Examining biological processes in the assessment for eastern Bering Sea snow crab

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Contents

Executive summary

Numerous challenges have arisen in the assessment for eastern Bering Sea snow crab in recent years, including convergence difficulties, bimodality in management quantities, finding appropriate ways to model survey selectivity, and time-varying population processes like natural mortality. Furthermore, when population processes (e.g. probability of terminally molting and survey selectivity) are modeled as the best available data suggest, the currently used tier 3 harvest control rule includes a target fishing mortality rate ($F_{35\%}$) that can allow ~100% of commercially exploitable males to be harvested. These issues have resulted in sometimes inconsistent management advice that can be difficult to reconcile with population trends and State of Alaska management strategies.

Members of the SSC and CPT (including ADFG representatives) met in March 2023 to discuss ways to simplify and/or focus the stock assessment models for Bering Sea crab to provide more consistent management advice that reflects the population processes for which we have informative data. Several takeaways relevant to the snow crab assessment model arose from this working group. Perhaps the most important was emphasizing appropriately capturing the biology in the model and letting that guide the reference points used and the suggestion to consider alternative reference points for snow crab (e.g. F_{MSY} = M as in Tier 4 rules, while retaining the realistic population dynamics model).

I present the results from four models representing four conceptual efforts aimed at making progress towards the goals set out in the SSC/CPT March working group: the 'status quo' model, a research model that explores different modeling questions (e.g. time variation in natural mortality or probability of maturing), bridging models that bring desirable aspects of the research model into the operational model, and a simple model based on tier 4 methods (i.e. survey index and natural mortality as an $\mathrm{F_{MSY}}$ proxy) that provides a back-stop/gut-check for the previous more complicated models.

The research model captures the dynamics of the data sources included well and produced reasonable estimates of population processes with more conservative retrospective catch advice than the status quo model when using M as a proxy for $\mathrm{F_{MSY}}$. However, transferring some of the desirable model structure (e.g. varying probability of having terminally molted and BSFRF priors on survey selectivity) to the status quo model proved challenging and did not result in a viable model. Clear paths forward to addressing the shortcomings of the bridge model exist (e.g. including an immature index of abundance) and should be available by September. The simplest tier 4 harvest control rule (i.e. model-free survey-based with F = M) resulted in catch advice generally more conservative than the State of Alaska rule.

The changes in model assumptions described below are the first steps in what will hopefully be a larger, iterative revision of the snow crab model and approach to management. Several decision points related to model assumptions and management are included at the end of this document that would benefit from CPT/SSC discussion.

CPT and SSC comments

First and foremost, I'd like to thank the SSC members, CPT members, and council staff that organized and attended the March working group. It was very productive and useful in guiding this document.

VAST modeling of trawl survey data including both the NBS and EBS should be prioritized. This could help understand some of the inconsistent recruitment/growth trends observed in recent years as well as prepare for potential changes in stock distribution or productivity under future warming of the Bering Sea.

Given the higher level issues within the assessment (several of which are discussed in this document), VAST indices should remain a secondary priority. VAST estimates of the indices of abundance have been used in the past in draft assessments for snow crab and produced markedly different estimates of quantities used in management when compared to assessments using the design-based indices (e.g. Szuwalski 2019b, Szuwalski 2021b). No rationale for why that should be was clear, particularly given a widely distributed and well-sampled stock such as snow crab. Consequently, the models were not adopted. Further, less than 1% of commercially viable males are observed in the northern Bering Sea. The focus of management should be on the fraction of the stock impacted by the fishery first because the available management levers can actually have some effect.

That said, a spatially explicit management strategy evaluation is currently underway and one of the project goals is understanding how the movement of commercially exploitable crab into the NBS could affect the current management strategy and assessment (including the use of a design-based index of abundance). If a larger fraction of commercially exploitable males appear in the NBS, including them in the assessment would quickly become a high priority. Until then, larger problems exist in the assessment.

Explore ways to simplify the number of selectivity parameters, particularly the selectivities used for the BSFRF data, especially in reducing the number of estimated parameters while still informing the relative selectivity and catchability of the NMFS trawl survey.

Models are presented here that treat the BSFRF data as priors on the NMFS survey selectivity, rather than as an extra index of abundance. This eliminates 88 availability parameters, but increases the number of survey selectivity parameters because of the move from logistic selectivity to a non-parametric ogive.

Continue to investigate an appropriate definition of maturity to describe the reproductive output of the stock. This issue highlights the unknown importance of the NBS, where a large proportion of the biomass (relative to the EBS) is composed of morphometrically mature males that are smaller than commercially preferred crab. Direct biological research is needed on this topic.

No definitive answers to this question are provided in this document, but several exercises are undertaken to explore the impacts of different definitions of maturity. A need for more biological research and annual surveys in the northern Bering Sea for snow crab is clear if it is ever to be included in the assessment, given the potential for spatially varying population processes.

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

No information on this topic that has not been presented in the past is included in this document, but it is clear that there are different spatial distributions of males and females that would be expected to result in different environmental influences for the sexes.

Avoid connecting 2019 and 2021 when plotting survey time-series (e.g., Figure 14) as there were no data in 2020

There was no data point shown in 2020, but there was a model prediction, which is what is plotted. For biennial surveys do you recommend not using lines at all?

Report the scale of standardized residuals where plotted (e.g., Figures 42 and 43).

This will be done for the September assessment as these figures were not presented here.

Recent issues

Numerous challenges have arisen in the assessment for eastern Bering Sea snow crab in recent years that have impacted management advice. Convergence difficulties and bimodality in management quantities revealed via jittering analyses have been a common issue (Szuwalski, 2017; Szuwalski 2018a, Szuwalski 2022a). Magnitudes of retrospective patterns have also been concerning (Szuwalski 2019b,), along with an inability to fit the survey index and size composition data with time-invariant assumptions (Szuwalski, 2021a). Repeated changes in the model structure have resulted in sometimes confusing management advice in which the OFL can increase as the trend in commercial biomass decreases (Szuwalski, 2020a). The sum of these issues can result in a lack of confidence in modeling outcomes and requires close attention to ensure continued buy-in from stakeholders.

The issues described above can arise because of time-variation in processes that are not allowed to vary over time in the assessment (e.g. natural mortality), assuming an incorrect form for the shape of a biological or fishery process (e.g. logistic survey selectivity), or from missing data (e.g. the missing survey in 2020). Each time issues like these arose in the assessment, they were addressed (at least partially) with focused fixes. For example, offsets were estimated for natural mortality in 2018 and 2019 when the model was unable to fit the decline in biomass observed in the 2021 survey (Szuwalski, 2021a). The male and female recruitment deviations were unlinked in a response to retrospective patterns (Szuwalski 2019a) and the piece-wise growth curves were replaced with linear growth increment models in response to bimodality in management quantities (Szuwalski, 2018a).

However, some of the potential fixes that best reflect the data and biological understanding for the species resulted in catch advice that exceeded reasonable catches or the application of very high exploitation rates and were consequently not adopted in management. For example, estimating non-parametric survey selectivity resulted in a higher estimated probability of having undergone terminal molt at smaller sizes. This results in a larger fraction of the population protected from the fishery, which in turn resulted in a larger $F_{35\%}$. Models in which the estimated probability of having undergone terminal molt matched observations more closely were not adopted for management because of the unrealistic management advice when coupled with the current Tier 3 reference points.

In March 2023, the SSC and CPT convened a working group to discuss ways to address some of the problems described above. A desire to focus and/or simplify the models for snow crab, Bristol Bay red king crab, and Tanner crab was expressed and, in particular, the working group encouraged assessment authors to think about how they might model their stock if they were to start over without the legacy decisions and assumptions imposed by previous CPT and SSC direction. The working group also stressed the need to work from biology towards management and suggested considering reference points for snow crab outside of those currently used for Tier 3 stocks.

Below, I briefly describe the state of our knowledge on important population processes, outline potential ways to model these processes, present several models at various stages of development that address some of the issues outlined, contrast the management advice derived from each, identify remaining issues, and make suggestions for future research and the September plan team.

Build from biology first

The information available to inform understanding of population processes of the eastern Bering Sea snow crab population is impressive compared to other U.S. crustacean stocks. The survey provides a long time series of indices of abundance and size composition data in which pseudocohorts can be clearly seen moving through the population (Figure 1). Chelae height data from the survey exist that inform what fraction of the population will no longer grow at a given size in a given year. Studies have been performed to characterize the growth increment for molting snow crab in addition to selectivity experiments to understand the efficiency of the NMFS survey gear (Somerton et al., 2013). Few other fisheries have this quality and breadth of data. At the same time, the population dynamics of snow crab are more complicated than many finfish species, particularly the discrete growth dynamics determined by the molting process and the resulting inability to age crab. Below, some of the issues with modeling key processes for snow crab are discussed.

Terminal molt and maturity

Snow crab undergo a terminal molt to maturity, after which they do not grow (Tamone et al., 2005). This can occur over a range of sizes for male snow crab and the probability of molting to maturity each year is quantified by calculating the ratio of large-clawed new shell male animals to small-clawed new shell male animals. The classification of 'large' or 'small' clawed animals is done via a cut-line analysis similar to Tamone et al (2007). Data exist starting from 1989 with a few gaps during years in which chelae height were not measured (Figure 2).

The terminal molt to maturity is a critical component to include in models that provide management advice because the discrete growth process in snow crab occurs between the survey and the fishery. This means that some fraction of the crab in the size classes smaller than the commercially preferred size will grow into the commercial size range, but whether or not they grow depends on if they are morphometrically mature or not. Consequently, the chelae height data are an important data source to collect annually.

Survey selectivity

Survey selectivity refers to the fraction of animals captured by the NMFS survey gear as a function of size. Historically, selectivity was estimated within the assessment and assumed to be logistic. The Bering Sea Fisheries Research Foundation (BSFRF) performed selectivity experiments in which *Nephrops* trawl gear was used in the same area as the National Marine Fisheries Service trawl gear (Figure 3; see Somerton et al., 2013 for a description). The *Nephrops* gear used by the BSFRF was assumed to capture all crab in its path given strong bottom contact. The resulting area-swept estimates of numbers of crab at size from the BSFRF and NMFS surveys ($\hat{N}_{y,s,NMFS}$ and $\hat{N}_{y,s,NMFS}$, respectively) can be used to infer the selectivity of the NMFS gear in year y as:

$$S_{y,NMFS} = \frac{\hat{N}_{y,s,NMFS}}{\hat{N}_{y,s,BSFRF}} \tag{1}$$

The experimental trawls captured snow crab in the years 2010, 2011, 2016, 2017, and 2018, but the spatial foot print and sample sizes varied by year (Figure 3). The calculated selectivities by size and by year were fairly consistent for snow crab of carapace widths 40 - 95 mm. The BSFRF data suggest that the largest snow crab in the EBS have a catchability close to one (i.e. the survey estimates of large crab are 'absolute' estimates, given the assumption that the entire population of large animals is within the surveyed area) and declines to somewhere near 0.55 for the smallest crab selected in the fishery (i.e. the survey estimates of the number of crab ~95mm carapace width are smaller than the true number of crab in the EBS). However, the sample size for the BSFRF surveys of large crabs is small relative to the sample size for medium and small crab (Figure 4), which might encourage caution in interpreting selectivities at larger sizes.

The BSFRF data have historically been used as an additional survey in the stock assessment and this has had the effect of reducing estimates of catchability. Decreases in catchability have the effect of increasing estimates of mature male biomass relative to the survey estimates, which then results in higher overfishing levels (OFLs) and acceptable biological catches (ABC). In past assessment documents, forcing the catchability to equal that implied by the BSFRF data resulted in much higher allowable catches than seemed reasonable (Szuwalski, 2020a). However, those analyses also retained the assumption of logistic selectivity, which may not be supported by the BSFRF data.

Appropriately capturing survey selectivity is important to providing catch advice because it scales the survey index of relative abundance at size estimates to an absolute value. The BSFRF data are the best available source of information on the selectivity of the survey gear.

Natural mortality

Prior to 2021, time-invariant natural mortality was estimated for both sexes and maturity states. However, with the large decline in the stock observed in the 2021 survey, it was necessary to incorporate a mortality event into the model to fit the data (Szuwalski, 2021a). Positive offsets to natural mortality were estimated for each sex and maturity state in 2018 and 2019 for the 2021 assessment. Although the estimation of a mortality event in these two years allowed the model to fit the data, the overarching assumption of time-invariant natural mortality during the remaining years in the model is likely false.

Analyses were presented in 2022 SAFE documents that estimated fully time-varying natural mortality for immature and mature males in a simplified population dynamics model (Szuwalski, 2022a). Links between estimated time-variation in mortality and indices representing various hypotheses for the collapse were examined using generalized additive models (GAMs). In this process, simulation tests were performed to evaluate the ability of size-structured population dynamics models to estimate time-variation in mortality. The trends in estimated mortality were highly correlated with the underlying simulated mortality when the model was correctly specified and observation error was similar to that assumed in the assessment, which suggests that estimating time-variation in M may be feasible for a stock with life history and data availability similar to snow crab.

Models presented

Given the influence of the above population processes on the dynamics of a stock, any model used to provide management advice should inform these with the best available information. For snow crab this means that the probability of having undergone terminal molt should reflect the observed annual variability and survey selectivity should reflect the BSFRF selectivity experiments. A more complete treatment of time-variation in natural mortality (rather than just two years of off-set) might also be useful to consider given the outcomes of the analyses aimed at understanding the collapse of snow crab presented in September 2022.

Four models representing four conceptual efforts are presented here and incorporate the above ideas to varying degrees: the ‘status quo’ model (currently used in management), a research model (i.e. a space to explore different modeling questions like e.g. time-varying natural mortality or probability of maturing), a bridging model that brings desirable aspects of the research model into the status quo model, and a simple model based only on the survey index of abundance that provides a back-stop/gut-check for the previous more complicated models. The way each of the more realistic models treat different population processes and data sets is summarized in (Table 2) and discussed in more detail below.

A limited number of figures, tables, and diagnostics compared to the full assessment are presented here because the aim of this document is to explore the high level impact of different assumptions about biological processes on the behavior of models, not provide catch advice. Furthermore, the research model is not a GMACS model and fits to different data sources (abundance for research model vs. biomass for GMACS models), which impairs the ability to concurrently plot the output with the GMACS models. Please excuse some growing pains with the figures as the transition to the GMACS plotting package *gmr* occurs. The research model is presented first as a demonstration of potentially desirable qualities of a model for snow crab. The status quo and modifications of the status quo to make it more similar to the research model (i.e. the bridge models) model are presented last.

Research model

The research model is an extension of the research model used to explore potential hypotheses behind the drivers of the collapse of EBS snow crab from 2018-2021 (Szuwalski, 2022a; also in review for publication). The original research model tracked male crab that were smaller than those harvested by the directed fishery (<95mm carapace width) and was a bespoke model coded in ADMB. The updated version of this model extends the size range of crab modeled to match the status quo assessment (27.5-132.5 mm carapace width) and incorporates the directed fishery (both retained and discarded crab) into the model. Key aspects of the research model not present in the status quo model include:

- an estimated annually varying natural mortality by maturity state
- a specified annually varying probability of having undergone terminal molt
- fits to immature and mature indices of abundance, rather than just an index of mature biomass
- BSFRF data are treated as a prior on survey selectivity, not an additional index of abundance
- size transition matrix is calculated outside of the model

The research model is a large departure from the status quo model that replaces important legacy decisions and assumptions. It is relatively simple (i.e. females and the non-directed fisheries are excluded) to minimize influence from assumptions related to the interaction of the sexes and fisheries on model output. A bespoke model framework was chosen because it is easier to modify quickly than GMACS. Once a model structure shows promise, more time can be taken to develop GMACS to accommodate the needed changes.

Population dynamics

The population dynamics within the research model operate on a half year time step, starting in July at the time of the NMFS survey. Natural mortality (M) is estimated by year (y) and maturity state (m). Other estimated parameters include the initial numbers at size by maturity state, yearly log recruitments, a vector of scalars that determine the proportions of estimated recruitment split into the first two size bins, and survey and fishery selectivity parameters. Parameters determining growth and maturity were estimated outside of the model and specified. Natural mortality is the only population process that occurs in the first half of a given year:

$$N_{t=y+0.5,s,m} = N_{t=y,s,m} e^{-M_{t,s,m}/2} \tag{2}$$

Growth occurs at the beginning of the second half of the year for immature crab and is represented in the model by multiplying the vector of immature crab at size by a size-transition matrix $X_{s,s'}$ that defines the size to which crab grow given an initial size. All immature crab are assumed to molt and no mature crab molt. The newly molted crab are assigned to a maturity state based on observed ogives of the proportion of mature new shell males by size calculated from chelae height measured in the NMFS survey data (Otto, 1998), which varies over time ($\rho_{y,s}$; Figure 2). The average probability of having undergone terminal molt is used in years during which data were not collected. This process results in two temporary vectors of numbers at size:

$$n_{t=y+0.5,s,m=1} = \rho_{y,s} X_{s,s'} N_{t=y+0.5,s,m=1} \tag{3}$$

$$n_{t=y+0.5,s,m=2} = (1-\rho_{y,s}) X_{s,s'} N_{t=y+0.5,s,m=2} \tag{4}$$

The size transition matrix $X_{s,s'}$ was constructed using growth increment data collected over several years (see Szuwalski [2022a] for a summary) to estimate a linear relationship between pre- and post-molt carapace width, ($\hat{W}^{pre}_{s,w}$ and $\hat{W}^{post}_{s,w}$, respectively) and the variability around that relationship was characterized by a discretized and renormalized normal distribution with a standard deviation informed by the growth increment data, $\mathrm{Y}_{s,w,w'}$.

$$X_{s,w,w'} = \frac{Y_{s,w,w'}}{\sum_{w'} Y_{s,w,w'}} \tag{5}$$

$$Y_{s,w,w'} = (\Delta_{w,w'})^{\frac{L\hat{s,w} - (\bar{W}_w - 2.5)}{\beta_s}} \tag{6}$$

$$\hat{L}^{post}_{s,w} = \alpha_s + \beta_{s,1} hat W^{pre}_{s,w} \tag{7}$$

$$\Delta_{w,w'} = \bar{L}_{w'} + 2.5 - W_w \tag{8}$$

Recruitment by year, τ_y, was estimated as a vector in log space and added to the first two size of classes of immature crab based on another estimated vector δ_y that determines the proportion allocated to each size bin.

$$n_{t=y+0.5,s=1,m=1} = n_{t=y+0.5,s,m=1} + \delta_y e^{\tau}_y \tag{9}$$

$$n_{t=y+0.5,s=2,m=1} = n_{t=y+0.5,s,m=1} + (1 - \delta_y) e^{\tau}_y \tag{10}$$

The directed fishery is modeled as a pulse fishery in which crab are removed from the ocean given an estimated fishery capture selectivity ($S_{tot,l}$). Then a fraction of the captured crab are retained based on an estimated retention selectivity ($S_{ret,l}$) and the rest are returned to the ocean with an assumed discard mortality of 20%, as used in the status quo assessment.

$$S_{tot,l} = \frac{1}{1 + e^{-S_{slope,tot}(L_l - S_{50,tot}}}) \tag{11}$$

$$S_{ret,l} = \frac{1}{1 + e^{-S_{slope,ret}(L_l - S_{50,ret}}}) \tag{12}$$

$$\tag{13}$$

Predicted retained ($C_{ret,y}$) and discarded crab ($C_{ret,y}$) by year y are calculated based on an estimated fully-selected fishing mortalitY (F_y) as:

$$C_{ret,y} = \sum_l \sum_m w_l S_{ret,l} S_{tot,l} N_{male,v,m,y,l} e^{-0.5 M_{s,m}} (1 - e^{-(F_{y,l})}) \tag{14}$$

$$C_{disc,y} = \sum_l \sum_m w_l (1 - S_{ret,l}) S_{tot,l} N_{male,v,m,y,l} e^{-0.5 M_{s,m}} (1 - e^{-(F_{y,l})}) \tag{15}$$

$$\tag{16}$$

Finally, the last half of the year of natural mortality is applied to the population after growth, molting, fishing, and recruitment occur. Note that this allows a crab to experience two different natural mortalities within a given year as it undergoes terminal molt.

$$N_{t=y+1,s,m=1} = n_{t=y+0.5,s,m=1} e^{-M_{t,s,m}/2} \tag{17}$$

$$N_{t=y+1,s,m=2} = (N_{t=y+0.5,s,m=2} + n_{t=y+0.5,s,m=2}) e^{-M_{t,s,m}/2} \tag{18}$$

Objective function

The objective function for the population dynamics model consists of likelihood components (representing the fit of the model to the data) and penalty components (which incorporate constraints in the fitting based on prior information) that are summed and minimized in log space to estimate parameters within the model. Several data sources were fit to using the following likelihoods. Observed survey size composition data by maturity state and retained and discarded size composition data were fit using multinomial likelihoods implemented in the form:

$$L_x = \lambda_x \sum_y N_{x,y} \sum_l p^{obs}_{x,y,l} ln(\hat{p}_{x,y,l}/p^{obs}_{x,y,l}) \tag{19}$$

L_x was the likelihood associated with data component x, where λ_x represented an optional additional weighting factor for the likelihood, $N_{x,y}$ was the sample sizes for the likelihood, $p^{obs}_{x,y,l}$ was the observed proportion in size bin l during year y for data component x, and $\hat{p}_{x,y,l}$ was the predicted proportion in size bin l during year y for data component x. Sample sizes were input as 50.

Observed indices of abundance for immature and mature males and retained and discarded numbers were fit with log normal likelihoods implemented in the form:

$$L_x = \lambda_x \sum_y \frac{(ln(\hat{I}_{x,y}) - ln(I_{x,y}))^2}{2(ln(CV^2_{x,y} + 1))} \tag{20}$$

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

Penalties and priors

Smoothing penalties were placed on estimated vectors of deviations for immature and mature natural mortality (and immature and mature catchability in the simulation analyses aimed at understanding the estimability of mortality and catchability in Szuwalski, [2022a]) using normal likelihoods on the second differences of the vectors. Normal priors were also placed on the mean value of natural mortality and the deviation of the estimated mortality from that mean. A prior value of 0.27 is used for the average natural mortality based on assumed maximum age of 20 and Hamel's (2015) empirical analysis of life history correlates with natural mortality. The priors used for catchability were derived from the BSFRF selectivity experiments described above. The normal priors were of the form:

$$P_x = \lambda_x \sum_y \frac{((\hat{I}_{x,y}) - (I_{x,y}))^2}{CV^2_{x,y}} \tag{21}$$

P_x was the contribution to the objective function of the penalty associated with model estimate x, λ_x was any additional weighting applied to the component, $\hat{I}_{x,y}$ was the predicted value of population process I relevant to penalty x during year y, $I_{x,y}$ was the prior value of process I relevant to penalty x during year y and $CV_{x,y}$ was the input coefficient of variation for penalty x during year y.

Fits and estimated population processes

The research model fits the immature and mature male survey indices of abundance and size composition data well, which is perhaps expected given the flexibility of the model provided by annually varying recruitment and mortality (Figure 5). When looking at the recent survy size composition data, the model struggled somewhat to fit the size composition in 2021 (Figure 6 & Figure 7), but the fits to 2022 improved. Fits to the retained and discard catch abundances were generally good (Figure 8), though some years of discard in the early 1990s were not fit well. The number of large males predicted in the retained catch size composition data was somewhat overestimated, though discard size composition data were well fit (Figure 8). Runs of years in which similar lack of fits (both greater or less than the observed data) appeared in the yearly catch size composition data (Figure 9 & Figure 10), which suggests fishery selectivity may have varied over time.

