationship. The sign of the relationship for predictive indicators is based on the importance method results, while the sign for contextual or monitoring indicators is based on the conceptual model and hypothesized relationship with the stock (Figure A.1). The color of the status cell (also referred to as the "traffic light") is related to the sign of the indicator and the status. If a high value of an indicator generates good conditions for the stock and is also greater than one standard deviation above the mean, then that table cell is colored blue. If a high value generates poor conditions for the stock and is greater than one standard deviation above the mean, then that table cell is colored red. All values less than or equal to one standard deviation from the long-term mean are average and there is no assigned color. Also, if the sign of the relationship between an ecosystem indicator and the stock is unclear, no relationship is assigned.

Overall, results from the traffic light table (Table A.1a) indicate that mature male range contraction and a strongly female-biased operational sex ratio are at anomalous values in 2025, and may represent potential red flags for the stock. Conversely, high female size at maturity and a low proportion of females with empty clutches relative to the long-term mean indicate positive signals for reproductive capacity of the stock. All remaining contextual indicators with 2025 updates remained within one standard deviation of their long-term mean. The Executive Summary at the beginning of this document provides a summary of contextual indicator trends, and an interpretation of results from the intermediate stage indicator analysis that can be used to inform ABC and TAC decisions.

Socioeconomic Indicator Analysis

We present 12 socioeconomic indicators that depict a historical time series of key socioeconomic information for the EBS snow crab fishery - 5 fishery-informed indicators derived from NMFS/ADFG in-season management monitoring systems, 3 selected from the Alaska Bering Sea Crabbers (ABSC) Snow Crab Skipper Survey - 2025, and 3 economic indicators drawn from mandatory economic reporting systems (ADFG’s Commercial Operators Annual Reports). All socioeconomic indicators are produced from observations captured during or after completion of the 2024/25 fishery. Indicators derived from agency monitoring and reporting systems use time series of historical data through the most recent (2024/25) fishery, which occurred during the initial months of 2024, and are used to assess current status of the fishery relative to long-term trends

Indicators from the ABSC Skipper Survey represent a synthesis of responses to the 2025 survey, which elicited single period comparisons between the 2024/25 fishery and the most recent previous fishery. Inclusion of these indicators is primarily aimed at informing ABC determinations, and is intended as a provisional mechanism for incorporating an alternative source of fishery-dependent data on fleet behavior and observations of abundance, age, sex, and other conditions of the catch, for consideration of authors and reviewers of the assessment. It is expected that recommendations from the CPT and SSC regarding the general suitability of the ABSC survey as a source of indicators for inclusion in the ESP, and the initial selection of three representative questions as indicators focuses on skipper’s perception of the abundance of industry-preferred males and perceived changes and drivers of fishing behavior. These are drawn from a total of 9 recurring questions, which also encompass questions regarding the abundance and explanatory factors for encounters with sublegal males and females, and shell condition of legal males. Additional indicators, including syntheses of survey time series (n = 3 as of 2024) may be developed for future ESPs pending CPT and SSC evaluation of the initial selection of indicators and of the ABSC survey as a candidate data source for the ESP generally.

The most recent fishery represented levels of fishing effort (number of active vessels and total potlifts) below 1-sd of the long term average (Table A.1b, c). The fleet consolidated from 42 in the 2021/22 fishery, to 25 in the 2024/25 fishery, compared to an average of 69 vessels in the post-rationalization period prior to 2021/22. Quota royalty income likely mitigates some financial impact of non-entry for vessel owners that have substantial crab quota share holdings, however, idling of a significant segment of the fleet has distributional effects, including for crew members and associated communities, and over time may have structural implications for the crab harvest sector. A commensurate decline in total potlifts occurred between 2021/22 and 2024/25. In contrast, efficiency of effort increased for the 2024/25 fishery, as indicated by a moderately increased CPUE (within the 1-sd range above the long-term average), and high (relative to the previous season) crab skipper perception of abundance of industry-preferred males. ABSC survey results indicated that the most common response regarding changes in fishing behavior relative to the previous season was shifting to greater depths, and the most common driver of changed fishing strategy was catch of crab with poor shell condition. The center of distribution of the fishery continued the recent shift of the fishery toward the northwestern bounds of the fishing grounds. Incidental catch in groundfish fisheries declined slightly, remaining near the lower bound of the 1-sd range about the long-term mean.

Data needed to produce economic indicators for the 2024/25 fishery are not yet available, and the fishery was closed for the 2023/24 season.

For this EBS snow crab ESP update, a more limited set of socioeconomic indicators is reported than for previous iterations, and compared to the full ESP produced for the 2025/25 Tanner crab assessment. Given resource limitations, a more inclusive set of socioeconomic indicators in crab ESPs (both full ESPs and update versions) awaits general guidance from the SSC and Council regarding priorities for ESP/socioeconomic indicators to inform TAC setting.

Conclusion

The EBS snow crab ESP follows the standardized framework for evaluating the various ecosystem and socioeconomic considerations for this stock (Shotwell et al., 2023). The conceptual model provides a reference for the comprehensive literature review and associated tables of the ESP full report (Fedewa et al., 2022). Fifteen ecosystem and twelve socioeconomic indicators were identified to monitor and analyze for EBS snow crab. Because EBS snow crab is a data-rich stock with an annual fishery-independent survey to assess population status, ecosystem indicators were evaluated using intermediate indicator analysis stage methods. We provide several overarching takeaways from the indicator assessment results. This information can be used for evaluating concerns in the main stock assessment or other management decisions and we organize the results by acceptable biological catch (ABC) and total allowable catch (TAC) considerations. Indicators that can inform ABC and risk tables include predictive, contextual, or fishery-informed indicators. Indicators that can inform TAC include all ABC indicators as well as economic and community indicators.

Because no predictive indicators were identified in the indicator analysis, ecosystem indicators are interpreted as providing contextual information only for EBS snow crab. Contextual indicators suggest potential red flags with directional downward shifts in male maturity and spatial extent, a strongly female-skewed sex ratio, and declines in the spatial extent of cold bottom water and winter/spring sea ice. However, energetic condition of juvenile snow crab remains high in 2025, predation and disease pressure have remained low, and temperatures occupied by juveniles suggest that cold-water habitat was available despite warming. Overall, ecosystem indicators show warm conditions and reduced ice extent in the EBS, but warming is not yet approaching critical thresholds for highly stenothermic juvenile snow crab. Ecosystem concerns are minor with uncertain impacts on the stock. Fishery-informed indicators suggest that, despite historically low levels of fishing effort during the 2024/25 season, efficiency of effort increased substantially from the most recent (2021/22) fishery, and was high relative to the most recent several open seasons. No economic indicators are reported for the 2024/25 season due to the normal lag in production of economic data. Overall, socioeconomic indicators generally support improved stock condition relative to the most recent (2021/22) fishery. Despite continued extreme northerly shift in the center of distribution of fishing activity, no considerations observed in the most recent fishery suggest greater than normal risk, independent of other considerations captured in the assessment and risk table.