Estimated natural mortality was higher for mature animals than immature animals, with pronounced peaks in 2018 and 2019 (Figure 11). Estimated fishing mortality also displayed two large peaks, one in 1992 and one in 2020 (Figure 11). Estimated recruitment was highest in the mid-1980s and 2010 when lagged 5 years (Figure 12). Estimated survey selectivity was somewhat lower than the prior derived from the BSFRF data for crab <90mm carapace width and slightly higher than the prior for crab >90mm carapace width (except for the two largest size classes; Figure 13). Capture selectivity in the fishery was ~50% at 90mm carapace width. Retention selectivity was 50% at approximately 105mm carapace width (Figure 13).

Status quo and bridge model(s)

The status quo model is coded in GMACS and models male and female dynamics by maturity state and size. The sizes included in the model range from 27.5 - 132.5 mm carapace width and the time frame included spans 1982-present. A directed fishery and a non-directed fishery are modeled as pulse fisheries occurring in mid-February. Retained and discarded biomasses and their respective size composition data from the directed fishery are fit in the assessment. All bycatch in other fisheries is lumped into a single fishery, with the majority of the bycatch coming from the non-pelagic trawl fisheries. The NMFS survey estimates (1982-present) of morphometrically mature male biomass and mature female biomass are fit in addition to the size compositions associated with both immature and mature individuals of both sexes. Sample sizes for survey size composition data are specified as 100 even though many thousands of crab are measured each year. Growth increment data are fit with a linear model against pre-molt size to estimate a size transition matrix. All immature animals are assumed to molt; no mature animals molt. The probability of having undergone terminal molt is a single estimated non-parametric ogive by sex. Selectivities for all NMFS surveys are estimated logistic curves with an estimated catchability coefficient. Non-parametric availability and selectivity ogives are estimated for BSFRF data in 2009 and 2010, which are linked to the NMFS survey selectivity. A constant natural mortality is estimated by sex and maturity state with offsets in 2018 and 2019 representing a mortality event. A complete description of the status quo model can be found in Szuwalski, 2022x.

Two bridge models are presented that are identical except one estimates annually varying natural mortality ("Focused + vary M") and one estimates offsets for natural mortality in 2018 and 2019 like the status quo model ("Focused"). The key differences between the bridge models and the status quo model are:

- the probability of having undergone terminal molt is specified and annually varying
- The first and second survey eras (1982-1988 and 1989-present, respectively) have the same selectivity and catchability and are specified (not estimated) based on inferred selectivity from the BSFRF data
- BSFRF data are removed as an index of abundance

Fits and estimated population processes

The fits of the status quo and bridging models to the survey data captured the trends in the data similarly on a decadal scale (Figure 14). There was a tradeoff among the models with respect to fits in the final two years of the model. The 'Focused' model fit 2021 well, but missed 2022 and 'Focused + vary M' missed 2021, but fit 2022. All catch data sources were well fit by all models (Figure 15). The male molt increment data were similarly fit across models, but fits to the female growth data were more varied, with the 'Focused' model fitting the data most poorly (Figure 16).

Total catch size composition data were relatively well fit by all models (Figure 17), but retained catch size composition data were better fit by the status quo model in many years (Figure 18). The 'Focused' model predicted more large males in the retained catch than the status quo, which is potentially related to the slightly higher slope of the estimated growth curve from the 'Focused' model. The female discard data from the directed fishery were similarly fit by all models (Figure 19). Trawl bycatch size composition data for both sexes were the least well fit of the size composition data, with the status quo model tending to predict more larger males in the non-directed fishery (Figure 20 & Figure 21).

No clear trends in fits were apparent for the survey size composition data among models (Figure 22 - Figure 29). Some years the status quo fit the data better; some years one of the bridging models did.

"Focused + vary M" fit the immature males in 2021 better than the other models, but fit 2022 poorly. The fits to mature male size composition survey data in 2021 and 2022 were poor across models, but poor in different ways. The status quo predicted a larger number of large males than observed in 2022, whereas the two bridging models predicted larger numbers of medium size males.

Estimated fishing mortality in the directed and non-directed fisheries in the bridging models were scaled up compared to the status quo model (Figure 30). This is likely related to both the estimated capture selectivity curve in the directed fishery being shifted to the right and the large changes in survey selectivity for the range of crab vulnerable to the fishery (Figure 31). The fishing mortalities estimated by the bridging models seem unreasonably high, with an average fully-selected exploitation rate of 75% over the history of the fishery and some years effectively 100%. The estimated probability of having undergone terminal molt from the status quo model was markedly below the average of the observed proportion of new shell males with large claws (Figure 32).

Natural mortality for mature males was estimated slightly higher in the 'Focused' model than in the status quo model; M for immature males was slightly lower (Figure 33). "Focused + vary M" estimated peaks in male mortality in similar, but not exactly the same, places to the research model. Trends in estimated recruitment were similar among models, but differences in the timing and magnitude of large recruitments existed (Figure 34). Trajectories of MMB differed substantially among the GMACS models presented here (Figure 35).

The changes made to the bridging models reduced the retrospective patterns in MMB (Figure 36) and model fits to the survey data (Figure 37). It also removed the bimodality in management quantities observed in the jittering analysis of the status quo model resulting from two different plausible explanations for the trajectory of the stock through the 2020 when no survey data were collected (Figure 38). However, while the changes made to the bridging models resulted in some improvements to model behavior, caution should taken when interpreting the estimated trends in poplation processes given unresolved issues in the model like unreasonably large estimates of fishing mortality and the inability of the model to converge when estimating selectivity parameters. Ultimately, it is difficult to endorse any of the GMACS models in their current form. However, there are still several aspects of the model that could be improved between now and September that may resolve the issues in the bridging models (discussed below) and the success of the research model suggests these issues may be overcome.

Reference points

Once a model that captures the key aspects of the biology informed by the best available information is developed, appropriate management targets need to be chosen. The tier system used for crab outlines management targets for stocks with differing amounts of information (NPFMC, 2007) and are briefly described below. OFLs are also compared for a range of models and reference points.

Tier 3

The status quo assessment calculates the overfishing level (OFL) using a tier 3 harvest control rule with proxies for biomass and fishing mortality reference points based on spawner-per-recruit methods (e.g. Clark, 1991). These are calculated by first fitting the assessment model to the data and estimating population parameters, then projecting the model forward 100 years using the estimated parameters under no exploitation and constant recruitment to determine 'unfished' mature male biomass-per-recruit. Projections are then repeated in which the bisection method is used to identify a fishing mortality that reduces the mature male biomass-per-recruit to 35% of the unfished level (i.e. $F_{35\%}$ and $B_{35\%}$). Calculations of $F_{35\%}$ are made under the assumption that bycatch fishing mortality is equal to the estimated average value over the last 8 years.

Calculated values of $F_{35\%}$ and $B_{35\%}$ are used in conjunction with a Tier 3 control rule to adjust the proportion of $F_{35\%}$ that is applied based on the status of the population relative to $B_{35\%}$ (Amendment 24; NPFMC, 2007). 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:

$$F_{OFL} = \begin{cases} Bycatch & if \frac{MMB}{MMB_{35}} \leq 0.25 \\ \frac{F_{35}(\frac{MMB}{MMB_{35}} - \alpha)}{1-\alpha} & if 0.25 < \frac{MMB}{MMB_{35}} < 1 \\ F_{35} & if MMB > MMB_{35} \end{cases} \tag{22}$$

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

Unfortunately, the bridging models that most appropriately represent the biology (in particular the probability of having undergone terminal molt) produce an $F_{35\%}$ of 83.9 ("Focused" model), which corresponds to an exploitation rate of ~100% on the largest crab in the population (Table 1). Consequently, other methodologies for developing reference points need to be considered.

Tier 4

Tier 4 harvest control rules have historically been used for Bering Sea crab stocks that have more limited data than snow crab. These data limitations can preclude the development of a population dynamics model, so the survey estimates of abundance and biomass are taken as absolute measures to be used in a harvest control rule to set the OFL. In the tier 4 HCR, natural mortality is used as a proxy for F_{MSY} and a B_{MSY} proxy is calculated as an average over a selected time period. Previous analyses have shown that using the currently used currency of management (i.e. morphometrically mature male biomass) in a tier 4 HCR can lead to OFLs that exceed the amount of exploitable >101mm carapace width biomass in the water (Figure 39; Szuwalski, 2022a). However, a simple tier 4 calculation is also needed for a sanity check and back stop for years in which unexpected modeling outcomes occur. To this end, a time series of OFLs starting after rationalization was calculated based on the survey estimates of biomass with carapace width 95 mm or greater and specifying the F_{MSY} proxy as 0.27 based on the relationship between natural mortality and an assumed maximum age of 20 years (Hamel, 2015). The B_{MSY} proxy was specified as the average biomass of >95mm carapace width crab from 1982-2021.

In addition to being a useful backstop/gut-check, the tier 4 rules can provide another option for specifying reference points that are more appropriate for the combination of a terminally molting life history of snow crab and size-selective fishing processes than the SPR methods in tier 3. OFLs for the bridging models and the research model were calculated using natural mortality as a proxy for F_{MSY} and specifying the proxy for B_{MSY} as the average MMB over the years 1982-2021.

Comparison of management advice from models

The status quo model estimated an $F_{35\%}$ of 1.5, which is fairly consistent with the recent estimates of $F_{35\%}$. However, this is only because the estimated probability of having undergone terminal molt far underestimates the observed probabilities. When that problem is fixed in the 'Focused' and 'Focused + vary M' models, the estimated $F_{35\%}$ increased to 83.9 and 127.89, respectively (Table 1). In reality, 35% of unfished biomass cannot be reached with the current fishery selectivity in these models and the model was attempting to achieve 35% by taking all of the large animals.

Replacing the SPR proxy for F_{MSY} with natural mortality yielded more reasonable fishing mortalities applied to the stock (Table 1). Revising the proxy for B_{MSY} to an average over the history of the fishery also resulted in much larger biomass targets (215kt vs 80kt for the 'Focused' model; Table 1). Given these changes in reference points and no change in the estimated terminal year biomasses, fishery closures would have occurred for two of the models and an OFL of 500t in another.

The State's total allowable catch (TAC) is ~40% of the Federal ABC on average (Figure 40). OFLs generated from the research model for the post-rationalization period were comparable to the TAC when the F_{MSY} proxy was 0.27, which is the value of the prior used to estimate natural mortality in all of the models presented here. However, when the average of the estimated natural mortality from the research model was used as the proxy (0.73), the resulting OFLs were more comparable to the ABCs. Applying the simplest tier 4 model (i.e. survey biomass + natural mortality) produced the most conservative management advice (Figure 40).

Decision points

None of the models in this analysis perfectly satisfy the needs of management. The research model is close in that it incorporates key aspects of the biology of snow crab that are not captured by the status quo model, but it doesn't include females or the non-directed fishery. There are remaining questions about the goodness of fit to large crab in the size composition data and the appropriateness of estimates of natural mortality for mature males. The bridging models included updated population processes in the research model and still includes females and the non-directed fishery, but issues existed with some fits to data, convergence when estimating some parameters, and estimated population processes that would likely preclude adoption for management. Data weighting considerations and changing the data that are fit (e.g. using immature and mature indices of abundance, rather than just mature biomass) may improve some of these issues. Regardless of what model is chosen, the use of alternative reference points appears to be a necessary change and using M as a proxy for F_{MSY} is a commonly used tactic.

Moving forward, there are several decision points related to model selection that would benefit from CPT/SSC discussion. In no particular order:

1. *How should the reference probability of terminally molting be selected?*

This is less of a problem if SPR proxies are no longer used, but, if proxies for reference points are used that require projecting the stock forward, a decision needs to be made about how to select reference period for maturity processes. This could be complicated by potential environmental and density dependent effects reported in the literature (Mullowney et al., 2021).

2. *Should natural mortality vary annually or only large mortality events delineated?*

It is clear that natural mortality is not likely time-invariant for wild populations, but this is still an often-made assumption that is considered to be useful in model fitting. Guidance on the conditions under which a model with annually varying natural mortality would be accepted would be useful. If a model with annually varying M is requested, discussion on what M to use for the projection from the survey to the fishery in order to calculate the OFL would also be useful.

Mature male crab that are too small to be captured in the fishery appear to exit the population 5-6 years after maturing (Szuwalski, 2019a). It's unclear how to interpret the longevity rationale used to specify a prior for M when an animal makes a life transition like terminal molt. The crab that mature enter the mature numbers-at-size matrix and then need to disappear in approximately 6 years. That requires a higher M than 0.27 and is likely related to the high estimated mature M in the research model relative to immature M. Hamel's (2015) empirical analysis suggests that a longevity of 6 years corresponds to an M of 0.95, which is not far off the average estimates for mature males from the research model.

3. *How should estimated parameters be chosen?*

The bridging models had convergence issues when selectivity and growth parameters were estimated. The convergence issues occurred when the probability of having matured were specified. Attempting to estimate the parameters associated with the probability of having matured would likely present further convergence issues. Additionally, when selectivity was estimated with a BSFRF-based prior rather than specified, the shape of the selectivity curve departed from the prior. This suggests that data weighting needs to be considered with respect to the quantity and quality of the priors used.

In general, discussion on when to estimate the parameters associated with a population process inside vs. outside the model would be useful. Generally, the assessment zeitgeist directs an analyst to estimate as many of the parameters within the model as possible to propagate uncertainty. However, this can cause problems if the model is mis-specified, which has been a consistent issue for snow crab.

4. *How to define B_{MSY} when using Tier 4?*

Tier 4 proxies for $\mathrm{B_{MSY}}$ are meant to be chosen over a period of time during which the stock was fished at $\mathrm{F_{MSY}}$, but this is difficult to define when there is no stock recruit relationship. One possible way of determining the year range is using the estimated fishing mortality from the assessment to identify years in which the fishing mortality was beneath a cutoff. However, this could also be seen as somewhat circular and the stock is not necessarily in equilibrium even if it is being fished at a consistent rate.

5. *How should the early survey period be treated (1982-1988)?*

All of the models presented here include the early survey period, but slight differences in the survey footprint makes the estimates of biomass not directly comparable between the periods. The extent of how incomparable they are has not been examined and historically the selectivity for the two eras were estimated separately to address this problem. However, survey selectivity could not be successfully estimated in the bridging models (yet). More appropriate data weighting that allows the priors on selectivity to perform as expected should allow the selectivity for the two eras can be estimated again, but this will require some trial and error.

6. *What data should be fit?*

The status quo model fits to mature biomass, but the research model fits to immature and mature male abundance indices. The Tanner crab model fits to total male and female numbers and the maturity data. Discussion on the relative merits of each would be useful. Given the importance of the commercially preferred males to setting catch advice, should they be fit in the model as well to ensure good estimates?

7. *What is the relative confidence in each data set available for snow crab?*

This matters when considering weighting schemes and the existing sample sizes and CVs may or may not reflect the relative confidence in each data set.

The process of producing a focused model and management strategy for snow crab will be an iterative process and, while the modeling exercises here yielded useful outcomes, further work needs to be done before use in September. Discussion on the above points will facilitate that work.

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Table 1: Changes in management quantities for each scenario considered. Reported management quantities are derived from maximum likelihood estimates.

Model	MMB	B35	F35	FOFL	OFL
Status quo	41.209	183.148	1.504	0.324	10.322
Focused	93.924	80.304	83.867	41.436	21.879
Focused + vary M	39.426	44.967	127.889	21.132	8.192
Status quo (tier 4)	41.421	249.183	0.285	0.000	0.119
Focused (tier 4)	93.904	215.388	0.412	0.092	0.500
Focused + vary M (tier 4)	39.426	162.445	0.192	0.000	0.036

Table 2: Key differences in presented models. ‘Focused + vary M’ is identical to Focused except for it allows annually varying M.

	Status quo	Research model	Focused
Sex	Male + female	Male	Male + female
Maturity	Single estimated ogive	Input as yearly data	Input as yearly data
BSFRF.data	Treated as an additional survey with estimated availability	Treated as prior on survey selectivity	Treated as prior on survey selectivity
Survey.sel.	Logistic by sex (1982-1988; 1989-present	Non-parametric	Non-parametric; shared by sex 1982-present
Growth	Linear estimated	Linear specified	Linear estimated
Natural.M	Immature + Mature by sex; offset in 2018 and 2019	Immature + Mature; time-varying	Immature + Mature by sex; offset in 2018 and 2019

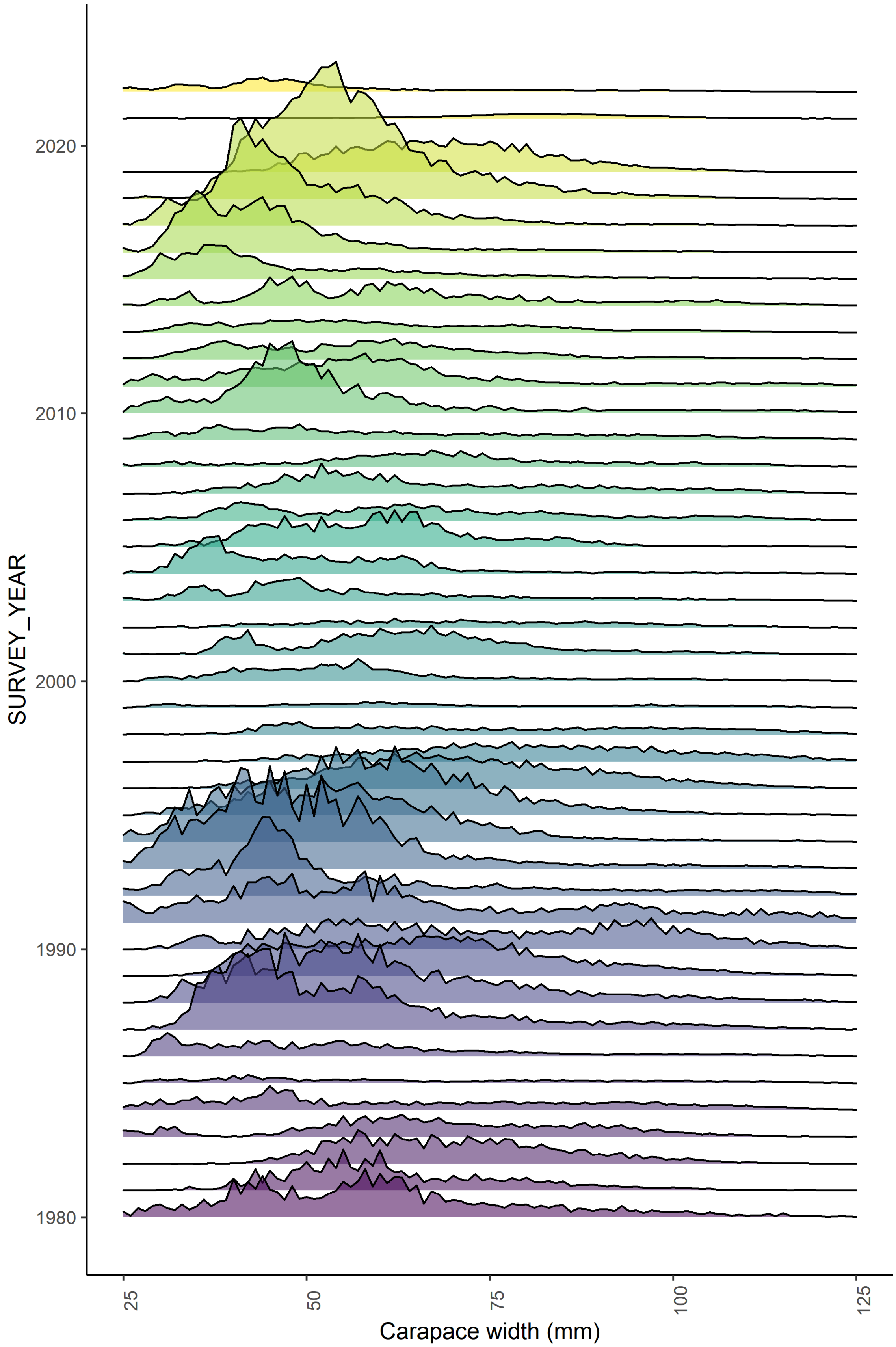

Figure 1: Relative numbers at size of male snow crab over time observed in the EBS survey.

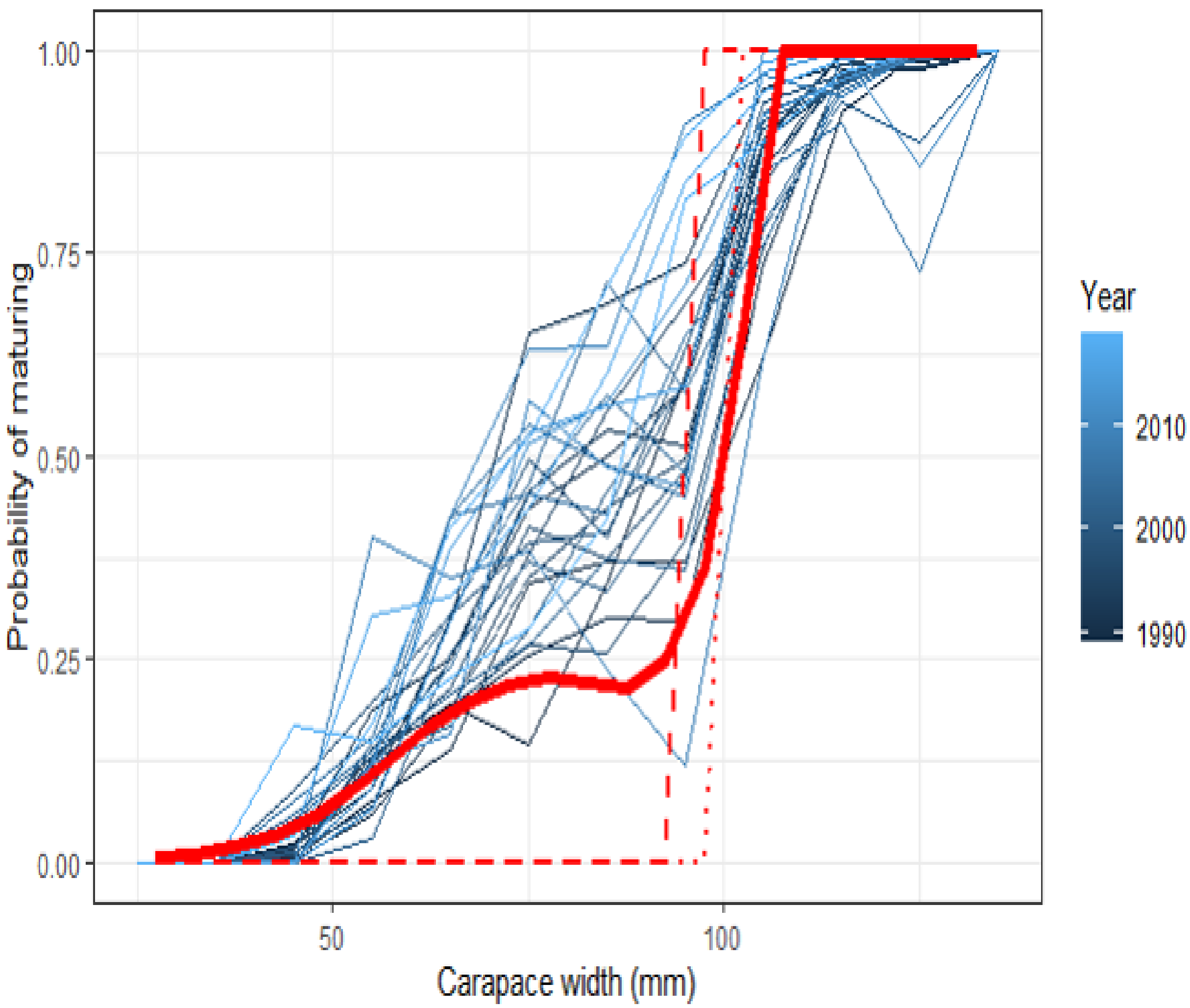

Figure 2: Observed probability of having undergone terminal molt for snow crab in the EBS, derived from the observed proportion of new shelled males at size with large claws. Solid red line is the estimate of the probability of having undergone terminal molt from the 2022 status quo model. Dashed and dotted red lines are alternate possibilities for 'functional' maturity.