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Tables

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

Indicator category	Indicator	2021 Status	2022 Status	2023 Status	2024 Status	2025 Status
Contextual	Juvenile Snow Crab Temperature of Occupancy	**high**	neutral	neutral	neutral	neutral
	Winter/Spring Sea Ice Extent	neutral	neutral	neutral	neutral	neutral
	Juvenile Snow Crab Disease Prevalence	neutral	neutral	neutral	neutral	neutral
	Juvenile Snow Crab Energetic Condition	neutral	neutral	neutral	neutral	neutral
	Pacific Cod Consumption	neutral	neutral	neutral	neutral	NA
	Male Snow Crab Size at Maturity	**low**	neutral	neutral	neutral	neutral
	Mature Male Snow Crab Area Occupied	neutral	neutral	neutral	**low**	**low**
	Mature Male Snow Crab Center of Abundance	*high*	*high*	*high*	neutral	neutral
	Female Snow Crab Reproductive Failure	neutral	**high**	*low*	neutral	*low*
	Snow Crab Operational Sex Ratio	neutral	neutral	neutral	neutral	**low**
Monitoring	Chlorophyll *a* Concentration	*high*	*high*	neutral	neutral	*high*
	Arctic Oscillation Index	neutral	neutral	neutral	neutral	neutral
	Spatial Extent of Bottom Waters < 0°C	**low**	neutral	neutral	neutral	neutral
	Benthic Prey Density	*high*	*high*	neutral	*high*	*high*
	Female Snow Crab Size at Maturity	neutral	neutral	neutral	neutral	*high*

Table A.1b: First stage socioeconomic indicator analysis for EBS snow crab, including indicator title and the indicator status of the last five years. The indicator status is designated with text, (greater than = "high", less than = "low", or within 1 standard deviation = "neutral" of long-term mean). A gray fill and text = "NA" will appear if there were no data for that year. A red color indicates a fishery closure and the text = "Closed" will appear. Note that the year heading references calendar year; the EBS snow crab fishery is prosecuted Jan-May, such that the calendar year corresponds to the second period of the crab season-year; the most recent snow crab fishery occurred during the 2024/25 crab season.

Indicator category	Indicator	2021 Status	2022 Status	2023 Status	2024 Status	2025 Status
Fishery Informed	Number of Active Vessels	neutral	low	Closed	Closed	low
	Fishery CPUE	neutral	neutral	Closed	Closed	neutral
	Fishery Total Potlifts	neutral	neutral	Closed	Closed	neutral
	Centroid of Fishery	high	high	Closed	Closed	high
	Annual Incidental Catch	neutral	neutral	neutral	neutral	neutral
	ABSC Skipper Survey: Perceived Abundance	NA	low	Closed	Closed	high
	ABSC Skipper Survey: Changes in Fishing Practices	NA	high	Closed	Closed	high
	ABSC Skipper Survey: Principal Driver of Changes	NA	high	Closed	Closed	high
Economic	Ex-vessel Value	neutral	low	Closed	Closed	NA
	Ex-vessel Price	high	high	Closed	Closed	NA
	Ex-vessel Revenue Share	high	neutral	Closed	Closed	NA

Figures

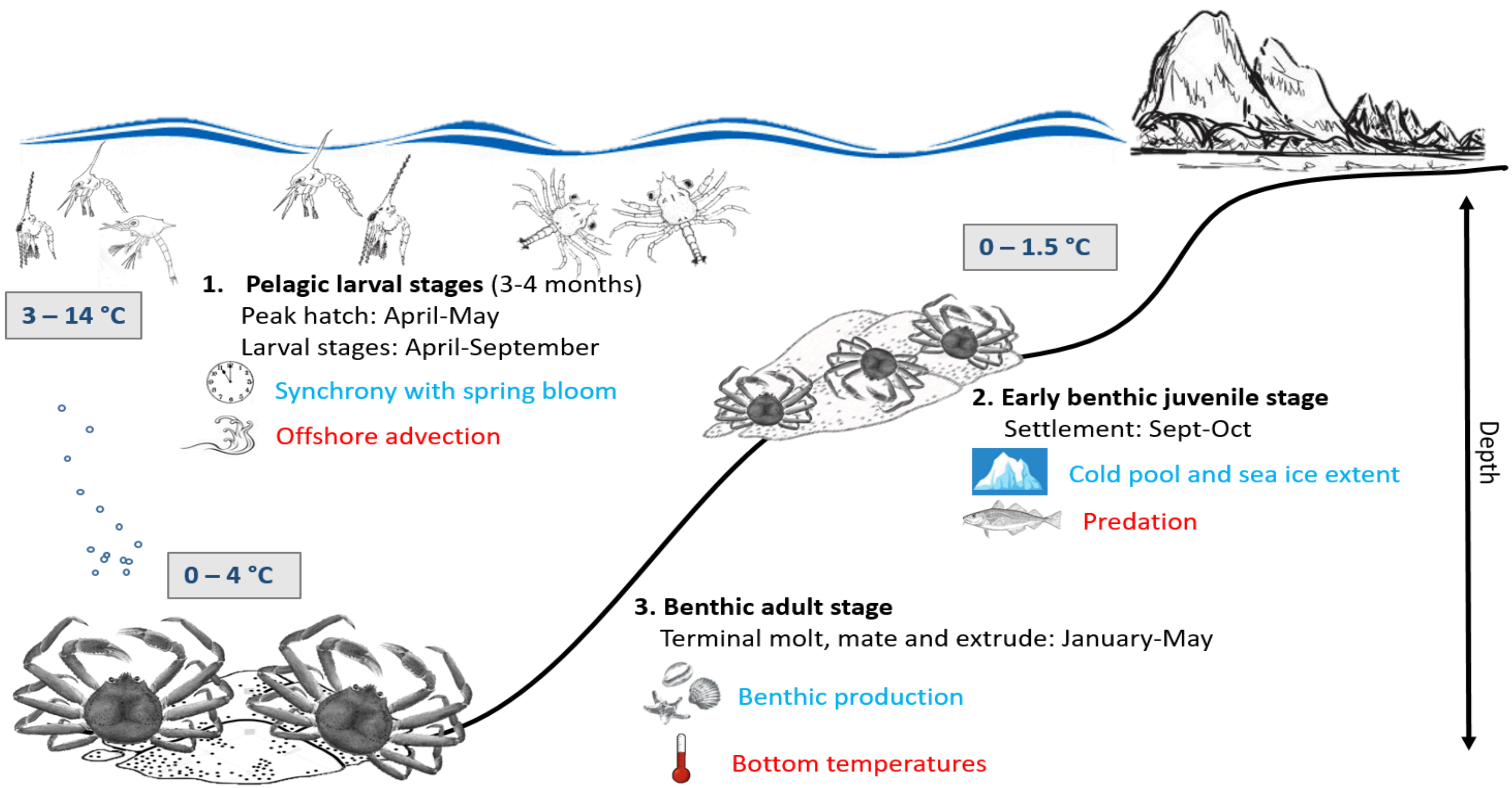

Figure A.1: Life history conceptual model for EBS snow crab summarizing ecological information and key ecosystem processes affecting survival by life history stage. Red text indicates that increases in the process negatively affect survival of the stock, while blue text means that increases in the process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