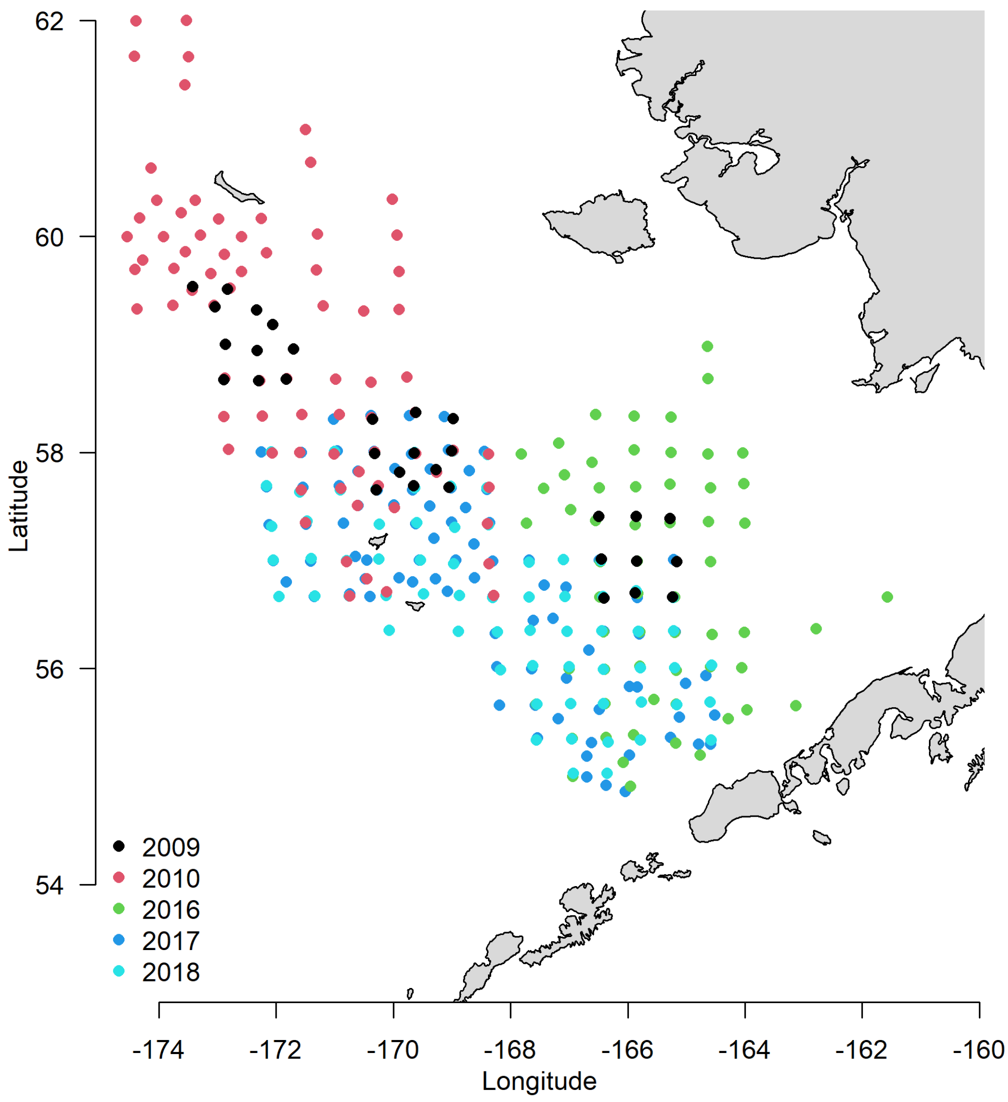

Figure 3: Location of BSFRF selectivity experiments by year.

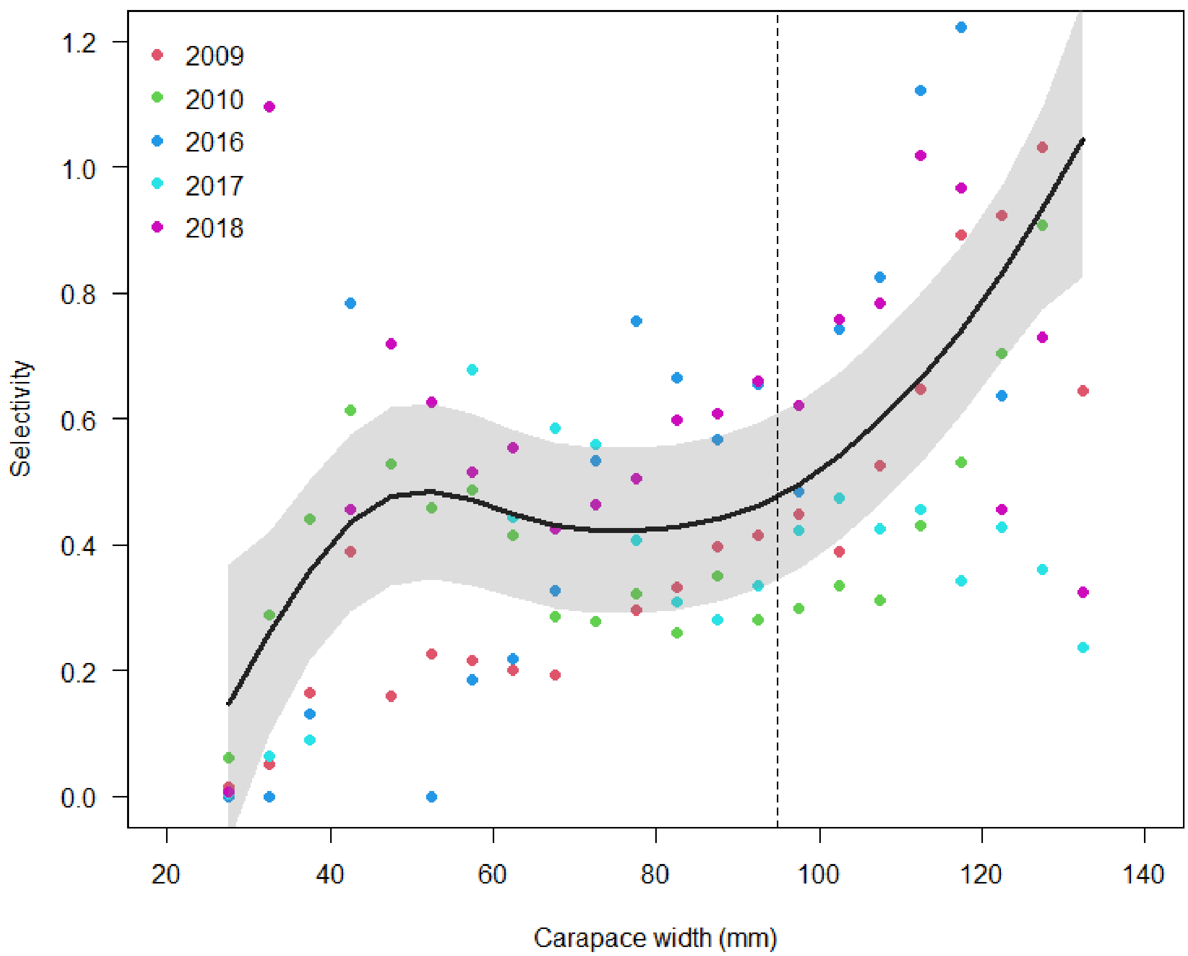

Figure 4: Inferred selectivity of NMFS gear based on BSFRF selectivity experiments.

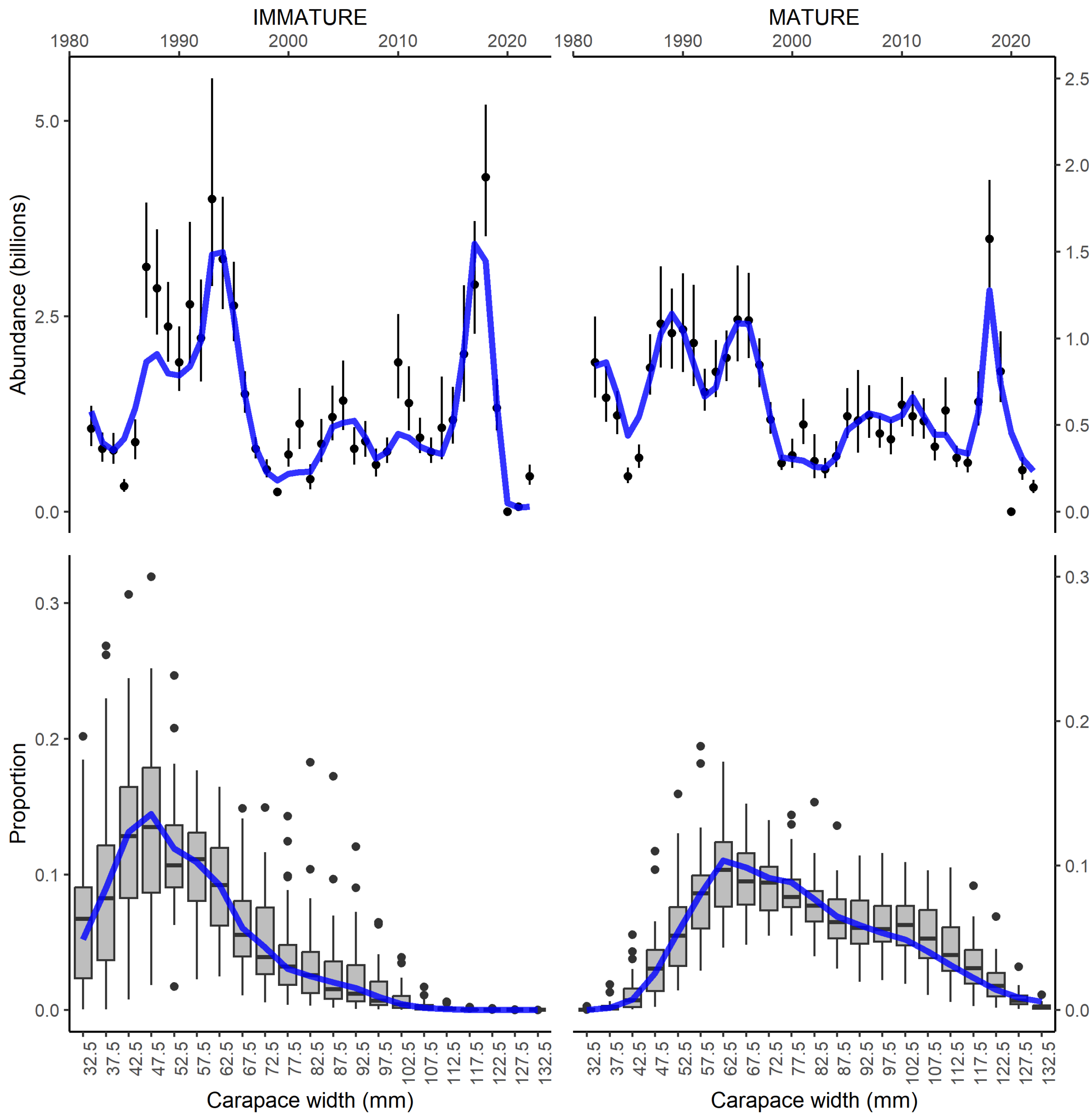

Figure 5: Fits to immature and mature male survey indices of abundance and aggregate size composition data from the research model. Points and vertical lines are observed abundances and estimates are blue, box plots are size composition data aggregated over the study period with average estimated size composition over year by size in blue.

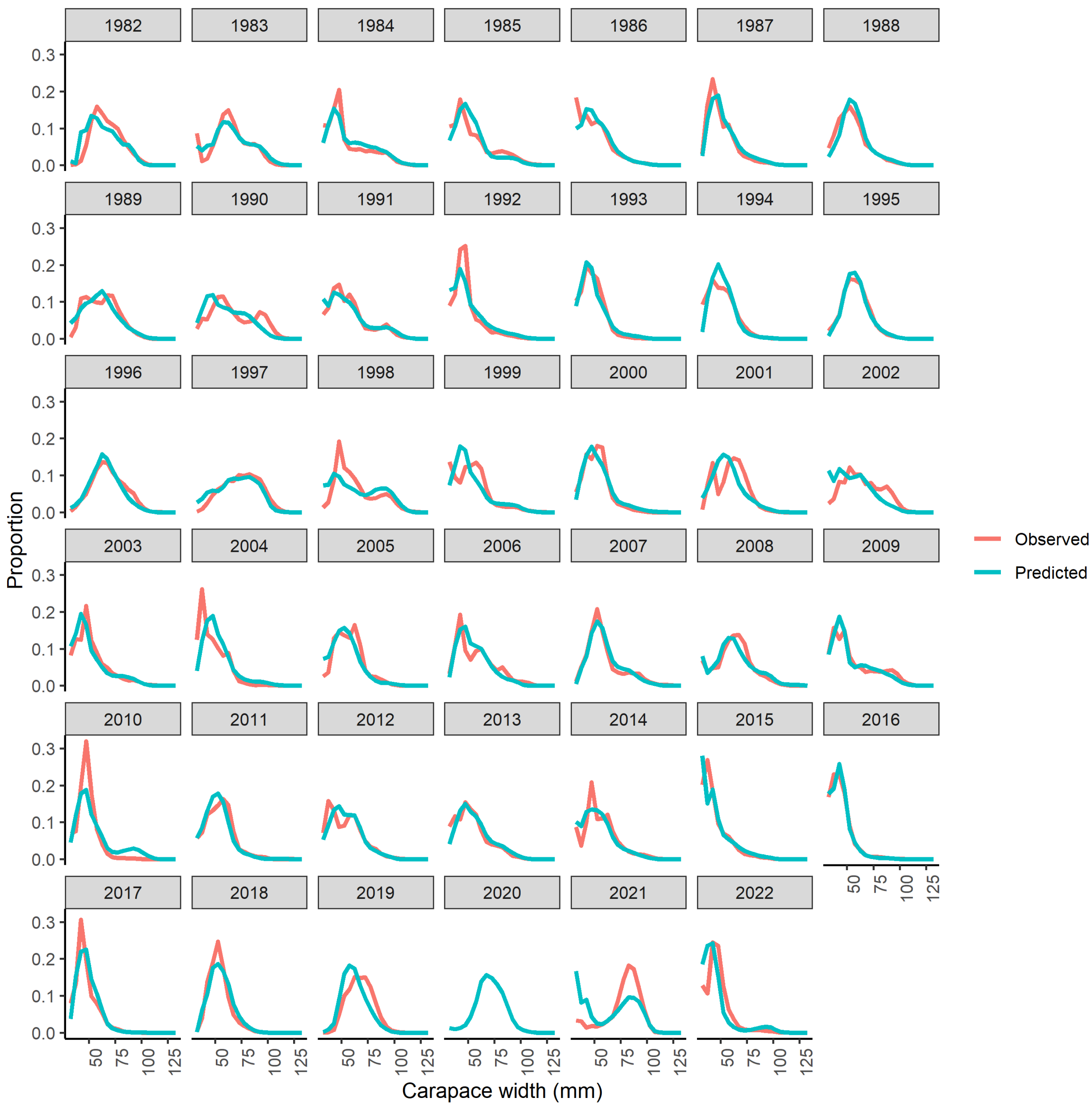

Figure 6: Fits to yearly survey size composition data for immature males from the research model.

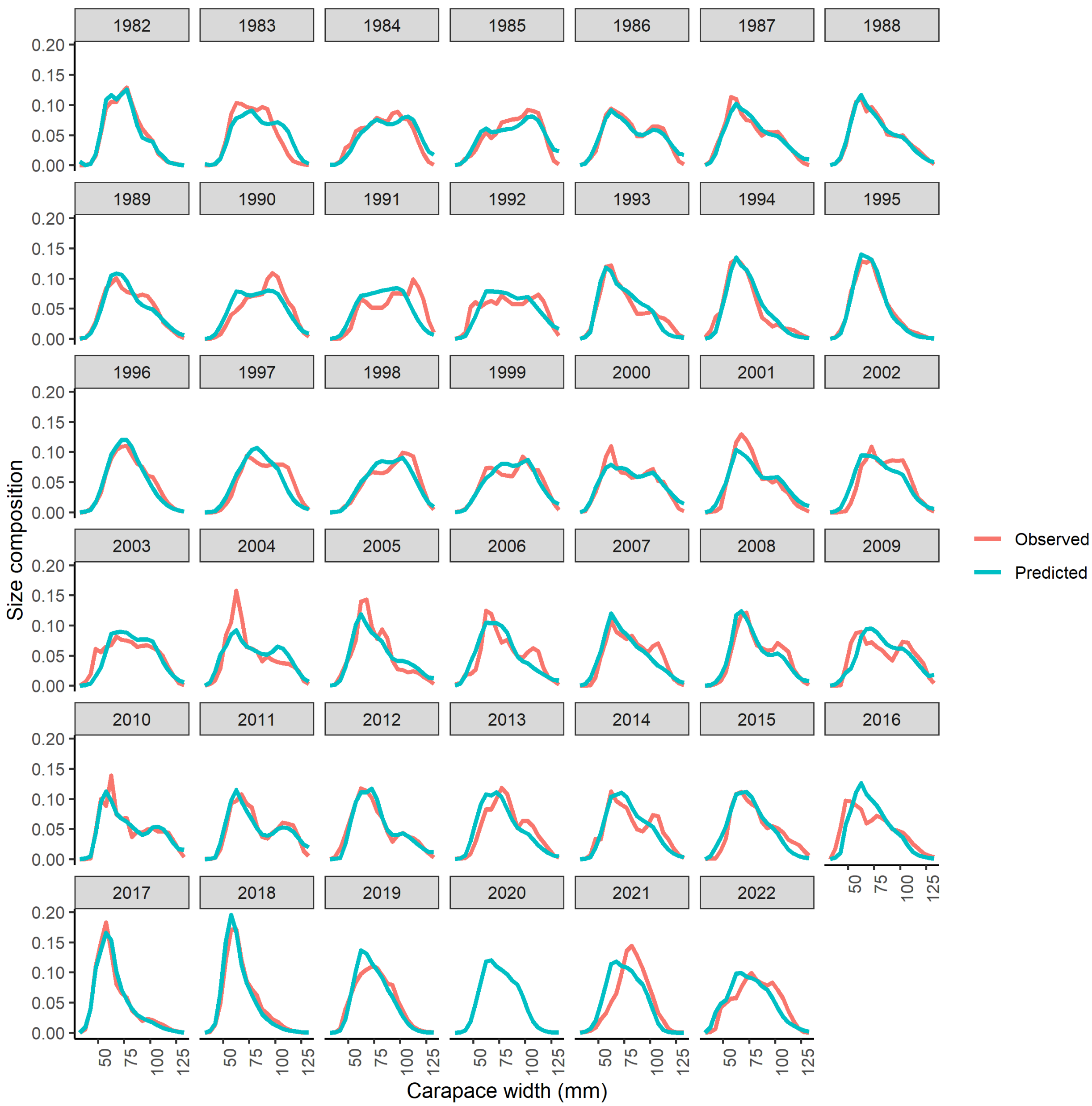

Figure 7: Fits to yearly survey size composition data for mature males from the research model.

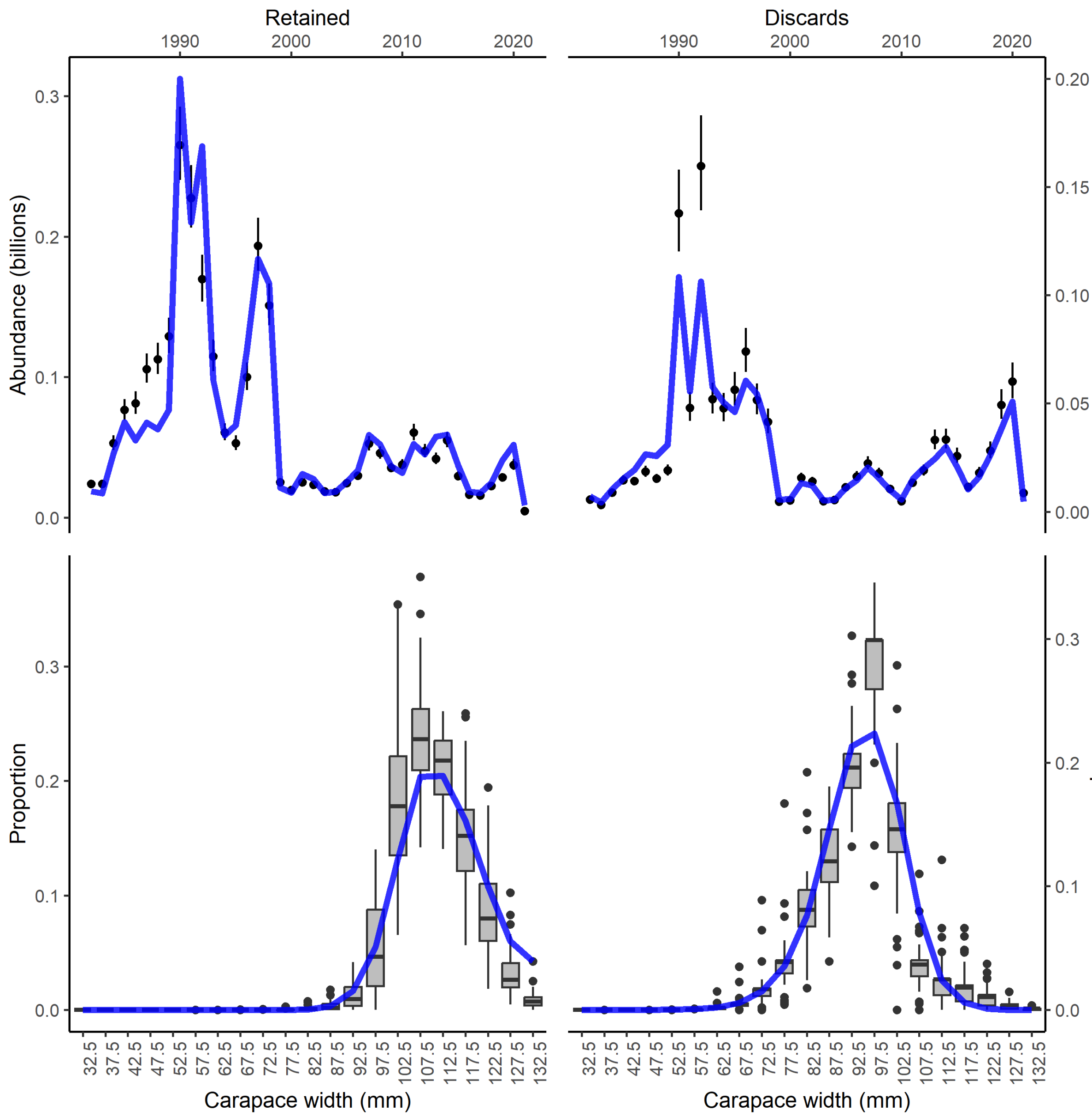

Figure 8: Fits to retained and discard male catch and aggregate size composition data from the research model. Points and vertical lines are observed abundances and estimates are blue, box plots are size composition data aggregated over the study period with average estimated size composition over year by size in blue.