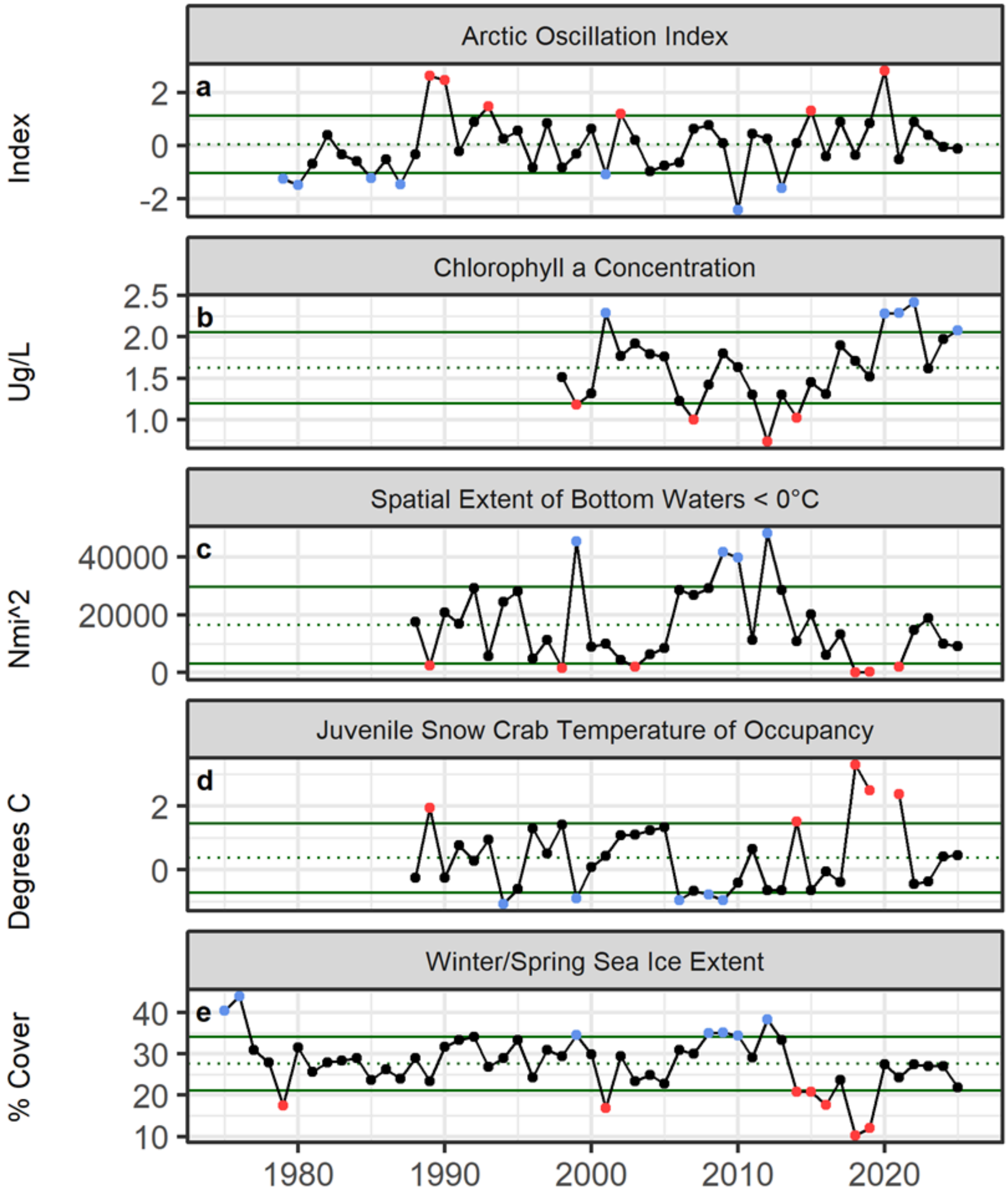

Figure A.2a: Selected ecosystem indicators for EBS snow crab with time series ranging from 1975 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

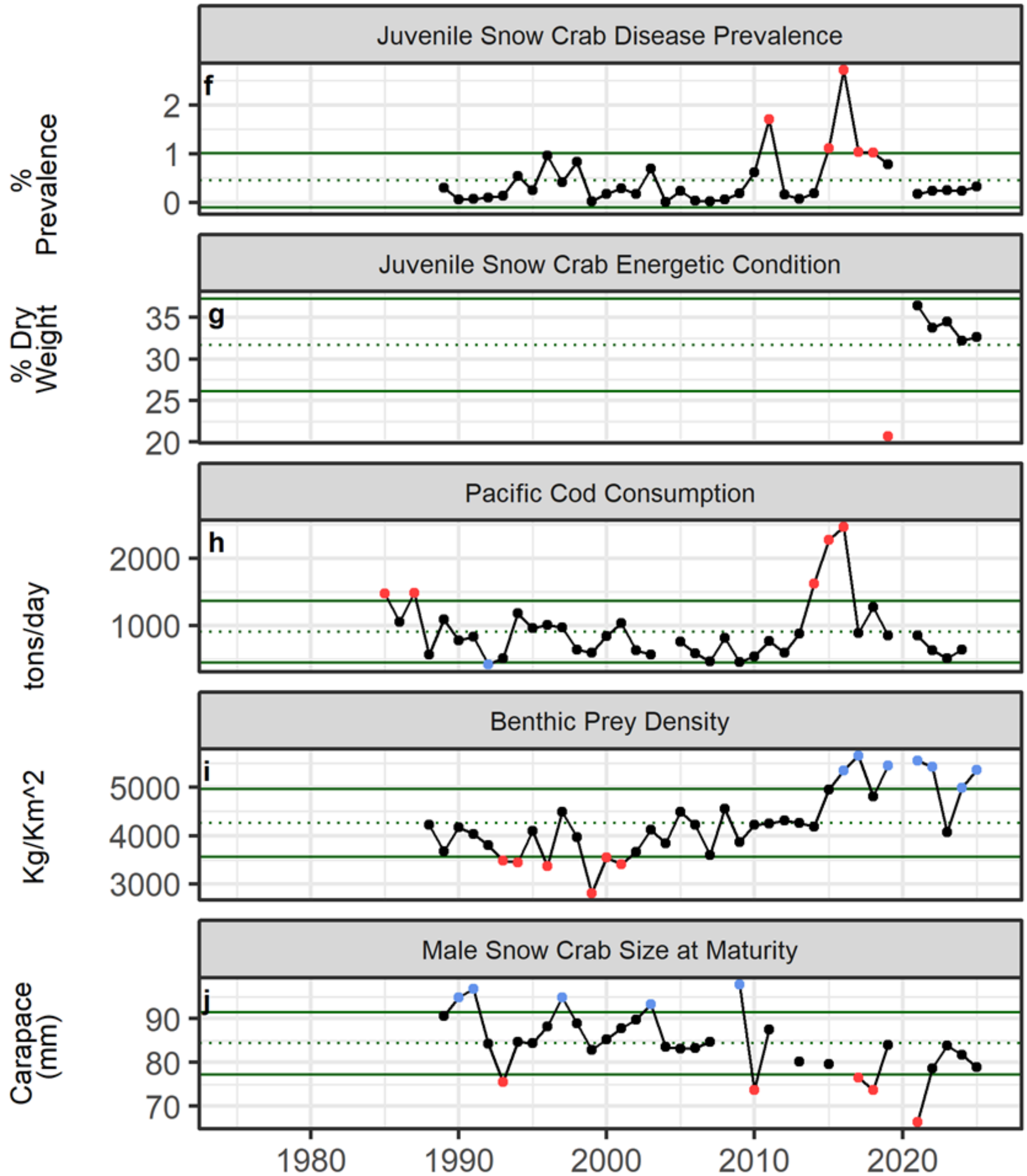

Figure A.2a (cont.): Selected ecosystem indicators for EBS snow crab with time series ranging from 1975 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