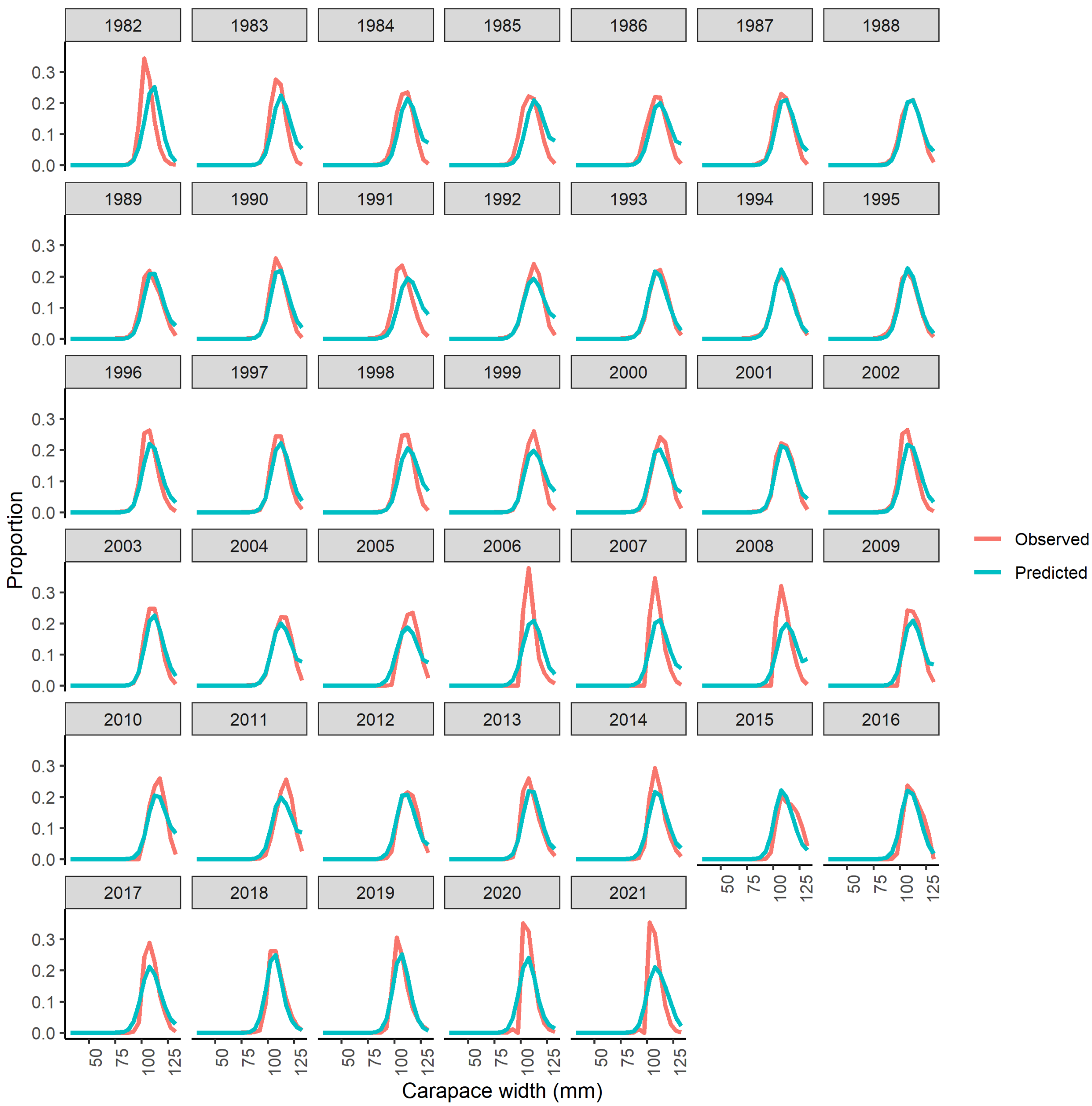

Figure 9: Fits to yearly size composition data to retained catch data in the research model.

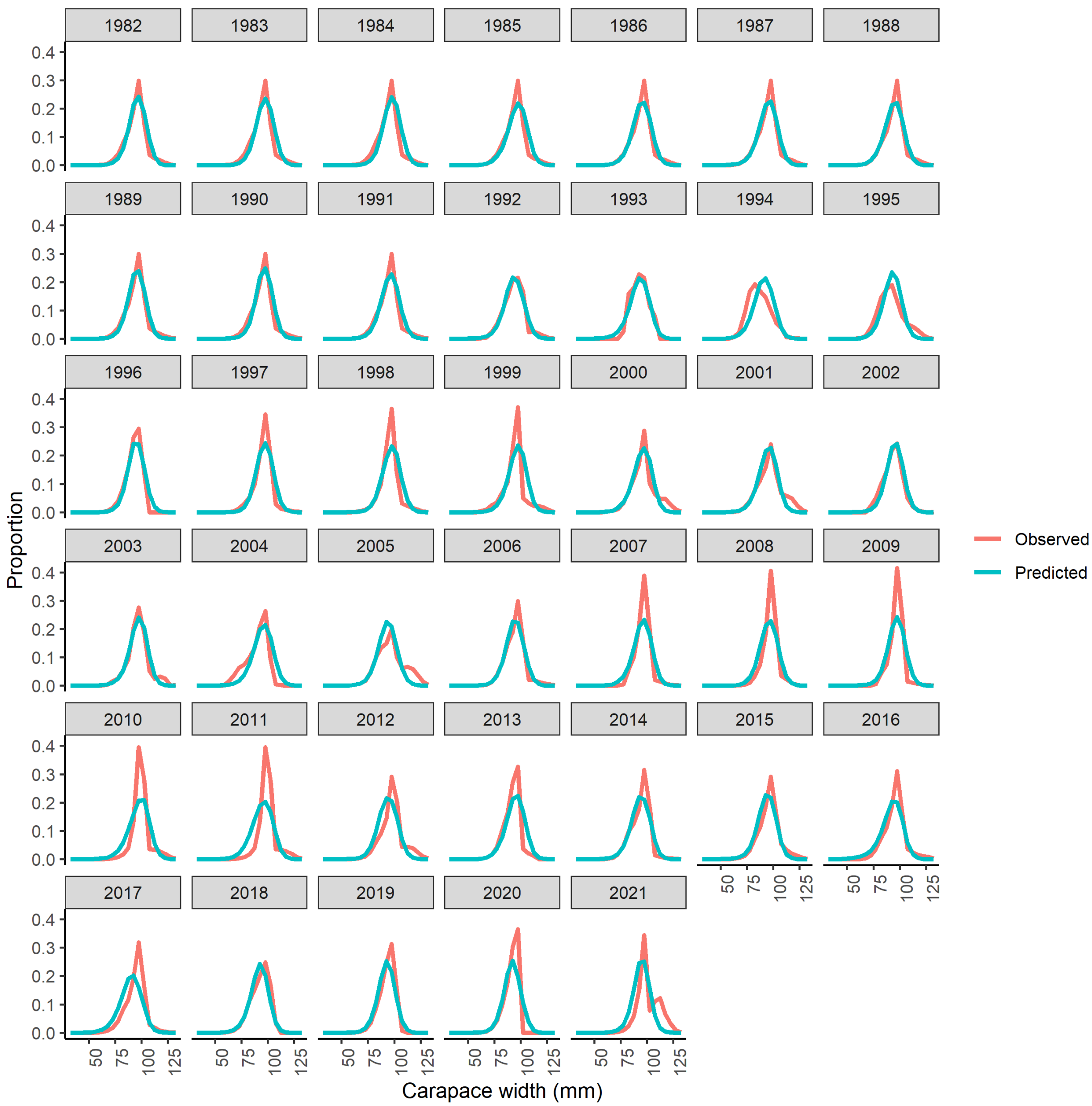

Figure 10: Fits to yearly size composition data to discarded catch data in the research model.

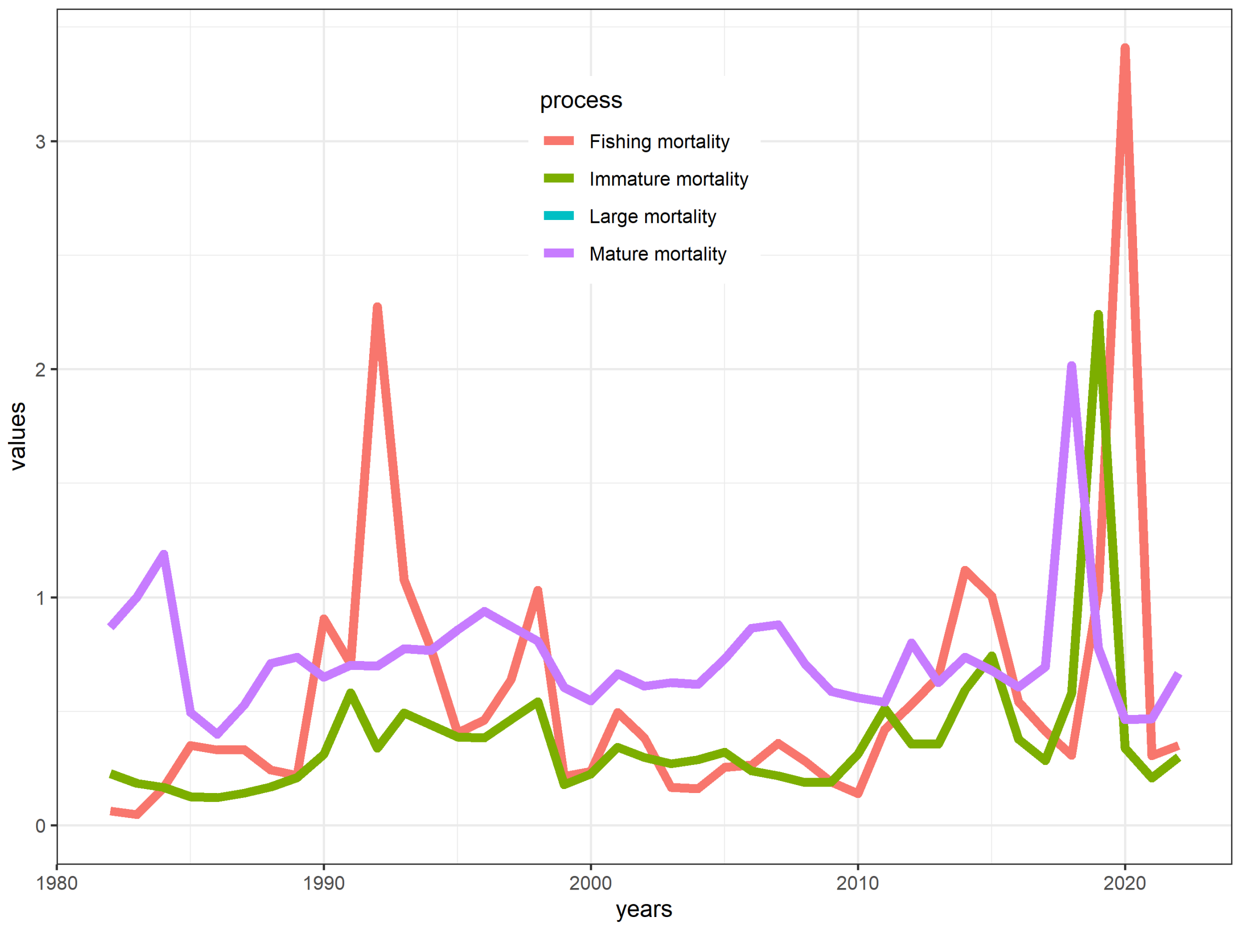

Figure 11: Estimated fishing mortality, immature mortality, and mature mortality from the research model. Large mortality is not estimated for this example, but a separate natural mortality can be estimated for crab larger than a specified size cutoff.

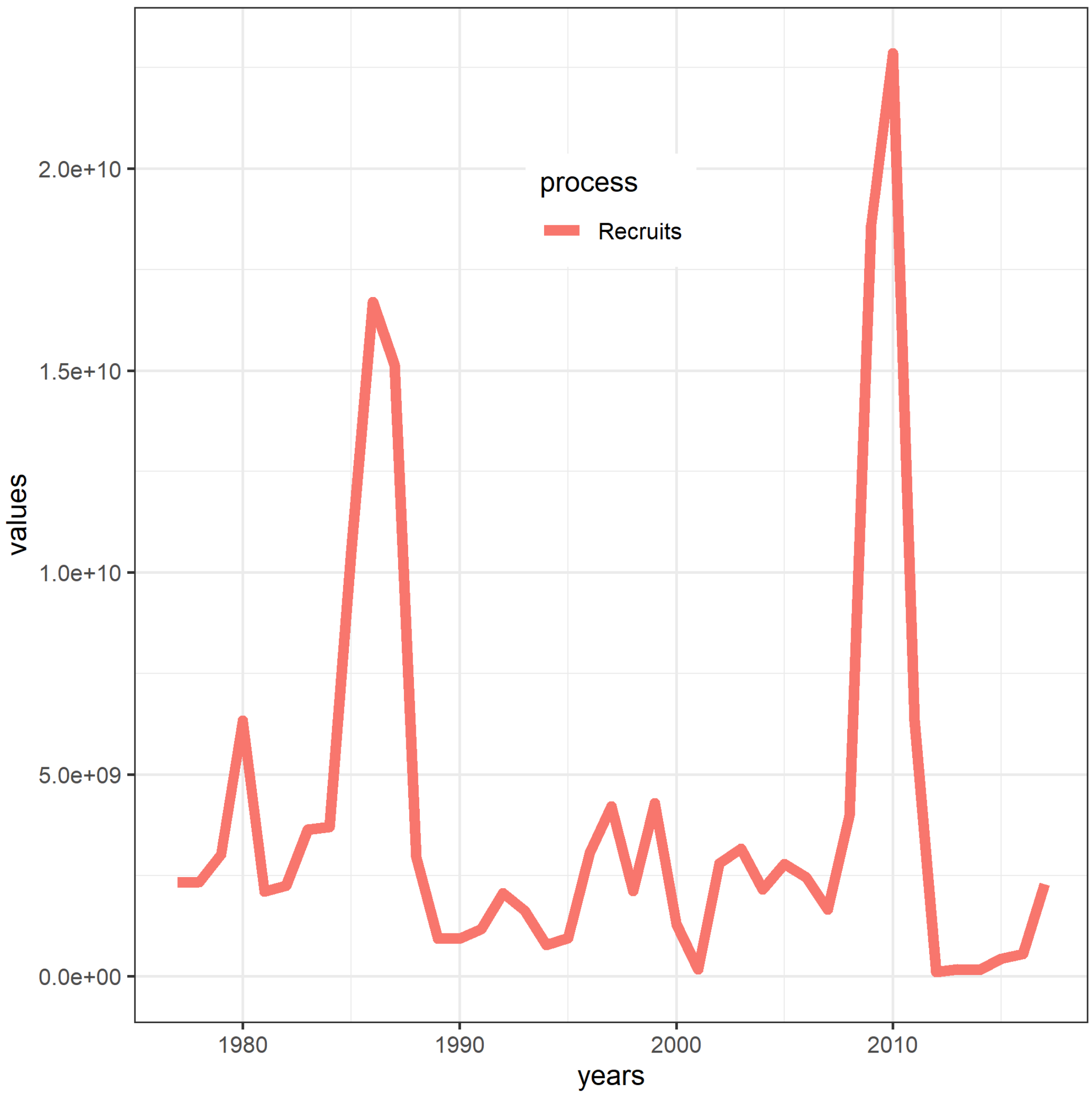

Figure 12: Estimated recruitment from the research model.

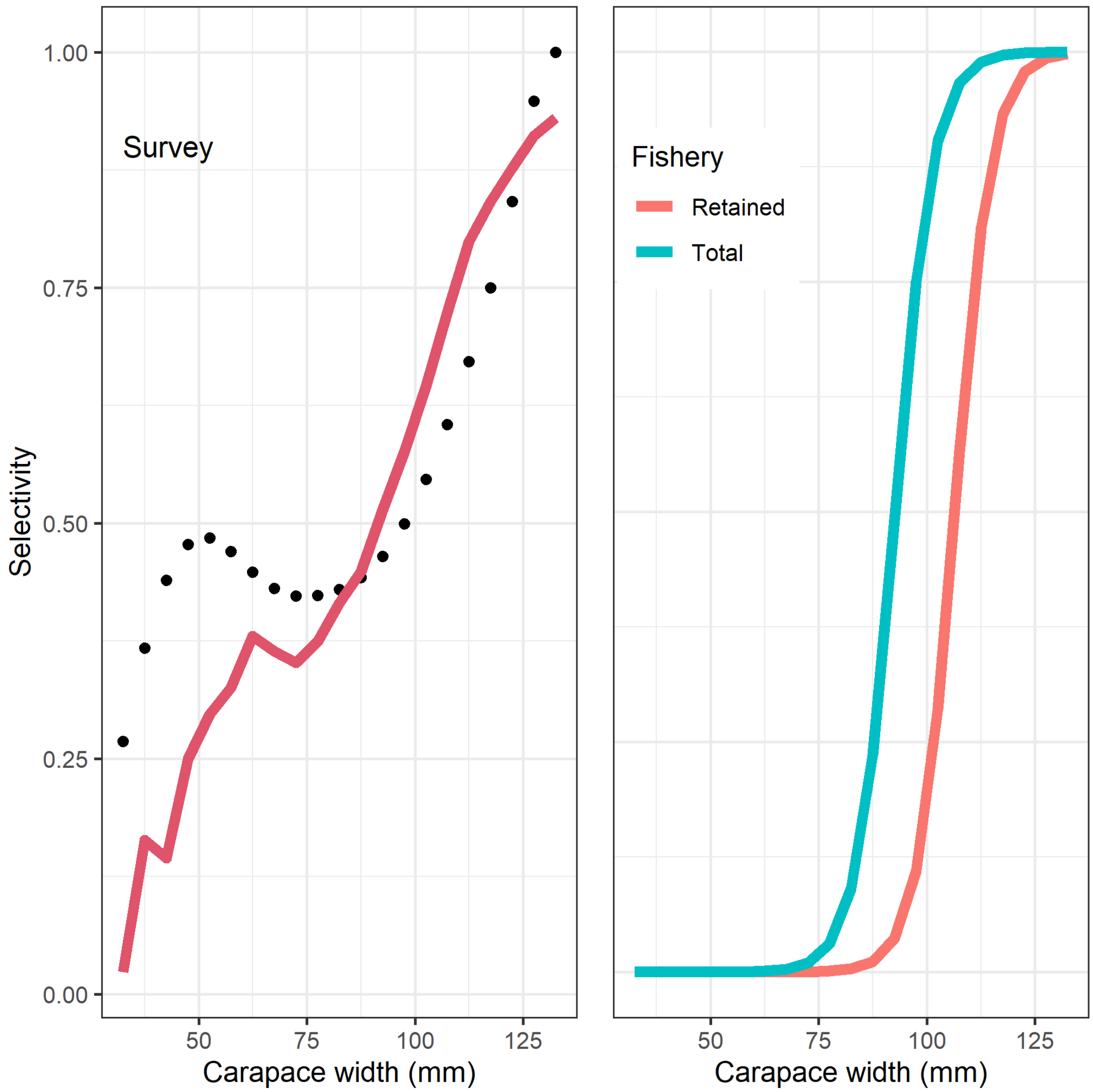

Figure 13: Estimated survey selectivity (red line) and priors (black dots) from the research model (left). Estimated capture and retention selectivity (right).

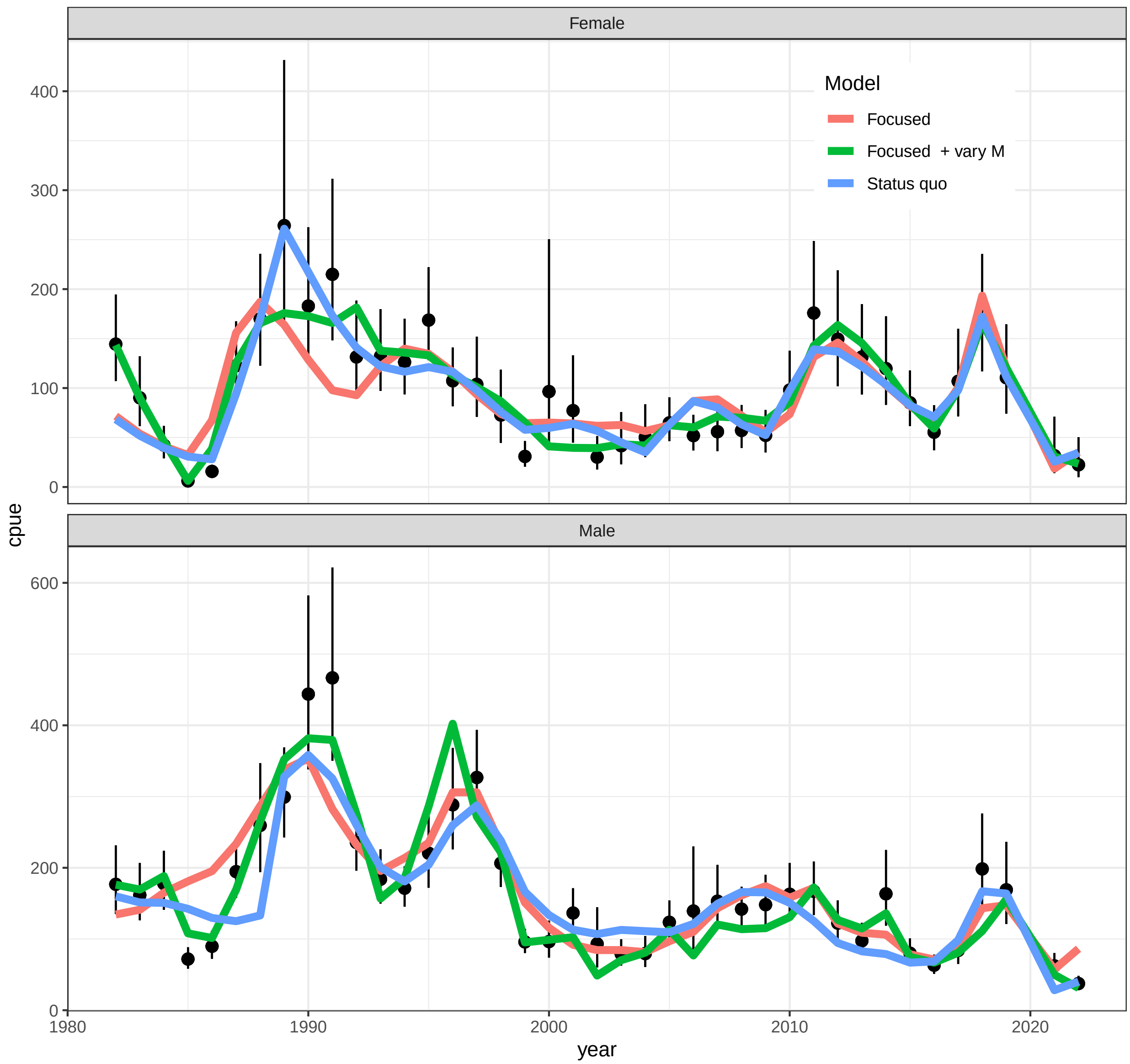

Figure 14: Model fits to the survey biomass indices.

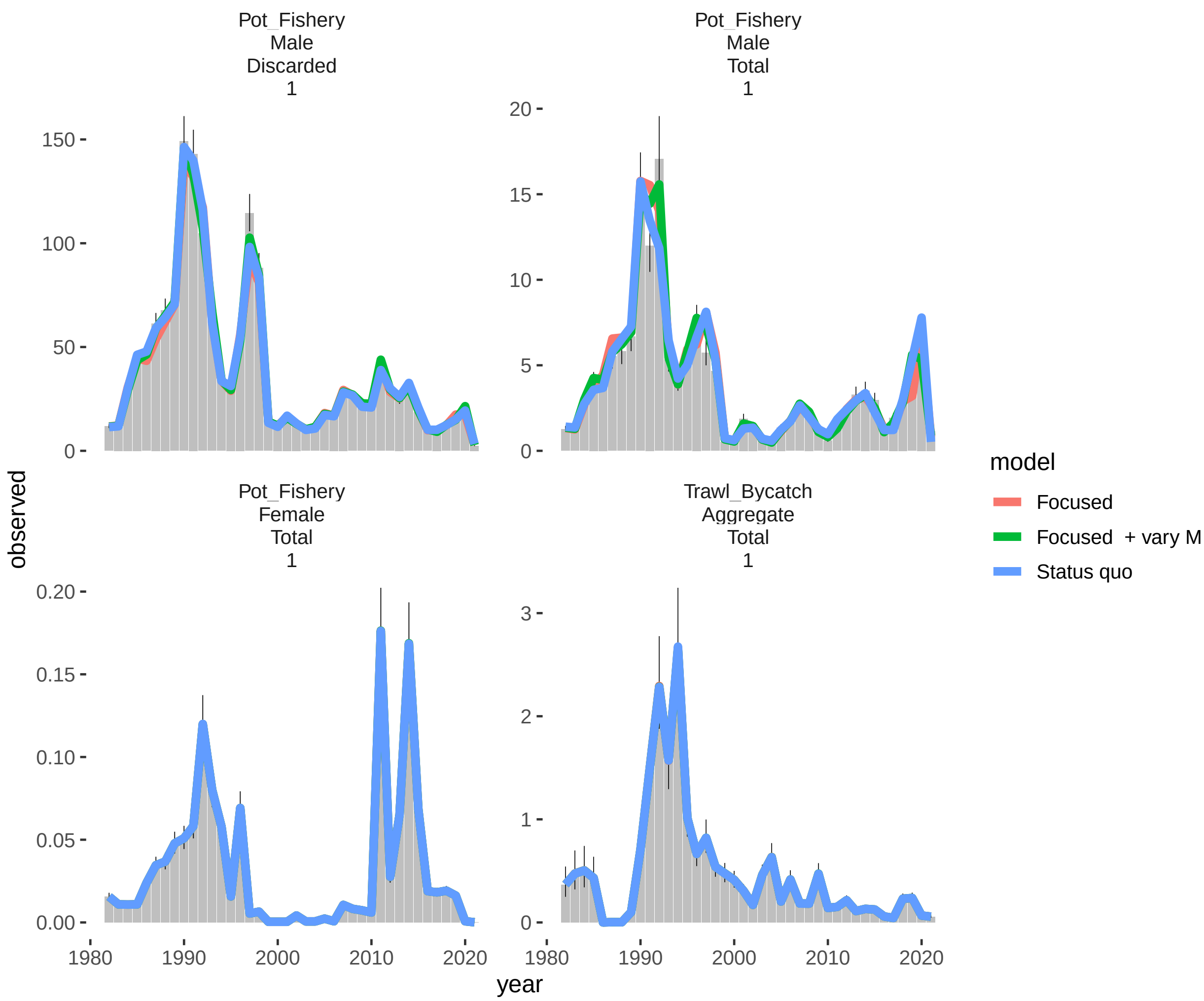

Figure 15: Model fits to the catch data. Units on the y-axis are 1,000 tonnes. Note the large differences between the panels in catch.

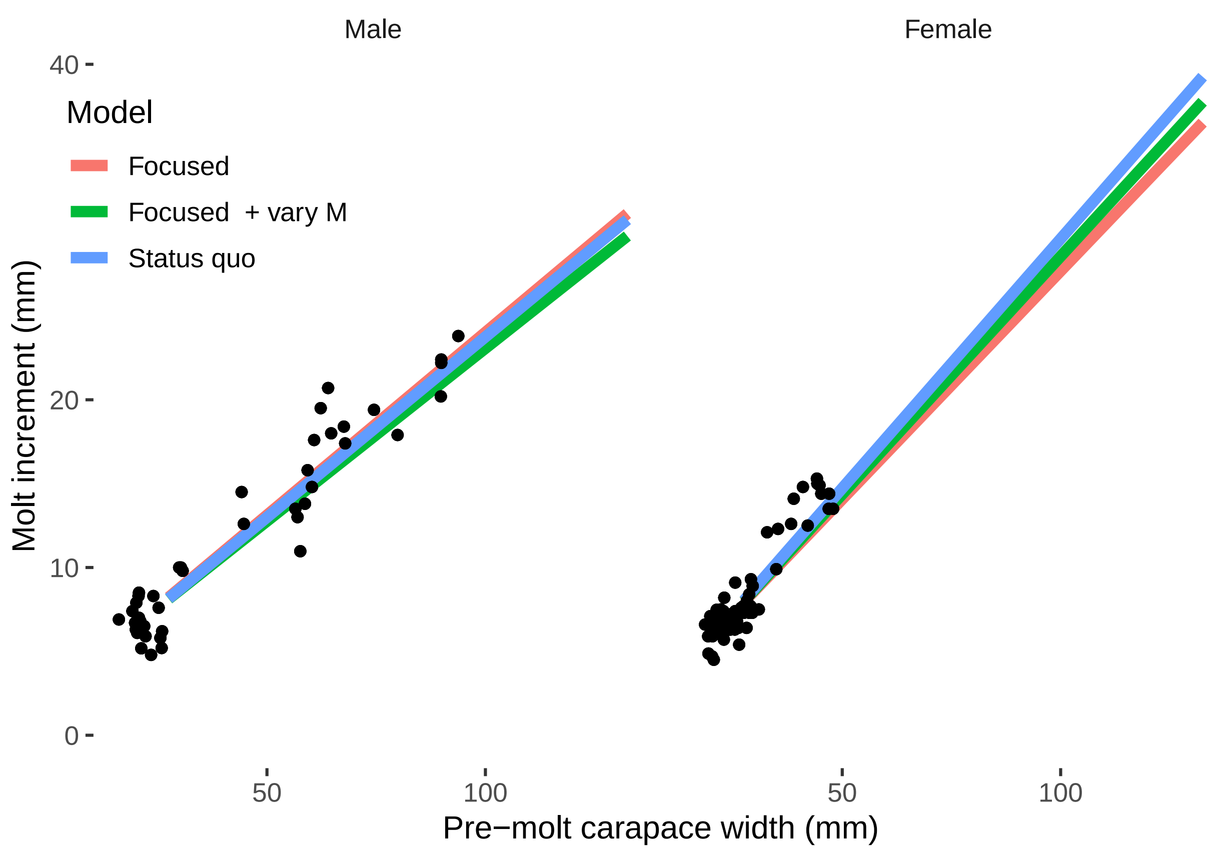

Figure 16: Estimated molt increment (line) vs. observed (points).

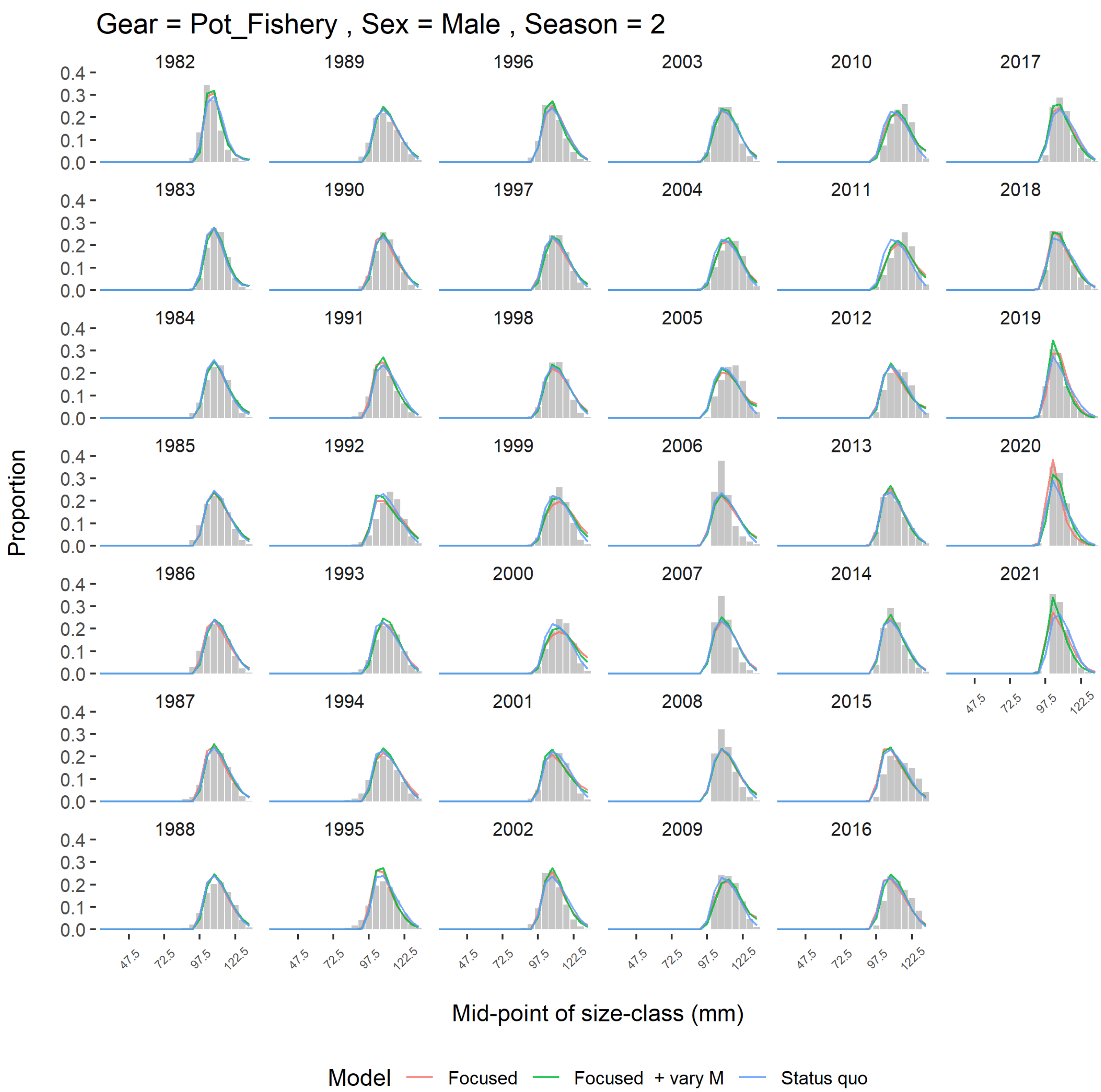

Figure 17: Model fits (lines) to the total catch size composition data (grey bars).

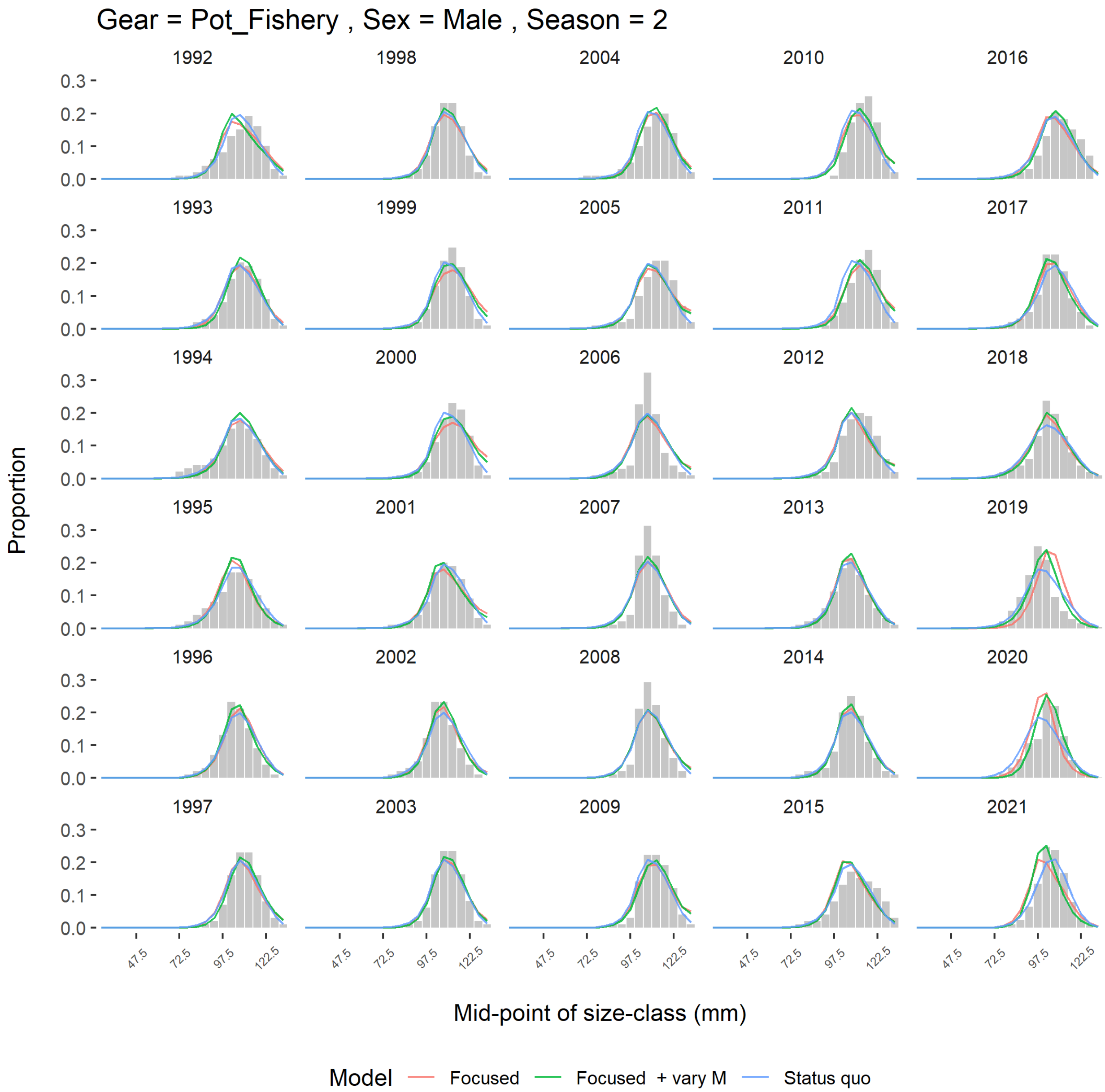

Figure 18: Model fits (lines) to the retained catch size composition data (grey bars).

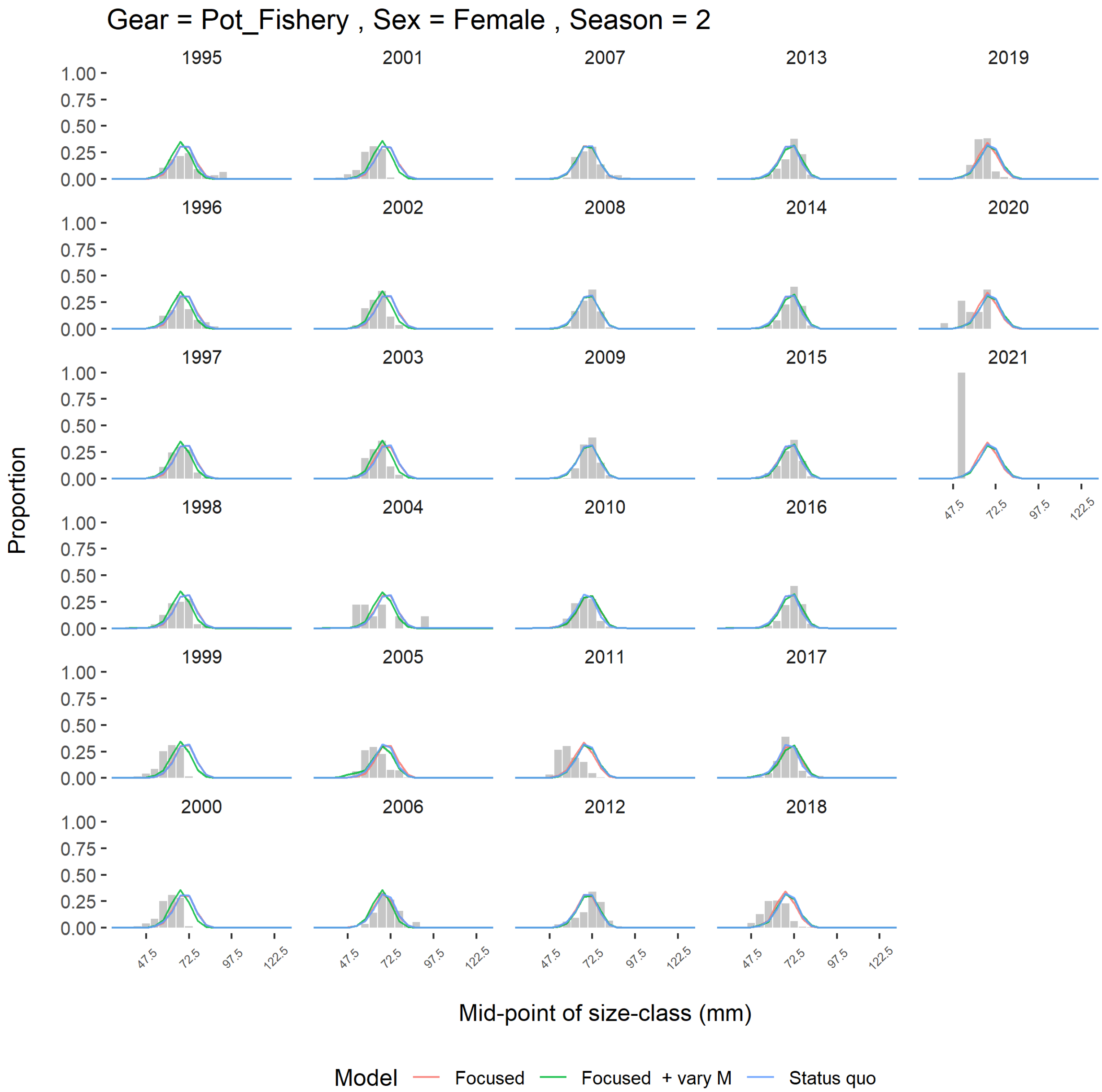

Figure 19: Model fits (lines) to the female discard size composition data (grey bars).

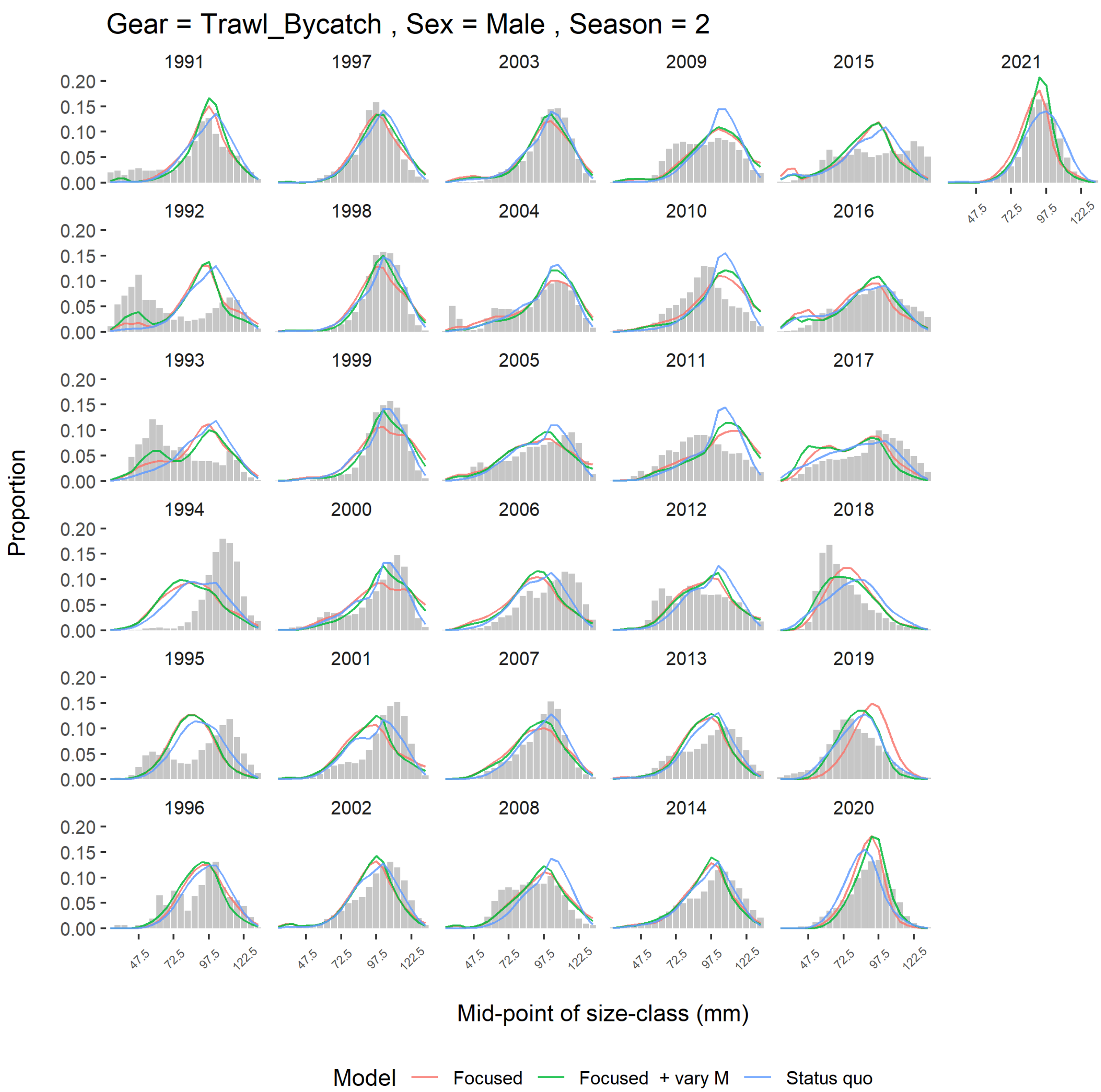

Figure 20: Model fits (lines) to the male non-directed fishery size composition data (grey bars).