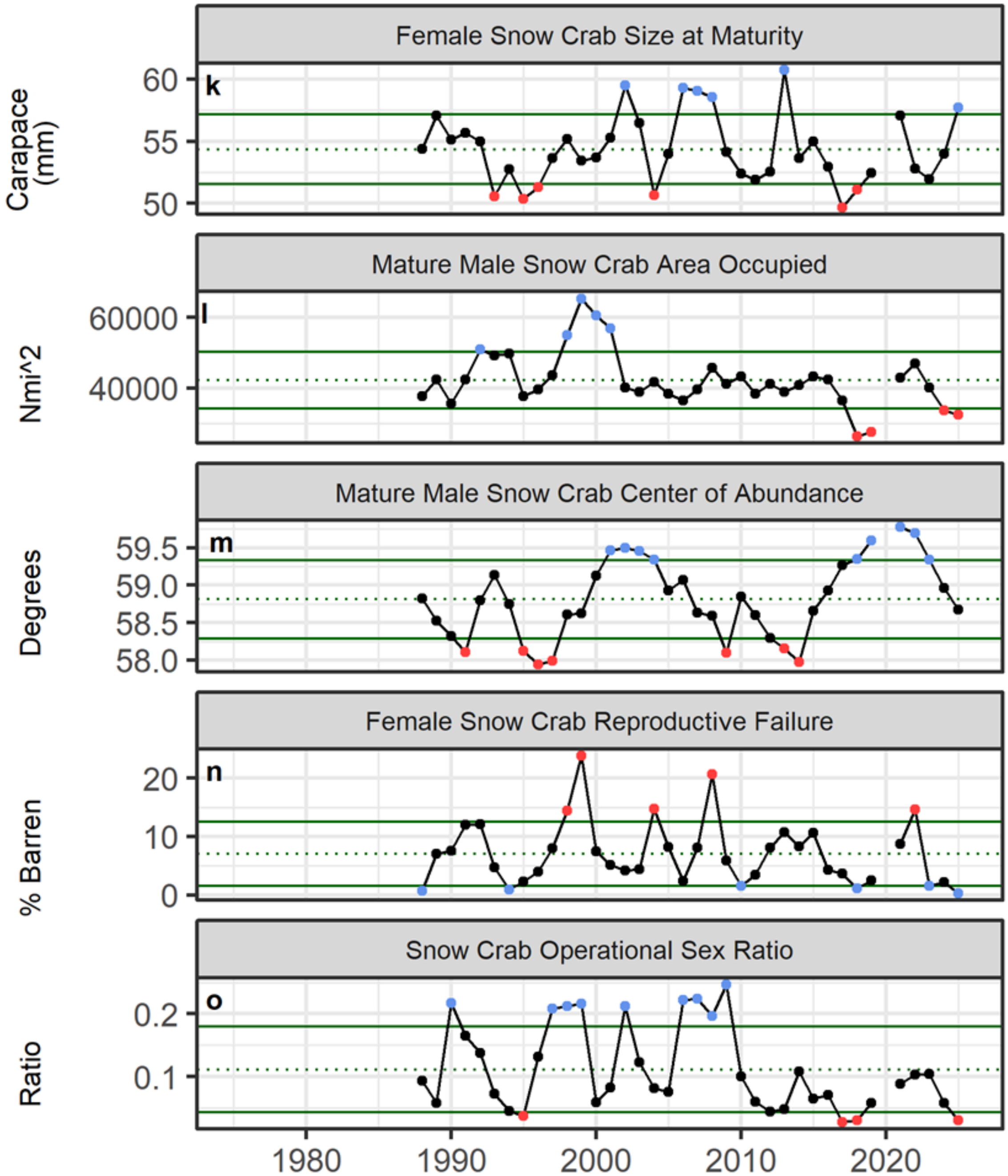

Figure A.2a (cont.): Selected ecosystem indicators for EBS snow crab with time series ranging from 1975 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

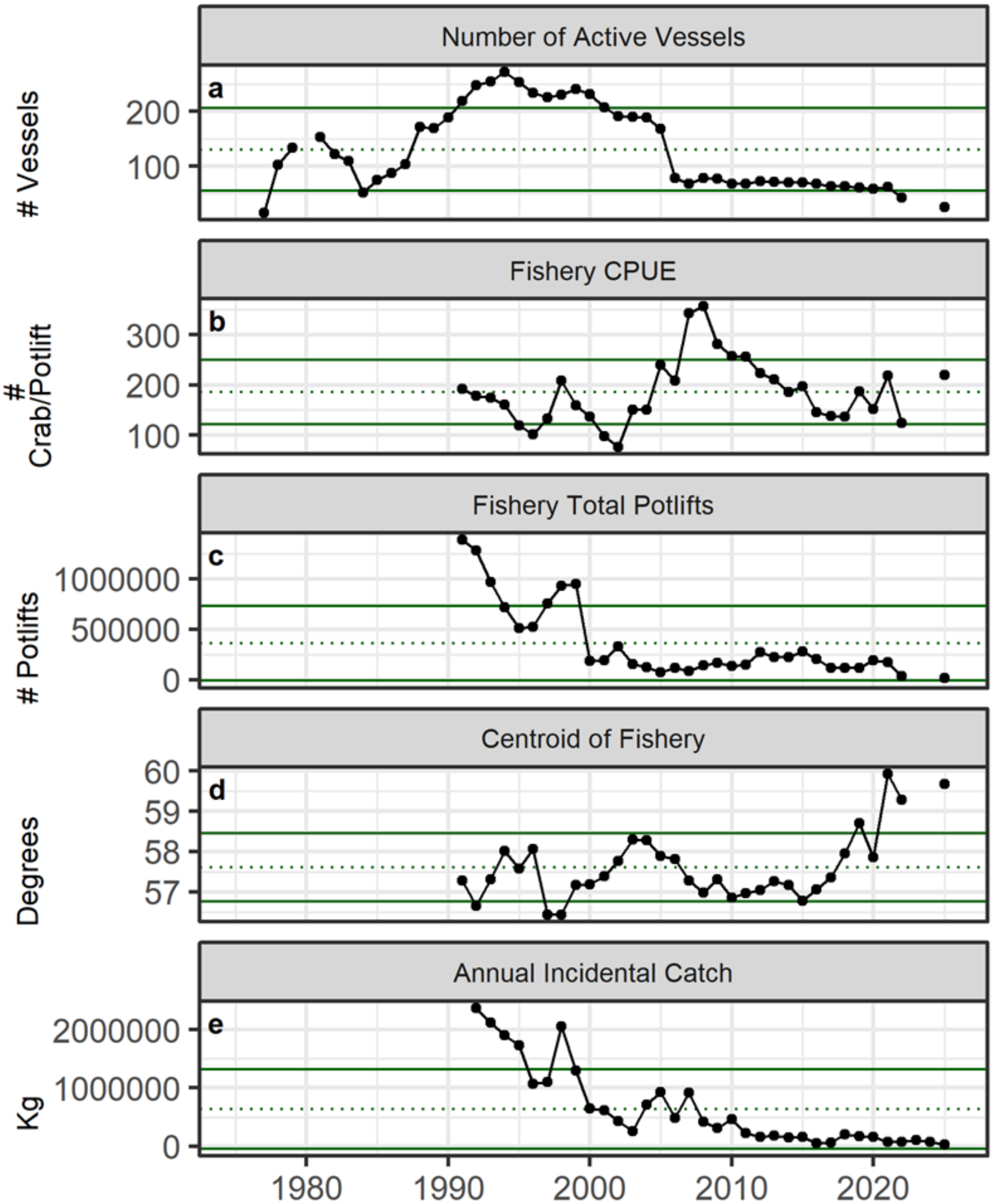

Figure A.2b: Selected socioeconomic indicators for EBS snow crab with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