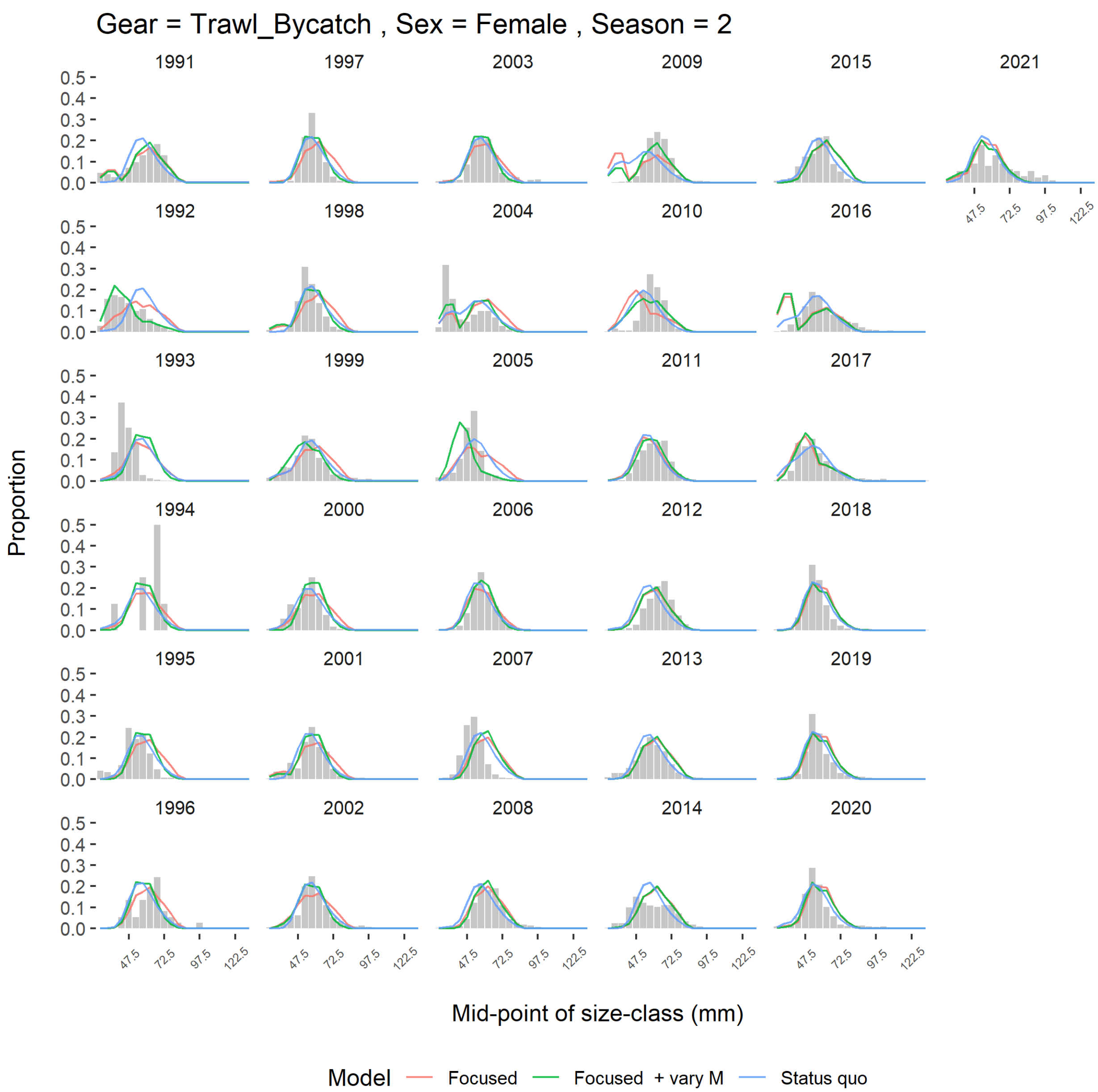

Figure 21: Model fits (lines) to the female non-directed size composition data (grey bars).

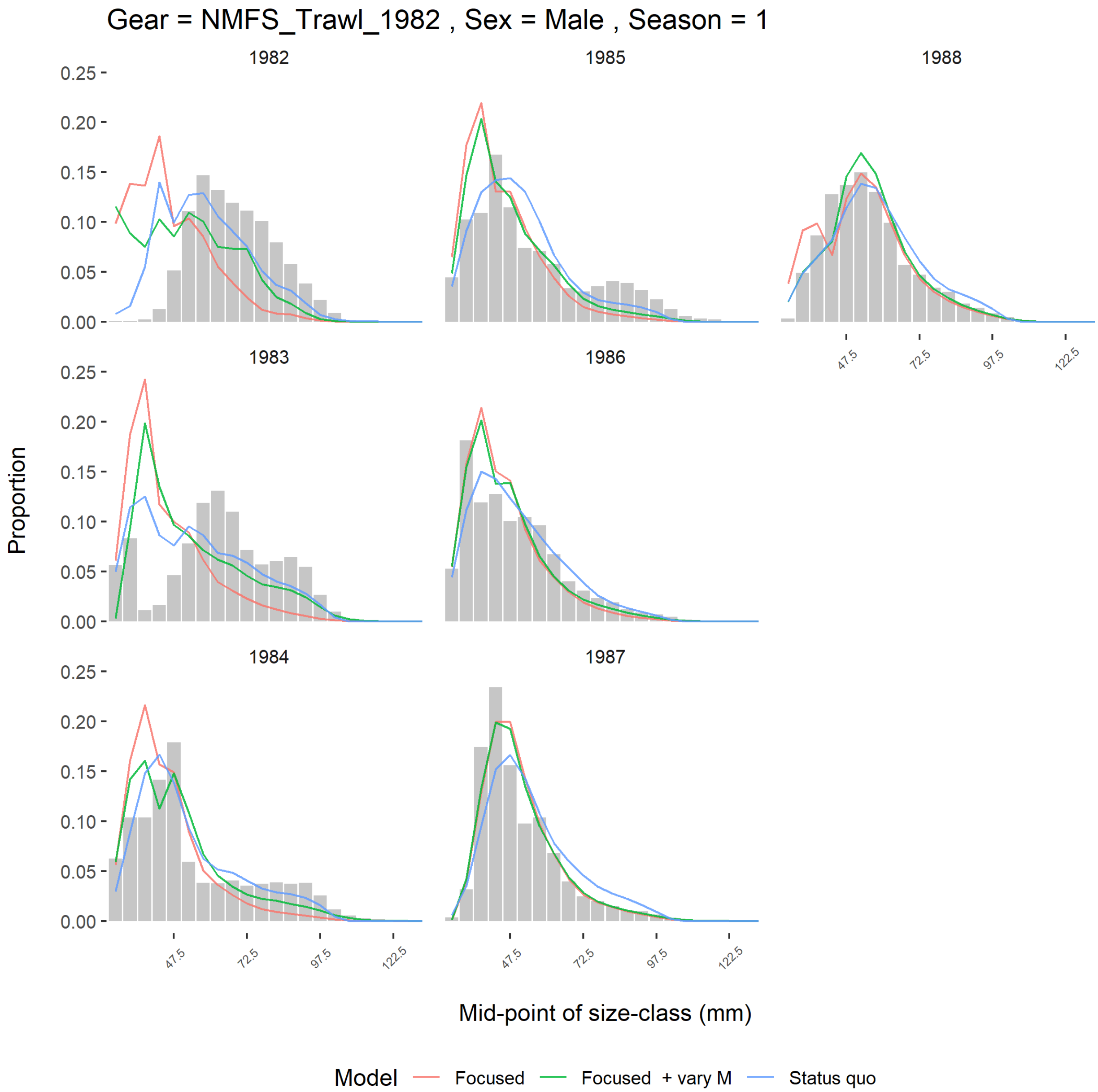

Figure 22: Model fits (lines) to the size composition data (grey bars).

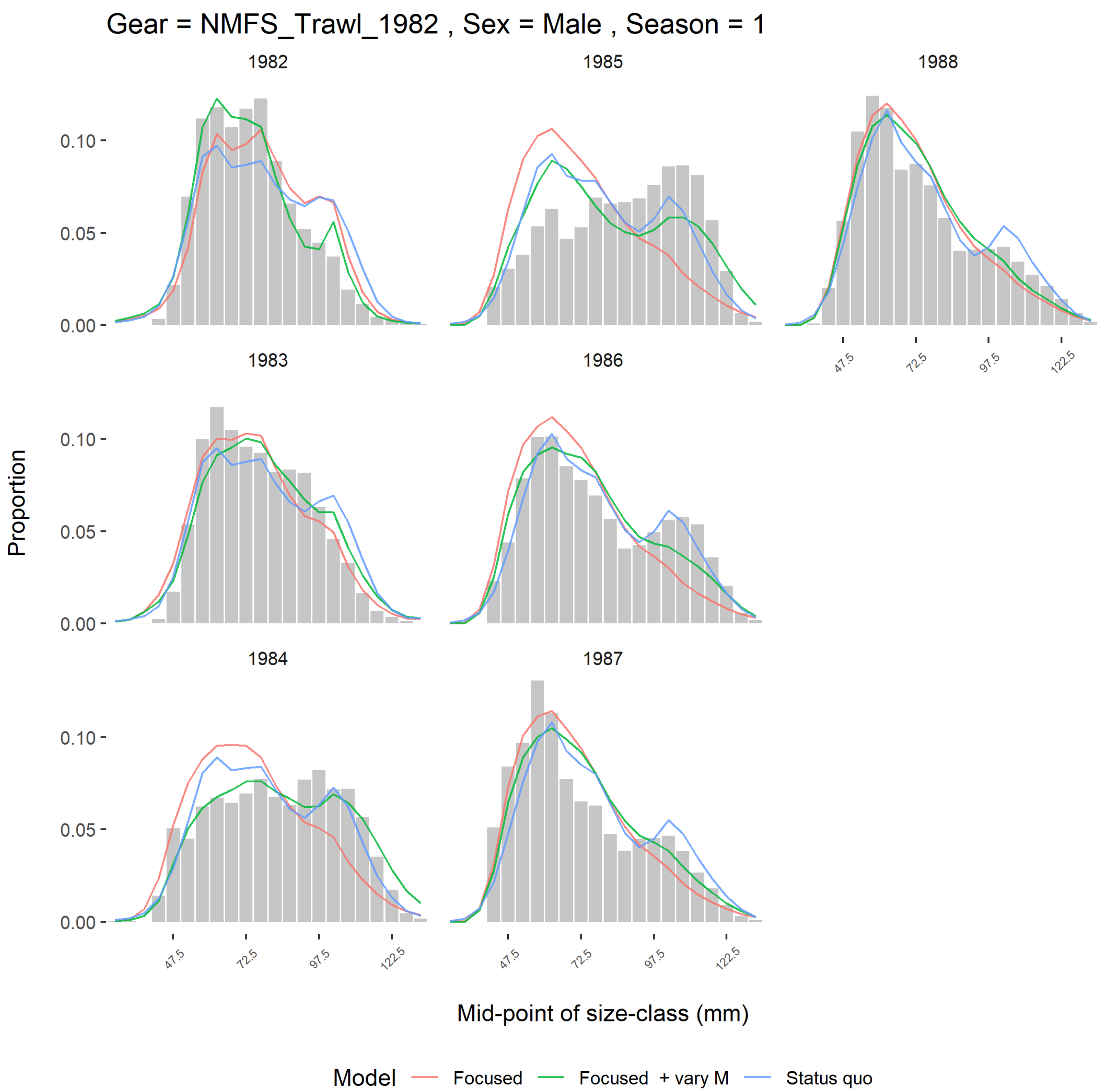

Figure 23: Model fits (lines) to the size composition data (grey bars).

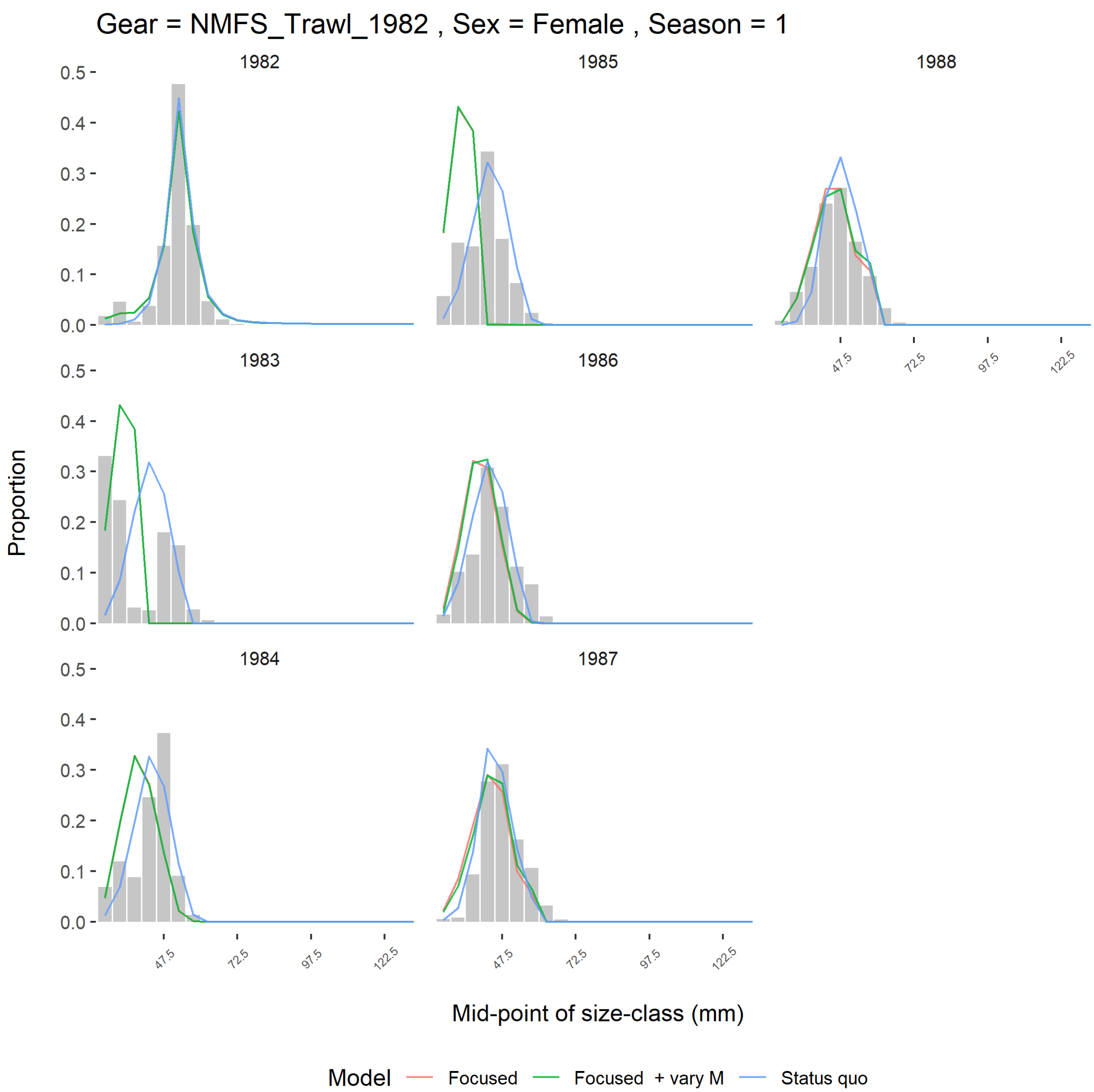

Figure 24: Model fits (lines) to the size composition data (grey bars).

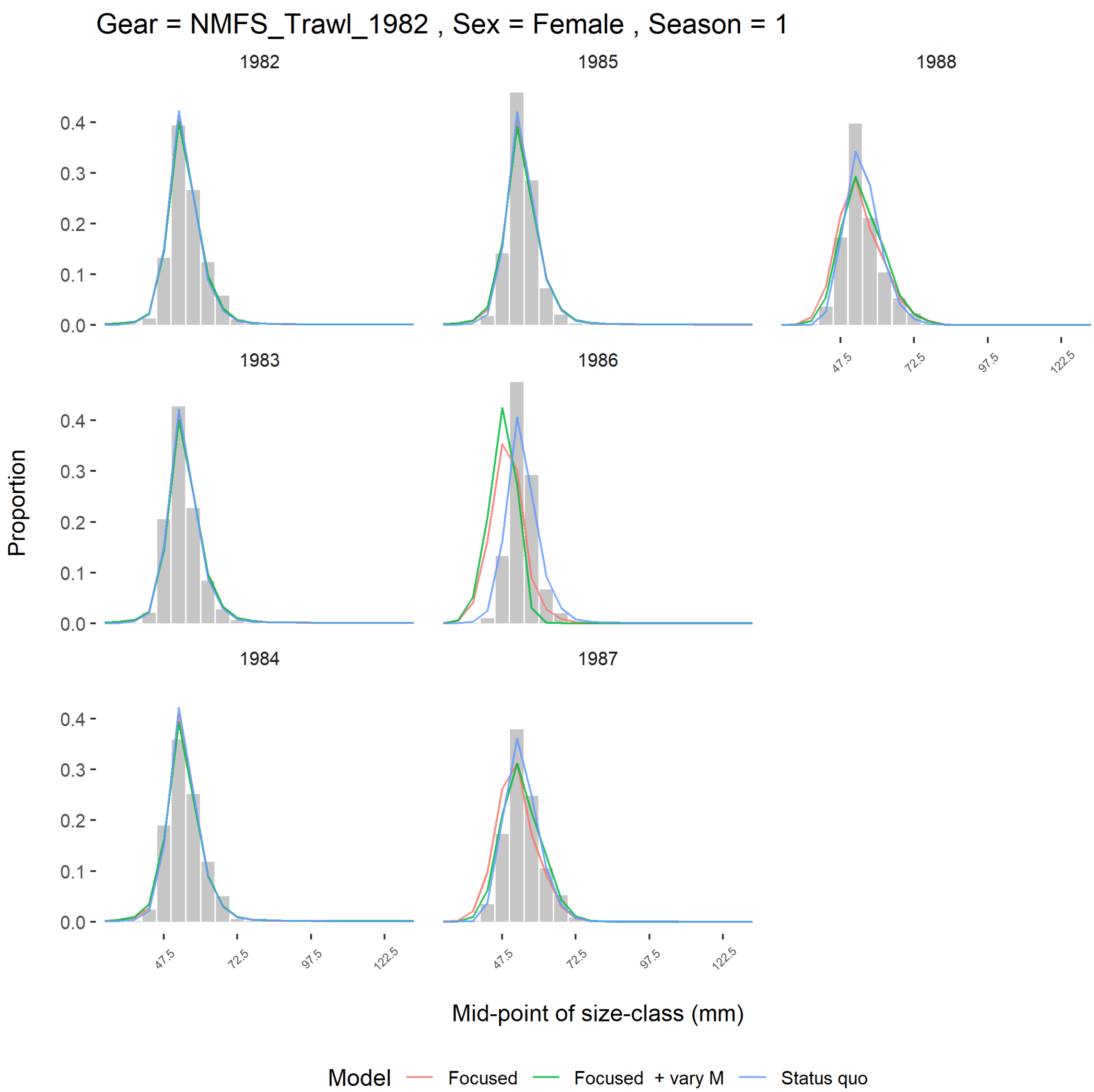

Figure 25: Model fits (lines) to the size composition data (grey bars).

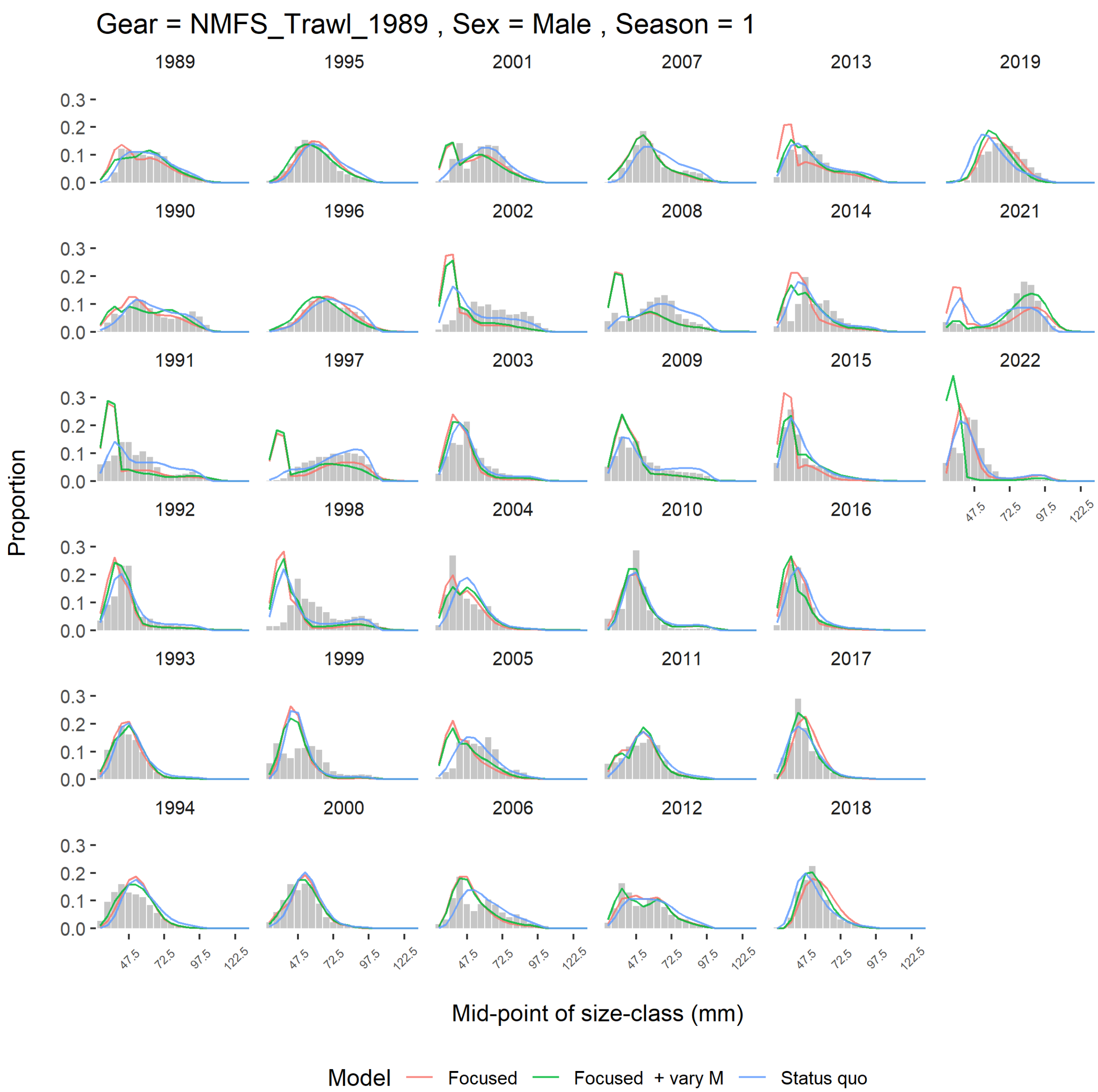

Figure 26: Model fits (lines) to the size composition data (grey bars).

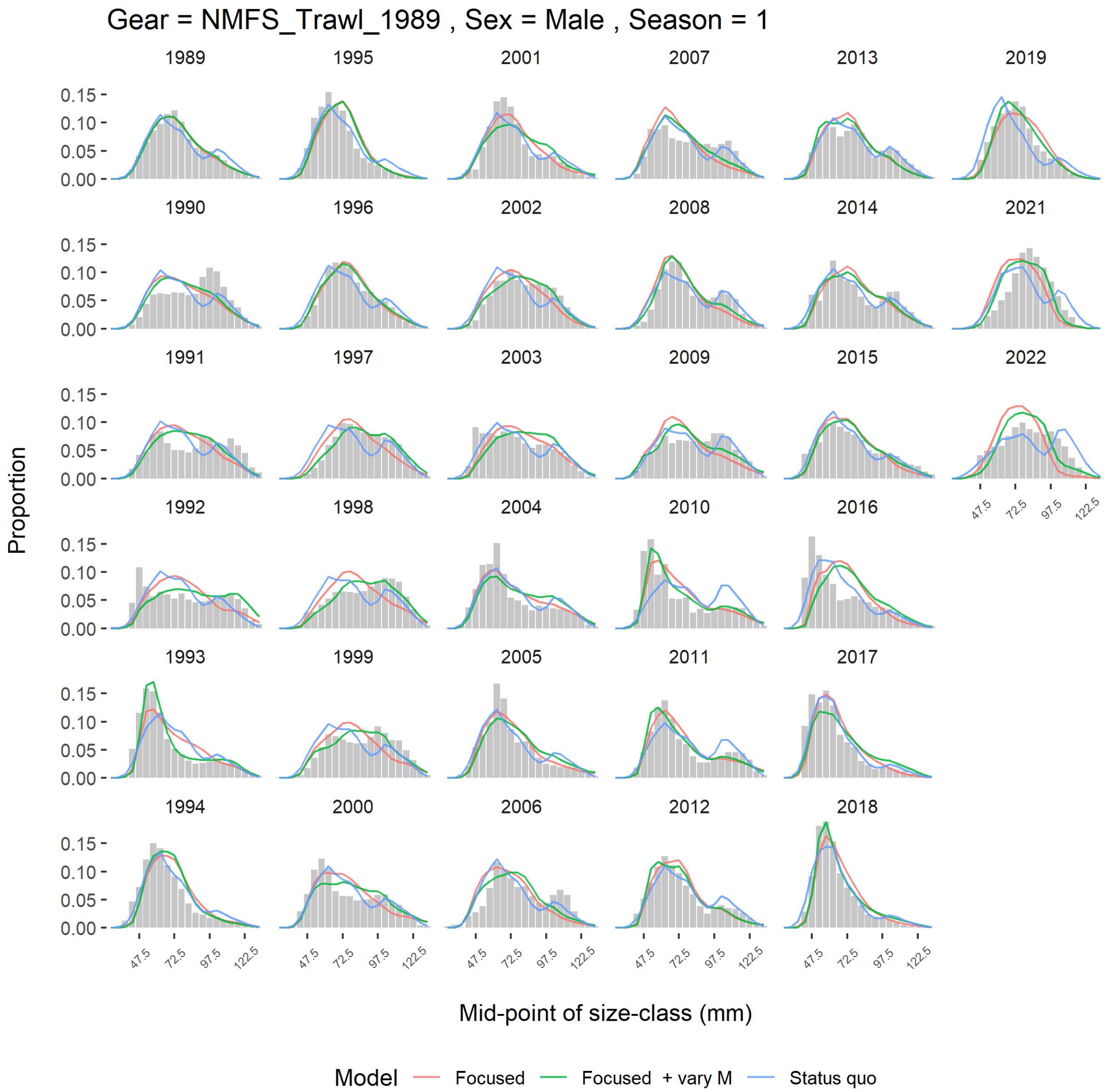

Figure 27: Model fits (lines) to the size composition data (grey bars).

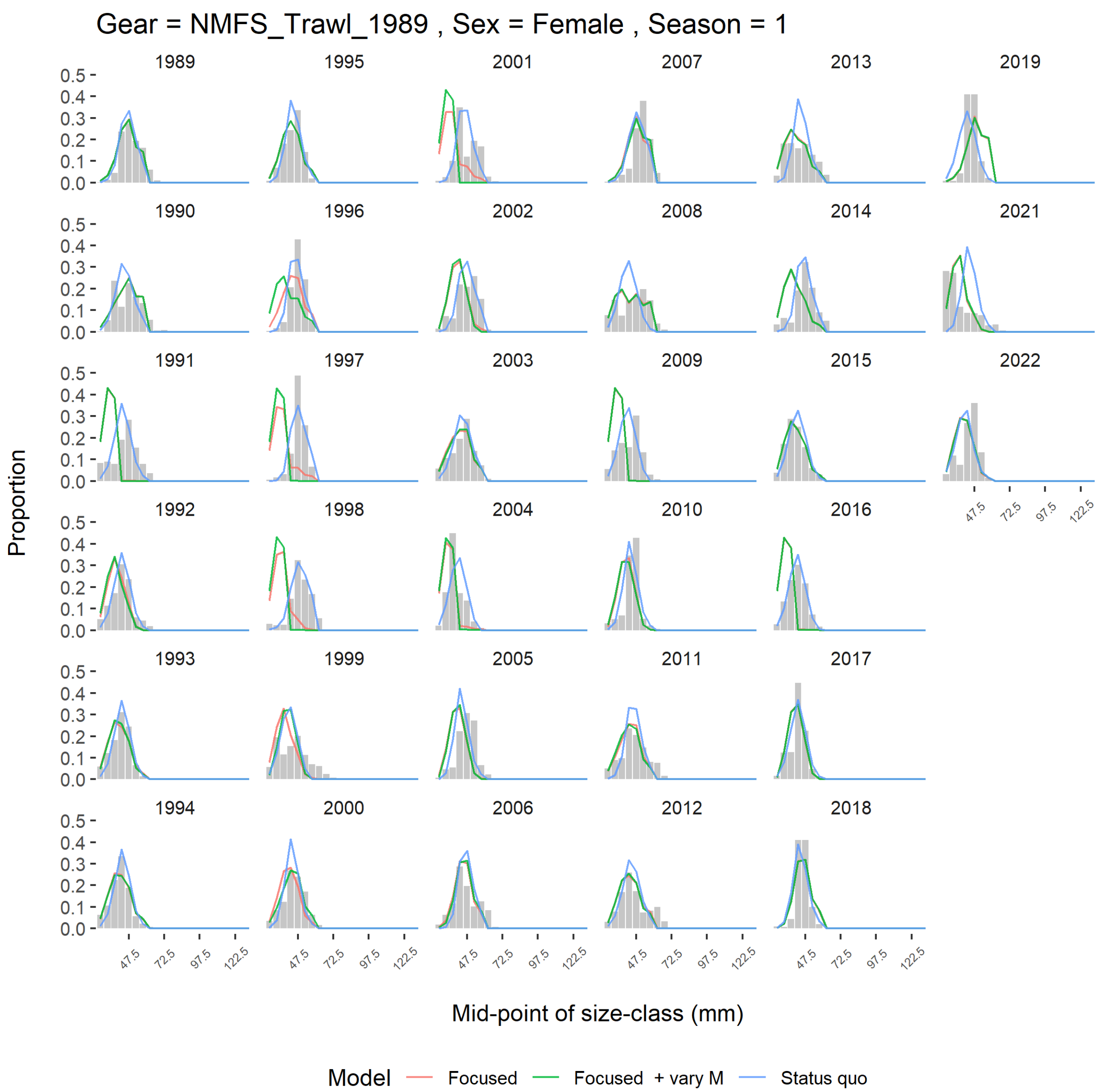

Figure 28: Model fits (lines) to the size composition data (grey bars).

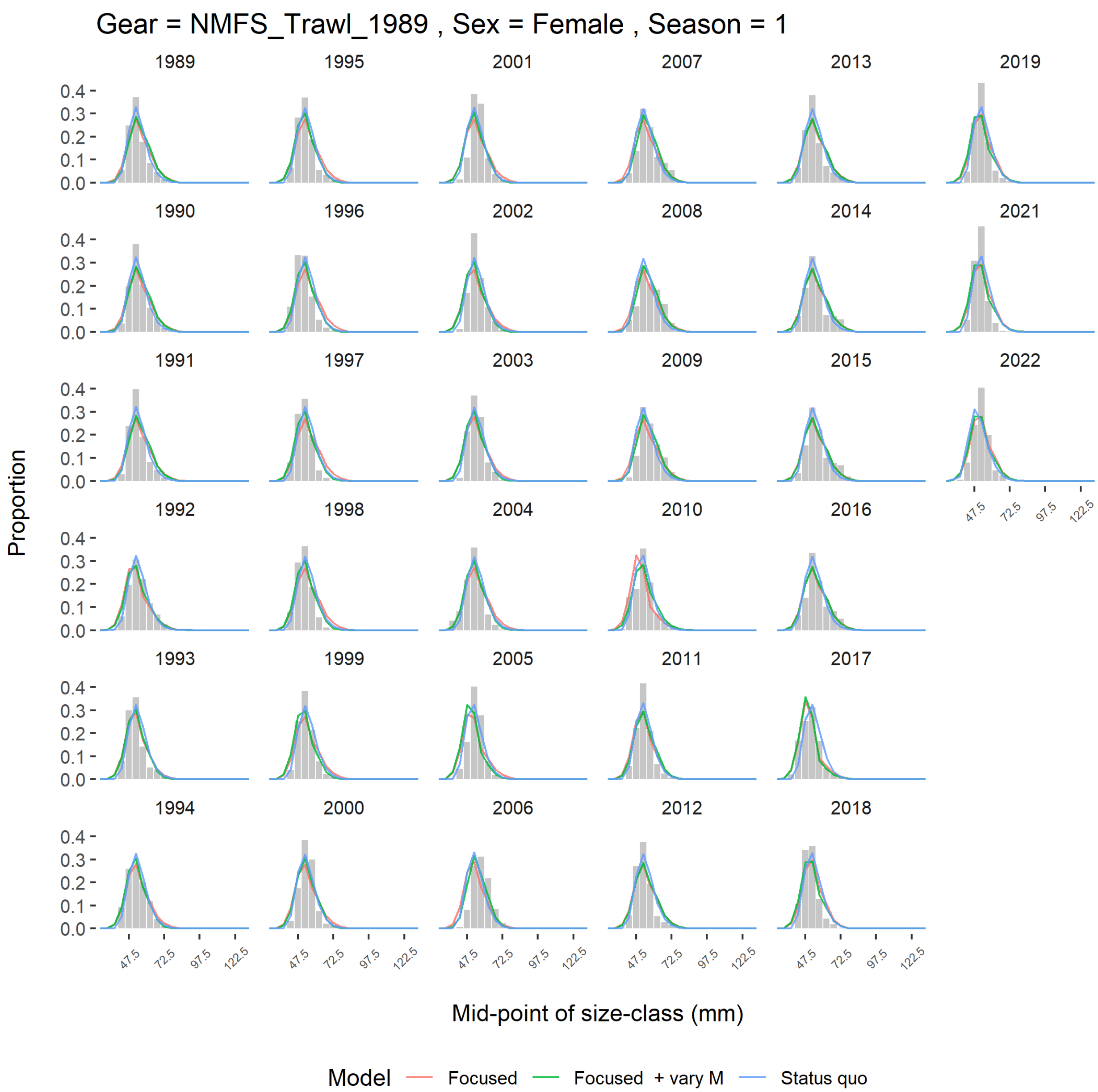

Figure 29: Model fits (lines) to the size composition data (grey bars).

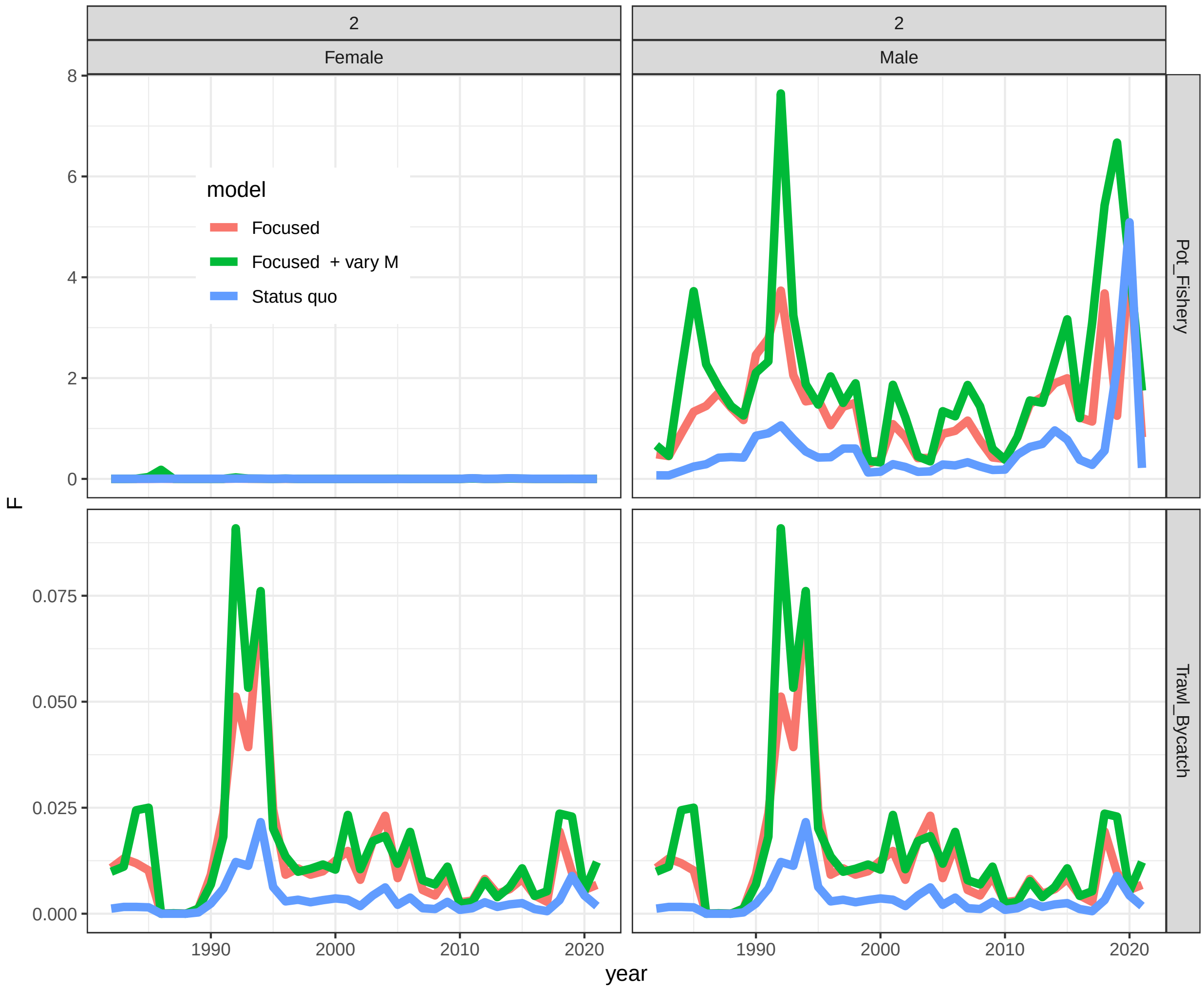

Figure 30: Estimated fishing mortality by fleet.

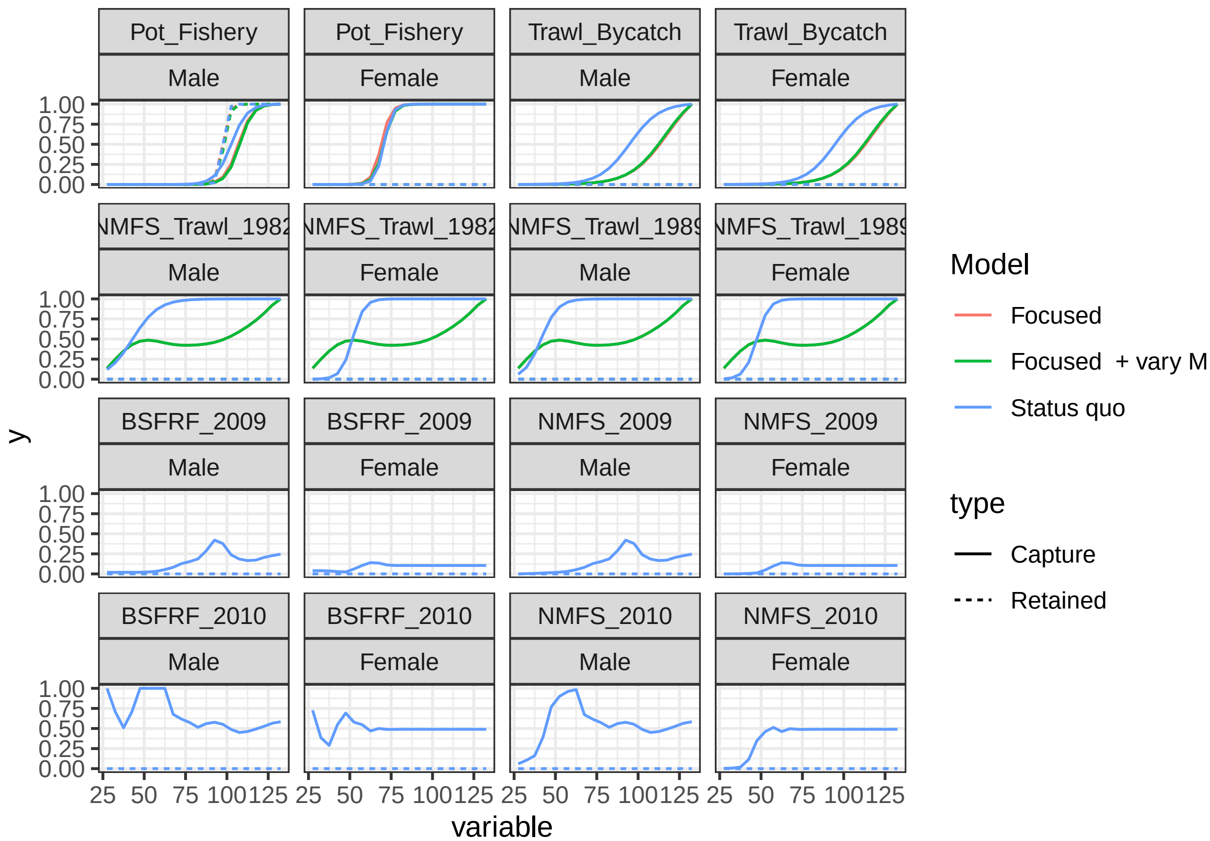

Figure 31: Estimated selectivities by survey and fleet. Survey selectivities for 'Focused' and 'Focused + vary M' are identical and only the status quo model estimates BSFRF selectivities and availabilities.

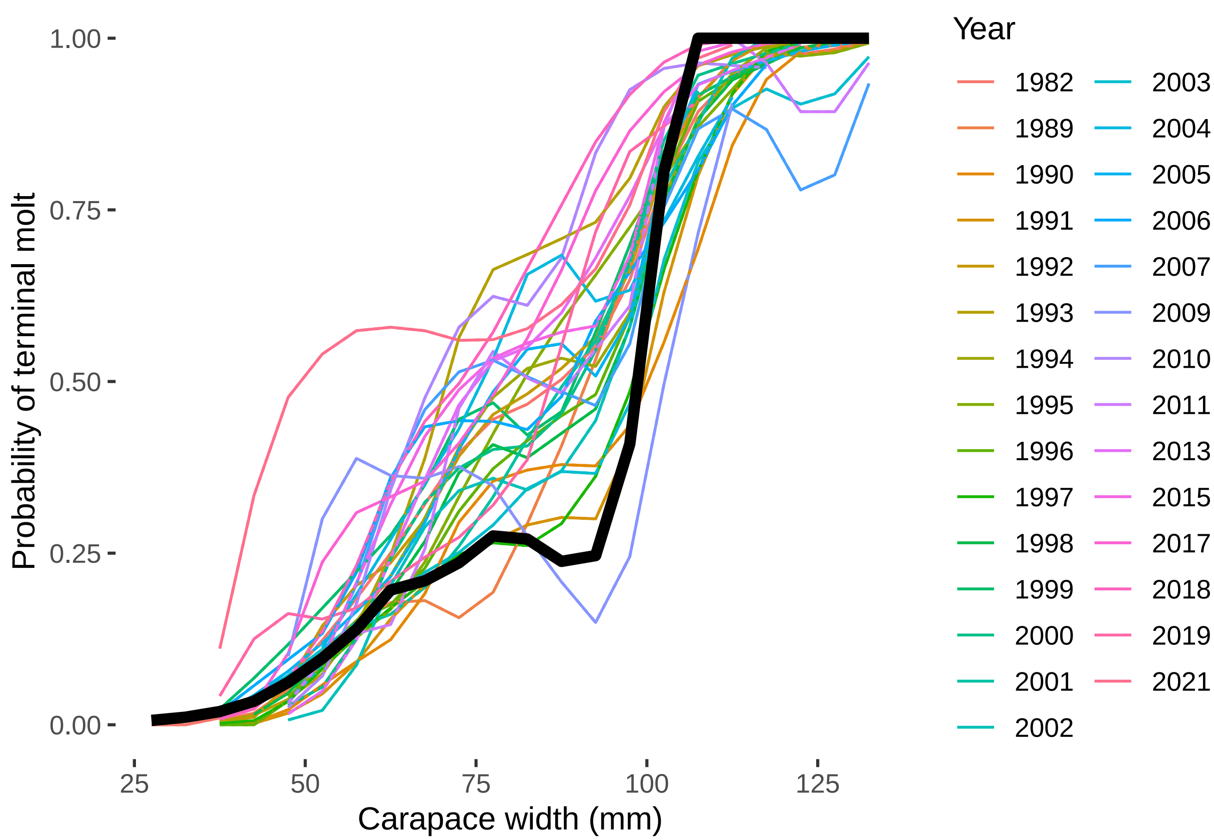

Figure 32: Specified probability of molting for male crab (colored lines). Black line is the status quo estimate.

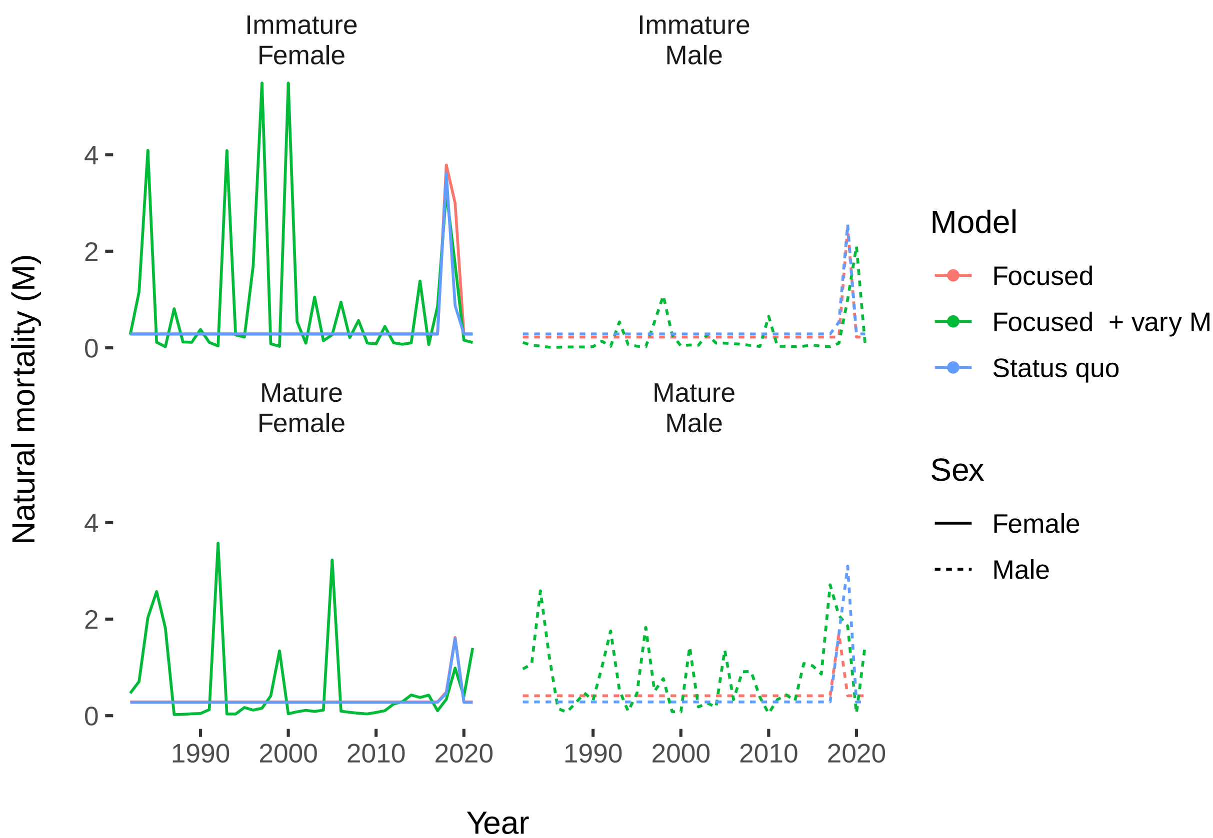

Figure 33: Estimated natural mortality.