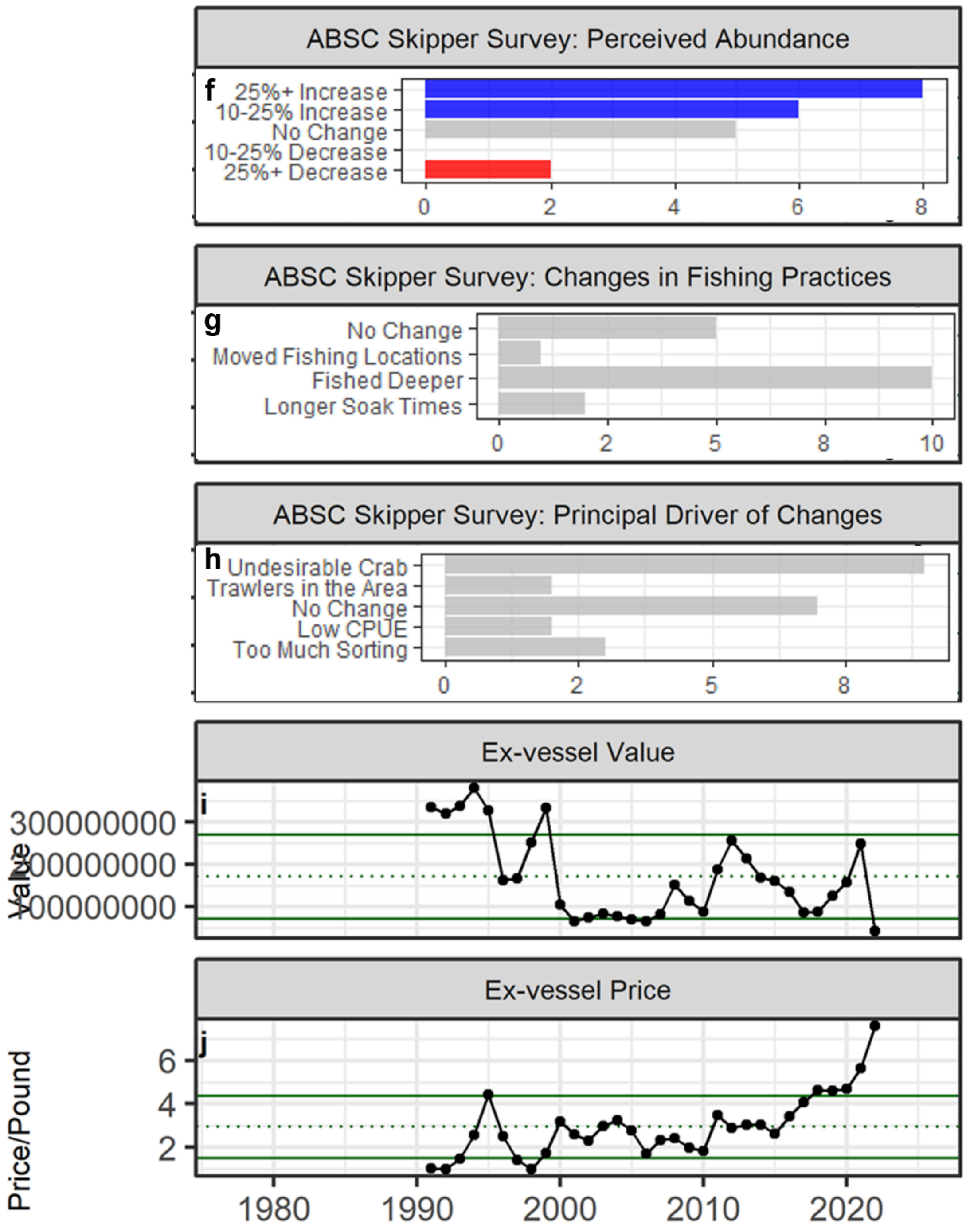

Figure A.2b (cont.): Selected socioeconomic indicators for EBS snow crab with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

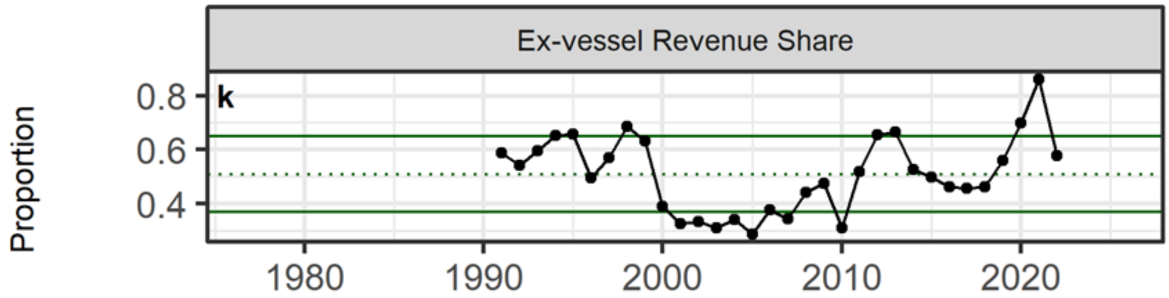

Figure A.2b (cont.): Selected socioeconomic indicators for EBS snow crab with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

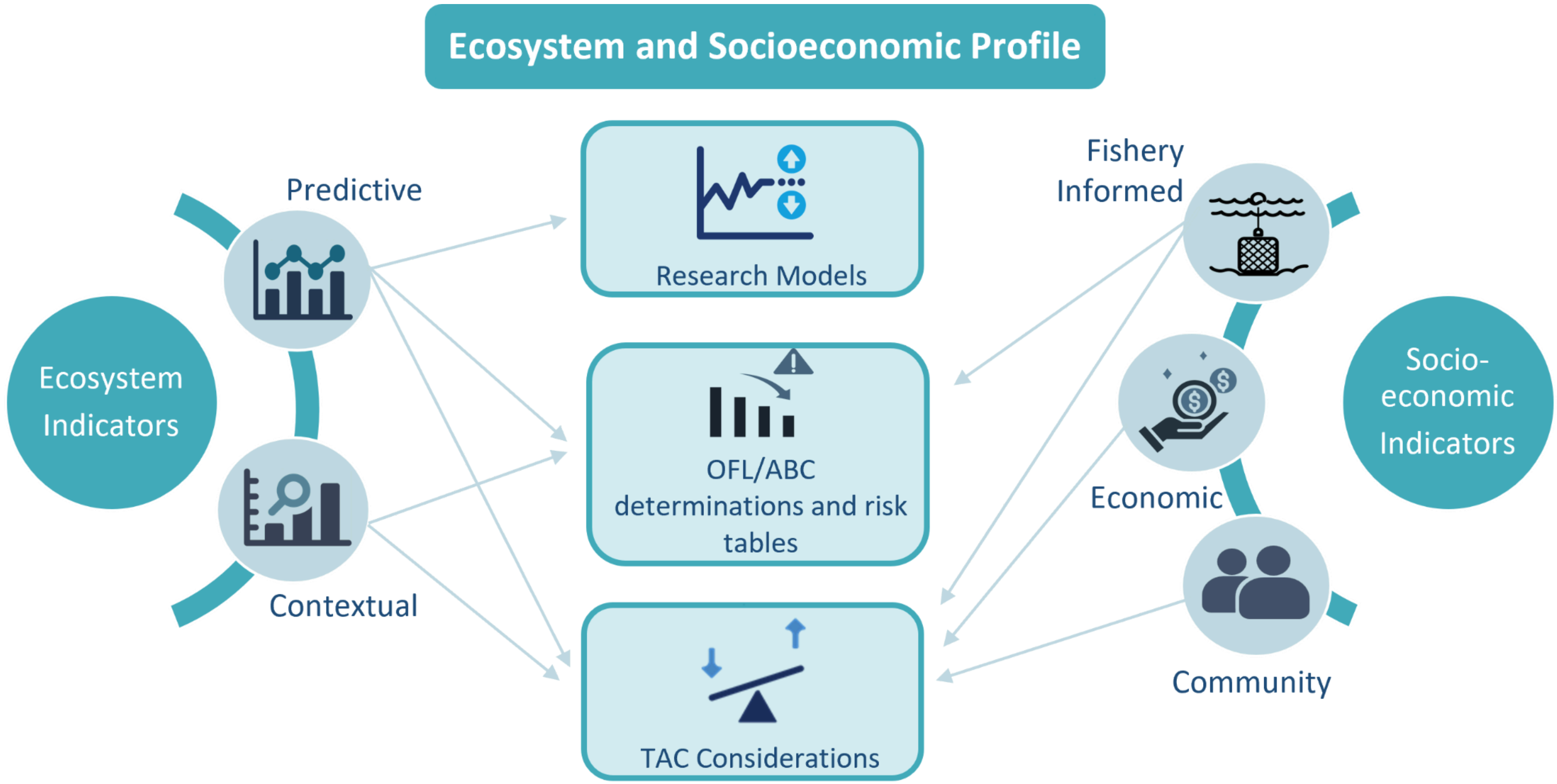

Figure A.3: Schematic of decision pathways for ecosystem and socioeconomic indicators.

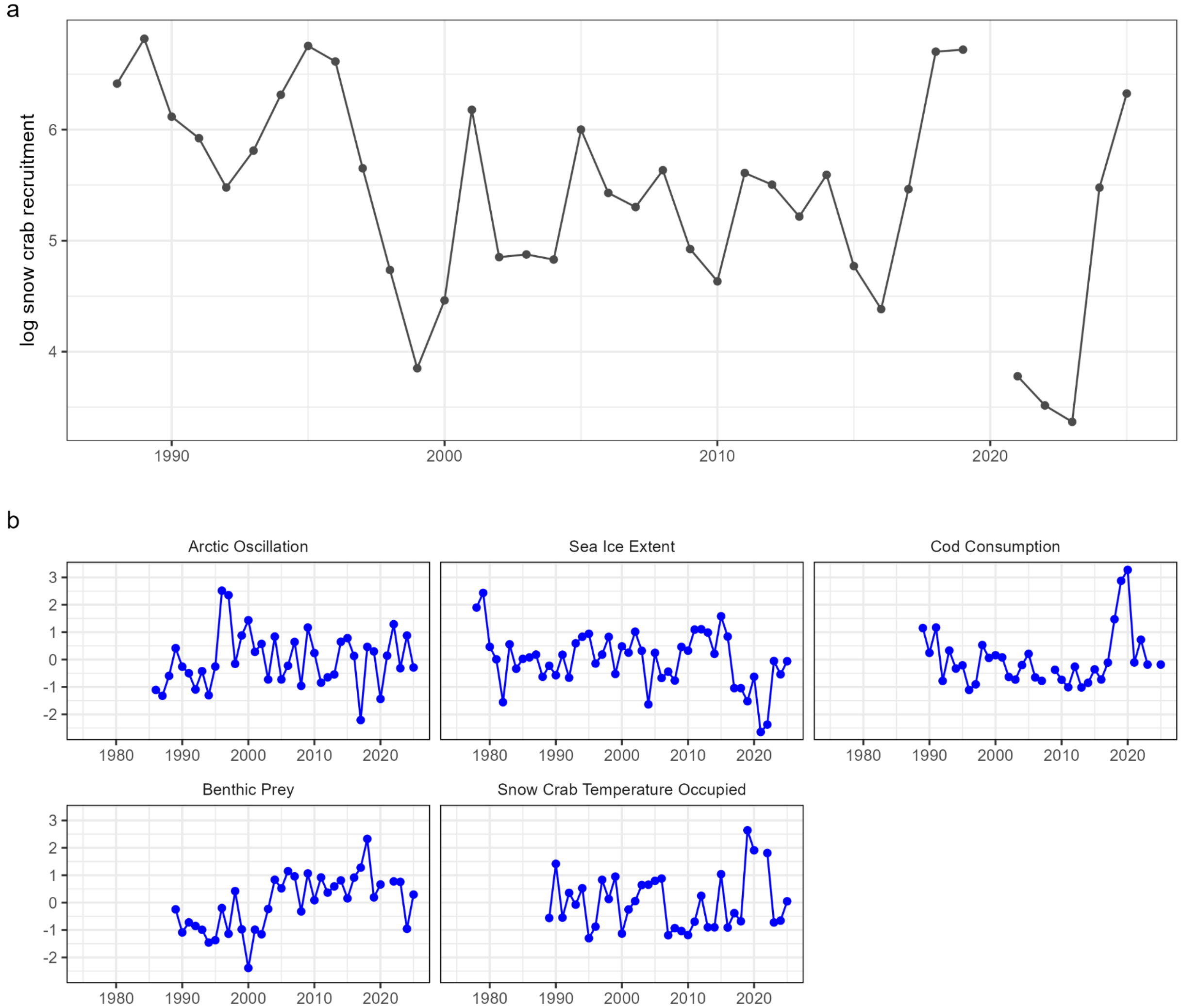

Figure A.4: Bayesian Adaptive Sampling response and predictor variables. a) Response variable, log-transformed snow crab recruitment (survey abundance of 65-80 mm males), and b) standardized ecosystem indicators tested in the final Bayesian Adaptive Sampling Model.