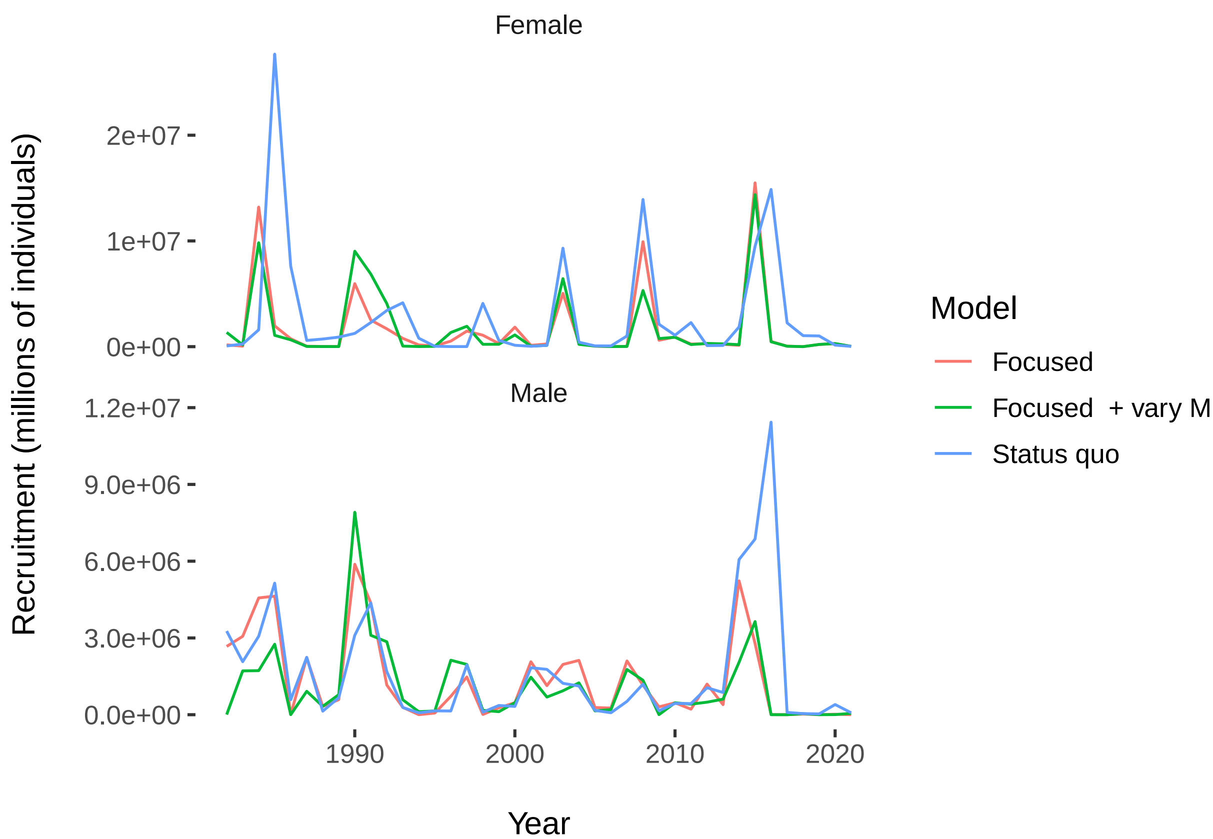

Figure 34: Estimated recruitment.

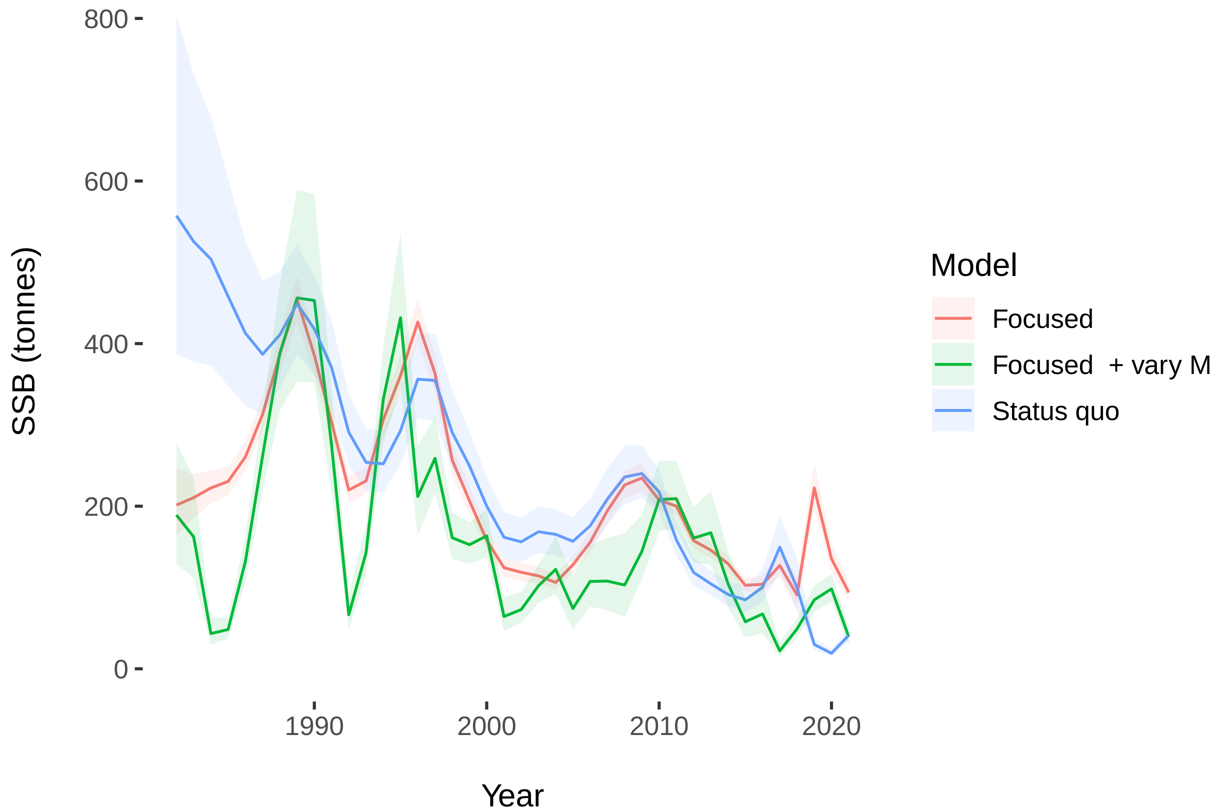

Figure 35: Estimated mature biomass

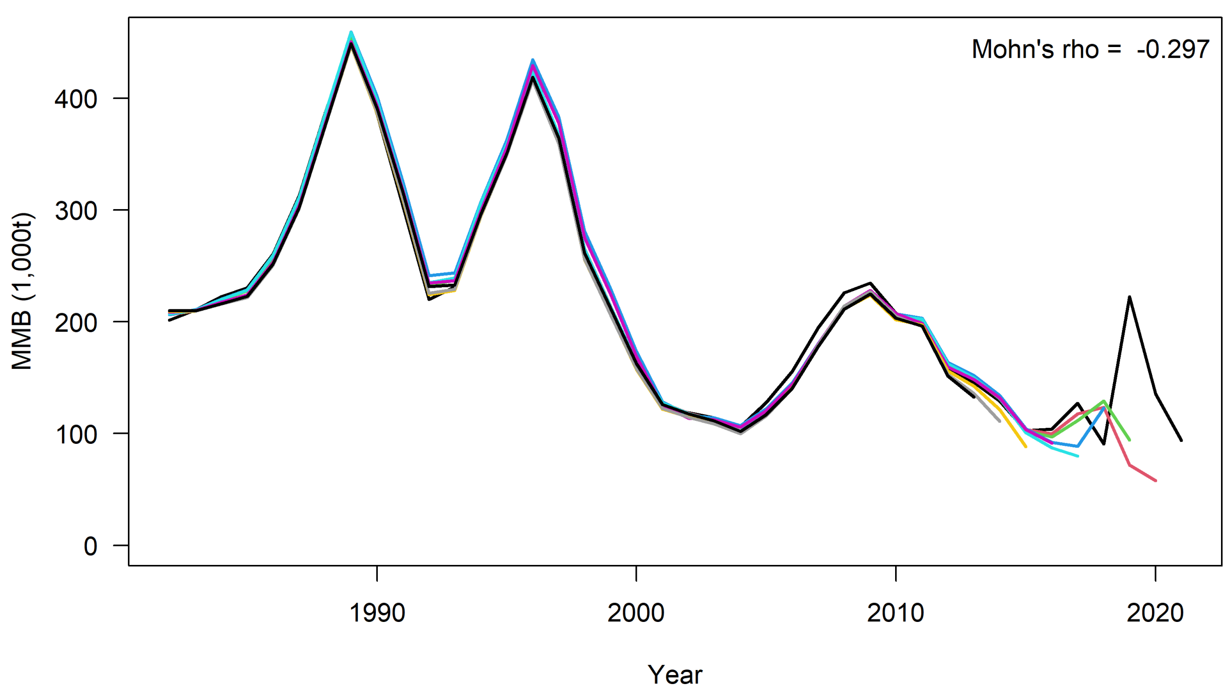

Figure 36: Retrospective pattern in MMB for the 'Focused' model.

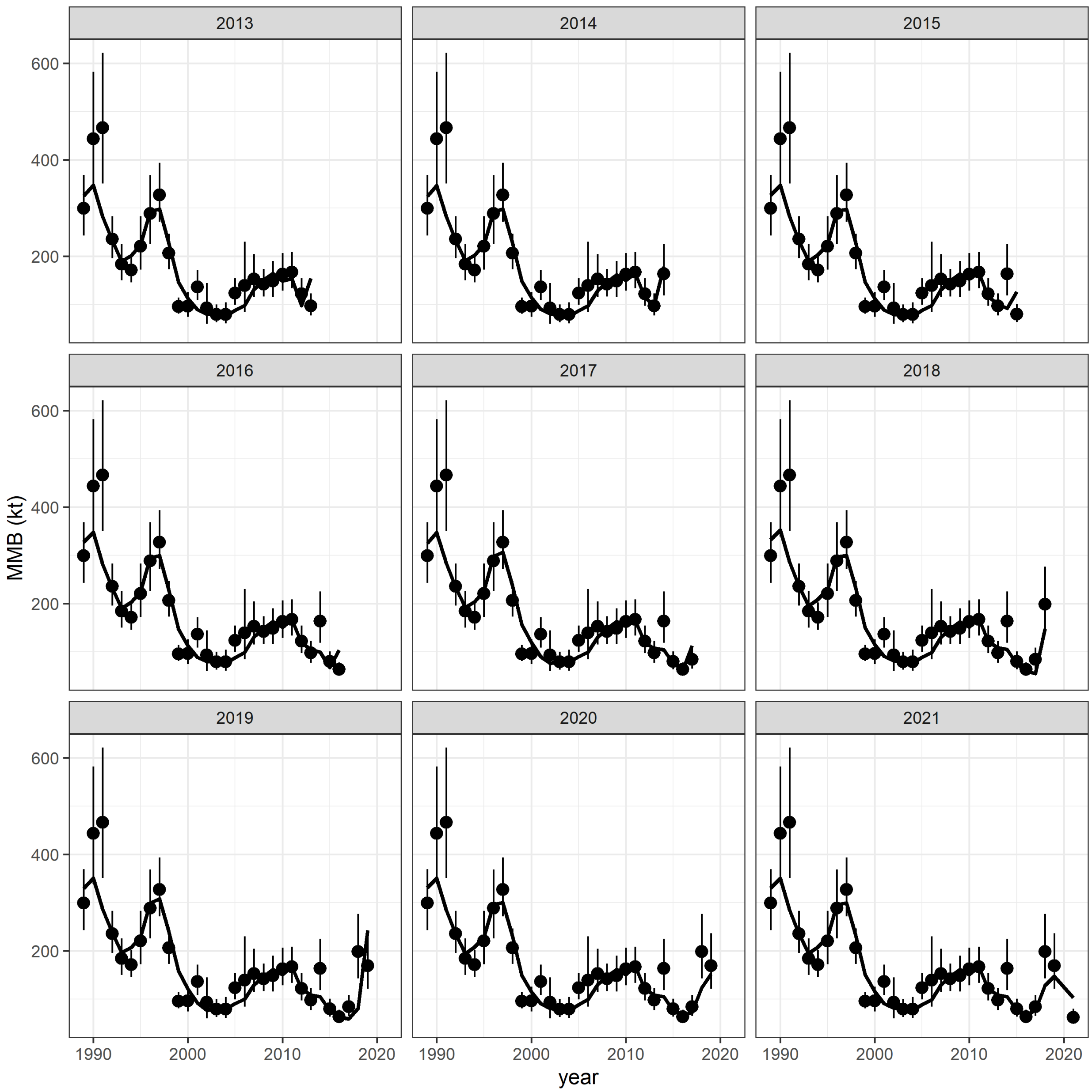

Figure 37: Fits to the survey MMB for each successive peel of the retrospective analysis.

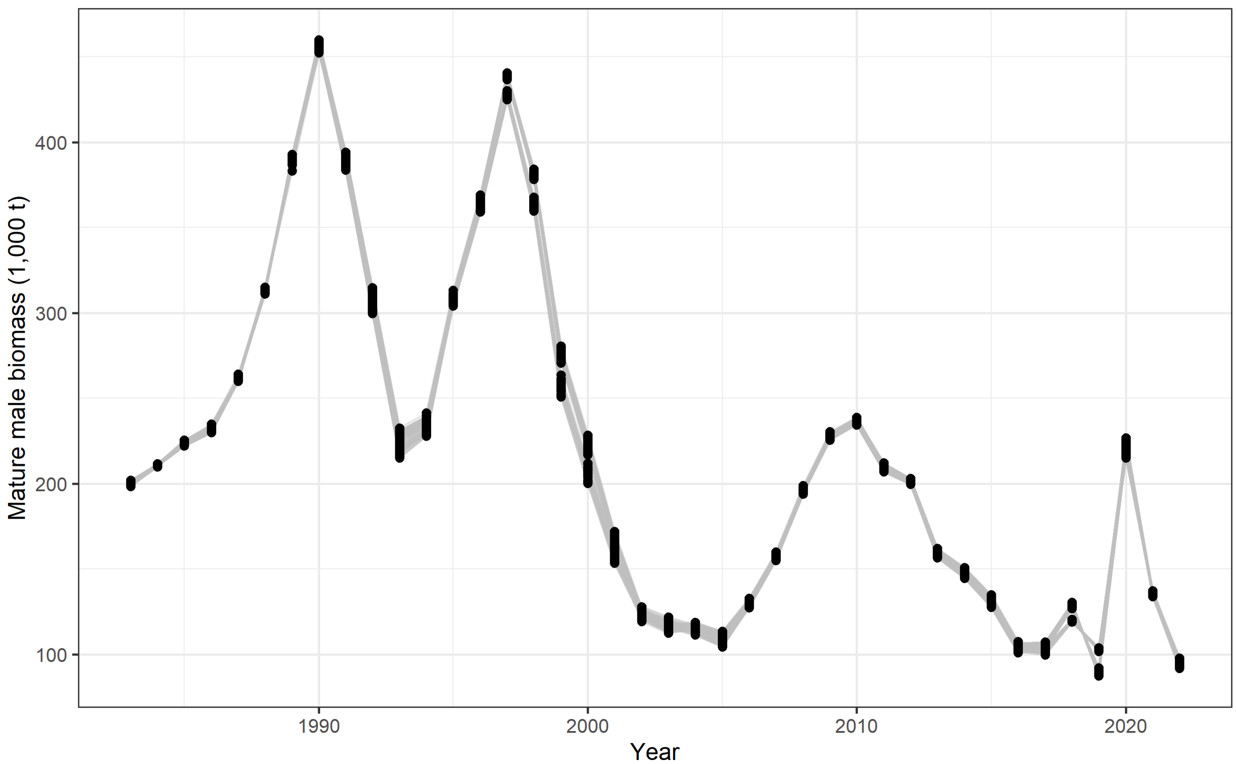

Figure 38: MMB trajectories from 100 iterations of the GMACS jittering algorithm.

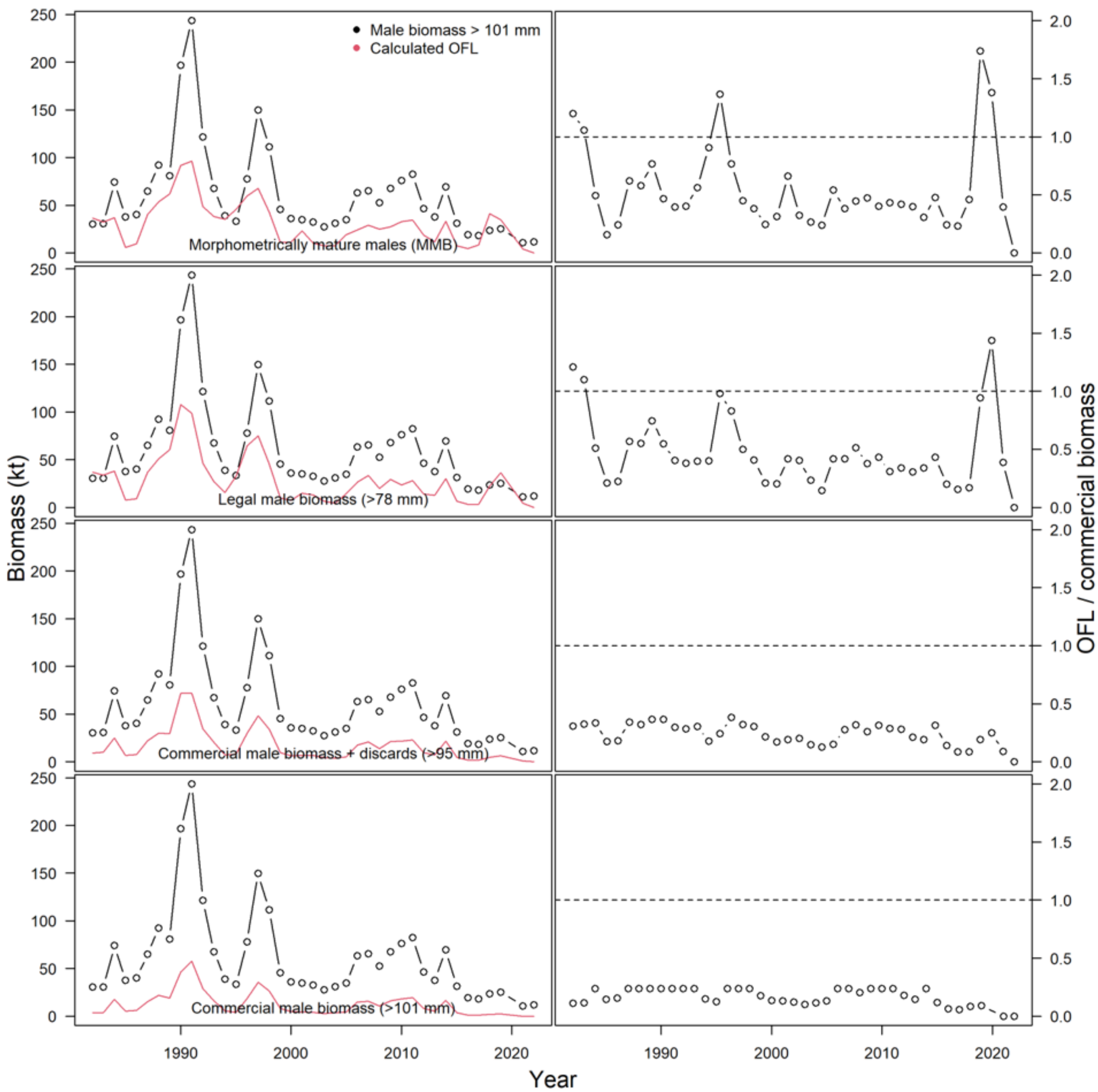

Figure 39: Tier 4 currency of management issues.

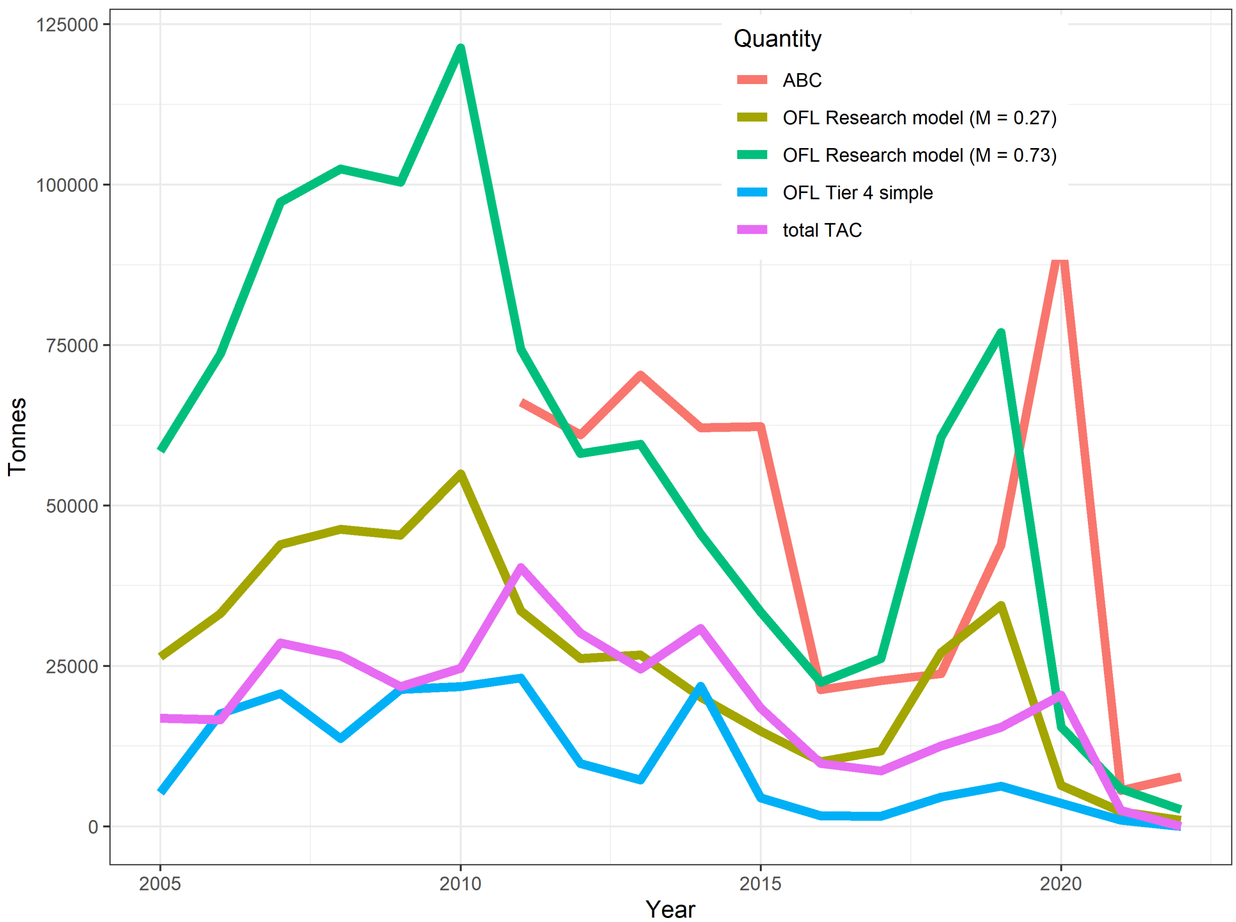

Figure 40: Retrospective comparison of OFLs calculated from the research model given two different assumptions about the FMSY proxy, the OFL resulting from the simplest tier 4 method, and the actual ABCs and TACs used in management in the post-rationalization period.