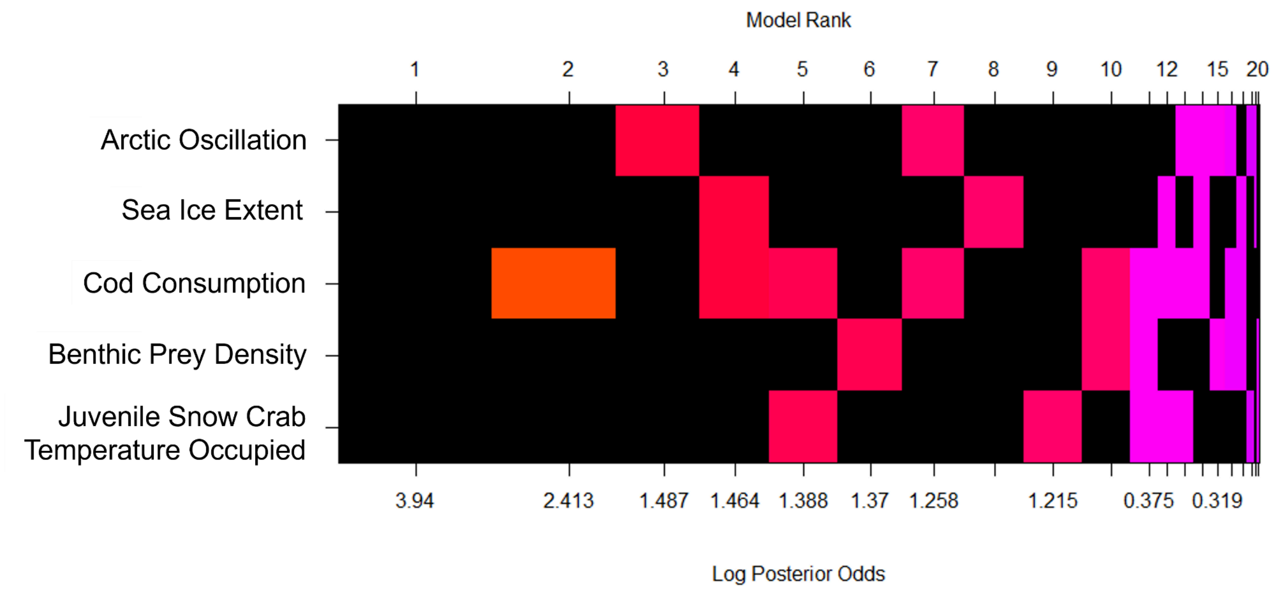

Figure A.5: Visualization of model space of the top models tested with Bayesian Adaptive Sampling. Models are sorted by their posterior probability from best at the left to worst at the right with the rank on the top x-axis, and each column represents one of the tested models.

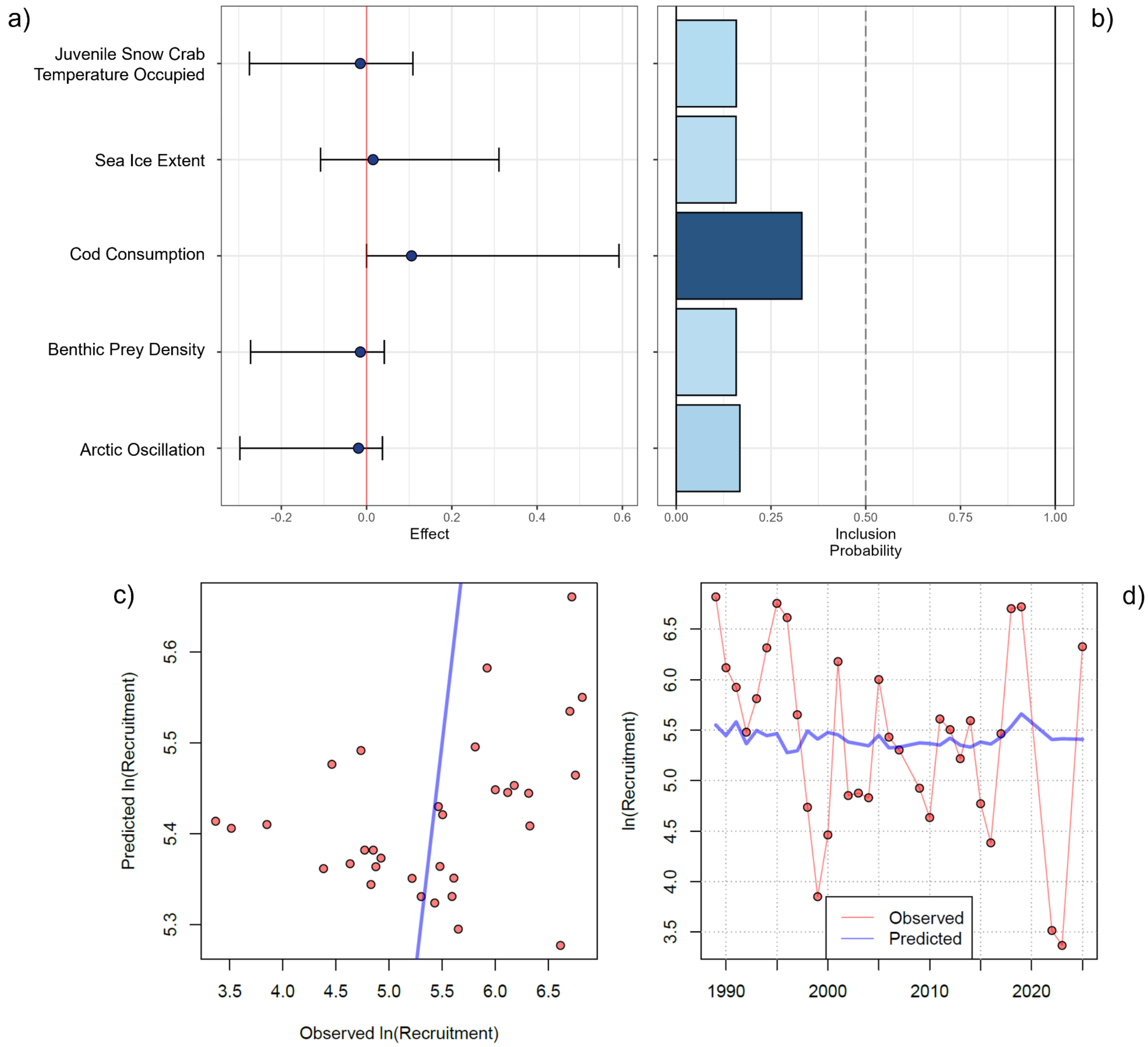

Figure F.6: Bayesian adaptive sampling output showing the mean relationship and uncertainty (± 1 SD) with log-transformed EBS recruitment (survey abundance of 65 - 90 mm males). a) The estimated effect and b) the marginal inclusion probabilities for each predictor variable of the subsetted covariate ecosystem indicator dataset. Output also includes c) model predicted fit (1:1 line) and d) average fit across the abbreviated recruitment time series (1989 - 2025).

Appendix B: Risk Table for Eastern Bering Sea Snow Crab

Erin Fedewa, Brian Garber-Yonts, Ebett Siddon, Kalei Shotwell, Cody Szuwalski

The following is a synthesis and interpretation of the most recent ecosystem and socioeconomic information available for Eastern Bering Sea (EBS) snow crab from the ecosystem and socioeconomic profile (ESP, Fedewa et al., 2025) and the Eastern Bering Sea Ecosystem Status Report (ESR, Siddon, 2024; Siddon, 2025, in press). This information may be helpful for evaluating risk table score levels and is organized below by the proposed risk table categories.

Using a Bayesian Adaptive Sampling (BAS) approach for indicator selection and importance, we identified no ecosystem indicators in the ESP that quantitatively predict recruitment of EBS snow crab. Because the suite of indicators tested using BAS did not strongly influence recruitment, population dynamics and ecosystem considerations below are interpreted as contextual information only (see Fedewa et al., 2025 for more details).

Category Summary:

Assessment-related Considerations	Population Dynamics Considerations	Ecosystem Considerations	Fishery-informed Stock Considerations
Level 2: Increased concern	**Level 2:** Increased concern	**Level 1:** Normal	**Level 1:** Normal
Instability in the model seen through jittering analyses increases uncertainty in output.	Stock-specific indicators related to natural mortality, growth and recruitment suggest no apparent population dynamics concerns. Directional downward shifts in male snow crab size at terminal molt have large implications for the fate of the medium-sized crab in the population.	Ecosystem indicators show current and projected warm conditions and reduced ice extent in the EBS, but warming is not yet approaching critical thresholds for highly stenothermic juvenile snow crab. Overall, ecosystem concerns are minor with uncertain impacts on the stock.	Fishery-informed indicators generally support improved stock condition relative to the most recent (2021/22) fishery. Despite continued extreme northerly shift in the center of distribution of fishing activity, no considerations observed in the most recent fishery suggest greater than normal risk of overfishing, independent of other considerations captured in the assessment and risk table.

Assessment-related Considerations:

Risk Level 2: Increased concern

- Jittering analyses produced two different clouds of ‘converged’ models that had markedly different OFLs, but nearly identical negative log likelihoods.
- Uncertainty around appropriate currency of management results in markedly different management advice.

Population Dynamics Considerations:

Risk Level 2: Increased concern

- The size at which 50% of the male snow crab population molted to maturity has been trending down for the past three decades, and decreased from 2024 to 2025. Mature female mean size at maturity increased substantially from 2024 to 2025, consistent with a cohort of large, immature females that were observed by the NOAA bottom trawl survey in 2024. These notable trends in growth and maturity alongside increased mature female abundance in 2025 point towards a strongly female-skewed operational sex ratio, although < 1% of mature females with empty clutches suggests high reproductive potential despite depressed abundances of large male snow crab (ESP: Fedewa et al., 2025).
- Juvenile snow crab energetic condition fell below laboratory-derived starvation thresholds during the population collapse, although a rebound in energetic condition post-collapse (2021-2025) coinciding with juvenile snow crab occupied temperatures < 1°C indicate conditions suitable for high survival, recruitment and stock recovery (ESP: Fedewa et al., 2025).
- Bitter crab disease and Pacific cod predation indicators that represent proximate mechanisms for increased mortality of juvenile snow crab have remained below average for the past 5 years (ESP: Fedewa et al., 2025; *Pacific cod consumption estimate for 2025 still in progress*).

Ecosystem Considerations:

Risk Level 1: Normal

Ecosystem indicators are organized into several categories to capture the scope of considerations available in the ESP and ESR reports:

- <u>Distribution</u>: December 2023 had significant along-shelf winds that could have driven offshore Ekman transport. March to May 2024 had weaker, but more sustained winds that also favored offshore transport (ESR: Hennon, 2024). Strong summer winds in 2024 resulted in a deep mixed layer (ESR: Hennon, 2024). A southward shift in the mature male snow crab center of abundance from 2021 to 2025 alongside a contraction in the area occupied by mature males coincided with a decline in the spatial extent of the cold pool since 2022 (ESP: Fedewa et al., 2025).
- <u>Environmental Processes</u>: During winter 2024-2025, the NPI was negative (ESR: Siddon, 2025) for the first time in 9 years, an indication of a stronger Aleutian Low Pressure System (ESR: Siddon, 2025). This means the Bering Sea was warm, stormy, and had less sea ice.
- Summer bottom trawl SSTs in the EBS were slightly cool, while mean bottom water temperature increased by 0.5°C from 2024 to 2025. The extent of the cold pool was below average and a 29% decrease from 2024 (ESR: Siddon, 2025).
- Winter/spring 2025 sea ice extent was below the 50-year time series mean, and declined substantially from 2024 to 2025 (ESP: Fedewa et al., 2025). Sea ice is expected to arrive in the northern Bering Sea later in winter 2025/2026 than 2024/2025 due to comparatively

low sea ice extent currently in the Chukchi Sea (ESR: Siddon, 2025 *forecast will be updated for final ESR*).

- The NMME ensemble forecasts as of today show moderate warm SST anomalies over much of the SEBS (<0.5°C) into fall 2025, except Bristol Bay shows anomalies up to +2 °C. The NBS is projected to have SSTs close to the historical mean (ESR: Siddon, 2025 *forecast will be updated for final ESR*).
- <u>Prey</u>: Diatom abundance anomalies, based on the Continuous Plankton Recorder, remained positive from 2023 to 2024 (ESR: Siddon, 2025), indicating above-average feeding conditions for pelagic crab stages in 2023 and 2024.
- <u>Competitors</u>: Over the southern shelf, motile epifauna (e.g., sea stars, brittle stars) biomass increased from 2023 to 2024 and remains above the long term mean (ESR: Siddon, 2024). Benthic forager (i.e., small-mouthed flatfish) biomass increased from 2023 to 2024, but remains below the time series mean, suggesting competition for prey resources remains low in 2024 (ESR: Siddon, 2024).
- <u>Predators</u>: The biomass of Pacific cod during the standard bottom trawl survey decreased 5.5% from 2023 to 2024 (ESR: Siddon, 2024), indicating a reduction in predation pressure in 2024.

Fishery-informed Stock Considerations:

Risk Level 1: Normal

Considerations are from updated fishery performance indicators reported in the ESP (Fedewa et al., 2025) and results from the ABSC Skipper Survey regarding the 2024/2025 snow crab fishery.

- Total effort in the fishery, as measured by number of active vessels (25) and total potlifts, 15.7 thousand, was at a historical low during the 2024/25 fishery (ESP: Fedewa et al., 2025).
- CPUE of retained crab in the 2024/25 fishery increased to 219, well above the long term average, from a relatively extreme low of 124 during the last open season (2021/22), and the highest level since 2011/12 (ESP: Fedewa et al., 2025).
- Crab vessel captain observations on fishing conditions in the 2024/25 fishery, as reported in the ABSC Skipper Survey (ABSC, 2025), are consistent with high fishery CPUE. The majority (67%) of captains reported a greater than 10% increase in abundance of industry-preferred males relative to the previous open season, with 38% of respondents reporting a 25% or greater increase. The most commonly reported change in fishing practice from 2021/22 was setting pots at greater depth (48% of respondents) and the principal driver of change in fishing practices (43% of responses) was proportion of undesirable (dirty, low meat fill, bitter crab, etc) crab, compared to 10% of respondents indicating low CPUE as the principal driver.
- The center of distribution of fishing activity in the 2024/25 fishery remained near the extreme northern bound of the historical range, at 59.67 degrees North latitude, marginally north of the center of distribution during the 2021/22 season, and only slightly south of the 59.92 degree historical extreme observed during the 2020/21 season (ESP: Fedewa et al., 2025).

- Incidental catch of EBS snow crab to date in 2025 groundfish fisheries is at a historical low of 27.4 thousand metric tons (ESP: Fedewa et al., 2025).

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